Regulatory review and CO2 hazards

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Authorisation

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Executive summary

International shipping takes care of the movement of goods and products between nations. It has the lowest carbon footprint per tonne for long-range transport but still creates around 2.5% of global CO2 emissions. The maritime sector has pledged to reduce these emissions by 50% by 2050 compared with their 2008 level.

Different low-carbon technologies are being explored, including ship-based carbon capture (SBCC), which could provide a solution compared to zero-emission fuels, such as ammonia and hydrogen. The EverLoNG project aims to encourage the uptake of SBCC by demonstrating its use on board LNG-fuelled ships and moving it closer to market readiness.

This report has been prepared to meet the requirements of EverLoNG project deliverables D5.1.1 and D5.1.3 and consists of three main sections:

- Identify applicable safety and environmental standards and codes.
- Major hazard of CO2 loss of containment.
- Assessment of technology novelty.

To identify the applicable safety and environmental standards and codes in a systematic way, ship-based carbon capture was divided in four main steps: CO_2 capture, CO_2 liquefaction, on-board CO_2 storage and CO_2 offloading. For each step, the per component generic hazards were listed over the course of several online workshops and meetings based on the partners' in-house knowledge, the HAZOP workshops performed for the EverLoNG containerised prototype as well as public sources.

A review of the generic hazards against existing regulations and standards indicated that, at this stage, not all aspects of a SBCC system are covered by prescriptive regulations or standards. While the technology status of equipment in SBCC was considered proven, the application on board ships of CO_2 recovery, solvent regeneration and large volume CO_2 offloading on other than CO_2 tankers were considered new.

A number of Classification Societies have already published Class Rules for SBCC installations, and others are expected to follow. Until then, Classification Societies and Flag States have the risk-based "alternative design" tools available to perform approval for early movers utilizing requirements for similar existing ship equipment and installations. Based on that, it can be concluded that there are no Regulatory, Class Rules or Standard barriers to implementing ship-based carbon capture. The identified potential risks, however, need to be properly assessed and adequately addressed.

A substantial number of the generic hazards were associated with loss of containment. No matter how good systems are designed, build and maintained, there remains a residual risk of equipment and pipework failure, which in turn could lead to a releases of process liquids and gases. A good design accounts for all probable leakage scenarios and implements appropriate safeguards to prevent or mitigate their associated consequences.

Having a good handle on what to expect, in terms of risks, at the start of a design allows for better and inherently safer designs to be created and reduces the risk of costly last-minute design changes required to meet the required levels of safety. Noting the large quantities of CO_2 needed to be captured and stored onboard, designers will need to consider a vast array of release scenarios. Part of this report was therefore aimed to deliver to designers, as well as reviewers, order of magnitude estimates for a wide range of CO2 release scenarios. By plotting the results in easy-to-use engineering

diagrams, designers can quickly find reasonable estimates. Equally, reviewers can use them to cross-check results from submitted detailed analyses and confirm if they are in-line with expectation. In no way or form are the diagrams in this report meant to replace sound engineering calculations that take design specific elements properly into account.

For any CO_2 release, the potential to cause harm is directly correlated to the number of persons present, the ability of the CO_2 to freely disperse and the safety distances adhered to. In other words, a CO_2 release can only cause harm if there is a person present and the concentration is sufficiently high. It may therefore come as no surprise, that the same release indoor or outdoor, could have significantly different consequences. Where the engineering diagrams were calculated for outdoor releases only, the indoor calculations showcase the effects of similar releases in a confined space.

To model outdoor release and dispersion representative environmental conditions are required. EverLoNG identified a gap in the industry standards, as to the authors' knowledge no global unified approach existed for recommended weather criteria in the marine industry, i.e. similar to what various States prescribe for land-based installations. Therefore, EverLoNG decided to interrogate 10-years' worth of historic weather data for various port locations around the world, in order to establish unified weather conditions for use in maritime dispersion analyses.

The results indicate that the Pasquill Stability Class "D" is most prevalent, 51.2% of the time, with the stability classes "D", "E" and "F" accounting for 76.8% of the total weather conditions. It was further established that 95% of the windspeeds are above 1 m/s and equally, 95% of the windspeeds are below 8 m/s. Based on these statistical analyses, EverLoNG recommends using the following unified weather conditions for ship-based dispersion analyses:

- D1 – *Neutral stability at 1 m/s as minimum windspeed.*
- F1 – *Stable at 1 m/s to conservatively showcase the impact of reduced turbulence.*
- D8 – *Neutral stability at 8 m/s as maximum windspeed.*

Using these unified weather conditions, outdoor dispersion was calculated for systematic variations in pipe diameter *(1" to 12")*, hole size *(1mm to full-bore)*, pressure *(5 to 60 barg)* and physical state *(gas or liquid)*. For comparison purposes against the indoor release cases, also the expanded volumetric release rates were plotted at different pressures, hole sizes and pipe diameters and a reasonable agreement was found.

To provide insight in how quickly an enclosed space would fill with CO_2 in case of pipe or equipment failure, three 4-millimetre leaks at different pressures *(10, 40 and 60 barg)* were modelled inside an unventilated 20-feet ISO container using 3D viscous CFD. The main objective was to estimate conservative orders of magnitude of time to reach hazardous CO_2 concentrations, assuming the leak would be detected and isolated in 30 seconds. The simulations indicated that CO_2 concentration above the "*Immediately Dangerous To Life or Health"* (IDLH) concentration of 40,000pmm would be reached within 14 and 10 seconds respectively for the 40 and 60 barg releases, with the IDLH level reached everywhere in the container after the release was stopped. For the 10 barg release, the IDLH level was only reached directly downstream to the leak point, up to about 1 m away, with no CO_2 concentration above IDLH once the release was stopped.

Based on the CO_2 release modelling, as well as the other findings reported in this document, the following recommendations can be made:

- Carry out detailed dispersion analyses for CO_2 offloading operations, in which the system specific safeguards are taken into account. Based on these analyses, sound safety distances can be set.
- Mechanical ventilation should be set in enclosed spaces containing risk of CO_2 leak. Further calculations are needed to determinate appropriate Ac/h. *(Note: Also refer to SOLAS 2/10.4.3/ for CO_2 storage in the case of fire-extinguishing medium and IGC Code Chapter 12-Artificial ventilation in the cargo area as framework for CO2 handling.)*
- As far as practicable, the CO_2 detectors should be located in the ventilation path, downstream to CO_2 piping and equipment.
- The layout of piping and equipment should be optimized to limit CO_2 accumulation.
- Carry out dedicated risk assessments for enclosed spaces, noting that the risk of asphyxiation resulting from smaller leaks is credible. Special attention needs to be paid to available escape times, especially when high pressure CO_2 systems are considered.

In summary, it can be concluded that the regulatory framework exists and is currently being expanded for the implementation of ship-based carbon capture (SBCC). The risks associated with SBCC installations are credible but well understood, with well-established safeguards and design principles available from other parts of the marine industry, like LNG-fuelled vessels. The authors hope with publicising this document, that designers, shipyards, ship-owners & -operators and reviewers obtain detailed insight in the risks associated with the technology, leading to inherently safer designs and a smooth approval process. In short, ship-based carbon capture can be implemented today.

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List of symbols and abbreviations

ACH	Air Change per Hour
BLEVE	Boiling Liquid Expanding Vapour Explosion
CCC	IMO sub-committee on Carriage of Cargoes and Containers
CFD	Computational Fluid Dynamics
CO	Carbon monoxide
CO_2	Carbon dioxide
FLACS	FLame ACceleration Software
GHS	Global Harmonised System
HAZID	HAZard IDentification
HAZOP	HAZard OPerability
HSE	UK Health and Safety executive
IDLH	Immediately Dangerous to Life or Health
IGC code	IMO International code for the Construction and equipment of ships Carrying liquefied Gases in bulk
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LoC	Loss of Content
MEA	Monoethanolamine
NIOSH	US National Institute for Occupational Safety and Health
NOx	Nitrogen Oxides
PCC	Post Combustion Capture
SBCC	Ship-Based Carbon Capture
SIMOPS	SIMultaneous OPerationS
SOx	Sulphur Oxides
US	The United States (of America)
UK	The United Kingdom
WP	Work Package

1. Introduction

1.1 Presentation of the EverLoNG project

International shipping takes care of the movement of goods and products between nations. It has the lowest carbon footprint per tonne for long-range transport but still creates around 2.5% of global CO2 emissions. The maritime sector has pledged to reduce these emissions by 50% by 2050 compared with their 2008 level.

Different low-carbon technologies are being explored, including ship-based carbon capture (SBCC), which could provide a solution compared to zero-emission fuels, such as ammonia and hydrogen.

The EverLoNG project aims to encourage the uptake of SBCC by demonstrating its use on board LNG-fuelled ships and moving it closer to market readiness.

1.2 Scope of this document

This report has been prepared to meet the requirements of EverLoNG project deliverables D5.1.1 and D5.1.3.

This report consists of three main sections as follows:

- Review of existing regulatory regime
- Major hazard of CO_2 loss of containment
- Assessment of technology novelty

Part 1: Review of existing regulatory regime

1 Methodology

Before the SBCC technology can be implemented on-board, a regulatory framework for the technology needs to be in place. In EverLoNG, the technology developers collaborate closely with three major Class Societies *(BV, LR, DNV)* to ensure that the design will be in line with available regulations regarding safety.

This subtask identifies and reviews the applicable safety and environmental technical requirements for the design and arrangement, construction and operation for SBCC systems. The review includes the existing requirements from the marine industry but also applicable references from the other industries. In order to achieve this goal, a workshop was put in place during several sessions to answer the following questions based on a as generic as possible design of a SBCC system:

a. What are the key elements of a Carbon Capture and Storage systems?
b. What are the associated risks for each element and the possible interactions?
c. Do we already have existing regulation covering those elements and/or risk?
d. What are the topics to be addressed by a future regulation?

Answers provided by the participants were recorded in a table and reviewed by all. Several iterations were needed to complete this document considering the diversity of elements and their interactions.

2 Description of considered technologies

The purpose of this section is to provide an overview of the existing technologies in terms of carbon capture. This overview is not limited to maritime application.

Three main methods exist for the capture of CO_2:

- ***Post-combustion capture***: capture of CO_2 from exhaust gases once the fuel has been burned with air. Several technologies for post combustion CO_2 separation exist:
    - **Chemical absorption**: Chemical contact with a solvent in absorption column (**Figure 1**). Chemical absorption by use of monoethanolamine (MEA) is by far the most advanced and used technique for carbon capture. This is the technology selected in EverLoNG.

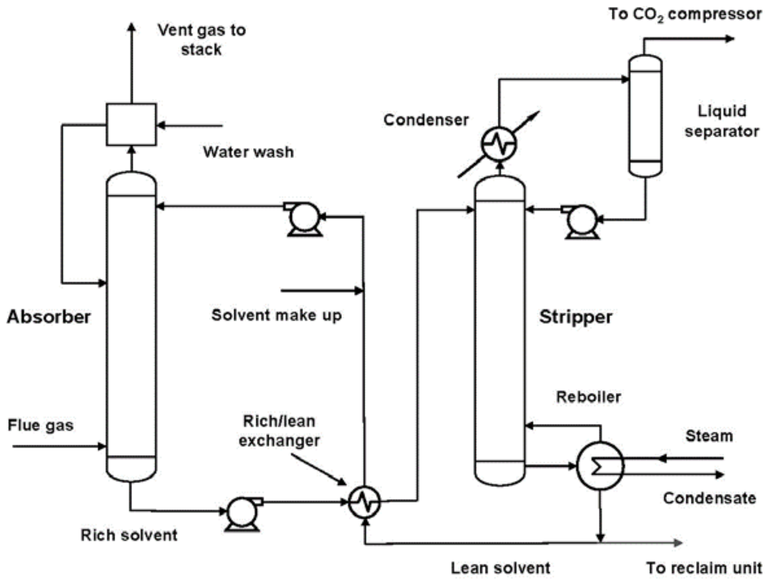

*Figure 1 Principle of chemical absorption carbon capture process **[1]***

    - **Physical absorption**: Physical separation using a solvent (ionic liquid).
    - **Physical adsorption**: Physical separation using a solid adsorbent (**Figure 2**).

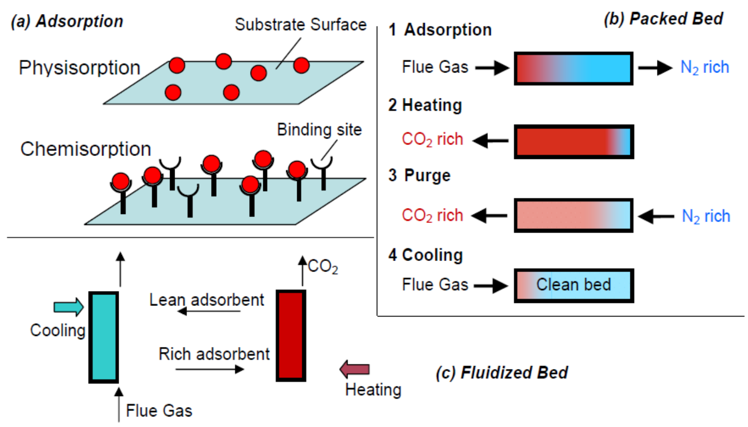

*Figure 2 Principle of physical adsorption carbon capture process **[1]***

- **Membrane filtration**: Separation using a polymeric or ceramic membrane (**Figure 3**).

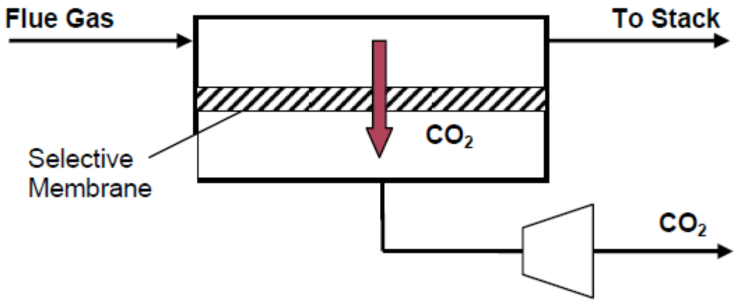

Figure 3 Principle of membrane filtration carbon capture process ***[1]***.

- **Cryogenic distillation**: Separation by cooling and condensing CO_2 (**Figure 4**).

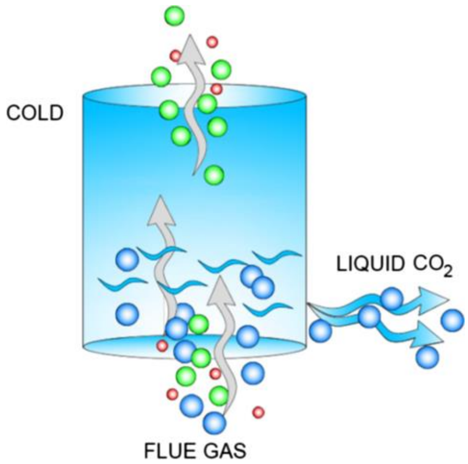

Figure 4 Principle of cryogenic distillation carbon capture process ***[2]***

- ***Pre-combustion capture***: capture of CO_2 in a synthesis gas after conversion of carbon monoxide (CO) into CO_2. Then, the fuel is hydrogen.
- ***Oxy-fuel combustion***: combustion in oxygen rather than in air, resulting in high CO_2 content in the combustion gases.

The ship-based carbon capture can be divided in four main steps: CO_2 capture, CO_2 liquefaction, on-board CO_2 storage and CO_2 offloading. An overview of those steps is provided below, with a specific focus for the most mature options for maritime application.

a. CO_2 capture (chemical absorption)

The CO_2 capture process by absorption consists of three main sections: exhaust gas pre-treatment, CO_2 recovery and solvent regeneration. Firstly, the exhaust gas is pre-treated in a direct contact cooler *(also named cooling tower or quench tower)* in order to cool the exhaust gas, control its pH *(caustic soda is used for reducing sulphur dioxide (SO_2) emissions in the exhaust gases)* and potentially to remove impurities *(removal of impurities in exhaust gas can be done upstream)*. Then, the pre-treated exhaust gas enters the CO_2 absorber column *(also named absorption tower)* at about 40-60°C where the CO_2 in the exhaust gas is chemically absorbed by the lean solvent. The rich solvent from the CO_2 absorber is then heated by the lean solvent in the lean-rich heat exchanger and directed to the CO_2 desorber column *(also named regeneration tower or stripper)*. In that, the CO_2 is stripped from the rich solvent at ab. 100-120°C. The lean solvent from the CO_2 desorber is then cooled in the lean-rich heat exchanger and re-directed to the CO_2 absorber. Finally, the CO_2 from the CO_2 desorber is washed and sent to the liquefaction unit. Refer to EverLoNG deliverable D1.2.1 **[3]** for more details about the design basis of EverLoNG (**Figure 5**). In EverLoNG, the selected solvent is amine (MEA).

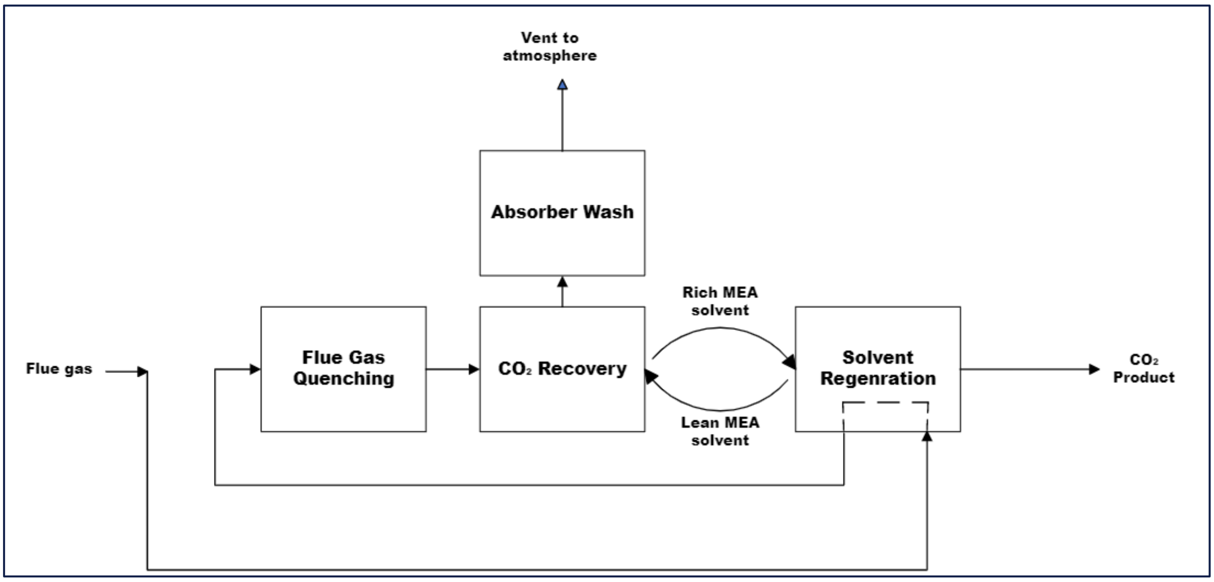

Figure 5 Block flow diagram of the capture process [3].

b. CO_2 liquefaction

The liquefaction process consists of three main sections: CO_2 compression, water removal and CO_2 liquefaction. Firstly, the wet CO_2 is compressed to the desired liquefaction pressure and water is removed by condensation to prevent hydration. After the compression train, the last water content is removed by a dryer. Finally, the CO_2 is condensed and non-condensable gases are removed. To condensate the CO_2, several options are possible, e.g. by Joule-Thomson effect, by liquefaction using a refrigerant or cryogenic fluid, etc. Also refer to EverLoNG deliverable D1.2.1 **[3]** for more details about the design basis of EverLoNG (**Figure 6**). In EverLoNG, two liquefaction options are investigated: Joule-Thomson effect in the prototype solution and LNG in the full-scale solution.

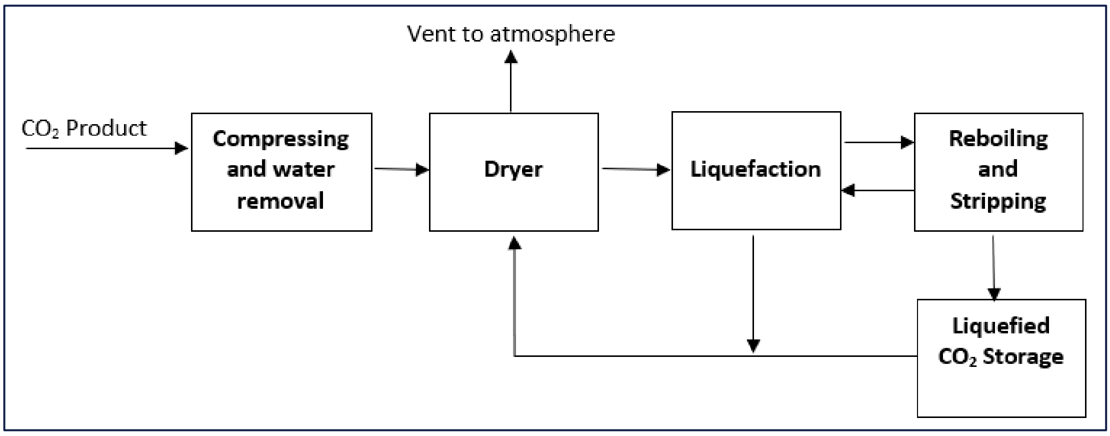

Figure 6 Block flow diagram of the liquefaction process ***[3]***

c. On-board CO_2 storage

In early stage of Ship-Based Carbon Capture, liquid CO_2 is expected to be temporary stored onboard in independent pressurized storage tank. The range of storage tank pressure is about 7 barg *(low pressure)* or from 15 to 20 barg *(medium pressure)*. To reduce the energy required for liquefaction, a pressure of 15-20 barg is more favourable. The storage tank pressure and temperature are maintained at all times by reliquification of CO_2 vapours or liquid CO_2 cooling.

d. CO_2 offloading

When offloading CO_2 from a ship, there are multiple ways this can be arranged:

- Onshore for land-based utilization.
- Onshore for permanent underground storage.
- Offshore for permanent underground storage.
- Offshore with intermediate storage *(e.g. ship-to-ship)*.

CO_2 may be offloaded as a container-swap or via offloading pipe depending on the cargo handling facility availability on the ship. It shall be noted that, for various carbon capture technologies, the logistics related to carbon capture medium *(e.g. chemical solvent)* shall also be addressed. Also refer to Maelum et al **[4]** for more details about CO_2 offloading and port integration in EverLoNG.

3 Identified hazards

General hazards were identified in order to support the review of the existing regulations. **Table 1** provides a preliminary list of hazards. This list is non-exhaustive and needs to be further developed for the HAZID workshops that will be conducted later in the project.

Table 1. List of identified hazards

Hazard category	Hazard	Related system(s)	Category
Loss of containment			
CO_2	Asphyxiation / toxicity	Capture (after regeneration tower), Liquefaction, Storage, Offloading	Safety, Environmental
	Low temperature Sublimation	Liquefaction (after CO_2 condenser), Storage, Offloading	
	BLEVE	Storage	
Amine	Flammability Toxicity Corrosivity Pollution	Capture (rich and lean amine loop)	Safety, Health, Environmental
Caustic soda	Chemical	Capture (caustic soda storage)	Health
Thermal oil	Flammability High temperature Pollution	Capture, Liquefaction (if thermal oil used)	Safety, Environmental
Water	High temperature Pollution	Capture, Liquefaction (water drum, cooling water, water removal in compression)	Safety, Environmental
LNG (if used to liquefy the CO_2)	Flammability Cryogenic	Liquefaction	Safety
Operational hazards	Malfunction, poor operation	Capture, Liquefaction, Storage, Offloading	Safety, Operational
	Unburnt fuel, SOx, NOx “slip”	Capture	Environmental
	Overpressure	Capture (pumps), Liquefaction (compression, drying, liquefaction)	Safety
	Crossover	Capture, Liquefaction (heat exchangers)	Operational
	Noise, vibration	Liquefaction (compressors)	Safety, Health
	Moving parts	Liquefaction (compressors)	Safety
	Sloshing	Storage	Safety

Hazard category	Hazard	Related system(s)	Category
	Lifting	Storage (if portable or containerized)	Safety
SIMOPS	LNG bunkering (if LNG-fuelled ship)	Offloading	Safety
Emergency situations	Collision Grounding Fire/Explosion	N/A	Safety
	Emergency venting	Storage	Safety, Environmental
Impact from adjacent areas	Cargo handling	N/A	Safety

In particular, the hazards related to equipment handling CO_2 are:

1. **Asphyxiation / toxicity:** CO_2 is considered as an asphyxiant substance **[5]** and can be considered as a toxic substance **[6]**, even if not classified as an acutely toxic substance **[7]**. Indeed, CO_2 has effect on blood acidity, triggering adverse effects on the respiratory, cardiovascular and central nervous systems. Many countries provide exposure limits for long term exposure *(e.g. 8 hours)* at 5 000 ppm (0.5 % vol/vol) and for short term exposure *(e.g. 15 minutes)* between 15 000 and 30 000 ppm (1.5-3.0 % vol/vol) **[6]**. Immediately Dangerous to Life or Health (IDLH) is given at 40 000 ppm (4.0% vol/vol) by the US National Institute for Occupational Safety and Health (NIOSH). The IDLH is defined as the maximum exposure concentration for a given chemical in the workplace from which one could escape within 30 minutes without any escape-impairing symptoms or any irreversible health effects. Unconsciousness in few minutes of exposure may be encountered above 7 000-8 000 ppm (7.0-8.0 % vol/vol) and death above 15 000 ppm (15.0 % vol/vol). The UK Health and Safety Executive (HSE) provides the probit constants linking the concentration *(C in ppm)*, exposure time *(t in minutes)* and probit value (Pr):

   $$Pr = -90.8 + 1.01 \times \ln(C^8 \times t)$$

   The probability of fatality is then estimated from this probit value. Acute effects due to asphyxiation occurs at higher CO_2 concentrations than the ones due to toxicity.

2. **Low temperature:** CO_2 can be stored in its liquid state at temperature below 0°C. Moreover, when depressurized *(e.g. accidental release)*, the expansion to the atmosphere will decrease the temperature of the fluid. Temperatures below -30°C may become harmful.
3. **Sublimation:** At atmospheric pressure, CO_2 is either gaseous or solid. Its temperature of sublimation is -78.5°C. Its triple point is 5.18 bar and -56.6°C. When depressurized, solid CO_2 may form a plug and block equipment or piping.
4. **BLEVE:** Boiling Liquid Expanding Vapour Explosion (BLEVE) is a rapid vaporization of a liquid *(e.g. liquefied gas)* caused by a sudden failure of a vessel containing the pressurized liquid at a temperature well above its normal *(atmospheric)* boiling point. BLEVE is a very unlikely but catastrophic phenomenon. In the past, BLEVE of CO_2 storage tanks have already happened.

The identified process hazards are standard for process units. Also refer to the HAZOP workshop of the prototype conducted in WP1 and reported in the EverLoNG deliverable D1.2.1 **[3]** for more details.

Simultaneous operations (SIMOPS) were identified as a potential hazard, especially for LNG-fuelled ship. Simultaneous LNG bunkering and CO_2 offloading *(if expected)* should be regarded with attention.

The identified hazards related to emergency situations and impact from adjacent areas are standard for ships. The identified hazards related to SIMOPS, emergency situations and impact from adjacent areas are not necessary originating from the SBCC system. They were rather identified as main hazards from the exterior that can impact the SBCC system. The CO_2 storage tank was identified as a critical target as regards those hazards.

Finally, **Table 2** provides a summary of the identified hazards per group of components of SBCC system. This table aims at guiding SBCC designers in their risk assessment.

Table 2. Identified hazards per component

CO_2 systems	**Specific component**	**Hazard category**	**Hazard**	**Category**
1. Capture	After regeneration tower	LoC of CO_2	Asphyxiation / toxicity	Safety, Environmental
	Rich and lean amine loop	LoC of amine	Flammability Toxicity Corrosivity Pollution	Safety, Health, Environmental
	Caustic soda storage	LoC of caustic soda	Chemical	Health
	If thermal oil used	LoC of thermal oil	Flammability High temperature Pollution	Safety, Environmental
	Water drum, cooling water, water removal in compression	LoC of water	High temperature Pollution	Safety, Environmental
		Operational hazards	Malfunction, poor operation	Safety, Operational
	Exhaust line		Unburn fuel, SOx, NOx “slip”	Environmental
	Pumps		Overpressure	Safety
	Heat exchangers		Crossover	Operational
2. Liquefaction	-	LoC of CO_2	Asphyxiation / toxicity	Safety, Environmental
	After CO_2 condenser		Low temperature Sublimation	
	If thermal oil used	LoC of thermal oil	Flammability High temperature Pollution	Safety, Environmental
	Water drum, cooling water, water removal in compression	LoC of water	High temperature Pollution	Safety, Environmental
	If used to liquefy the CO_2	LoC of LNG	Flammability Cryogenic	Safety

CO_2 systems	Specific component	Hazard category	Hazard	Category
	-	Operational hazards	Malfunction, poor operation	Safety, Operational
	Compression, drying, liquefaction		Overpressure	Safety
	Heat exchangers		Crossover	Operational
	Compressors		Noise, vibration	Safety, Health
	Compressors		Moving parts	Safety
3. Storage	-	LoC of CO_2	Asphyxiation / toxicity Low temperature Sublimation BLEVE	Safety, Environmental
	-	Operational hazards	Malfunction, poor operation	Safety, Operational
	-		Sloshing	Safety
	If portable or containerized		Lifting	Safety
	-	Emergency situations	Emergency venting	Safety, Environmental
4. Offloading	-	LoC of CO_2	Asphyxiation / toxicity Low temperature Sublimation	Safety, Environmental
	-	Operational hazards	Malfunction, poor operation	Safety, Operational
	-	SIMOPS	LNG bunkering *(if LNG-fuelled ship)*	Safety

4 Review of existing regulation

Considering the equipment and hazards pointed out during the first sessions of the workshop, a list of existing regulation has been identified. Those regulations may be of different kinds. Some of them are directly applicable to the SBCC system or parts of it, other may act as a guidance considering they cover similar technology systems or operational aspects.

Except for Class Rules that were recently published (see **Part 1-5.3**), none of them are dedicated to SBCC. However, they can provide valuable insight for most of the equipment considered.

Table 3 below provide a list of regulation of interest and their applicability field:

Table 3 List of identified regulations

Entity	Reference	Field	Scope	Applicable to:
IMO	SOLAS	Safety	Safety Of Life At Sea Convention	Part II-1 and II-2 gives generic requirements applicable to equipment regardless of their specificities as SBCC
	IGF CODE	Safety	Code of Safety for Ships using Gases or other Low-flashpoint Fuels	Guidelines as it is applicable to the use of tanks other than CO_2 tanks
	IGC CODE	Safety	Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk	Guideline as it is applicable to the sea transportation of liquefied CO_2 in bulk
	MEPC.340(77)	Environmental	2021 Guidelines for exhaust gas cleaning systems	Water removal and discharge system
	IBC Code	Safety	Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk	Guideline as it is applicable to the sea transportation of MEA in bulk
	IMDG Code	Safety	Code for the maritime transport of dangerous goods in packaged form	Guideline as it is applicable to the sea transportation of

				MEA in packaged cargo
	MARPOL	Environmental	Convention for the Prevention of Pollution from Ships	Guideline for amine as it is applicable to carriage, not use
	London Convention+ Protocol	Environmental	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter	Disposal of captured CO_2 under seabed
	FSS Code Ch. 5	Safety	Fire-Safety Systems Code	Guideline as it is applicable for CO_2 storage for fire-extinguishing system
	STCW	Operational	Convention on Standards of Training, Certification and Watchkeeping for Seafarers	Basic requirements on training, certification and watchkeeping for seafarers on an international level
IACS	UR M78	Safety	Safety of Internal Combustion Engines Supplied with Low Pressure Gas - Rev.1 Feb 2021	Gas fuelled engine, if any, upstream of the CO_2 capture system to cover risks related to inputs in the system
	UR M81	Safety	Safety measures against chemical treatment fluids used for exhaust gas cleaning systems and the residues which have hazardous properties - New Jan 2021	Caustic soda system for CO_2 capture, if any.
	UR M46	Operational	Ambient conditions –	Equipment that could be affected

			inclinations - Rev.2 Dec 2018	by inclinations, e.g. absorber
Class Societies	Rules	Safety	Classification rules of each Class society covering safety aspects.	For Rules dedicated to SBCC, see **Part 1 - 5.3** Other Rules are applicable for most equipment entirely when they are not specific to the system (e.g. cooling water system) or completed with dedicated rules
ISO	18683:2015	Safety	Guidelines for systems and installations for supply of LNG as fuel to ships	Normally applicable to LNG: elements of interest that can be relevant for CO_2 offloading
	20519:2017	Safety	Ships and marine technology - Specification for bunkering of gas fuelled ships	Normally applicable to LNG: elements of interest that can be relevant for CO_2 offloading
Other	EIGA Doc 56/21	Recommendations	Guide for the delivery of bulk carbon dioxide	CO_2 offloading: good practices to avoid hazards related to CO_2 transfer

At this stage, not all aspects of a SBCC system are covered by prescriptive standards or regulation. It is in fact necessary to categorize the new technology used in order to evaluate regulations suitability and to what degree a risk-based "alternative design" will be necessary. This topic has been dealt with in subtask 5.1.3 and the conclusions are given in Part 3 of this report.

5 Ongoing work at the international level

5.1 IMO MEPC status

a. MEPC 78 *(June 2022)*

Minimal discussion around onboard CO_2 capture has taken place recently, particularly around calculation, verification and certification of systems within the existing short-term GHG emissions reduction framework. With a view to promoting this technology, a proposal suggesting options to show CO_2 emissions reduction as a consequence of capture and removal on board by modifying the existing EEDI and EEXI calculation formulas was discussed during MEPC 78, a variety of views were expressed on the matter, including those suggesting that onboard CO_2 capture should be addressed via operational means rather than instruments such as EEXI and EEDI that are design related, discussions are expected to continue.

MEPC 78 invited interested Member States and international organizations to submit further information and concrete proposals to future sessions.

b. MEPC 79 *(December 2022)*

MEPC deferred discussion on a number of proposals on the use of carbon capture technology in GHG regulations under MARPOL Annex VI to MEPC 80 *(July 2023)*.

MEPC will consider including obtained CO_2 reduction in the regulatory framework for the calculation of CO_2 emissions at the design (EEDI/EEXI) and operational (CII) stages, as well as the forthcoming LCA Guidelines.

Accordingly, the following are proposed:

- Draft MEPC.1 circular on sample format for the information to be included in the CO_2 Receipt Note, providing evidence for the quantity of CO_2 delivered ashore.
- Draft amendments to MEPC.308(73) 2018 Guidelines on the method of calculation of the Attained Energy Efficiency Design Index (EEDI) for new ships to amend the EEDI Formula, and to incorporate Carbon Capture system for Ship Exhaust gas (CCSE).
- Draft amendments to MEPC.352(78) 2022 Guidelines on operational Carbon Intensity Indicators and the calculation methods (CII Guidelines, G1).
- Draft amendments to the MEPC.254(67) 2014 Guidelines on survey and certification of the Energy Efficiency Design Index (EEDI) to incorporate CCSE; and to establish a correspondence group to consider the proposals. Another proposal requests MEPC to establish a dedicated work stream for Carbon Capture and Storage (CCS) to:
    - Review the status of technological development on onboard carbon capture applications and their potential to reduce GHG emissions.
    - Identify possible options for the accounting, verification and certification of CO_2 captured onboard ships.
    - Consider how to incorporate carbon capture in the IMO's regulatory framework, both current and future. Implication: If agreed this will provide a mechanism for carbon capture technology to be included in the short-term GHG reduction measures, and in future GHG reduction measures.

If agreed, carbon capture technology could be available to assist those ships to which EEDI, EEXI and CII apply, but also to any ships to which future GHG reduction measures apply.

c. MEPC 80 *(July 2023)*

Attention will now be turning to MEPC 80 due in July, given that important regulatory decisions have been deferred to this meeting. Primarily, the issue of agreeing a revised IMO GHG reduction strategy will be addressed, with mounting pressure from a broad and growing number of member states. Also, up for agreement is the role of carbon capture and storage (CCS) technology in the context of emission reduction strategies.

5.2 IACS status

With the development and use of new technologies for the use of carbon capture and storage technologies (CCS), the maritime industry is increasingly seeking practical, technical, and operational standards to address the safety aspects of these new technologies and fuels.

IACS established a Safe-Decarbonisation Panel (SDP) to show its determination to support industry through this challenge. To help deliver common technical requirements at speed, the SDP convene a project team to work on carbon capture and storage. SDP has also adopted a structured consultative approach so that stakeholders – technology providers, owners, builders and marine insurance – have opportunities to engage with IACS at different levels in order to allow for the resulting outputs to be properly targeted either in the form of IACS Resolutions or recommendations or submissions to IMO to support the development of detailed regulations.

5.3 Class Rules status

Most of the Classification Societies are working on SBBC and are in the process of developing dedicated rules. Among them:

- Bureau Veritas published in January 2023 a new set of rules in NR 467 Part C, Chapter 1, Section 12 "Onboard Carbon Capture and Storage Systems" **[8]** and a corresponding additional service feature named OCC. This section introduces requirements for ships fitted with an onboard carbon capture and storage (CCS) system intended to separate the carbon-dioxide (CO_2) from the exhaust gases and store it on board. It covers systems using an amine-based absorption process for CO_2 capture, compression or liquefaction process before storage and offloading. It addresses the safety aspects of such a system regarding the general design, arrangement and installation of the CO_2 system and the solvent components, the personnel protection and the certification of equipment and related survey at works.

- Lloyd's Register published in March 2023 new rules requirements in the existing Part 5, Ch. 24 Emissions Abatement Plant for Combustion Machinery named "Emissions Abatement Carbon Capture and Storage (EACCS)" in Section 13/ "Class notations EACCS" and "Descriptive notes READY EACCS''**[9]**. It introduces rule requirements for the design, construction and installation survey of EACSS and also for preparation of a vessel to receive an EACSS. Requirements associated to the new class notation addresses the safety risks they may present to the vessel, covering aspects such as materials, structure, containment, piping, refrigeration plant, electrical, control, safety systems, vessel integration and manufacturing. Requirements associated to the descriptive note covers aspects related to the preparation of a vessel for the future installation and integration of an EACCS, such as structures, layout, interfacing, materials, electrical and safety systems.

- ABS published in December 2022 a new document "Requirements for onboard carbon capture and storage" **[10]** establishing the requirements for the use of Onboard Carbon Capture and Storage (OCCS), focusing on wet scrubbing post-combustion technologies and defining two notation *"EGC-OCCS"* and *"EGC-OCCS Ready"* with an indication on the level of readiness. It is intended as an extension of the requirements for exhaust emission abatement and provide criteria for the arrangements, construction, installation and survey of machinery, equipment, and systems for marine and offshore assets with installed OCCS equipment to minimize risks to the vessel, crew, and environment.

5.4 EU's Emission Trading System (EU ETS)

The EU's legislative bodies have reached an agreement on including shipping in its Emission Trading System (EU ETS). The EU ETS is an emission cap-and-trade system where a limited amount of emission allowances – the cap – is put on the market and can be traded. The cap is reduced each year, ensuring that the EU's emission target by 2030 of 55% reduction, relative to 1990, can be met while becoming climate-neutral by 2050.

Under the EU ETS each company with ships trading in the EU/EEA is required to surrender emission allowances corresponding to a certain amount of its GHG emissions emitted over a calendar year. The emissions will be reported and verified through the existing EU MRV *(Monitoring, Reporting and Verification)* system, which will be revised and extended to cover necessary GHG emissions, ship types and sizes.

From 2024 the EU ETS will include ships above 5000 GT transporting cargo or passengers for commercial purposes. The EU MRV system will be extended from 2025 to apply to offshore ships above 400 GT and general cargo ships between 400 and 5000 GT transporting cargo for commercial purposes. Offshore ships above 5000 GT will from 2027 be included in the ETS. By 2026 the European Commission will review whether general cargo and offshore ships between 400 and 5000 GT will also be included in the ETS.

From 2024 the EU ETS will include CO_2 emissions only, while the EU MRV will be extended the same year to include reporting of methane (CH_4) and nitrous oxide (N_2O) emitted by ships. From 2026 the EU ETS will also include these two GHGs.

All 100% of emissions on voyages and port calls within the EU/EEA, and 50% of emissions on voyages into or out of the EU/EEA are subject to the EU ETS.

The emissions in scope for surrendering allowances will be gradually phased-in, starting with 40% of emissions according to the scope described above for 2024, increasing to 70% for 2025 and to 100% for 2026 onwards.

Certain activities are exempted or have reduced obligations to surrender allowances, such as certain ice classed ships, certain ships servicing low population islands without rail or road link or located in the outermost regions, and ships performing public service obligations.

Ships that fail to comply with the EU MRV requirements for two or more consecutive periods may be expelled and denied trading in the EU. Companies that fail to surrender allowances are liable to an excess emissions penalty and are still liable for the surrendering of the required allowances. Companies that fail to comply for two or more consecutive periods may be denied entry in the EU for all ships under its responsibility.

The ETS provides an incentive for CCS deployment. According to the EU legal framework, CO_2 that is captured and safely stored is considered as “not emitted” under the ETS. Since the 2015 amendment to the Emissions Trading Directive, capture, transport and storage installations are explicitly included in the ETS.

The European Parliament has approved that they will require shipping to be included in the EU’s Emissions Trading System (ETS).

5.5 London Protocol

The key objective of the London Protocol is to protect and preserve the marine environment from all sources of pollution by prohibiting unregulated dumping of wastes or other matter. An amendment in 2006 lead to the inclusion of carbon dioxide in Annex 1, thereby allowing storage of carbon dioxide under the seabed for permanent insolation.

While primarily aimed at preventing the export of wastes to non-Parties, Article 6 of the London Protocol also prohibits the transboundary transfer of carbon dioxide for the purpose of geological storage. An amendment to Article 6 was adopted in 2009 to allow for the export of carbon dioxide intended to be stored in sub-seabed geological formations. This amendment is not yet into force as it needs to be formally accepted by two-thirds of the Contracting Parties to the London Protocol. However, a preliminary solution was agreed, allowing for the provisional application of the 2009 amendment pending its entry into force by those Contracting Parties which have deposited a declaration on provisional application of the 2009 amendment.

The application of the London Protocol for the delivery for permanent storage of CO2 captured on ships still needs to be clarified and Norway is planning a separate proposal for consideration by the Governing bodies of the London Convention and London Protocol. Guidelines have been developed for the activity allowed for in the amended Article 6. (LC 34/15, annex 8)

One of the points addressed in the guidelines is a specific characterization of the carbon dioxide stream, including any incidental associated substances, and should include, as appropriate: the origin, amount, form and composition; the physical and chemical properties; toxicity, persistence and the potential for bioaccumulation. The guidelines further state that "if the carbon dioxide stream is so poorly characterized that proper assessment cannot be made of the risks of potential impacts on human health and the environment, that carbon dioxide stream shall not be dumped".

With respect to a characterization of the carbon dioxide stream as referred to in paragraph 20, different geological storage locations will have their own specifications when it comes to the purity of carbon dioxide that is accepted for storage. For ships using carbon capture technology, it would be useful to consider how the carbon dioxide delivered to a CO_2 terminal or a reception facility can be characterized. It could be done during the certification of the carbon capture technology and thereafter it could be follow-up by an annual analysis of the carbon dioxide.

Part 2: Major hazard of CO_2 loss of containment

1. Introduction

No matter how good systems are designed, build and maintained, there is always a residual risk of equipment and pipework failure, which in turn could lead to a releases of process liquids and gases. A good design accounts for all these probable leakage scenarios and implements appropriate safeguards to prevent or mitigate their associated consequences.

Therefore, having a good handle on what to expect, in terms of risks, at the start of a design allows for better and inherently safer designs to be created and reduces the risk of costly last-minute design changes required to meet the required levels of safety. Noting the large quantities of CO_2 needed to be captured and stored onboard, designers will need to consider a vast array of release scenarios.

The work done in Task 5.1.2 aims to deliver to designers, as well as reviewers, order of magnitude estimates for a wide range of CO_2 release scenarios. By plotting the results in easy-to-use diagrams, designers can quickly find reasonable estimates. Equally, reviewers can use them to cross-check results from submitted detailed analyses and confirm if they are in-line with expectation.

2. Intent

The engineering diagrams provided in this report are to provide system designers, as well as reviewers, with order of magnitude estimates for various CO_2 release scenarios. In no way or form are the diagrams meant to replace sound engineering calculations that take design specific elements properly into account.

3. Failure frequencies and leakage sizes

To be able to calculate the risks associated with various CO_2 release scenarios, one needs to know how often equipment or pipework fails and how large the typical hole sizes are. Owing to the typical low failure frequencies, obtaining this knowledge would require long-term statistical data collection on a significant number of installations. As a project specific failure data collection campaign would render almost any project financially unviable, industry wide data sources are often referred to. The OREDA handbooks **[11]** are one of the most commonly used sources for failure data in the oil and gas industry. Compiled with the assistance of universities, OREDA presents failure data from a large number of oil and gas industry installations. For the vast majority of equipment found in ship-based carbon capture installations reliability data and failure modes can be found in OREDA. It is duly noted that other sources for reliability data exist and may be more applicable to certain components.

For pipe failure frequencies and associated hole sizes, the UK HSE **[12]** has provided recommendations to be used in the oil and gas industry, as well as the land-based process industry. Their recommended failure frequencies cover different pipe diameters and couple them with reasonably foreseeable hole diameters, see **Table 4**. This includes when full bore ruptures need to be considered.

*Table 4 Failure rates as function of pipe diameter and hole size, reproduced from UK HSE **[12]***

Failure rates (per m per y) for pipework diameter, UK HSE [12] Item FR 1.3					
Hole size	**0 - 49**	**50 - 149**	**150 - 299**	**300 - 499**	**500 - 1000**
3 mm diameter	$1\cdot10^{-5}$	$2\cdot10^{-6}$			
4 mm diameter			$1\cdot10^{-6}$	$8\cdot10^{-7}$	$7\cdot10^{-7}$
25 mm diameter	$5\cdot10^{-6}$	$1\cdot10^{-6}$	$7\cdot10^{-7}$	$5\cdot10^{-7}$	$4\cdot10^{-7}$
1/3 pipework diameter			$4\cdot10^{-7}$	$2\cdot10^{-7}$	$1\cdot10^{-7}$
Guillotine	$1\cdot10^{-6}$	$5\cdot10^{-7}$	$2\cdot10^{-7}$	$7\cdot10^{-8}$	$4\cdot10^{-8}$

For the engineering diagrams, a systematic variation of pipeline diameters and hole sizes has been conducted, covering the wide range of pipework expected to be found in a ship-based carbon capture system. The intermediate values have been obtained by fitting straight lines through the available calculation points.

4. Outdoor vs. Indoor

For any CO_2 release, the potential to cause harm is directly correlated to the number of persons present, the ability of the CO_2 to freely disperse and the safety distances adhered to. In other words, a CO_2 release can only cause harm if there is a person present and the concentration is sufficiently high. It may therefore come as no surprise, that the same release indoor or outdoor, could have significantly different consequences.

The release location determines to large extend how the CO_2 disperses and whether it can pose a risk to human life. Onboard ships the releases can originate from pipelines and equipment located on the open deck, as well as inside the superstructure. Where outdoor releases can, generally, freely disperse with the prevailing wind, indoor releases disperse around complex geometries with or without the assistance of mechanical *(forced)* ventilation.

Outdoor releases are typically calculated with far field dispersion methods, like EFFECTS *(Gexcon)* **[13]** and PHAST *(DNV)* **[14]**, amongst others. The benefit for these methods is that they can calculate a large number of release scenarios quickly, i.e. under various weather conditions, thereby providing a holistic overview. For indoor releases more complex 3D CFD calculations are required for the detailed flow characteristics of the release and any mechanical ventilation, which heavily influences mixing and concentrations.

The work done in Task 5.1.2 therefore covers both outdoor and indoor releases. Where the engineering diagrams have been calculated for outdoor releases only, the indoor calculations showcase the effects of similar releases in a confined space.

5. Weather conditions

Where land-based carbon capture installations have fixed geographical locations, with well-defined weather conditions, ships navigate the globe. As weather conditions, especially wind, have a substantial impact on outdoor gas dispersion, the question arose which weather conditions to apply when assessing release scenarios onboard ships?

To the authors' knowledge, various States across the world have recommended weather criteria for land-based applications, but no global unified approach exists for the marine industry. Therefore, EverLoNG decided to interrogate 10-years' worth of historic weather data for various port locations around the world, in order to establish unified weather conditions for use in dispersion analyses.

5.1 Port selection

To derive unified weather conditions, representative for the vast array of weather conditions encountered by ships around the world, port locations were selected based on trade volume as well as geographical spread. This ensured that not only the busiest ports were captured, but equally the widest spread of global weather patterns. In total 54 ports were selected across 6 continents, plotted in **Figure 7**, with their names and locations provided in **Appendix 8.1**.

Figure 7 Global ports selected to derive unified weather conditions

5.2 Weather data source

Weather data for calculating wind speed and Pasquill Stability statistics was taken from the ERA5 global climate and weather database, which is a product of the EU Copernicus project **[15]**. Using reanalyses, ERA5 combines model data with global observations from across the world and provides a consistent dataset at hourly intervals. For all selected port ten-years' worth of data was download, between the 1st of January 2012 and the 31st of December 2021.

In-line with international standards and practices, the data download contained wind speeds in *"U"* and *"V"* direction at 10 metres above ground. In addition, the *"Total cloud cover"* and *"Surface solar radiation downwards"* were downloaded for the Pasquill Stability Class calculation.

5.3 Pasquill Stability Class

The Pasquill Stability Class is a *"method for categorizing the stability of a region of the atmosphere in terms of the horizontal surface wind, the amount of solar radiation, and the fractional cloud cover"* **[16]**. Atmospheric stability plays an important role in dispersion analyses, for a neutral atmosphere neither enhances nor inhibits mechanical turbulence, whereas an unstable atmosphere enhances turbulence and a stable atmosphere inhibits mechanical turbulence. Given that mechanical turbulence contributes significantly to the mixing of gasses, the dispersion *(read dilution)* of releases is directly depending on it.

The Pasquill Stability Class is based on based on time of day, wind speed, cloud cover and the sun's intensity. There are six Classes, ranging from "very unstable" to "stable", as shown in **Table 5**, which are assigned based on the parameters shown in **Table 6**. Using the parameters from the ERA5 database, a Pasquill Stability Class could be calculated on an hourly basis.

Table 5 Pasquill Stability Class definitions

Stability Class	Description
A	Very unstable
B	Moderately unstable
C	Slightly unstable
D	Neutral
E	Slightly stable
F	Stable

Table 6 Pasquill Stability Class assignment

	Solar radiation			Cloud cover		
	Day	Day	Day	Night	Night	Day
	High	Moderate	Low	4/8 - 7/8	< 3/8	> 7/8
Wind (m/s)	>700 W/m2	350-700 W/m2	<350 W/m2	%	%	%
< 2	A	A-B	B	F	F	D
2 - 3	A-B	B	C	E	F	D
3 - 5	B	B-C	C	D	E	D
5 - 6	C	C-D	D	D	D	D
> 6	C	D	D	D	D	D

5.4 Global ports weather statistics

For the 54 ports, ten-years' worth of data was download, resulting in 4,730,400 records that provided a $2.11 \cdot 10^{-7}$ record probability. In the statistical analyses, all records were considered independent and binned based on wind speed and Pasquill Stability. Non-uniform bin sizes were used for the wind speeds, which aligned with the Beaufort scale and provided higher fidelity in data dense ranges. The resulting probabilities of each wind speed and Pasquill Stability Class combination are provided in **Appendix 8.2**.

The results indicate that the Pasquill Stability Class "D" is most prevalent, 51.2% of the time, with the stability classes "D", "E" and "F" accounting for 76.8% of the total weather conditions. The mean wind speed averages around 3.3 m/s, which closely matches the 3.3 m/s calculated by Zeng et al **[17]**. Using the cumulative sums, it can further be established that 95% of the windspeeds are above 1 m/s. Equally, 95% of the windspeeds are below 8 m/s.

5.5 Unified global weather conditions for release scenarios

Based on the global ports weather statistics, the following 3 weather conditions are recommended to be used for ship-based dispersion analyses:

- D1 – *Neutral stability at 1 m/s as minimum windspeed.*
- F1 – *Stable at 1 m/s to conservatively showcase the impact of reduced turbulence.*
- D8 – *Neutral stability at 8 m/s as maximum windspeed.*

6 Outdoor releases

With the unified weather conditions determined and the recommended hole sizes available, a parametric study of outdoor releases could be conducted to construct the engineering diagrams. In this study both gaseous and liquid CO_2 releases were modelled for the unified weather conditions: D1, D8 and F1, using EFFECTS 12.1.0 from Gexcon.

6.1 Setup

For the outdoor releases the terrain is assumed to be an infinite flat surface *(no obstacles)* over which the atmospheric boundary layer, belonging to the selected weather condition, is fully developed. All releases modelled as horizontal, originating from a 1-meter-long pipe section that is situated 1 meter above ground and attached to a storage vessel of 1000 m^3. The maximum release duration was conservatively set to 3600 seconds or until the storage vessel was empty, whichever came first.

6.2 Input parameters

Based on a short review of available bunkering hoses, as well as transfer lines on existing gas carriers, typical pipe/hose diameters on board ships range from 1" to 12". To manage the number of calculations performed, the following pipe/hose diameters were selected: 1", 2", 4", 7", 10" and 12".

The representative hole sizes were selected in-line with the UK HSE's recommendations, see **Table 4**, with a slight modification that also for the smallest pipe diameters the minimum hole size was set 4 mm. Hence for all pipe diameters, 4mm, 25mm, D/3 and full-bore ruptures were modelled. In addition, to study the effects of smaller hole sizes, all releases originating from a 2" pipe diameter, considered hole sizes of 1mm, 2mm, 3mm, 4mm, 5mm, 25mm, D/3, D/2 and full-bore ruptures. The complete run matrix, combining pipe diameters and hole sizes, is provided in **Table 7**.

Table 7 Run matrix for outdoor releases containing pipe diameters and hole sizes

D_{pipe}		Hole sizes									
mm	inch	$D_{pipe}/3$	$D_{pipe}/2$	D_{pipe}	small leaks						
25.4	1	8.47		25.4				4		25
50.8	2	16.93	25.40	50.8	1	2	3	4	5	25
101.6	4	33.87		101.6				4		25
177.8	7	59.27		177.8				4		25
254.0	10	84.67		254				4		25
304.8	12	101.60		304.8				4		25

To cover an as wide as possible pressure range, the triple *(5.18 bara, -56.6°C)* and critical points *(73.8 bara, -31.1°C)* of CO_2 were used to select 5 release pressures. These were 5.18, 10, 20, 40 and

60 barg. For the gaseous releases, the storage temperature was set to 25°C. For the liquid releases, the storage temperatures were set as close as possible to the liquid saturation line, see **Table 8**. Initial release calculations, however, indicated that no suitable temperature could be found that prevented dry ice forming upon releasing CO_2 at 5.18 barg. In **Figure 8** the correlation of the minimum storage pressure and temperature not leading to dry formation upon release from a 2” pipe is provided.

Table 8 Outdoor release storage pressures and temperatures

	Storage temperature	
Pressure	**Gaseous**	**Liquid**
5.18 barg	25°C	n.a.
10 barg	25°C	-40°C
20 barg	25°C	-25°C
40 barg	25°C	0°C
60 barg	25°C	15°C

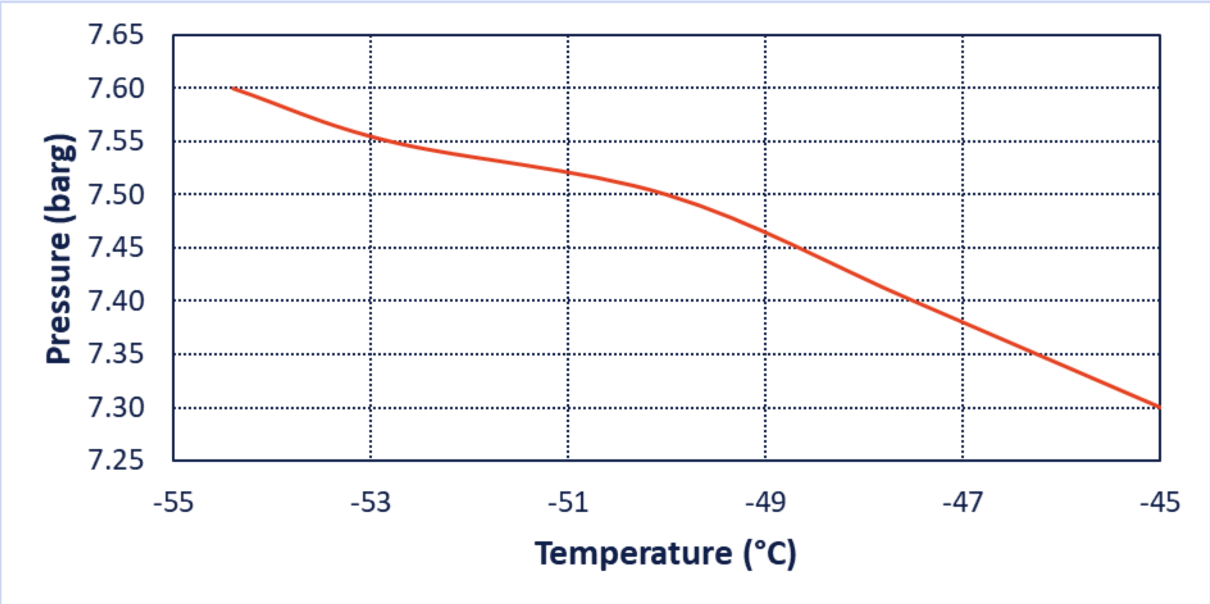

Figure 8 Minimum CO2 release pressure from 2" pipe not resulting in dry ice formation

6.3 Output parameters

To provide insight into the gaseous dispersion patterns of the released CO_2, apart from the standard release rates, the maximum concentrations at the cloud centre lines were collected over the length required to dilute the CO_2 to 400 ppm, which is the typical atmospheric CO_2 concentration **[18]**. As shown in **Figure 9**, this allowed for the distance to any concentration to be interpolated. Given that full expanded CO_2 is heavier than air, the cloud centreline is often well below the typical reporting height of 1.5 metres, seen in Quantitative Risk Assessments (QRAs). Therefore, the reported results can, to certain extend, be considered conservative in terms of their potential impact on humans.

The following four concentrations, used in the result reporting, which were selected from **[18]** based their impact on human health:

- 5,000 ppm – UK HSE long term exposure limit
- 15,000 ppm – UK HSE short term exposure limit
- 30,000 ppm – ACGIH TLV *(occupational)* short term exposure limit
- 40,000 ppm – Immediately Dangerous to Life or Health (IDLH)

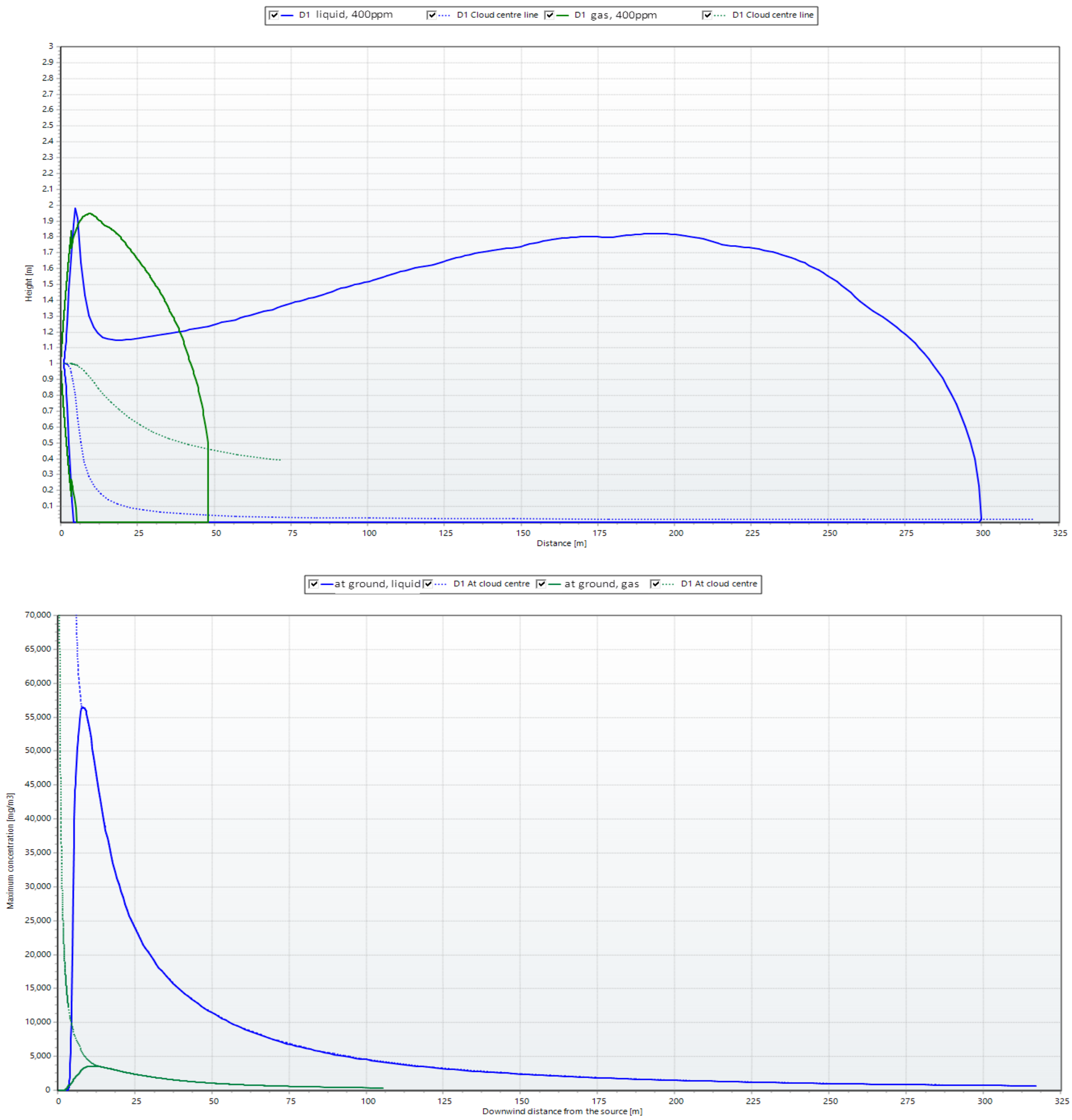

Figure 9 Plume side view (top) and maximum downwind concentration (bottom) for 4mm hole liquid (blue) and gaseous (green) releases from 2" pipe

6.4 Results

6.4.1 Plume/Jet length as function of pipe diameter

The maximum extend of plume/jets for various concentrations, pipe diameters, hole sizes and weather conditions are plotted respectively for gaseous and liquefied releases in **Appendix 8.3** and **Appendix 8.4**. From the results it becomes clear that releases with the same absolute hole size in different pipe diameters yield fairly similar results. The release pressure has some impact on the maximum extend of the plume/jet, but to a lesser extent than the absolute hole size, with results for the same hole size falling within the same order. This indicates that the release dispersion is driven by the hole size diameter and the corresponding plume/jet dynamics.

6.4.2 Plume/Jet length as function of hole diameter

To provide further insight in the impact of hole diameter on the associated plume/jet length, the 2" pipe diameter results were used. In **Appendix 8.5** and **Appendix 8.6**, respectively for gaseous and liquefied releases, the maximum extend of the plume/jet are plotted against the hole diameter.

6.4.3 Concentration as function of hole size

Typically, hazardous zones are used around pipelines and vent masts, to indicate areas where dangerous concentration of the gas or liquid may be present in case of a leak. To establish reasonable estimates of the dimensions of these zones, **Appendix 8.7** and **Appendix 8.8** plot the concentrations at 1, 5, 10 and 20 metres away from the source for respectively gaseous and liquefied releases originating from 2" pipelines. In-line with expectation, liquefied releases lead to substantially higher concentrations for comparable release pressures and hole sizes.

6.4.4 Release rate as function of pipe diameter and hole size

The release rates provided in **Appendix 8.9** could be considered representative for both outdoor and indoor releases *(assuming no back pressure)*. These can be used to estimate release quantities over the time required to detect and isolate the leak.

6.4.5 Expanded volumetric release rate as function of pipe diameter and hole size

Assuming complete and instantaneous expansion of CO_2 to its gaseous phase at 25°C, the release rates in **Appendix 8.9** can be converted to volumetric release rates, see **Appendix 8.10**. Although the results were calculated for outdoor releases, the volumetric release rates provide insight in how quickly a confined space would be flooded with CO_2 if no ventilation would be present. Equally, the results could be used to provide a first estimation of the required ventilation rate if the CO_2 concentration inside a space need to be maintained below a given threshold for a given leak size.

7 Indoor releases

Piping and equipment processing CO_2 may be located in enclosed spaces *(potentially staffed)*. In such spaces, a CO_2 release will lead to less dilution and potentially higher concentrations than in open decks, which raises the importance of a proper ventilation to prevent CO_2 concentrations above hazardous thresholds.

Indoor release simulations were conducted in order to investigate the CO_2 concentration build-up in enclosed spaces. The main objective was to estimate orders of magnitude of time to reach hazardous CO_2 concentrations.

The FLACS software version 22.2 **[19]** was used to perform the simulations. FLACS developed by Gexcon is a commercial CFD software used for dispersion, fire and explosion modelling within the field of industrial safety and risk assessment. It has been extensively validated and is a standard, especially in the offshore industry.

7.1 Setup

The CO_2 release was set up in a 20-feet ISO container. The container was modelled by a 6 m × 2.35 m × 2.35 m box *(volume = 33.1 m^3)*, see **Figure 10**. Two openings were modelled at both side of the container. No mechanical ventilation was modelled through these openings. This is a conservative assumption because SOLAS and Class Rules require mechanical ventilation in enclosed spaces where CO_2 may accumulate. The main purpose of these openings was to prevent from unphysical pressure build-up in the simulation domain.

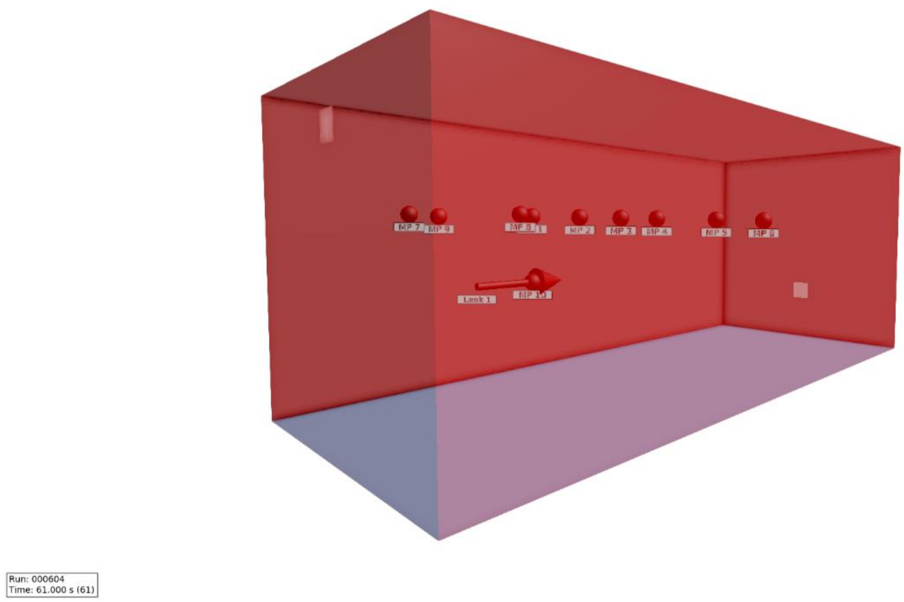

Figure 10 Indoor simulations – Geometry

The CO_2 release was located 1 m above the ground and 1 m away from the left side of the container, see red arrow in **Figure 10**. Its direction is horizontal. The release was set at a continuous leak rate over 30 seconds *(time to detect the leak and to automatically shut-down the release)*, then the simulation will last for 30 additional seconds *(total simulation time = 61 seconds, including 1 second at the start of the simulation for stabilization purpose)*.

Three different simulations were run. A mesh was built for each simulation following the FLACS guidelines **[19]**. **Table 9** provides the total number of cells per simulation.

Table 9. Indoor simulations – Mesh characteristics

Simulation ID	**000604**	**000404**	**000104**	
Number of cells	69 192	96 192	197 370	
Min. cells size	0.03	0.03	0.01	m

7.2 Input parameters

A 4 mm hole size leak was modelled for three different tank pressures: 60 barg, 40 barg *(high pressures)* and 10 barg *(medium pressure)*. The 4 mm hole size was selected based on the UK HSE leak frequency data **[12]**. The idea was not to study catastrophic release *(e.g. full-bore)*.

Table 10 summarises the main input parameters of the simulations. In order to calculate the conditions of the sonic jet after its expansion to the atmosphere, the jet utility program *(from the FLACS package)* was used. The outcomes of this program were used to set up the dispersion simulation.

Table 10. Indoor simulations – Input and jet parameters

Simulation ID	**000604**	**000404**	**000104**	
Input parameters:				
Fluid		CO_2		
State		Gas		
Tank volume		1 000		m^3
Tank pressure	60	40	10	barg
Tank temperature		25		°C
Atm. pressure		1		bara
Atm. temperature		25		barg
Jet2 utility:				
Hole size		4		mm
Discharge coefficient		0.9		-
Post-expansion area	0.000747	0.000501	0.000133	m^2
Flow rate	0.191	0.128	0.034	kg/s
Post-expansion speed	139.20	139.38	141.03	m/s
Post-expansion temperature	14.82	14.79	14.55	°C

7.3 Output parameters

The mass of CO_2 in the container versus the time was monitored.

Several monitor points located at 1.5 m above the ground were set, see red spheres in **Figure 10**, in order to monitor the CO_2 concentration versus the time.

In particular, the threshold to IDLH (Immediately Dangerous to Life or Health) was monitored as a good indicator to acute toxicity related to an accidental release of CO_2 leading to the necessity of an immediate escape of the enclosed space.

7.4 Results

Figure 11, **Figure 12** and **Figure 13** display a 2D view along the centreline length of the container of the CO_2 concentrations from IDLH level (40 000 ppm) to above 10 times IDLH level (400 000 ppm) when the leak stops (31 seconds), respectively for the 60 barg, 40 barg and 10 barg release.

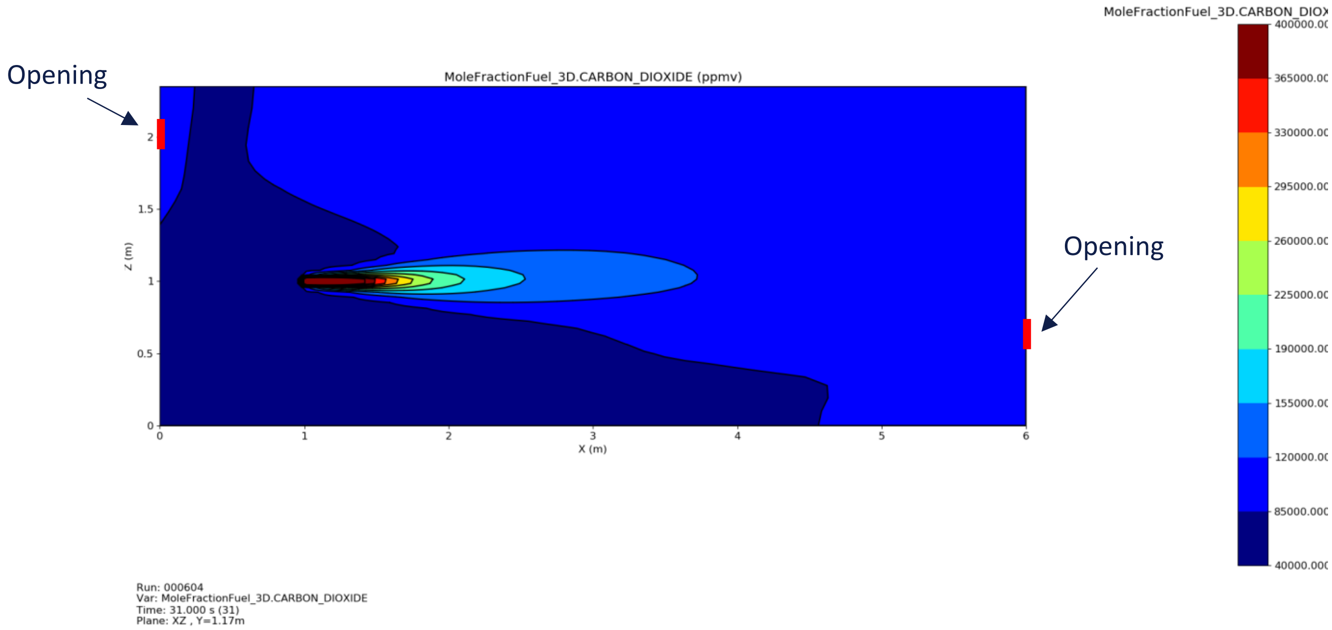

Figure 11 Indoor releases – 60 barg jet. CO_2 concentration (ppm). Blue contour = IDLH (40 000ppm) level. Red contour = 10×IDLH level.

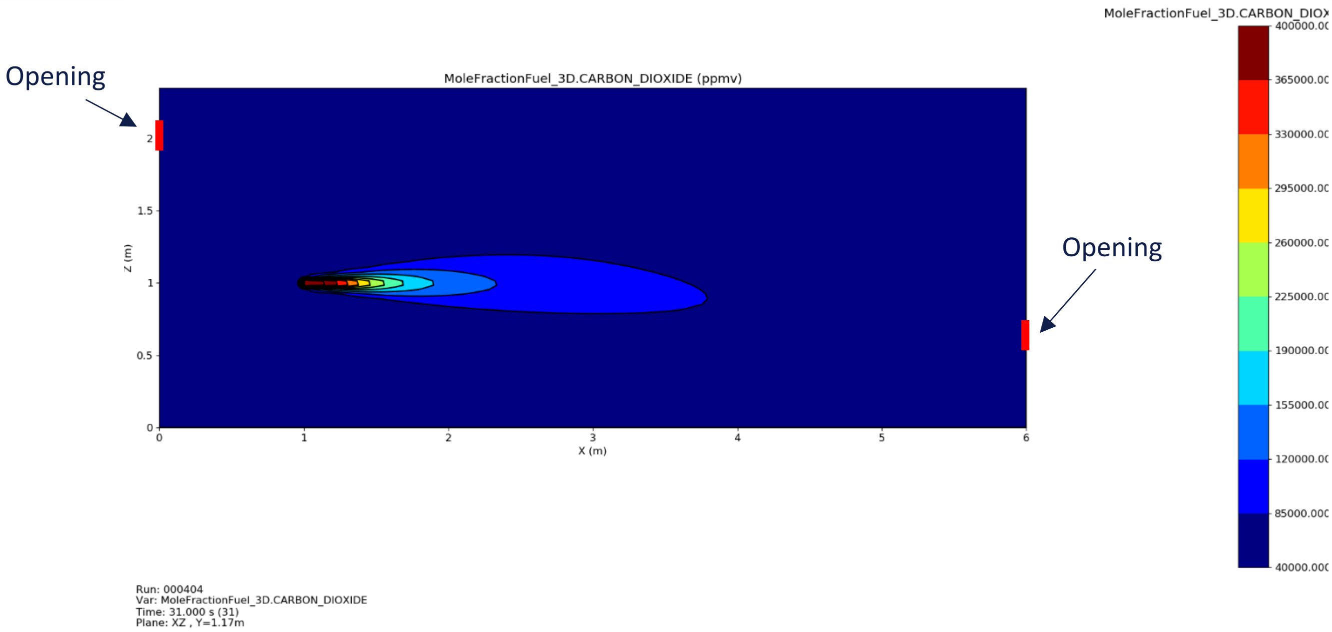

Figure 12 Indoor releases – 40 barg jet. CO_2 concentration (ppm). Blue contour = IDLH (40 000ppm) level. Red contour = 10×IDLH level.

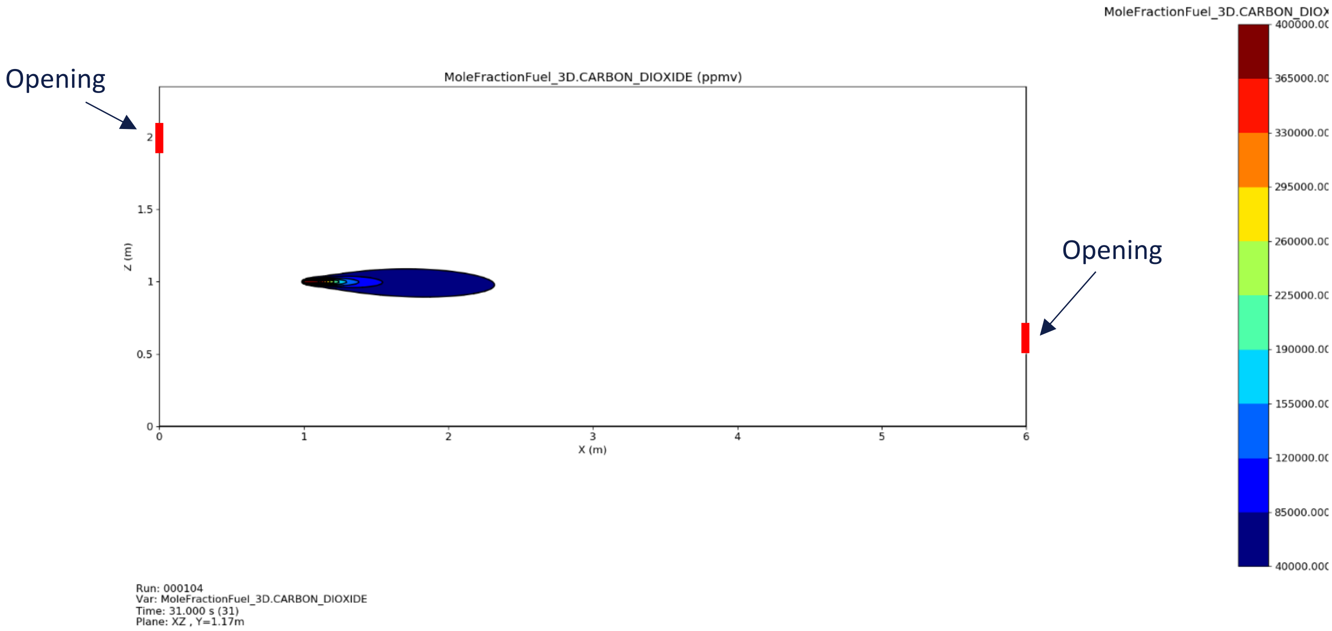

Figure 13 Indoor releases – 10 barg jet. CO_2 concentration (ppm). Blue contour = IDLH (40 000ppm) level. Red contour = 10×IDLH level.

When the leak stops, the CO_2 concentration reaches IDLH level everywhere in the container for the 60 barg and 40 barg releases. The lowest CO_2 concentrations are found upstream to the leak point, in the bottom left of the container, where the velocities are the lowest. Then, the CO_2 concentration slowly decrease but is still above the IDLH level 30 seconds after the end of the leak. For the 10 barg release, the IDLH level is reached only downstream to the leak point, up to about 1 m away at leak point elevation. After the end of the leak, no CO_2 concentration above the IDLH level is monitored in the container.

Table 11 provides the main results of the three simulations. CO_2 concentration above IDLH (40 000 ppm) is reached at 10 and 14 seconds after the start of the leak, respectively for the 60 barg and 40 barg release. This time is quite short and no escape is possible in such time. But in that case, the assumptions are very conservative *(e.g. high-pressure releases and no mechanical ventilation considered in the confined spaces)*. For the 10 barg release, CO_2 concentration above IDLH is not reached at monitor points. However, CO_2 concentration above IDLH is found at 1 m above the ground level *(leak elevation)* and at least 1 m away from the leak point (**Figure 13**). In summary, CO_2 concentration above IDLH can be found close to the leak point and, depending on the leak direction or location, it may impair a human. These results were found with conservative assumptions *(see above)*.

Table 11. Indoor simulations - Results

Simulation ID	000604	000404	000104	
CO_2 released in the container	5.418	3.703	0.764	kg
Max. CO_2 concentration at monitor points	100 000	70 000	16 900	ppm
Time to reach IDLH (40 000 ppm) at monitor points	10	14	Not reached(1)	s

(1) Not reached at monitor points.

Wang et al also investigated leaking and dispersion of CO_2 in an indoor space **[20]**. They compared experimental data and numerical simulation *(using FLUENT)* of continuous release and dispersion process of CO_2 in a ventilated room. The room was 4 m × 1.6 m × 2.5 m (16 m^3) and had two openings on both sides. The room was naturally ventilated. The CO_2 leak had a 4 mm hole size and directed vertically upwards. Different wind speed (1.5-4.0 m/s) and release rate (0.01-0.10 kg/s) were analysed, as well as the influence of an obstacle. For an equivalent release rate, the results of the FLACS simulations (EverLoNG) were compared with the results of the FLUENT simulations (Wang et al.) and the results matched in order of magnitude. The work of Wang et al concluded that:

- The CO_2 detectors should be located at the down-wind position of the leaking point.
- The concentration of CO_2 decreases with increment of wind speed.
- CO_2 may accumulate close to obstacles.

8 Discussion

It is duly noted that in none of the releases modelled dry ice formation took place. If dry ice would be formed, arguably the liquid release results would provide a conservative estimate of the consequence, for less gaseous CO_2 would be present. However, simultaneously, the cryogenic cooling effects of dry ice on the surrounding structure would need to be assessed to complete the risk picture.

The outdoor release results currently do not take account for safeguards commonly applied in industry and assumed a continuous release of 1 hour *(3600 seconds)* or until the storage vessel of 1000 m^3 was empty. Commonly the LNG industry assumes that larger leaks can be detected and isolated within 30 seconds. If a similar approach would be taken for CO_2 transfer lines, the dispersion based *(lower concentrations)* plume extend would reduce and hence the associated safety distance. For ship-based carbon capture systems this impacts mostly the required safety zones when offloading large quantities of CO_2 to shore or a receiving barge. It is therefore recommended to carry out detailed dispersion analyses for CO_2 offloading operations, in which the system specific safeguards are taken into account.

A reasonable agreement was found with the calculated indoor concentration build-up when using the outdoor expanded volumetric release rates. Although useful as a first indication in the design stage, due consideration should be given to the non-conservative nature of using the outdoor expanded volumetric release rates. Complex geometries typically found indoors can generate higher concentration gas pockets and recirculation zones and heavily influence mixing.

The indoor results for 4-millimetre holes at various CO_2 pressures indicate that enhanced safety measures will likely be required for high pressure CO_2 systems situated in attended enclosed spaces. Even with forced ventilation running at 30 Ac/h it is unlikely that the calculated 40 and 60 barg releases would result in escape times in excess of 30 seconds. For lower operating pressures, enhanced safety measures may still be required in enclosed spaces, subject to dedicated risk assessments, noting the risk of asphyxiation, even with small leaks, is credible.

9 Recommendations

Based on the work carried out in Task 5.1.2, as well as the other subtasks, the following recommendations can be made:

- The unified weather conditions to be used for ship-based dispersion analyses are:
    - D1 – *Neutral stability at 1 m/s as minimum windspeed.*
    - F1 – *Stable at 1 m/s to conservatively showcase the impact of reduced turbulence.*
    - D8 – *Neutral stability at 8 m/s as maximum windspeed.*

- Carry out detailed dispersion analyses for CO2 offloading operations, in which the system specific safeguards are taken into account.

- Mechanical ventilation should be set in enclosed spaces containing risk of CO_2 leak. Further calculations are needed to determinate appropriate Ac/h. *(Note: Also refer to SOLAS 2/10.4.3/ for CO_2 storage in the case of fire-extinguishing medium and IGC Code Chapter 12-Artificial ventilation in the cargo area as framework for CO_2 handling.)*

- As far as practicable, the CO_2 detectors should be located in the ventilation path, downstream to CO_2 piping and equipment.

- The layout of piping and equipment should be optimized to limit CO_2 accumulation.

- Carry out dedicated risk assessments for enclosed spaces, noting that the risk of asphyxiation resulting from smaller leaks is credible. Special attention needs to be paid to available escape times, especially when high pressure CO_2 systems are considered.

Part 3: Categorization of new technology

1 Introduction

Subtask 5.1.3 aims to determine the degree of novelty of SBCC concepts developed in WP1-3, in order to evaluate to what degree existing Rules and regulations are suitable to cover the risk of implementing the technology, and to what degree it will be necessary to implement a risk-based "alternative design" approval regime to ensure an acceptable safety level for SBCC technology onboard ships.

The sub-systems of the post-combustion chemical absorption carbon capture and storage system will be categorized and the degree of novelty of the applied technology on component and system level will be discussed with respect to existing regulatory design support to evaluate areas where greater attention may be required in the approval process.

2 Risk picture

As described in the above, the main safety challenges related to onboard carbon capture and storage systems are associated with the following:

- Personnel exposure to hazardous chemicals in the carbon capture system through leakages, maintenance work or replenishment of system fluids.
- Personnel exposure to low and high temperature fluids in the carbon capture system through leakages, maintenance work or replenishment of system fluids.
- Asphyxiation because of loss of containment in the CO_2 distribution and storage systems.
- Energy release as a result of damage to pressurised CO_2 tank containment systems.

Any safety regulations developed to address the safety of SBCC installations will have to ensure that proper safety barriers are in place to mitigate these risks.

3 Shipboard carbon capture and storage system process breakdown

As described in Part 1 above, the EverLoNG CO_2 capture and storage plant can be divided into nodes categorised by the process. In the following we will evaluate each of these process nodes to assess the degree of novelty of the applied CCS technology with respect to its use onboard ships.

In accordance with the process description in Part 1, the carbon capture plant can be divided into three main sections:

- flue gas quenching section.
- CO_2 recovery section *(absorber)*.
- solvent regeneration section *(desorber)*.

The CO_2 produced by the capture plant will need further processing for storage trough a:

- CO_2 compression and drying section.
- CO_2 liquefaction section.

To finalise the CO_2 recovery process the ship must be arranged with:

- Suitable pressurised storage for captured CO_2.
- CO_2 offloading facilities.

4 Technology novelty evaluation

4.1 Step 1 – Flue Gas Quenching

Before entering the CO_2 recovery section, the flue gas will be run through a quenching stage. This is done to:

- reduce flue gas temperature to 30-40 °C to promote absorption and reduce solvent loss due to evaporation *(part of the heat is recovered through a heat exchanger to be used in the stripping process)*.
- minimize particulate dust and other impurities before entering the CO_2 absorber.
- control pH to prevent corrosion in the system *(using NaOH)*.

The flue gas enters the quenching column where sodium hydroxide solution (NaOH) is added regularly to maintain the pH of the environment. The NaOH is dosed based on the pH value in the quench scrubbing water, which is circulated back to the column by the quench circulation pump. The flue gas moves upward into the column which works at approximately atmospheric pressure, while the *(slightly)* alkaline solution is sprayed from the top in two steps through spray nozzles. The circulating alkaline solution itself is cooled by a quench liquid cooler.

Novelty of quenching technology
Very similar quenching processes has been used for a long time in shipping to make inert gas for tankers and to remove sulphur from the exhaust gases. Scrubbing technologies were initially transferred to the marine market as an inexpensive way to produce inert gas for reducing the fire hazard in the cargo tanks of tankers during unloading. During the 1960s, scrubbers were introduced as a method for scrubbing exhaust gas emissions from the tanker's boiler plant. In 2008 IMO accepted scrubbers as an alternative method for complying with SOx emission reduction regulations.
Class Rules for safe operation of inert gas scrubbers and SOx scrubbing technology have been developed in parallel with the introduction of the corresponding technologies. The regulations have been properly tested and verified and can be applied to this part of the CCS process without major modifications.

4.2 Steps 2 to 3 – CO_2 absorption, absorber washing, and solvent regeneration

CO_2 absorption
The cooled flue gas is introduced at the bottom of a CO_2 absorber after passing through a blower which is located upstream of the absorber column. Like the quench column, the flue gas moves upward through the structured packings, while the lean solvent is showered from the top of the

absorption section onto the packing. The counter-current contact is made between the flue gas and the solvent on the packing surface, where CO_2 in the flue gas is chemically absorbed by the solvent.

The rich solvent from the bottom of the CO_2 absorber is then directed to the desorber via the Lean-Rich (LR) heat exchanger by the rich solvent pump. The schematic view of the CO_2 capture section is illustrated in the figure below.

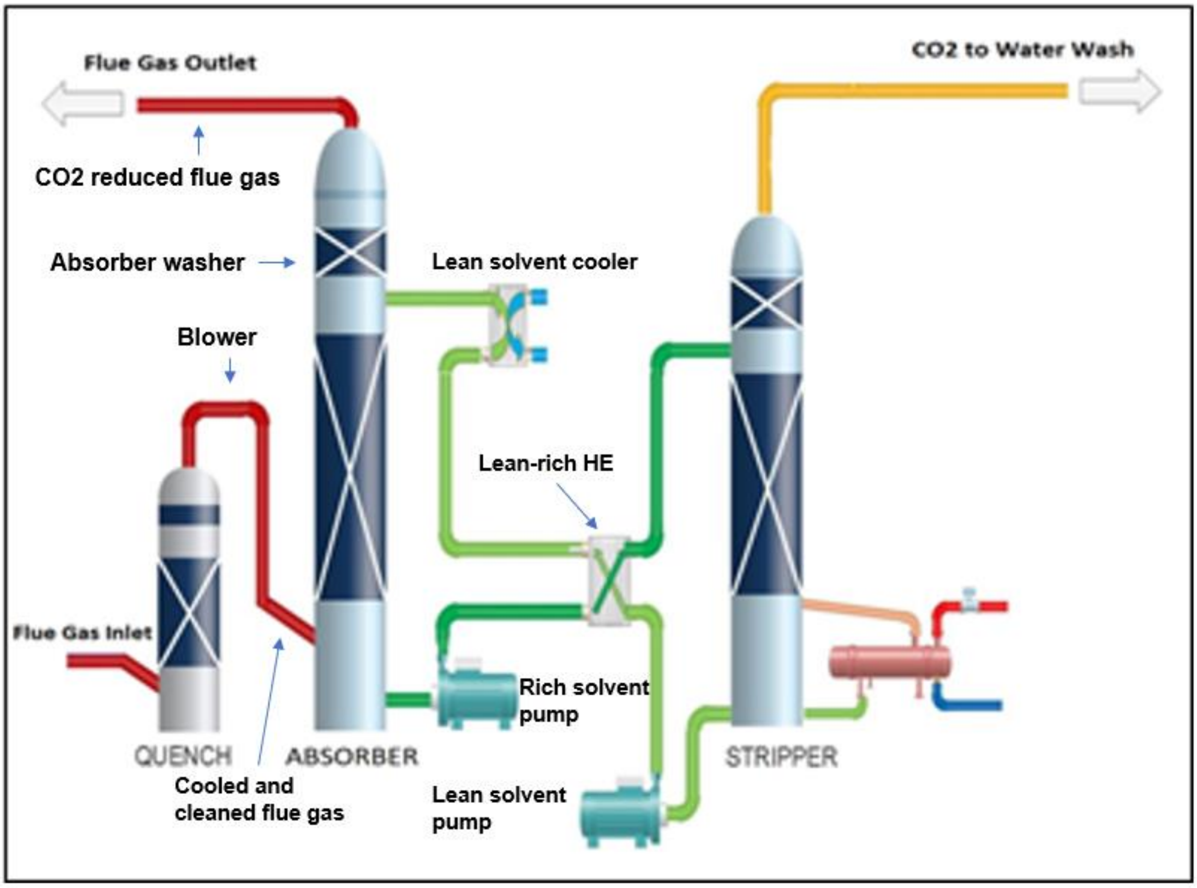

Figure 14 Schematic of carbon capture plant

Absorber Washing

The flue gases with low CO_2 concentration from the top of the CO_2 absorber column enter the absorber washer. A recirculation pump collects the wash water from the bottom and sprays it back to the top of the column. The water contacts with the CO_2-free flue gas in a structured-packed bed, capturing the entrained/evaporated MEA. In the end, CO_2-free flue gas is vented into the atmosphere at a temperature of about 40-45 °C.

Solvent Regeneration

Solvent regeneration takes place in a stripping column called a desorber. Here the CO_2 is stripped from the rich solvent which has already been warmed partially passing through the lean/rich (LR) heat exchanger. The pre-heated rich solvent is introduced to the upper section of the desorber where the rest of the required heat to raise the temperature and generate the vapor is provided by hot flue gas. An electrical heater is mounted as the backup in case the possible heat recuperation from the flue gases is not sufficient. The generated vapor *(stripping steam)* provides the reverse reaction energy for the rich solvent to release the absorbed CO_2.

The lean solvent from the bottom of the desorber is cooled in two steps by the LR heat exchanger and the lean solvent cooler before being sent to the CO_2 absorber by the lean solvent pump.

Novelty of chemical absorption carbon capture technology

There is obviously very little experience with installation of carbon capture technology onboard ships. However, the individual carbon capture system components like pressure vessels, pumps, heat exchangers, pipes, valves, and pipe connections have been used on every ship since the tall ship era. Existing Class Rules for certification of these components and rules for manufacture, workmanship and testing of the completed system can be applied.

The novelty is mainly in the content of the system, i.e., the chemicals used in the process:

Table 12 Listing of chemicals used in the EverLoNG carbon capture plant

Chemical	Purpose	Concentration	Initial filling (kg)	Make-up needed (kg/day)
Monoethanolamine (MEA)	CO2 absorption	Pure	150	Negligible
Sodium Hydroxide (NaOH)	Quench pH control	20 wt%	0	4
Desiccant	CO2 Dehydration	Pure	8	0
R-410A	Refrigerant	Pure	6.5	0
TBF	Antifoam agent	VTA	TBF	TBF
Calibration gases	Analyzer	TBF	VTA	0

Sodium Hydroxide is commonly used in SOx scrubber systems, and refrigerants are extensively used in HVAC and cooling systems on most ships. Hence, the handling and storage of the amines used to capture CO_2 from the exhaust is the more unknown quantity from a shipping perspective.

From the regulatory side, the toxicity, corrosivity and flammability of the amines should be investigated to establish to what degree the properties of the fluid warrants limitations on arrangement onboard. In this context it should be noted that mixing different amines together can substantially impact their flammability and toxicity.

4.3 Step 4 & 5 – CO_2 Compression and Drying and Liquefaction

The CO_2 compressor is a two-step compressor with inter and after coolers. The two dryers are built according to an advanced regeneration system, which can lower the dewpoint of the gaseous CO_2 to -60°C at atmospheric pressure.

The liquefaction is done in a CO_2 condenser with the help of the Joule-Thomson effect in a downstream throttling valve. The condenser is a heat exchanger and on one side the gaseous CO_2 is partially liquefied by cooling it down below the relative high saturation temperature (0 °C). On the other, side a water/glycol circuit is providing the needed cooling which itself is cooled down by a conventional refrigeration cycle utilizing R-410A.

After this liquefaction in the condenser at high pressure (40 bar), liquid CO2 with a relatively high temperature is flashed off to create lower-pressure liquid CO2 with a significantly lower temperature. In this way, the liquefaction itself is done at high pressure and relatively high temperature and the actual storage of liquid CO2 takes place at medium pressure of 15~18 bar with a lower temperature.

Novelty of CO_2 compression and liquefaction technology
Gas compression is not new in shipping. Gas in various forms have been transported on gas carriers for more than 60 years, and compression and reliquification of cargo boil-off have been integral to this trade. With the introduction of LNG as a fuel at the beginning of this century, this type of technology has also been taken into use on cargo ships not used for gas transport. Applicable rules and regulations for gas compression and liquefaction are provided in Classification Rules for gas carriers, IGC Code and IGF Code. Safety barriers against asphyxiation risks caused by leaking CO_2 containment systems in enclosed spaces are provided in Class Rules, e.g., for nitrogen generation systems. For designs where LNG is used in the cooling process, there will be an inherent risk of cross-contaminating the CO_2 with methane *(or vice versa)* through a leakage in the heat-exchanger. Such arrangements will necessitate leakage detection in both the LNG and CO_2 side of the system, and an automatic shut-down arrangements to prevent escalation. Safety barriers considering the same issue are described in IGF Code and Class Rules to address the same hazard in heat exchangers vaporising LNG to natural gas in fuel consumption systems or used for pressure build-up in vacuum insulated IMO Type C tanks.

4.4 Step 6 – CO_2 Storage

Once liquefied, CO_2 is stored inside a storage tank. While stored in the tank a part of the CO_2 evaporates. Therefore, a reflux line is also considered between the storage tank and the liquefaction section to recover the evaporated CO_2.

Novelty of CO_2 storage
CO_2 is stored in large, pressurized tanks on gas carriers, and in significant volumes onboard many ships for fire extinguishing purposes. Gaseous fuels are also stored onboard LNG fuelled vessels in accordance with the IGF Code. The main hazards related to CO_2 storage is damage to the tank containment system. Since the CO_2 is in pressurized condition, the tanks represent significant potential energy which will be released if the tank is damaged. A secondary effect of tank damage will be the release of large amounts of asphyxiating gas. The same hazards are addressed by the IGF Code where the stored fuel represents the additional hazard of being flammable. Consequently, it would be reasonable to look to the IGF Code for guidance on tank protection, where protection against collision, grounding, fire, and mechanical damage from operations is considered.

4.5 Step 7 – CO_2 offloading

SBCC will be one part in a long logistic chain if GHG reductions is the target. Consequently, ships using this technology will have to be arranged with offloading facilities to land-based reception infrastructure for further transport to permanent storage facilities.

Novelty of CO_2 offloading
Gas offloading is an integral part of marine gas transport. The novelty of offloading captured and stored CO_2 in shipping will be the location of gas offloading manifolds. On gas carriers the cargo manifolds are located in a dedicated cargo area away from the accommodation superstructure. This will not necessarily be the case for other ship types. Gas fuelled vessels have the same issue with bunkering manifolds, and the IGF Code have detailed requirements for their location of arrangement which may be directly applied to CO_2 offloading systems. A CO_2 offloading manifold will have fewer associated risks compared to bunkering facilities for gas fuelled vessels since there is no need to account for flammability of potential leakages.

4.6 Summary – CCS novelty

At this stage, not all aspects of a SBCC system are covered by prescriptive standards or regulation. However, it should be noted that some Classification Societies already have published Class Rules for SBCC installations, and others are expected to follow. Until then, is seems that Classification Societies will have tools available to perform approval for early movers utilizing requirements for similar existing ship equipment and installations.

Table 13 CCS- Novelty of technologies

Technology used for	Application area	Technology status	Existing regulations
Flue gas quenching	Known	Proven	Class rules for exhaust gas scrubbers
CO_2 recovery	New	Proven	Class rules for piping systems and pressure vessels
Solvent regeneration	New	Proven	Class rules for piping systems and pressure vessels
CO_2 compression	Known	Proven	Class rules for Gas carriers
CO_2 liquefaction	Known	Proven	Class rules for Gas carriers, IGC Code
CO_2 storage	Known	Proven	Class rules for Gas carriers, IGF Code, IGC Code
CO_2 offloading	New	Proven	Class rules for Gas carriers, IGF Code, IGC Code

5 References

Part 1

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6 Indexes

a. Index of tables

b. Index of figures

7 Acknowledgements

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8 Appendices

8.1 Ports selected for unified global weather conditions

Port	Country	Continent	LAT (º)	LON (º)
Rotterdam	Netherlands	Europe	51.95	4.05
Antwerp	Belgium	Europe	51.25	4.35
Hamburg	Germany	Europe	53.5	9.95
Valencia	Spain	Europe	39.45	-0.3
Piraeus	Greece	Europe	37.95	23.65
Algeciras	Spain	Europe	36.15	-5.45
Dar es Salaam	Tanzania	Africa	-6.8	39.3
Port Elizabeth	South Africa	Africa	-33.95	25.65
Port of Casablanca	Morocco	Africa	33.6	-7.6
Tolanaro Port	Madagascar	Africa	-25.05	47
Dakar	Senegal	Africa	14.7	-17.4
Mombasa	Kenya	Africa	-4.1	39.7
Lagos	Nigeria	Africa	6.4	3.35
Port Said	Egypt	Africa	31.25	32.5
Djibouti	Djibouti	Africa	11.6	43.15
Singapore	Singapore	Asia	1.25	103.65
Shanghai	China	Asia	30.6	122.05
Tianjin	China	Asia	38.95	117.8
Dalian	China	Asia	38.95	121.65
Kaohsiung	Taiwan	Asia	22.6	120.3
Laem Chabang	Thailand	Asia	13.05	100.9
Busan	South-Korea	Asia	35.1	129.05
Hong Kong	Hong Kong	Asia	22.3	114.15
Tokyo	Japan	Asia	35.6	139.85
Mumbai	India	Asia	18.95	72.9
Klang	Malaysia	Asia	2.9	101.25
Jakarta	Indonesia	Asia	-6.05	106.9
Colombo	Sri Lanka	Asia	6.95	79.85
Ho Chi Minh City	Vietnam	Asia	10.5	106.9
Manila	Philippines	Asia	14.6	120.9
Dubai	United Arab Emirates	Asia	25	55.05
Jeddah	Saudi Arabia	Asia	21.45	39.15
Fujairah	United Arab Emirates	Asia	25.2	56.4
Los Angeles	USA	North America	33.7	-118.25
Vancouver	Canada	North America	49.3	-123.1
New York	USA	North America	40.65	-74.1
Montreal	Canada	North America	45.55	-73.55
Savannah	USA	North America	32.1	-81.1
Balboa	Panama	North America	8.95	-79.55

Port	Country	Continent	LAT (º)	LON (º)
Belize	Belize	North America	17.5	-88.2
Caldera	Costa Rica	North America	9.9	-84.5
Itagui	Brazil	South America	-2.6	-44.35
Santos	Brazil	South America	-23.9	-46.35
Callao	Peru	South America	-12.05	-77.15
Cartagena	Colombia	South America	10.4	-75.55
San Lorenzo-San Martin	Argentina	South America	-32.75	-60.7
Paranagua	Brazil	South America	-25.5	-48.5
Brisbane	Australia	Australia	-27.45	153.05
Sydney	Australia	Australia	-33.85	151.2
Fremantle	Australia	Australia	-32.05	115.75
Melbourne	Australia	Australia	-37.85	144.9
Hedland	Australia	Australia	-20.3	118.55
Wellington	New Zealand	Australia	-41.3	174.75
Darwin	Australia	Australia	-12.45	130.85

8.2 Global wind and Pasquill stability statistics

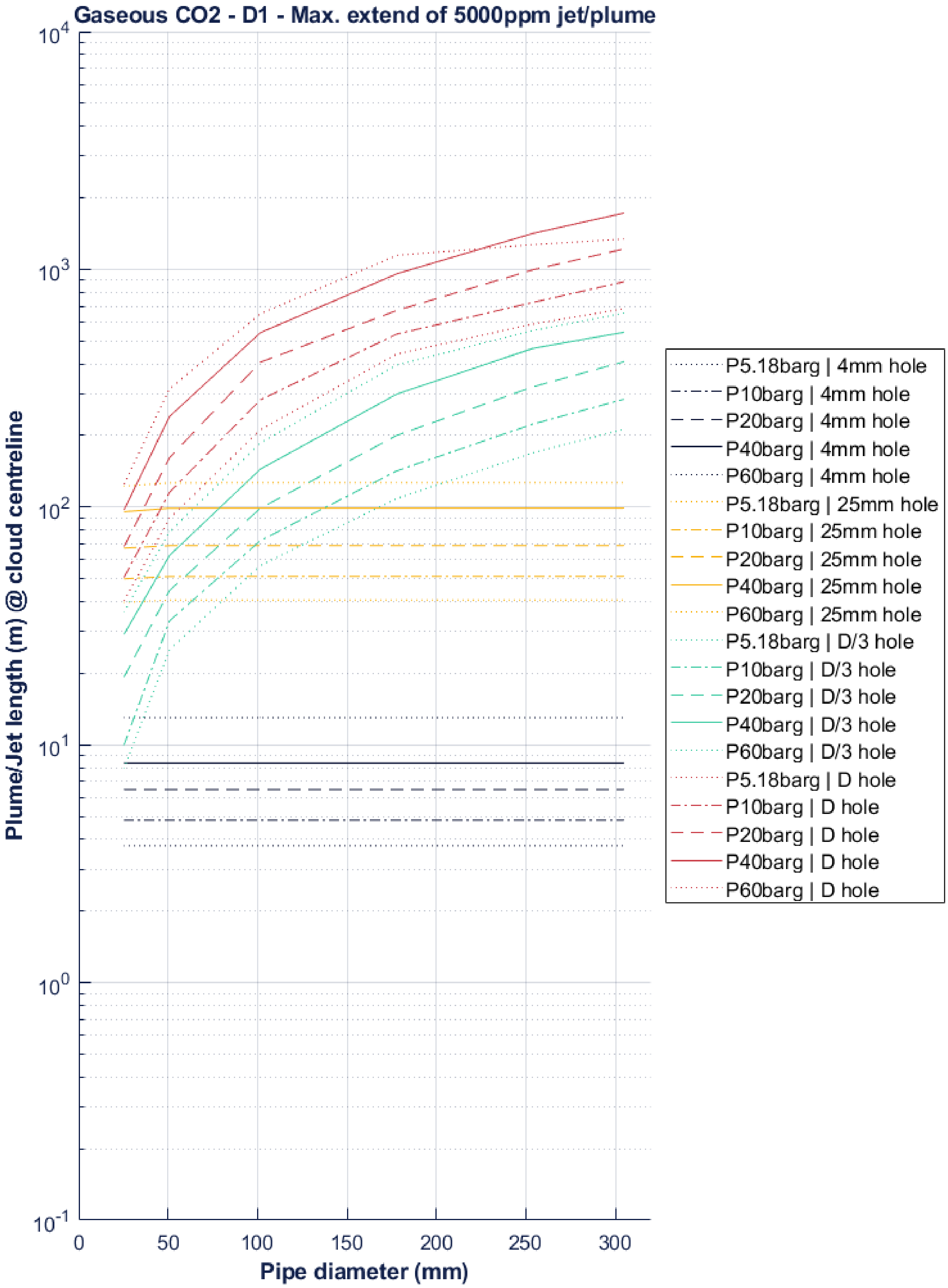
Beaufort	Stability Class	'A'	'A-B'	'B'	'B-C'	'C'	'C-D'	'D'	'E'	'F'		Sum Bft.	Culminative sum	
	Wind speed (m/s)	0.8%	3.3%	6.3%	4.7%	6.4%	1.8%	51.2%	11.4%	14.2%	Sum		Down	Up
0	0 to 0.3	1.7E-04	6.1E-04	4.4E-04				2.1E-03		1.8E-03	0.5%	0.5%	0.5%	100.0%
	0.3 to 0.45	2.1E-04	7.5E-04	5.5E-04				2.6E-03		2.2E-03	0.6%		1.1%	99.5%
	0.45 to 0.55	1.9E-04	6.6E-04	4.9E-04				2.2E-03		1.9E-03	0.5%		1.7%	98.9%
	0.55 to 0.65	2.4E-04	7.8E-04	6.1E-04				2.7E-03		2.3E-03	0.7%		2.3%	98.3%
	0.65 to 0.75	2.8E-04	8.9E-04	7.2E-04				3.1E-03		2.7E-03	0.8%		3.1%	97.7%
	0.75 to 0.85	3.0E-04	1.0E-03	7.9E-04				3.5E-03		3.2E-03	0.9%		4.0%	96.9%
1	0.85 to 0.95	3.6E-04	1.1E-03	9.0E-04				3.9E-03		3.6E-03	1.0%	11.8%	5.0%	96.0%
	0.95 to 1.05	3.9E-04	1.2E-03	9.9E-04				4.3E-03		4.1E-03	1.1%		6.1%	95.0%
	1.05 to 1.15	4.4E-04	1.4E-03	1.1E-03				4.6E-03		4.6E-03	1.2%		7.3%	93.9%
	1.15 to 1.25	4.6E-04	1.5E-03	1.2E-03				5.0E-03		5.1E-03	1.3%		8.6%	92.7%
	1.25 to 1.35	5.2E-04	1.5E-03	1.2E-03				5.2E-03		5.6E-03	1.4%		10.0%	91.4%
	1.35 to 1.5	8.4E-04	2.5E-03	2.0E-03				8.3E-03		9.3E-03	2.3%		12.3%	90.0%
	1.5 to 1.7	1.3E-03	3.6E-03	2.8E-03				1.2E-02		1.4E-02	3.3%		15.6%	87.7%
	1.7 to 1.9	1.4E-03	3.9E-03	2.9E-03				1.2E-02		1.5E-02	3.6%		19.2%	84.4%
	1.9 to 2.1	7.6E-04	2.8E-03	3.6E-03		1.6E-03		1.3E-02	2.3E-03	1.4E-02	3.8%		23.0%	80.8%
	2.1 to 2.3		1.7E-03	4.3E-03		3.1E-03		1.3E-02	4.6E-03	1.2E-02	3.9%		26.8%	77.0%
2	2.3 to 2.5		1.8E-03	4.4E-03		3.2E-03		1.3E-02	4.5E-03	1.2E-02	3.9%	33.8%	30.7%	73.2%
	2.5 to 2.7		1.9E-03	4.5E-03		3.3E-03		1.3E-02	4.4E-03	1.2E-02	3.9%		34.6%	69.3%
	2.7 to 2.9		2.0E-03	4.6E-03		3.3E-03		1.3E-02	4.2E-03	1.1E-02	3.9%		38.5%	65.4%
	2.9 to 3.1		1.0E-03	3.4E-03	2.4E-03	3.2E-03		1.5E-02	7.6E-03	5.6E-03	3.8%		42.3%	61.5%
	3.1 to 3.3			2.2E-03	4.7E-03	3.2E-03		1.7E-02	1.1E-02		3.8%		46.1%	57.7%
	3.3 to 3.5			2.2E-03	4.8E-03	3.2E-03		1.7E-02	1.0E-02		3.7%		49.8%	53.9%
	3.5 to 3.7			2.3E-03	4.8E-03	3.1E-03		1.6E-02	1.0E-02		3.7%		53.5%	50.2%
	3.7 to 3.9			2.3E-03	4.8E-03	3.0E-03		1.6E-02	9.8E-03		3.6%		57.1%	46.5%
	3.9 to 4.1			2.4E-03	4.8E-03	3.0E-03		1.5E-02	9.3E-03		3.4%		60.5%	42.9%
	4.1 to 4.3			2.3E-03	4.7E-03	2.9E-03		1.4E-02	8.8E-03		3.3%		63.8%	39.5%
3	4.3 to 4.5			2.3E-03	4.6E-03	2.8E-03		1.4E-02	8.5E-03		3.2%	34.1%	67.0%	36.2%
	4.5 to 4.7			2.2E-03	4.5E-03	2.6E-03		1.3E-02	8.0E-03		3.0%		70.0%	33.0%
	4.7 to 4.9			2.2E-03	4.4E-03	2.5E-03		1.2E-02	7.4E-03		2.8%		72.9%	30.0%
	4.9 to 5.1			1.1E-03	2.1E-03	2.2E-03	2.1E-03	1.5E-02	3.5E-03		2.6%		75.5%	27.1%
	5.1 to 5.3					2.0E-03	4.0E-03	1.9E-02			2.5%		78.0%	24.5%
	5.3 to 5.5					1.8E-03	3.7E-03	1.7E-02			2.3%		80.2%	22.0%
	5.5 to 5.7					1.6E-03	3.5E-03	1.6E-02			2.1%		82.3%	19.8%
	5.7 to 5.9					1.5E-03	3.2E-03	1.4E-02			1.9%		84.2%	17.7%
	5.9 to 6.1					1.3E-03	1.5E-03	1.4E-02			1.7%		85.9%	15.8%
4	6.1 to 6.3					1.2E-03		1.4E-02			1.5%	15.2%	87.4%	14.1%
	6.3 to 6.5					1.0E-03		1.3E-02			1.4%		88.8%	12.6%
	6.5 to 6.7					9.6E-04		1.1E-02			1.2%		90.0%	11.2%
	6.7 to 6.9					8.2E-04		1.0E-02			1.1%		91.1%	10.0%
	6.9 to 7.1					7.1E-04		9.2E-03			1.0%		92.1%	8.9%

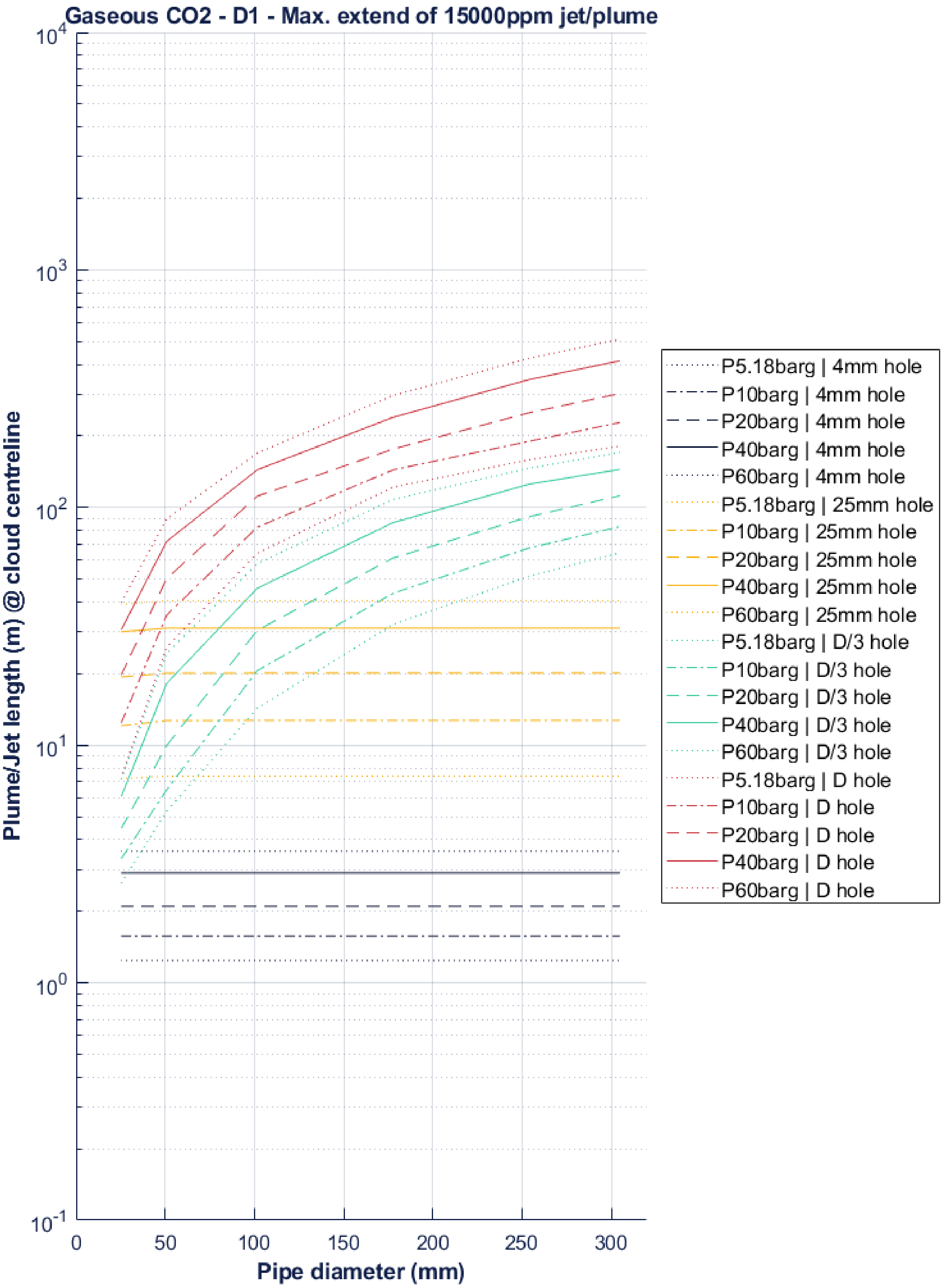
Beaufort	Stability Class	'A'	'A-B'	'B'	'B-C'	'C'	'C-D'	'D'	'E'	'F'		Sum Bft.	Culminative sum	
	Wind speed (m/s)	0.8%	3.3%	6.3%	4.7%	6.4%	1.8%	51.2%	11.4%	14.2%	Sum		Down	Up
	7.1 to 7.3					6.4E-04		8.2E-03			0.9%		93.0%	7.9%
	7.3 to 7.5					5.4E-04		7.3E-03			0.8%		93.8%	7.0%
	7.5 to 7.75					6.0E-04		8.1E-03			0.9%		94.7%	6.2%
	7.75 to 8					4.7E-04		6.9E-03			0.7%		95.4%	5.3%
	8 to 8.2					3.3E-04		4.8E-03			0.5%		95.9%	4.6%
	8.2 to 8.4					3.0E-04		4.3E-03			0.5%		96.4%	4.1%
	8.4 to 8.6					2.6E-04		3.7E-03			0.4%		96.8%	3.6%
	8.6 to 8.8					2.2E-04		3.4E-03			0.4%		97.1%	3.2%
	8.8 to 9					1.8E-04		2.9E-03			0.3%		97.5%	2.9%
	9 to 9.2					1.7E-04		2.6E-03			0.3%		97.7%	2.5%
5	9.2 to 9.4					1.4E-04		2.3E-03			0.2%	3.7%	98.0%	2.3%
	9.4 to 9.6					1.1E-04		2.1E-03			0.2%		98.2%	2.0%
	9.6 to 9.8					9.7E-05		1.9E-03			0.2%		98.4%	1.8%
	9.8 to 10					9.5E-05		1.7E-03			0.2%		98.6%	1.6%
	10 to 10.2					8.1E-05		1.5E-03			0.2%		98.7%	1.4%
	10.2 to 10.4					6.8E-05		1.3E-03			0.1%		98.9%	1.3%
	10.4 to 10.6					5.9E-05		1.2E-03			0.1%		99.0%	1.1%
	10.6 to 10.8					5.3E-05		1.0E-03			0.1%		99.1%	1.0%
	10.8 to 11.05					5.2E-05		1.2E-03			0.1%		99.2%	0.9%
	11.05 to 11.35					5.2E-05		1.2E-03			0.1%		99.4%	0.8%
	11.35 to 11.65					4.7E-05		1.0E-03			0.1%		99.5%	0.6%
	11.65 to 11.95					3.7E-05		8.9E-04			0.1%		99.6%	0.5%
	11.95 to 12.25					3.0E-05		7.5E-04			0.1%		99.6%	0.4%
6	12.25 to 12.55					2.6E-05		6.1E-04			0.1%	0.8%	99.7%	0.4%
	12.55 to 12.85					1.8E-05		5.0E-04			0.1%		99.8%	0.3%
	12.85 to 13.15					2.0E-05		4.1E-04			0.0%		99.8%	0.2%
	13.15 to 13.45					1.3E-05		3.5E-04			0.0%		99.8%	0.2%
	13.45 to 13.7					1.2E-05		2.4E-04			0.0%		99.9%	0.2%
	13.7 to 13.9					4.9E-06		1.7E-04			0.0%		99.9%	0.1%
	13.9 to 14.15					7.8E-06		1.8E-04			0.0%		99.9%	0.1%
	14.15 to 14.45					5.7E-06		1.6E-04			0.0%		99.9%	0.1%
	14.45 to 14.75					4.4E-06		1.5E-04			0.0%		99.9%	0.1%
	14.75 to 15.05					4.2E-06		1.2E-04			0.0%		100.0%	0.1%
	15.05 to 15.35					3.2E-06		1.0E-04			0.0%		100.0%	0.0%
7	15.35 to 15.65					2.3E-06		7.3E-05			0.0%	0.10%	100.0%	0.0%
	15.65 to 15.95					1.1E-06		5.9E-05			0.0%		100.0%	0.0%
	15.95 to 16.25					1.3E-06		5.4E-05			0.0%		100.0%	0.0%
	16.25 to 16.55					4.2E-07		3.7E-05			0.0%		100.0%	0.0%
	16.55 to 16.9					6.3E-07		3.5E-05			0.0%		100.0%	0.0%
	16.9 to 17.2					4.2E-07		2.5E-05			0.0%		100.0%	0.0%
8	17.2 to 17.45							1.6E-05			0.0%	0.01%	100.0%	0.0%
	17.45 to 17.75							1.3E-05			0.0%		100.0%	0.0%

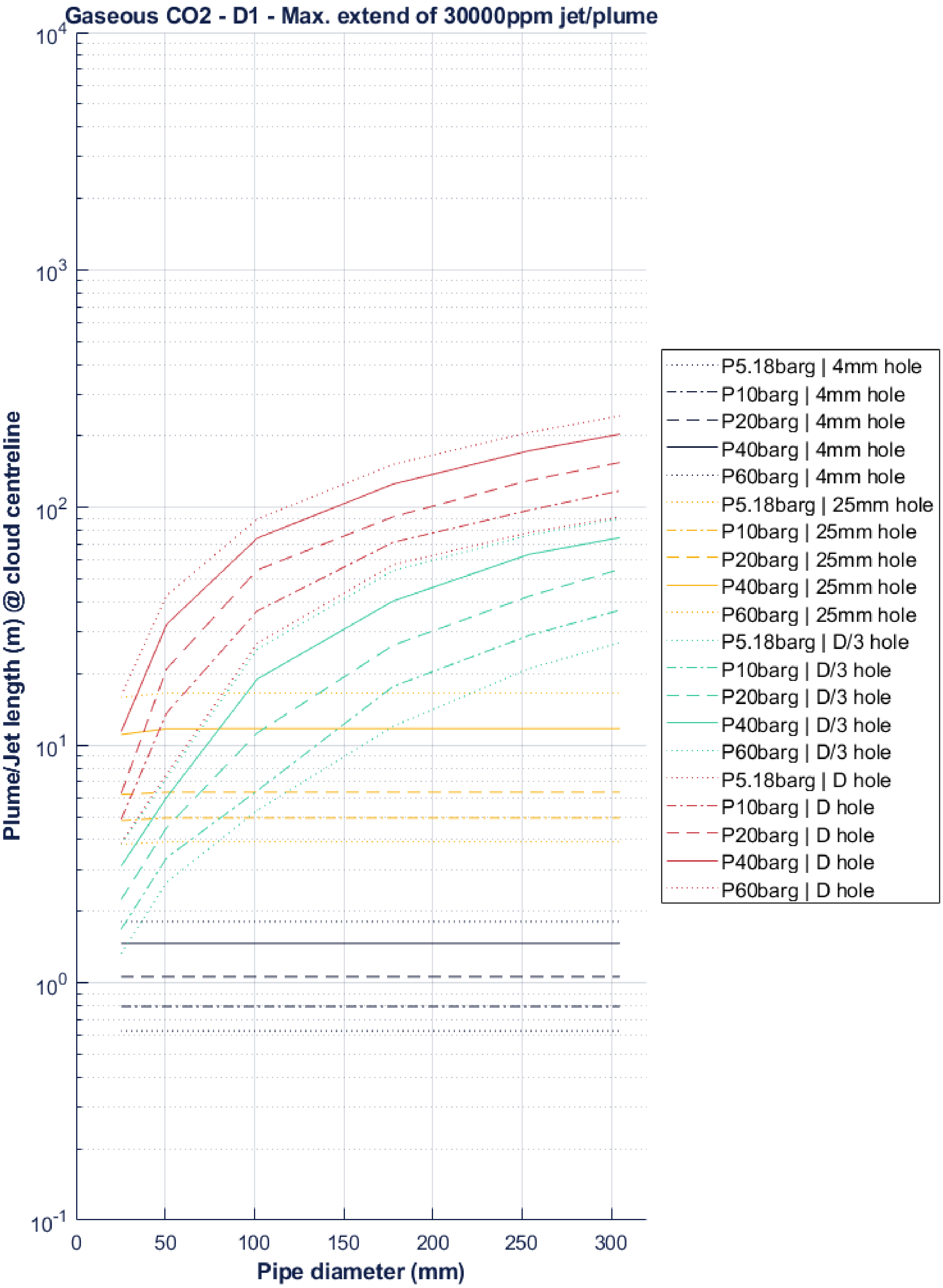
Beaufort	Stability Class	'A'	'A-B'	'B'	'B-C'	'C'	'C-D'	'D'	'E'	'F'		Sum Bft.	Culminative sum	
	Wind speed (m/s)	0.8%	3.3%	6.3%	4.7%	6.4%	1.8%	51.2%	11.4%	14.2%	Sum		Down	Up
	17.75 to 18.05							1.5E-05			0.0%		100.0%	0.0%
	18.05 to 18.35							8.0E-06			0.0%		100.0%	0.0%
	18.35 to 18.65							5.5E-06			0.0%		100.0%	0.0%
	18.65 to 18.95							7.4E-06			0.0%		100.0%	0.0%
	18.95 to 19.25							6.5E-06			0.0%		100.0%	0.0%
	19.25 to 19.55							6.1E-06			0.0%		100.0%	0.0%
	19.55 to 19.85							4.4E-06			0.0%		100.0%	0.0%
	19.85 to 20.15							3.6E-06			0.0%		100.0%	0.0%
	20.15 to 20.45							3.2E-06			0.0%		100.0%	0.0%
	20.45 to 20.7							2.7E-06			0.0%		100.0%	0.0%
9	20.7 to 21							2.5E-06			0.0%	0.001%	100.0%	0.0%
	21 to 21.4							1.7E-06			0.0%		100.0%	0.0%
	21.4 to 21.8							1.5E-06			0.0%		100.0%	0.0%
	21.8 to 22.2							8.4E-07			0.0%		100.0%	0.0%
	22.2 to 22.6							1.5E-06			0.0%		100.0%	0.0%
	22.6 to 23							2.1E-07			0.0%		100.0%	0.0%
	23 to 23.4							6.3E-07			0.0%		100.0%	0.0%
	23.4 to 23.8							2.1E-07			0.0%		100.0%	0.0%
	23.8 to 24.2										0.0%		100.0%	0.0%
	24.2 to 24.5										0.0%		100.0%	0.0%
10	24.5 to 24.8										0.0%	0.0%	100.0%	0.0%
	24.8 to 25.2							2.1E-07			0.0%		100.0%	0.0%
	25.2 to 25.6										0.0%		100.0%	0.0%
	25.6 to 26										0.0%		100.0%	0.0%
	26 to 26.4										0.0%		100.0%	0.0%
	26.4 to 26.8										0.0%		100.0%	0.0%
	26.8 to 27.2										0.0%		100.0%	0.0%
	27.2 to 27.6										0.0%		100.0%	0.0%
	27.6 to 28.05										0.0%		100.0%	0.0%
	28.05 to 28.4										0.0%		100.0%	0.0%
11	28.4 to 28.75										0.0%	0%	100.0%	0.0%
	28.75 to 29.25										0.0%		100.0%	0.0%
	29.25 to 29.75										0.0%		100.0%	0.0%
	29.75 to 30.25										0.0%		100.0%	0.0%
	30.25 to 30.75										0.0%		100.0%	0.0%
	30.75 to 31.25										0.0%		100.0%	0.0%
	31.25 to 31.75										0.0%		100.0%	0.0%
	31.75 to 32.25										0.0%		100.0%	0.0%
	32.25 to 32.6										0.0%		100.0%	0.0%
12	32.6 to 33.85										0.0%	0%	100.0%	0.0%
	33.85 to 37.5										0.0%		100.0%	0.0%
	37.5 to 45										0.0%		100.0%	0.0%

Beaufort	Stability Class	'A'	'A-B'	'B'	'B-C'	'C'	'C-D'	'D'	'E'	'F'		Sum	Culminative sum	
	Wind speed (m/s)	0.8%	3.3%	6.3%	4.7%	6.4%	1.8%	51.2%	11.4%	14.2%	Sum	Bft.	Down	Up
	45 to 55										0.0%		100.0%	0.0%
	55 to 100										0.0%		100.0%	0.0%

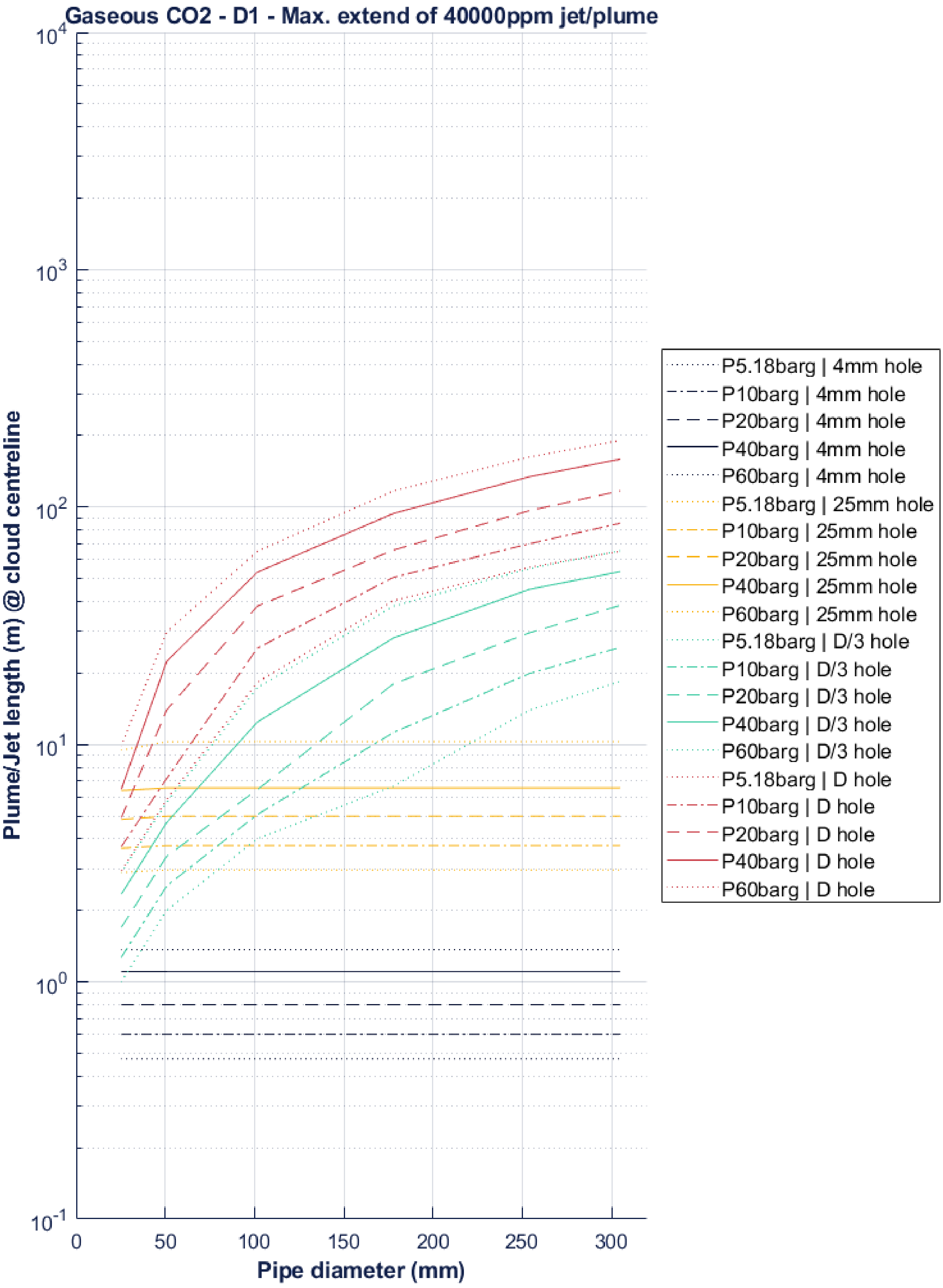
8.3 Gaseous releases – Plume/Jet length as function of diameter



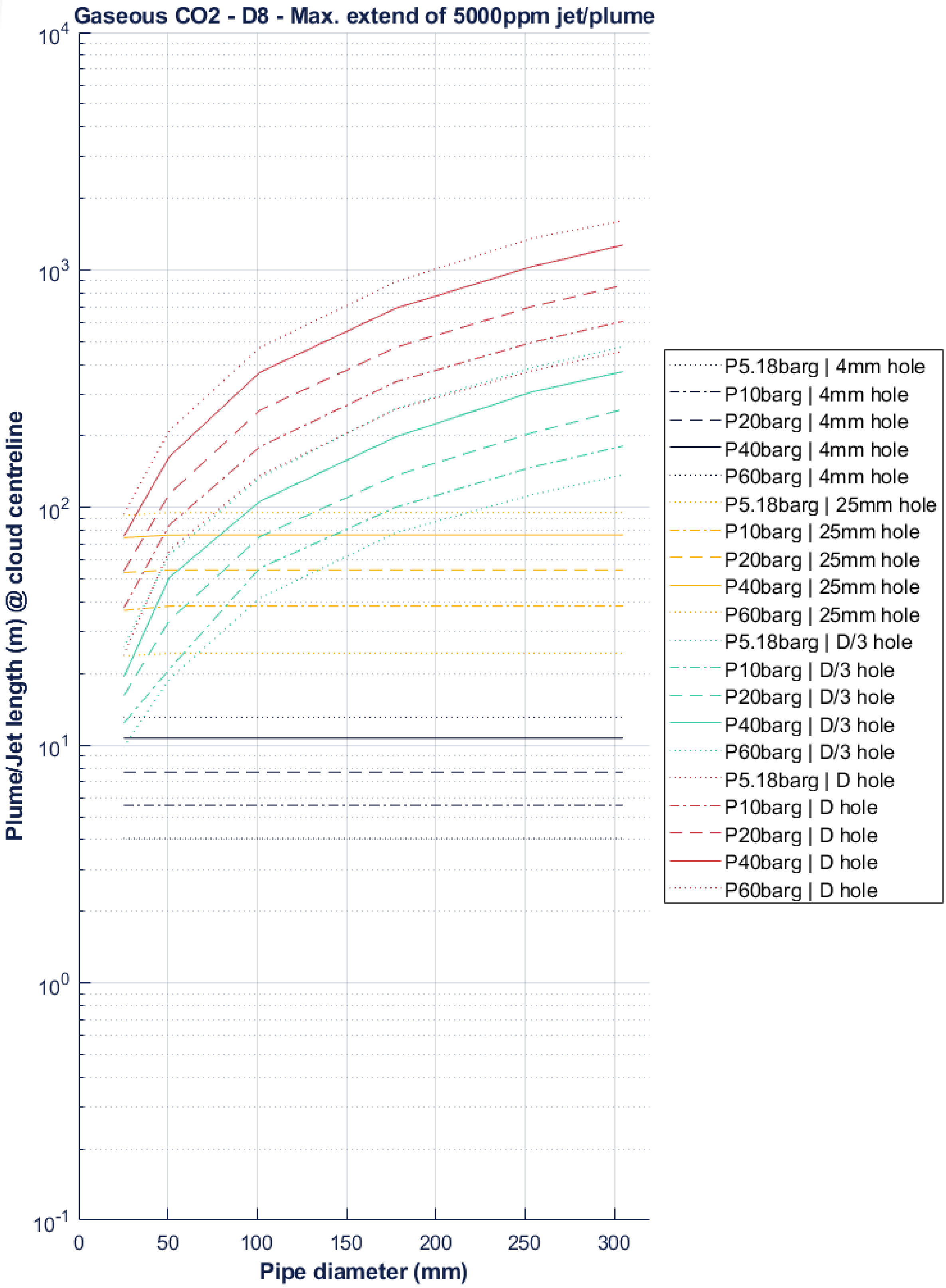

Gaseous CO2 - D1 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

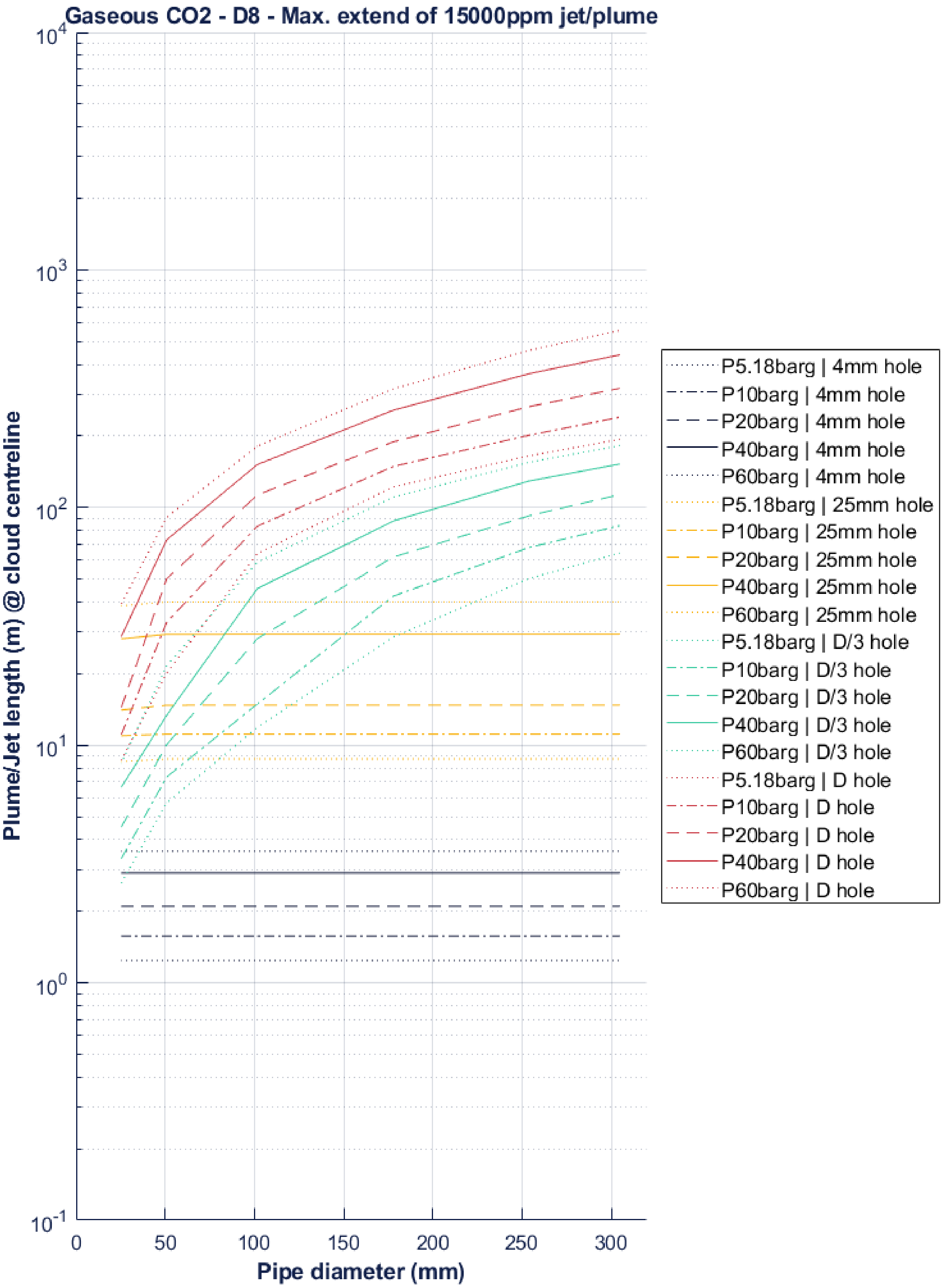


Gaseous CO2 - D1 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

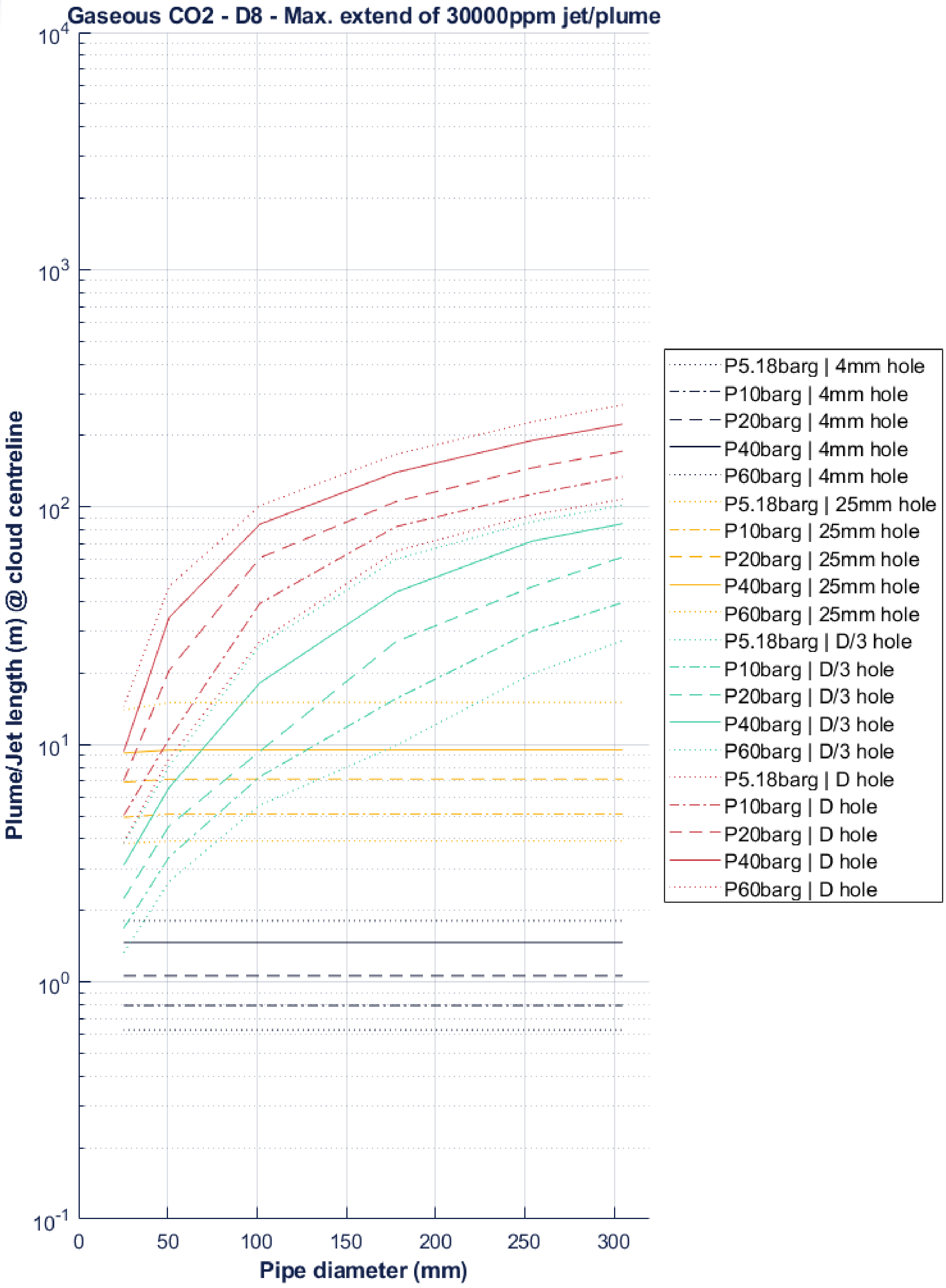


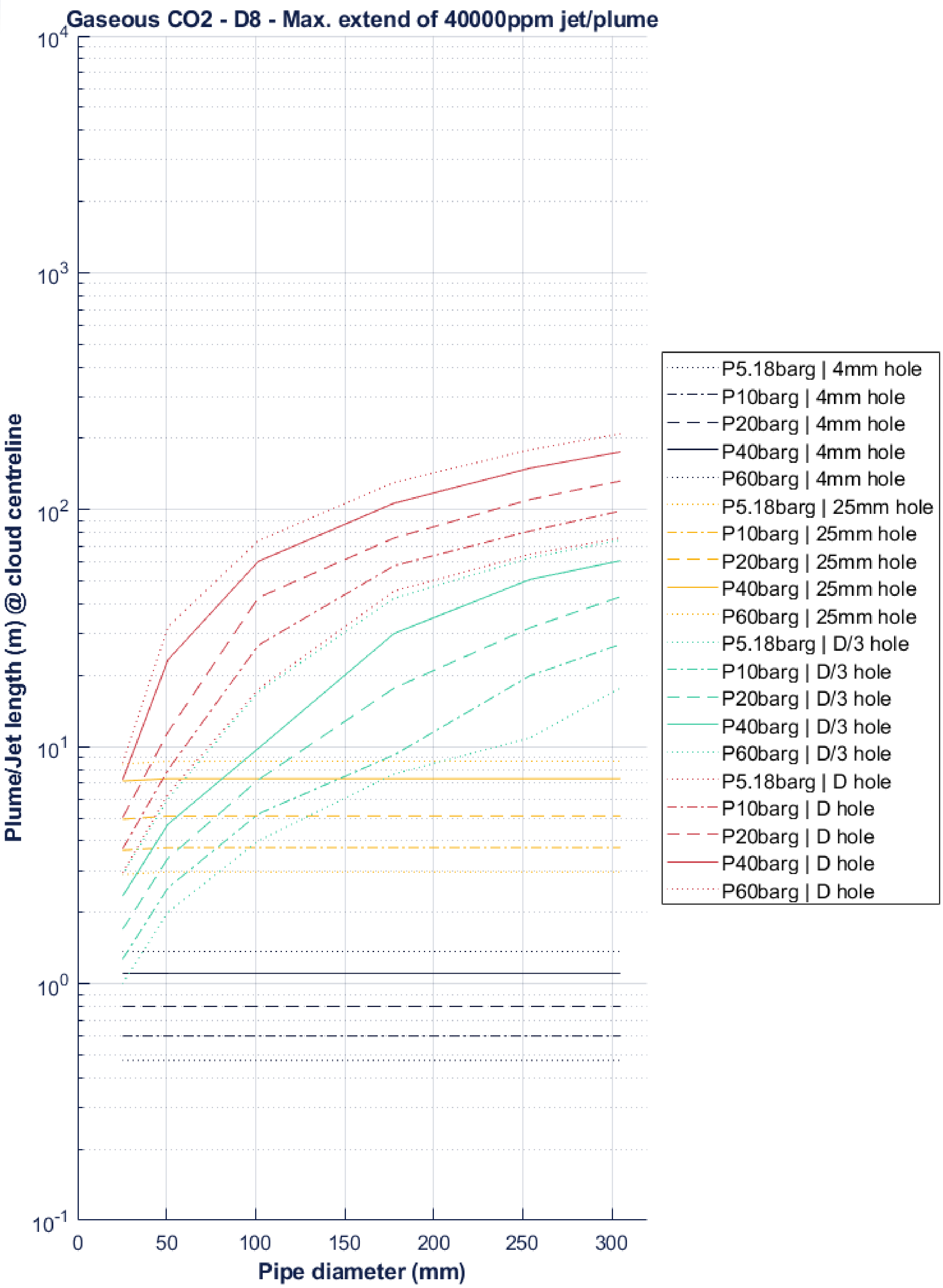
Gaseous CO2 - D1 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

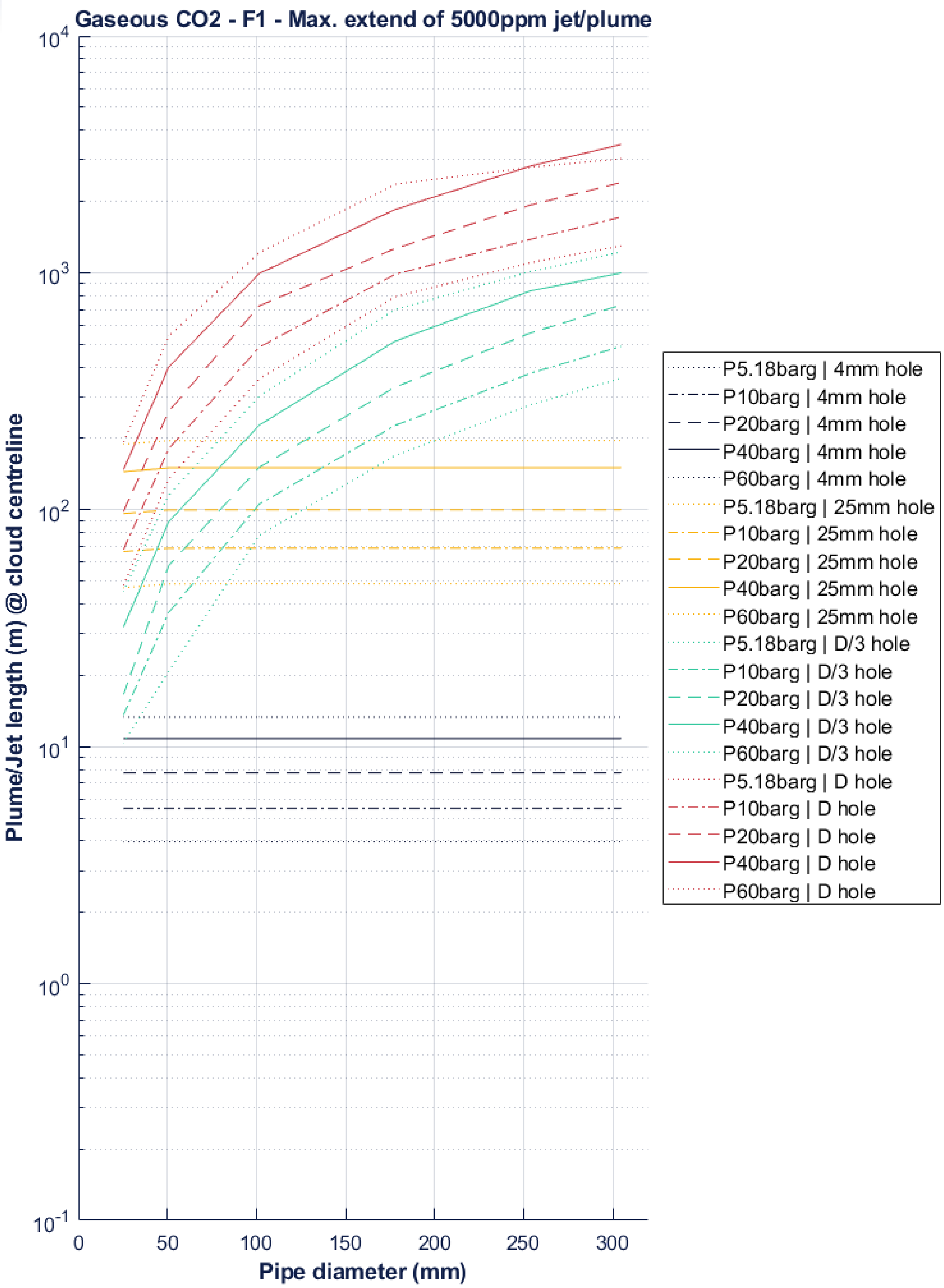

Gaseous CO2 - D8 - Max. extend of 5000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

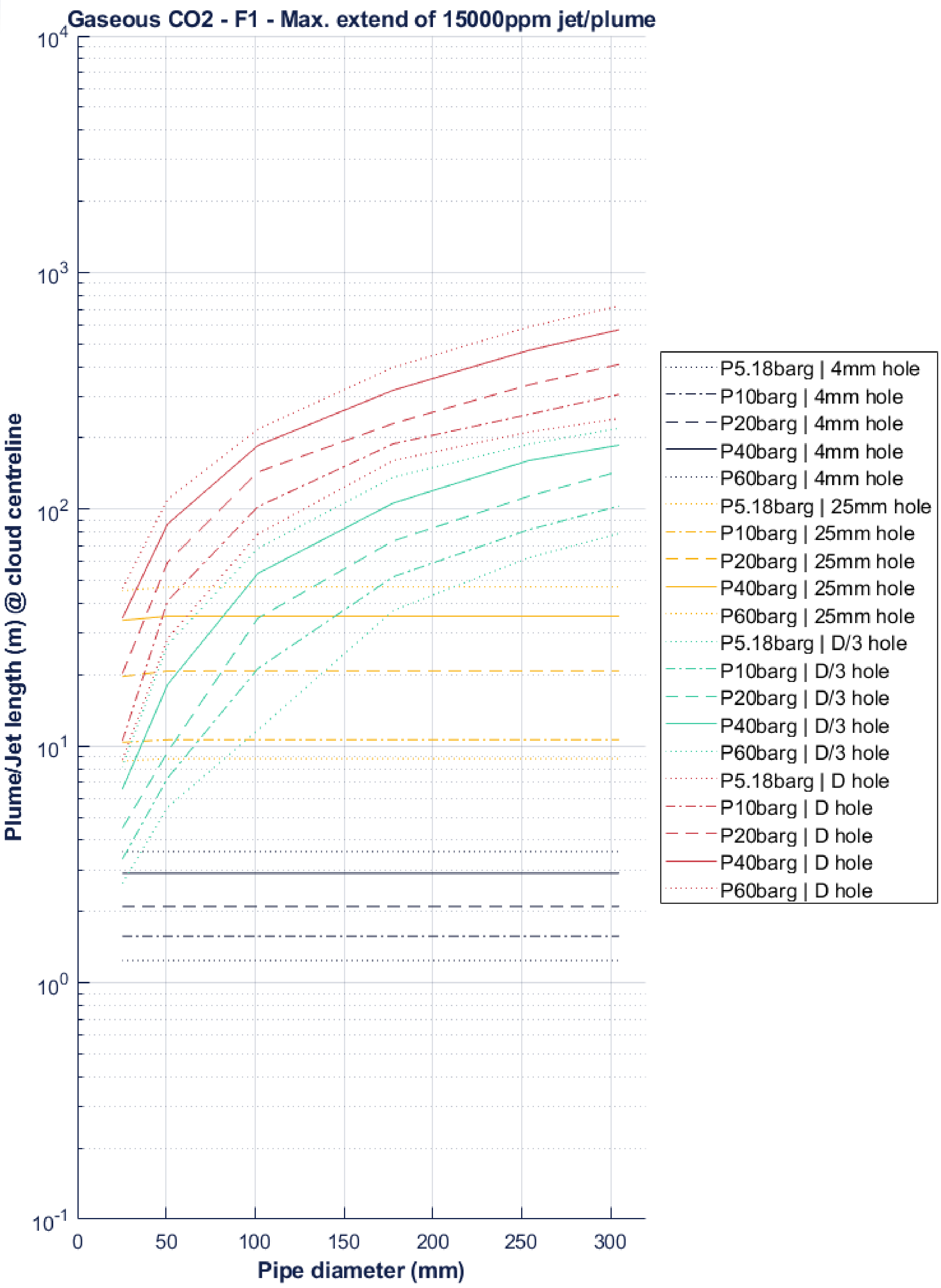


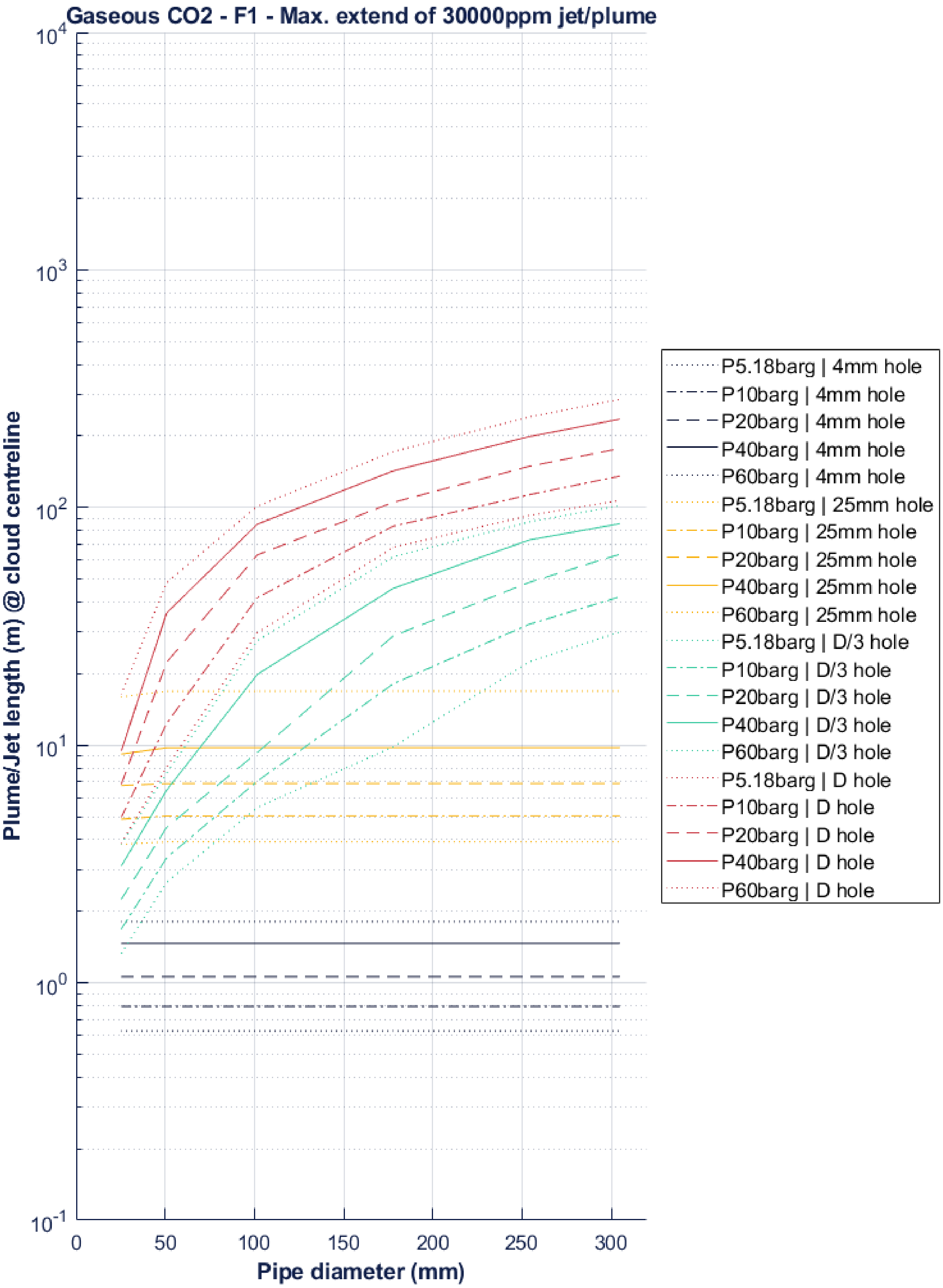
Gaseous CO2 - D8 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole


Gaseous CO2 - D8 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

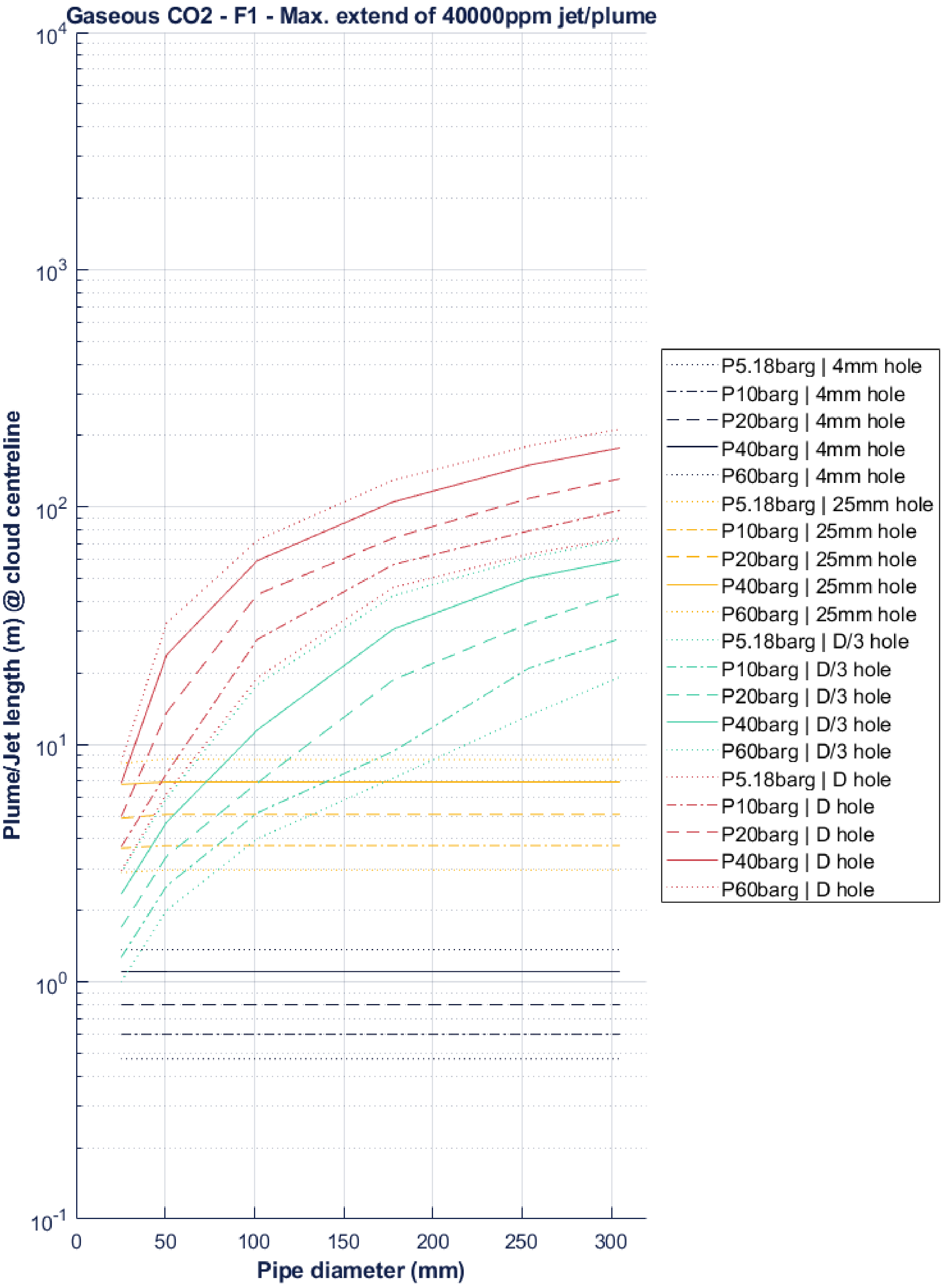

Gaseous CO2 - D8 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole


Gaseous CO2 - F1 - Max. extend of 5000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

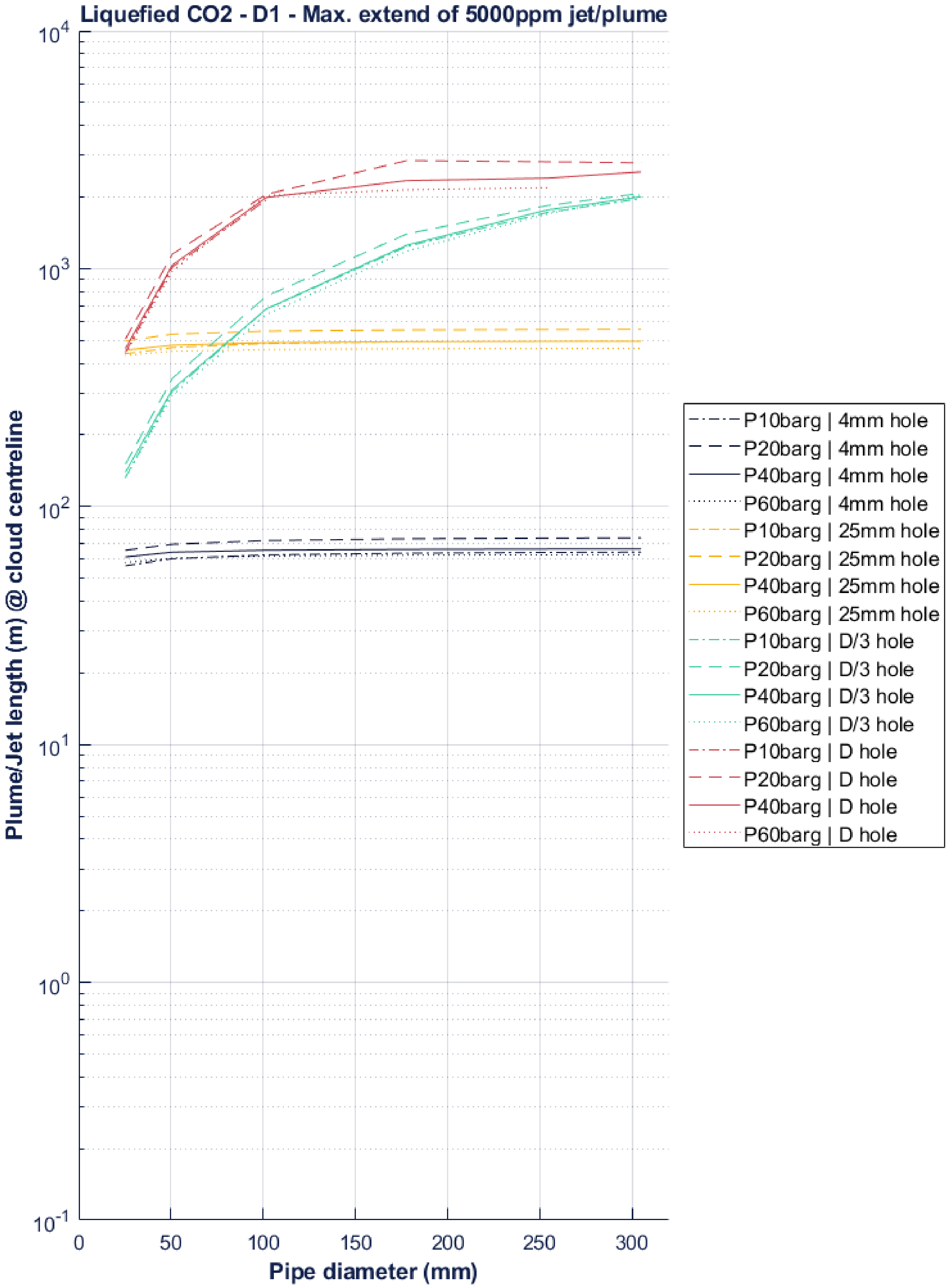

Gaseous CO2 - F1 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

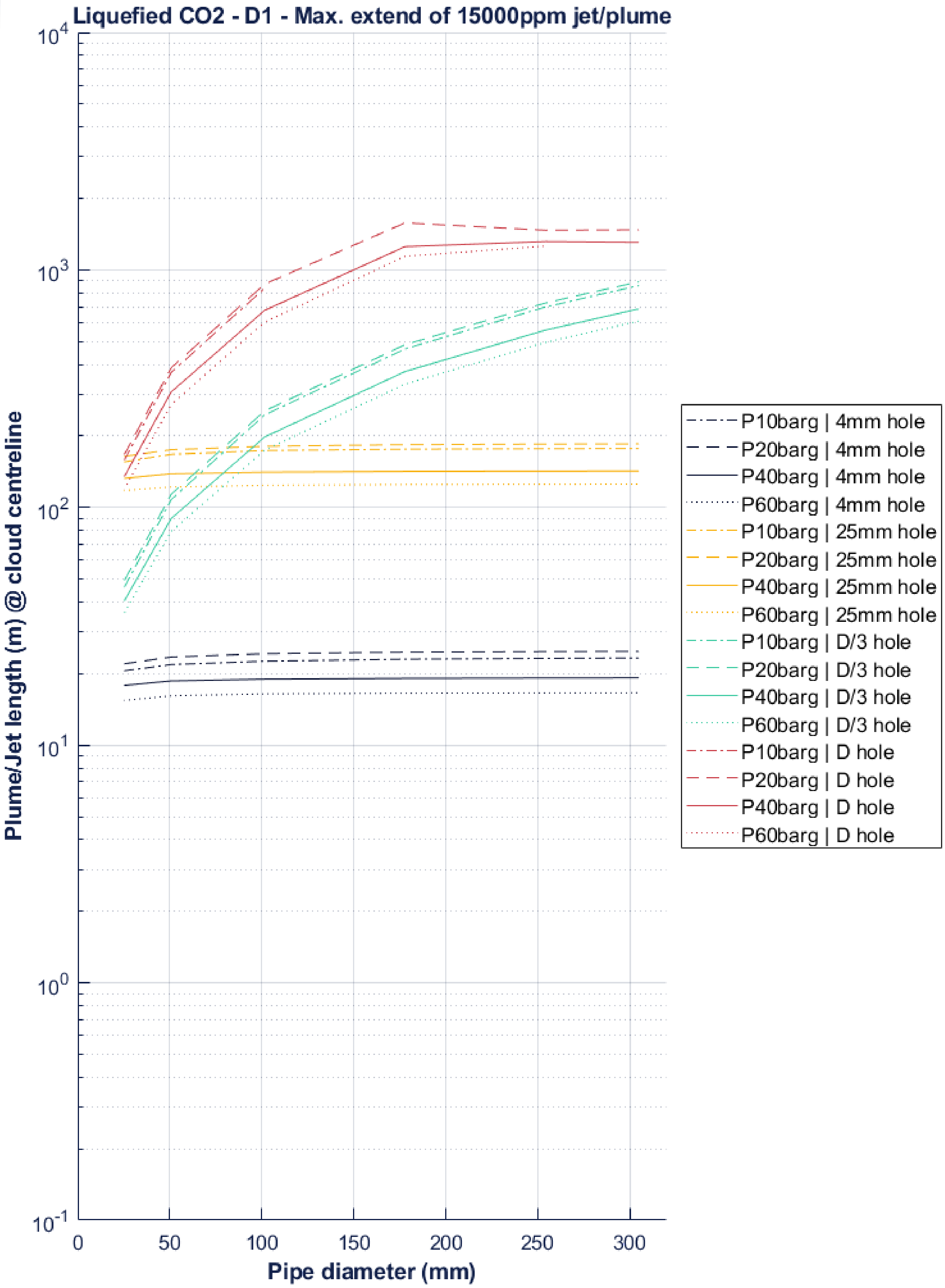


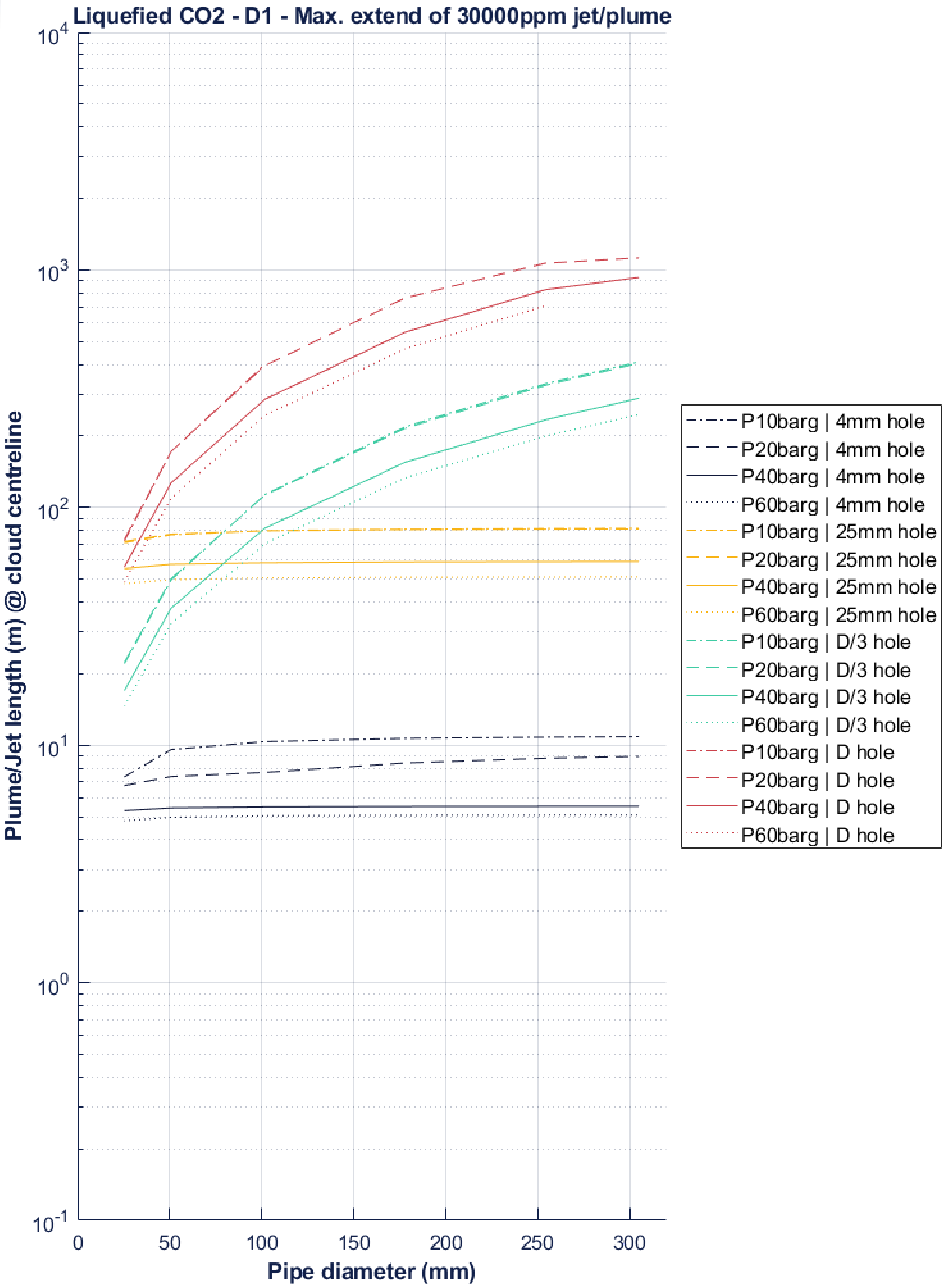
Gaseous CO2 - F1 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

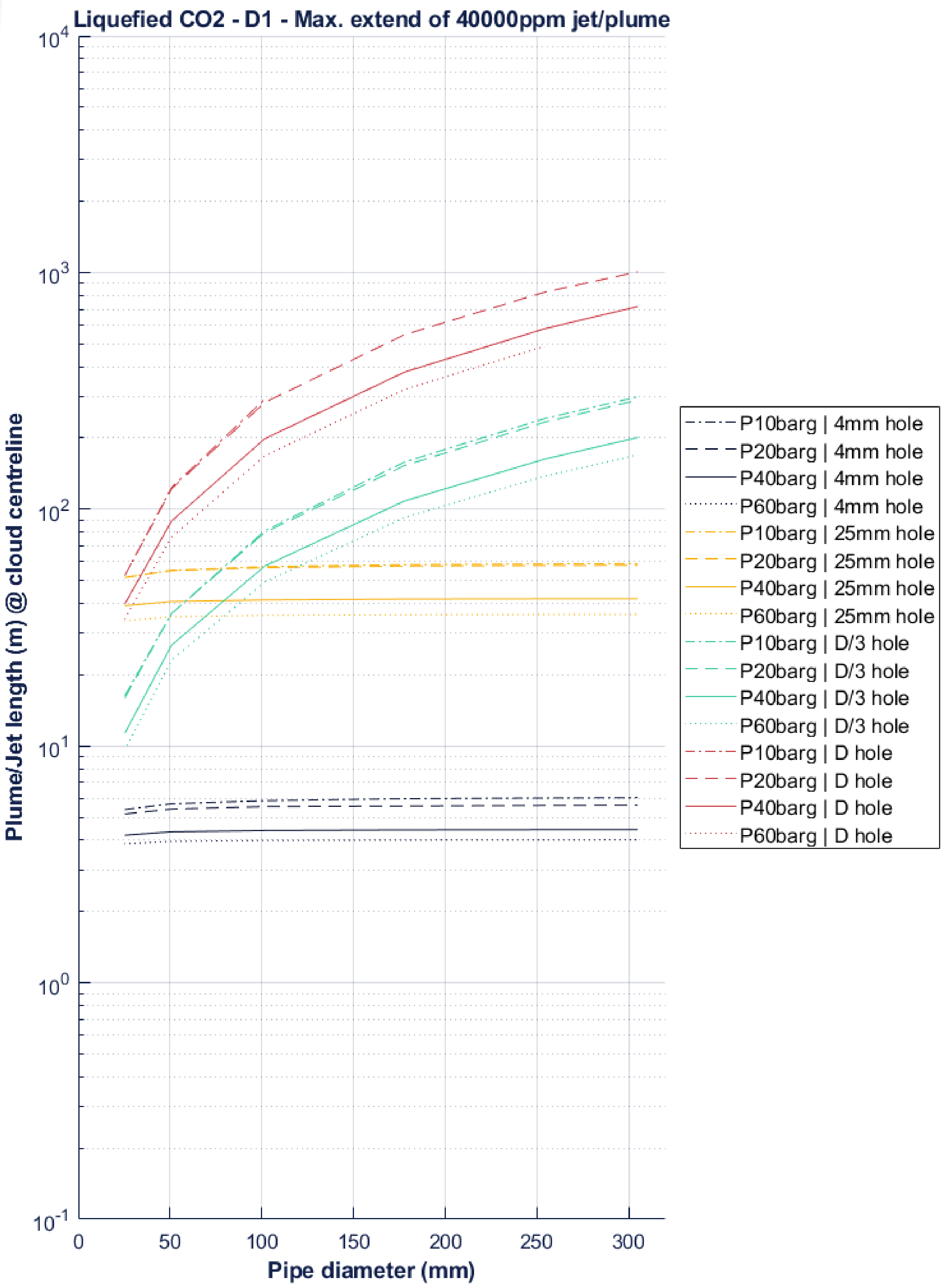

Gaseous CO2 - F1 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

8.4 Liquefied releases – Plume/Jet length as function of diameter

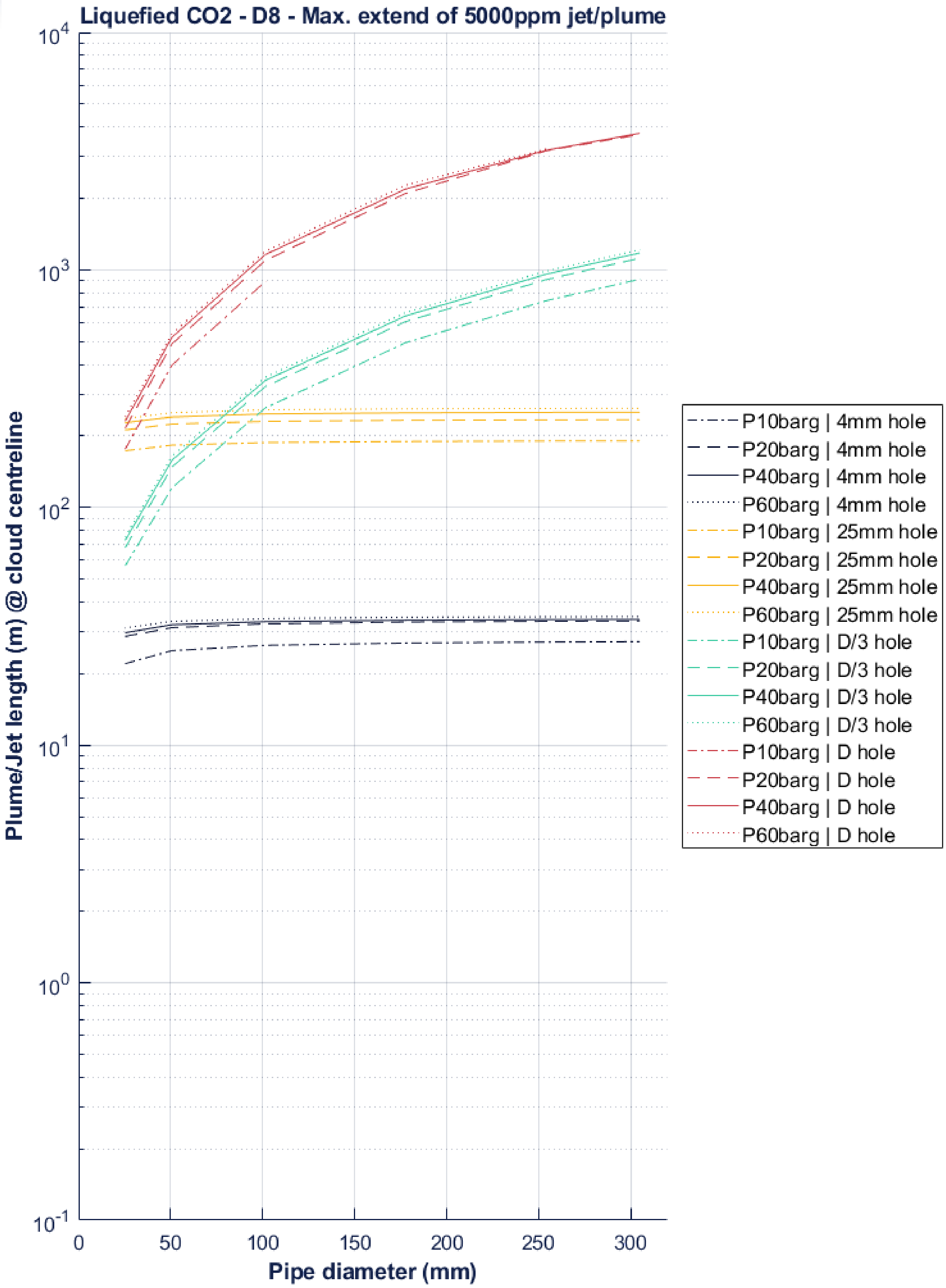



Liquefied CO2 - D1 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

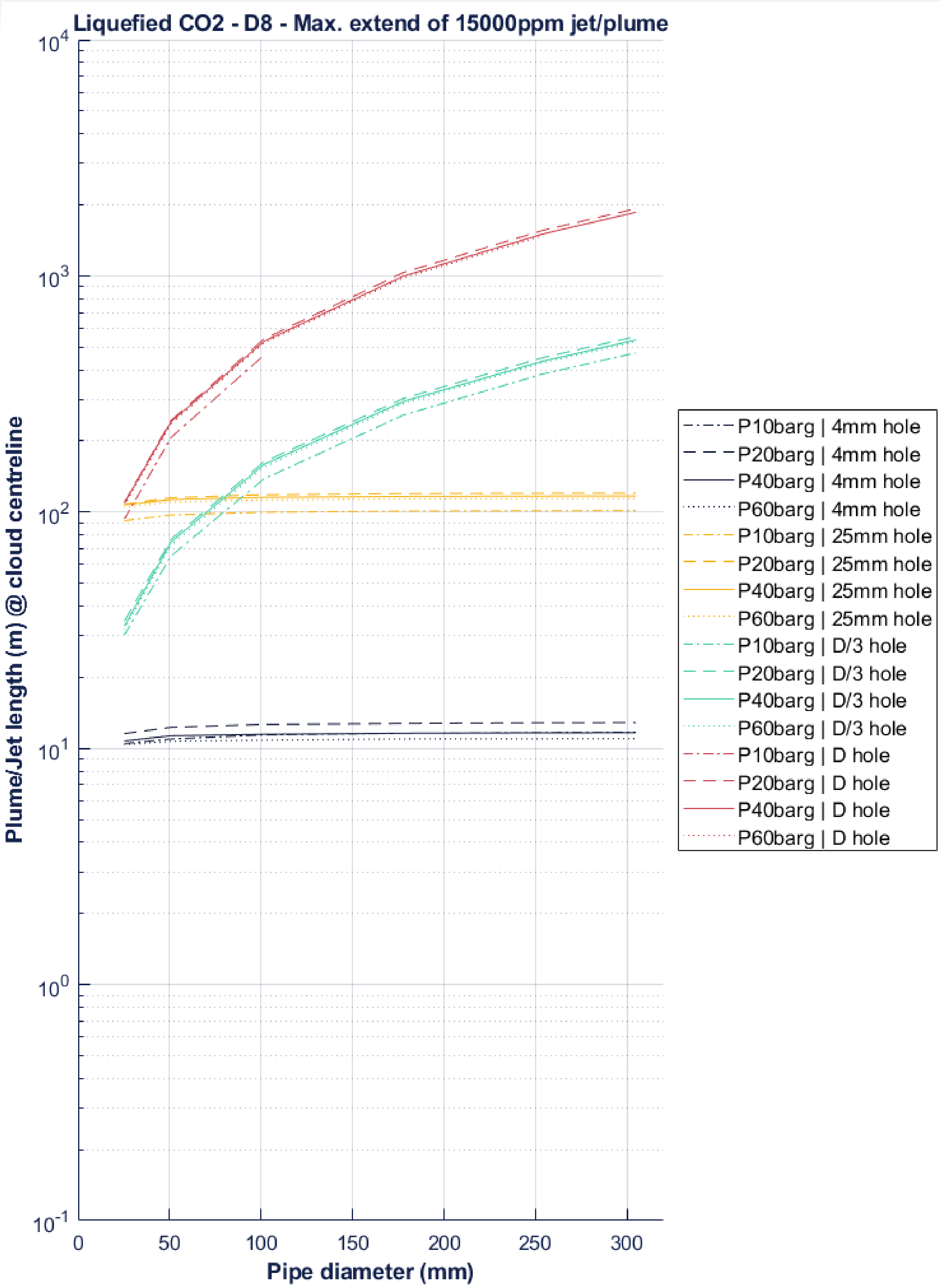

Liquefied CO2 - D1 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

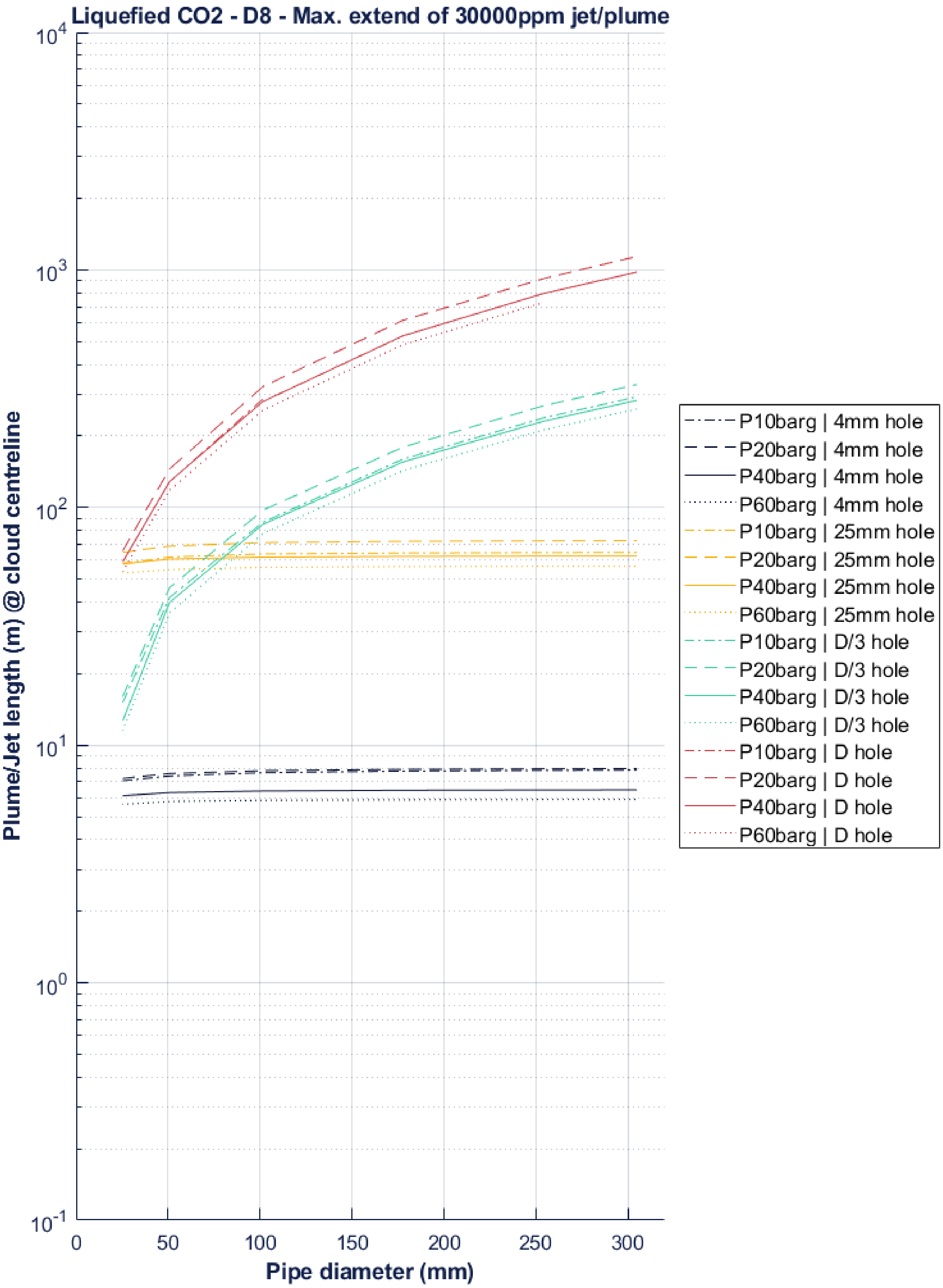


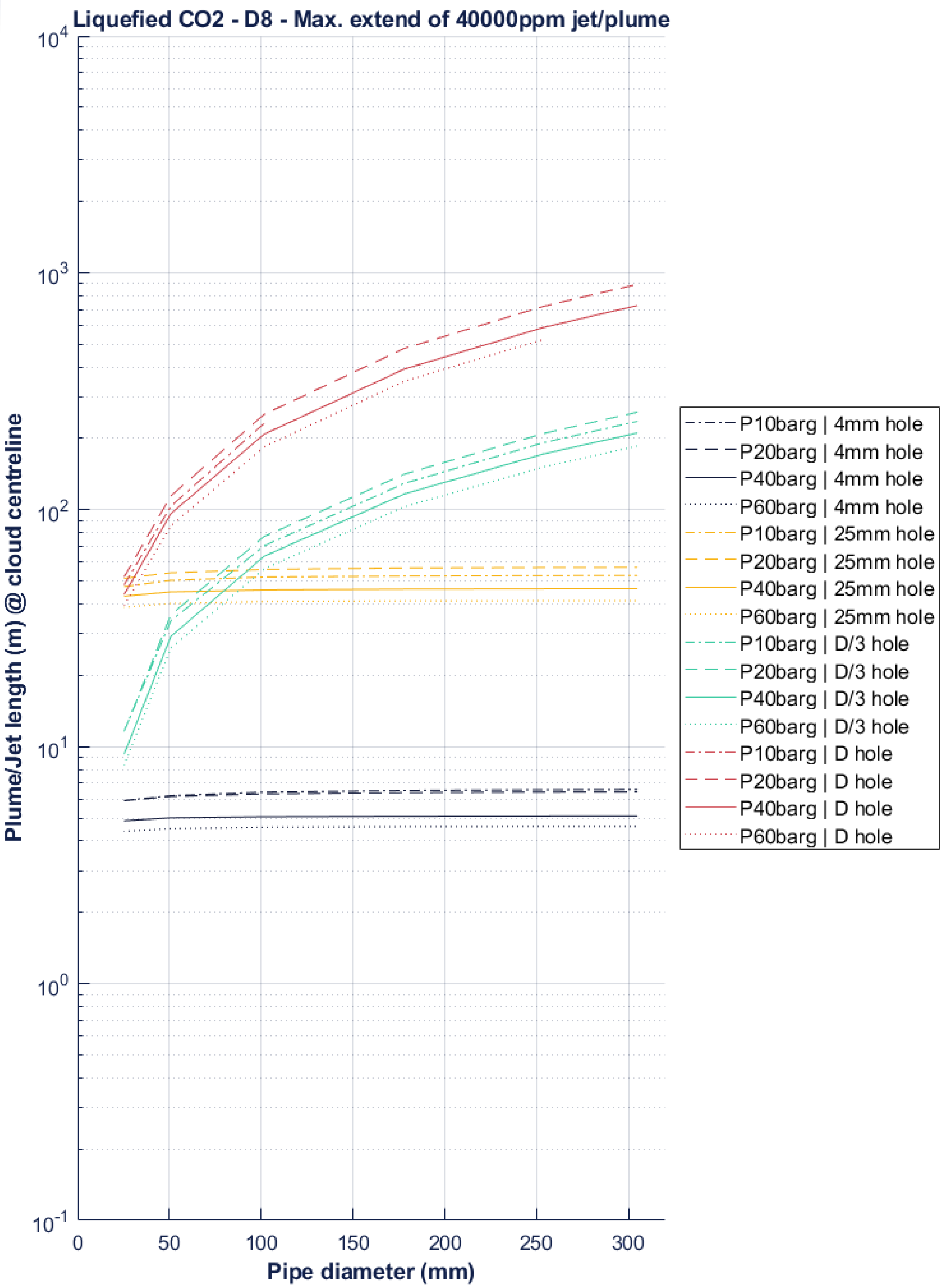
Liquefied CO2 - D1 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

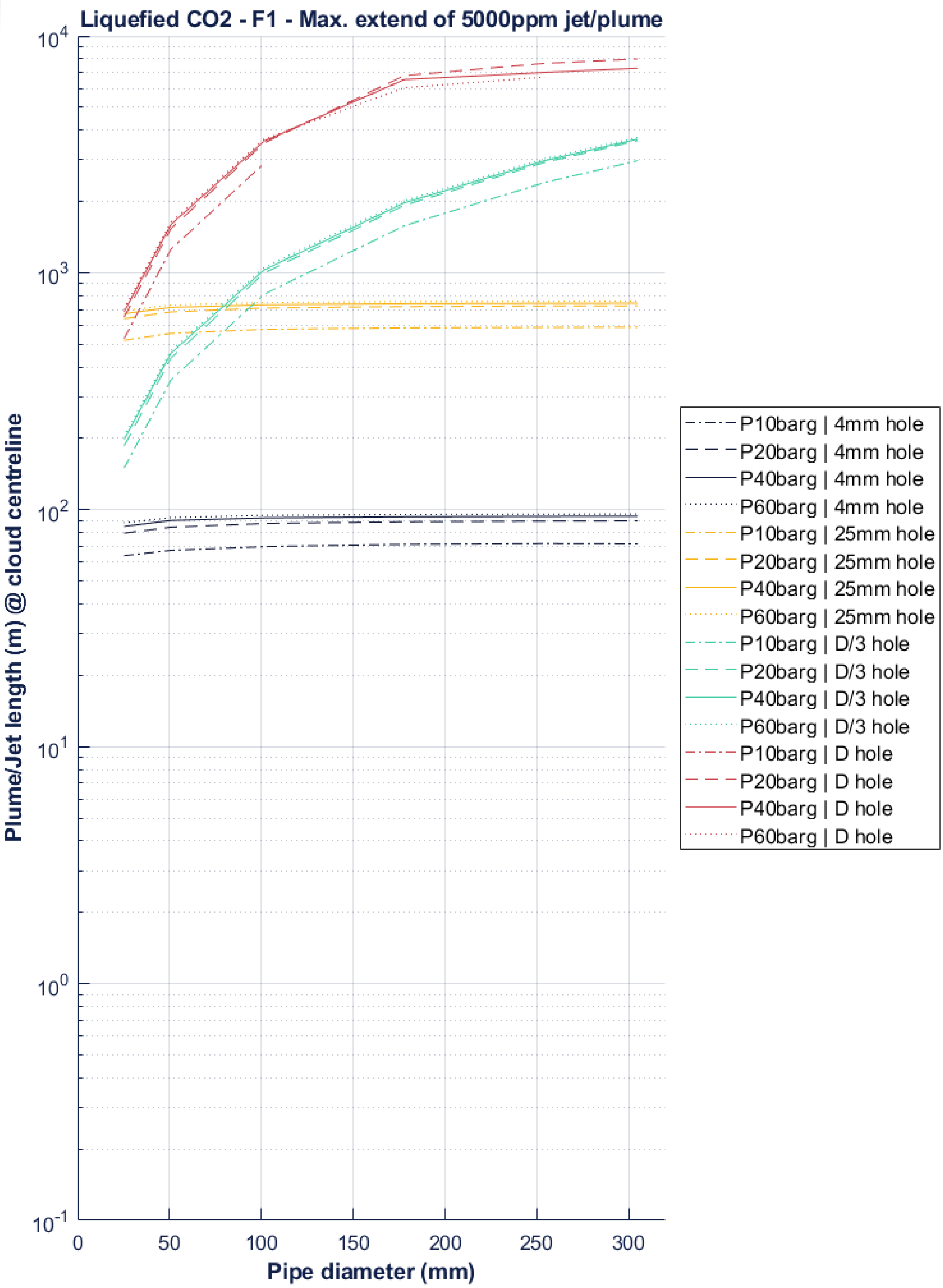


Liquefied CO2 - D8 - Max. extend of 5000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

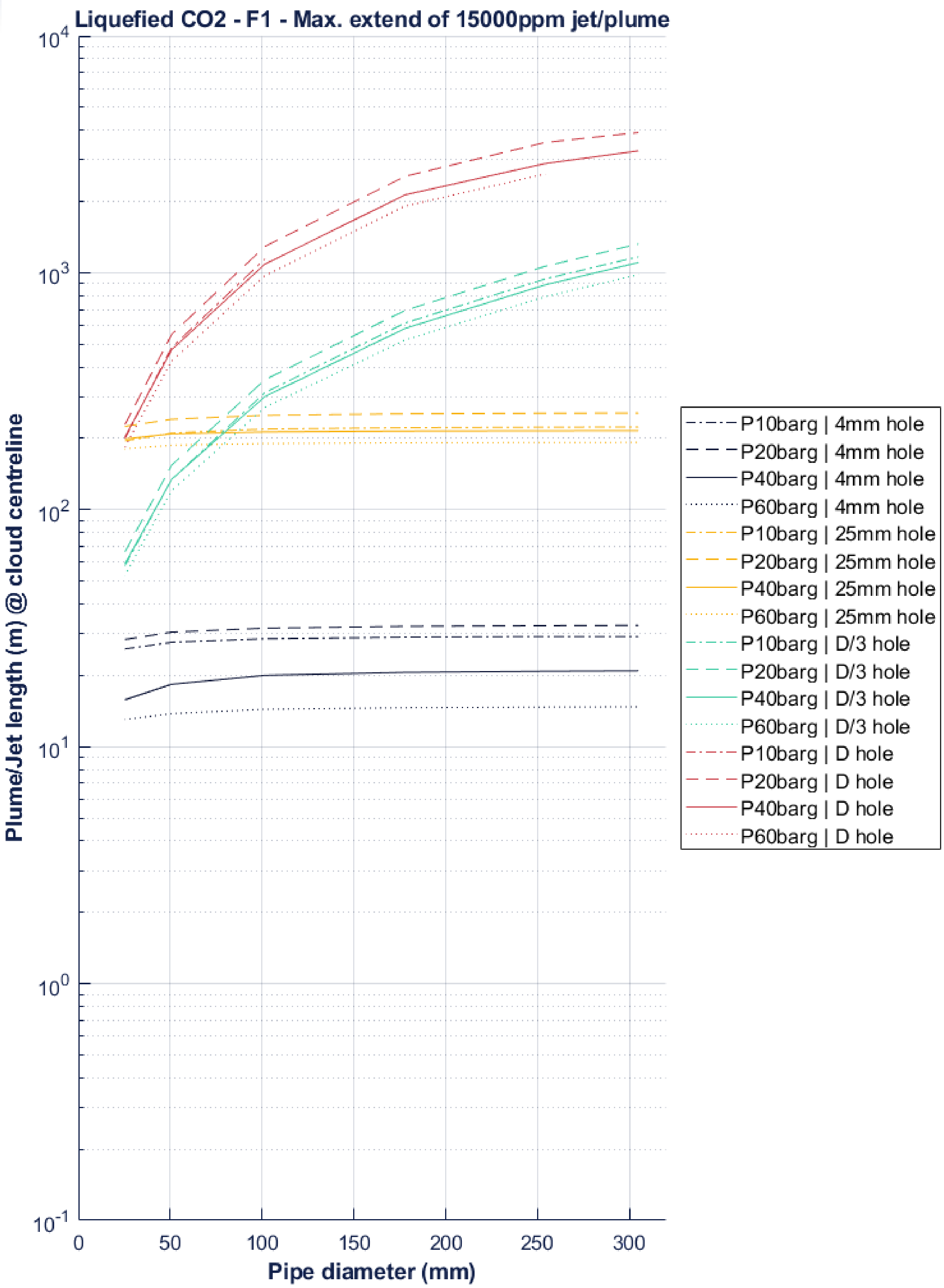

Liquefied CO2 - D8 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

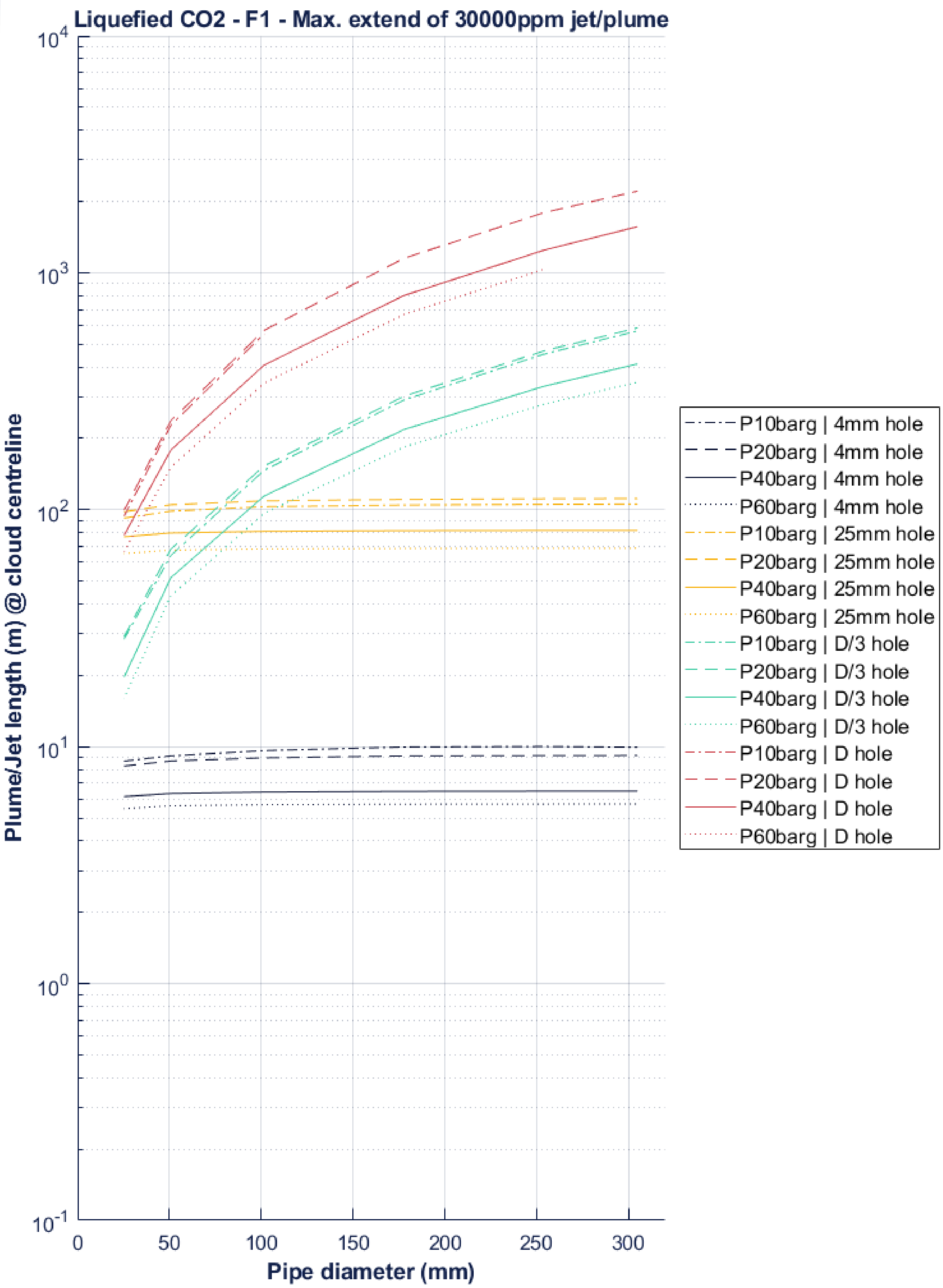

Liquefied CO2 - D8 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole


Liquefied CO2 - D8 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^{-1}
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

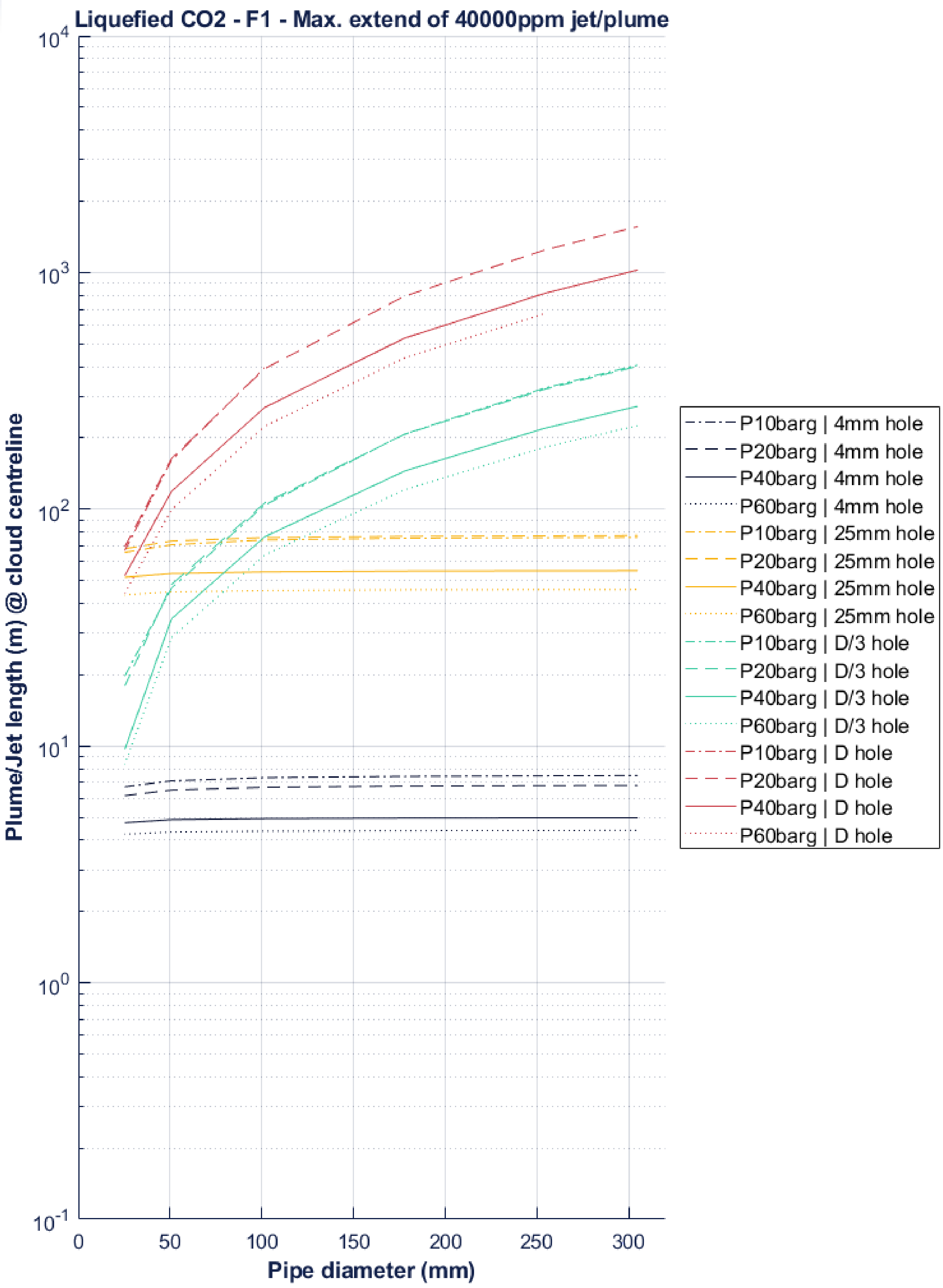


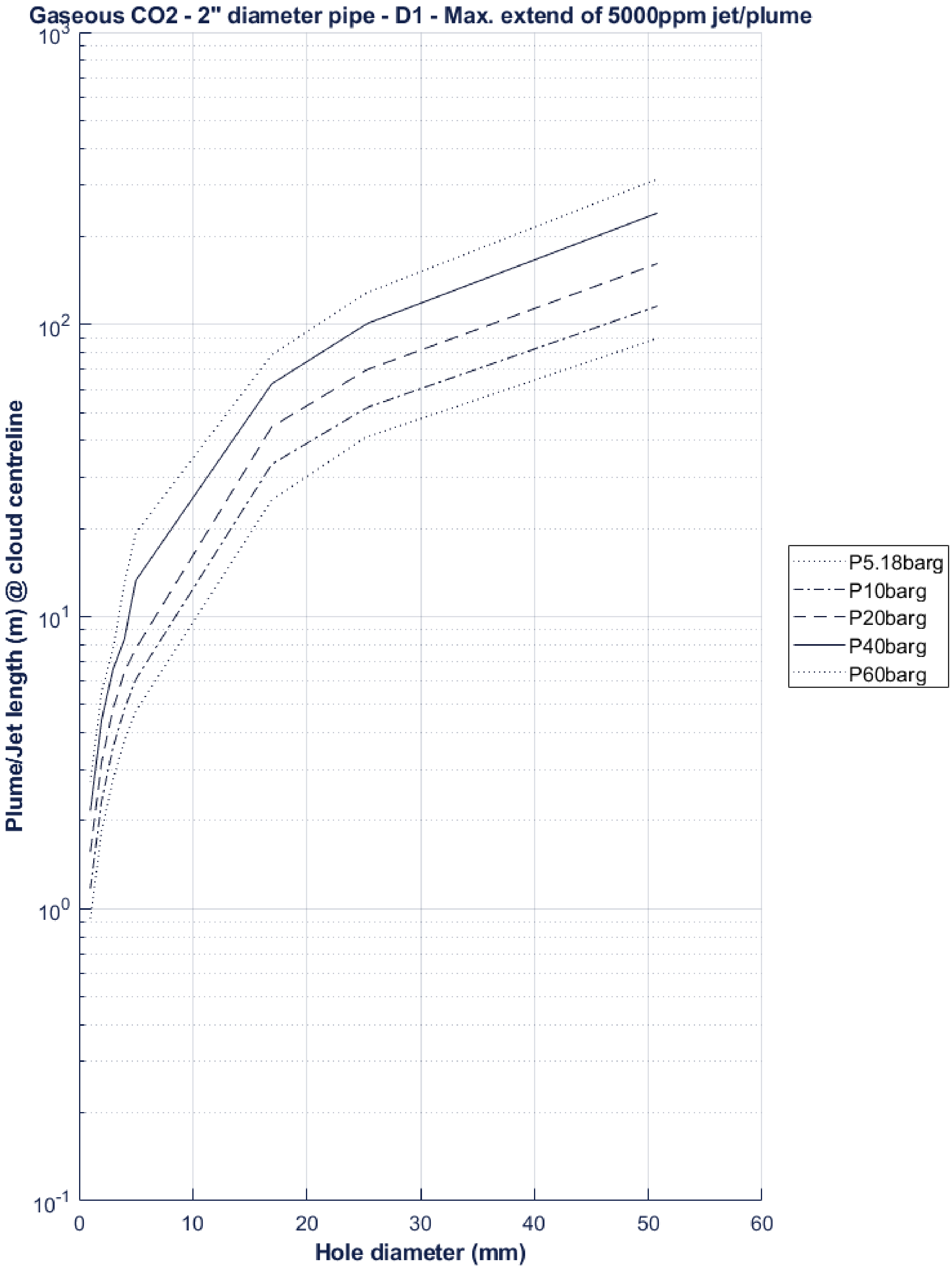
Liquefied CO2 - F1 - Max. extend of 5000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

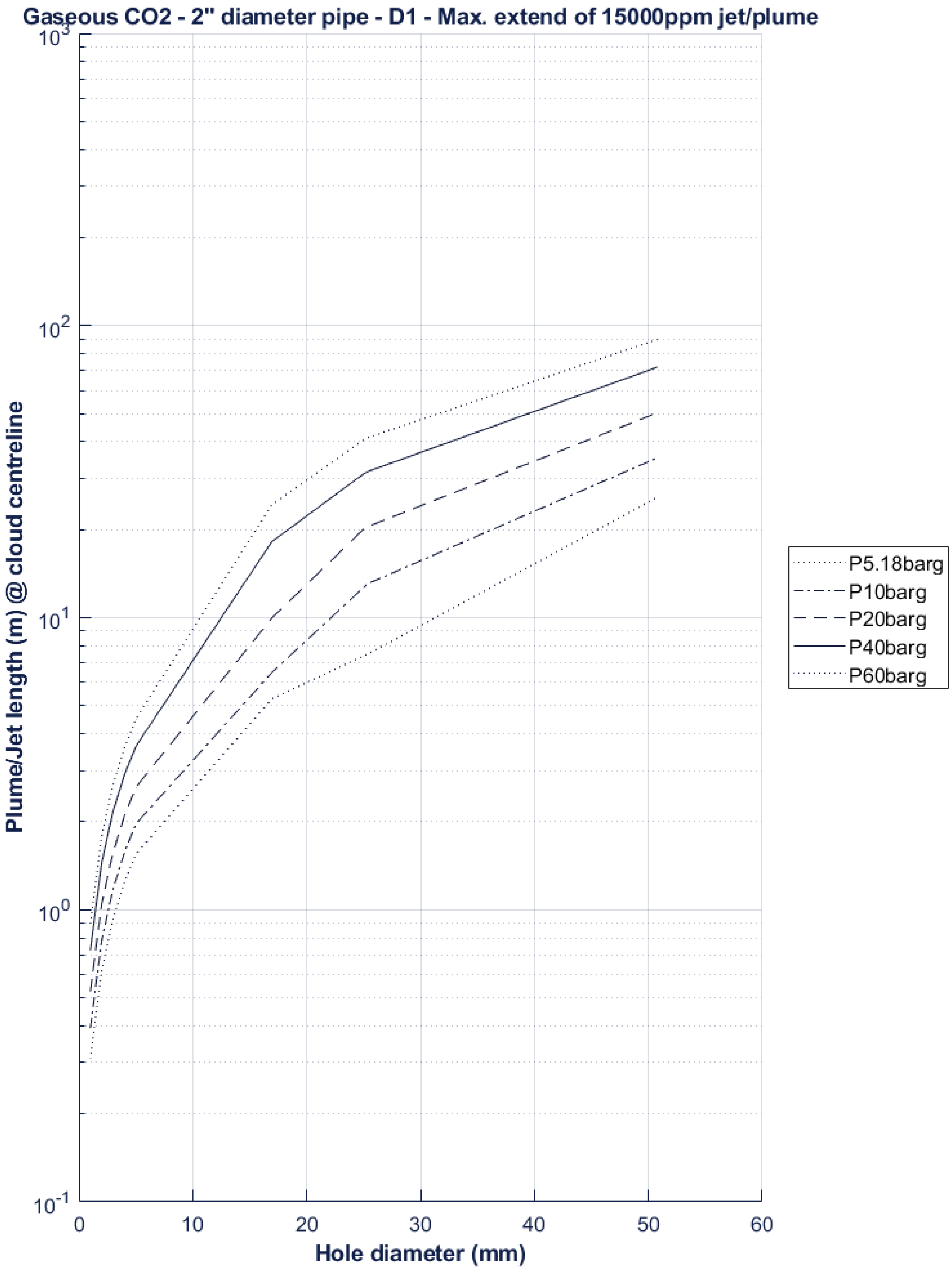

Liquefied CO2 - F1 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

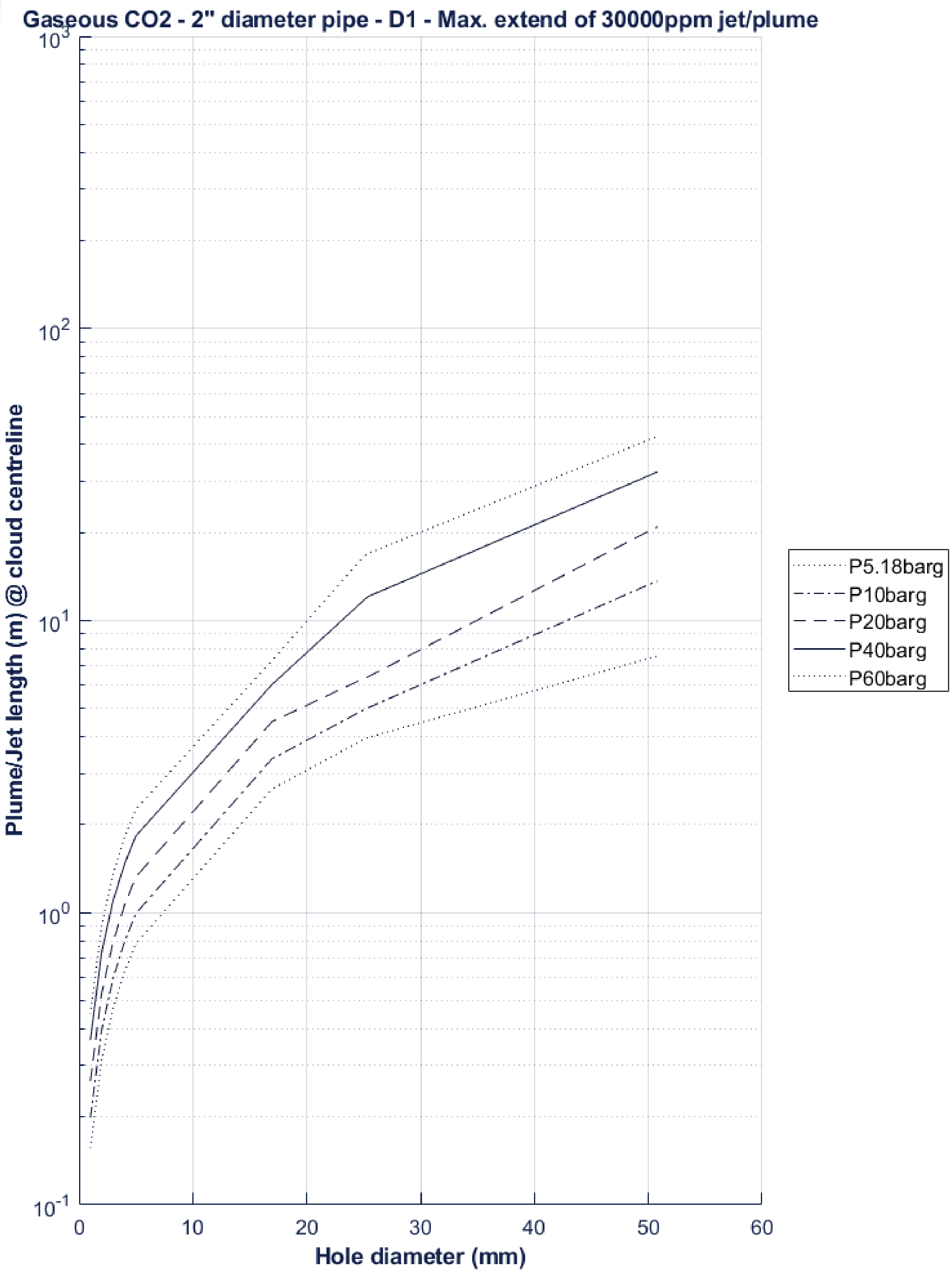


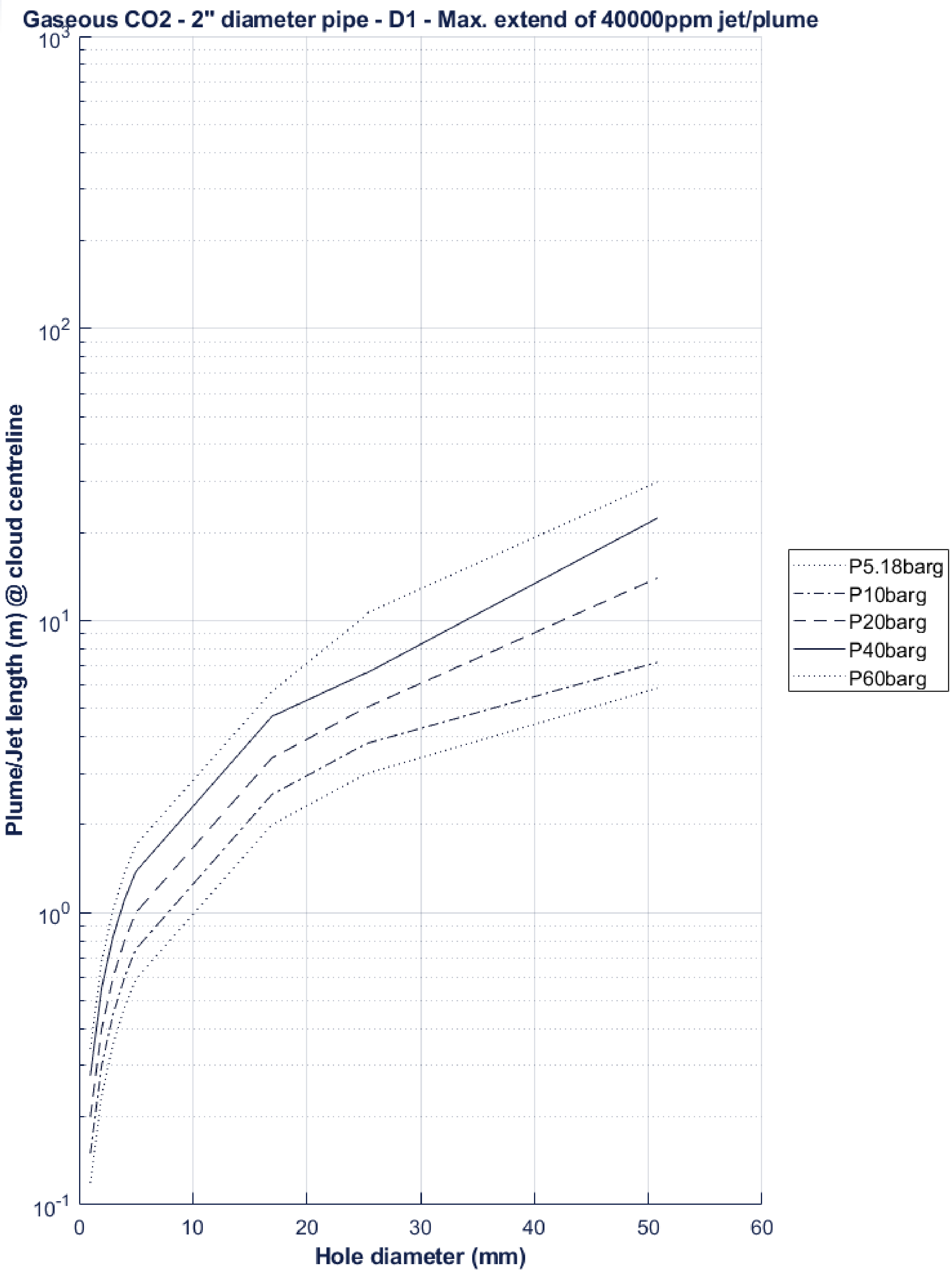
Liquefied CO2 - F1 - Max. extend of 30000ppm jet/plume
10^4
10^3
10^2
10^1
10^0
10^-1
Plume/Jet length (m) @ cloud centreline
0
50
100
150
200
250
300
Pipe diameter (mm)
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

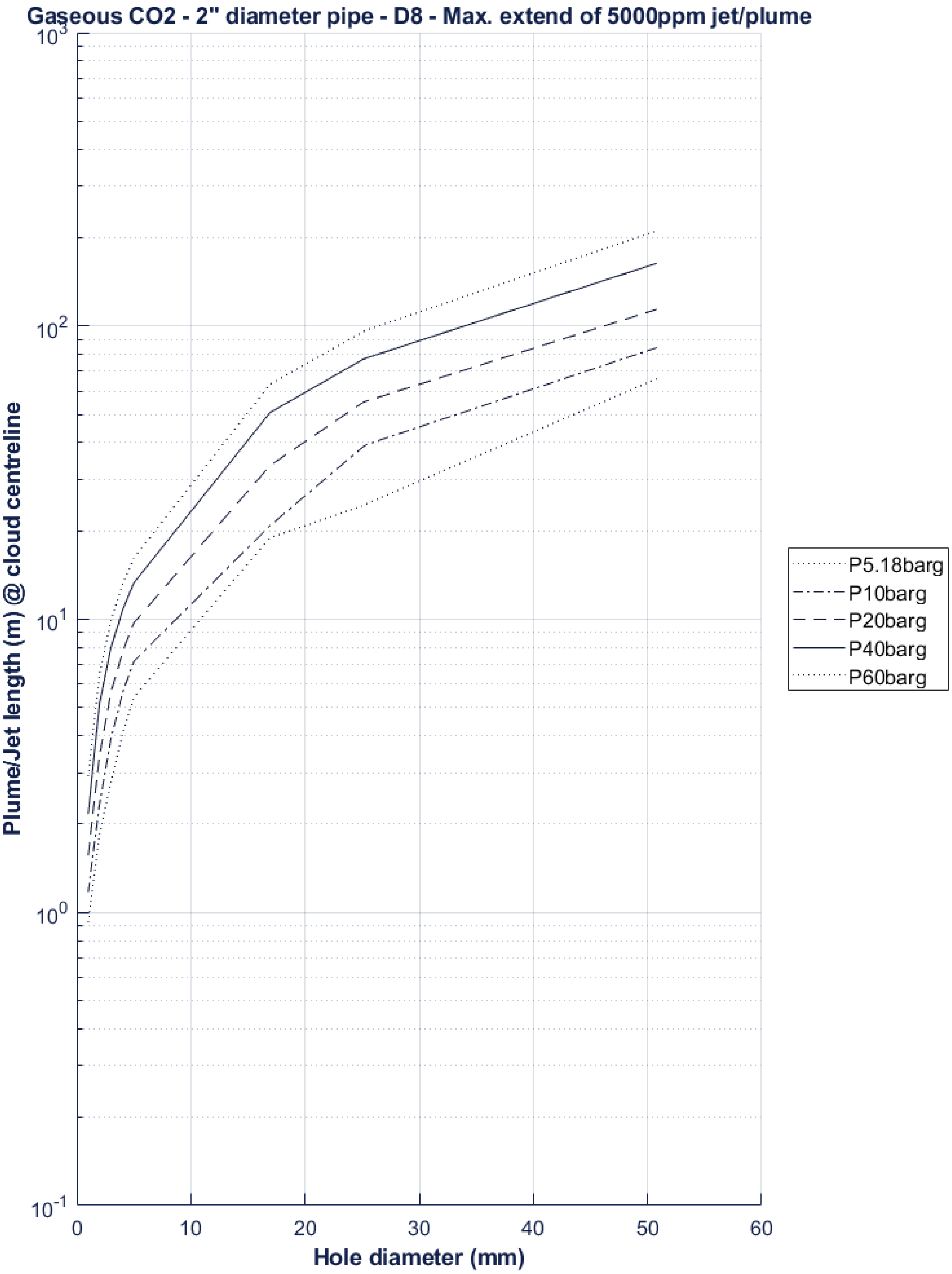

Liquefied CO2 - F1 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole


Gaseous CO2 - 2" diameter pipe - D1 - Max. extend of 5000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg

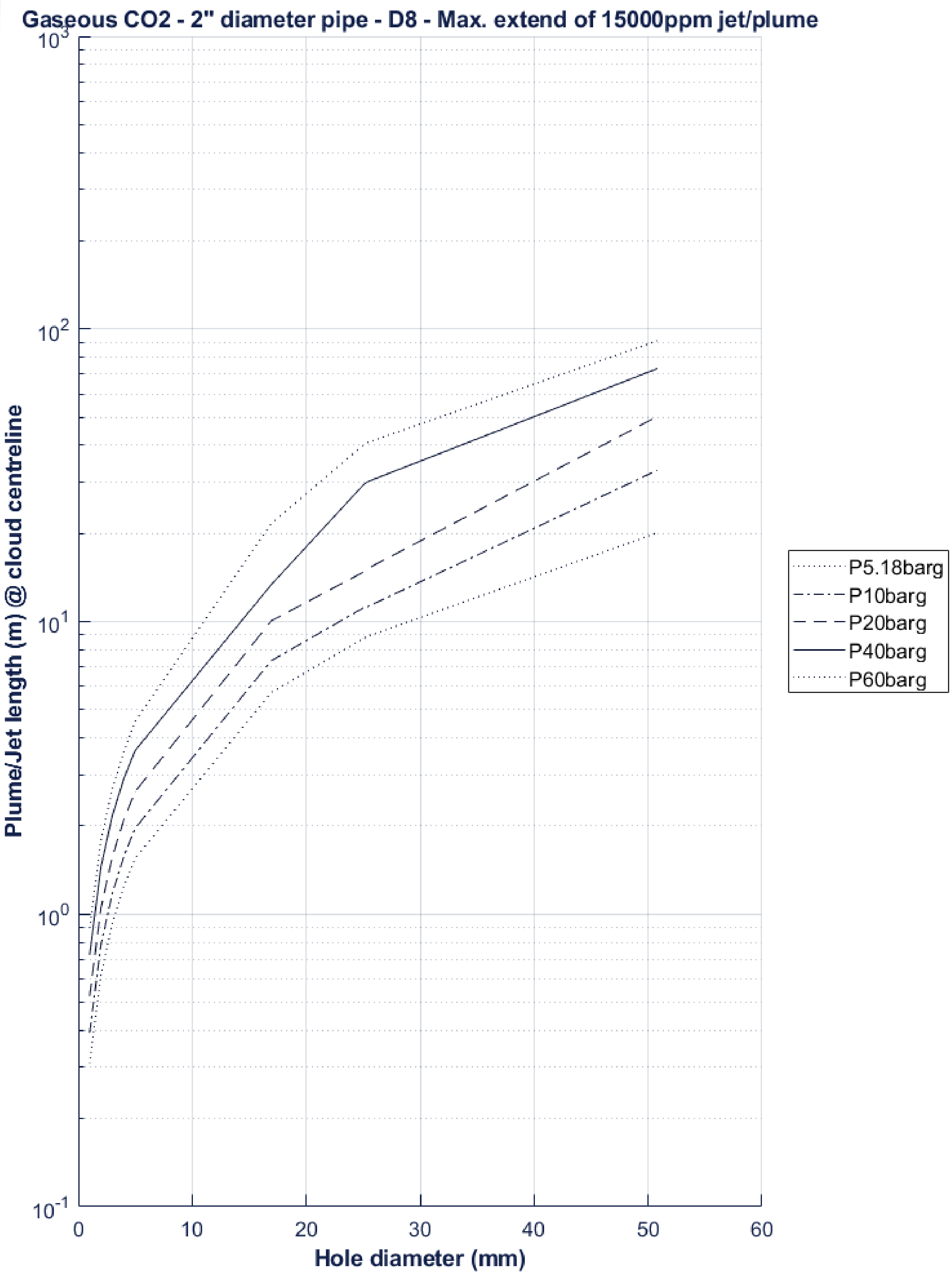

Gaseous CO2 - 2" diameter pipe - D1 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
10^3
10^2
10^1
10^0
10^-1
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg

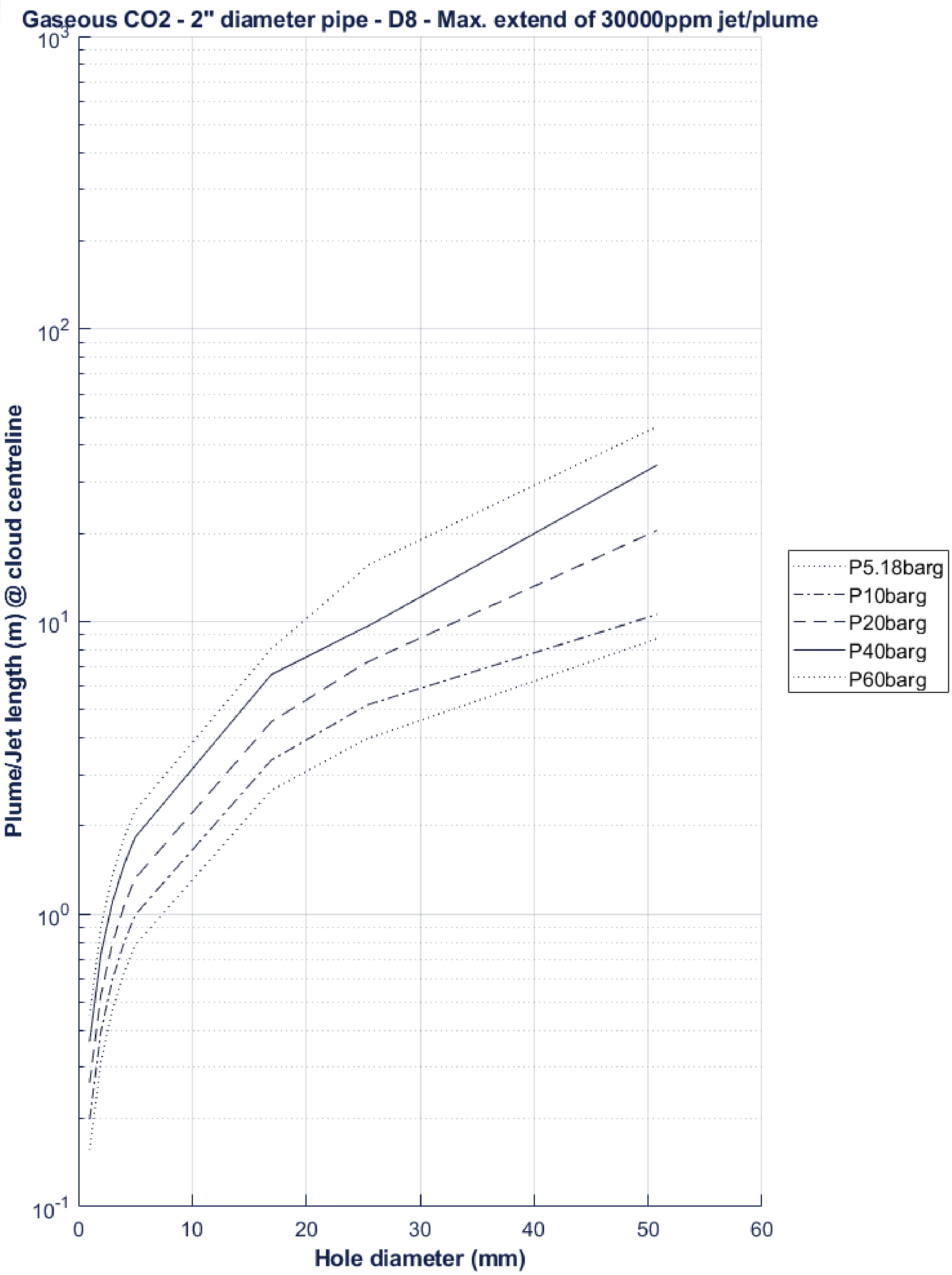

Gaseous CO2 - 2" diameter pipe - D1 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg


Gaseous CO2 - 2" diameter pipe - D1 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg

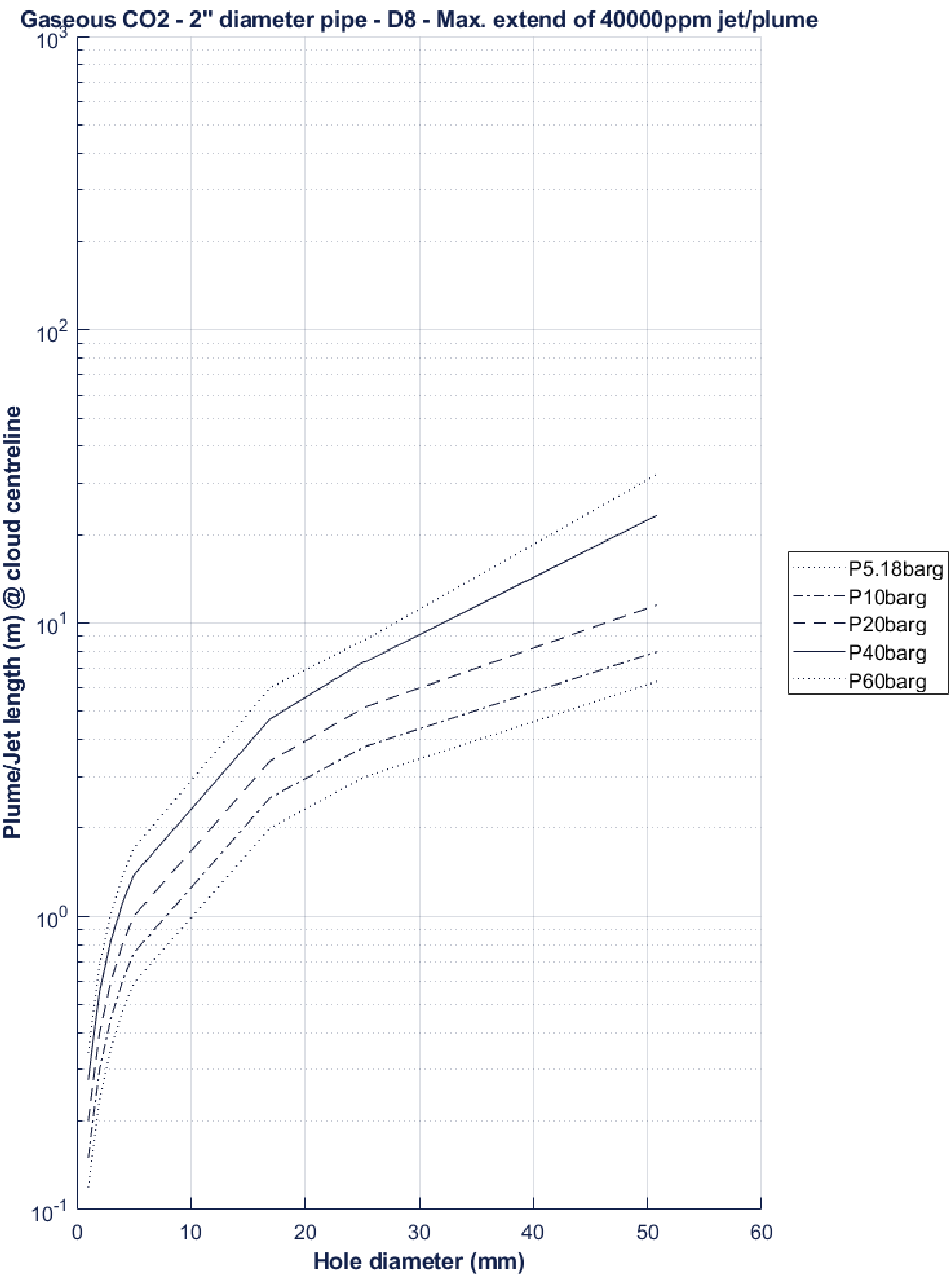


Gaseous CO2 - 2" diameter pipe - D8 - Max. extend of 5000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg

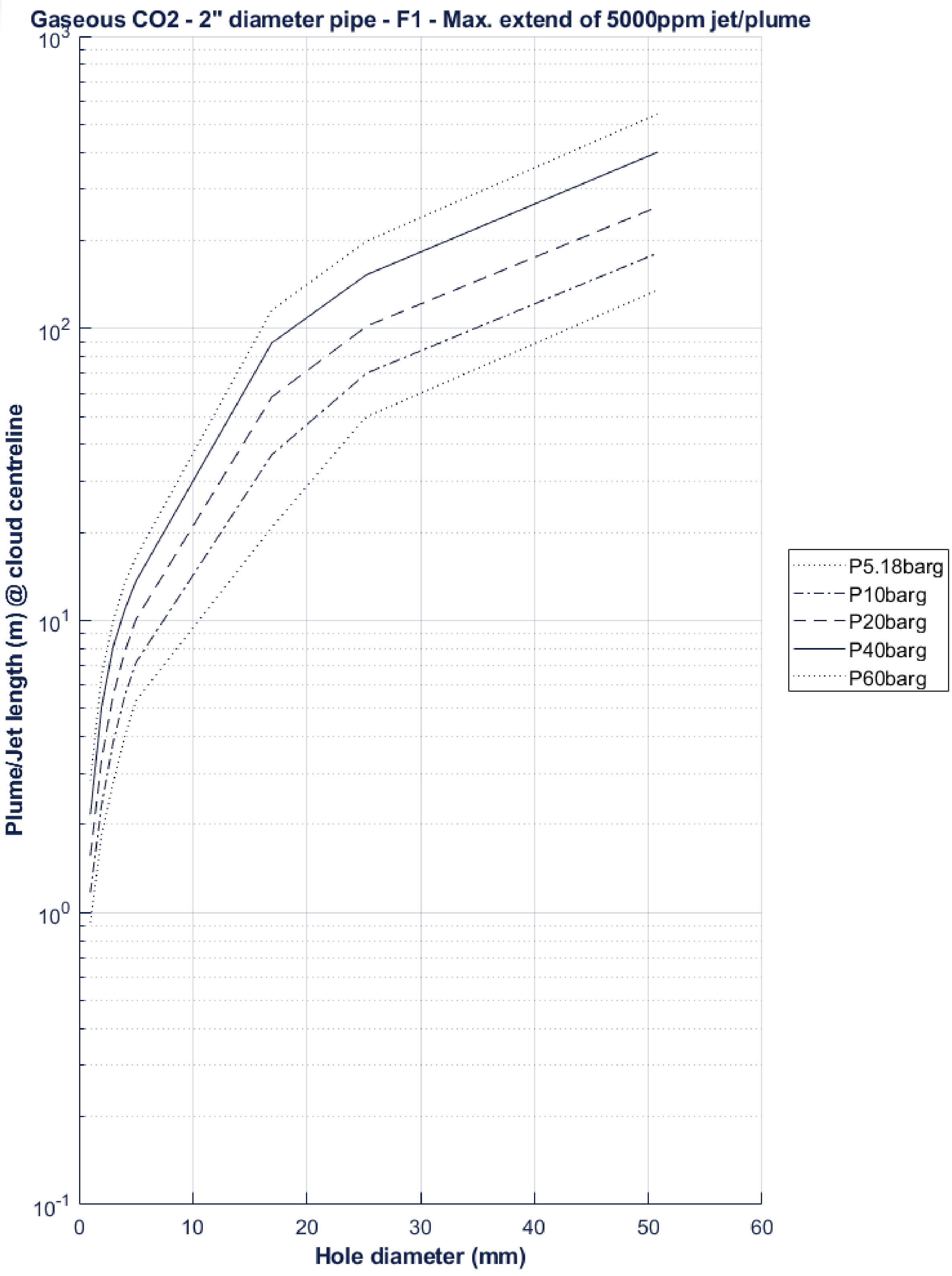

Gaseous CO2 - 2" diameter pipe - D8 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
10^3
10^2
10^1
10^0
10^-1
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg



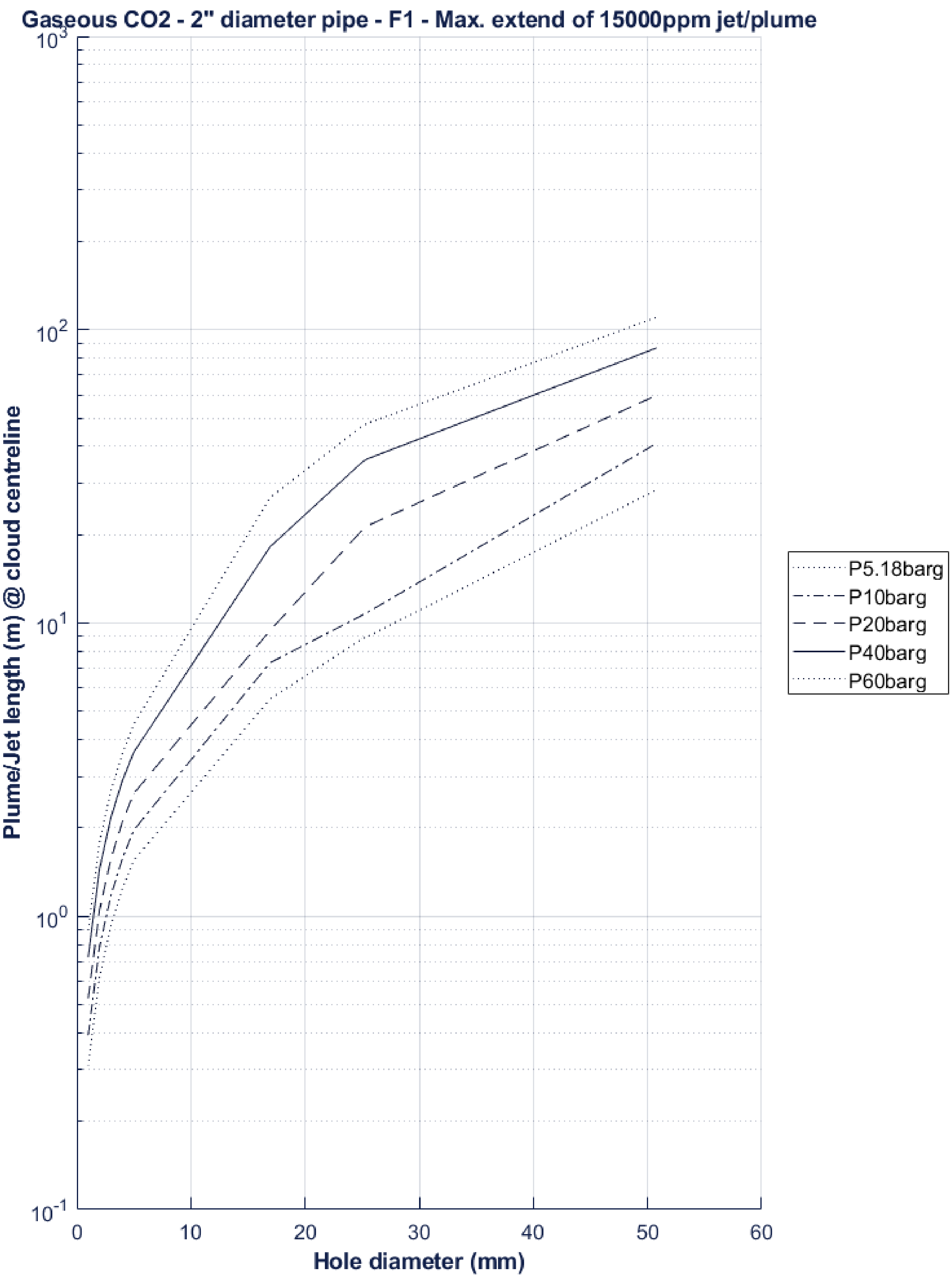
Gaseous CO2 - 2" diameter pipe - D8 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
10^3
10^2
10^1
10^0
10^-1
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg



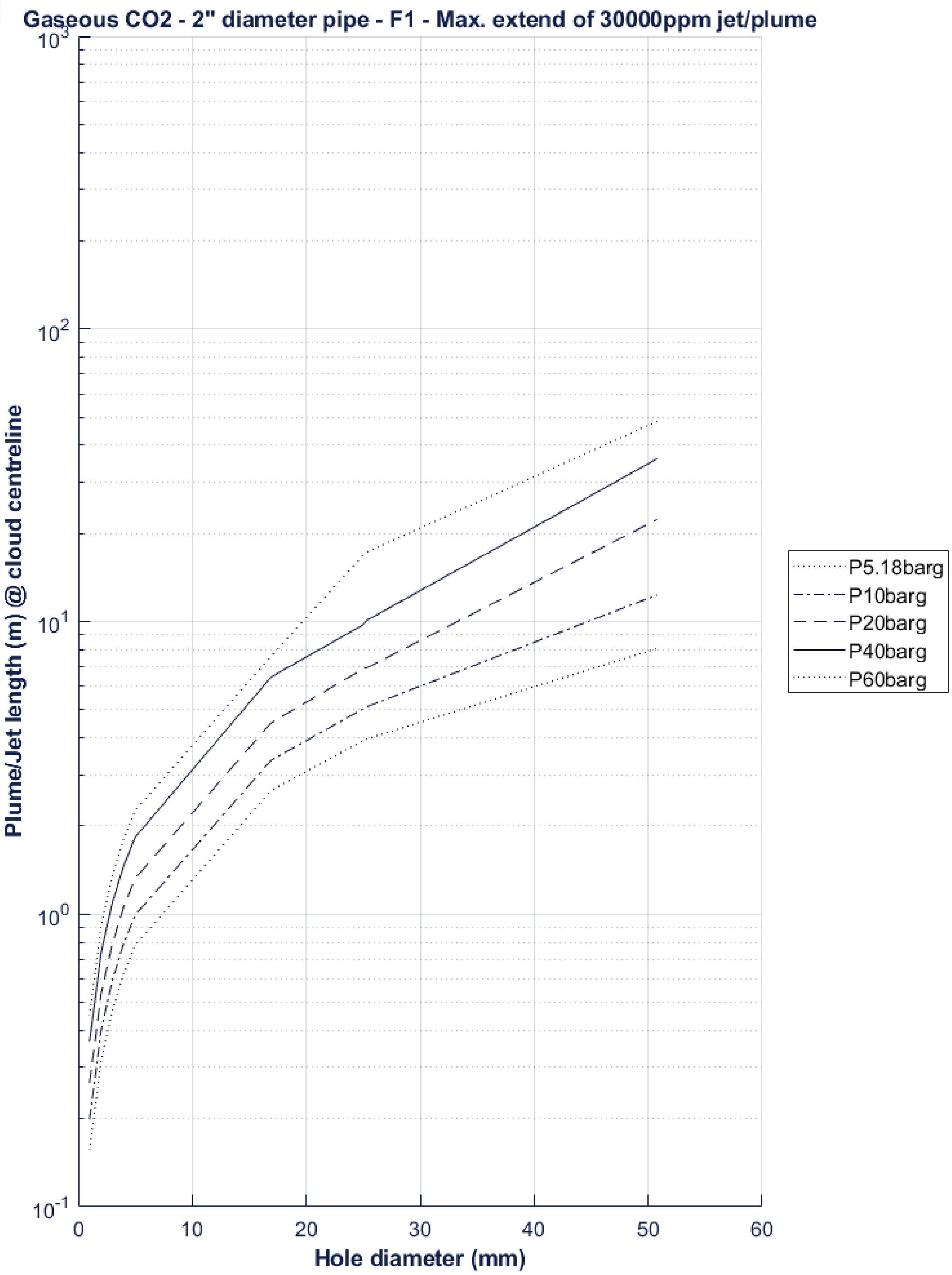
Gaseous CO2 - 2" diameter pipe - D8 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg

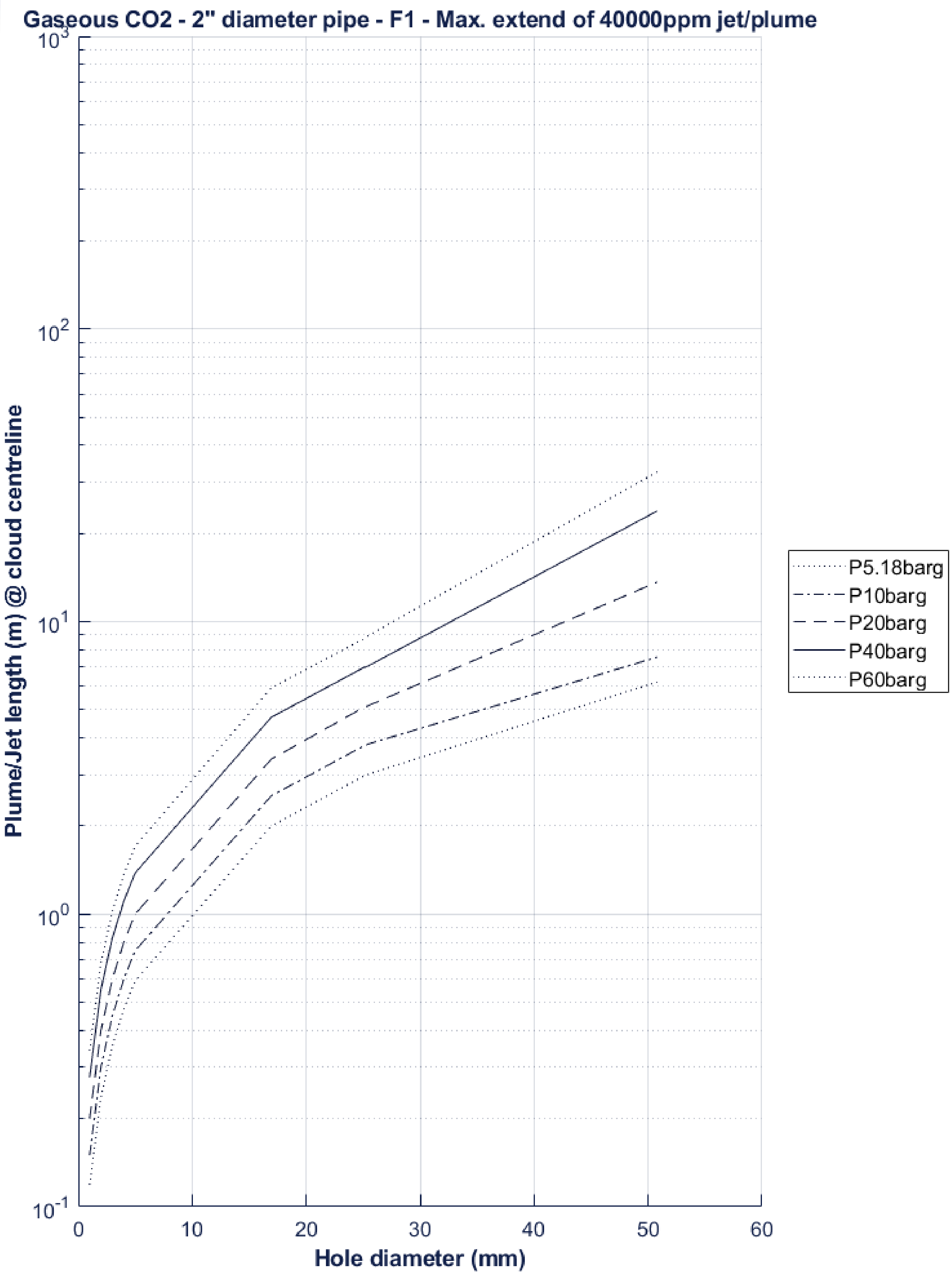


Gaseous CO2 - 2" diameter pipe - F1 - Max. extend of 5000ppm jet/plume
10^3
10^2
10^1
10^0
10^{-1}
Plume/Jet length (m) @ cloud centreline
0
10
20
30
40
50
60
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg

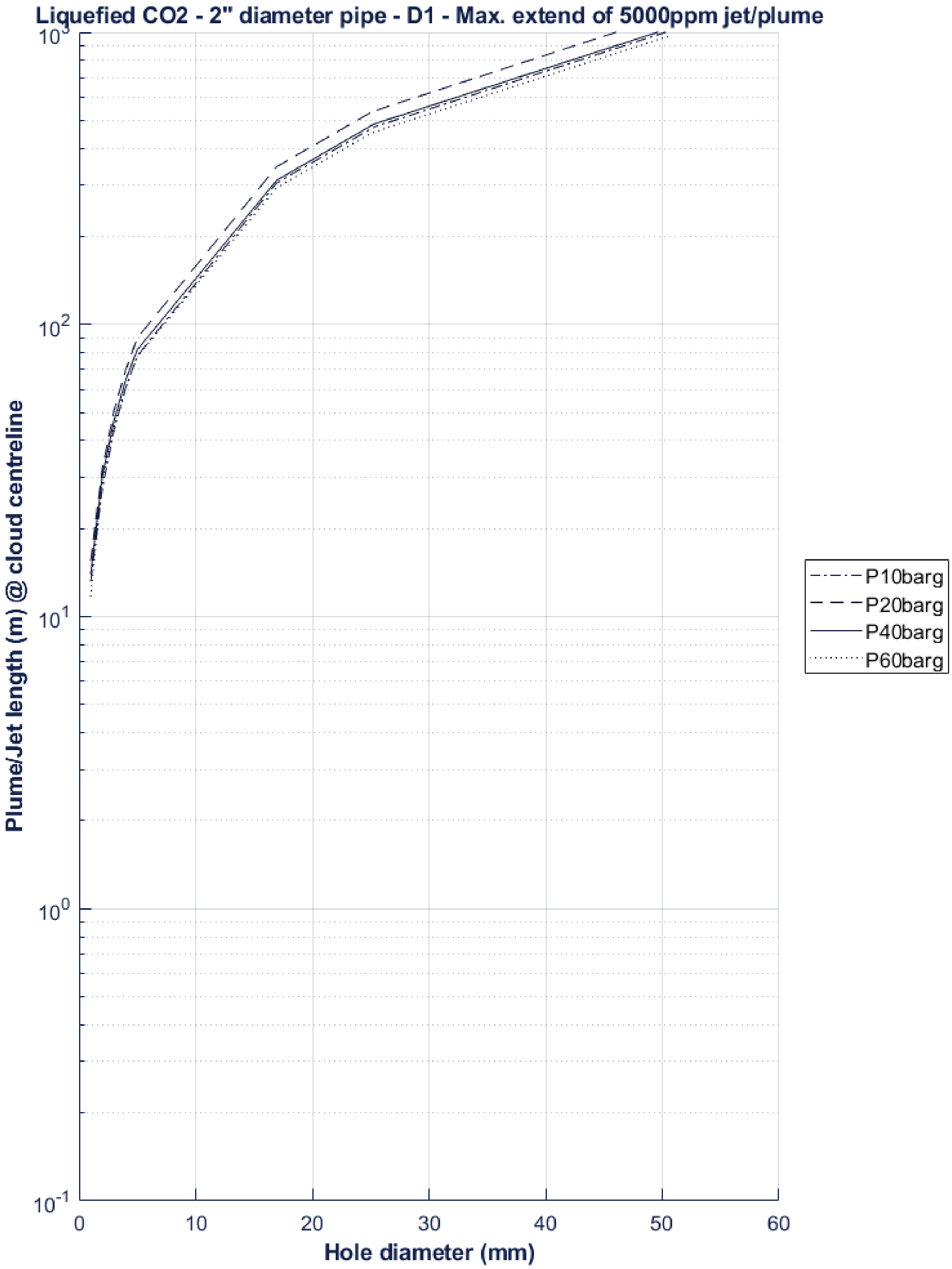


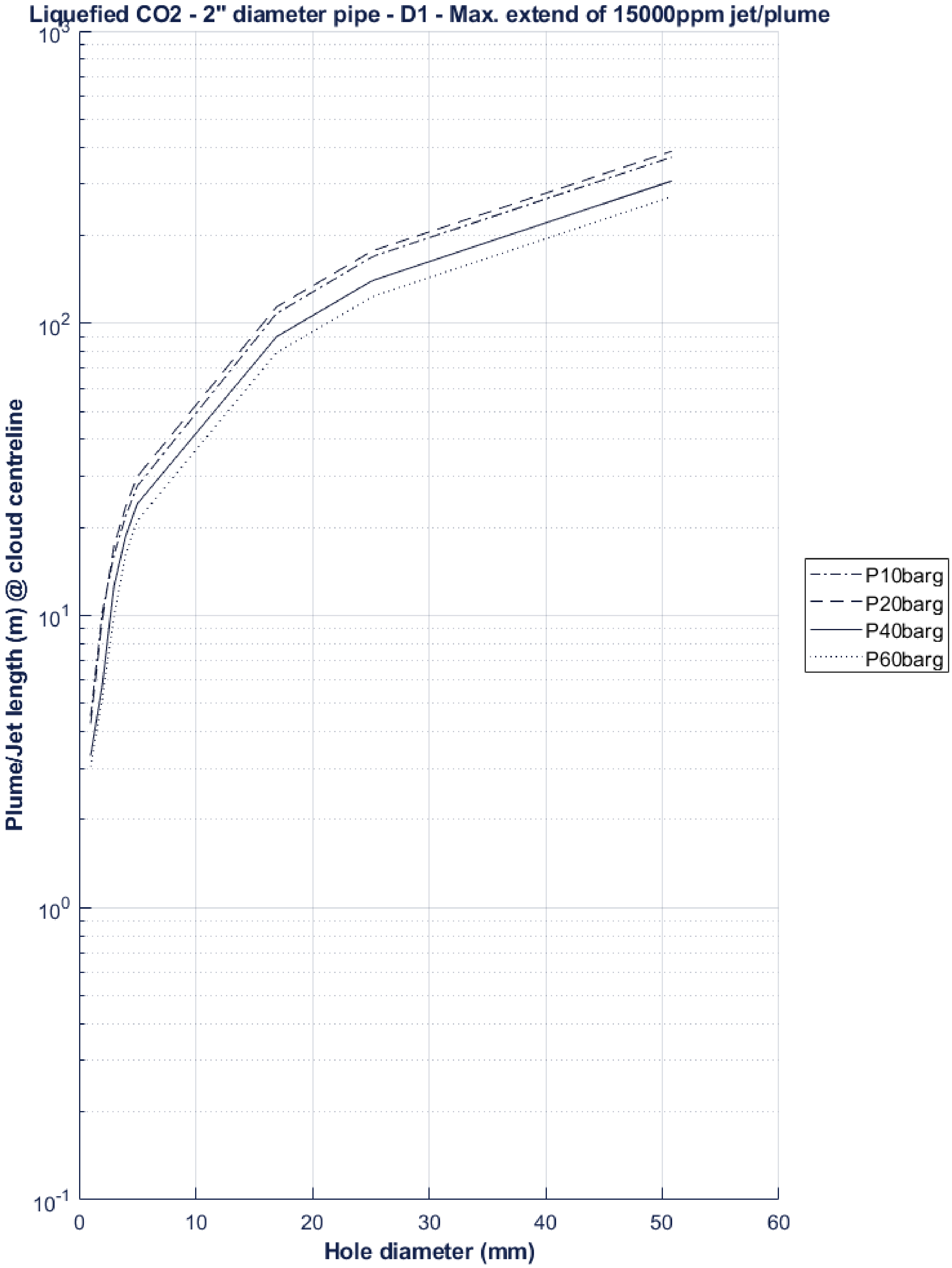
Gaseous CO2 - 2" diameter pipe - F1 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg

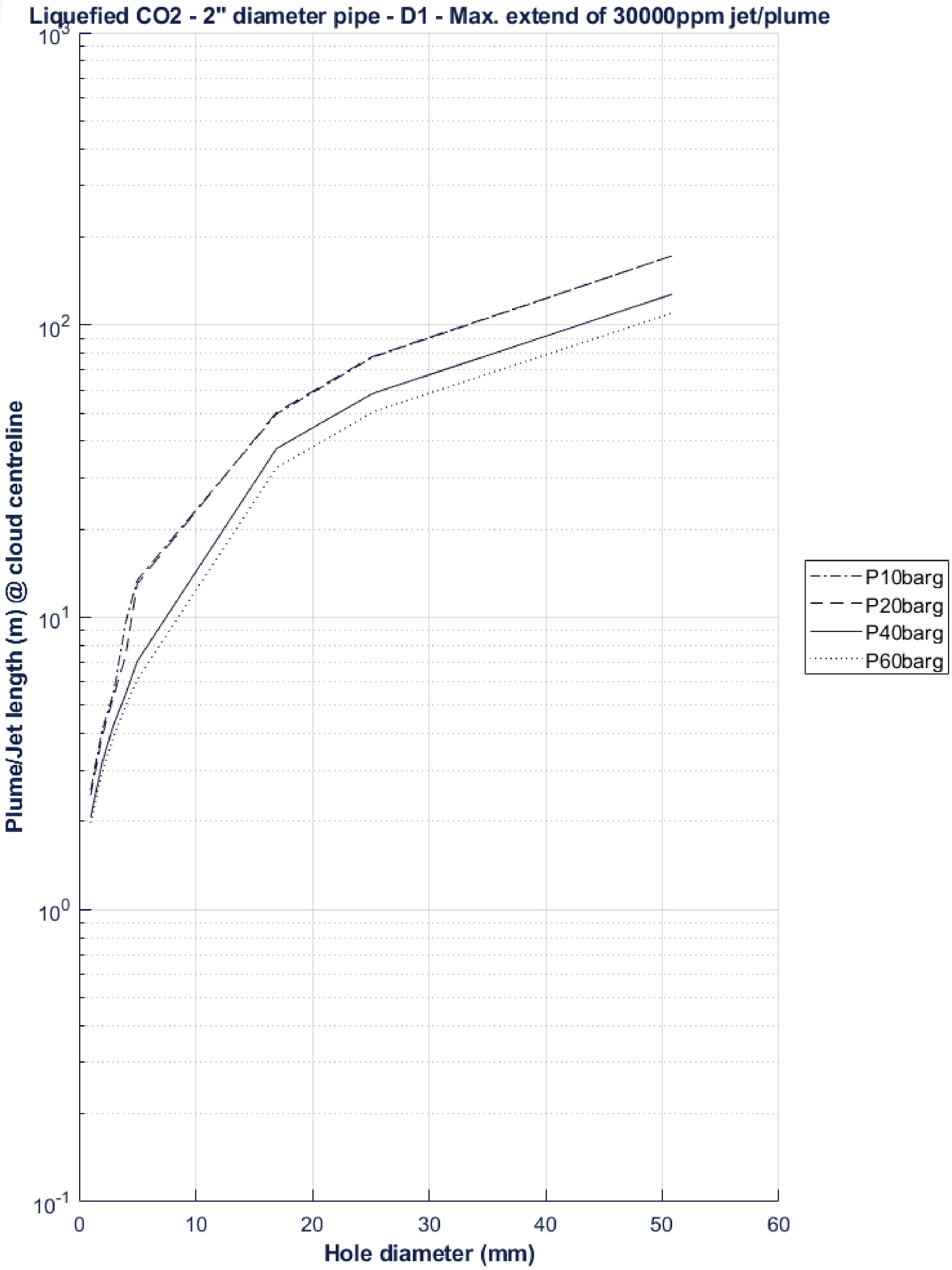

Gaseous CO2 - 2" diameter pipe - F1 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg
0
10
20
30
40
50
60

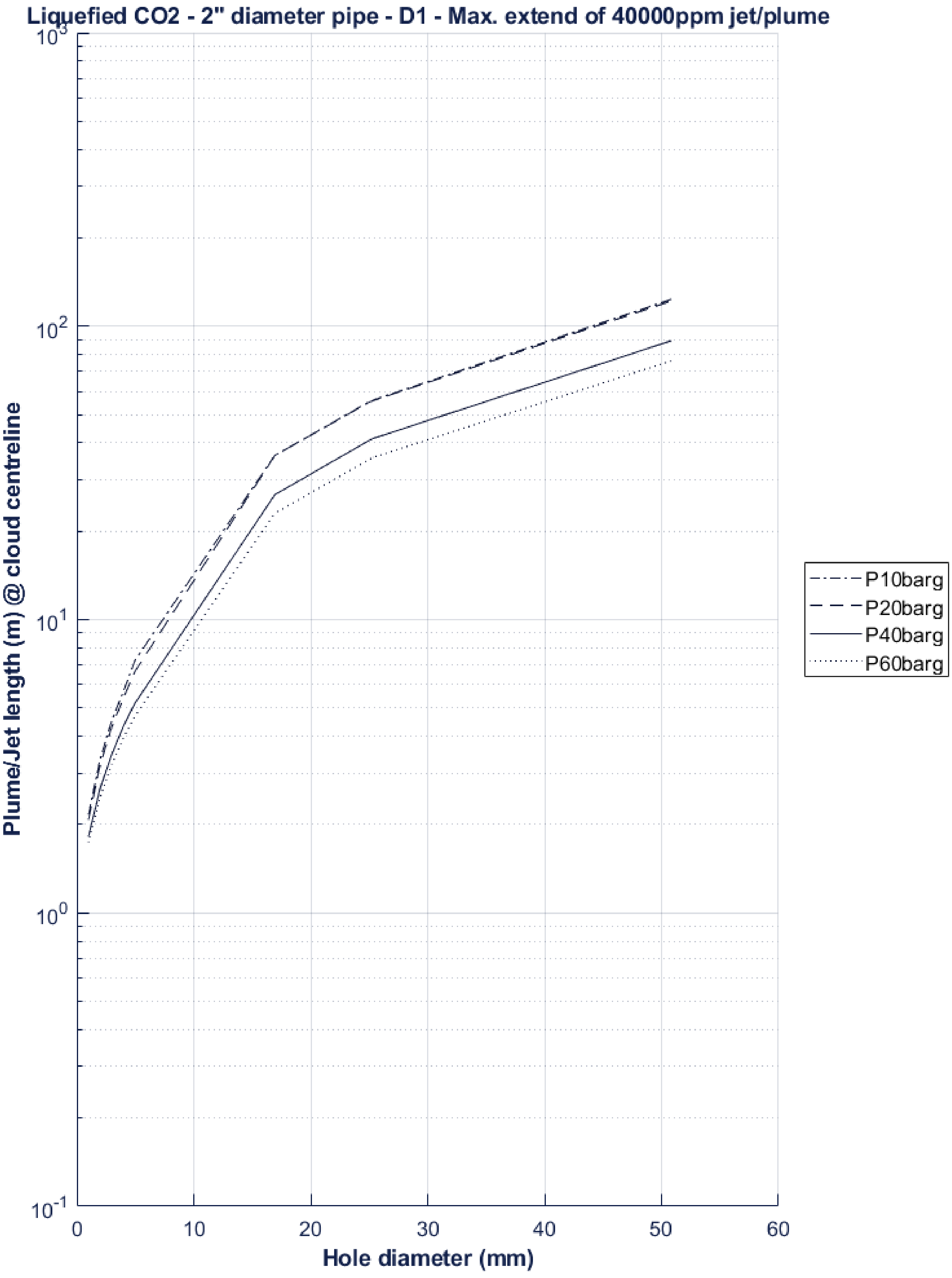

Gaseous CO2 - 2" diameter pipe - F1 - Max. extend of 40000ppm jet/plume
10^3
10^2
10^1
10^0
10^-1
Plume/Jet length (m) @ cloud centreline
0
10
20
30
40
50
60
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg

8.6 Liquefied releases – Plume/Jet length as function of hole size

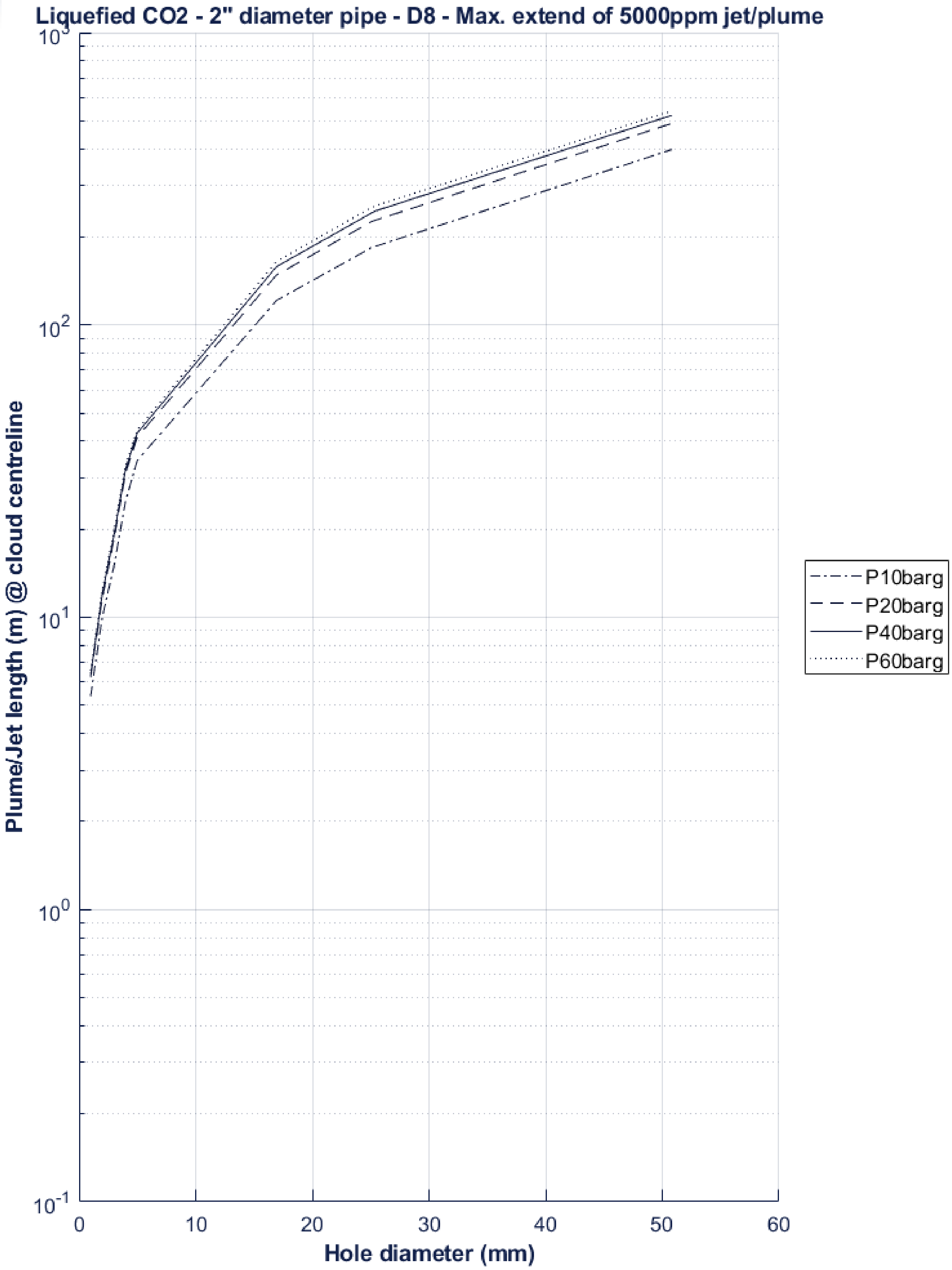


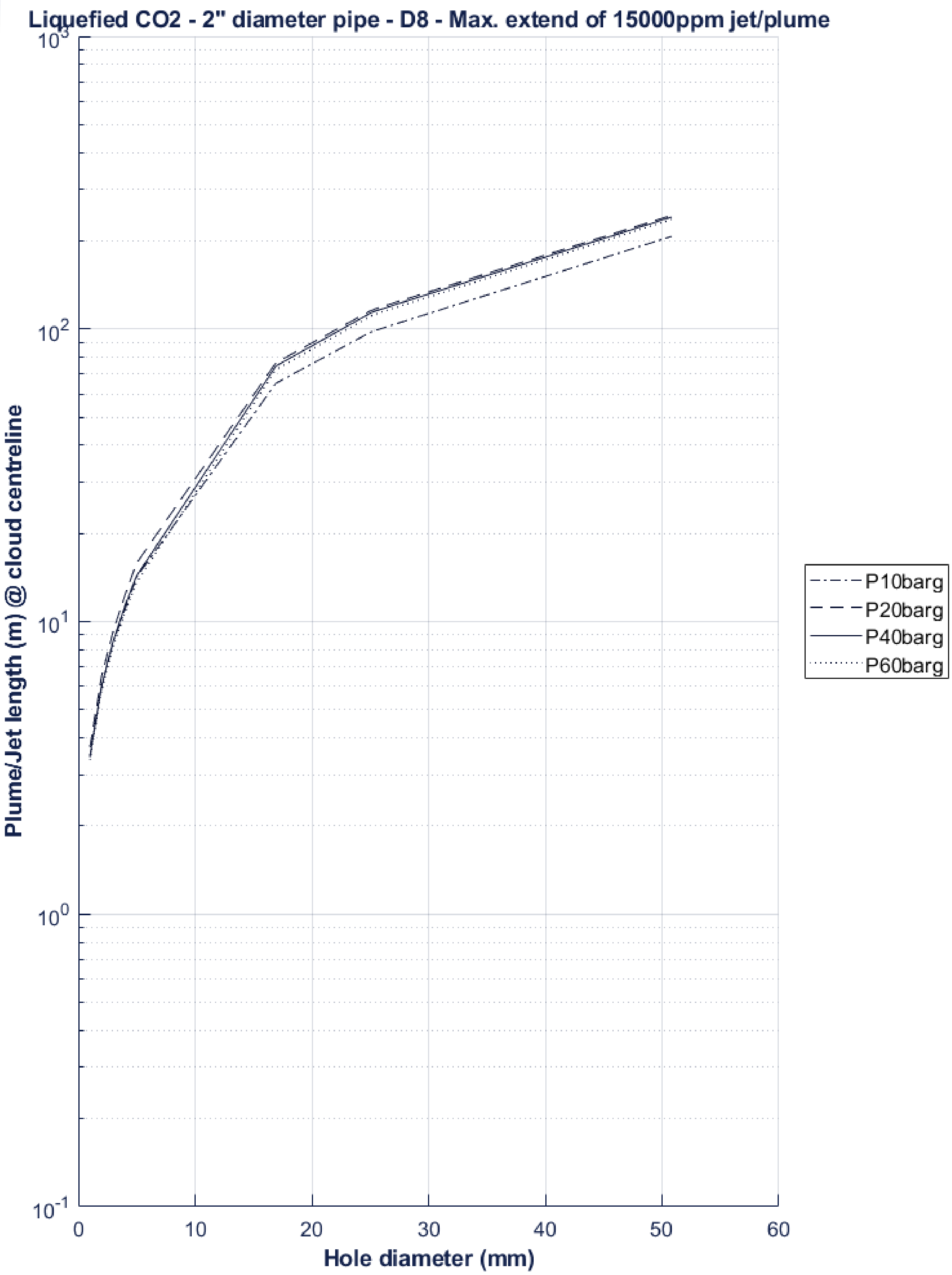

Liquefied CO2 - 2" diameter pipe - D1 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg


Liquefied CO2 - 2" diameter pipe - D1 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg

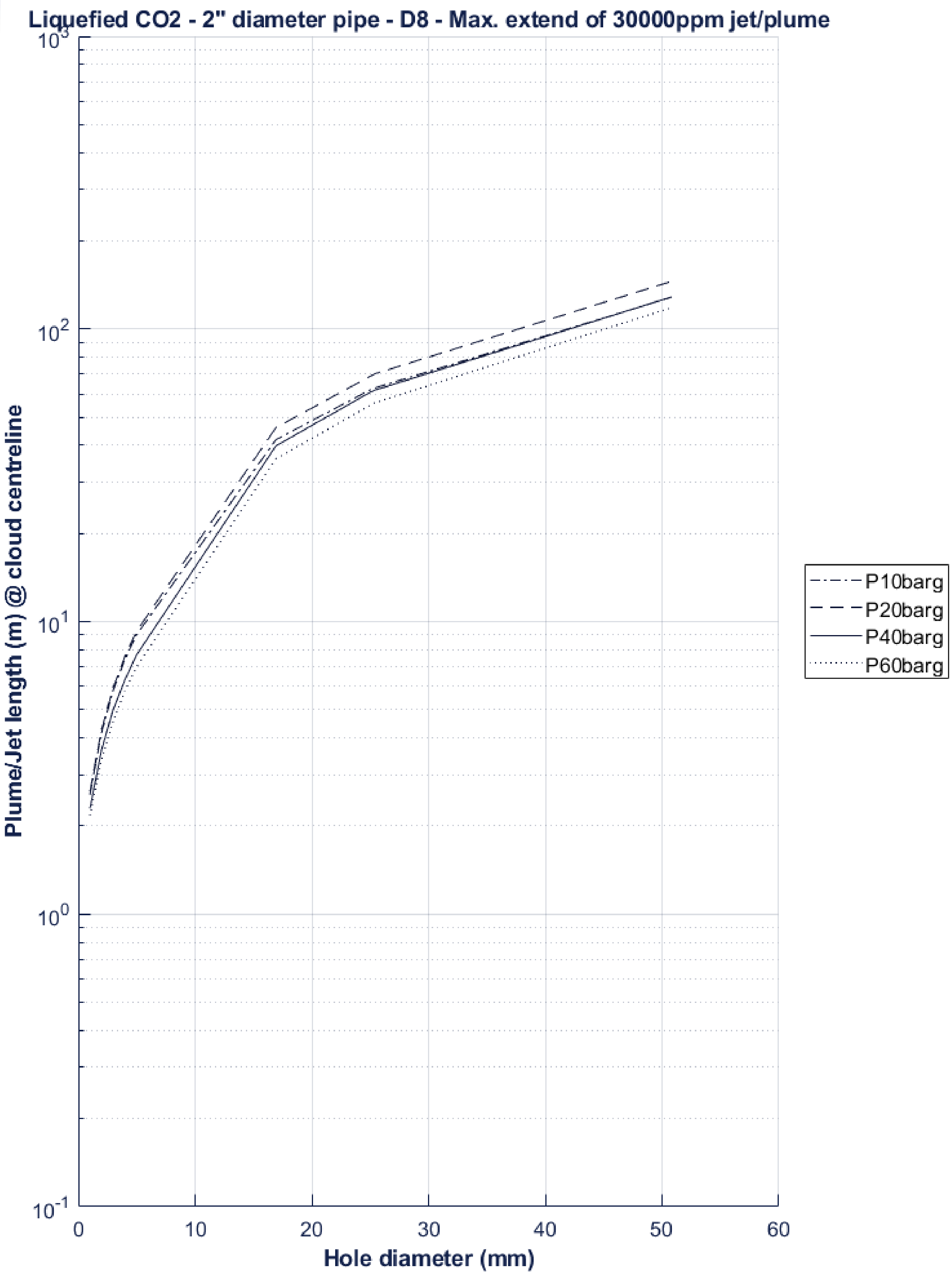


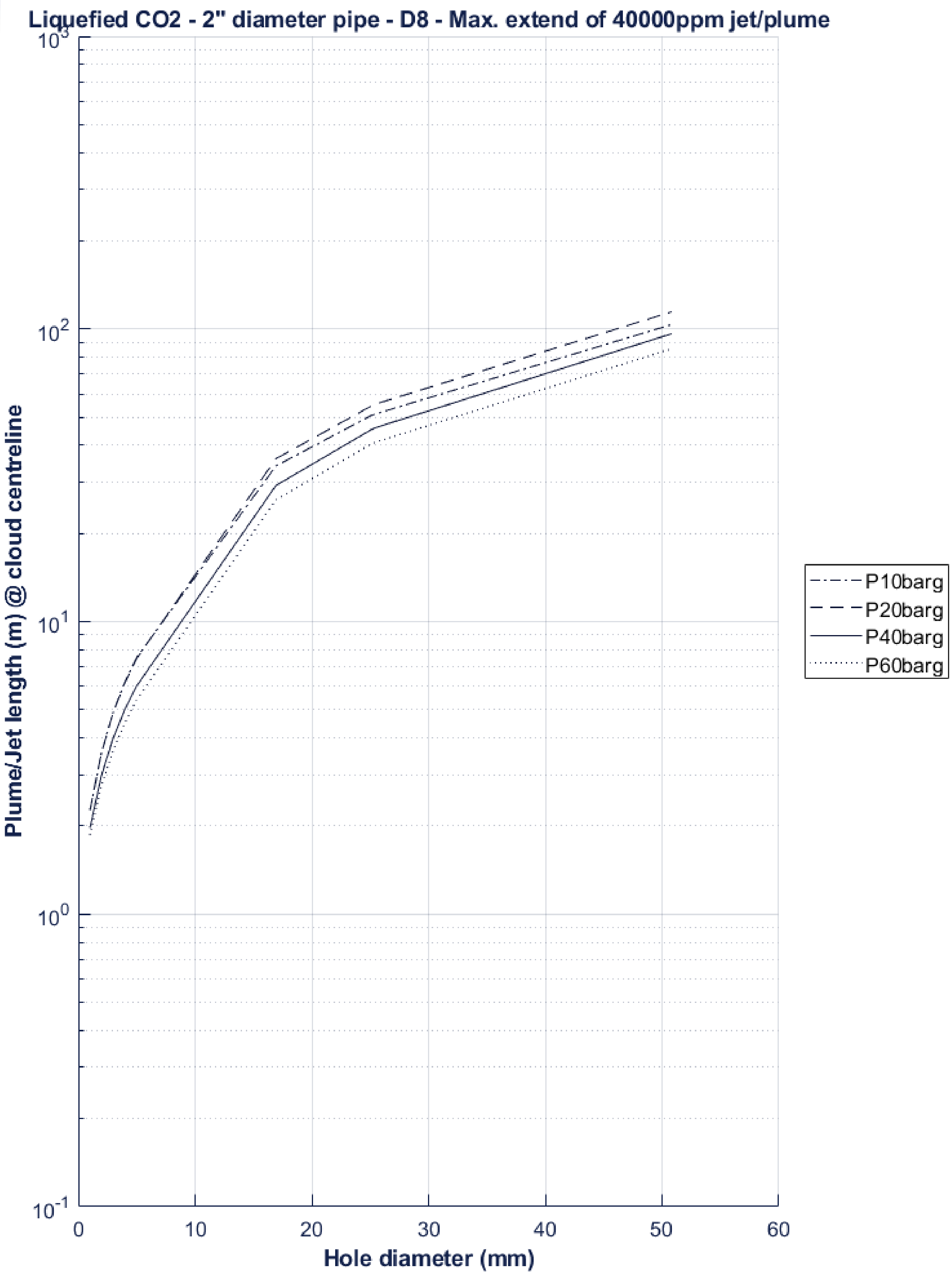
Liquefied CO2 - 2" diameter pipe - D1 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg


Liquefied CO2 - 2" diameter pipe - D8 - Max. extend of 5000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
10^3
10^2
10^1
10^0
10^-1
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg

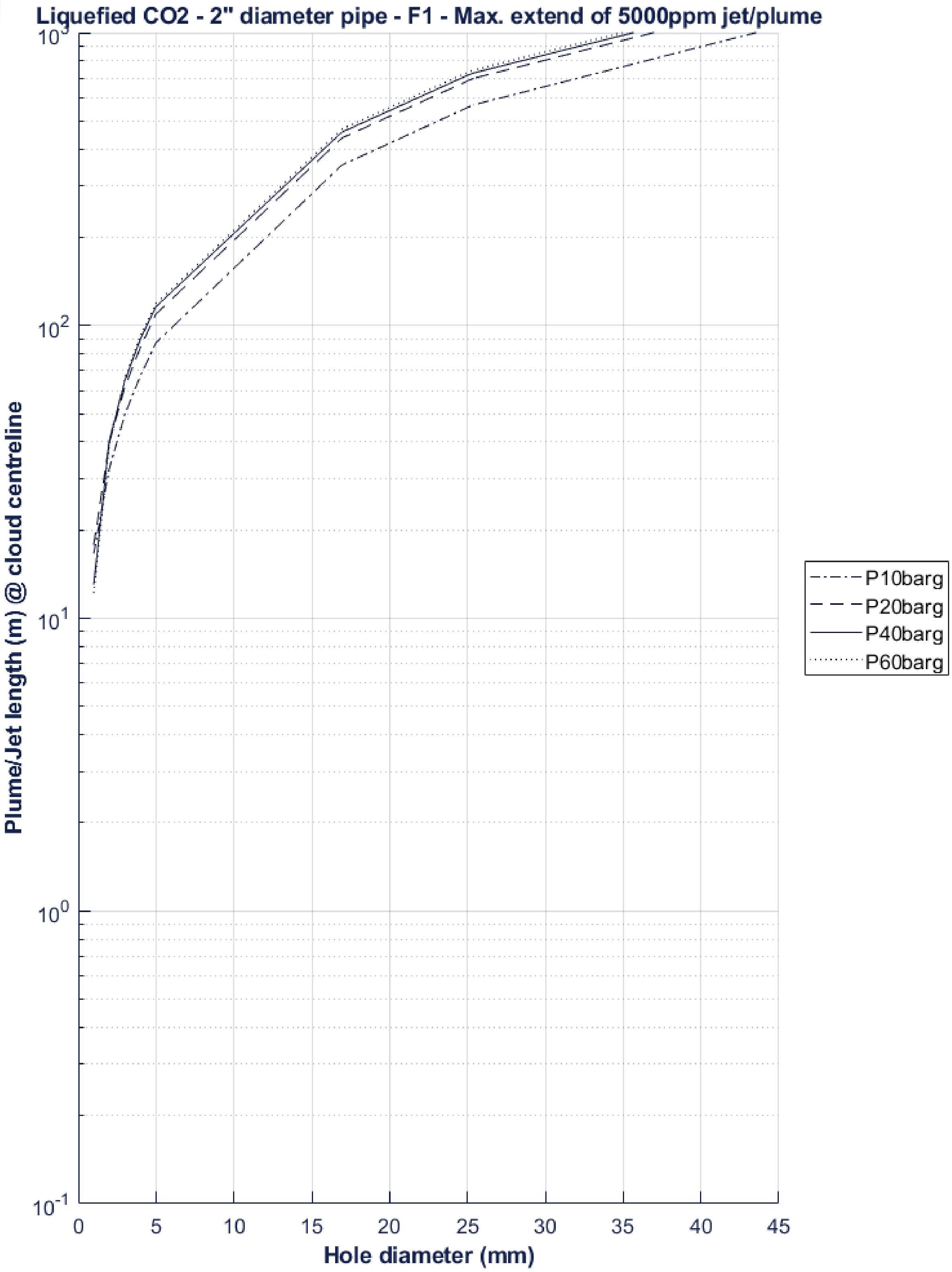


Liquefied CO2 - 2" diameter pipe - D8 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg

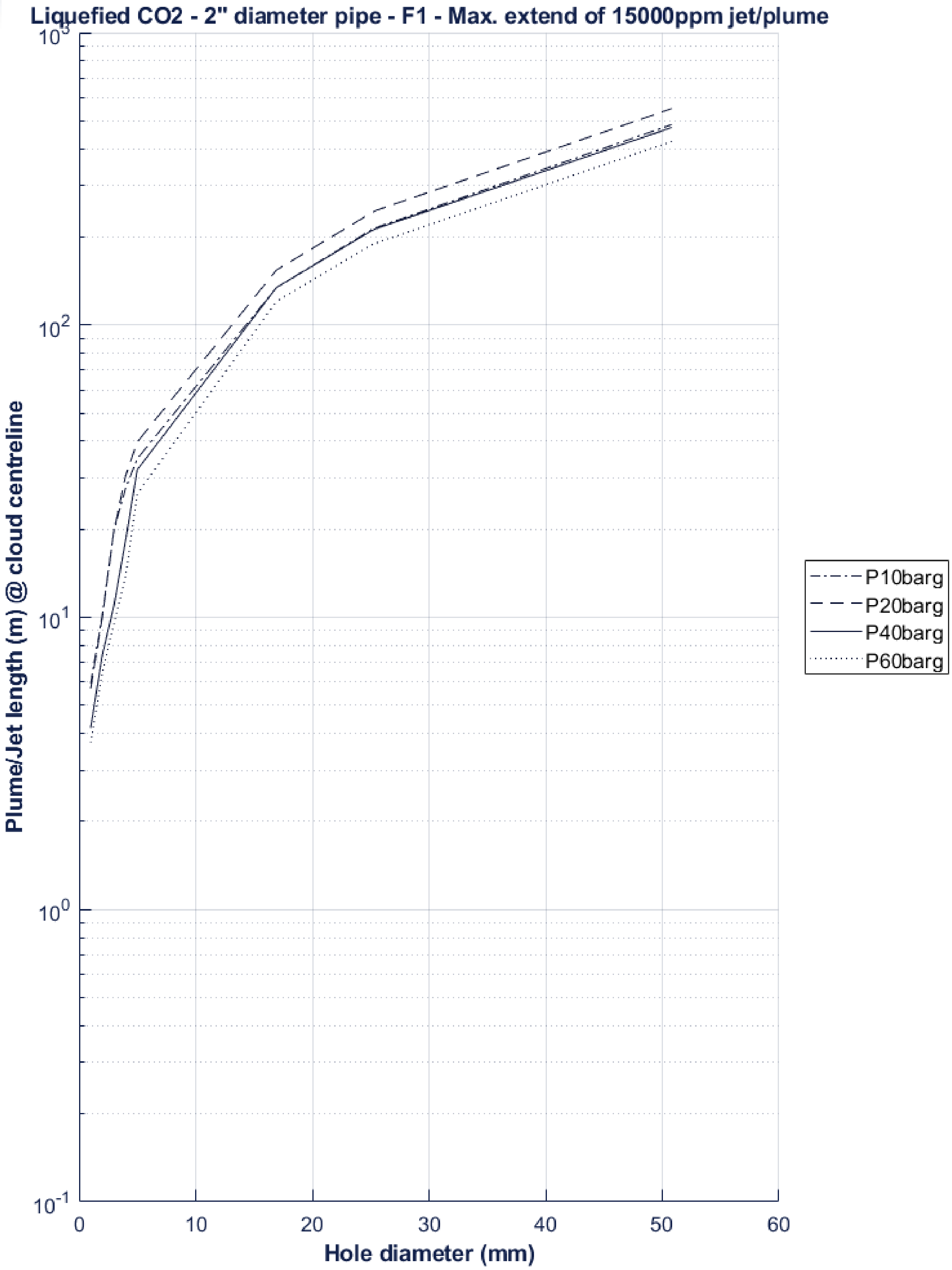

Liquefied CO2 - 2" diameter pipe - D8 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg

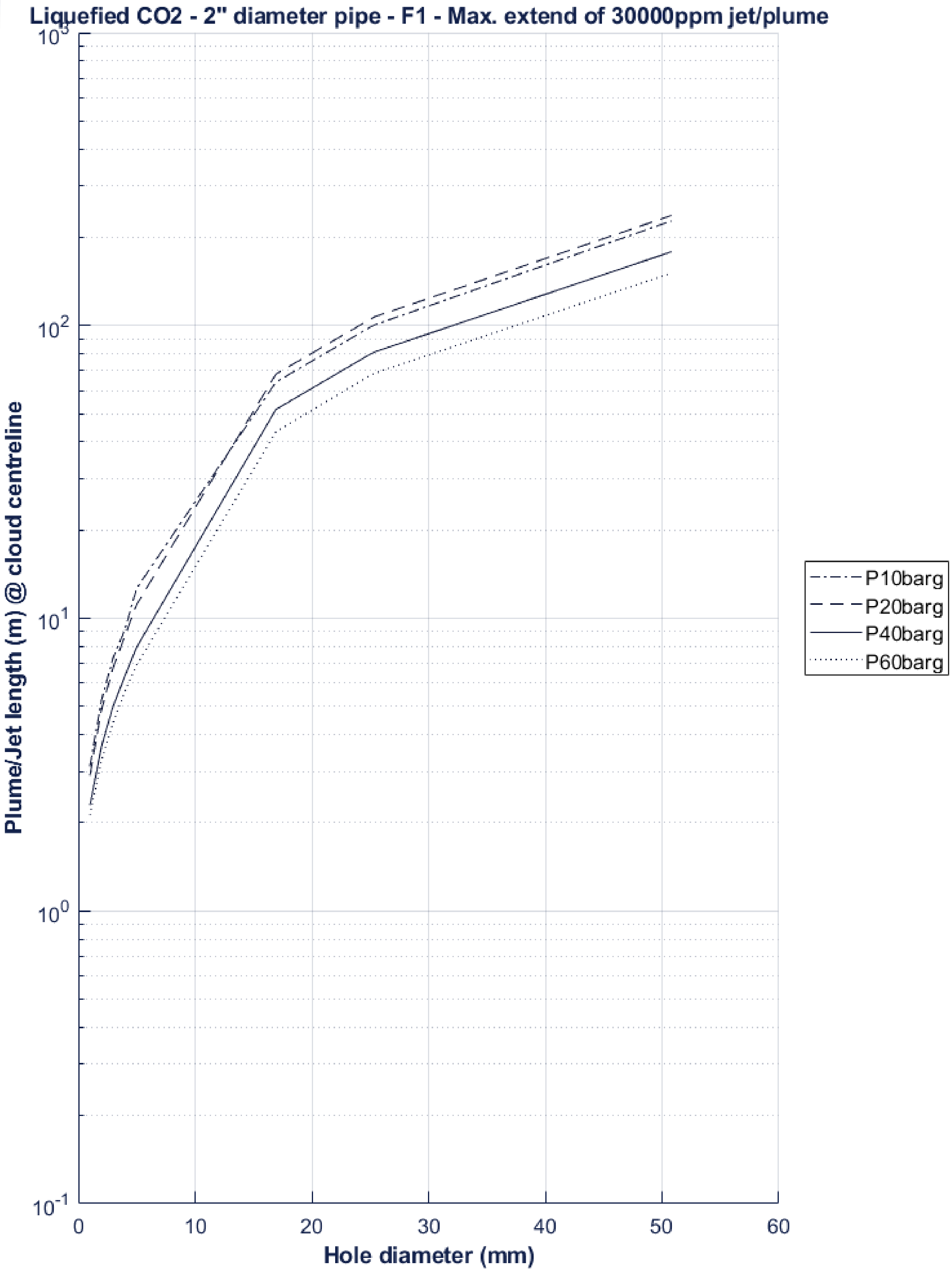


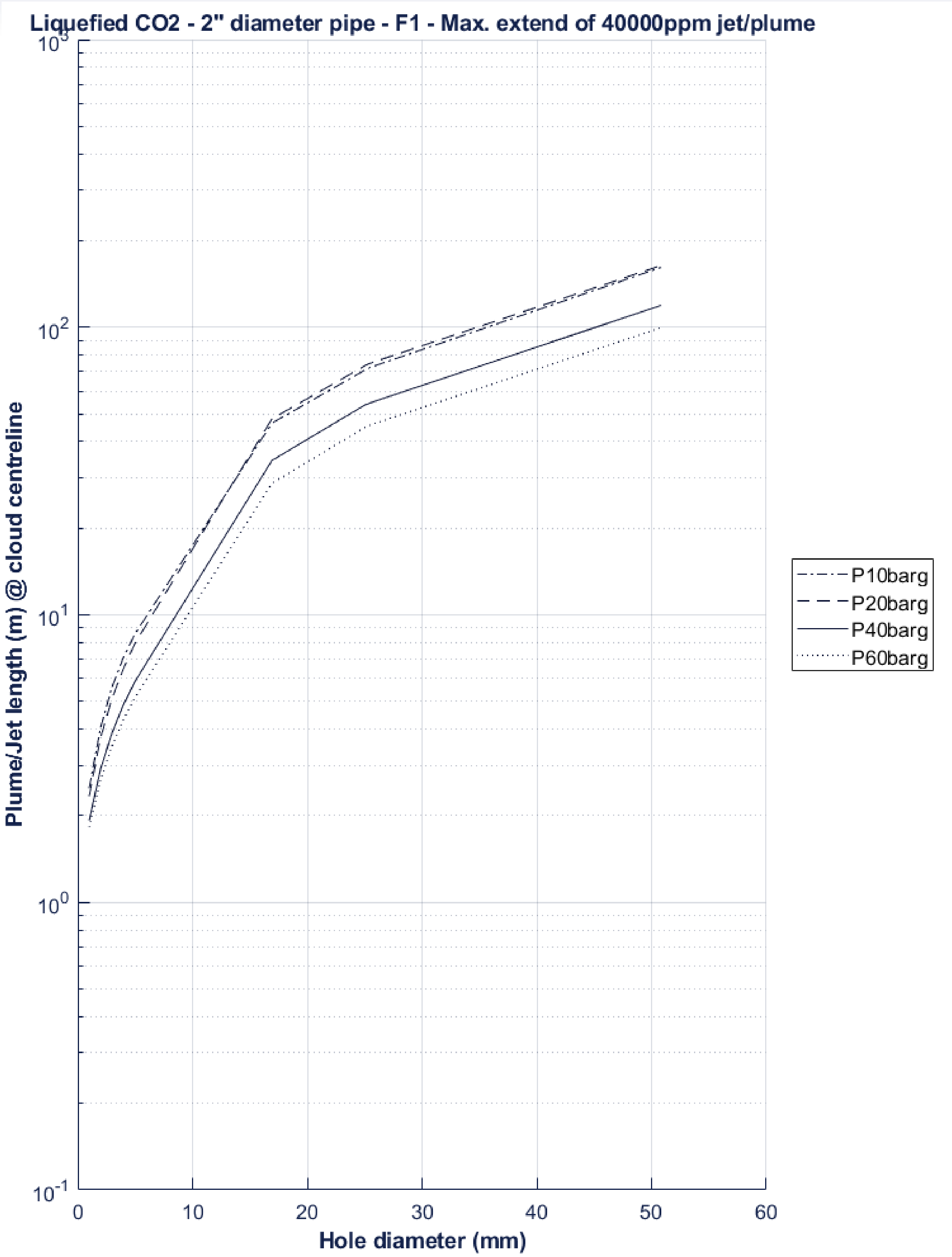
Liquefied CO2 - 2" diameter pipe - D8 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg



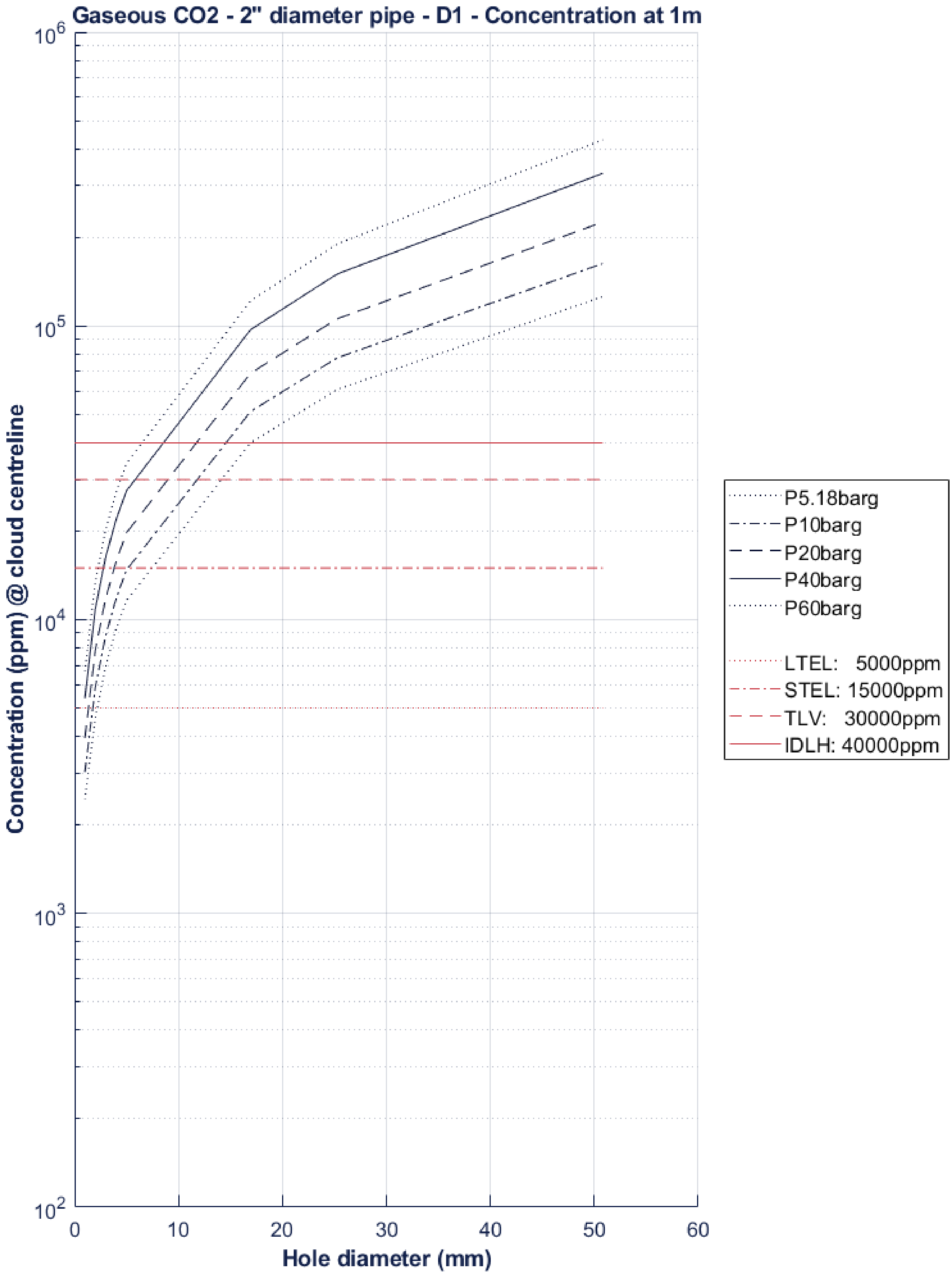
Liquefied CO2 - 2" diameter pipe - F1 - Max. extend of 5000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg

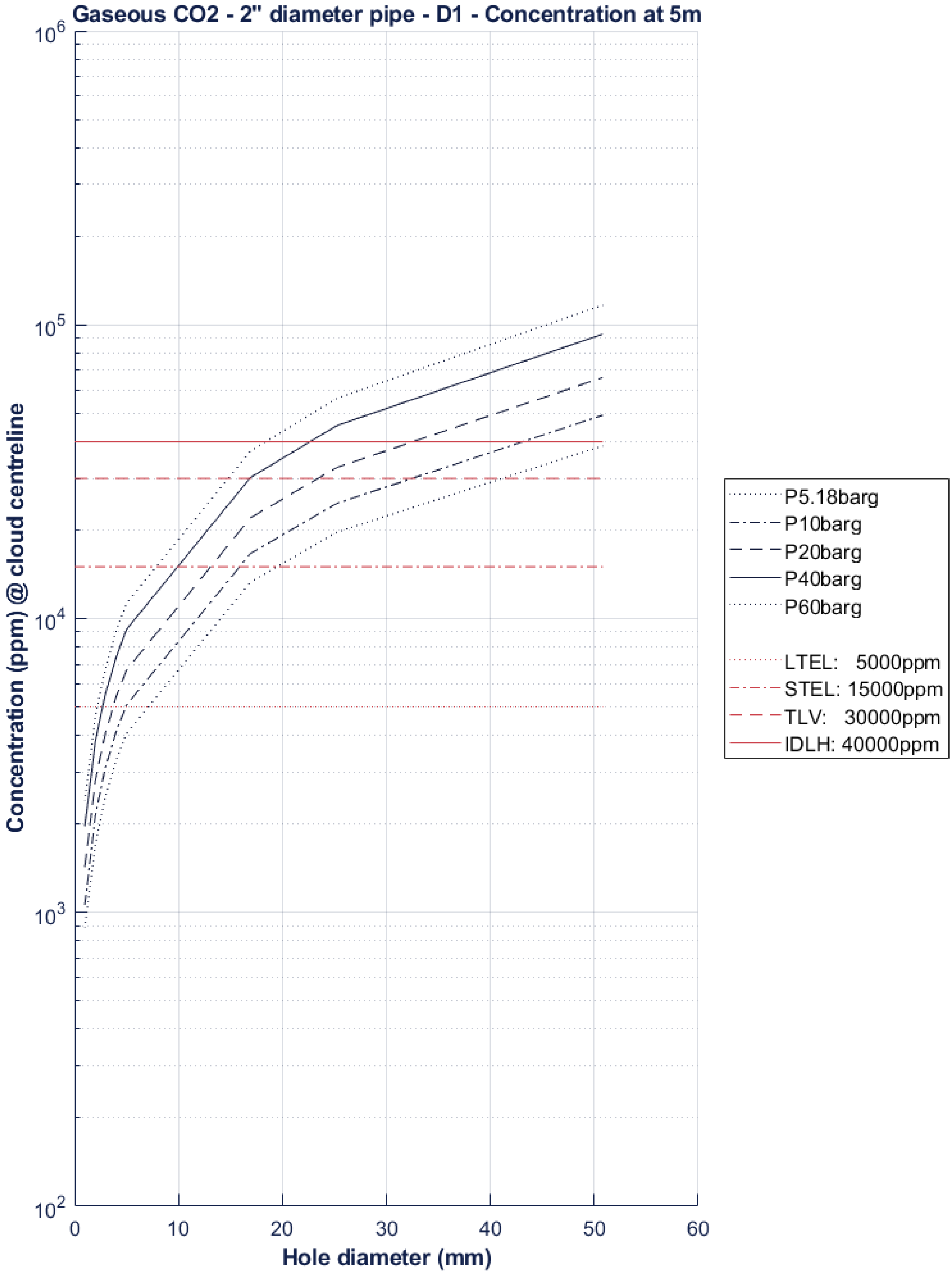

Liquefied CO2 - 2" diameter pipe - F1 - Max. extend of 15000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg


Liquefied CO2 - 2" diameter pipe - F1 - Max. extend of 30000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
10^3
10^2
10^1
10^0
10^-1
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg

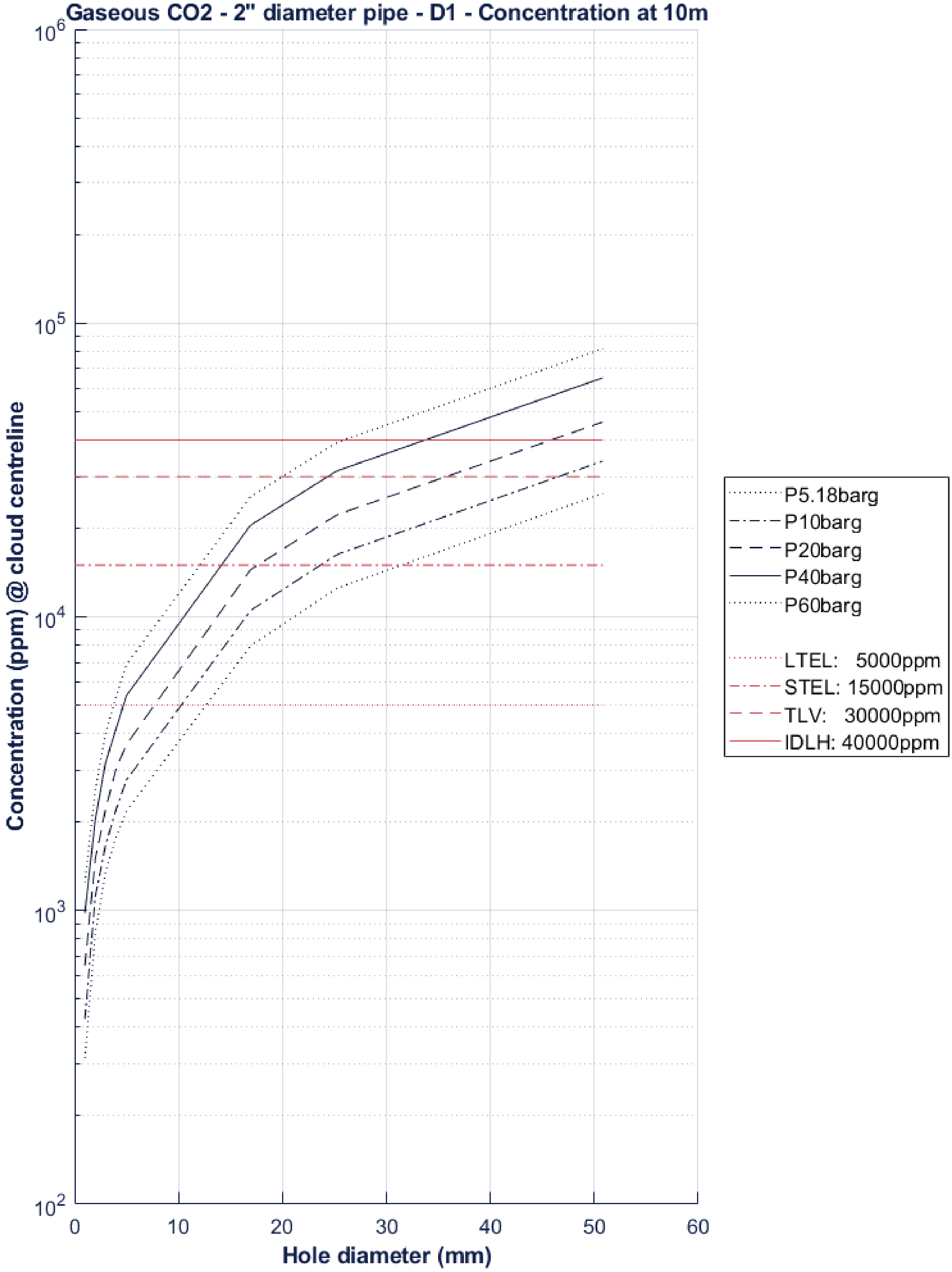

Liquefied CO2 - 2" diameter pipe - F1 - Max. extend of 40000ppm jet/plume
Plume/Jet length (m) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg

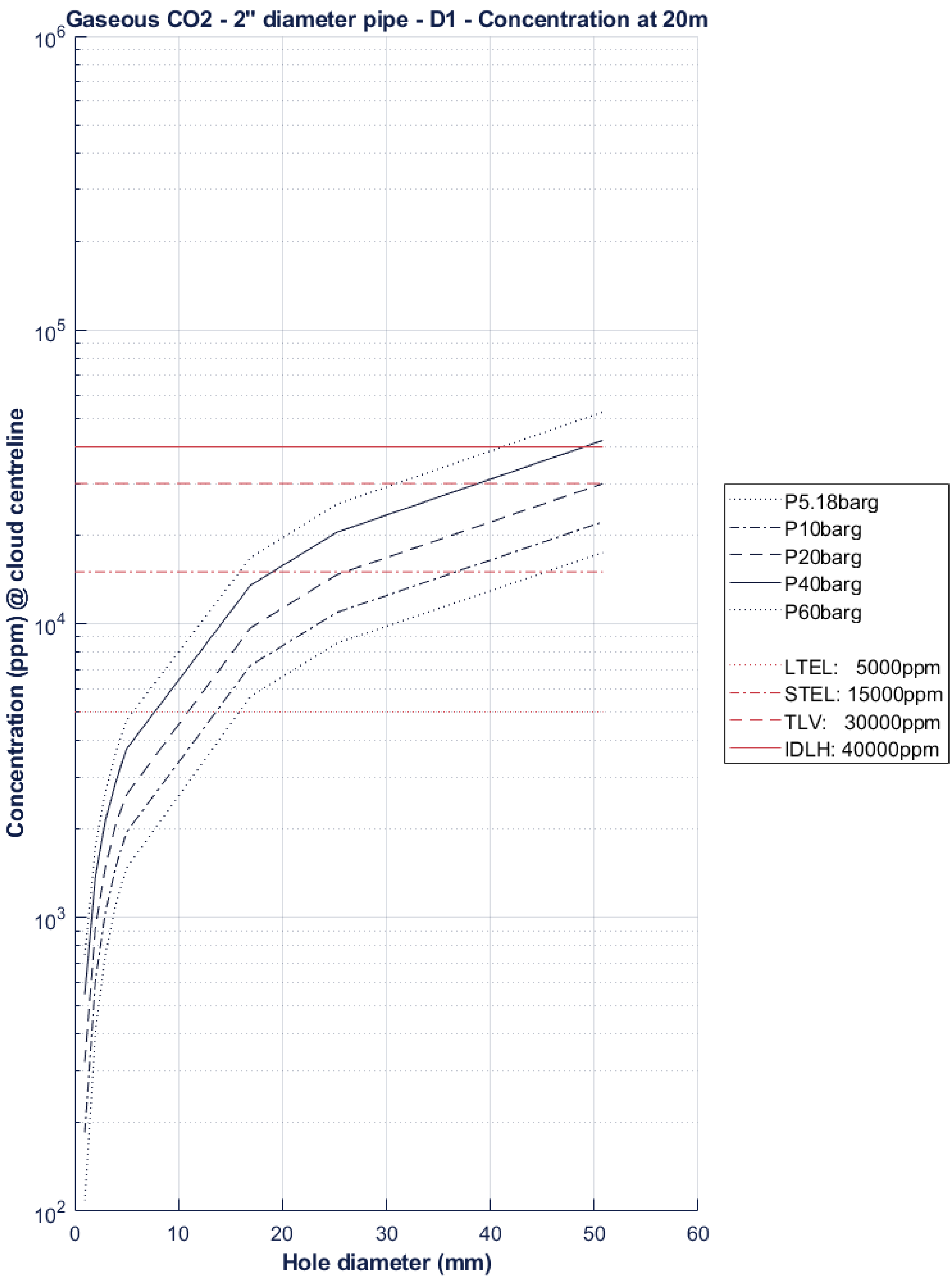
8.7 Gaseous releases – Concentration as function of hole size

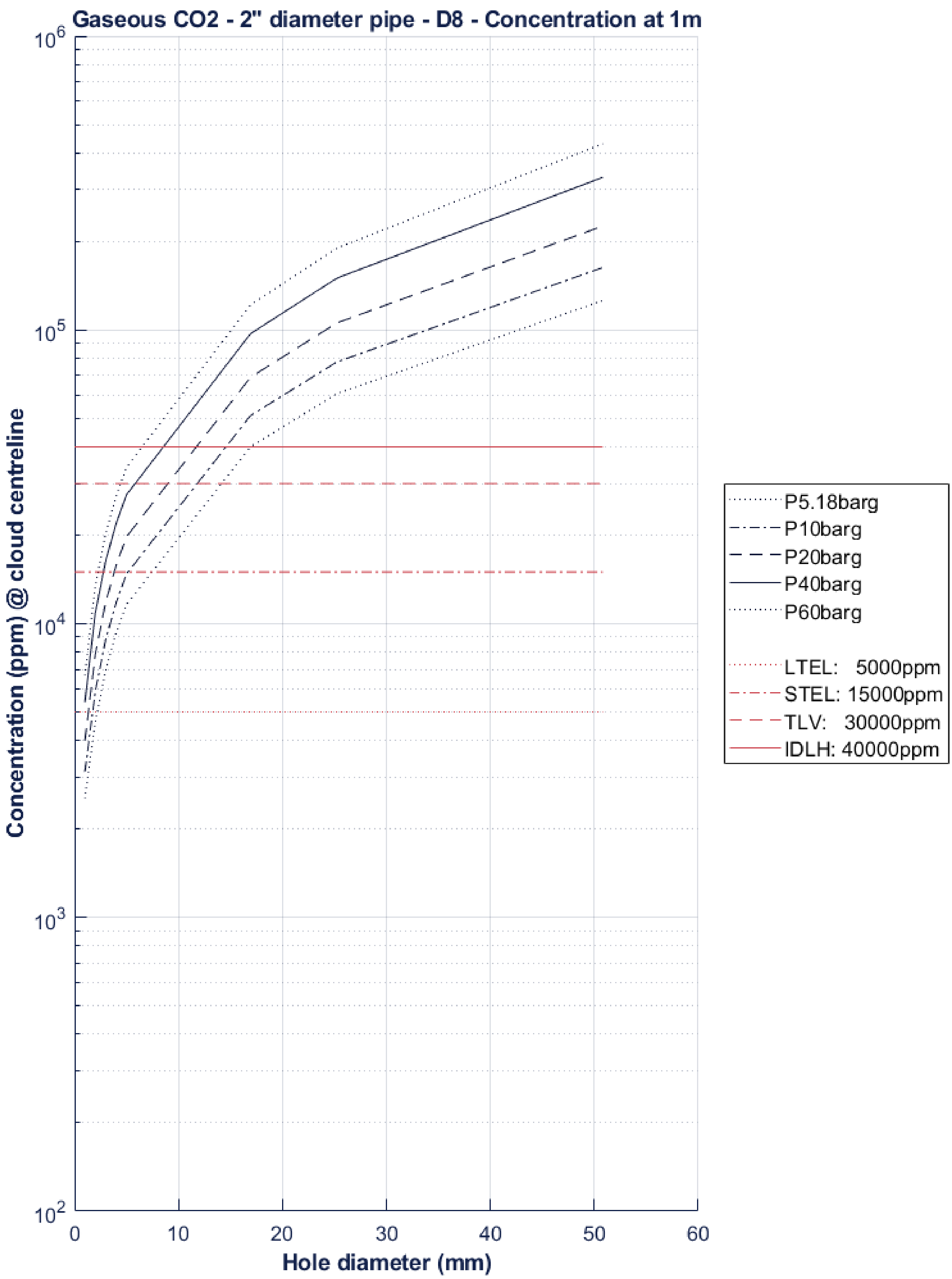


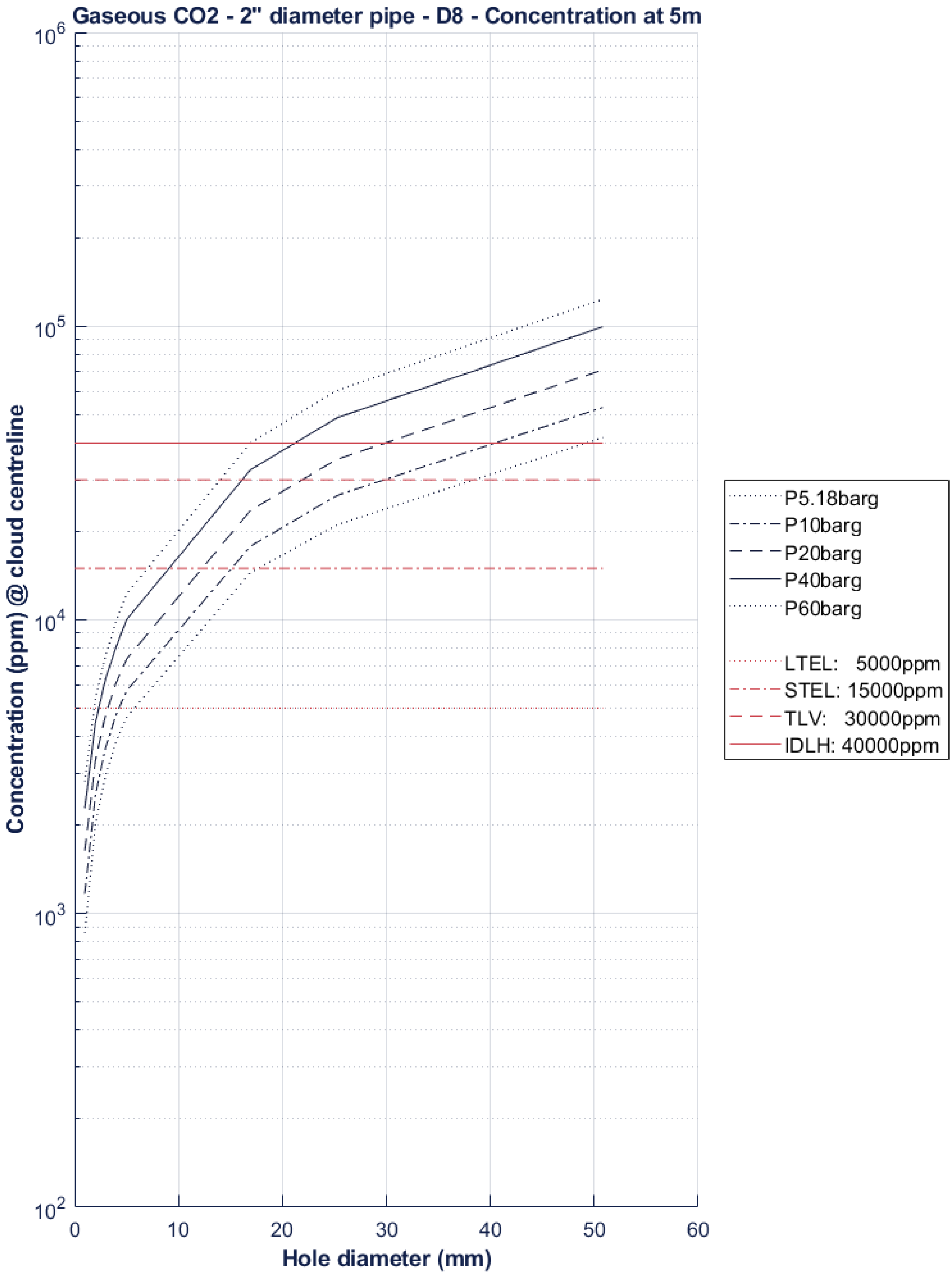


Gaseous CO2 - 2" diameter pipe - D1 - Concentration at 5m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

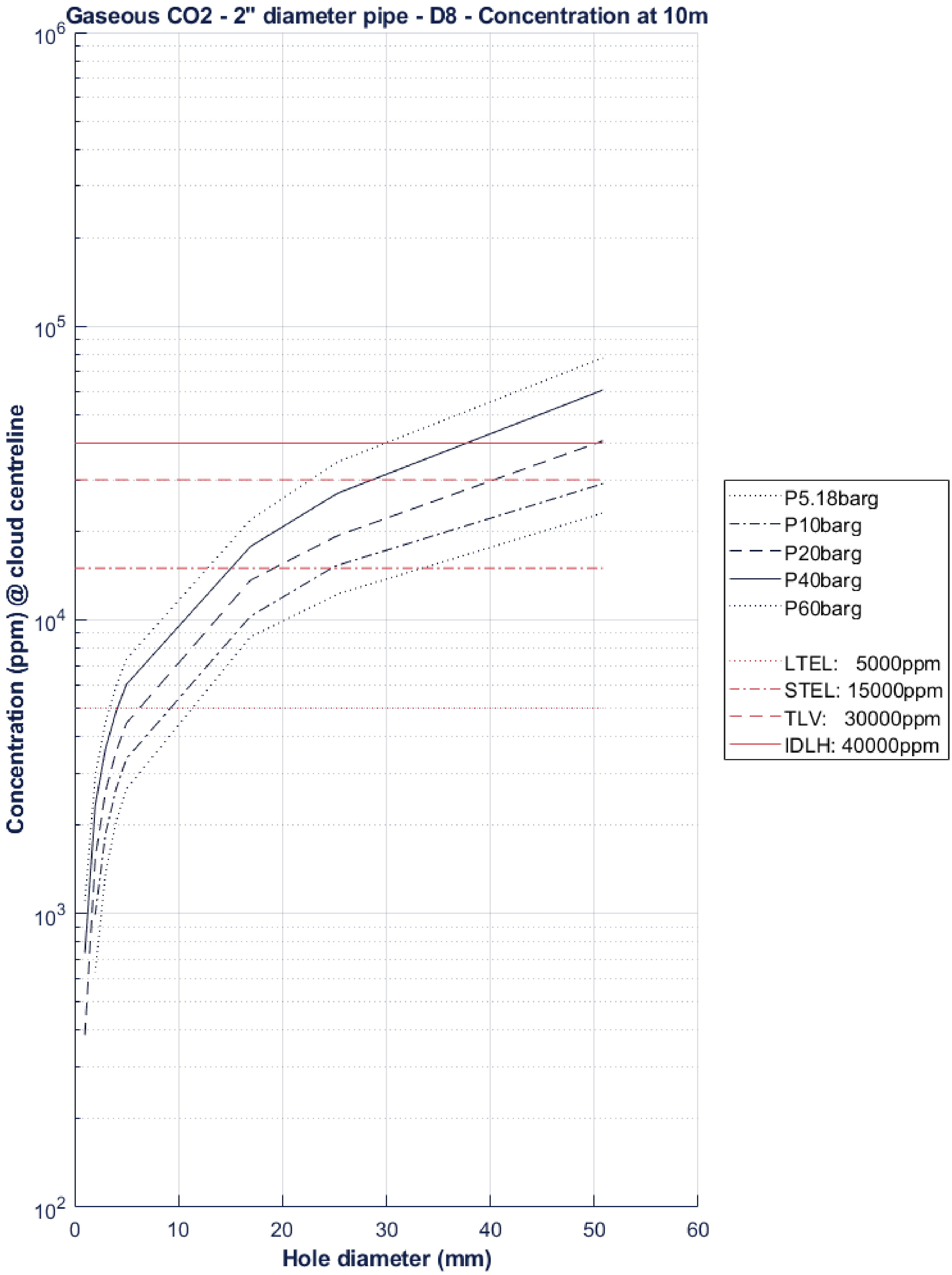

Gaseous CO2 - 2" diameter pipe - D1 - Concentration at 10m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

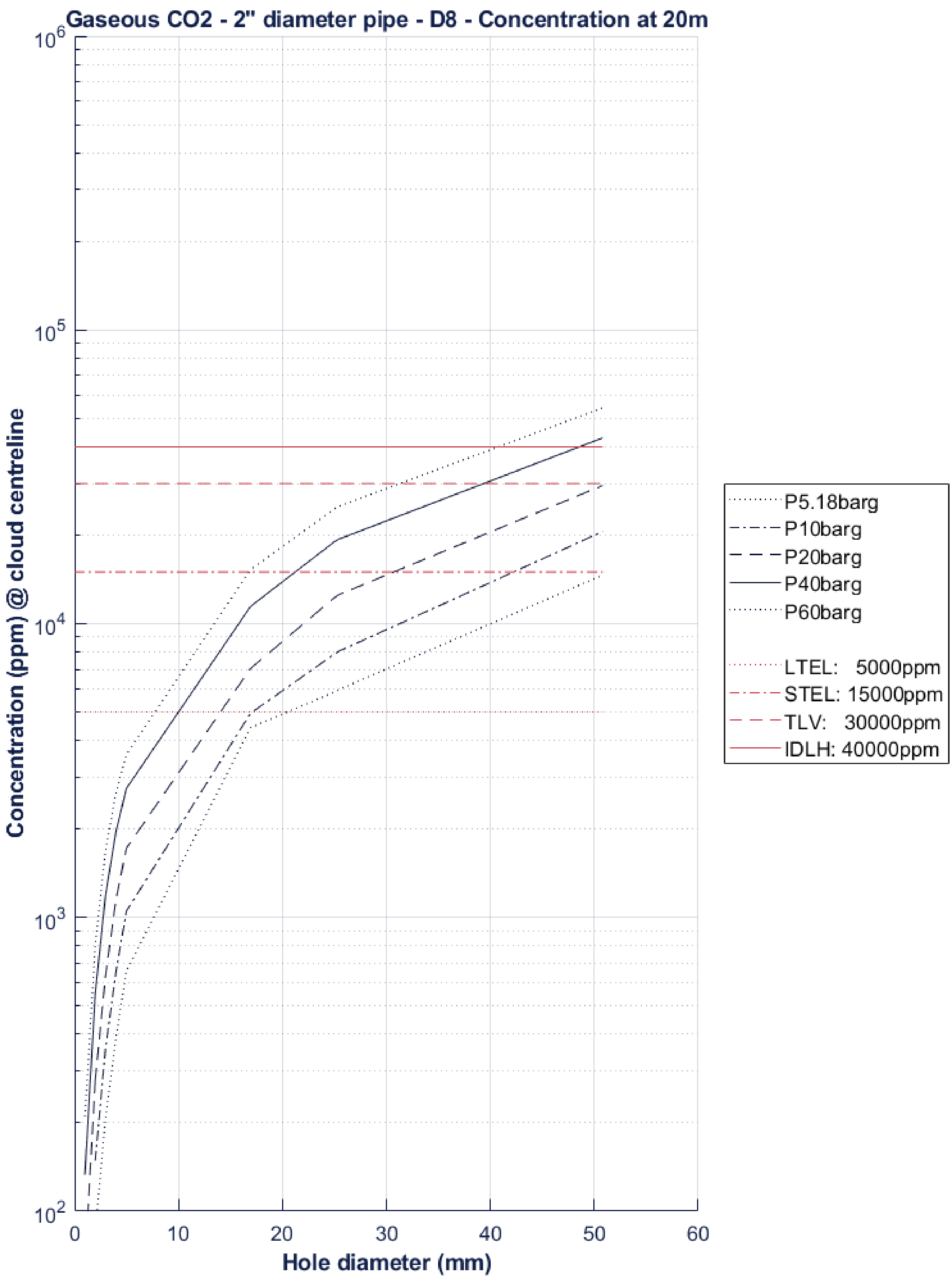

Gaseous CO2 - 2" diameter pipe - D1 - Concentration at 20m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

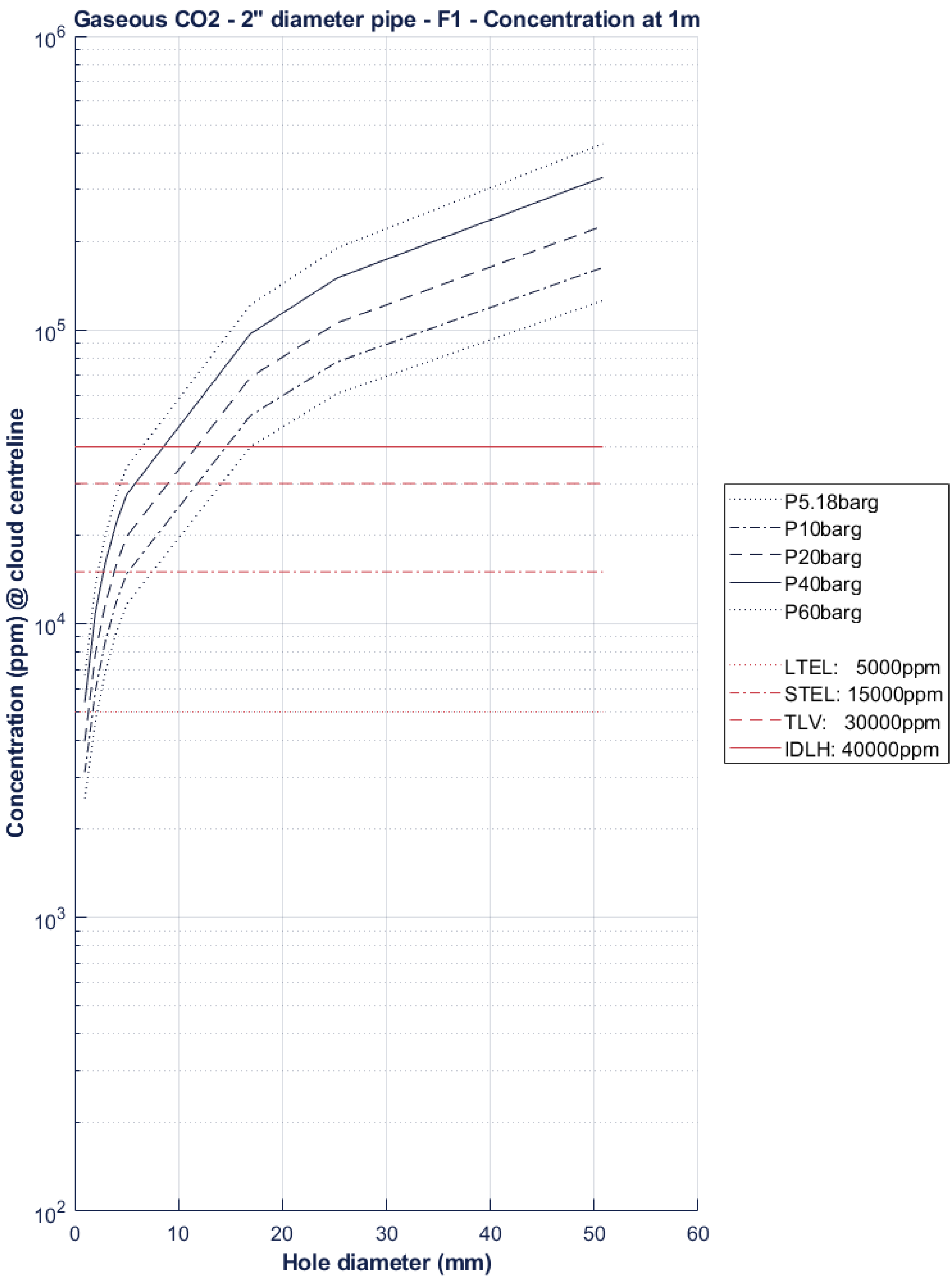

Gaseous CO2 - 2" diameter pipe - D8 - Concentration at 1m
Concentration (ppm) @ cloud centreline
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

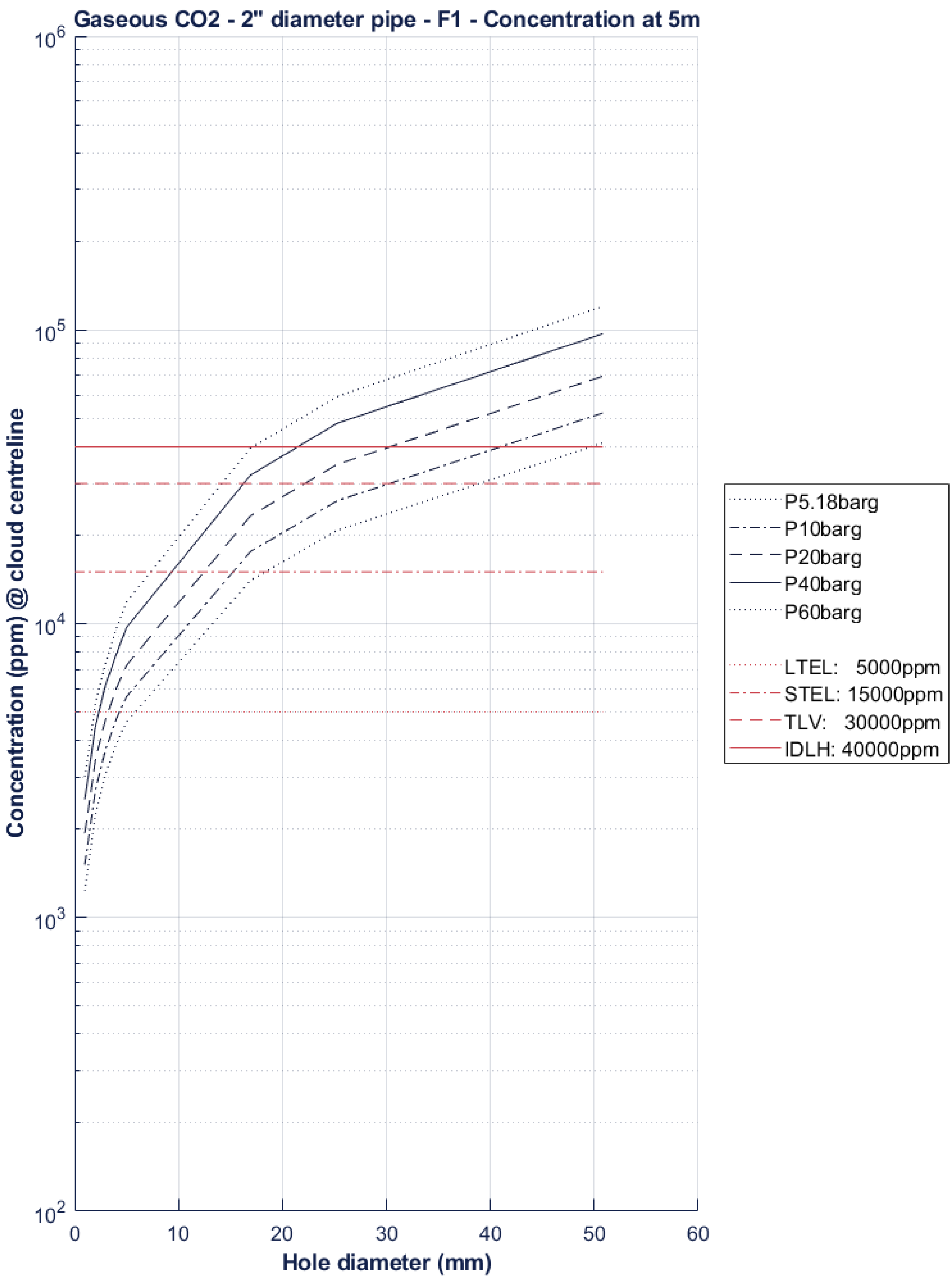


Gaseous CO2 - 2" diameter pipe - D8 - Concentration at 5m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

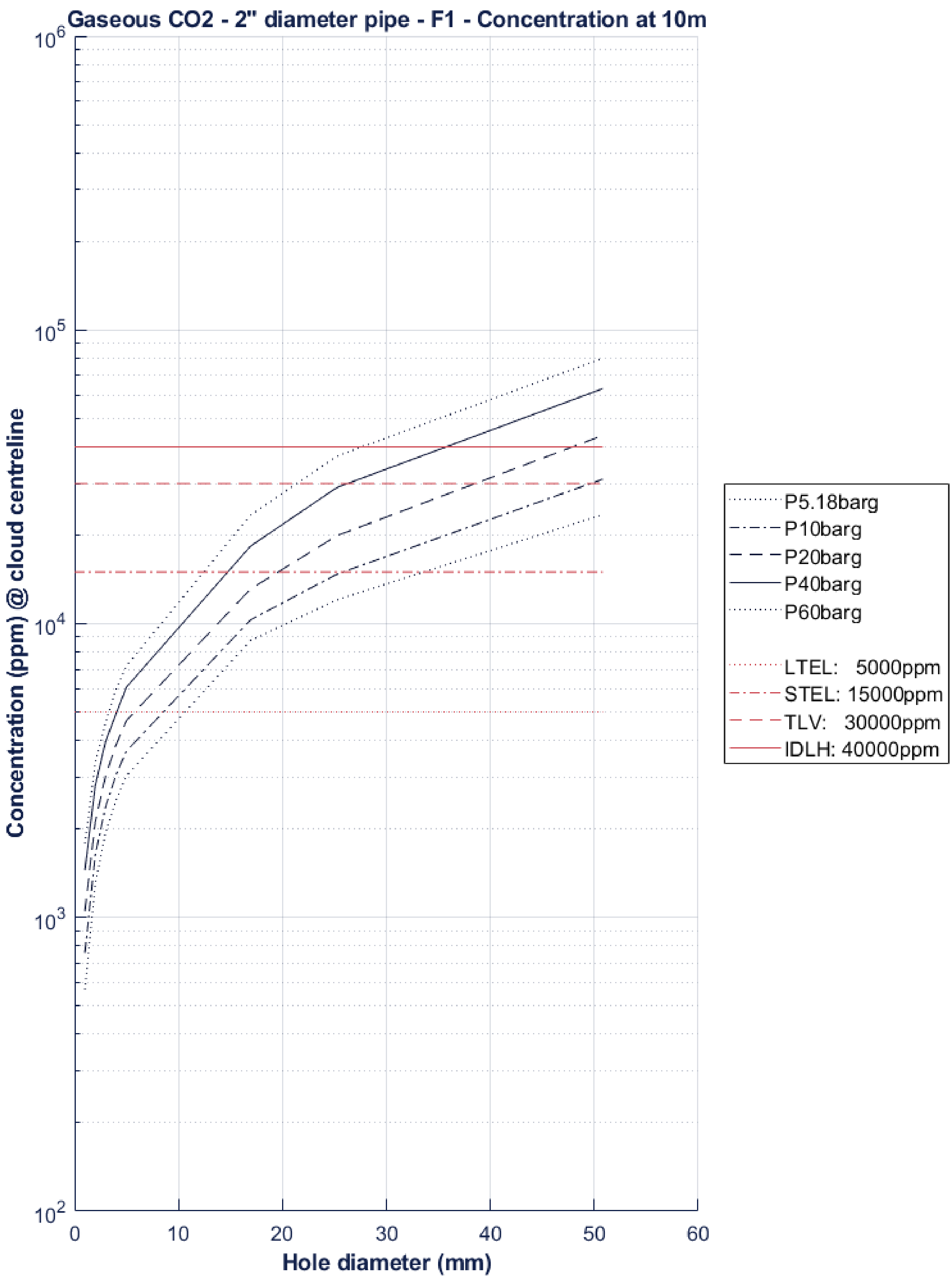

Gaseous CO2 - 2" diameter pipe - D8 - Concentration at 10m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

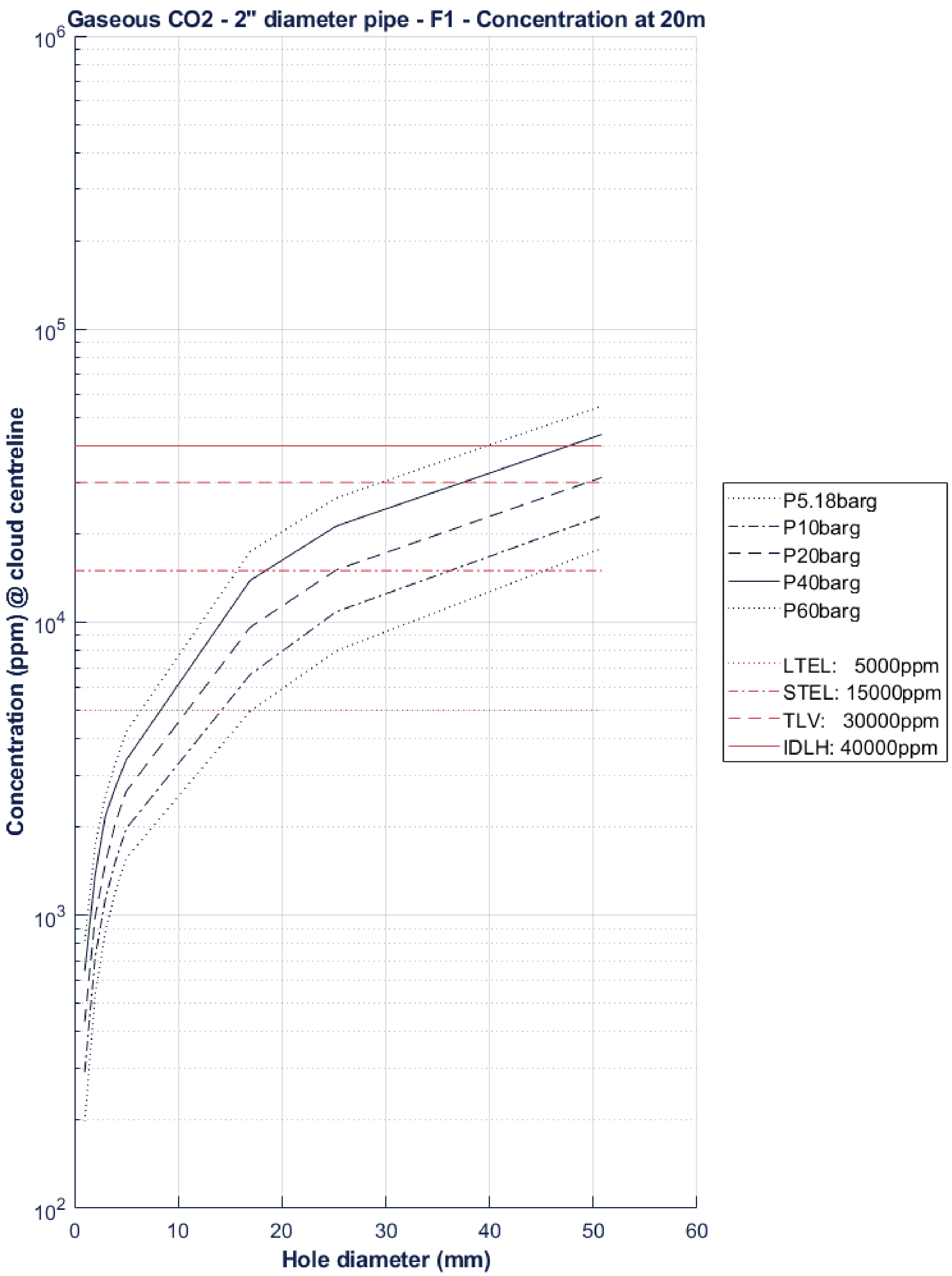

Gaseous CO2 - 2" diameter pipe - D8 - Concentration at 20m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^2
10^3
10^4
10^5
10^6
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm


Gaseous CO2 - 2" diameter pipe - F1 - Concentration at 1m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm



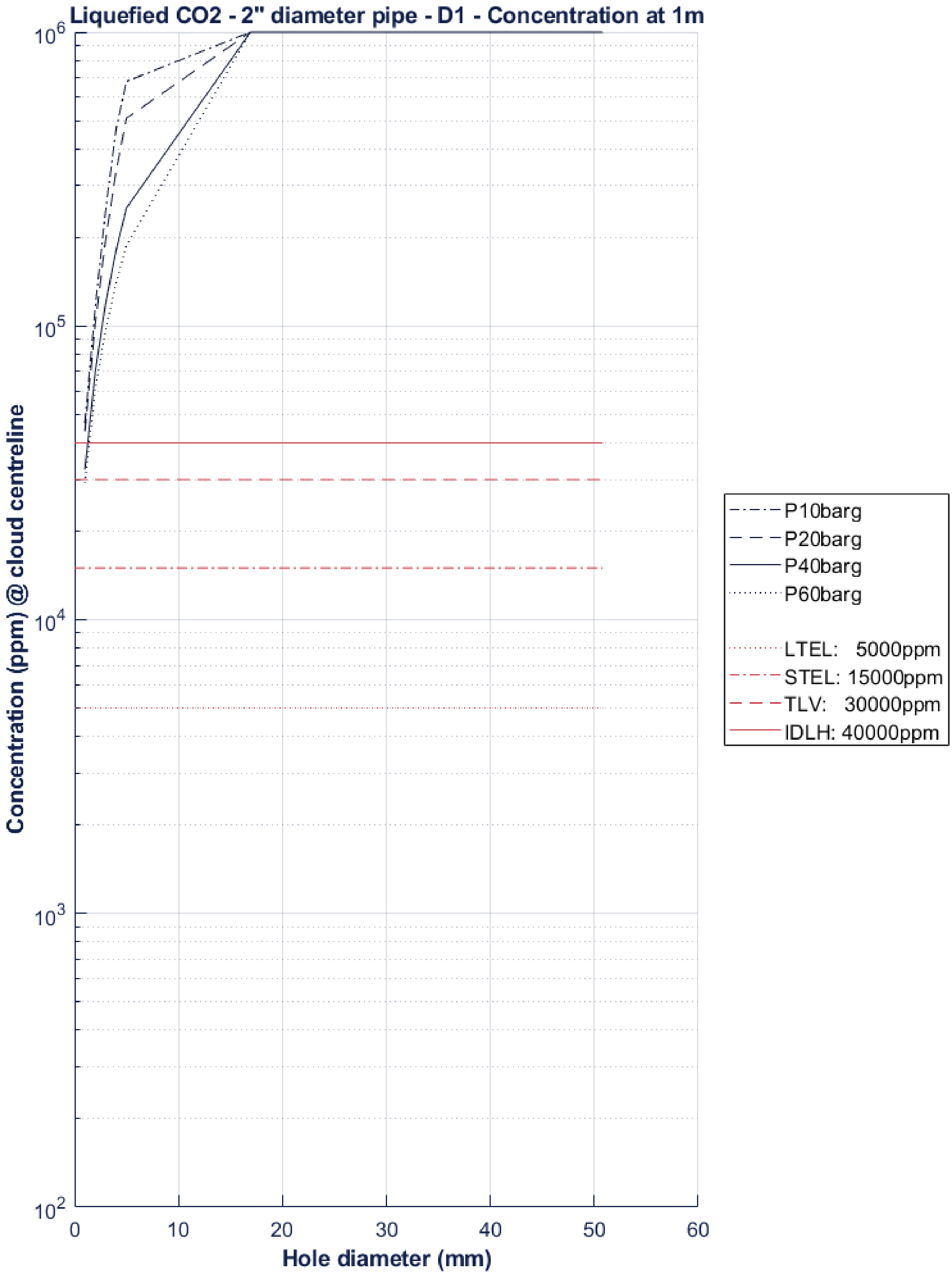
Gaseous CO2 - 2" diameter pipe - F1 - Concentration at 5m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

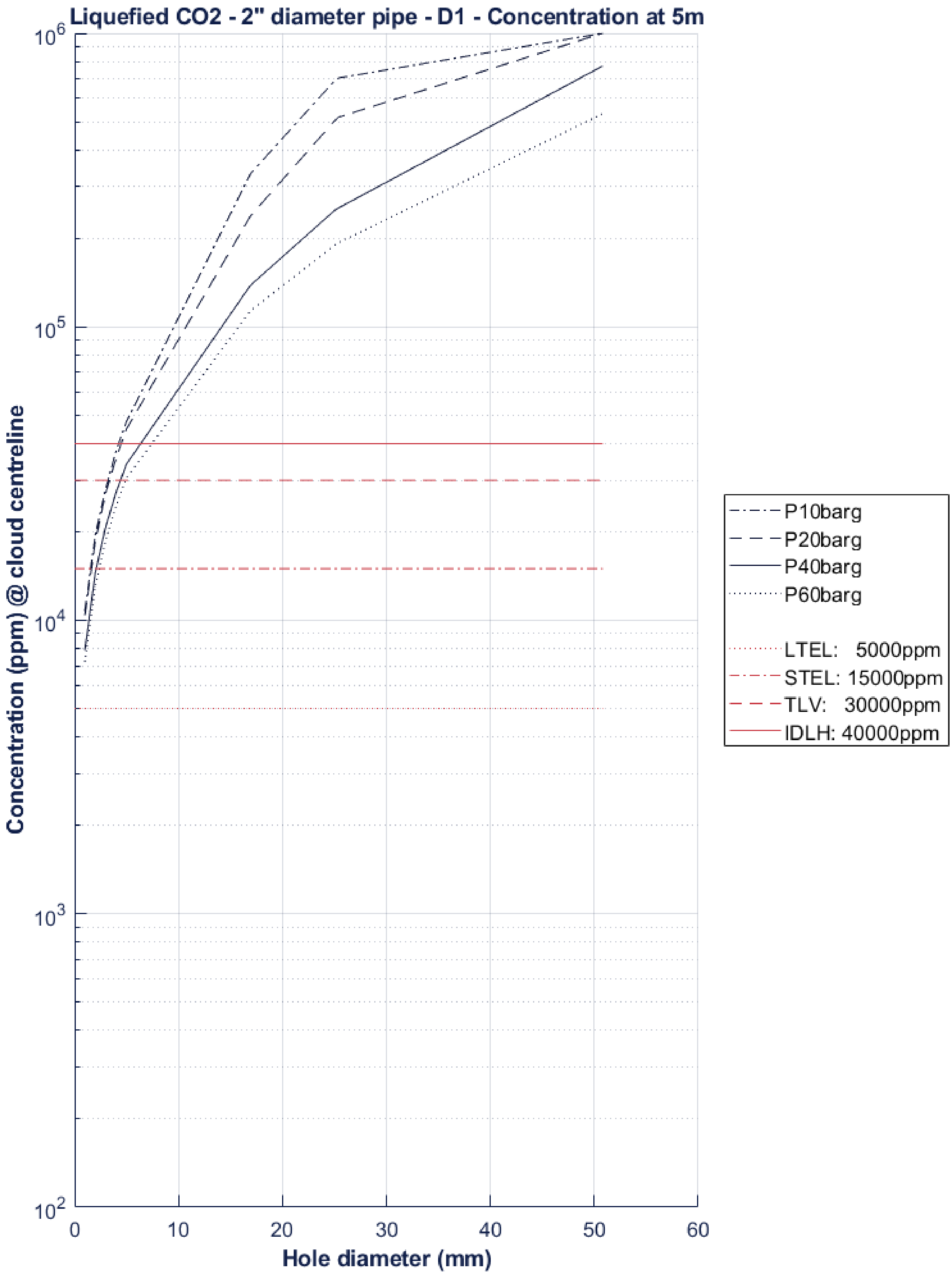

Gaseous CO2 - 2" diameter pipe - F1 - Concentration at 10m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

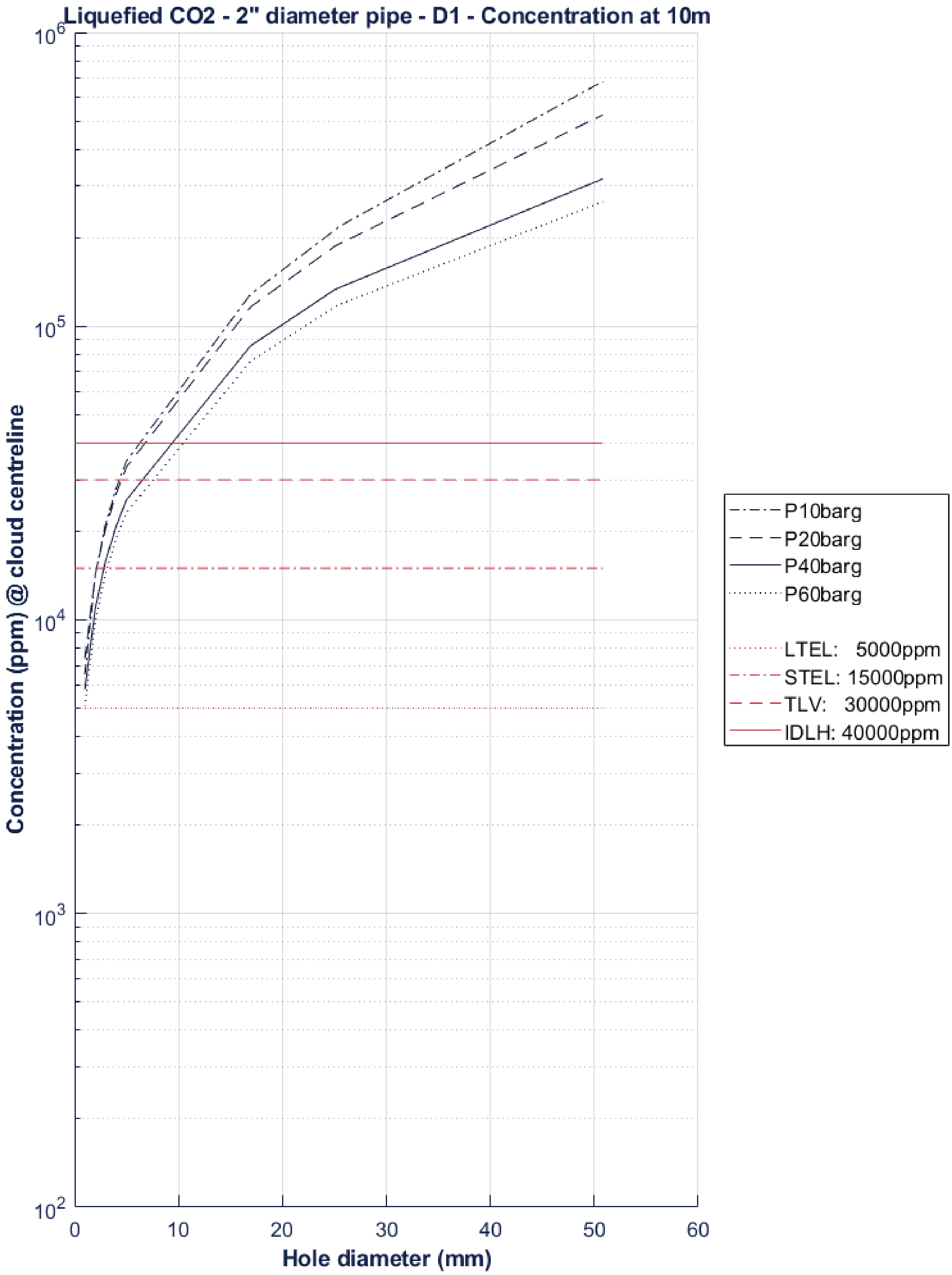


Gaseous CO2 - 2" diameter pipe - F1 - Concentration at 20m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P5.18barg
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

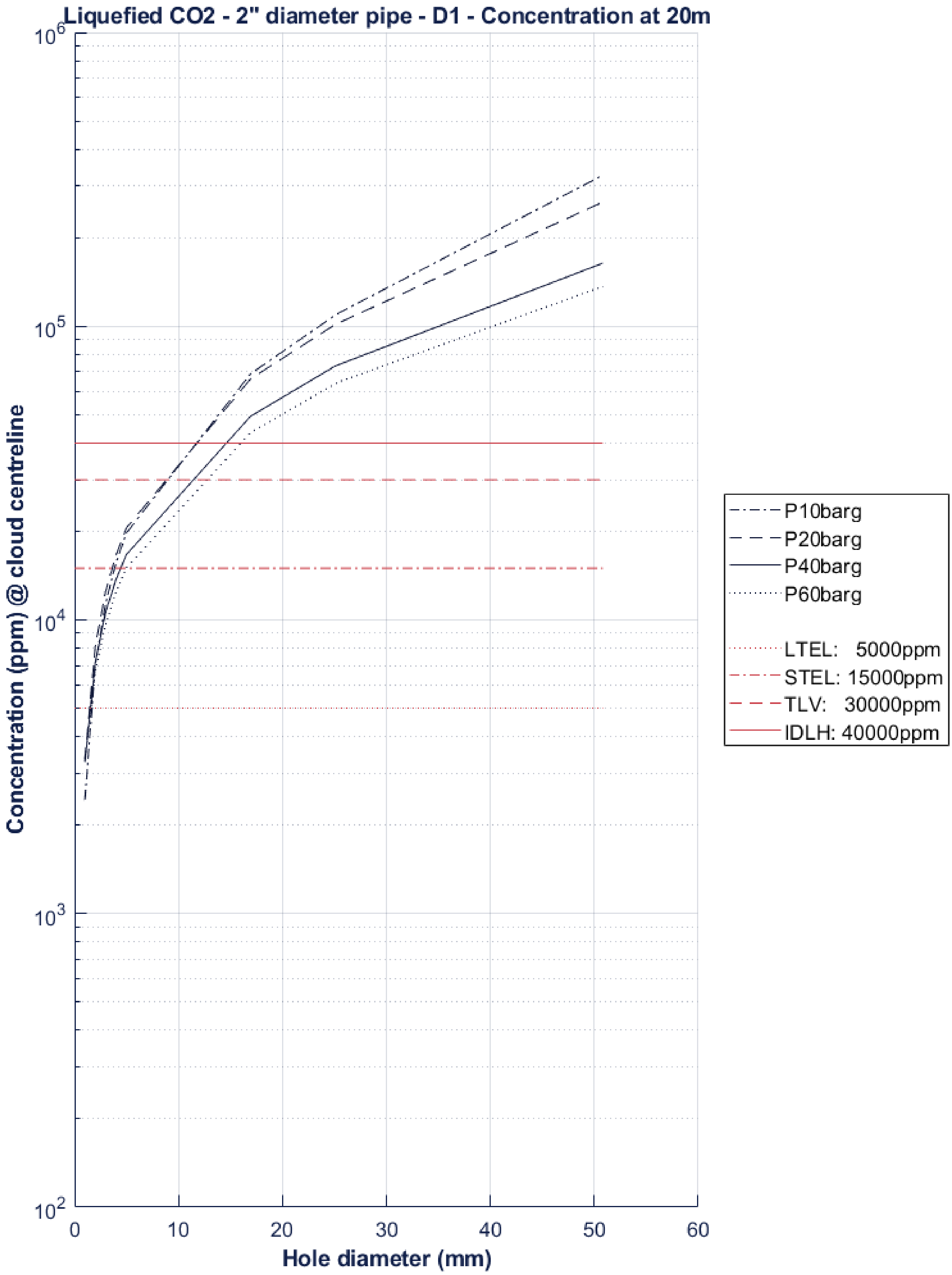
8.8 Liquefied releases – Concentration as function of hole size



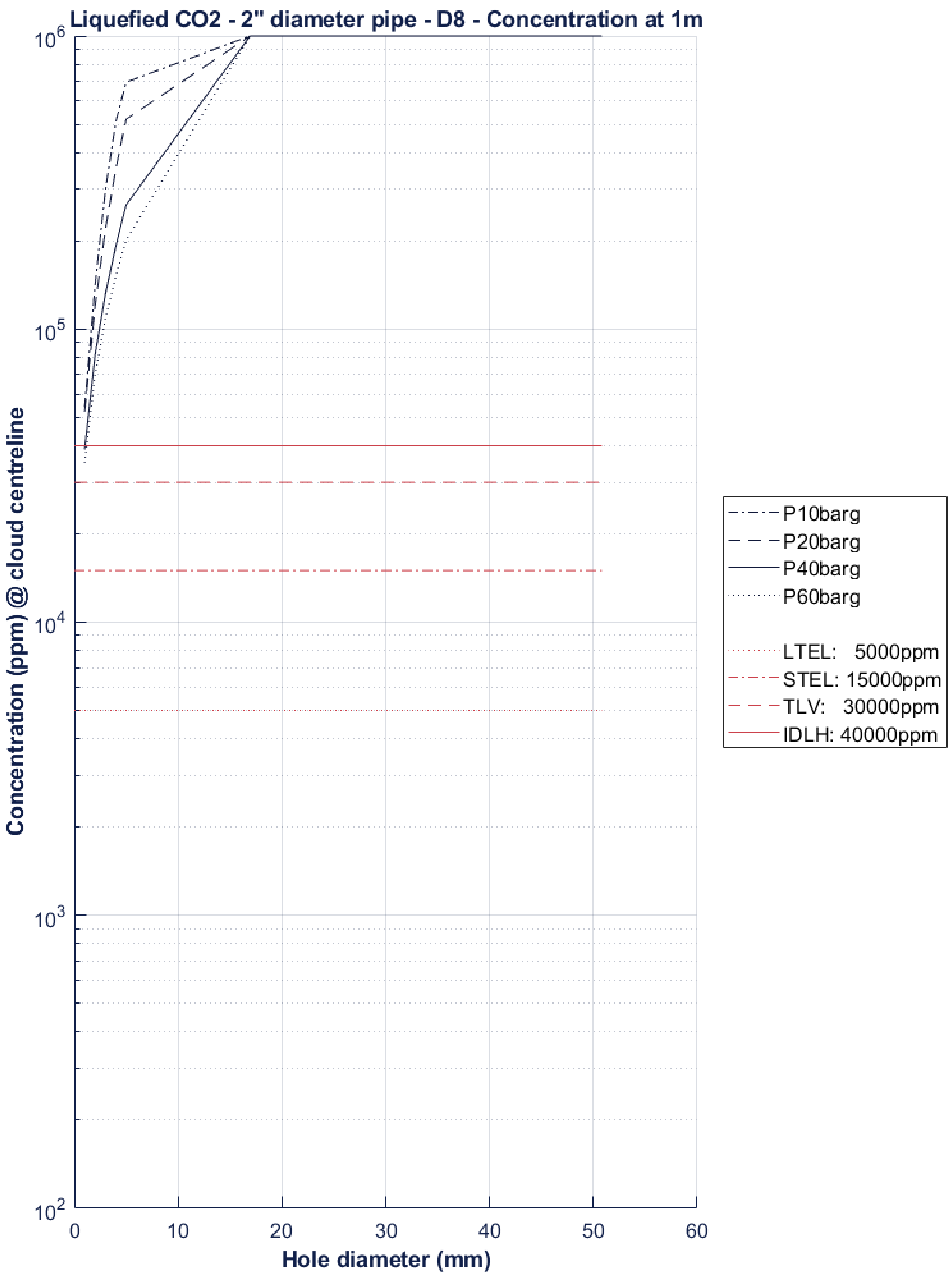

Liquefied CO2 - 2" diameter pipe - D1 - Concentration at 5m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

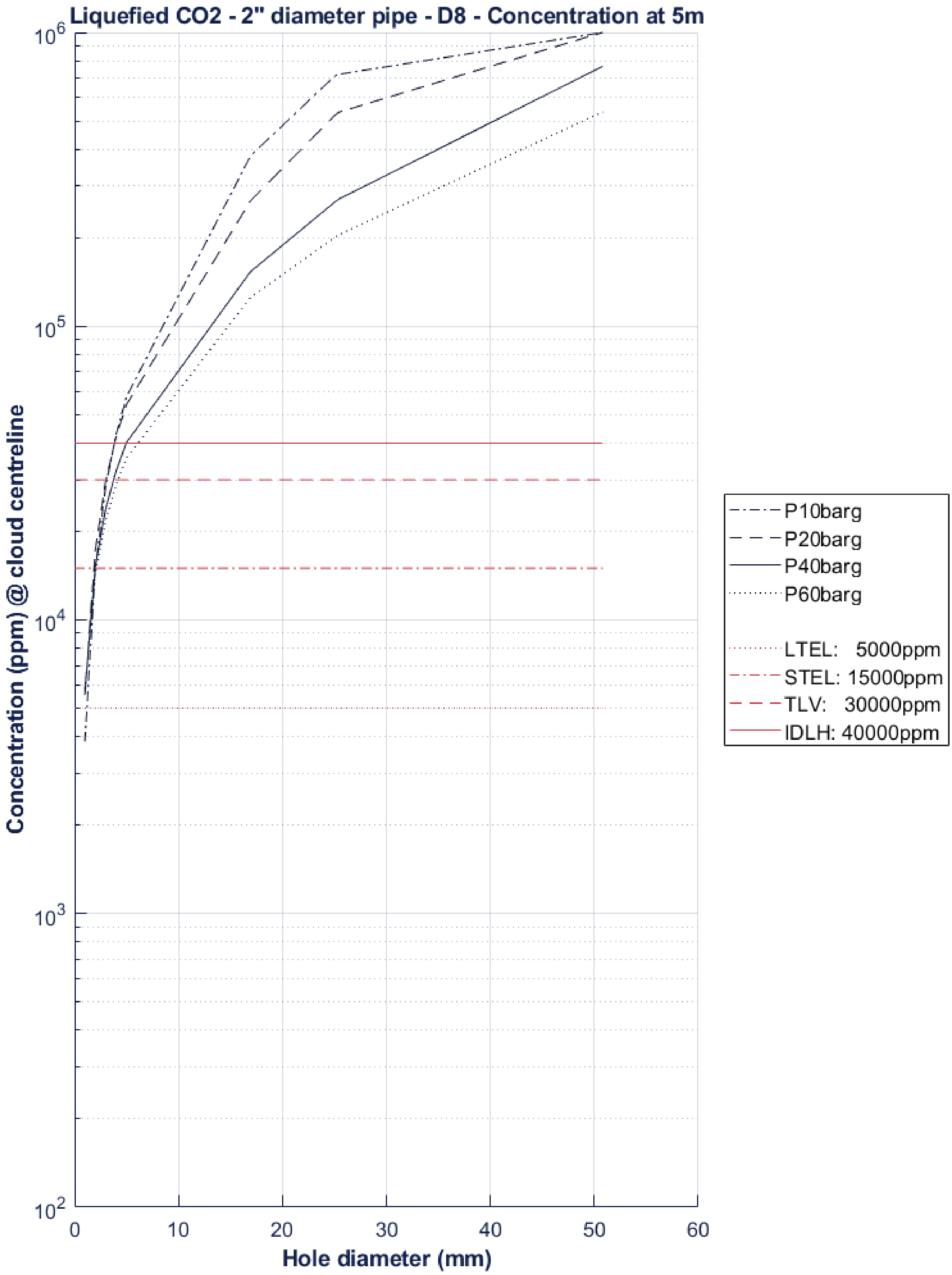


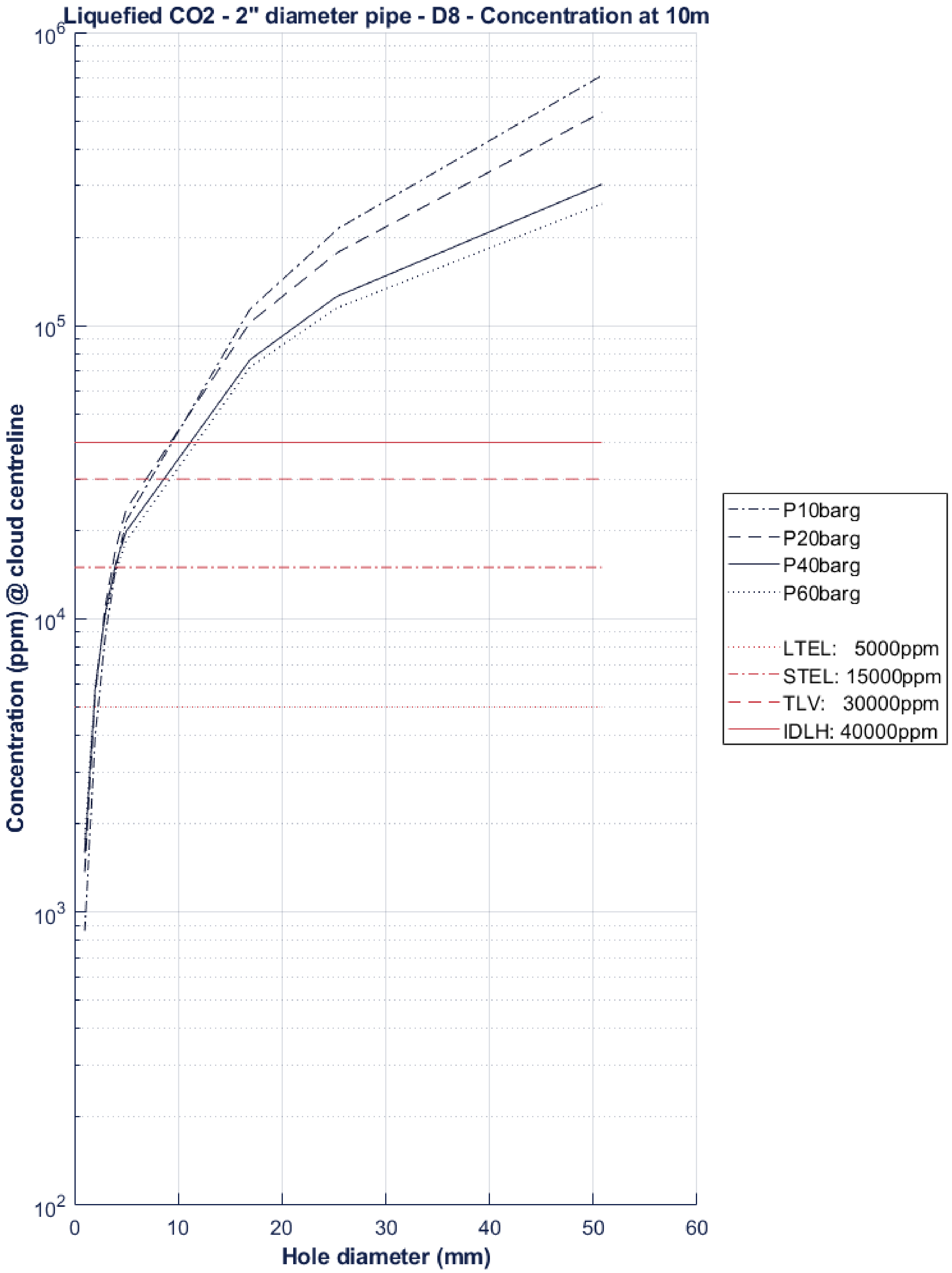
Liquefied CO2 - 2" diameter pipe - D1 - Concentration at 10m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm



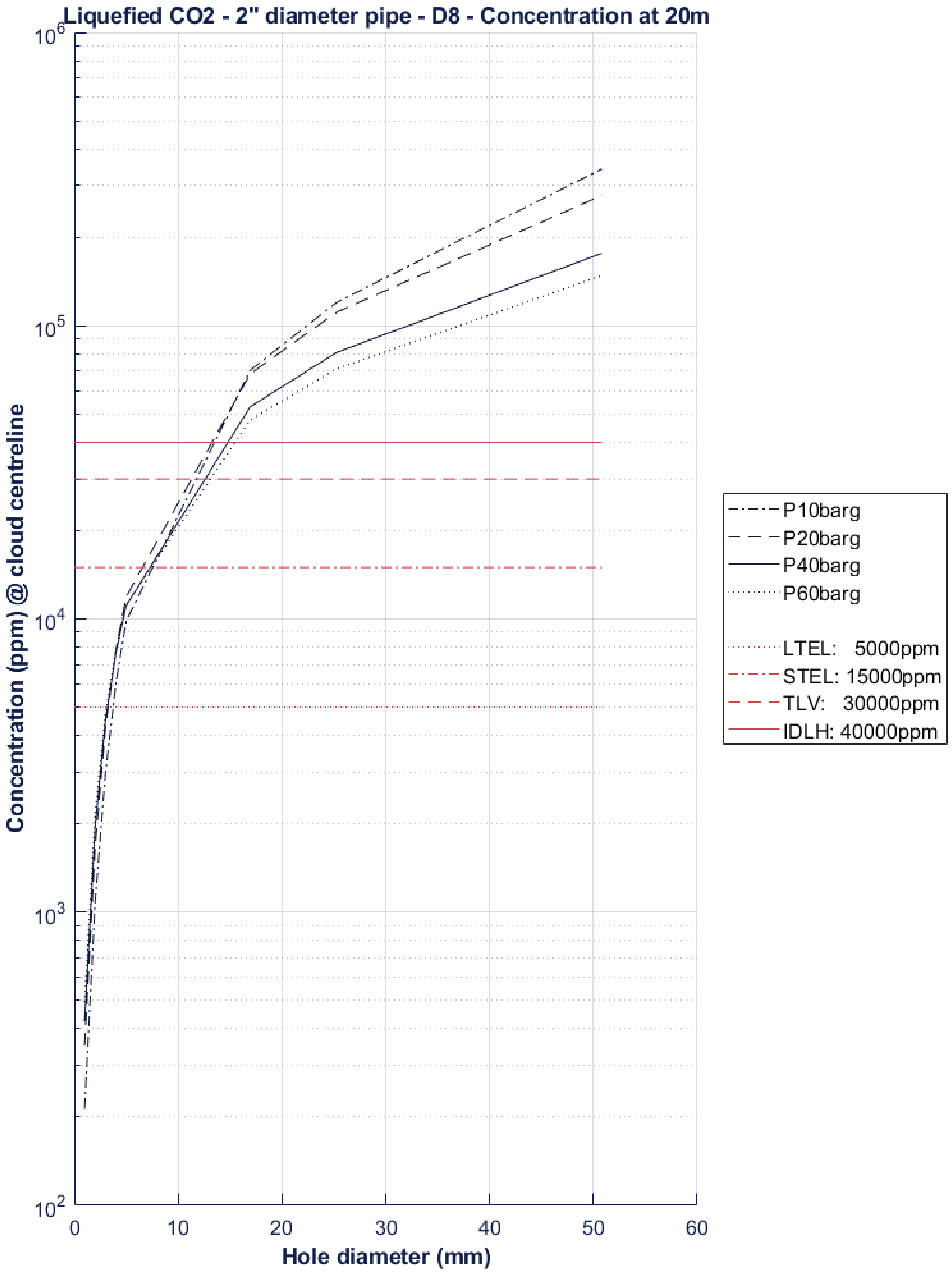
Liquefied CO2 - 2" diameter pipe - D1 - Concentration at 20m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

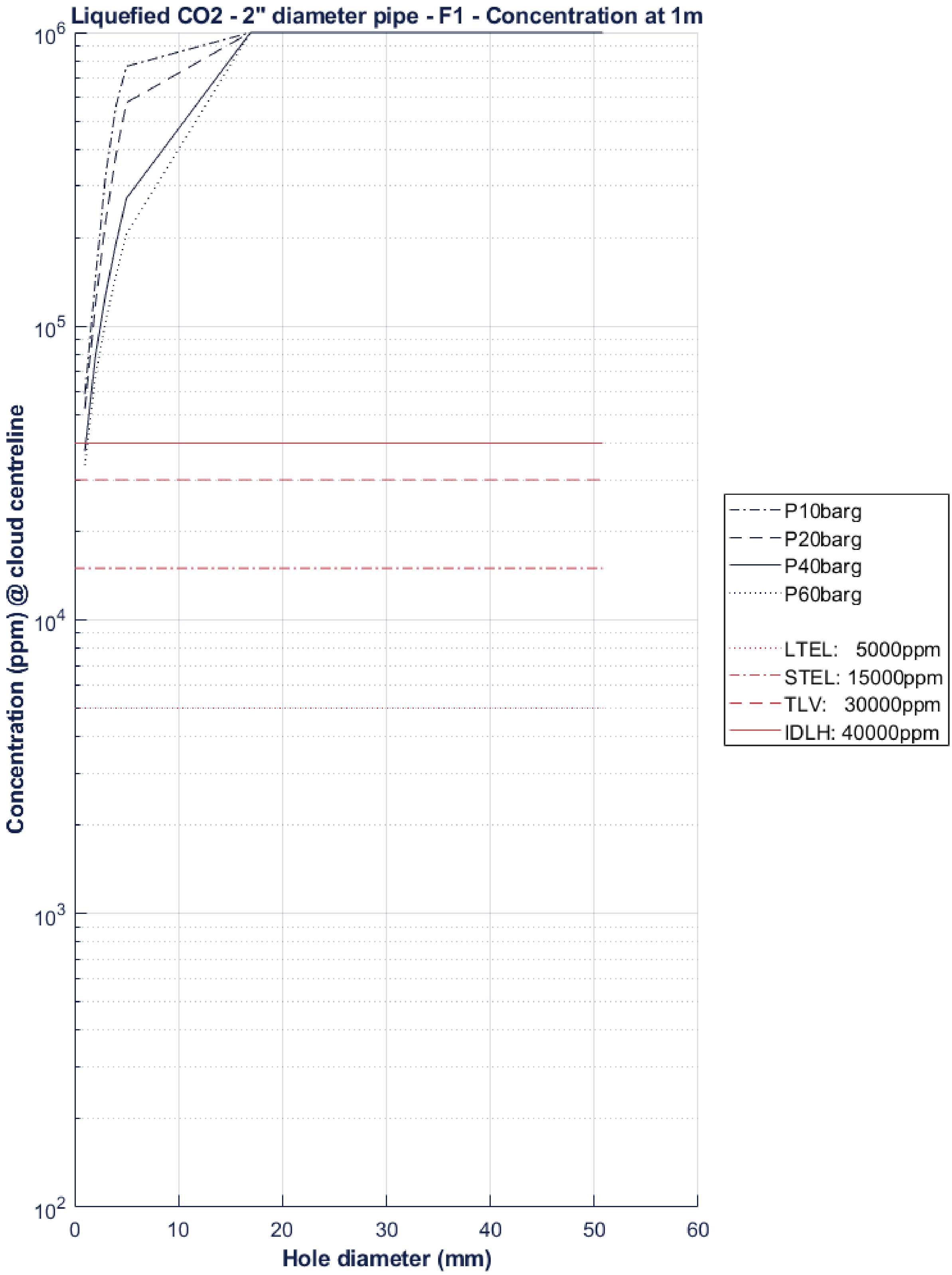

Liquefied CO2 - 2" diameter pipe - D8 - Concentration at 1m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm


Liquefied CO2 - 2" diameter pipe - D8 - Concentration at 5m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

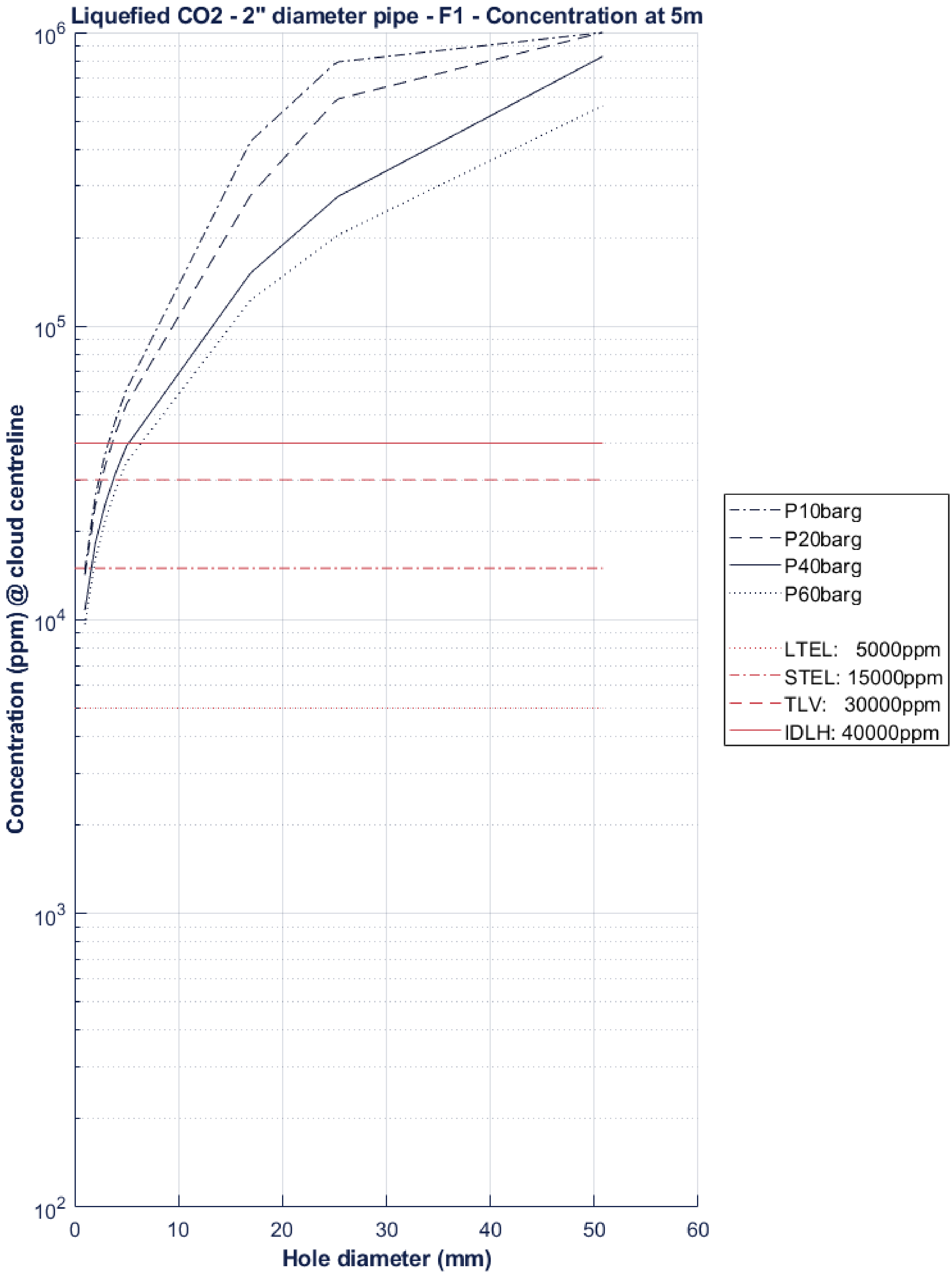


Liquefied CO2 - 2" diameter pipe - D8 - Concentration at 10m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

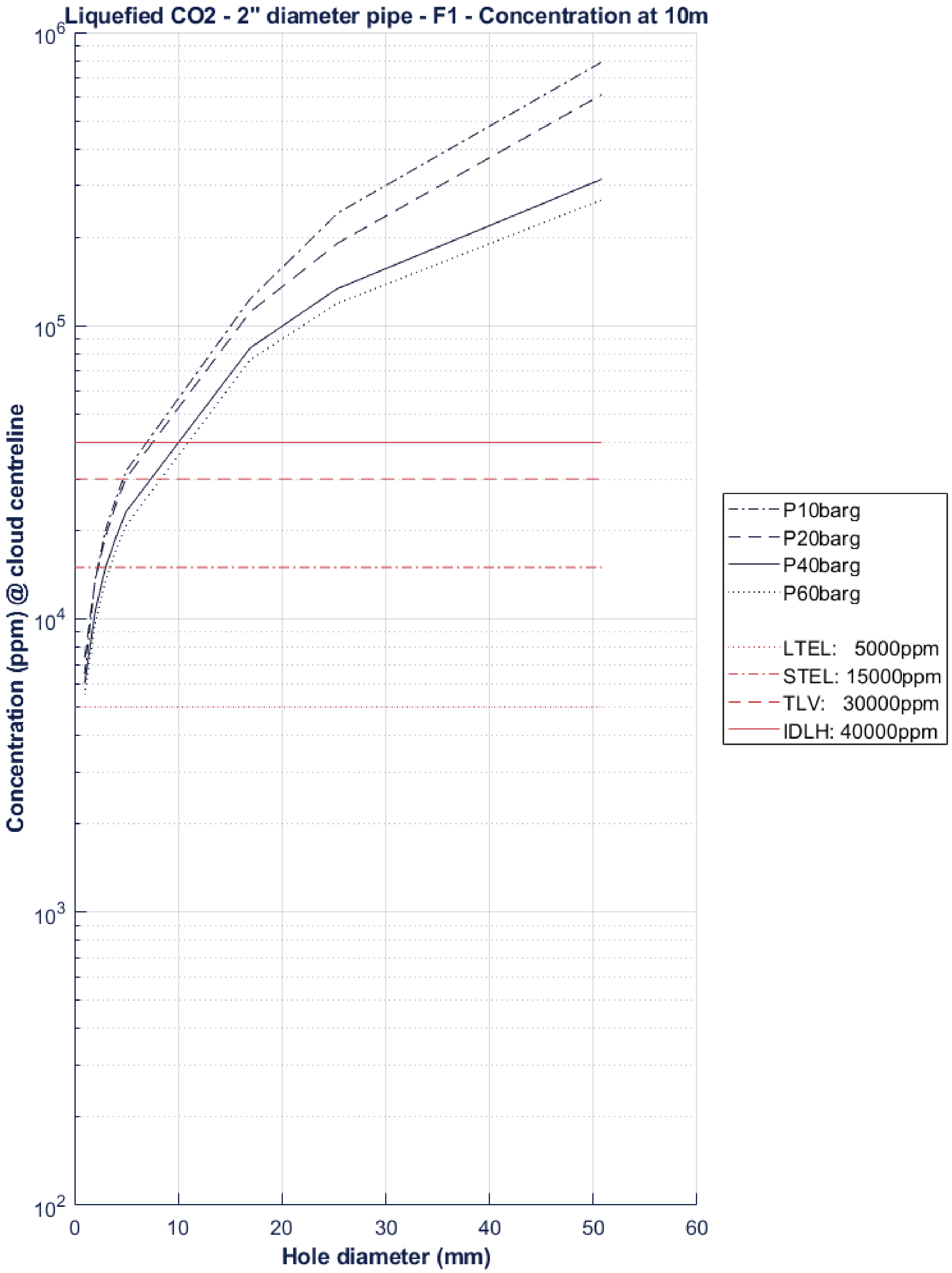

Liquefied CO2 - 2" diameter pipe - D8 - Concentration at 20m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm



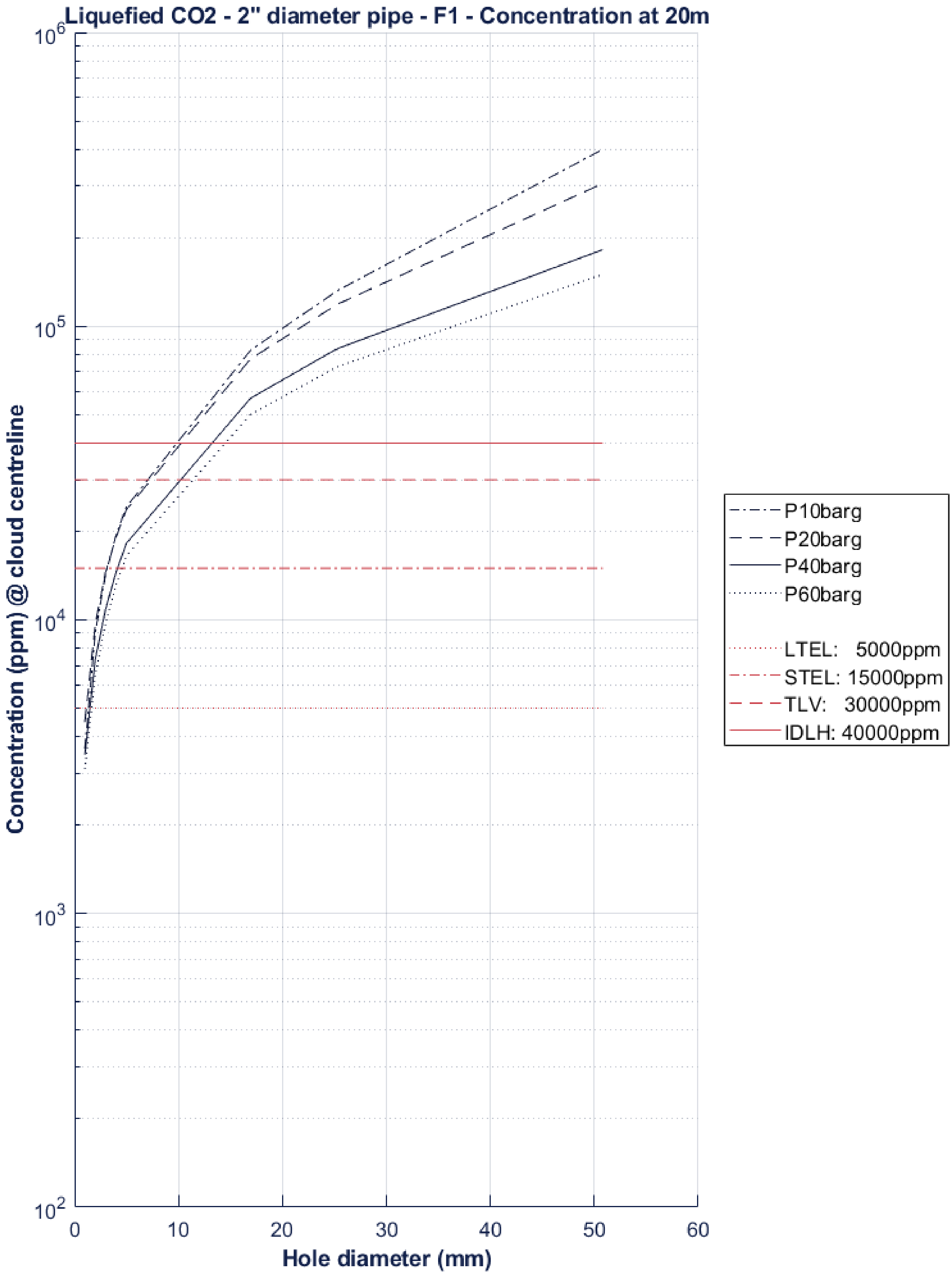
Liquefied CO2 - 2" diameter pipe - F1 - Concentration at 1m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm



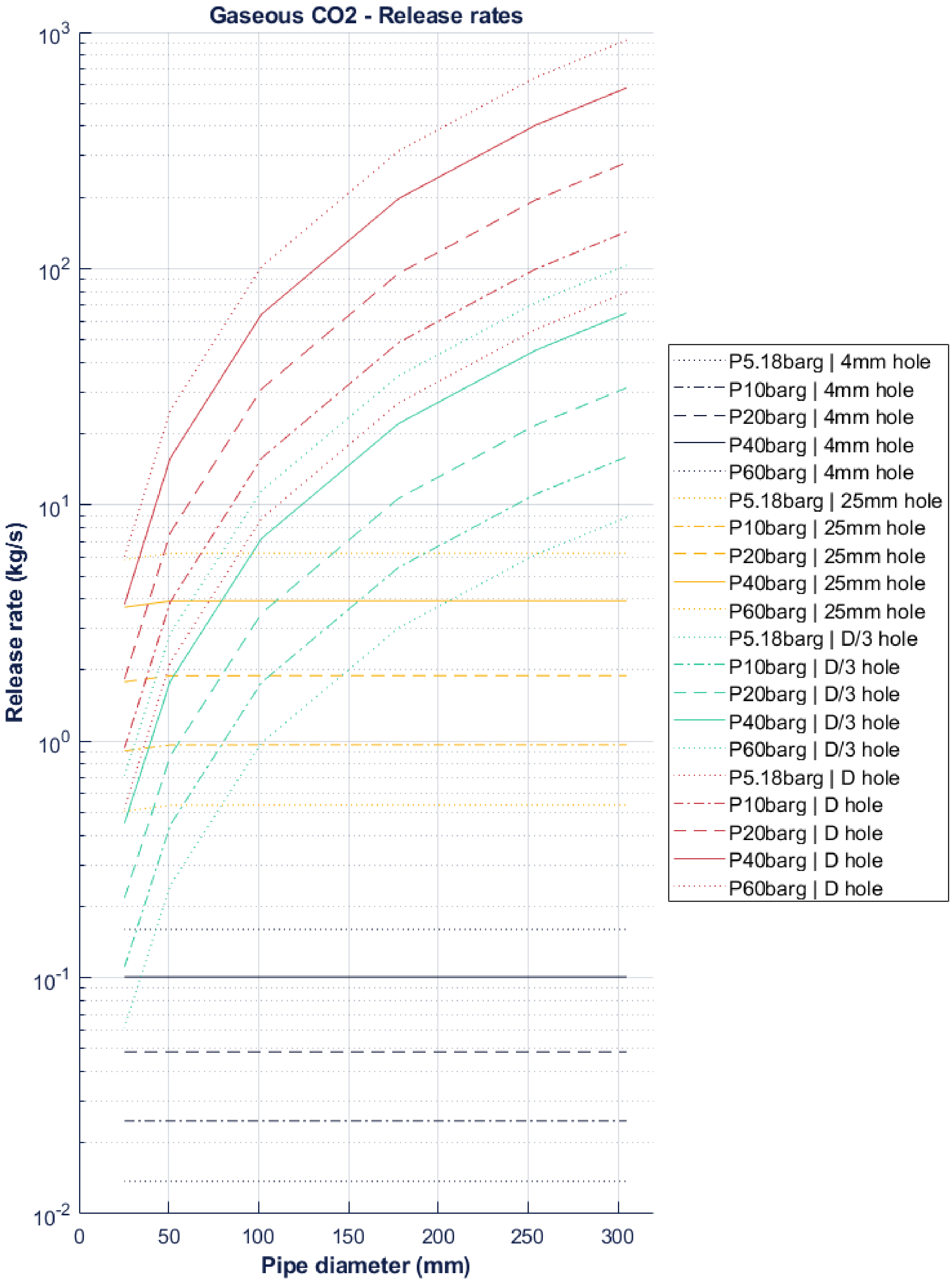
Liquefied CO2 - 2" diameter pipe - F1 - Concentration at 5m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

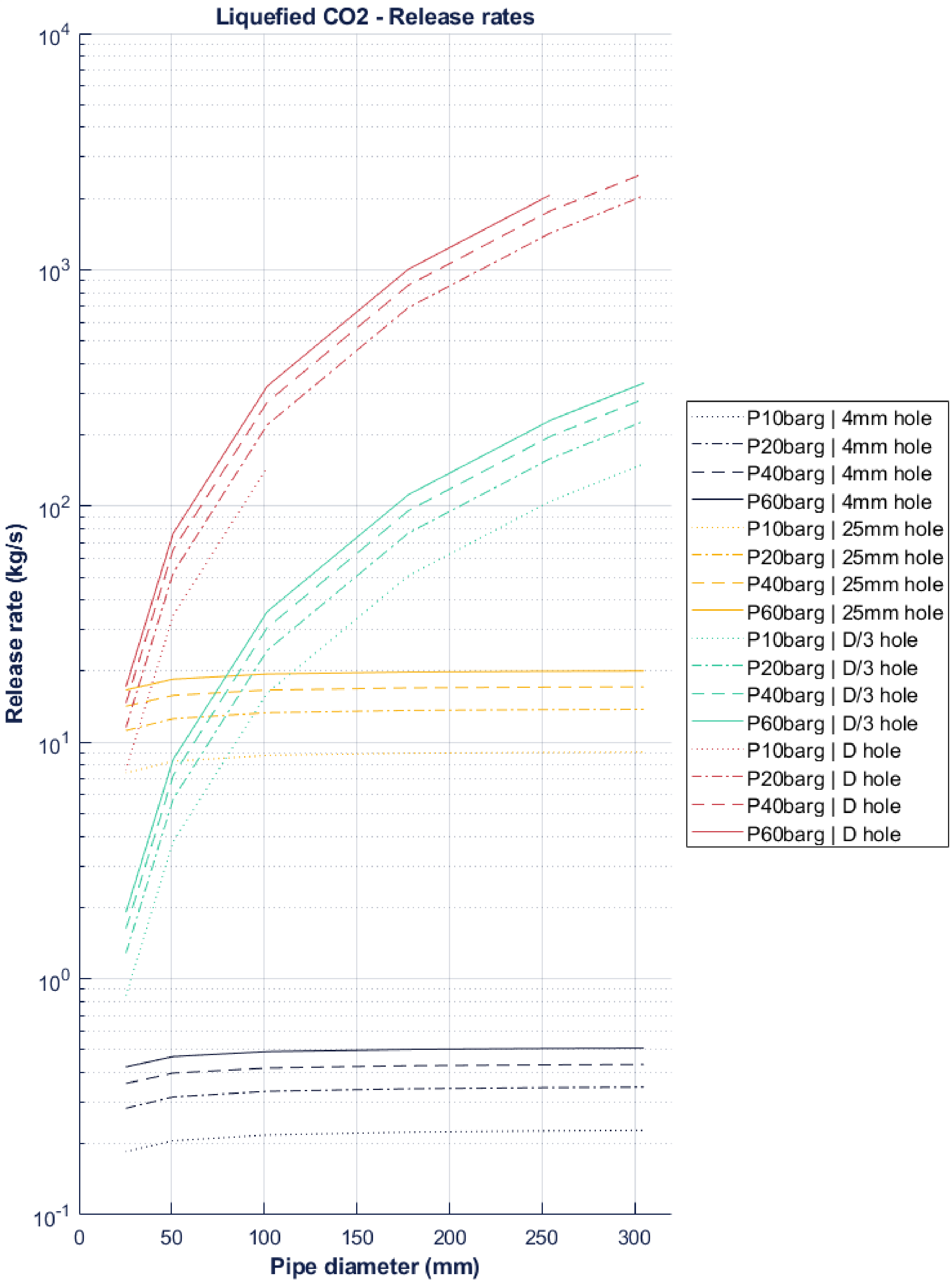


Liquefied CO2 - 2" diameter pipe - F1 - Concentration at 10m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm



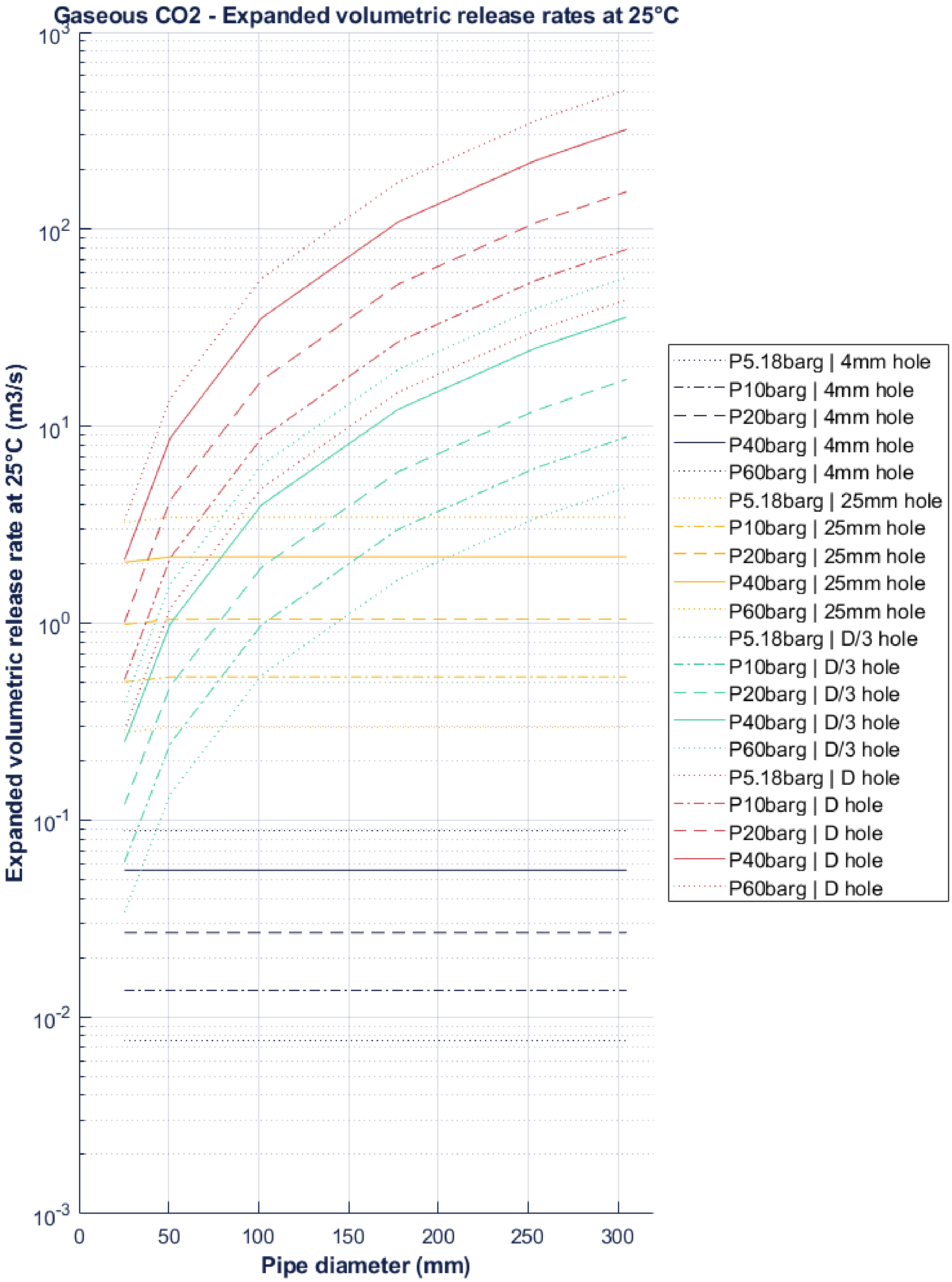
Liquefied CO2 - 2" diameter pipe - F1 - Concentration at 20m
Concentration (ppm) @ cloud centreline
Hole diameter (mm)
10^6
10^5
10^4
10^3
10^2
0
10
20
30
40
50
60
P10barg
P20barg
P40barg
P60barg
LTEL: 5000ppm
STEL: 15000ppm
TLV: 30000ppm
IDLH: 40000ppm

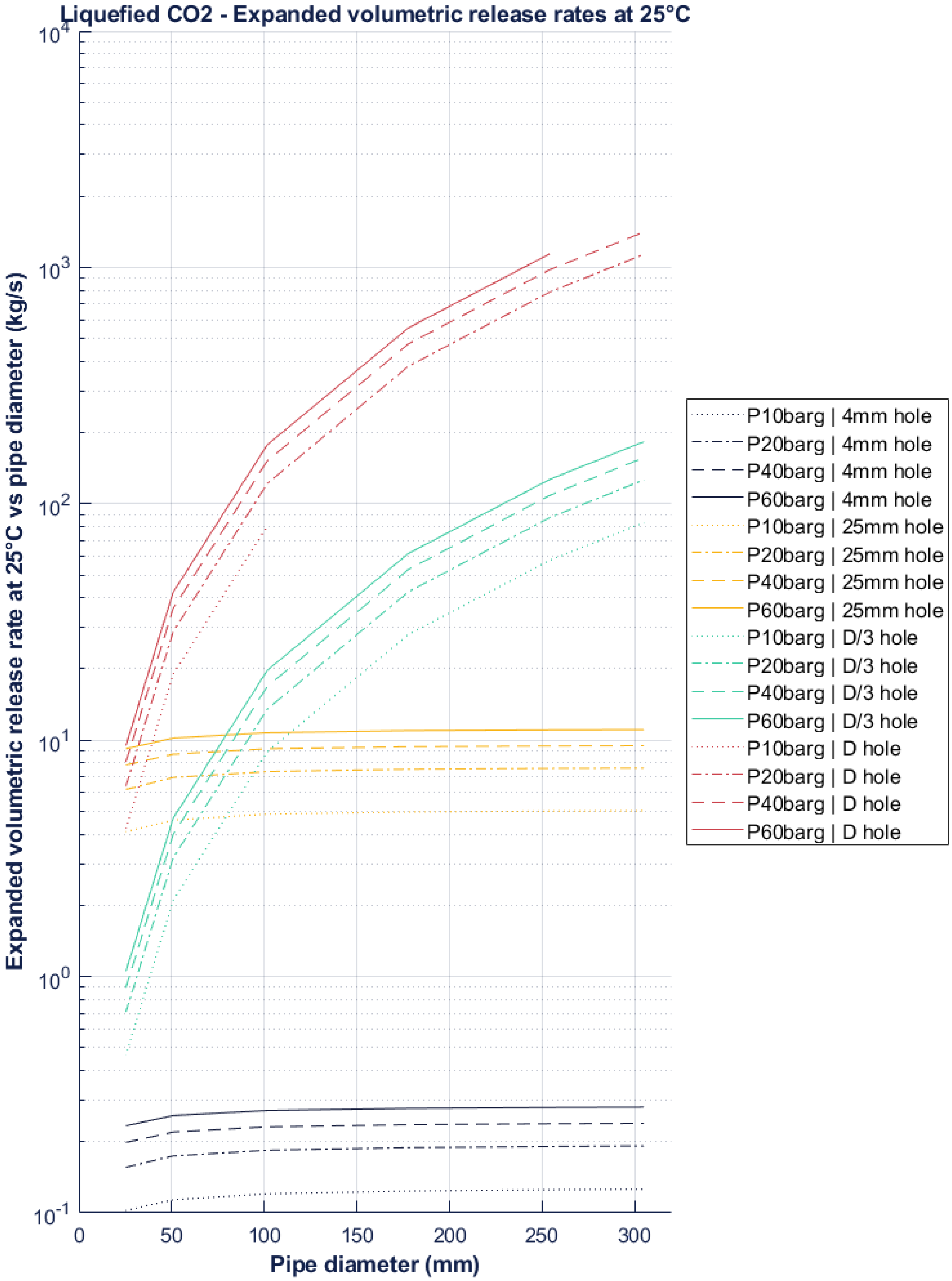

Gaseous CO2 - Release rates
Release rate (kg/s)
Pipe diameter (mm)
10^3
10^2
10^1
10^0
10^-1
10^-2
0
50
100
150
200
250
300
P5.18barg | 4mm hole
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P5.18barg | 25mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P5.18barg | D/3 hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P5.18barg | D hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole



Liquefied CO2 - Release rates
Release rate (kg/s)
Pipe diameter (mm)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole

8.10 Expanded volumetric release rates at 25°C




Liquefied CO2 - Expanded volumetric release rates at 25°C
Expanded volumetric release rate at 25°C vs pipe diameter (kg/s)
10^4
10^3
10^2
10^1
10^0
10^-1
0
50
100
150
200
250
300
Pipe diameter (mm)
P10barg | 4mm hole
P20barg | 4mm hole
P40barg | 4mm hole
P60barg | 4mm hole
P10barg | 25mm hole
P20barg | 25mm hole
P40barg | 25mm hole
P60barg | 25mm hole
P10barg | D/3 hole
P20barg | D/3 hole
P40barg | D/3 hole
P60barg | D/3 hole
P10barg | D hole
P20barg | D hole
P40barg | D hole
P60barg | D hole