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DELIVERABLE D8.4

Risk Analysis of the laser drill cryogenic system

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Document History

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ABBREVIATIONS AND GLOSSARY OF ACRONYMS

Acronym	Extended definition
CA	Consortium Agreement
D	Deliverable
DCM	Dissemination and Communication Manager
D&C	Dissemination and Communication
EC	European Commission
EM	Exploitation Manager
EP	Exploitation Plan
GA	Grant Agreement
HE	Horizon Europe
IPR	Intellectual Property Rights
M	Month
PC	Project Coordinator
PDEC	Plan for Dissemination and Exploitation including Communication activities
SC	Steering Committee
VRE	Virtual Research Environment
WP	Work Package

PUBLISHABLE SUMMARY

The " Risk Analysis of the Laser Drill Cryogenic System" report is part of the DeepU project aimed at developing an advanced drilling technology using a high-power laser, especially for depths exceeding 4000 meters. The report focuses on the preliminary risk assessment of the laser drill cryogenic system. This assessment identifies and evaluates failure modes associated with both the cryogenic system and other non-cryogenic factors such as the mechanical design of a laser drilling string intended for deep geothermal wells.

Objectives:

One of the primary objectives of this report is to identify and classify all potential failure modes resulting from pressure, temperature and energy-related hazards that cannot be avoided by design. Given the highly sensitive nature of handling cryogens, it is critical to highlight the specific hazards posed by this medium, particularly when it is used to transport and lift debris from the wellbore. Cryogenic substances, due to their extremely low temperatures, introduce a unique set of challenges in terms of safety, material integrity, and operational stability.

The second objective is to present scenarios of potential failures, which will help to understand the possible paths that failures might take, as well as to understand methods for mitigating associated risks. By analyzing and anticipating these scenarios, the aim is to reduce the likelihood of issues arising during the operation of the device. The analyses provided in the report delivers essential data for the design, construction, and operational phases, equipping teams with a detailed understanding of how to minimize operational risks. This comprehensive approach will support the DeepU cryogenic system's device's functionality with an emphasis on achieving the most reliable performance possible.

Conclusions:

Two failure modes have been identified as the worst-case scenarios:

- Cryogenic nitrogen flow to vacuum insulation
- Laser energy deposit on the pipe wall

These failure modes are highlighted as having a high likelihood of occurrence, with the potential to severely impact all systems within at least one module. Moreover, the consequences of those modes may include catastrophic damage to one or more drill string modules, potentially setting off a chain reaction that would activate other failure modes, leading to broader system failure.

It has been indicated that a thorough understanding of all process parameters plays a crucial role in minimizing risk, as this knowledge enables risk reduction at the design stage.

1. INTRODUCTION

Due to its extremely low temperature, cryogenic nitrogen is widely used in various industrial and scientific applications. However, handling this substance poses significant safety risks, making proper procedures essential to ensure the well-being of both on-site employees and external contractors. One of the primary objectives of this report is to identify and classify all potential failure modes resulting from pressure, temperature and energy-related hazards. Given the highly sensitive nature of handling cryogens, it is critical to highlight the specific hazards posed by this medium, particularly when it is used to transport and lift debris from the wellbore. Cryogenic substances, due to their extremely low temperatures, introduce a unique set of challenges in terms of safety, material integrity, and operational stability. To provide a more detailed understanding of these risks, selected calculations have been included in this report. These calculations illustrate key scenarios where the use of cryogenic nitrogen could present risks, helping to pinpoint the areas that require closer attention in subsequent project phases.

2. PRELIMINARY FAILURE MODE AND EFFECTS ANALYSIS OF THE LASER DRILL CRYOGENIC SYSTEM

Due to the early stage of the DeepU technology and the lack of input data required for quantitative risk analysis, Failure Mode and Effects Analysis (FMEA) of the laser drill cryogenic system has been applied. FMEA was developed in the late 1940s by US Military as a tool to improve the evaluation of reliability of equipment. This method was adopted by NASA for Apollo program and by Ford company, becoming a useful and well known project management tool. FMEA is a tool enabling potential errors or faults predicted during the early design stages. It provides a structured approach to the analysis of failure causes, the estimation of severity or impact, and the effectiveness of strategies for risk mitigation. The analysis is based on three fundamental questions that need be answered:

1. What could wrong (problem identification) ?
2. How badly it might go wrong ?
3. What needs to be done to prevent or mitigate the problem.

FMEA or FMECA (Failure Mode, Effects and Criticality Analysis) have been already used by Wroclaw University of Technology (WUST) to inspect safety of the LHC Cryogenic System [1, 2], the European Spallation Source (ESS) Cryogenic Distribution System for Eliptical Linac, ESS Cryogenic Distribution System for Lund Test Stand 2, ITER Cry distribution System [3] and underground liquid Ar transportation [4].

The aim of Deliverable D8.4 is to identify and classify all potential failure modes for the laser drill cryogenic system caused by the defect of the system component or external conditions. This document gives the analysis of possible causes, consequences and event scenarios for all recognized failure modes that cannot be avoided by design.

It must be emphasized that Deliverable D8.4 is a preliminary document that must be constantly updated with each design change in subsequent stages of the DeepU project.

2.1 LASER DRILL CRYOGENIC SYSTEM DESIGN

The drill string is divided into 12-meter segments (cryogenic modules) connected in series and one drill head (end module). All segments have the same design described in details in Deliverable D8.3.

The general concept of the drill string configuration and cryogenic module (one segment of drill string) is presented in Figure 2.1.

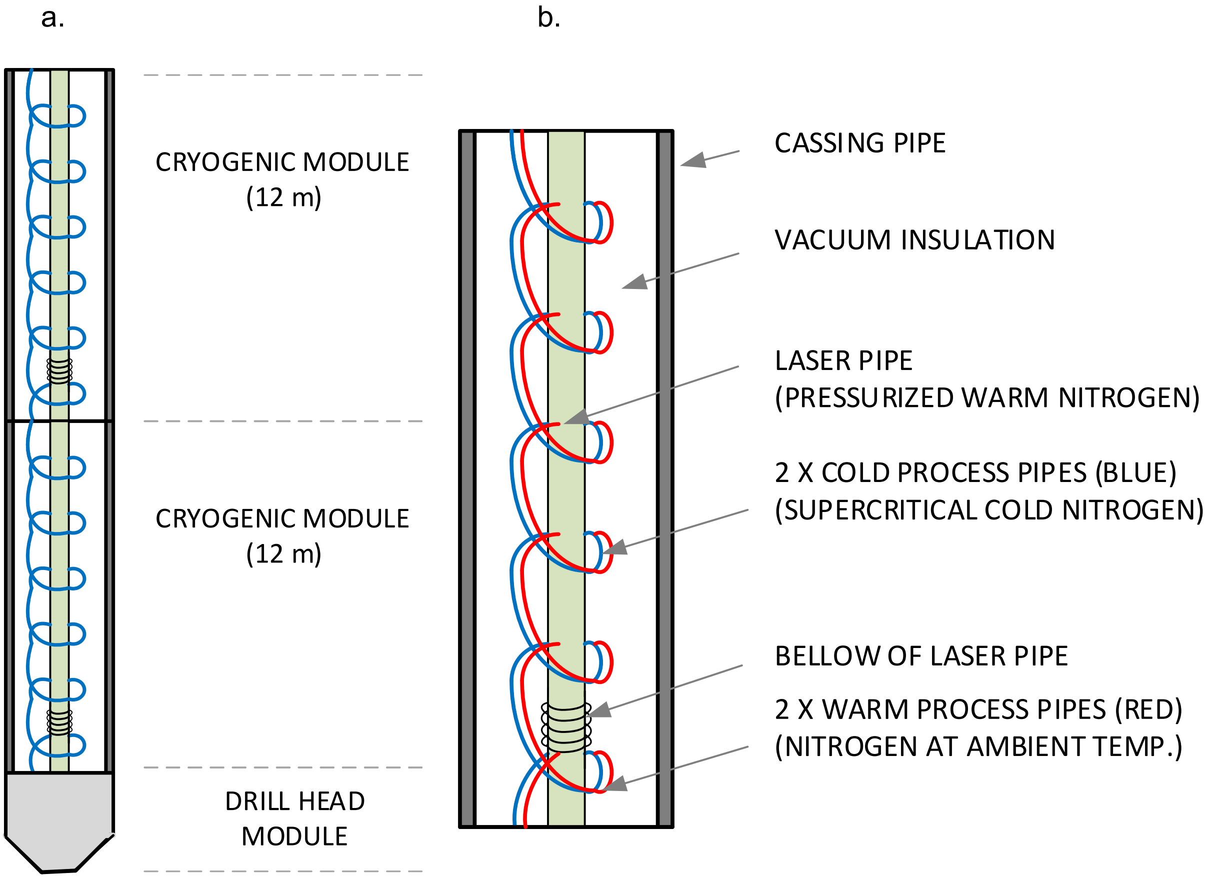

Figure 2.1. General concept of the drill string (a) and cryogenic module (b); casing pipe stands for outer drill string pipe

Each cryogenic module consists of the following elements:

1. Outer Drill String pipe Ø178.9 x 6.3 mm
2. Laser pipe DN50
3. Two cold process pipes DN15 (supply cryogenic gas down to the borehole)
4. Two warm process pipes DN15 (supply shield gas down to the borehole)

This document gives the risk assessment of the cryogenic module only (analysis of the drill head is not a part of Deliverable 8.4 therefore is not included in this document).

2.2 IDENTIFICATION OF THE POSSIBLE FAILURE MODES

The cryogenic-related failure mode of laser drill has been defined as the accident event involving nitrogen transfer between process pipes, vacuum insulation, laser pipe or casing pipe resulting from any system component defect, break or malfunctioning. Six cryogenic-related failure modes have been recognized and described.

CRYOGENIC FAILURE MODES

F1. Cryogenic nitrogen flow to vacuum insulation

Event resulting in cold nitrogen release to the vacuum space from damaged cryogenic process pipe or defect to any of its component.

F2. Gaseous (warm) nitrogen flow to vacuum insulation

Event resulting in warm nitrogen release to the vacuum space either from damaged process pipe (shield gas) or laser pipe.

F3. Contaminated nitrogen flow to vacuum insulation

Event resulting in nitrogen flowing to vacuum space due to outer drill string pipe damage.

F4. Cryogenic nitrogen flow from the module

Event resulting in cold/warm nitrogen release from process pipes due to non-tight interconnection of drill string modules.

F5. Electrical arc

Event resulting in drill string damage due to energy release and the high temperature generated by this phenomenon.

F6. Laser energy deposit on the pipe wall

Event resulting in damage of all systems (cryogenic, vacuum, shield gas, lenses) due to laser power. One or more drill string modules destroyed.

A non-cryogenic failure mode of the laser drill system has been defined as the accident event with no break/damage or malfunctioning of any component. However, this still could prevent the system from achieving the required parameters, such as drilled particles not being transported to the surface. Three non-cryogenic failure modes have been recognized and described.

NON-CRYOGENIC FAILURE MODES

F7. Ice blockage of process pipes during module assembly

Event resulting in the loss of process parameters due to blocking the flow of cold nitrogen.

F8. Heat load underestimation

Event resulting in the loss of process parameters due to external conditions.

F9. Mechanical blockage of pneumatic transport

Event resulting in the retention of the drilled particles inside a borehole.

2.3 RECOGNITION OF THE POTENTIAL CAUSES, CONSEQUENCES AND FAILURE SCENARIOS

The analysis has been performed to identify potential causes, physical consequences and the event scenarios of the failure modes. The results are presented in two Tables for each failure. Table 2.1 outlines potential causes together with the list of critical components whose defect/damage can lead to the failure. Table 2.2, provides details such as event scenario, potential consequences or risk mitigation actions.

F1. Cryogenic nitrogen flow to vacuum insulation

Table 2.1. Potential causes of failure F1.

Cause	System component	Potential reason
Pipe leak	2 process pipe (DN15) with nitrogen in cryogenic temperature	- material defect - pipe break due to thermal stress - pipe break during assembly
Non-return component* leak	TBD	- leak through the component body
Weld leak	Process pipe connection to upper/bottom plate Non-return component connection with process pipe	- poor quality weld - weld break due to thermal stress

*Non-return component (installed in the process pipe) prevents high-pressure nitrogen from being released during the drill string assembly. This component has not been designed yet.

Table 2.2 Summary of failure F1 details.

<table>
<tr><td>Failure code</td><td>F1. Cryogenic nitrogen flow to vacuum insulation</td><td>Actions required</td></tr>
<tr><td>Event scenario:</td><td>1. Cold and high-pressure nitrogen flows to the vacuum space of the module (pressure inside one module increases to the nitrogen process pressure at a specified depth – more details in point 3)
2. Loss of module vacuum insulation:
temperature inside the vacuum space of one module will first drop to the temperature of the released nitrogen and then will increase rapidly due to the environmental conditions
pressure inside the vacuum space will constantly increase due to the environmental conditions
3a Massive heat load to process pipes: temperature of nitrogen increases, gas expansion expected – nitrogen pressure significantly increases
3b Rapid cool down of the laser pipe and bellow (due to high mass flow rate of released cold nitrogen) than massive heat load) – temperature and pressure of nitrogen in laser pipe can increase</td><td>➢ nitrogen evacuation from the vacuum space of the module
➢ nitrogen evacuation from process pipes</td></tr>
<tr><td>Potential consequences:</td><td colspan="2">1. Drilling process/system stop
2. In case of inefficient evacuation of nitrogen from process pipe – pipe rupture due to excessive pressure
3. In case of inefficient evacuation of nitrogen from the module – module damage due to excessive pressure – all modules below can be disconnected
4. Laser pipe and / or laser pipe bellow break due to thermal stress or excessive pressure – in case of vacuum-powder insulation – contamination of the laser pipe - can result in damage to the lens system
5. Power/signal cables damage possible (loss of control signals from all modules below damaged module)</td></tr>
<tr><td>Risk mitigation actions:</td><td colspan="2">Design phase:
1. Analysis of using vacuum-powder insulation, attention: vacuum-powder insulation causes an additional risk to the lens system (further analysis required)
2. Pressurization of laser pipe with pure nitrogen (to avoid water vapor condensation / ice formation inside laser pipe in case of F1)</td></tr>
</table>

	3. Analysis of nitrogen evacuation from both module and process pipes 4. Analysis of lenses' resistance to temperature change Production phase (preliminary recommendations, to be completed in the next phase of the project): 1. High-quality materials for process pipes used (see Deliverable D8.3) 2. High-quality welds (e.g. company should be certified in conformity with ISO 3834) 3. Bellow (laser pipe) - high-quality material resistant to cryogenic temperature 4. Weld / bellow tests 5. Pressure tests of the cryogenic module

F2. Gaseous (warm) nitrogen flow to vacuum insulation

Table 2.3. Potential causes of failure F2.

Cause	System component	Potential reason
Pipe leak	2 process pipe (DN15) with shield gas (high-pressure nitrogen at ambient temperature) Laser pipe (pressurized nitrogen to a few bars, ambient temperature)	- material defect - pipe break during assembly
Bellow leak	One bellow (laser pipe)	- material defect - bellow break - mechanical damage
Non-return component leak	TBD	- leak through the component body
Weld leak	Process pipe connections to upper/bottom plate Bellow connections to laser pipe Non-return component connections with process pipe	- poor quality weld - weld break due to thermal stress

Table 2.4 Summary of failure F2 details.

<table>
<tr><td>Failure code</td><td>F2. Gaseous (warm) nitrogen flow to vacuum insulation</td><td>Actions required</td></tr>
<tr><td>Event scenario:</td><td><u>Failure caused by warm process pipe break:</u>
1. Warm and high-pressure nitrogen flows to the vacuum space of the module (pressure inside the module increases to the nitrogen process pressure at a specified depth)
2. Loss of module vacuum insulation:
<u>temperature</u> inside the vacuum space of one module will increase rapidly due to the environmental conditions
<u>pressure</u> inside the vacuum space will increase due to the environmental conditions
2a Massive heat load to cold process pipes: temperature of nitrogen increases, gas expansion expected – nitrogen pressure significantly increases
2b Massive heat load to the laser pipe – temperature and pressure of nitrogen in the laser pipe can increase (temperature in the borehole can exceed 200°C)

<u>Failure caused by laser pipe or bellow break:</u>
1. Warm nitrogen is sucked into the vacuum space of the module (pressure in the module increases to the nitrogen pressure inside the laser pipe) – gas flowing into the module can damage the lens mount
2. Loss of module vacuum insulation (temperature and pressure of nitrogen inside the vacuum space will increase due to environmental conditions)
3. Massive heat load to cold process pipes: temperature of nitrogen increases, gas expansion expected – nitrogen pressure significantly increases
4. Massive heat load to warm process pipes – temperature and pressure of warm nitrogen will increase (consequences covered by the consequences of event 3)</td><td>➢ nitrogen evacuation from the vacuum space of the module

➢ nitrogen evacuation from cold process pipes

➢ nitrogen evacuation from the vacuum space of the module

➢ nitrogen evacuation from cold process pipes</td></tr>
<tr><td>Potential consequences:</td><td colspan="2">1. Drilling process/system stop (shield gas lost)
2. In case of inefficient evacuation of nitrogen from process pipe – pipe rupture due to excessive pressure – F2 (warm process pipe break) can potentially cause F1</td></tr>
</table>

	3. Damage to the lenses due to high temperature – lens deformation – **F2 can potentially cause F6** 4. Damage to the lenses' mount due to high-speed gas flowing into vacuum space (laser pipe/bellow break) - **F2 can potentially cause F6**
Risk mitigation actions:	Design phase: 1. Analysis of using vacuum-powder insulation, attention: vacuum-powder insulation causes an additional risk to the lens system (see F1) 2. Analysis of nitrogen evacuation from cold process pipes 3. Analysis and tests of lenses' resistance to temperature change 4. Analysis and tests of lenses' mount (not designed yet) – it must be resistant to high-velocity gas flow Production phase (preliminary recommendations, to be completed in the next phase of the project): 1. High-quality materials and components (bellows, non-return) 2. High-quality welds 3. Weld / bellow tests 4. Pressure tests of the cryogenic module

F3. Contaminated nitrogen flow to vacuum insulation

Table 2.5. Potential causes of failure F3.

Cause	System component	Potential reason
Pipe break	Outer Drill String pipe (external diameter 178,9 mm)	- material defect - pipe break during assembly - mechanical damage by high-velocity drilled particles

Table 2.6 Summary of failure F3 details.

<table>
<tr><td>Failure code</td><td>F3. Contaminated nitrogen flow to vacuum insulation</td><td>Actions required</td></tr>
<tr><td>Event scenario:</td><td>1. High-temperature and high-pressure nitrogen contaminated with drilled particles flows to the vacuum space of the module (pressure inside the module increases to the pressure outside casing pipe at a specified depth)
2. Loss of module vacuum insulation:
<u>temperature</u> inside the vacuum space of one module will increase rapidly due to the environmental conditions
<u>pressure</u> inside the vacuum space will increase due to the environmental conditions
2a Massive heat load to cold process pipes: temperature of nitrogen increases, gas expansion expected – nitrogen pressure significantly increases
2b Massive heat load to warm process pipe – temperature and pressure of nitrogen in laser pipe can increase (consequences covered by the consequences of 3a)
2c Massive heat load to the laser pipe – temperature and pressure of nitrogen in the laser pipe can increase (temperature in the borehole can exceed 200°C)
3. Mechanical damage to process pipes inside one module is possible
4. Mechanical damage to power/signal cables</td><td>➢ nitrogen evacuation from the vacuum space of the module

➢ nitrogen evacuation from cold process pipes</td></tr>
<tr><td>Potential consequences:</td><td colspan="2">1. Drilling process/system stop
2. In case of inefficient evacuation of nitrogen from cold process pipe – pipe rupture due to excessive pressure – F3 can potentially cause F1
3. Mechanical damage to cold process pipe – F3 can potentially cause F1
4. Mechanical damage to warm process pipe – F3 can potentially cause F2
5. Mechanical damage to laser pipe – F3 can potentially cause F6
6. Loss of control signals (information from all modules below damaged module)</td></tr>
<tr><td>Risk mitigation actions:</td><td colspan="2">Design phase:
1. Analysis of nitrogen evacuation from cold process pipes
2. Analysis of pneumatic transport parameters in terms of the mechanical strength of the casing pipe (input data from D8.1 and D8.2)</td></tr>
</table>

	Production phase: to be completed in the next phase of the project

F4. Cryogenic nitrogen flow from the module

Table 2.7. Potential causes of failure F4.

Cause	System component	Potential reason
Gasket non-tight	Module gasket Process pipe gasket	- gasket material defect - human error during assembly (lack of gasket)
Misaligned connection	2 x DN15 cold process pipes (cryogenic gas) 2 x DN15 warm process pipes (shield gas) (consequences are covered by cold gas release)	- human error during assembly - poor quality module (production)

Table 2.8 Summary of failure F4 details.

Failure code	**F4. Cryogenic nitrogen flow from the module**	Actions required
Event scenario:	1. Cold nitrogen flow from the module 2. Cool down of the module material 3. Pneumatic transport disturbed	
Potential consequences:	1. Drilling process/system stop 2. Loss of cryogenic gas (required parameters at the bottom of borehole not met) 3. Loss of pneumatic transport (retention of drilled particles inside the borehole)	
Risk mitigation actions:	Design phase: 1. Experimental tests of proposed process pipe coupling 2. Experimental tests of module coupling (gasket tests) Production phase: to be completed in the next phase of the project	

F5. Electrical arc

In the preliminary design of the laser drill cryogenic system, part of the cold nitrogen stream was heated at the bottom of the borehole by an electrical heater. This idea has been replaced by two warm process pipes DN15 providing shield gas. However, we included the failure mode Electrical arc (F5) in the analysis due to the low TRL for this project and a possible change in design back to the previous concept.

Each module is equipped with an electrical feedthrough which may be a potential source of an electrical arc. In the case of high voltage, the consequences can be catastrophic as the electrical arc can destroy all systems (vacuum, cryogenic and laser). If the current design concept changes, further analysis of the electrical arc is required.

If electrical cables inside the cryogenic module are intended to provide control signals only (low voltage) and the connections described in Deliverable 8.3 remain unchanged, F5 can be omitted.

F6. Laser energy deposit on the pipe wall

Table 2.9. General information about failure F6.

Failure code	**F6. Laser energy strike on the pipe wall**
Event causes:	1. The drilled well is never completely straight 2. Lenses' position misaligned
Event scenario:	1. Laser beam damages one or more cryogenic modules 2. Loss of vacuum in all damaged modules 3. Cold and warm process pipe(s) rupture 4. Laser pipe rupture
Potential consequences:	1. Catastrophic – all systems (vacuum, cryogenic, laser) in one or more cryogenic modules damaged **2. F6 can potentially cause F1, F2, F3 and F4 at the same time**
Risk mitigation:	This failure mode requires detailed analysis together with the laser/optic team in the next phases of the project.

F7. Ice blockage of process pipes during module assembly

Table 2.10. General information about failure F7.

Failure code	**F7. Ice blockage of process pipes during module assembly**
Event causes:	Installing another cryogenic module requires disconnecting the already installed module from the cryogenic supply system. Therefore, all process pipes are open for a short time. Cold process pipes operate at cryogenic temperatures, so ice formation occurs immediately.
Event scenario:	1. Disconnecting the already installed module from the cryogenic supply system 2. Ice formation at the cold process pipes 3. Connection of another cryomodule – blocking the supply of cryogenic nitrogen
Potential consequences:	1. Loss of process parameters required for pneumatic transport 2. Retention of the drilled particles inside the borehole 3. Drilling process / system stop

F8. Heat load underestimation

Table 2.11. General information about failure F8.

Failure code	**F8. Heat load underestimation**
Event causes:	Lack of input data for the analysis of heat load along the borehole. Further detailed analysis required
Potential consequences:	1. System works 2. Loss of process parameters required for pneumatic transport 3. Retention of the drilled particles inside the borehole 4. Drilling process / system stop

F9. Mechanical blockage of pneumatic transport

Table 2.12. General information about failure F9.

Failure code	**F9. Mechanical blockage of pneumatic transport**
Event causes:	1. The drilled well is never completely straight 2. Drilled particles larger / heavier than expected 3. Process parameters required for pneumatic transport not met
Potential consequences:	1. Retention of the drilled particles inside the borehole 2. Drilling process / system stop

2.4 CLASSIFICATION OF THE CRYOGENIC-RELATED FAILURE MODES

The classification of the failure modes has been presented in Table 2.13. The DeepU project is at an early stage of development. Therefore, the failure mode classification is limited to the quality-based comparison of the probability of potential causes and the severity of consequences.

Failure mode	Potential cause	Probability	The most severe consequence	Impact to	Module destruction	Chain of failure modes
F1. Cryogenic nitrogen flow to vacuum insulation	Cold process pipe break (DN15)	LIKELY	Module destruction	Cryogenic system Vacuum system Pneumatic transport	POSSIBLE due to high-pressure	NA
F2. Gaseous (warm) nitrogen flow to vacuum insulation	Warm process pipe break (DN15)	LIKELY	Vacuum loss Lenses damage	Cryogenic system Vacuum system Optic system	F2 NO If F2 → F1 POSSIBLE	F2 → F1 F2 → F6
F3. Contaminated nitrogen flow to vacuum insulation	Outer drill string pipe break	UNLIKELY	Vacuum loss	Cryogenic system Vacuum system	F3 NO If chain reaction POSSIBLE	F3 → F1 F3 → F2 → F1 F3 → F6
F4. Cryogenic nitrogen flow from the module	Assembly error	HIGHLY LIKELY	Cryogen loss Pneumtic transport stop	Cryogenic system Pneumatic transport	NO	NA
F5. Electrical arc (only if the electrical heater is in the borehole)	Poor-quality cable connection	LIKELY	Module destruction	All systems	POSSIBLE due to energy released	NA
F6. Laser energy deposit on the pipe wall	Lenses misaligned Borehole not straight	HIGHLY LIKELY	One or more modules destroyed	All systems in one or more modules	POSSIBLE	F6 → F1/F2/F3/F4 (at the same time)
F7. Ice blockage of process pipe	Assembly error	HIGHLY LIKELY	Pneumatic transport stop	Pneumatic transport	NO	NA
F8. Heat load underestimation	Incorrect analysis during the design phase	LIKELY	Pneumatic transport stop	Pneumatic transport	NO	NA
F9. Mechanical blockage of pneumatic transport	Loss of process parameters Drilled particles size	HIGHLY LIKELY	Pneumatic transport stop	Pneumatic transport	NO	NA

Failure mode F6. Laser energy deposit on the pipe wall has been recognized as the worst-case scenario. This is a failure mode identified as a high-probability mode, the occurrence of which will impact all systems of at least one module. Additionally, its consequence may include the destruction of at least one drill string module and the initiation of a chain reaction that triggers failure modes F1 to F4. However, F6 may occur due to a malfunction of the laser/optic system, so F1. Cryogenic nitrogen flow to vacuum insulation has been pointed out as the worst-case scenario caused by the cryogenic system component. The release of cryogenic nitrogen in the vacuum space caused by the rupture of a cold process pipe may, in extreme cases, lead to the destruction of the module as a result of a pressure explosion.

To accurately identify all risks and effectively mitigate them, it is essential to understand both the nitrogen parameters inside the process pipes and how these parameters are impacted by initial conditions and the heat influx. Chapter 3 gives the thermodynamic analysis of cryogenic nitrogen supplying laser drill string.

3. IMPACT OF INITIAL NITROGEN CONDITIONS ON ITS PARAMETERS IN THE PROCESS PIPE

It is essential to understand the thermodynamic conditions of nitrogen at the inlet to the drill string, at its outlet at the bottom of the well, and at every intermediate height. This is important because it is necessary to ensure that at no stage of the transmission will parameters exceed those causing excessive stresses or transmission blockages. To address this, flow and thermodynamic calculations have been prepared.

The main parameters of the gas are temperature and pressure. Based on these, as well as on the geometry of the pipeline and the required mass flow rate, any parameter characterizing the state of the gas can be determined. During the flow of gas through the drill string down the well, changes in nitrogen temperature and pressure occur, which are the result of a combination of effects acting on this gas in the process conditions. Examples of such effects include heat inflow, pneumatic resistance, and height difference.

To perform the calculations, the entire pipeline was divided into computational sections. Each of these sections corresponds to a certain specified length L of the pipeline. The length of the computational section can be adjusted depending on the required accuracy of the calculations. For the initial calculations, the length of the computational section L was set to 10 meters.

3.1. EQUATIONS FOR PRESSURE DROP CALCULATION

Cryogenic nitrogen transfer through the process pipe along the drill string will result in pressure fluctuations . These changes are caused by various factors, including temperature variations, frictional losses, and potential phase transitions of nitrogen as it moves through the system. The cryogenic nature of nitrogen introduces a significant temperature difference between the gas and the surrounding environment, which can lead to pressure drops. The formulas used to calculate the pressure drops in each L-meter section of the process pipe are presented below.

The pressure drop Δp along the flow in the drill string process pipe was determined as the sum of four effects:

1. pressure change caused by linear losses – Δp_l,
2. pressure change caused by dynamic losses – Δp_d,
3. pressure change caused by an increase in depth – Δp_h,
4. pressure change caused by an increase in temperature – Δp_T,

The pressure change Δp is the pressure change in a given L-meter-long section. It can be expressed using the equation (3.1.1).

$$\Delta p = \Delta p_l + \Delta p_d + \Delta p_h + \Delta p_T \tag{3.1.1}$$

The pressure change caused by linear losses Δp_l refers to the gradual change in pressure as gas flows through the pipeline due to frictional forces between the gas and the internal surface of the pipe. It is always positive in value meaning that it always causes the decrease of the pressure along the pipe.

The pressure drop Δp_l can be expressed using the equation (3.1.2).

$$\Delta p_l = \lambda \frac{L}{D} \rho \frac{v^2}{2} \tag{3.1.2}$$

where:

λ – linear pressure drop coefficient, dimensionless

L – length, m

D – Internal diameter of process pipe, m

ρ – density, kg/m^3

v – gas velocity, m/s

The linear pressure drop coefficient λ is calculated using the Haaland equation (3.1.3) [1]:

$$\lambda = \frac{1}{\left(-1.8\, log_{10}\left(\left(\frac{k}{3.7D}\right)^{1.11} + \frac{6.9}{Re}\right)\right)^2} \tag{3.1.3}$$

where:

k – the pipe roughness, m, assumed = 45 μm

Re – Reynolds number, dimensionless

The Reynolds number is calculated using the following equation:

$$Re = \frac{\rho \cdot v \cdot D}{\mu} \tag{3.1.4}$$

where:

μ – dynamic viscosity of the fluid, Pa.s

The fluid velocity v in the process pipe can be calculated using the following equation:

$$v = \frac{W}{\rho\left(\pi \frac{D^2}{4}\right)} \tag{3.1.5}$$

where:

W – gas mass stream, kg/s

The pressure change caused by dynamic losses Δp_d refers to the pressure change due to the loss (or gain) of the momentum of the gas. The change in the momentum is caused by the thermal expansion of the nitrogen, and indicated by the change in the density and velocity of the gas. The pressure change Δp_d can be positive or negative in value. The positive value refers to the pressure drop, the negative value refers to the pressure gain.

The pressure change Δp_d can be expressed using the equation (3.1.6).

$$\Delta p_d = \rho_{n-1} \frac{v_{n-1}^2}{2} - \rho_n \frac{v_n^2}{2} \tag{3.1.6}$$

where subscripts:

$_{n-1}$ – refers to the previous computational section

$_n$ – refers to the current computational section

The pressure change caused by the increase in depth Δp_h refers to the pressure change in the nitrogen stream due to the elevation change. As the calculation is made from the ground level downwards, and the depth increases, the Δp_h has always a negative value. The negative value means, that the increase of depth always causes the pressure increase.

The value of the Δp_h can be expressed using the equation (3.1.7).

$$\Delta p_h = \rho_{n-1} g h_{n-1} - \rho_n g h_n \tag{3.1.7}$$

where:

g – gravitational acceleration constant, m/s^2

h – depth of given computational section, m (always positive)

The pressure change Δp_T refers to the pressure change in the nitrogen stream due to the temperature change caused by the thermal loads to the nitrogen stream. The Δp_T can have a negative or positive value. Normally as the temperature of the gas increases along the process pipe, the Δp_T value is negative (pressure increase).

The value of the Δp_T can be devied using the van der Waals equation (3.1.8).

$$\left(P + n^2 \frac{a}{V}\right)(V - nb) = nRT \tag{3.1.8}$$

where:

P – pressure, Pa

a – attraction constant, Pa·m^6/mol^2

b – molar volume, m^3/mol

n – mole quantity, moles

V – volume, m^3

R – universal gas constant, J/molK

T – temperature, K

Taking into account that the calculation volume V does not change as it refers to the volume of the pipe at the calculation length L, but the temperature and the amount of gas (moles) dues change, the derived equation can be represented by the equation 3.1.9.

$$\Delta p_T = \frac{n_{n-1}RT_{n-1}}{V-n_{n-1}b} - \frac{n_nRT_n}{V-n_{n-1}b} - \frac{a}{V^2}(n_{n-1}^2 - n_n^2) \quad (3.1.9)$$

The shown pressure drop Δp is the pressure change determined for each L-meter calculation section of the process pipe. To calculate the total pressure drop, all pressure drops over the entire length of the pipe should be summed.

3.2. EQUATIONS FOR TEMPERATURE CHANGE CALCULATIONS

The flow of cryogenic nitrogen through the process pipe also causes temperature changes. In most cases, there is an increase in temperature caused by both heat influx and pressure changes. Due to the cryogenic properties of the gas, in certain cases, the gas temperature may decrease in the event of throttling. The formulas used to determine temperature changes at each point along the process pipe are presented below. These formulas apply to every L-meter section of the pipe.

The temperature drop ΔT along the flow in the drill string process pipe was determined as the temperature change caused by the thermal load.

Temperature change in the gas due to heat influx (thermal load) is related to the temperature difference between the cryogenic nitrogen and the surrounding environment. Despite the use of high-quality insulation, some heat transfer from the environment to the nitrogen is unavoidable. This is caused by thermal bridges, which are inevitable due to the need to ensure the integrity and strength of the equipment. An additional factor increasing heat influx is thermal radiation.

The temperature change due to heat influx ΔT can be calculated using equation (3.2.1).

$$\Delta T = \frac{QA}{\dot{m}C_p} \quad (3.2.1)$$

where:

Q – Average thermal load per unit area, W/m^2

$\dot{m}$ – mass stream of the nitrogen, kg/s

C_p – specific heat capacity of nitrogen, J/kgK

3.3. BOUNDARY CONDITIONS AND ASSUMPTIONS

The formulas shown in the preceding sections serve as the foundation for calculating the thermodynamic properties of nitrogen at each depth within the process pipe. These equations allow us to check how pressure, temperature, and thus the other relevant parameters change as nitrogen moves through the system. However, given the current early stage of the project, not all necessary data points are available. As a result, many of the parameters used in these calculations need to be approximated by either averaging existing data or making informed assumptions. This is an inherent challenge when working with preliminary designs, where certain conditions and variables are not yet entirely defined. Nevertheless, these approximations are essential to move forward with the analysis and gain valuable insights at this stage.

The nitrogen intended for delivery to the bottom of the well must be maintained in cryogenic conditions to meet the operational requirements. This includes ensuring an adequate mass flow rate to perform two crucial functions: first, to protect the laser equipment from overheating or damage during operation, and second, to facilitate the removal of debris generated by the drilling process. The parameters required to achieve these objectives will naturally fluctuate depending on the specific depth of the well, as deeper sections may present different thermal and pressure conditions compared to shallower areas.

In order to more accurately highlight the hazards of using cryogenic nitrogen as a lifting medium for for the drilled borehole material, selected calculations have been presented in this report to identify the risks associated with cryogen transfer., d to Therefore, the following preliminary assumptions for the calculations have been adopted:

- depth of the borehole – 5 000 m
- the initial temperature of nitrogen – 80 K
- the initial pressure of nitrogen – 35 bara
- minimal pressure on the bottom of the pipe before exiting from process pipes, 40 bara
- mass stream of nitrogen through a single process pipe – 0.3 kg/s
- average heat inflow to the nitrogen – 200 W/m^2
- internal diameter of process pipe – 15 mm

The above computational assumptions are not intended to precisely replicate the actual geometry of the system. The purpose of the calculations is to indicate how the initial conditions of nitrogen (temperature, pressure, and mass flow), the diameter of the process pipes, and heat inputs affect the thermodynamic state of nitrogen at various depths.

The analysis focuses on the nitrogen parameters within the process pipe. All temperature and pressure calculations are aimed at determining the state of the nitrogen at various levels inside the pipe, providing detailed insights into its conditions throughout the length of the pipe. These calculations, however, are not intended to predict the nitrogen parameters after it exits the process pipe into the wellbore through the outlet nozzles.

During the calculations, individual parameters were varied around the assumed baseline values to examine how fluctuations in specific variables affect the condition of the gas within the process pipe.

3.4. CALCULATION RESULTS

The calculations showing the state of nitrogen at different depths, based on the assumptions from section 3.3, are presented in Table 3.4.1 and illustrated in Figure 3.4.1. The arrow in Figure 3.4.1 highlights the changes in nitrogen parameters during its flow through the system. It's important to note that these calculations are focused on nitrogen inside the process pipe, and do not cover the process of nitrogen escaping into the wellbore space.

Tab. 3.4.1. State of nitrogen at different depths, based on the basic assumptions.

Depth	flow	temp	temp	pressure	density	velocity	Q
m	kg/s	K	°C	bar(a)	kg/m3	m/s	W/m2
0	0.30	80.0	-193.15	35.0	803.0	2.11	200
500	0.30	87.8	-185.36	61.2	775.7	2.19	200
1000	0.30	95.6	-177.58	88.1	749.4	2.27	200
1500	0.30	103.4	-169.79	114.7	724.1	2.34	200
2000	0.30	111.2	-161.98	141.0	699.9	2.43	200
2500	0.30	119.0	-154.11	166.7	677.0	2.51	200
3000	0.30	127.0	-146.16	191.8	655.3	2.59	200
3500	0.30	135.0	-138.10	216.3	634.9	2.67	200
4000	0.30	143.2	-129.91	240.0	615.8	2.76	200
4500	0.30	151.6	-121.54	263.1	597.9	2.84	200
5000	0.30	160.2	-112.99	285.5	581.0	2.92	200

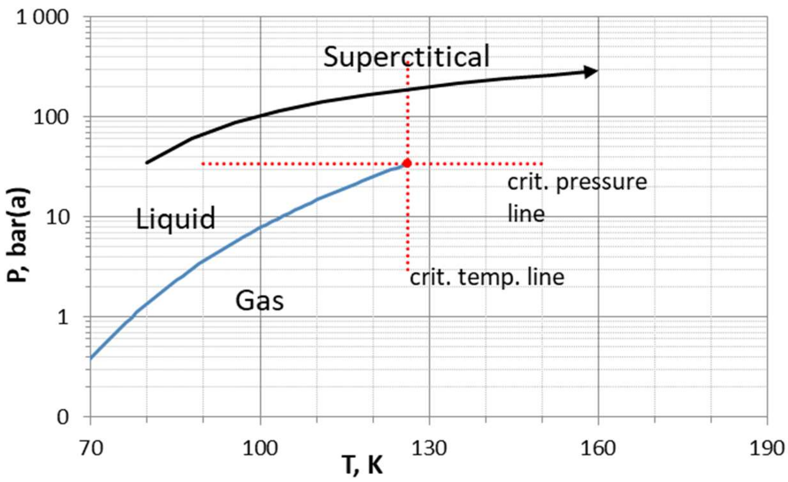

Fig. 3.4.1. State of nitrogen during the flow through the process pipe, based on the basic assumptions.

The results indicate that as nitrogen flows down the process pipe deeper into the well, both its temperature and pressure increase. The temperature rise is the result of heat inputs, which cause a gradual transfer of heat to the nitrogen. The increase in pressure is attributed to the dominance of hydrostatic pressure and the pressure increase due to heat load over the flow resistance within the pipe. It is worth noting that under the conditions presented, the pressure at the bottom of the process pipe can reach as high as 285 bar. This leads to the risk of the drill string rupturing. Under normal conditions, elevated pressure at the bottom of the process pipe will result in a greater outflow of nitrogen (a higher mass flow rate), which will automatically reduce the pressure. However, in the event of any blockage in the outlet channel restricting the gas flow into the wellbore, one must account for the danger of excessive pressure buildup.

After exceeding certain thermodynamic parameters, the density of nitrogen can decrease to a point where the pressure drops related to flow exceed the increase related to hydrostatic pressure or thermal compression.

This phenomenon is better illustrated in Table 3.4.2 and Figure 3.4.2, where the heat inputs to the nitrogen are increased to 400 W/m².

Tab. 3.4.2. State of nitrogen at different depths, for increased heat inflow.

Depth m	flow kg/s	temp K	temp °C	pressure bar(a)	density kg/m3	velocity m/s	Q W/m2
0	0.30	80.0	-193.15	35.0	803.0	2.11	400
500	0.30	95.4	-177.71	64.2	741.4	2.29	400
1000	0.30	110.5	-162.68	92.5	679.6	2.50	400
1500	0.30	125.0	-148.13	117.7	618.4	2.75	400
2000	0.30	139.2	-133.95	138.8	558.8	3.04	400
2500	0.30	153.3	-119.83	155.1	500.8	3.39	400
3000	0.30	167.8	-105.32	166.1	443.9	3.82	400
3500	0.30	183.2	-89.97	170.8	386.6	4.39	400
4000	0.30	199.8	-73.31	167.8	326.9	5.19	400
4500	0.30	218.3	-54.84	153.7	261.1	6.50	400
5000	0.30	239.2	-33.92	120.2	179.5	9.46	400

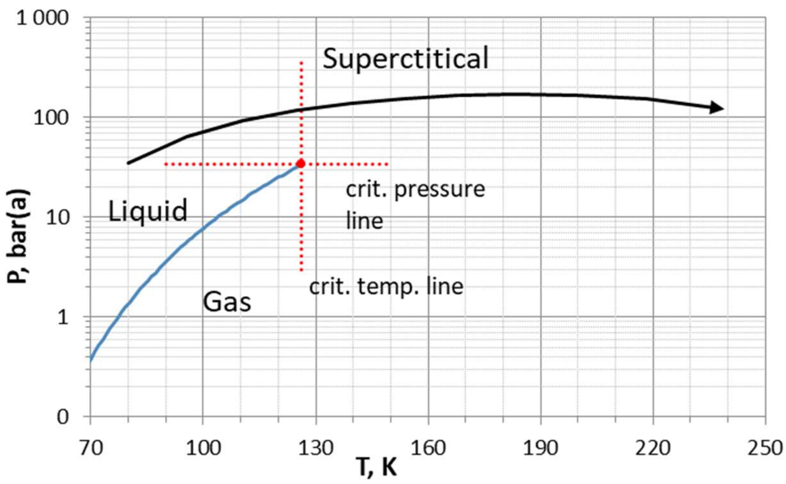

Fig. 3.4.2. State of nitrogen during the flow through the process pipe, for increased heat inflow.

Both Table 3.4.2 and Figure 3.4.2 clearly show a decline in nitrogen pressure after it crosses the point where the pressure drops related to flow exceed the increase related to the hydrostatic pressure and thermal compression.

If the borehole reaches excessive depths or if there are unexpectedly high heat inflows, the gas pressure might drop to such a low level that maintaining the intended mass flow rate becomes unfeasible. Elevated heat inflows could arise from various factors, including unexpectedly high temperatures of the surrounding rock formations outside the drill string, as well as accidental damage to the thermal insulation.

A similar effect to the increase of heat load gives the increased mass flow. Table 3.4.3 and Figure 3.4.3, show the nitrogen parameters for the mass flow increased (in comparison to the base assumptions) to 0,4 kg/s.

Tab. 3.4.3. State of nitrogen at different depths, for increased mass flow.

Depth	flow	temp	temp	pressure	density	velocity	Q

m	kg/s	K	°C	bar(a)	kg/m3	m/s	W/m2
0	0.40	80.0	-193.15	35.0	803.0	2.82	200
500	0.40	85.8	-187.32	47.7	780.5	2.90	200
1000	0.40	91.6	-181.53	59.3	757.6	2.99	200
1500	0.40	97.4	-175.78	69.4	734.2	3.08	200
2000	0.40	103.0	-170.11	77.6	709.9	3.19	200
2500	0.40	108.6	-164.53	83.7	684.4	3.31	200
3000	0.40	114.1	-159.08	87.2	657.1	3.44	200
3500	0.40	119.4	-153.80	87.5	626.9	3.61	200
4000	0.40	124.4	-148.78	84.1	591.4	3.83	200
4500	0.40	129.0	-144.18	75.5	545.1	4.15	200
5000	0.40	132.7	-140.44	58.2	457.3	4.95	200

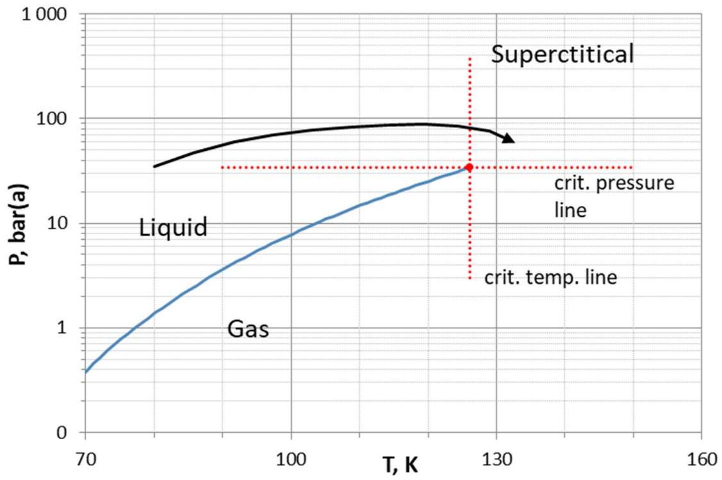

Fig. 3.4.3. State of nitrogen during the flow through the process pipe, for increased mass flow.

Figure 3.4.3 and Table 3.4.3 clearly show that the further increase of the mass stream can cause the pressure on the bottom of the process pipe to be lower than the assumed 40 bar. As a result, maintaining an increased mass flow rate may prove to be impossible.

The additional analysis was performed to assess how the nitrogen parameters at the process pipe's inlet influence the conditions at the lower sections of the pipe, just before the nitrogen flows into the wellbore space. The study examines variations in both temperature and pressure as the gas moves through the pipe. The figures provided below (Figure 3.4.4. and Figure 3.4.5.) give a visual representation of how the initial temperature and pressure of the nitrogen affect the evolution of its properties along the full length of the process pipe, helping to illustrate the trends and changes observed at different stages.

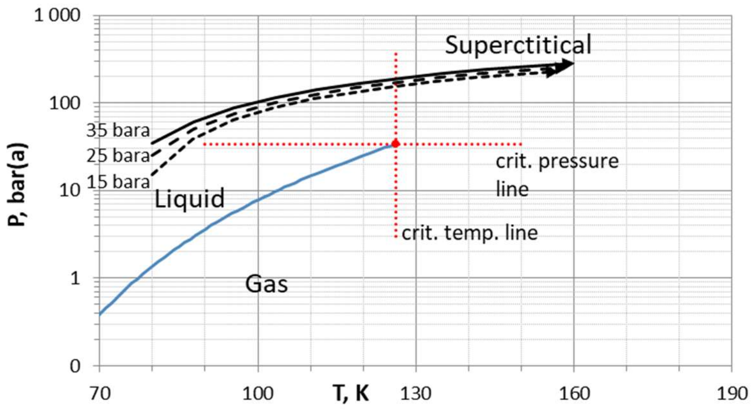

Fig. 3.4.4. Influence of the initial pressure on the parameters of nitrogen.

As shown in Figure 3.3.4, the initial pressure of nitrogen does not significantly impact the nitrogen parameters inside the process pipe. The calculations revealed a relationship where lower initial pressure leads to slightly lower final pressure and temperature, but the variations are minimal. Regardless of the initial pressure, nitrogen at the bottom of the well remained in a supercritical state. This suggests that whether nitrogen is introduced in liquid or supercritical form, the parameters at the bottom of the well will be similar. Liquid nitrogen, however, carries the risk of sudden vaporization and a rapid increase in volume (in cases of uncontrolled heat influx or flow stoppage), which presents a danger of explosion. Considering this, it is recommended to use nitrogen in its supercritical state, which eliminates this risk.

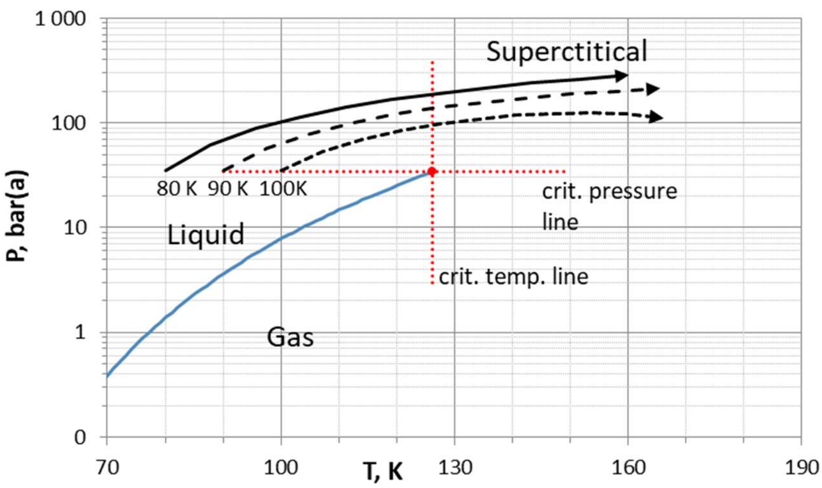

Fig. 3.4.5. Influence of the initial temperature on the parameters of nitrogen.

The effect of the initial temperature of the nitrogen, as demonstrated in Figure 3.3.5, on nitrogen parameters at each depth is significant. Higher initial temperatures result in a lower nitrogen density, which consequently increases the resistance to flow. This increased resistance leads to a drop in nitrogen pressure along the length of the pipe. While this pressure reduction might seem manageable, the real concern lies in the potential for excessive heating of the gas before it reaches the bottom of the well. When nitrogen is introduced at a higher temperature, it risks absorbing too much heat from the surrounding environment, particularly in deep wells or high heat flow geological conditions where temperatures can rise significantly. This overheating could lead to operational challenges, such as diminished control over nitrogen flow or even a failure to maintain the desired temperature or pressure levels.

Given these factors, it is clear that the initial temperature has a substantial impact on both the flow dynamics and the overall safety of nitrogen use in the process pipe. To ensure safe and efficient operation under these conditions, a detailed thermodynamic analysis is not only recommended but necessary. Such an analysis would allow for a thorough understanding of how nitrogen behaves at various stages, helping to mitigate risks and optimize performance. Furthermore, this analysis must be carried out in conjunction with the finalized design of the process pipe and the operational parameters of the drill string, ensuring that all aspects of the system work harmoniously to achieve the required safety and efficiency standards.

4. CONCLUSIONS

This document presents the preliminary risk assessment of the laser drill cryogenic system. This assessment identifies and evaluates failure modes associated with both the cryogenic system and other non-cryogenic factors for the drill string. Each failure mode is analyzed comprehensively, focusing on potential causes and possible consequences. For each identified failure mode, specific preventive actions are recommended that should be taken to mitigate this risk during the design, production, and operation phases. In addition to individual mode assessments, the analysis identifies causal links between various failure modes, revealing potential chain reactions that could occur in the event of an operational failure.

Two failure modes have been identified as the worst-case scenarios: cryogenic nitrogen flow to vacuum insulation (F1) and laser energy deposit on the pipe wall (F6). These failure modes are highlighted as having a high likelihood of occurrence, with the potential to severely impact all systems within at least one module. Moreover, the consequences of mode F6 may include catastrophic damage to one or more drill string modules, potentially setting off a chain reaction that would activate failure modes F1 through F4, leading to broader system failure.

It has been indicated that a thorough understanding of all process parameters plays a crucial role in minimizing risk, as this knowledge enables risk reduction at the design stage.

The presented risk analysis should be updated in case of any major changes in the system design and/or gathering of experimental exploitation data.

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