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Deep U-tube heat exchanger breakthrough: combining laser and cryogenic gas for geothermal energy exploitation

Laser drill cryogenic system

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Agenda

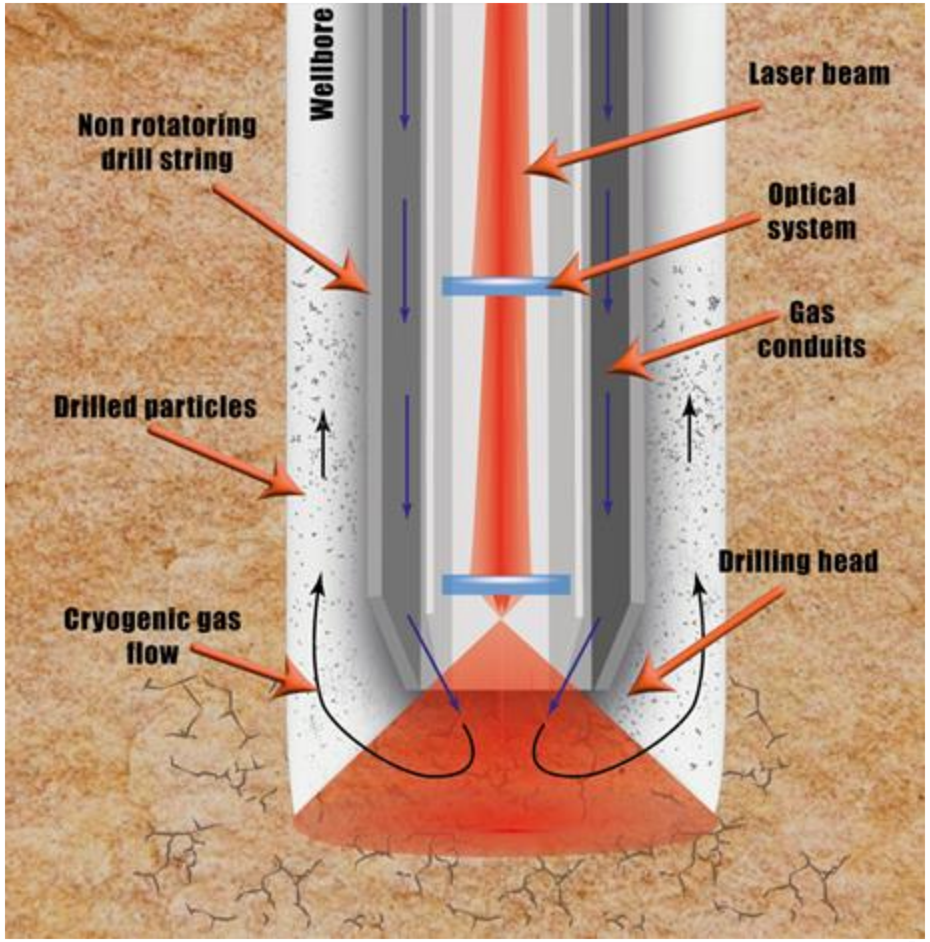
- Flushing cryogen analysis
- Process requirements
- Cryogenic supply system
- Mechanical design for a low temperature system
- Risk assessment of a cryogenic system
- Conclusions

Cryogen as flushing for deep drilling

The role of the cryogen is to transport rock cuttings to the surface, remove excess heat and protect the lens housed within the drill head.

Due to the pressures reaching hundreds of bars and temperatures in the range of thousands of degrees present at the bottom of the borehole, water-based agents are not a suitable option, primarily because of the associated safety risks. In addition, thermodynamic stability, heat transfer capabilities, and economic feasibility must all be carefully considered.

Cryogenic nitrogen has been chosen as the most suitable candidate for the flushing medium.



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Basic properties of nitrogen

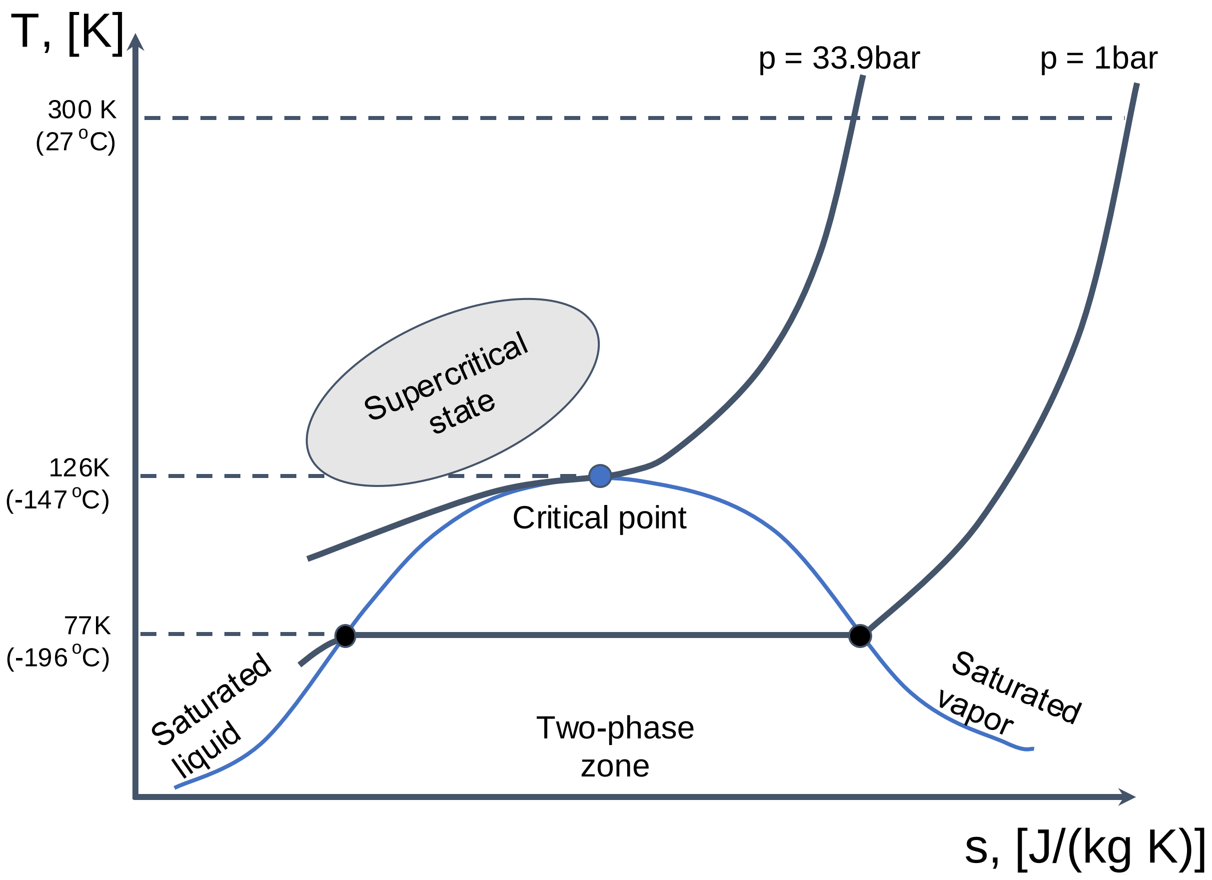
Nitrogen is inert, non-toxic, and non-flammable, making it an excellent flushing medium.

It meets key thermodynamic criteria:

- high density to limit velocity and pressure loss,
- high pressure at the bottom of the borehole for effective cuttings transport,
- low temperature for effective heat transfer.

Liquid nitrogen was initially considered due to its cooling potential from phase change, but uncontrollable phase change along the supply channel made it impractical and challenging.

Supercritical nitrogen was proposed, since it meets all requirements and simplifies the system through single-phase flow along the whole channel.



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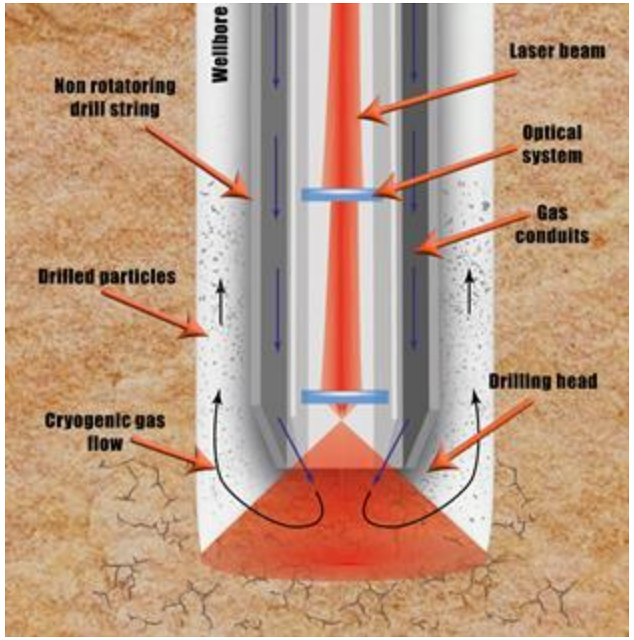
Process requirements

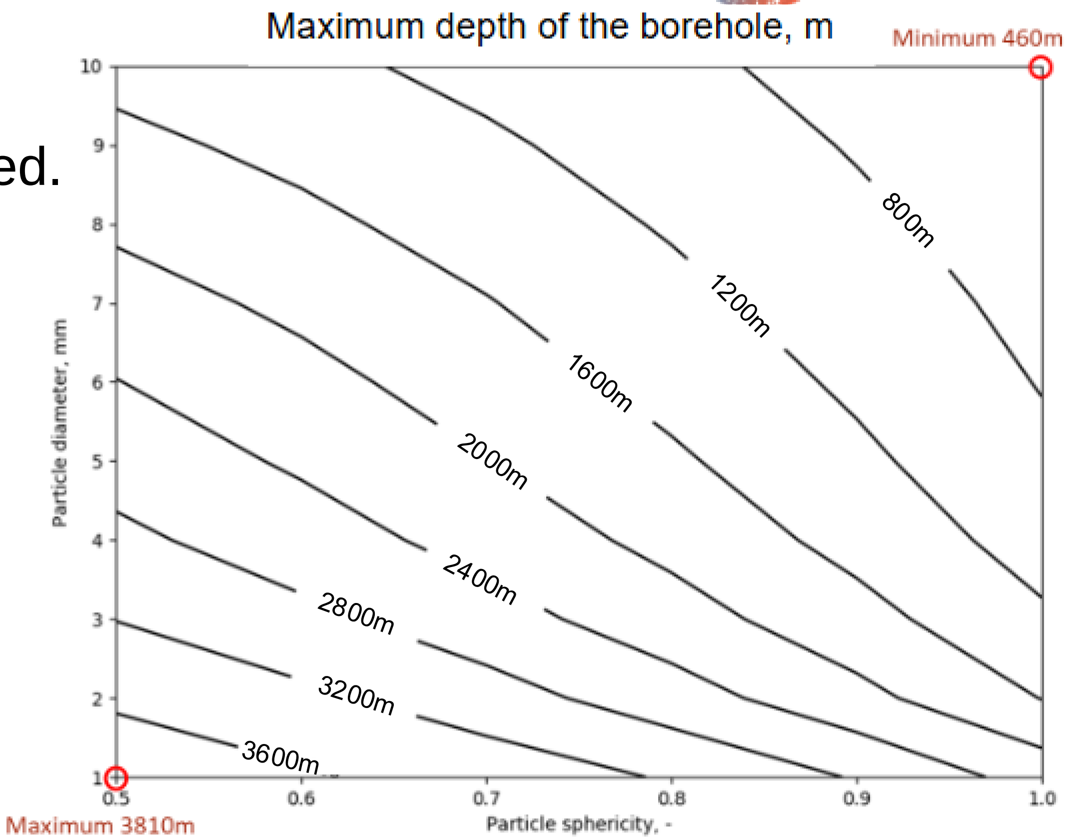
To clean the borehole of spalled or melted and resolidified cuttings, a sufficient flow rate of working gas must be supplied.

As borehole depths reach several kilometers, pressure losses in both the supply line and the return canal may become a limiting factor for deeper operation if the pressure at the bottom is to be limited.

The required flow rate depends on several factors:

- Shape, size and density of the drilled particles
- Borehole depth, diameter, and annulus area
- Thermodynamic state of the flushing gas





Assumption: pressure at the bottom limited to 30 bar(a). Higher allowable pressures enables deeper boreholes.

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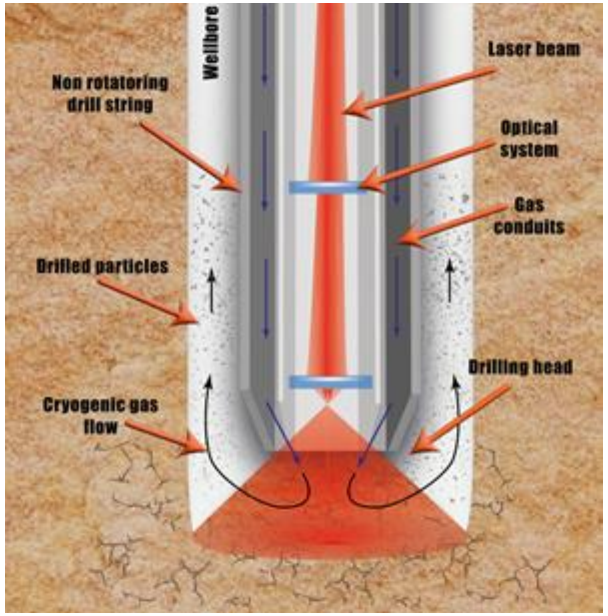
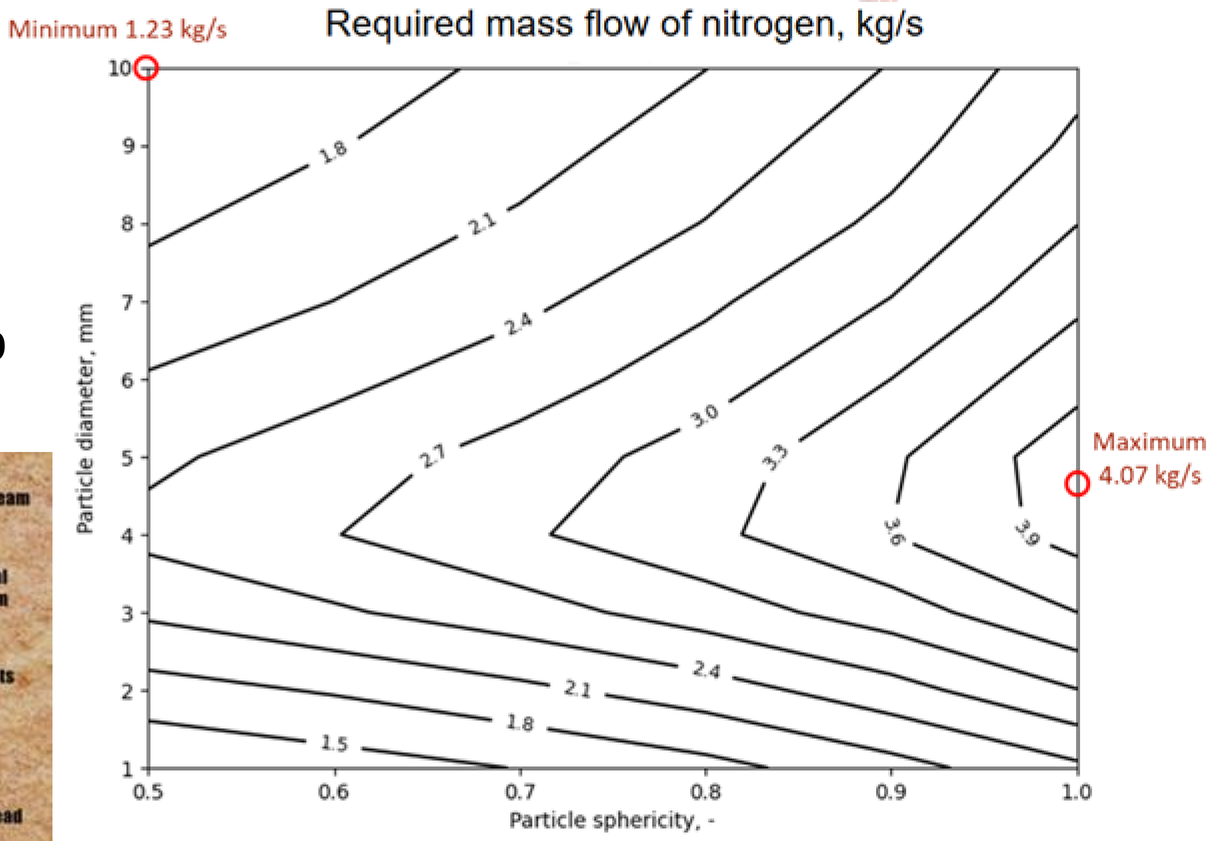
Process requirements

Since the mass flow rate required for pneumatic transport is the highest, meeting it also ensures sufficient cooling and effective lens protection.

Laser pipe severely limits the space available for the supply lines. Fluid with sufficient density is required to provide necessary flow rates at depths reaching over 4000m.

N_2 supercritical state is essential to maintain an adequate mass flow rate despite significant pressure drops in small process pipes and to prevent the formation of two-phase flow.





Assumption: pressure at the bottom limited to 30 bar(a). Higher allowable pressures require even higher mass flow rates.

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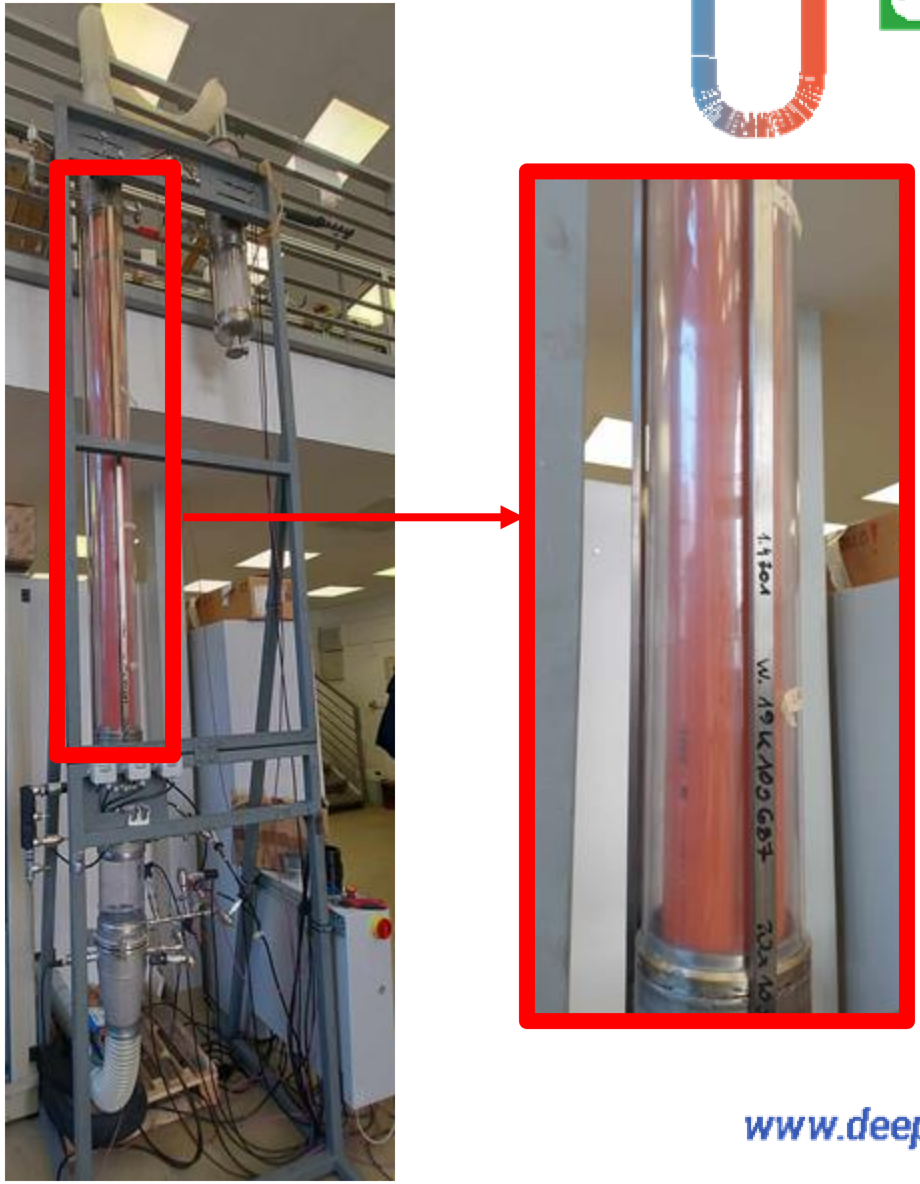
Model validation

Tests of pneumatic transport within the borehole geometry are being carried out within a defined range of parameters derived from the developed model.

The purpose is to ensure the model's accuracy and reliability by validating it against experimental results.



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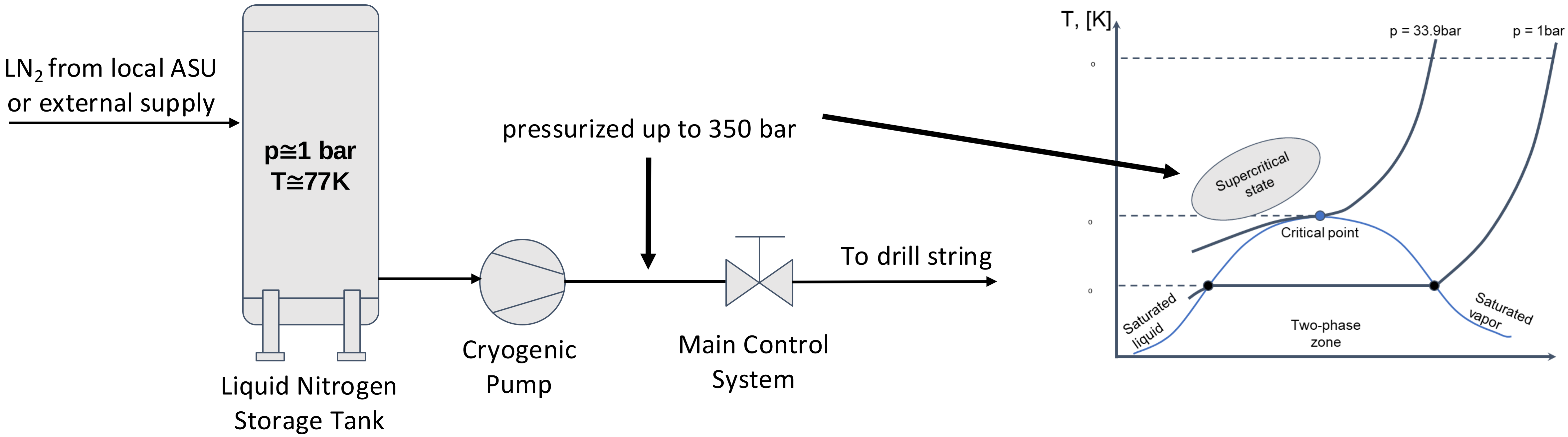
Cryogenic supply system



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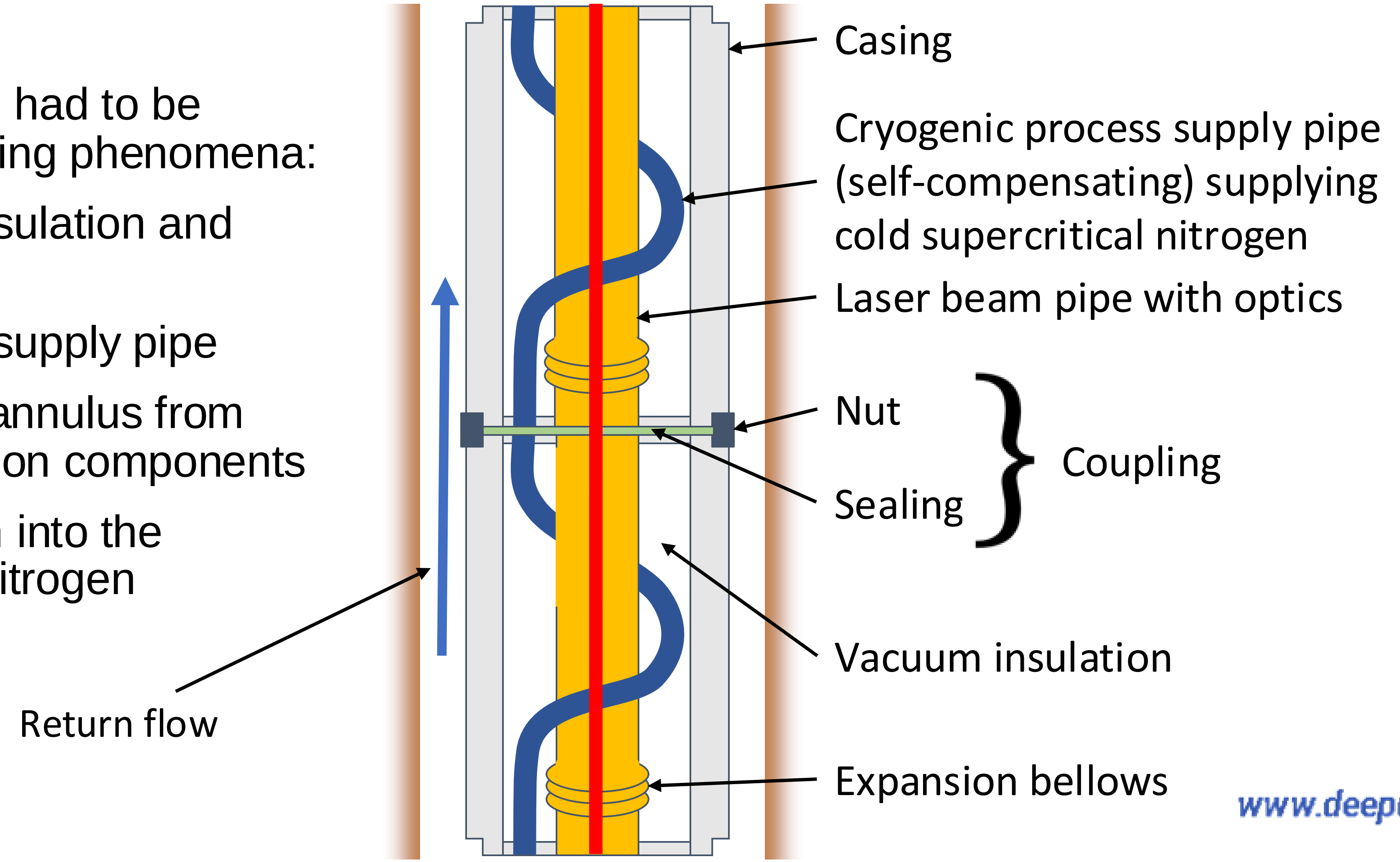
Supercritical nitrogen supply system

Complex analytical model had to be developed to cover following phenomena:

- Heat inleaks through insulation and coupling
- Pressure losses within supply pipe
- Pressure losses in the annulus from both solid and fluid friction components
- Laser power dissipation into the returning supercritical nitrogen



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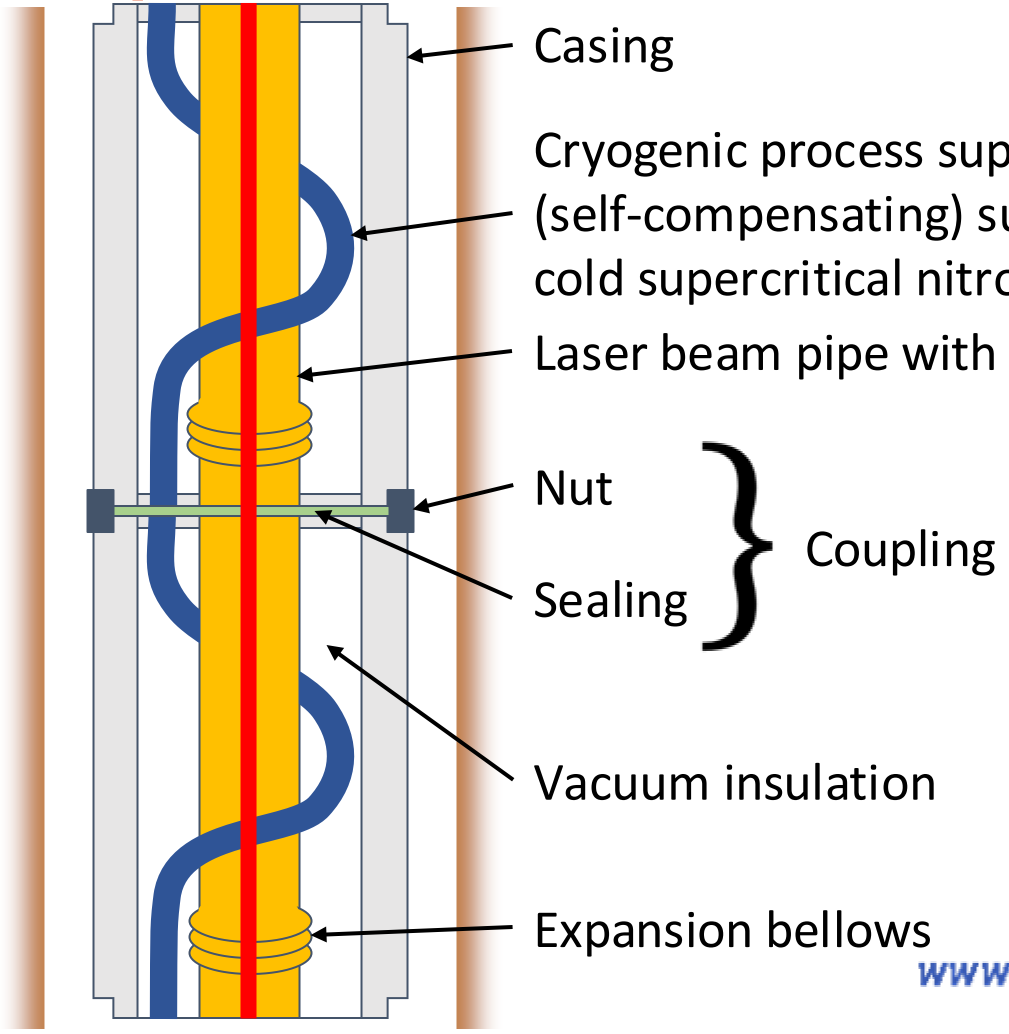
Mechanical design - requirements

The mechanical design of the cryogenic system must meet numerous requirements related to:

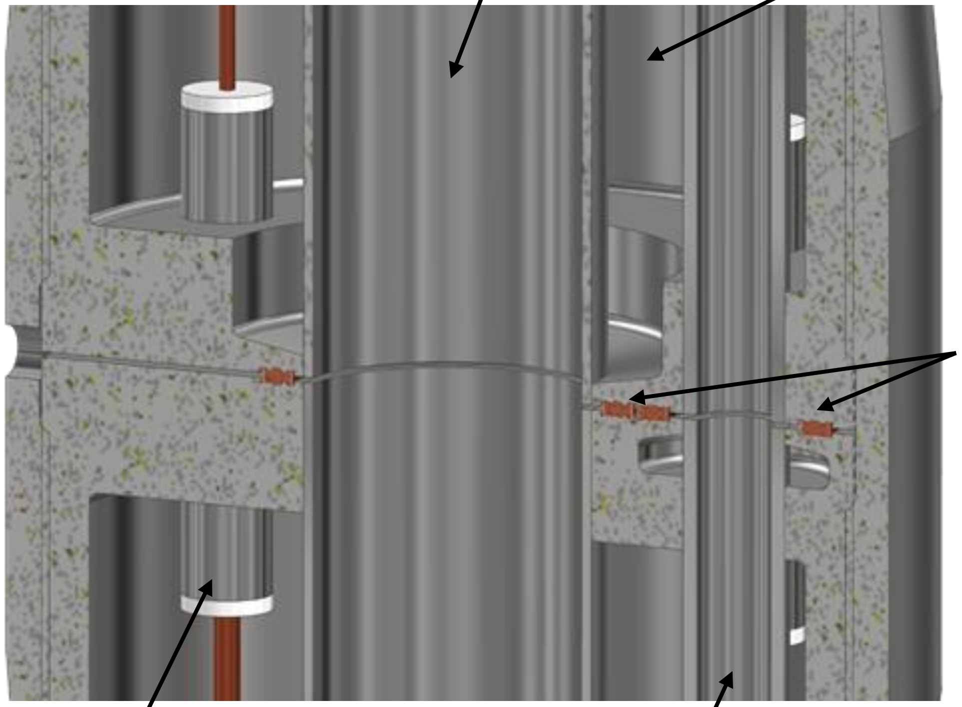
1. **Temperature** - materials must retain their key properties even at cryogenic temperatures.
2. **Heat load** - The design should minimize direct and short connections between cryogenic and room-temperature components.
3. **Vacuum** - The casing and process pipes should exhibit low permeability and outgassing rates.
4. **Mechanical load** - Significant pressure differences and weight pose challenges for many common materials.
5. **Economics** - Materials should be readily available and easy to work with, such as being suitable for welding and machining.



Mechanical design - coupling

Coupling two drill string segments in a cryogenic environment presents several engineering challenges. The connection must perform reliably under extreme conditions while remaining practical for field operations.

- **Leak-tight sealing feasible at cryogenic temperatures**
- **Mechanical strength**
- **Fast and robust assembly**
- **Low thermal load**



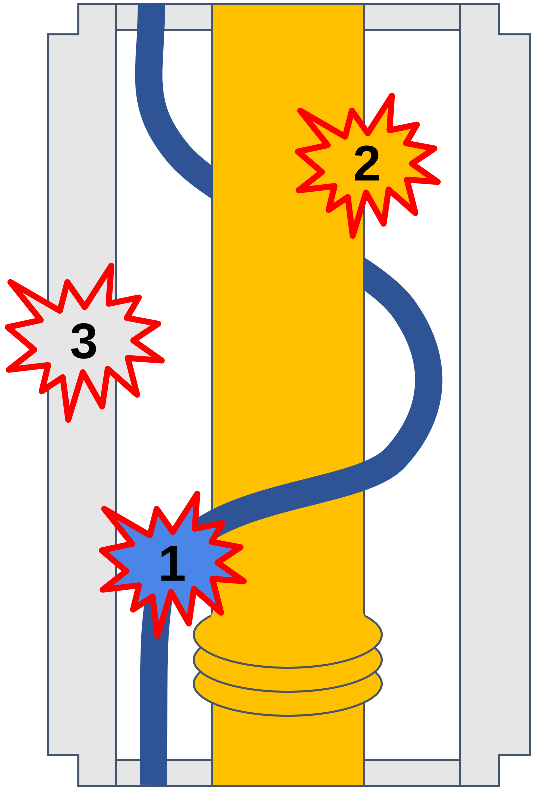
Risk assessment for cryo system

Introducing a cryogenic system into deep geothermal drilling brings new failure modes that must be considered.

Failure modes directly related to the cryogenic system in most cases are related to vacuum insulation degradation.

Vacuum loss can result from the following failure scenarios:

1. **Process pipe break** – cryogenic fluid leaks into the vacuum space
2. **Laser pipe break** – warm shielding gas enters the vacuum
3. **Casing pipe break** – warm return gas, contaminated with cuttings, flows into the vacuum



Each failure mode has a different set of potential consequences to all subsystems within the drill string.

Proper mitigation actions were proposed for each identified failure scenarios.

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Cryogenics is well prepared to deliver cold nitrogen down the deep bore hole!

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Appendix - Cryogen parameters

	Methane	Oxygen	Nitrogen	Hydrogen	Helium
Normal boiling point	111.9 K	90.2 K	77.8 K	20.9 K	4.2 K
Critical temperature	190.7 K	154.6 K	126.2 K	32.9 K	5.2 K
Critical pressure	4.63 MPa	5.04 MPa	3.39 MPa	1.29 MPa	0.23 MPa
Latent heat of evaporization	512 kJ/kg	213 kJ/kg	198 kJ/kg	446 kJ/kg	20.7 kJ/kg
Triple point temperatur	88 K	54 K	63 K	13.8 K	---
Triple point pressure	10.1 kPa	0.15 kPa	12.5 kPa	7.04 kPa	---
Vapor-liquid ratio	590	797	646	788	701

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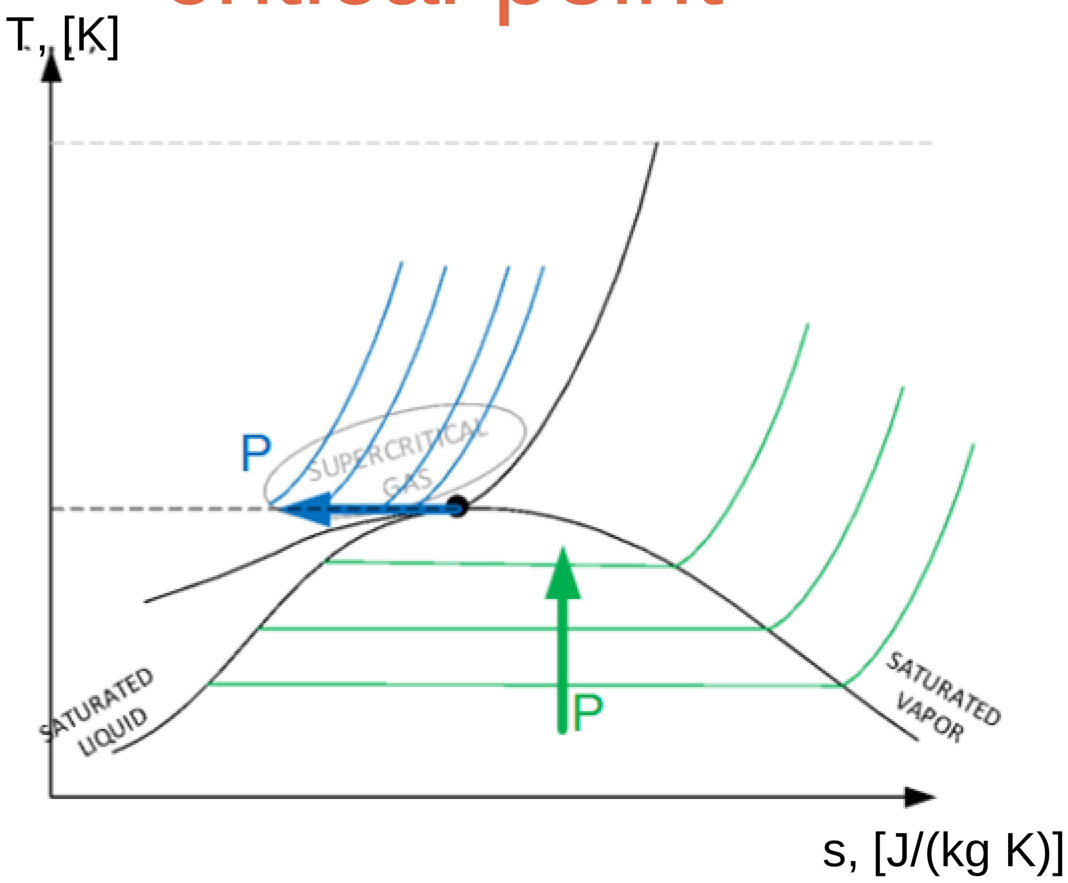
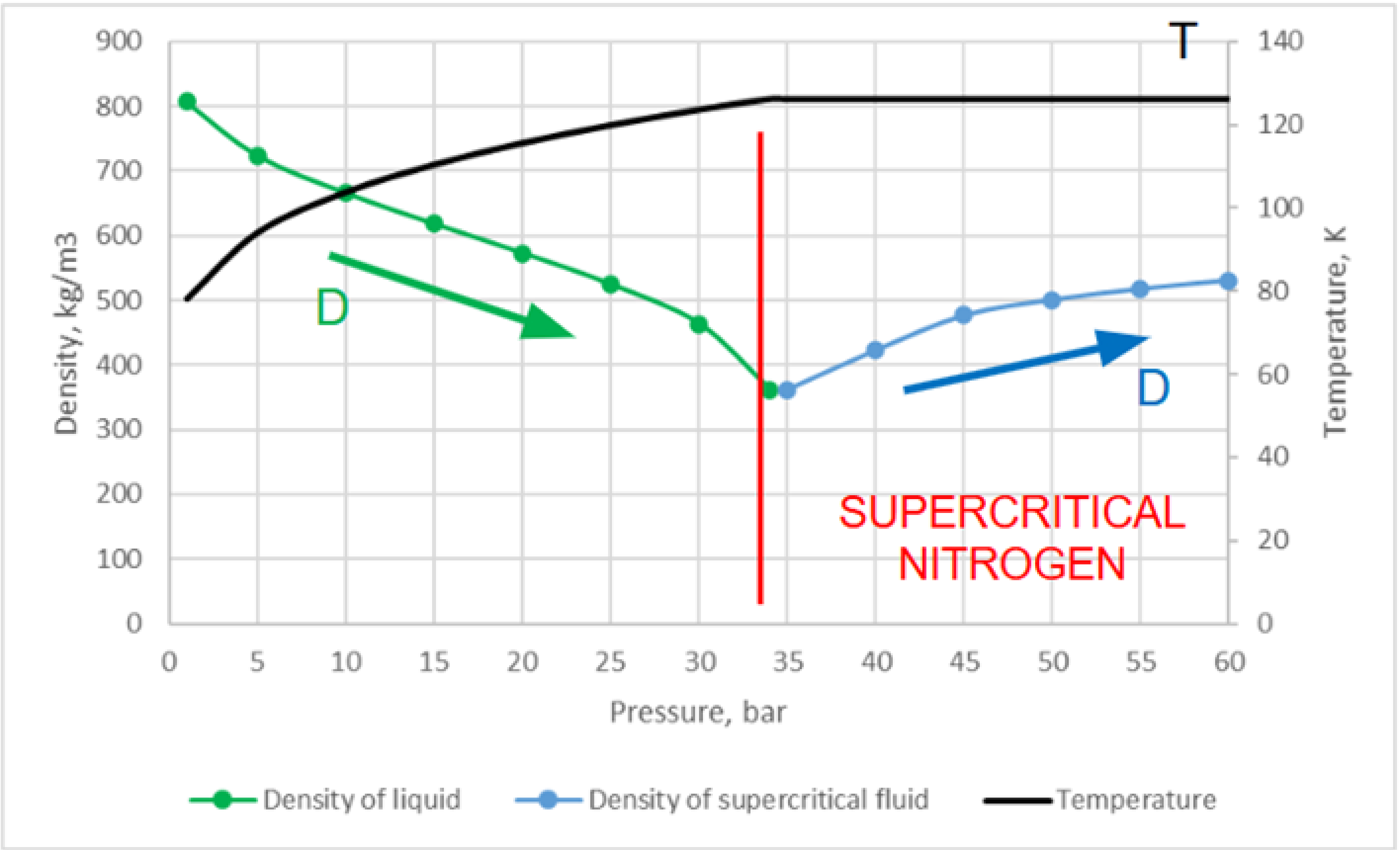
Appendix - Nitrogen parameters around critical point





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Appendix - Nitrogen cooling capacity at supercritical state vs saturated liquid