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Cryogenics in the drilling of deep, multi kilometre geothermal wells

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Abstract. The potential of geothermal resources is currently limited by existing drilling technology. To address this issue, the DeepU project is investigating the use of laser to drill deep wells (>4 km) to create a U-shaped closed-loop geothermal heat exchanger. This technology includes a high-power laser source and optics, a drill string, a drill head, a flushing system making use of cryogenic supercritical nitrogen and some ancillary systems required for successful rock penetration. Supercritical nitrogen is transferred down the borehole, then after isenthalpic expansion of the gas, it vitrifies the rock and flushes the rock debris to the surface. Mathematical model of nitrogen flow during the laser drilling was developed. Pneumatic transport modelling provided information on the required supply of supercritical nitrogen to provide the necessary cooling power and pneumatic transport of cuttings to the surface. Vacuum insulation was selected for the supercritical nitrogen transfer pipe. A custom coupling system was designed to ensure tightness, robustness and ease of assembly. Potential failure modes of the proposed system were identified and mitigation steps were proposed. The study demonstrates the feasibility of delivering supercritical nitrogen to a borehole several kilometres deep.

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1. Introduction

The idea of laser deep well drilling is presented in Figure 1 with cryogenic supply system (left) and drill string schematic depiction (right). The laser beam is focused by optical system and finally deposits its energy in a bed rock causing its melting or spallation. 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.

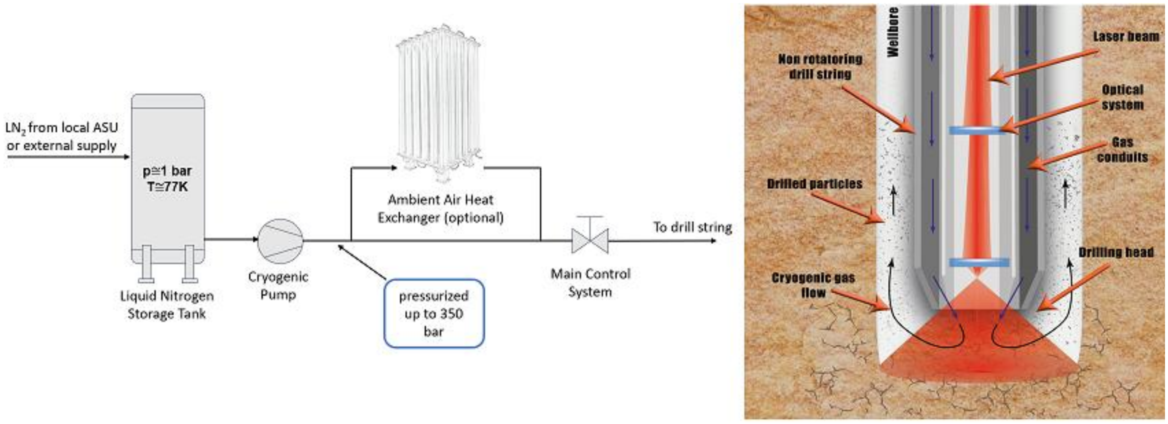

Figure 1. Laser deep drilling system, supply system (left) and process cross section (right) [1]

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 supercritical nitrogen has been chosen as the most suitable candidate for the flushing medium. 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 resulting from evaporation, 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.

2. Laser-rock interactions

Laser-rock interactions were examined in series of preliminary experiments that revealed three main processes occurring during laser irradiation: thermal spallation, melting, and vaporization. Detailed analysis of IR-images and lasing products allowed to define power density (W/cm³) necessary to induce particular response of the rock. Thermal spallation came out as the most efficient rock removal process therefore further experiments and final design was developed to thermally spall the rocks (Fig. 2).

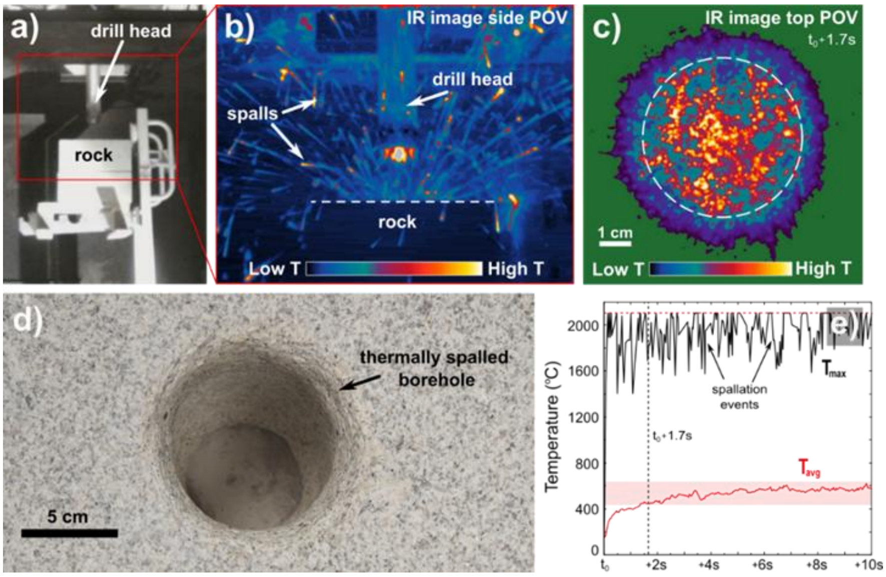

Figure 2. Photograph of the experimental setup (a) used to test DeepU drilling head. IR images of the thermal spallation drilling, side point of view (b), and top point of view (c). Photograph of the thermally spalled borehole in granite, depth 150mm, diameter ~80mm (d). The temporal temperature of laser drilling, Tmax – the maximum recorded temperature at a single point, Tavg – the average temperature in beam spot area (e).

2.1 Spalls characterization

The spalled material was collected after laser drilling experiment performed on granite. The granulometric analysis of spalled material show two distinctive classes 125-250 μm and 1-2mm that are responsible for the majority of the material. Then representative portion of spalled flake was immersed in epoxy resin and polished to uncover the spalls on the surface (Fig. 3). Subsequent, electron microscope study allowed to describe geometrical parameters of spalls according to Wadell's definitions. Particle shape influences the microscale behaviour of material, including the polarizability, the intrinsic viscosity, and the settling velocities of particles in suspension. BSE images of granite spalls have shown evidence of melt presence therefore, the granite particles were divided into two categories 1) spalls and 2) melt droplets. The spalls are composed mostly of quartz and feldspars with rare partially molten biotite crystals. Granite spalls are characterized by low sphericity (0.49) and low roundness (0.39), while melt droplets show high sphericity (0.65) and high roundness (0.72).

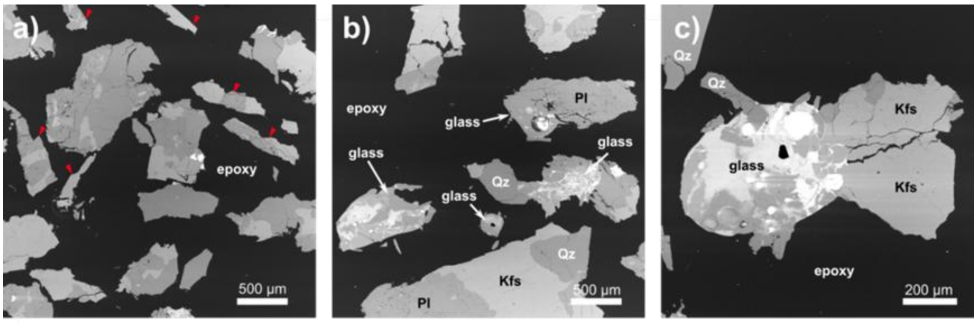

Figure 3. BSE images of spalled particles immersed in epoxy resin. Granite particles, red arrows indicated perpendicular orientation with exposed thickness (a), granite particles with partially molten minerals with present glass (b), melt droplets adhesively attached to spalled particles (c).

3. Supercritical nitrogen supply and gas return flow modelling

During laser drilling, sufficient flow of nitrogen must reach the drilling head at all depths to ensure pneumatic transport of spalled cuttings. Figure 4 shows the required nitrogen mass flow for 1 mm cuttings with 0.5 mm sphericity significantly rising with borehole depth. For multi-kilometre wells, gas supply becomes challenging and requires supercritical cryogenic nitrogen (SCCN) for low-loss transport in needed quantities. The drill must withstand both the low temperature and high pressure—up to several hundred bars—due to hydrostatic forces and pressure drop.

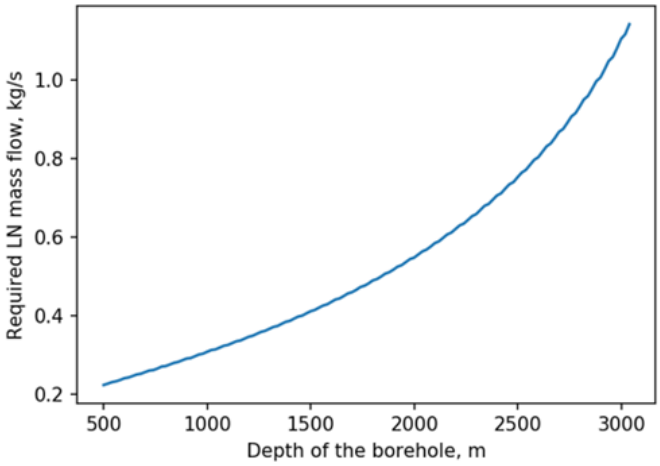

Figure 4. Nitrogen mass flow requirement for pneumatic transport of cuttings from the borehole.

Figure 5 shows pressure and temperature profiles of SCCN along a 2 km vertical supply line. Despite hydraulic losses, pressure increases with the depth reaching 160 bar and 88 K at 2 km depth, because hydrostatic gain outweighs frictional losses. Drilling to great depths demands a drill string combining a laser conduit (transferring 100–200 kW of power), a SCCN supply line withstanding both high internal and external pressures, and efficient cryogenic insulation. Holistic modelling of SCCN flow, laser heating, and pneumatic transport is required to understand component interactions, find mechanical requirements and estimate maximum drilling depths. The required pressures are the limit of available materials used in cryogenic and drilling systems.

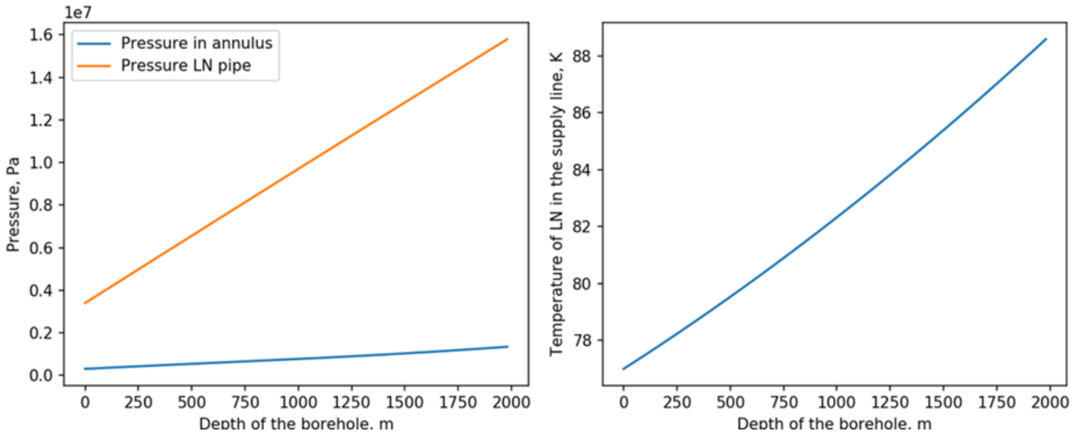

Figure 5. Pressure (left) and temperature (right) profiles as a function of borehole depth, annulus – throttled nitrogen return line, see fig. 1.

3.1 Experimental validation of modelling results

The experimental test stand, shown in Figure 6 consists of over 2-meter-long transparent polycarbonate (PC) pipe with inner core, that forces the flow into the annular space with the same equivalent diameter as the drill string.

Figure 6. Experimental test stand with highlighted transparent polycarbonate pipe sections.

Two specific components of the mathematical model will be experimentally validated – terminal velocity of particles as a function of their size given by [2], material and shape, and linear pressure drop for solid-gas flow given by [3]. Initial experimental campaign results for pure gas flow were compared with theoretical values, for which void fraction ε=1, and presented in Figure 7 below.

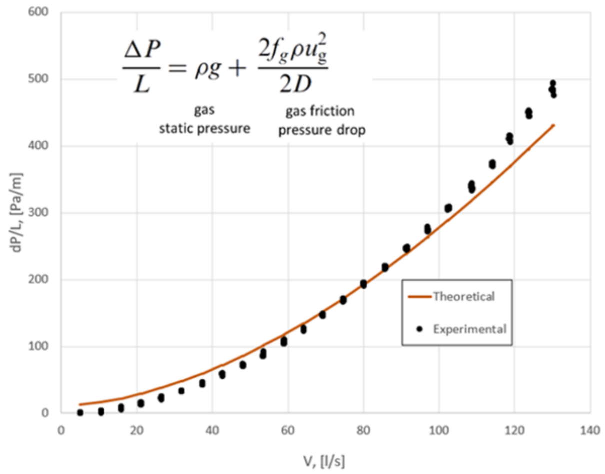

Figure 7. Experimental validation of the simplified linear pressure drops for pure gas flow.

4. Design and construction challenges of supercritical supply system

The laser drilling string integrates two conflicting technologies: cryogenic nitrogen delivery, requiring efficient vacuum insulation, and structural robustness for demanding drilling conditions. To enable multi-kilometre drilling, the string must also be segmented for logistical reasons, with joints meeting stringent mechanical standards. Defining these requirements begins with load analysis.

As shown in Figure 8, the vacuum-insulated drill string of length L is under standard gravity. Various pressure profiles generate different loads - SCCN flow generates load onto the process pipe (blue line) and casing (red line), whereas green line shows aerostatic pressure in laser pipe.

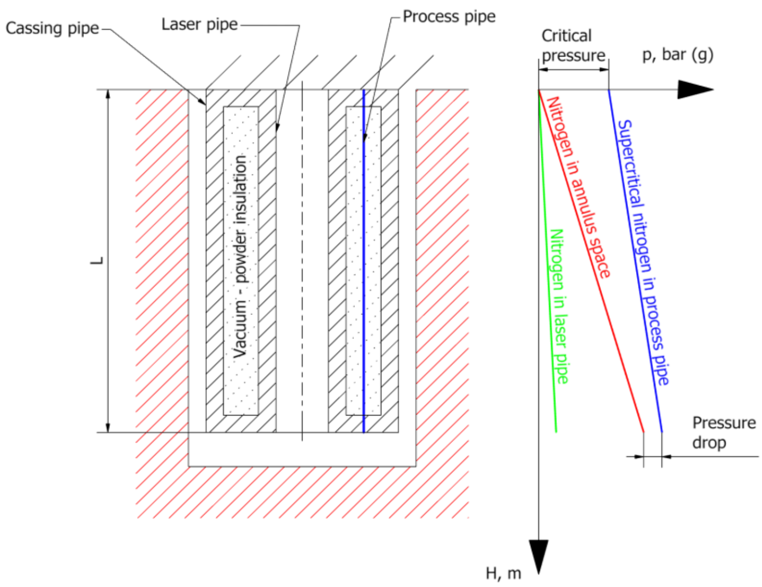

Figure 8. Simplified view of the laser drill string segment with characteristic loads.

The loads of the most important structural element, the casing pipe, are the system own weigh and external pressure. Casing pipe, acting as vacuum jacket, at the bottom of the borehole is loaded by 35 MPa, thus careful material selection is mandatory. Given that self-weight is the dominant load, the casing material needs high strength to density ratio. Additional factors, such as high modulus of elasticity, low permeability, good machinability, low temperature ductility and good market availability pushed selection towards stainless steels. Figure 9 shows the stress distribution in a drill string made of 1.4563 steel with 178.9mm casing pipe and 2x DN15 supply lines for borehole depth of 4km.

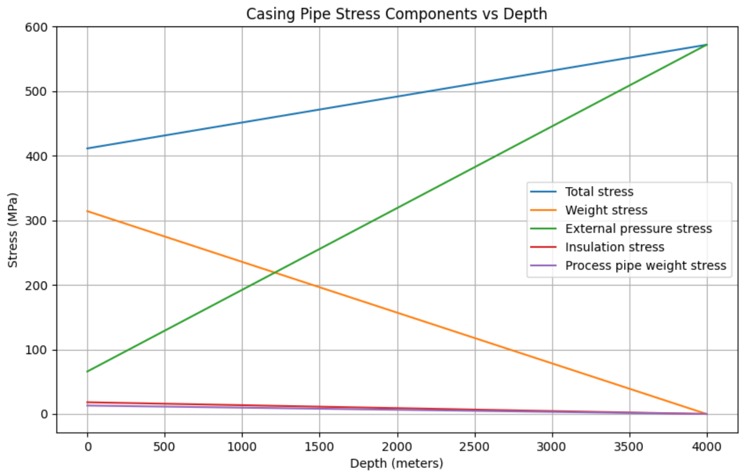

Figure 9. Stress distribution along the drill string.

Drill string elements have to be joined with fast and robust couplings. The coupling mechanism for drill string segments must meet several critical requirements. It must ensure a reliable mechanical connection with sufficient load capacity, stiffness, proper coaxiality, and angular alignment, while also allowing for quick assembly. Additionally, it must connect the process pipes in a way that withstands pressures up to 350 bar and temperatures as low as 77 K, maintaining tightness under these conditions. The coupling must also provide continuity for electrical cables between segments. To fulfil all those requirements a custom coupling dedicated to DeepU project was designed.

4.1 Risk analysis of the proposed solutions

Failure modes associated with pressure, temperature, and energy hazards that cannot be eliminated by design were thoroughly analysed. Key failure scenarios are identified and presented in Figure 10. Cryogenic nitrogen gas flow into the vacuum and laser energy deposition on the pipe wall are highlighted as the most severe cases, potentially resulting in module or full system destruction, respectively. These failure modes are expected to cause further damage, potentially triggering additional failure modes in a chain reaction.

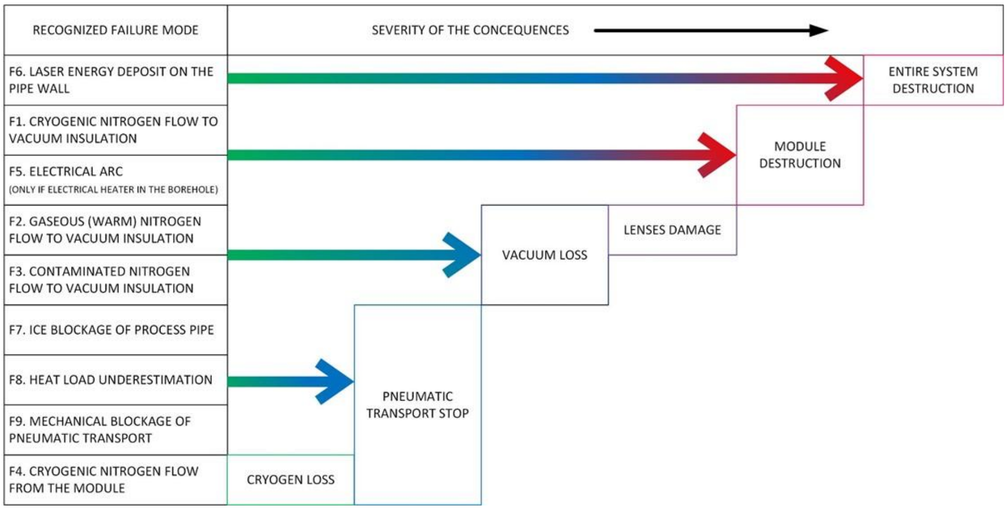

Figure 10. Recognized and analysed failure modes with their consequences, sorted by severity.

5. Conclusions

Deep geothermal drilling requires new technologies allowing acceleration of the drilling process. Mechanical drilling may be replaced by laser rock melting or spallation. The technology is at early stage of development and requires new constructions of cryogenic supercritical supply lines lines combined with laser beam tube and annulus return channel. Standard cryogenic solutions can be adapted to these challenging requirements.

Acknowledgments

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