Final Ultra Deep Disposal -A Novel Wellbore Concept Utilizing Pulsed Power Drilling Technology - 24175

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Beyond engineered safety with ultra deep disposal in boreholes

Electro Pulsed Power drilling is a promising novel technology for the new Final Ultra-Deep Disposal borehole concept

ABSTRACT

The "Final Ultra Deep Disposal" (FUDD) initiative, led by TNO, builds upon previous work in the field of high-radioactive nuclear waste storage within boreholes. The safety case for ultra-deep borehole disposal relies on a geological barrier that is kilometers thick, in contrast to the shallower mined disposal facilities. While the storage capacity per borehole is limited, this concept could provide a straightforward, robust, and economically viable solution for countries with a limited number of reactors.

The FUDD concept involves a mono diameter borehole with a large diameter of at least 1 meter. The temporary borehole casing is designed to accommodate placement of currently used canisters and containers at a depth beyond 5 kilometers. Before the final closure the casing is removed, preventing possible migration via the casing annulus, and the borehole is sealed with bentonite and natural formation materials. Additionally, the borehole must be truly vertical with a smooth borehole surface to facilitate placement of the casing. However, drilling a deep borehole with such a large diameter and smooth surface presents a challenge with conventional mechanical drilling as it requires significant weight-on-bit and torque to generate the necessary forces for penetration and rock breaking.

This study assesses the feasibility of the innovative Pulsed Power Drilling technology developed by Royal IHC, with the aim of realizing the FUDD concept. Central to this concept is a large-diameter cased borehole, consistent in diameter from top to bottom, which enables the placement of present cylindrical container of the current diameters for disposal at a depth of at least 5 kilometers. Pulsed Power Drilling is distinguished by its "contactless" rock-cutting process, achieved through controlled high-voltage electric discharges that eliminate the need for mechanical force to break the rocks. This characteristic is advantageous, as the borehole diameter is typically limited by the mechanical strength and power of existing drilling equipment. Beyond enabling straight vertical drilling, this approach minimizes the Excavation Damage Zone (EDZ) typically associated with mechanical drilling.

Currently, this technology is being piloted in the geothermal production sector, catering to the need for large-diameter wells at greater depths to enhance production for improved economic viability. It is worth noting that the requirements for borehole disposal for nuclear waste storage are quite distinct from those of the oil and gas industry. Traditional casing cement constructions may give rise to migration pathways. These potential pathways will be broken and blocked by removing casing construction and restore the formation of with natural material including bentonite.

The innovative Pulsed Power Drilling technology serves as the foundation of this development, providing the unique capability to drill large diameter boreholes at significant depths without incurring excessive additional drilling costs. This development also involves creating a new casing design to accommodate functionalities for the nuclear waste sector with focus on sustainable long term disposal.

This study examines the distinctive attributes of pulsed power drilling technology and its alignment with the essential requirements of an ultra-deep borehole for the FUDD concept. The key findings of the study and future plans are discussed.

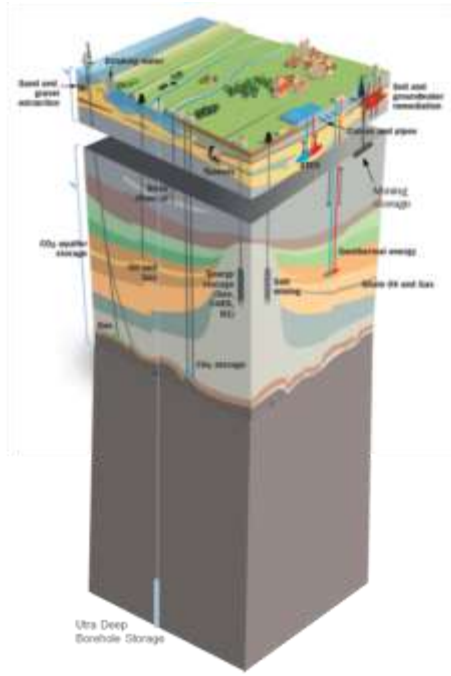


Figure 1- Activities in the subsurface

INTRODUCTION

It is imperative to remove high-level and long-lived nuclear waste from the biosphere for a duration equal to the isotope's half-life. Over several decades, international research has been conducted to develop a safe, technologically feasible, and socially acceptable final disposal solution for high-level radioactive waste. Storing and disposing of radioactive waste in geological formations is considered a technically and scientifically sound solution [1,2,3].

One concept for geological disposal involves creating an underground mine where waste containers can be placed. After a certain operational period during which waste could be retrieved, the mine can be hermetically sealed, typically using materials like cement and bentonite clay. However, constructing a mine for geological waste disposal requires substantial investments and can have a significant impact on the local environment near the mining site during both the construction and operational phases. The extent of this impact depends on factors such as population density and open space in the surrounding area.

The subsurface is expected to play an increasingly important role in achieving these goals, potentially posing constraints on using locations for nuclear waste storage at depths where other activities take place, such as CO2 Capture and Storage (CCS), geothermal energy extraction, seasonal heat storage, and gas storage. Depending on the geology, these sustainable energy activities in the subsurface can range from shallow depths (above 1,000 meters) for geothermal production and storage to depths of up to 3,000 meters for deep geothermal and oil & gas production. Mines for the geological disposal of nuclear waste are generally situated at depths ranging from 200 to 700 meters.

The scarcity of available subsurface space for industrial activities is particularly relevant in densely populated countries like the Netherlands, which has a population density of approximately 523 people per square kilometer [6], in contrast to for example the United States, which has roughly 33.

Borehole disposal

While constructed mines are well-suited for accommodating large disposal volumes, boreholes have also gained significant international attention as a concept for storing smaller volumes of radioactive waste over the years. Boreholes and casing construction can be achieved using the same equipment and construction methods as those employed in the oil and gas industry. However, it's essential to acknowledge the differences between the two, as borehole drilling for the oil and gas sector is primarily developed for producing hydrocarbon-containing fluids, which can be explosive, and not for the one-time placement of cylindrical nuclear waste containers.

Drawing upon advancements in drilling technology from other sectors and leveraging knowledge of well construction and tunneling concepts from civil engineering, an alternative borehole solution can be explored. Building upon existing borehole technology, TNO is collaborating with IHC to investigate a newly emerging drilling technology, pulsed power drilling, aimed at facilitating a novel borehole concept. The ambition of this project is to enhance the safety case beyond any doubt through ultra-deep placement. This approach may also lay the groundwork for an affordable disposal concept in densely populated regions with sedimentary formations, although it is not limited to such conditions. The pulsed power drilling technology, can operate in both crystalline and sedimentary formations. This initiative will draw upon TNO's experience gained in our research work in the oil and gas sector, including exploration, production, well technology, data from the National Geological Survey of the Netherlands and IHC's expertise in pulsed power technology for drilling.

GEOLOGICAL BARRIER

The effectiveness of a geological barrier several kilometers thick is expected to significantly enhance the reliability of long-term containment compared to a thinner geological barrier. While igneous or metamorphic host rocks are often considered for disposal, sedimentary formations have a demonstrated capacity to seal hydrocarbons, and carbon dioxide. Within this conceptual framework, for an ultra-deep borehole, any location with an overburden composed of a multi-layered stack of sealing rocks like shales, clays, anhydrites, salts or chalks, even if containing faults, could be considered. Over millions of years, these lithologies have proven their ability to serve as a potential impermeable sealing barrier for oil and gas [26].

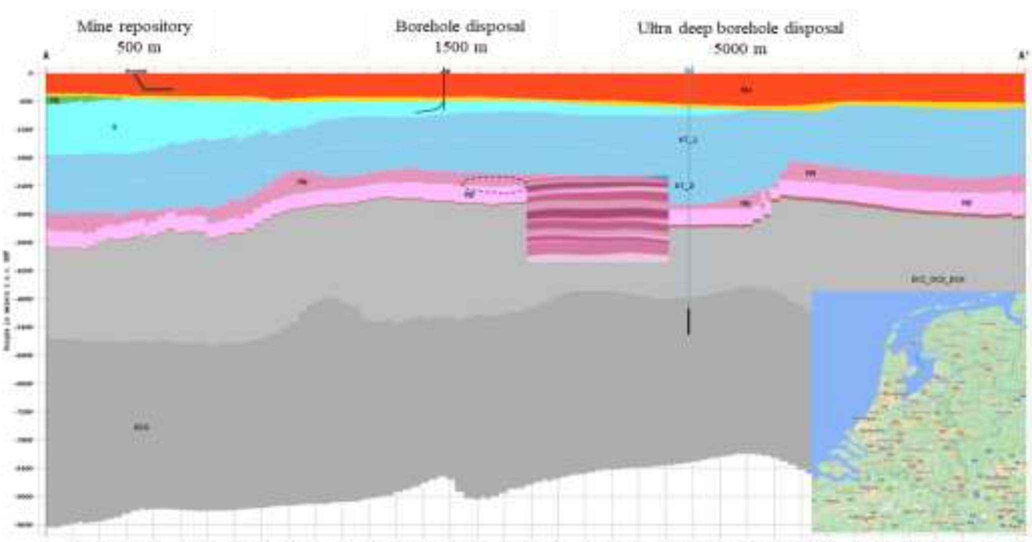


Figure 2–For Illustration barrier thickness with an arbitrary cross-section the deep surface in the Netherlands [29]

Enveloping Objectives:

- Enhance the geological safety barrier.
- Reduce infrastructure costs compared to mining.
- Minimize the impact on the immediate environment during construction.
- Minimize reliance on local geology by targeting ultra-deep host formations and a thick natural barrier.
- Achieve a shorter realization time for disposal infrastructure compared to mining.
- Provide adequate disposal volume.
- Utilize standard cylindrical nuclear waste containers with qualified barrier features.

The following guiding constraints are defined for the assessment of the ultra-deep well concept:

1. The borehole must be vertical for simplicity of placement.
2. The depth of the vertical borehole should be at least 5 kilometers.
3. The borehole diameter must be at least 1 meter to accommodate standard cylindrical nuclear waste containers.
4. The borehole casing must be equipped with a lifting shaft function to support placement and retrieval during the operational period.
5. The borehole construction must support the restoration of the overburden for final closure.

Most proposed borehole disposal concepts start with smaller-diameter borehole, similar to those used in the oil and gas industry. The concept proposed in this study, however, is designed to accommodate large-diameter containers. The idea of deep borehole disposal with a larger diameter has been studied by R. Rigali et al. in 2017 [5]. The construction methodology for the borehole, as proposed, was based on traditional borehole casing principles, involving the gradual lowering of long sections of threaded pipes and the pumping of cement into the annulus. The surface casing had a diameter of 1.47 m (58 inches), divided into 3 sections, which reduced to 0.81 m (32 inches) at the lower section. This guidance tieback inner casing of 32 inches weighed 1.5 million pounds, necessitating special procedures and equipment for placement.

The concept under consideration in this study, which involves pulsed power drilling technology, features a single large diameter from the surface to the disposal depths. To support this concept, an alternative method for the installation of the 'casing' will be proposed, although this is beyond the scope of this paper.

ASSESSING THE FEASIBILITY FOR A NEW BOREHOLE SOLUTION FOR FINAL ULTRA DEEP DISPOSAL

The scoping phase of the study entails identifying conceptual considerations to establish the framework for technology assessment of the necessary enabling technologies. In the table below, we outline the functional considerations related to application features for boreholes, encompassing both oil and gas production and nuclear waste disposal.

Factors for consideration	Borehole oil & gas	Ultra deep borehole disposal
Function of the infrastructure	Provide for a defined period of time a safe containment of af fluid flow of oil and gas from reservior formations to the surface.	Provide an ultradeep cavity (> 5 km) which is, for a defined period, accessible and equiped with means for stacking cilindrical containers and closure providing a saftey barrier simular to the present geological barrier.
Objective of the infrastructure	Extract oil and gas-containing fluids from subsurface formations to the surface cost-effectively and safely for efficient transportation, optimizing economics.	A cavity with a non permeable barrier for nuclide migration for the final disposal of cilindrical contrainers packed with long lived nuclear waste.
Product type facilitated with the infrastructure	Transport of formation fluids which is a mix of gas and hydrocabon containing mineralized water.	To transport and keep hold cilindrical containers containing long lived nuclear waste.
Specific requirements	Construct the subsurface infrastructure for duration of production until the reservoir is depleted.	Establish a barrier which is well byond the possible lifespan of present confirment possible integrity of man made constructuctions targetting 1 M+ years.
Environment of operation	Subsurface at depths average range 1000 - 4000 meters.	Depths below 5000 meters.
Prodution	Hydrocarbon fluid flow is facilitated with relative small pipe diameters 4" - 7" (100 - 178 mm) at	Support cilindrical containers placement, closure for containment and monitoring.
Societal	Focus on protecting the environment for uncontrolled fluid formation leakage during the production phase, and, in addition, by paying more attention to reducing methane emissions, there is a growing effort towards the sustainable well closure.	Focus on protecting the environment from longlived radiactive nuclides migration to the surface.

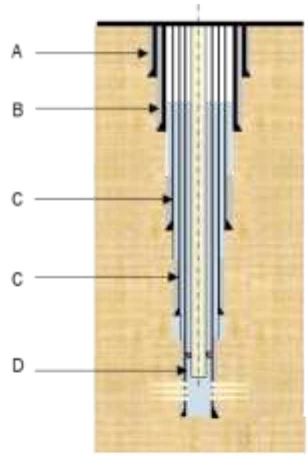
Table 1 – Functional considerations for wellhole constructions for deep nuclear waste disposal and oil & gas production.

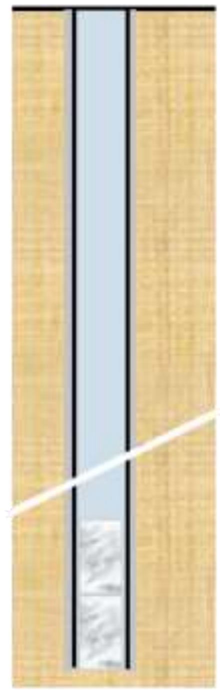
The listed considerations are taken into account for the current conceptualization of the borehole construction for the proposed Final Ultra-Deep Disposal solution. While there are overlapping aspects in both applications, there are also distinct differences to consider, as these may necessitate different solutions.

The basic outline of our ultra deep borehole design assessment;

- **Safety case; geological** barrier focus on sedimentary formations, full depths core confirmation of formation properties, engineered barrier including borehole closure and the nuclear waste container, handling and logistics.
- **Hole making, drilling;** large single diameter borehole, steering capabilities, minimal damaged zone in the borehole wall, cutting removal and logging.
- **Borehole casing; single** large diameter borehole casing, well control while construction and operations, lifting placement structure, monitoring and maintenance.
- **Final borehole closure;** clear the borehole construction above disposal section and seal the borehole, bentonite and native material based restoring formation sealing, monitoring infrastructure.
- **Monitoring;** foundation for monitor of geophysical parameters.

In this paper, our primary focus is on the hole-making process, commonly referred to as borehole drilling. Drilling a borehole involves two fundamental steps: rock breaking and the removal of fractured rock fragments to the surface, referred to as cutting removal. Rock breaking for borehole drilling is a mechanical process that has inherent limitations. In this paper, we present a novel alternative expected to provide the drilling capabilities required for the proposed single, large-diameter diameter borehole design for waste disposal.





Casing name	Borehole size in" depending local condition
A. Conductor	36"
B. Surface conductor	26"
C. Intermediate casing	17 ½"
C. Intermediate casing	12 ¼
D. Production casing	8 ½ "

Figure 3 – For illustration, left a schematic oil & gas borehole casing concept and right a mono diameter borehole concept.

Deep borehole drilling is primarily founded in the oil and gas sector. However, deep boreholes with a large diameter have no specific application for oil and gas production, as fluid flow can be facilitated with smaller diameters. The current practice for constructing a borehole casing for oil and gas production is based on a telescopic design, starting with a larger diameter at the surface and progressing to smaller diameters at deeper sections. Figure 3 illustrates a typical well construction used in the oil and gas industry. It is not to scale, but it visualizes the basic concept. In Figure 3 on the right, the borehole concept proposed for the ultra-deep disposal of standard nuclear waste containers is shown. In this concept, a simple, mono-diameter vertical borehole is proposed to guide the containers into the subsurface. Lowering the nuclear waste containers can be achieved using commercially available mining technology or equipment used for offshore lifting cables. The borehole will be equipped with mechanical structures to guide the containers downhole and provide passive drop prevention. The water column in the borehole, during operation, serves as a natural barrier borehole design for the ultra-deep disposal of stacked cylindrical containers. The following factors of mechanical drilling have to be considered when exploring options to drill large diameters at great depths;

- Although oil and gas wells are drilled to deep depths, the required diameters for fluid production are relatively small, typically ranging from 4-7 inches and boreholes drilled with large drill bits are not known to be drilled very deep.
- Mechanical rock-breaking necessitate significant torques and weight on the bit. These mechanical forces and vibrations accelerate the wear and tear of the expensive drill bit.
- Rotation and torque are transferred from the surface to the drill bit using a so-called drill pipe. However, these pipes have limitations in strength, especially at greater depths which require increasing torque due to friction. Alternative downhole mud motors have limitations in torque and weight on bit and do not support large diameter drilling.
- Considerable amounts of energy is needed for the rock-breaking process and to overcome friction when the rotating drill pipe contacts the well bore.

- Mechanical rock breaking creates a damaged zone in the borehole, often leading to borehole surface breakout, loss of circulation, a rough borehole wall, and an unstable borehole, which can pose challenges during casing placement. Larger diameter drill bits require more mechanical force which increase the risk of larger damaged zone.
- Hard rock significantly reduces the rate of penetration and shortens the lifespan of the drill bit.

Mechanical rock breaking for drilling can contribute to various shape deviations of the borehole and induce a wall damaged zone. In addition the mechanical bit interaction with the different type of formation, such volcanic, crystalline formation, sediments, sandy layers or fault zones and the influence of hydraulic pressure will impact the borehole wall quality and cause for example borehole wall outbreaks, borehole damaged zones with cavities. Additional problems may be the result of mud settlement in formed cavities due to reduced mud speed potentially jamming the drill string. Borehole wall quality but also integrity is essential for casing construction. This aspect is even more challenging for the mono large diameter borehole concept for both sealing and borehole construction installation. Typical variables of borehole surface damaged zones are illustrated below.

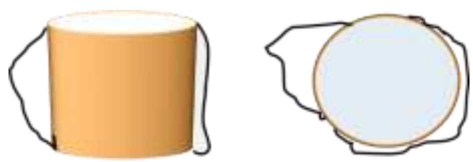


Figure 4 – Example features for assessing the quality of the borehole

INTRODUCTION TO PULSED POWER TECHNOLGY IN UNDERWATER APPLICATIONS

IHC Pulsed Power BV, a subsidiary company of IHC Mining BV, a division of Royal IHC, is developing pulsed power drilling-technology which is expected to be capable to enable 1 meter diameter, 50 deep drilling for secure waste storage. The tool is a drilling tower, driven by pulsed-plasma explos at the mud-rock interfaces of the drilling front. The unique strength of the technology is the ability to repetitively deposit kilo-Joule bits of electric energy into a very small time-space window.

Pulsed power for underwater electric discharge-driven interactions has been a continuing subject of research and development over the past decennia. A wealth of literature is available, including the referenced ones [7-24]. Opportunities for applications are multiple but technological and scientific challenges have delayed progress. Analysis and control of the mechanisms, development of adequate pulsed power devices and development of the tools that achieve efficient and reliable interaction between pulsed power and target are the crucial subjects of research and development.

The crucial tool is the plasma channel that forms between electrodes. This plasma channel converts a high-power electric pulse into an extreme pressure pulse. The result is an electric explosion into the surrounding medium. In dense media, like water, rock or even dirt, it has a forceful effect. To describe some details of this process: the medium of the narrow plasma channel will evaporate and partly ionize, get a high temperature and the molecules will fully dissociate. The attainable pressure is very large. The channel will start to expand fast, causing shock waves in the water. The electrodes to create the plasma channel are in a potential damage zone of the water/rock explosion. It poses a main challenge for the design. Important other challenges are: efficiency in terms of energy per removed volume, achieving a narrow electric power pulse, performance at high hydrostatic pressure.

A powerful rock breaking breakdown process

Summarizing a selection of results from literature and results of our laboratory work, this process can tentatively be described as follows:

- A fast rising high-voltage pulse is being applied across electrodes at the water-rock interface.
- At random locations at electrodes, streamers develop at micro-bubbles, micro-protrusions, triple points and sharp edges.
- A few streamers meet after a while and short the gap.
- When meeting at a sufficiently short distance a strong electrical discharge follows that forms a hot plasma channel after a short time.
- A peaking circuit and close vicinity of the interface strongly facilitate the breakdown process.
- A power pulse of typically 1 microsecond or less is needed to cause a sufficiently strong explosion of the plasma channel.

Our pulsed power development focusses on

- Reliable, repetitive pulsed power in the range of kJ/pulse energy and GW peak power at short pulse times.
- Analysis and control of the basic mechanisms.
- Development of the electrodes of the drill bit. Development of the complete drilling tool (drill bit, pulsed power source, enclosure, mud flow system, AC power).

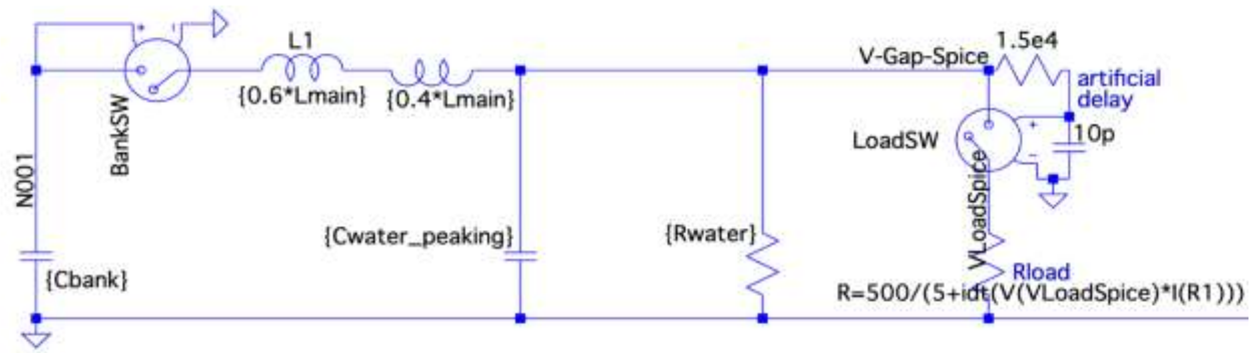


Figure 5 – Equivalent circuit for pulsed-power driven rock fracture. R_{load} is the plasma channel, LoadSW is the electrode gap, BankSW is the pulsed power switch. C_{bank} is a capacitor bank in series or parallel, a Marx generator or similar.

The capacitor bank is charged to a high voltage U_0. At t = 0 the spark gap switch closes and a current starts to flow. Since C_{bank} >> Cwater_peaking, the voltage across the water/rock gap rises to up to twice the bank voltage and performs a damped very fast oscillation. The water-rock gap is intended to break down during this initial period, allowing a high current to flow through the load.

The analytic solution for the circuit of Figure 5 can be derived by solving the circuit equations. Some approximate solutions are given in literature [14, 30, 31]. For example: if Rwater is large, the voltage U_2 across the load in the case before water/rock breakdown, is approximately given by:

$$U_2(t) = U_o[e^{-t/(R_{water}*C_{bank})} - e^{-t/(2R_{water}*C_{water})} * \cos(\omega t)] \qquad (1)$$

A full solution but implicit in circuit parameters and in time dependence, can be found in the book by Paul W. Smith [32]. Simulations using the circuit of Figure 5 and the result of (1) are shown in Figure 6.

Plasma channel in dense media, simplified approach

We suggested a very simple model [27] to easily obtain an impression of the pressure ranges achievable with pulsed-power driven explosion of water or rock. These pressures can then be compared with rock strengths, e.g., the granite compressive strength of ca. 2.5 kbar and its tensile strength of 0.2 kbar. The model assumes the fast, ad hoc creation of a narrow plasma channel, within a time range of 1 microsecond or less.

The model does not describe the details of the formation process, it only defines initial and its end state. The formation stage should be short, 1 microseconds. Expansion of the channel during this stage is neglected. The formation phase is followed by the plasma expansion phase, in the time span from 1 to >> 10 microseconds. The formation and the expansion are thus considered as separate processes in this simple approach. Both stages are driven by the same electric pulse of short duration and high power level. As an example for this model, we set the electric energy of the pulse at Wetot = 1 kJ. This energy is delivered by one half-period of a sine wave current. The electric circuit to produce such a pulse is similar to the model in Figure 5. An example of achievable waveforms of power input to the plasma channel and voltage across the plasma channel are shown in Figure 6. The supposed channel is a cylindrical body of homogeneous plasma. The medium of the channel starts as water or/and rock. During the short formation phase, the channel becomes a fully dissociated medium at a high temperature. Surrounding the channel, we have a body of homogeneous water/rock. The formation stage consumes electric power to evaporate the medium, to partly ionize it, to dissociate the medium and to heat the medium to a high temperature. The energy needed to produce the channel can be calculated if we know the channel dimensions. For the expansion phase we apply the energy balance equation, and other thoughts from literature [16-24]. Energy balance: the net input energy $W_{in}(t)$ that was consumed by the plasma column until time = t, equals the sum of the following energy demands: the increase of internal energy of the medium, Δ(1.5pV) (ideal fully dissociated monoatomic gas) plus integral pdV, the energy demand by the work done to expand the plasma channel, p is the gas kinetic pressure:

$$W_{in}(t) = 1.5 * \Delta(pV) + \int p * dV \qquad (2)$$

The net energy input $W_{in}(t)$ is result of electric energy production $W_e(t)$ from input power $P_e(t)$, minus initial plasma formation energy W_f. Details can be found in [27].

An example of results according to the described model is given in Figure 7. It is the estimate for an explosion in rock. The important result is that the attainable peak pressure is in the high tens of kbar. This is much higher than the strength of rock material, both tensile and compressive.

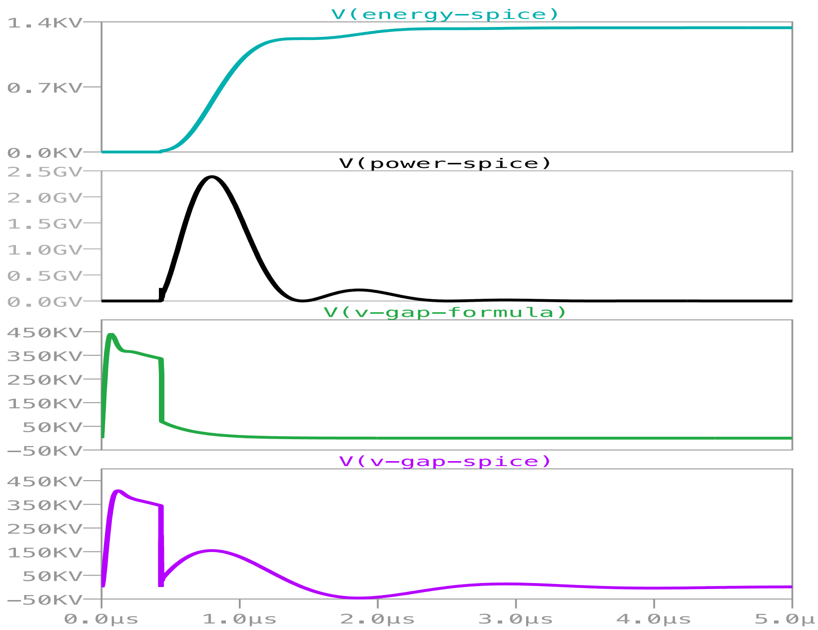


Figure 6 – An example of achievable energy/power waveform and electrode-gap voltage according to the formula and according to LTspice. After breakdown of this gap, the load is the plasma channel. The circuit parameters have been chosen in accordance with the example of the plasma channel explosion. The unit of energy, depicted by the software as kV, actually is kJ.

INTERPRETATION

The simple models of circuit and physics of previous sections are indicating that the electric power pulse should be short (ideally ca. 1 microsecond) and that the load should have a resistance value capable to consume this power quickly. These model results coincide with the following rationale: By dumping kJ's of energy into a narrow channel faster than the channel can expand we create a very high-pressure channel.

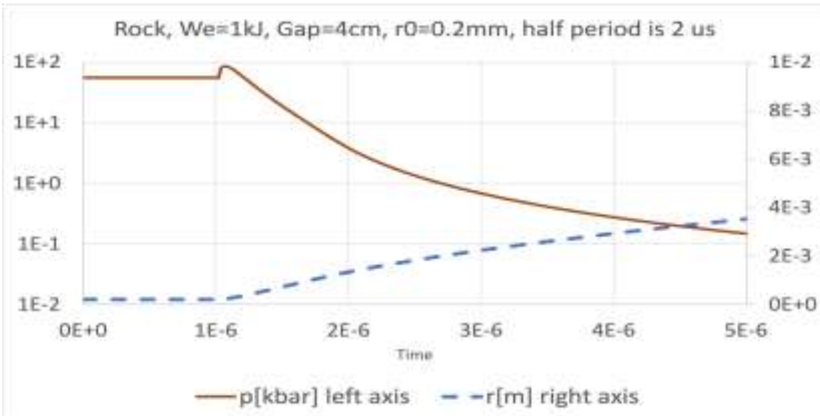


Figure 7 – Plasma channel formation in rock and expansion according to the simple model. r0 is the initial channel radius. The temperature of the initial formation stage is set at 5000K. r is the radius of the channel, p the pressure.

The channel starts to expand with the sound velocity of the medium of the channel (ca 1 mm/microsecond). So, the pressure will drop very quickly. Adding more energy after the initial phase helps but is much less effective in breaking.

A requirement for the channel resistance is the following. The electrical resistance of the channel should consume a sufficient portion of the available power within the channel formation stage of ca. 1 microsecond. This can be achieved if the relevant characteristic time constant of the electric circuit, Lmain/Rchannel fits the formation time while Rchannel << Rwater. In most cases Rwater is 10 Ohm or even less. Rchannel is 1 Ohm at most, so Lmain ideally is 1 micro Henry or less.

These conditions are hard to achieve. It may occur in practice that we are already taking advantage of an early more resistive phase of the channel. A tool to increase the resistance value is channel length. But, by increased length, the initial breakdown becomes harder to achieve. Higher voltage peaking is needed, achievable through the adopted well-known peaking mechanism. A tool to decrease Lmain is more compactness and higher voltage. Both actions demand higher voltage and better insulation.

DESIGN OF THE TOOL

To design a drilling tool according to the basics denoted in foregoing sections, we propose a modular approach with one module defined by the combination of the following ingredients:

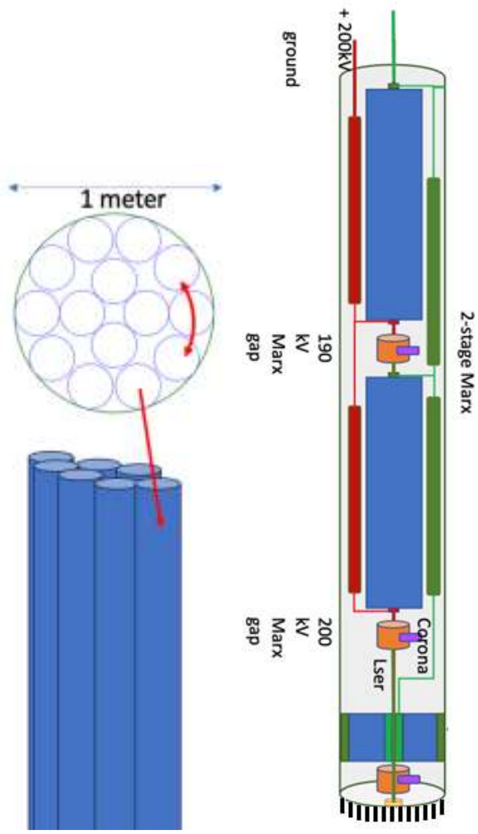
1. A Marx generator of 2-4 sections, each charged to a voltage of 100 or 200 kV, with a nominal peaking output voltage of 500 kV.
2. A pulse energy of 1 kilo Joule.
3. A pulse repetition rate around 10 Hz.
4. Duration of the dominant power pulse of ca 1-2 microseconds.
5. A multiple drilling electrode set as the load to the generator.

6. The electrode gaps at a gap distance of 1 cm per 100 kV output voltage.
7. Module diameter ca 20-25 cm, length 4-6 meters.

Design Parameters of One Module	
Energy per pulse	1000 Joule
Repetition rate	10 Hz
Expected excavation yield	2 cc per 1000 Joule

Table 2 – Module design parameters

The modules will be housed in metal tubes that can be stacked together into a drilling tool of 1 meter diameter. The anticipated layout and the design specs of the complete tool are shown next, in Fig. 8 and adjacent table.
together.



Complete Tool Design Target	
Diameter	1 meter
Required drilling speed	1 meter per hour
Req. excavation per second	220 cc per second
Req. energy per second	110 kilo Joule
Req. power	110 kilo Watt
Available per module	10 kilo Watt
So: Number of modules	11

Figure 8. – Draft of one module and of the complete pulsed power drilling tool of modules stacked.

Table 3 – Tool design, and energy targets.

The assumed excavation yield of 2 cc per kilo Joule is a number chosen by considering data available in literature and data from lab measurements. From our measurements we collected the information shown in the table next to the Figure 8. Energy cost per volume is very much dependent of particle size distribution. By controlling the size distribution to some extend we can manage the energy cost. We aim at a size distribution between 1 mm and 10 mm. This size seems convenient for ease of removing the drilling debris. From our data we see that the energy cost in this size range varies between 30 Joule and 300 Joule per cc of material. The data are shown in Figure 10.

These data were obtained in the ideal situation of our lab size setup, see Figure 9. To be conservative in specifying the energy cost for the depicted design, we applied a cost figure of 500 J per cc. This is similar to designs found in literature [28].

Submersible design. *Present set-up, without submersible casing.*

Figure 9 – Lab setup to test rock fragmentation, drilling electrodes and to obtain data on energy cost.

LABORATORY RESULTS AND RESEARCH ENDEAVORS

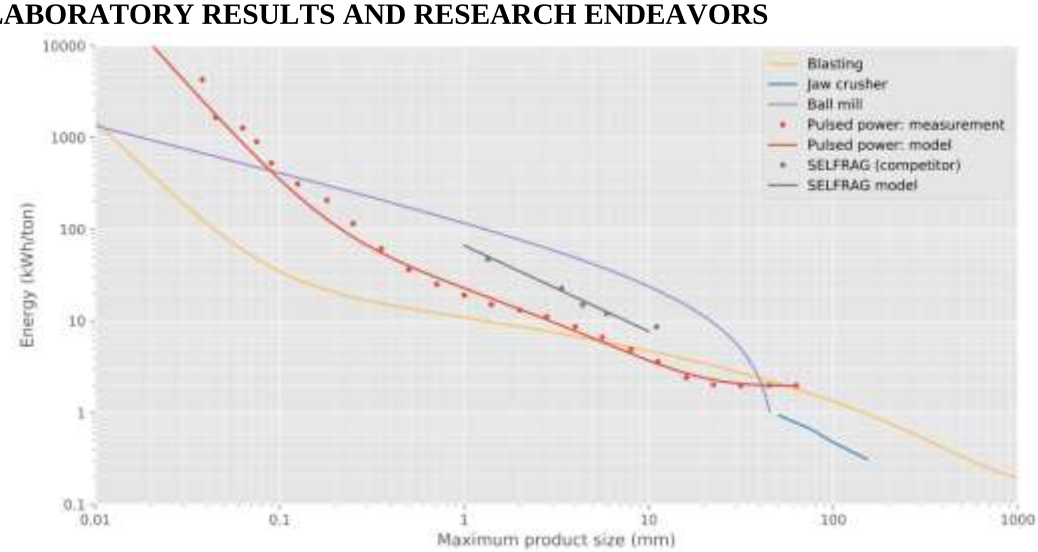


Figure 10 – Results of our lab-setup (Fig. 9). Size distribution compared to data from literature.

Presented results are the outcome from years of research taking place in the High Voltage laboratory at Eindhoven University of Technology, located in the Netherlands.

Royal IHC has been working at the laboratory since 2016, focusing on Pulsed Power rock-breaking systems for dredging and mining operations. Knowledge has been gained steadily, commencing with fundamental rock breaking mechanisms in 2017, as illustrated in Figure 11.

Figure 11 - Left- Electrical discharge traveling through the rock causing it to explode moments later photo middle, Right Demonstration first Drilling electrode.

Since 2019, Royal IHC has expanded its research into to the Geothermal drilling market, as an alternative method for drilling larger diameter and deeper boreholes. Utilizing equipment and insights gained from earlier experiments, drilling electrodes were developed, as shown in Figure 11. The current efforts are aimed at a prototype to be tested in 2024/2025.

Summary

1) Geological disposal of nuclear waste is considered a safe and sustainable solution. The thickness of the geological barrier contributes to the robustness, reliability, and safety of the system. Ultra disposal in boreholes will enhance the benefits of the concept.
2) Large, mono-diameter boreholes can simplify placement of containers, reduce the risk of getting stuck, and eliminate the need for new storage containers. A mono-diameter borehole will require alternative borehole casing principles.
3) The concept of pulsed power technology for rock breaking is explained. This technology is "contactless," eliminating the need for mechanical force to break rock pieces. It does not necessitate heavy mechanical equipment, is not subject to wear on drill bits/drill pipes, it is expected to improve borehole wall integrity and it is predicted it requires less energy.
4) Proof of principle has been demonstrated, and the basic design of the pulsed power rock-breaking system for drilling boreholes has been described.

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