

Influence of Process Parameters on Thermal Rock Fracturing under Ambient Conditions

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ABSTRACT

In order to make geothermal energy more competitive on the market and therefore to reduce the drilling cost of deep boreholes, during the last few decades, researchers are trying to develop new drilling techniques. A potential solution is a contact-free drilling method by means of a flame jet. Exposing a rock surface to the heat of a flame, which penetrates through a rock sample and increases the internal stresses, small disk-like fragments are formed and removed from the surface creating a hole. At the Institute of the Process Engineering, ETH Zurich, the research is focused on giving an explanation of rock fracturing, called spallation drilling and to link the gained results to the required process parameters. An existing high pressure drilling pilot plant, which models experimentally the conditions in a borehole, has a small optical access, limitation in rock probe size and limited number of suitable measurement techniques. Therefore an ambient spallation drilling setup has been constructed, to perform more convenient measurements. Performing the preliminary spallation experiments with the ambient spallation setup, the presented work gives the resulting relation between the required operating conditions for successful thermal spallation and the rock fracturing. Maximum used heat of combustion was up to 45 kW, reached penetration rate was 1.97 m/h and removal rate around 3 m³/h. Different rock types have been also tested in order to find the one with the best spallation results and hence, it will be used for the further research. Additionally, an infrared camera is used for monitoring the thermal spallation drilling process and the hole creation.

1. INTRODUCTION

A method that is still under development to drill deep geothermal wells is thermal spallation drilling where heat from a flame jet or a laser beam induces stresses in the rock causing its failure. Results are more successful with the flame jet than with the laser beam, because the jet also removes created disc-like fragments called spalls. This impinging flame jet introduces both the heat transfer and the spall removing as important factors for successful thermal spallation drilling.

With the development of technology in the last hundred years and industrialization of the society new opportunities came for development of spallation drilling techniques and culminated in period between 1950 and 1976. Actually, a reason for the development of mentioned technology came from the first half of the twentieth century when industry was looking for a drilling technique that can be applied on all rock types, that has minimum shutdown time, economic operation costs, continuous operation, and reasonable capital and overhead costs keeping in mind environmental factors (Clark1971). Thermal spallation drilling has been shown as a possible technique that can fulfill some of the listed requirements.

In literature thermal spallation drilling has been also named as jet piercing, jet channeling, rocket jet mining and quarrying, flame cutting, thermal rock fragmentation etc. Companies that used thermal spallation as drilling method are The Linde Air Products Division of Union Carbide Corporation (Tonowands, New York) from 1930 till 1983 who drilled 61 m, Browning Engineering Corporation (Hanover, New Hampshire) who managed to drill 331 m in Colman quarry with maximum penetration rate (drilling velocity) of 30 m/h (average 15.7 m/h) between 1960s and 1980s and also Flame Jet Partners Limited (Encino, California) that were dealing with blasthole drilling in 1976 producing a flame with the temperature of 3871 °C (Pierce et al. 1996, Rinaldi1984). Rinaldi presented in detail all those companies and gave an overview of their drilling history mentioning also that spallation drilling presents a good potential for oil and gas wells, geothermal wells, hot dry rock wells, in-situ leaching and water wells (Rinaldi1984). In 1970s price of fuel oil and oxygen that have been used for the combustion process was increasing, hence the development of the thermal spallation drilling method was slowed down.

Thermal spallation started to be interesting again around 1984 for some research institutes like Massachusetts Institute of Technology (Boston), Los Alamos National Laboratory (Los Alamos, New Mexico), later National Institute of Space Research (Sao Paulo Brazil, 2004) and nowadays the Institute for Process Engineering at ETH Zurich under atmospheric and high pressure conditions. Actually, many laboratories tried to observe spallation on laboratory level and on small rock samples in order to describe spallation phenomena and later to predict a behavior of rock under the flame jet. Rauenzahn and Wilkinson were using a welding torch and combined their results with the drilling results of Browning for developing a model that can predict the heat transfer at the bottom of a drilled borehole and its geometries (Rauenzahn et al. 1991, Wilkinson et al. 1993). They also explained the spallation mechanism based on the work of Dey and Kranz with the Weibull statistical failure theory (Rauenzahn et al. 1991). The agreement of the model with the experiments was successful when the hole radius has been compared, but there is a disagreement in heat transfer rate. Also, the model is based on the stagnation conditions, but the spallation process is very time dependent process. The next interesting step in thermal spallation was conducted by Los Alamos National Laboratory who designed a burner only for drilling purposes. Their best spallation result was around 3 m/h of penetration rate with perforation depth till 18 mm, but the rock sample started to melt what stopped thermal spallation (Silva et al. 2006).

Thermal spallation drilling presents a great potential not only for mining, but also for drilling of deep geothermal wells. Therefore, a high pressure drilling pilot plant (HPDP) has been built at the Institute for process engineering at the ETH Zurich simulating the conditions under the earth surface (Stathopoulos 2013). The water is used as the drilling fluid to transport created spalls. In order to improve rock drilling experiments under high pressure in an aqueous environment, the spallation drilling mechanism should be

better understood. The required heat for successful rock fracture and its link to the structure of treated rocks remains still unknown. Thus, an ambient spallation drilling setup (ASDS) has been built in order to improve the understanding of the rock fracture mechanisms and to define required heat transfer conditions for thermal spallation drilling. Compared to the high pressure setup, the ambient spallation drilling setup has an optical access, which is an advantage for optical measuring methods, it has a shorter shut down and start up procedure, replacement of rock samples is simple and even possible at flame presence. The goal is to compare the heat transfer studies of ASDS and HPDP and thus, to define the spallation potential of HPDP. Before the comparison of heat transfer studies and before finding the explanation for the thermal spallation mechanism, some preliminary experiments with ASDS have to be performed. In this work it is presented the obtained spallation results at ambient pressure, spallable rock types, an influence of the rock size on fragmentation at the lab scale, a link between the operating conditions and the spallation results and also the rock surface temperatures when spallation starts. Additionally, the ambient spallation drilling setup is briefly described.

2. THEORY

Different theories have been developed in order to give an explanation of the thermal spallation process for hard, polycrystalline rocks. Thermal spallation presents a surface fragmentation of a material, in our case rock sample, due to thermally induced stresses. Preston and White claimed that the spallation mechanism is based on the growth of already existing flaws in the material due to induced compressive stress (Preston 1934). Rocks with larger grains could contain more flaws than fine grained samples and, therefore, soft, elastic and/or fine grained minerals reduce the stress development because they tend to yield rather than expand upon heating (Rinaldi 1984). Researchers tried to define the most important influencing factors on thermal spallation. Rinaldi mentioned that the grain size and their distribution influences the thermal rock fracturing process, as same as thermal elongation, rock compressive strength, thermal diffusivity and other factor like quartz content. Calman introduces the term “thermal spallability” that is proportional to the thermal diffusivity, expansion, grain size and inverse proportional to the compressive strength of a rock sample (Calman 1968). Besides, Gray claimed that thermal shock is caused not because of the reached temperature of the body, but because of the existing temperature gradients in it (Gray 1965). All existing definitions indicate the complexity of thermal spallation and difficulty to model it.

3. EXPERIMENTS

3.1 Experimental Setup and Procedure

The used ambient spallation drilling setup presents a potential drilling tool but only on the laboratory scale, where the size of the rock samples is limited till around 200 mm in height. For the presented preliminary experiments, however the mentioned rock sample size is suitable to test their spallation properties. As it is shown in Fig. 1, the main element of the setup is a burner where the combustion takes place. The exhaust gases exit the burner through the nozzle and impinge the rock surface. The maximum tested heat of combustion was in the adiabatic case 45 kW with the chamber temperature close to the exit nozzle around 1000°C. Methane is used as a fuel and air as an oxidant with the air-fuel equivalence ratio of 1,1. The pressurized methane at 13 bars and air at 7 bars are controlled in kg/h over the digital flow controllers. After the combustion process exhaust gases are released in the surrounding and lead with 11 000 m³/h of air into the ventilation system. The pressure in the burning chamber and temperatures (burning chamber, cooling water) was measured by the EtherCAT terminals (Beckhoff, Switzerland). Nitrogen is used to purge the methane pipeline after the experiments.

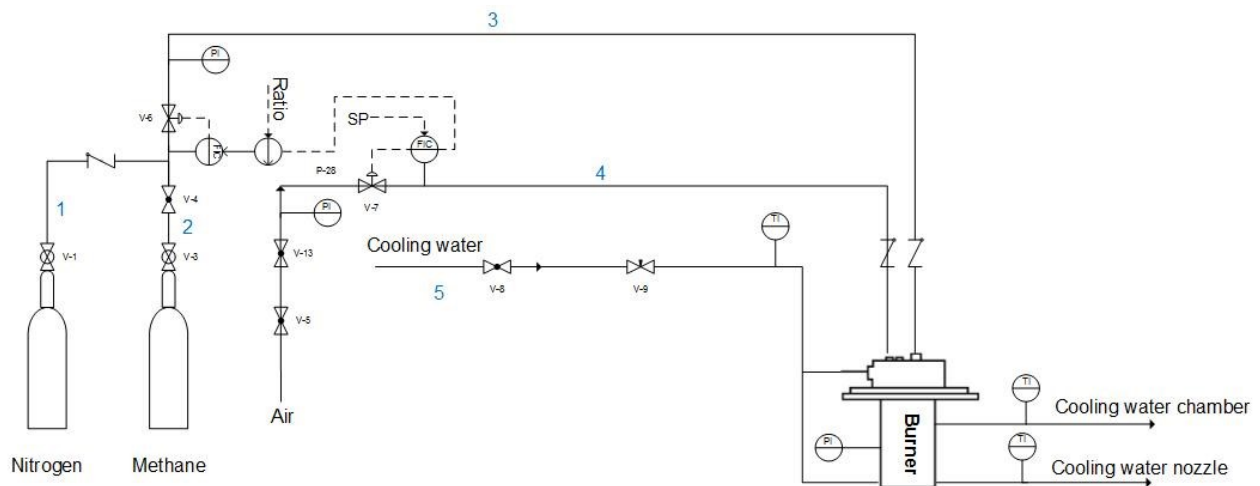


Figure 1: Flow sheet of ambient spallation drilling setup.

The burner, which provides premixed flame, consists of three parts as presented in the Fig. 2. :

- Mixing part: Methane mixes with air before entering the ignition area
- Combustion chamber: Intermediate part of the burner where the gaseous mixture (methane and air) is ignited and combusted
- Exit part: Lower part of the burner where exhaust gases exit the burner through a replaceable nozzle.

After defining the set point for methane and air-fuel equivalence ratio, methane enters the mixing part of the burner and gets in contact with air. Fuel and oxidant flow through a perforated plate to improve the mixing and enter the combustion chamber. Right after the mixing pipe, a silicon nitride heater in a form of a thin and long cylinder is used to ignite the flammable mixture.

Connecting the ceramic heater to an AC power supply it is possible to reach surface temperatures up to 1000°C. The combustion reaction starts at lower mass flows of the gaseous mixture and afterwards the heat of combustion is slowly increased till a desired value. The combustion products exit the burner through the nozzle, which can be replaced if different nozzle diameters had to be tested. Both combustion and exit part of the burner are cooled with water.

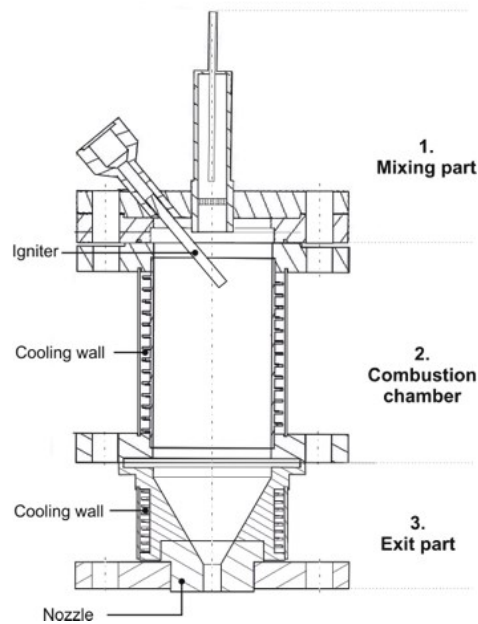


Figure 2: Burner of the ambient spallation drilling setup

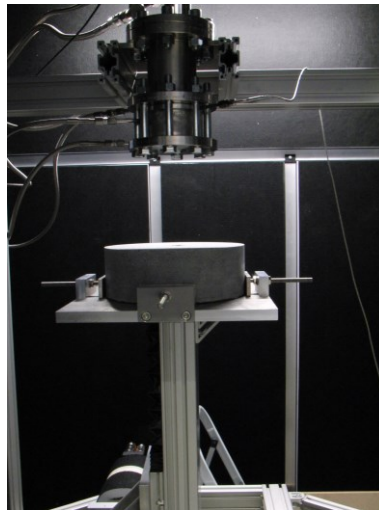


Figure 3: Ambient spallation drilling setup with the rock sample prepared for spallation drilling.

The installed elements of the ASDS and the prepared rock sample for spallation are present in Fig.3. On the upper part of Fig. 3, above the rock, the burner can be seen. With the linear actuators it is possible to bring the rock sample rapidly under the hot jet of exhaust gases moving it horizontally and also vertically to adjust the rock surface – to – nozzle distance (standoff distance). Everything is placed in an insulation cabin to reduce the noise produced by the burner during spallation experiments.

Preliminary spallation experiments at the ASDS started always with 70 mm standoff distance having successful thermal spallation even at the lower flame powers. The exit nozzle diameter of the burner was also kept unchanged at 7,4 mm during all preliminary spallation experiments. The power of the flame was slowly increased and when the desired value has been reached, a rock sample was rapidly brought under the burner at the desired position. Only the types of rock samples and the mass flow of fuel and oxidant were varied, having the fuel-air equivalence ratio constant.

3.2 Drilled Rock Samples

The tested rock samples with the ambient spallation drilling setup are listed in Fig. 4. The choice has been made according to the grain size, available physical properties in literature and origin. The rock samples had a form of a cylinder with a diameter of 300 mm and a height of 150 mm.

Name	Properties	Origin	Type
Gotthard 1	light grey coarse grained no layers	Switzerland	Igneous rock
Paradiso 2	red fine grained with layers	India	Igneous rock
Gabbro 3	dark coarse grained no layers	China	Igneous rock
Bethel 4	white medium grained no layers	USA	Igneous rock



Figure 4: Tested rock samples for ambient spallation drilling. Left-top 1: Gotthard granite, right-top 2: Paradiso migmatit, left-bottom 3: Gabbro granite and right-bottom 4: Bethel granite.

3.3 Surface Temperature Measurement

Infrared thermal imaging device (infrared (IR) camera), used to monitor temperature development on the rock surface during the spallation process, was Optris PI450 with the frequency of 80 Hz and the wavelength range between 7,5 and 13 μm . To perform the measurement with any infrared thermal imaging device an emissivity of measured surface has to be known. Thus, the used IR camera had been first calibrated before the spallation experiments were performed. Rock surface emissivity was measured by means of a black paint Pyromark 2500 with known emissivity. Half of the rock sample painted with black paint had a surface temperature which represented a reference temperature for the unpainted rock part. The emissivity of the rock sample was determined by assuming that painted and not painted surface part had the same temperature. Obtained emissivity for tested rock samples is temperature dependent property, but for temperature monitoring during spallation process a mean value has been taken. The error from emissivity averaging was included in the final uncertainty calculation of surface temperature measurements. Depending on the rock sample type emissivity is between 0.78 and 0.80. The final uncertainty of the rock surface temperature measurement with IR camera is between 15 and 30 $^{\circ}\text{C}$ at 170 $^{\circ}\text{C}$ and 650 $^{\circ}\text{C}$ respectively.

4. RESULTS

4.1 Spallation Drilling Results

Results of preliminary spallation drilling experiments at the ambient conditions are present in Fig. 6 and 7. By increasing the heat of combustion, the higher heat transfer from the flame to the rock surface enhances the spalls creation and their removal. Penetration rate is the ratio between the drilled depth and the spallation time reaching the maximum at 1.97 m/h for tested combustion heat and with tested sample size. It is presented on Fig. 6 as a function of the heat of combustion indicating that the fastest spallation was achieved with Paradiso and Bethel granite rock samples. Paradiso has very small grain size and spalls result more in a form of sand. Once a sample of sandstone has been shortly tested, with even smaller grains and similar spallation effect has not been recorded in the Transport Process and Reaction Laboratory. Quite the opposite, the surface cracked only once with a large spall that covered half of the rock sample surface. Hence, it is assumed that smaller the grain size, better spallation drilling can be reached, but never the less too small grain size might lead also to less flaws existing in the rock sample and therefore bad spallation. As an example of less successful thermal spallation it was the experiment with the Gabbro rock samples, where the fragmentation stopped after 5 mm of penetration for low combustion energy (27 kW). Even being optical very similar, Bethel and Gotthard granite showed different penetration velocity. In order to find an explanation for the observed phenomena further research is required.

At the lowest reported heat of combustion the first detaching of spalls occurs 0,70 s after bringing the rock sample under the flame. The spallation process lasts, in the best case, 86 s creating a hole 47 mm deep with 40 kW of combustion heat (Paradiso granite). Resulting holes in spalled rock samples are shown in Fig. 5. Deeper penetration was not possible because of the rock samples brakeage through the whole volume from the outside to the center of the probe. At the beginning of the spallation process thermal stresses are present in the center of the rock probe causing spalls creation only in that area. After some time the stresses expand through the whole rock sample and engenders the large fracture. From that moment spallation does not take place anymore because all induced thermal stresses are released through the created crack. The smaller the rock samples the sooner it cracks causing the end of thermal spallation. The formed large cracks of spalled rocks can be also seen in Fig. 5.

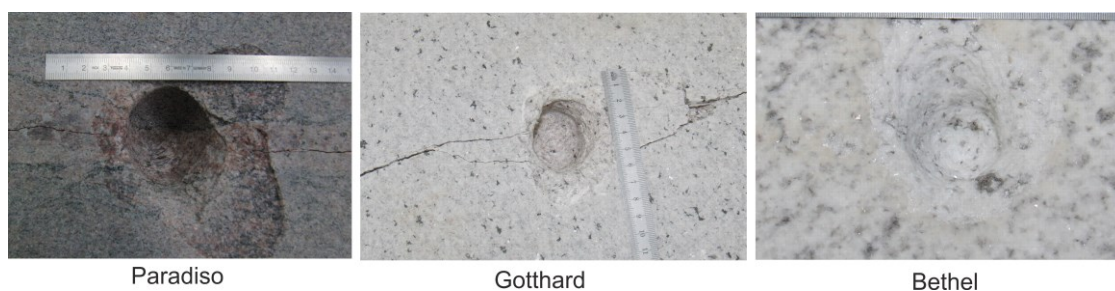


Figure 5: Spalled rock samples: Paradiso 40 kW, Gotthard 45 kW, Bethel 40 kW.

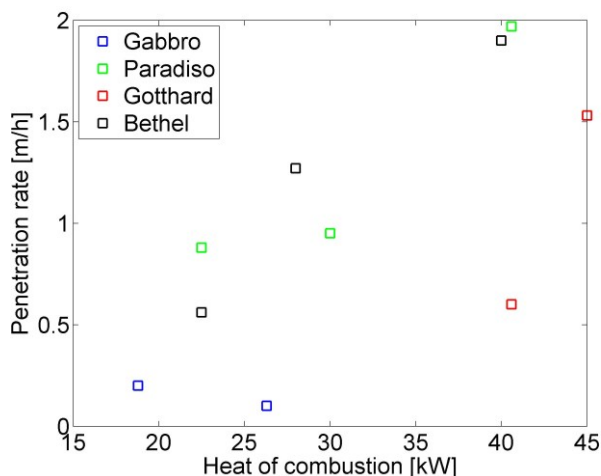


Figure 6: Resulting penetration rate of different tested rock samples at ASDS.

The heat of combustion presented in Fig. 6 and 7 is calculated assuming ideal combustion where all reactants are consumed. Heat losses due to cooling in the wall of the reactor have been also considered. Furthermore, it would be beneficial for the description of thermal spallation to perform the heat transfer study from the hot jet. Tested heat flux sensor has to be adjusted and improved to measure more accurate the heat fluxes higher than 1 MW/m^2 . From the already performed heat flux measurements with high temperature heat flux sensor (Wuntronic GmbH, Munich), it is believed that the heat flux in the case of ASDS exceeds 2 MW/m^2 .

From Fig. 6 it could be concluded that good spallable rocks, rocks with faster spall removal, are Paradiso and Bethel. But if the removed volume over time (removal rate) presented in Fig. 7 is taken into account, Paradiso is far more spallable rock than Bethel. Therefore, only the penetration rate does not describe quantitatively the thermal spallation drilling process. In the case of the Gotthard sample, the hole was wide and shallow, but still the same amount of rock has been removed as in the case of Bethel granite which had higher penetration rate (at 40 kW combustion heat). Possible reason for that is still unknown and the experiment should be repeated. Additionally, it could be concluded that the removal rate also increases with the combustion heat.

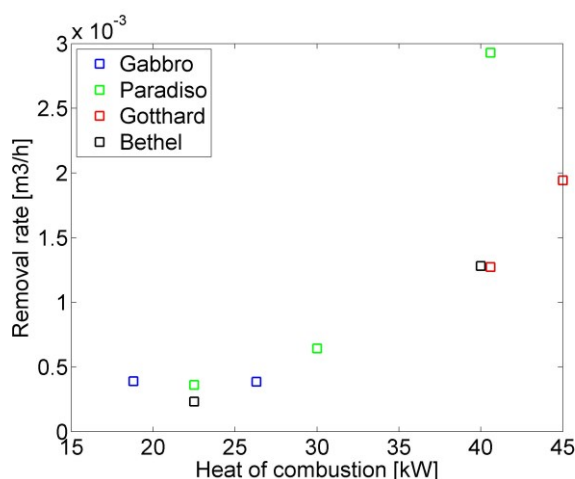


Figure 9: Resulting removal rate of different tested rock samples at ASDS.

4.2 Surface Temperature Measurements

Each spall detected from the surface during the spallation process flies off in very short time intervals. IR camera gives a possibility to monitor temperature development over the whole surface, thus in the post-processing phase of recorded video the temperature measurement can be focused on one spall wherever it is detached. After positioning the rock sample under the 22.5 kW impinging flame the surface temperature increased for around $50 \text{ }^\circ\text{C}$ in every 0.5 s. At the combustion heat higher than 40 kW rock surface temperature raise is very fast, thus, the 80 Hz recording frequency of the IR camera is not fast enough for temperature monitoring. The surface temperatures in that case are measured with much lower accuracy. Anyhow, this measuring method of rock surface temperature can give us a trend of temperature development during the spallation process. Surface temperatures of the first spall 1/80 s before being detached from the surface (spallation surface temperature) are shown in Fig. 8. For the tested rock probes the obtained spallation temperatures are not much dependent on the heat of combustion. Indeed, in the experiments with higher penetration rate (Paradiso and Bethel granite) the rock sample start to spall at lower surface temperatures (around 500°C). This is due to less heat accumulation along the surface caused by faster spalls removal.

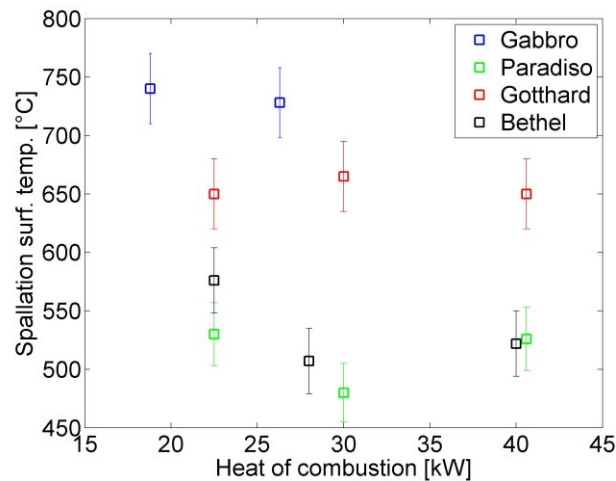


Figure 8: Surface spallation temperatures 1/80 s before the spall was detached from the surface.

5. CONCLUSION

Ambient spallation drilling setup has been designed for thermal spallation drilling experiments at ambient pressure. Results of the preliminary spallation experiments are penetration rate in m/s, removal rate in m³/h and surface temperatures 1/80 s before the spall was removed. It can be concluded that the penetration is very dependent on the combustion heat of impinging flame. Preliminary experiments have been performed with the heat of combustion up to 45 kW reaching penetration and removal rate around 2 m/h and 3 dm³/h respectively. Recorded surface spallation temperatures at the moment of the first spall detaching are in the range between 480°C and 750°C, depending on the tested rock type. As a consequence, the rock type that will be used in the future for the thermal spallation experiments is Paradiso and Gotthard granite as examples of one high and one medium spallable rock. It is possible to spall rock samples with the combustion heat above 19 kW, but much better results are reached at 30 kW flame and more. The goals of further research is to define required heat transfer conditions for the successful spallation drilling, to proceed more experiments in order to link the spallation results with the physical properties of the rock samples, to improve surface temperature measurement and to spall the rock samples also with the heat of combustion higher than 45 kW in order to analyze the thermal spallation at higher flame powers for possible improvement.

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