CONCEPT OF LARGE-SCALE THERMOMECHANICAL URL EXPERIMENTS IN THE NIZHNEKANSKIY ROCK MASSIF

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Numerical simulation of thermomechanical processes in a deep underground radioactive waste repository requires information on the host rock and the engineered barriers properties at a scale of dozens of centimeters, meters and more. However, extrapolation of values obtained on small-scale samples in surface laboratories yields excessive uncertainties. Materials behavior is also influenced by conditions that cannot be reliably reproduced in a surface laboratory, such as water content or initial stress-strain state. The following experiments are planned to study the host rock and the engineered barriers behavior during heating under conditions similar to those expected in the repository, as well as to assess their large-scale thermomechanical properties. In the experiment focused on the excavation damaged zone, thermal mechanics, the behavior of reinforced drift walls and vaults under heating will be studied. The experimental facility will involve two drifts with the same orientation as the planned repository ones. As a result, spatial distribution of excavation damaged zone thermomechanical parameters and their evolution due to heating will be identified. The second experiment focuses on the host rock mass behavior under spatially non-uniform unsteady heating. The facility will feature two vertical boreholes with heaters. The experiment will be divided into several stages: study of the host rock initial state, estimation of the main rock thermomechanical properties, temporal evolution of the stress field due to 3D temperature gradients and processes in the host rock occurring during its cooling and re-saturation with water. Following the completion of the separate-effect test program, an integrated experiment should be carried out to study the coupled processes with respect to their mutual influence. The obtained results will be used to refine the values of input parameters for numerical simulations and their uncertainty ranges, as well as to validate the computer codes.

Keywords: *radioactive waste, deep geological repository, thermal mechanics, experiment, underground research laboratory, host rock, engineered barriers.*

Introduction

Reliable data on the properties of the host rock and EBS materials is required to simulate thermophysical and mechanical processes in the disposal system. At the same time, enclosing rock mass is heterogeneous both considering the composition of the constituent rocks and its structure: it may involve cracks, cavities, crushing zones, etc. This heterogeneity yields significant uncertainties in the assessment of the rock mass on the whole. Moreover, no realistic estimates can be obtained from the study of small-size samples being of the order of several centimeters. Unlike composition inhomogeneity and its influence on the thermophysical properties which can be actually accounted for granted a rather large number of samples, effects driven by mechanical degradation can be studied only on a scale of at least tens of centimeters and preferably meters or more. The same applies to the mechanical properties of the rock mass heavily depending on the bedrock state.

Mining operations also introduce uncertainty. Drilling and blasting operations (DBO) cause additional damage to the surrounding rocks. Further on caverns and cracks in the excavations are grouted resulting in a spatially inhomogeneous medium with its properties depending both on the initial state of the rock mass and on the applied excavation method. Therefore, direct measurement method is the only way allowing robust identification of these properties. Despite available stochastic methods allowing to estimate fracturing in the DBO area, their application without preliminary experimental studies would result in excessive uncertainty. After the start of RW disposal operations, this inhomogeneous medium will be exposed to thermal loads, which due to the difference in the thermomechanical parameters of concrete and the bedrock, will contribute to additional mechanical stresses. This may drive the transformation of existing cracks and the appearance of new ones, thus negatively affecting both the strength and the sealing capacity provided by EBS.

Two large-scale experiments are proposed to be implemented in the URL being currently constructed in the Nizhnekanskiy rock mass to evaluate the thermomechanical parameters of the rock mass. These are focused on thermal and stress-strain state (SSS) of the rocks when heated:

- experiment focused on heat and strain stress impacts produced on the excavation damaged zone (EDZ), grouted vaults and walls of excavations (EDZ thermomechanics);
- experiment focused on heat and strain stress impacts produced on the host rocks (rock thermomechanics).

In addition, a large-scale integral experiment is planned: it focuses, in particular, on the final refinement and testing of disposal methods. During this experiment the reliability of forecasts performed using computational software packages to predict thermomechanical, chemical, transport and other phenomena with an account taken of their mutual interaction will be also checked. Thermomechanics will also play a significant role in it, since the processes occurring in the medium will largely depend on its temperature with mechanical loads being seen as a key factor contributing to EBS integrity.

EDZ thermomechanics

The first experiment focuses on the behavior of grouted walls and tunnel vaults at elevated temperatures. During wall and vault grouting, concrete penetrates into cavities and cracks available in the EDZ contributing to a heterogeneous environment. This is especially true for excavation sections lying within the increased fracturing zones. In these zones, rocks can be grouted before the start of drilling and blasting operations commonly via high-pressure concrete pumping into pre-drilled wells. At the same time, the concrete can penetrate through the cracks into the rocks to a depth of several tens of centimeters. The rock mass containing DDF RW structures is subject to heating. In this case, due to a rather complex three-dimensional temperature field [1, 2], substantial shear stresses will arise along with the compressive ones. This can cause deformation and possible degradation of grouted walls and vaults. Metal structures used for vault reinforcement purposes will account for an additional source of stress inhomogeneity.

It should be noted that the above is a qualitative description of heating effects on a grouted crushing zone. Thus, detailed information on the crack geometry, actual rock and concrete properties and the initial stress field in the rock mass is required for any reliable numerical estimates of stresses and deformations.

Some approaches were developed to model the stress-strain state of EDZ [3, 4]. These are based on stochastic methods of crack generation, nevertheless requiring preliminary experimental study of EDZ fracturing to obtain necessary initial data and should be validated in experiments carried out under realistic conditions. Thus, anyways their application requires an experimental study of the rock mass intended for DDF RW construction.

EDZ fracturing largely depends on the orientation of the excavation relative to the main stresses available in the rock mass [5]. Therefore, boreholes having the same orientation relative to the main stresses as the excavations envisaged in the disposal designs should be used to obtain the results that could be considered relevant to actual disposal conditions. Thus, the experimental unit should consist of two perpendicular sections of a tunnel running in the direction that would correspond to the one of transport and service excavation and disposal chambers with their length amounting to about 5 m. The sections should be located within a highly fractured area in the host rocks and should be subject to further grouting. These sections should be desirably located close to each other, so that the observed differences in stresses and displacements would depend solely on the tunnel orientation relative to the main stresses, and not on the rock properties.

The cross-section of the excavations will be similar to the one shown in Figure 1 having a horizontal floor and an arched vault. Thermomechanical

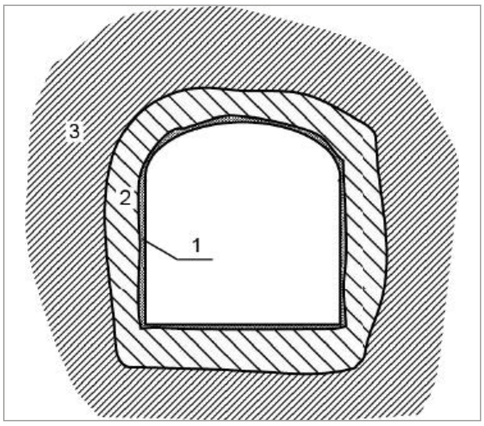

Figure 1. Proposed cross-section of disposal excavations: 1 — spray-concrete lining, 2 — EDZ, 3 — intact rock

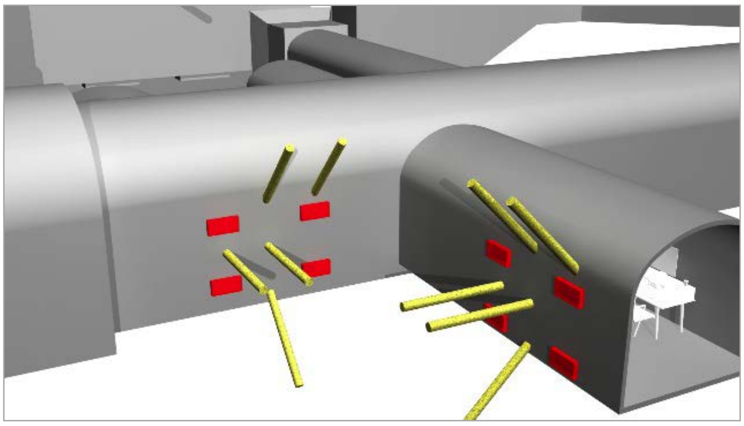

Figure 2. Layout of an experimental unit designed to study thermomechanical processes in EDZ

processes evolving in the entire section are considered to be of interest; therefore, areas near the floor, on the vertical wall and near the roof of the tunnel should be heated. Heat sources (4 per section) with a capacity of 1—1.5 kW each are proposed to be installed into the walls of the tunnels. Approximate location of the sources shown in red in Figure 2 is seen as a preliminary one and will be further refined based on calculations, as well as the required power. In addition, tool boreholes (shown in yellow) will be drilled to accommodate the sensors. The experiment will last approximately 1—3 years. According to preliminary estimates, other sources of heat and mechanical stresses should be located at a distance of no less than 10 m from it.

The experimental study will help to determine the spatial distribution of estimated mechanical EDZ parameters, primarily stresses, displacements and possible failures and their evolution due to heating. In addition, material will be sampled to allow further studies in the surface laboratory primarily aimed at assessing its pre- and post-heating strength properties. Ultrasonic exploration of the crushing zone before rock grouting is of a particular interest since its state can be compared to the one that will evolve after rock grouting and heating. This will require some coordination with the tunnellers during excavation, since the preliminary ultrasonic measurements are to be carried out at the excavation stage.

Geophysical measurements, including ultrasonic ones, are considered essential since intact cores should be used during compression studies in a surface laboratory. At the same time, ONKALO URF studies [6] show that micro-fracturing of intact samples is subject only to some minor changes. On the other hand, geophysical methods show that due to mining operations noticeable changes in the properties occur on a macroscopic scale. This may be due to the dynamics of larger cracks not manifesting itself on intact samples.

In Situ Concrete Spalling Experiment conducted in ONKALO laboratory (Finland) [7] pursues a similar goal: to study an EDZ grouted with concrete. Upgraded installation previously used in the POSE experiment is used for these purposes: a vertical well in the host rock with its walls grouted with concrete and heaters placed in the rock around it.

It should be emphasized that since the ONKALO experiment involves a vertical well, these two experiments (the indicated one and the proposed one) will complement each other taking into account the dependence between stresses and degradation in the EDZ and the orientation of the excavation.

Rock thermomechanics

Another experiment focuses on host rock behavior under spatially inhomogeneous unsteady heating. Preliminary calculations show [1, 2] that at the bedrock heating stage, significant temperature gradients will arise in several wells due to the heat generated by HLW. Therefore, high shear stresses may appear along with the compressive ones.

Thus, preliminary estimates show that effective (von Mises) stresses will amount to over 10 MPa considering the proposed DDF RW layout with HLW being disposed of in long vertical wells. In this case, typical shear strength for gneisses will amount to tens of MPa, i. e., values of the same order of magnitude. Accordingly, an experimental study is required to:

- to calculate the temperatures and stresses in the rocks given the heating expected under HLW disposal conditions;
- to identify thermomechanical parameters of the rock mass on a macroscopic scale allowing further calculations;

- check the accuracy of numerical modeling dealing with temperature field and SSS in the rock mass.

Otherwise, the distribution of stresses and deformations in the rock mass enclosing the disposal facility cannot be reliably evaluated which is required for safety demonstration purposes.

Similar experiments have already been implemented abroad, for example, in Sweden (Äspö Pillar Stability Experiment, APSE [8], external section of Äspö Prototype Repository, APR [9, 10]). POSE experiment conducted in ONKALO URF pursued similar goals [11, 12]. Results of these experiments can be used during the development of Russian R&D program. Nevertheless, these cannot be applied directly in the safety assessment, since they consider different rock composition and properties.

Recent studies focused on the thermal rock properties [13] of the Nizhnekanskiy rock mass revealed potentially higher uncertainties than the ones assumed earlier. According to handbooks (see, for example, [14, 15]), thermal conductivity of gneisses commonly amounts to more than 2.5 W/(m·K). Similar values were derived from the study of granitoids constituting to the rock mass enclosing the Swedish HRL Äspö [16]. At the same time, according to [13], thermal rock conductivity of 0.8 W/(m·K) was derived from the measurements of dried samples collected from drilling wells. It was noted that such low values can be due to the impact that the defects can produce on large samples: a thermal conductivity of 2.5 W/(m·K) and more can be expected in case if the defects get saturated with water. Whatever were the causes of such large discrepancies, it seems critical to study the properties of rocks constituting to the Nizhnekanskiy rock mass on a large scale, at least several meters, and under actual saturation conditions.

Figure 3 shows the proposed layout of the experimental unit involving two vertical wells with 1—2 containers (SC) simulating actual containers with HLW installed in each of them spaced by 4—6 m. The length of the heated section for each well will account for 3—6 m. The heater capacity should account for 2—9 kW per well depending on the layout of a particular installation. It should be noted that the distance between the wells in the experimental unit will be less than the one assumed in DDF RW designs, whereas the heat release will be slightly higher: this allows faster heating of the bed rock. Well diameter should correspond to the one provided for in the designs (currently a 1.3 m diameter was assumed) which is necessary to recreate realistic heat fluxes near the heaters. A number of vertical instrumental boreholes and possibly some inclined boreholes (IB, shown in yellow in Figure 3) will be also required for logging and sensor installation purposes. Moreover, some IB should be drilled before the drilling of wells for heater installation takes place, allowing to monitor the changes in the mechanical properties of the rock during drilling of large-diameter wells. Simulated containers will have a simplified design: a metal body and heating elements (possibly additional structural elements) also providing for a thermal contact between the heaters and the rock. This allows to reduce the influence of additional factors, primarily thermal resistances, produced on unsteady rock heating process. It's proposed to introduce redundant heating elements allowing to minimize the risks of their possible failure during the experiment, as was done under CROP (GRS) study [17].

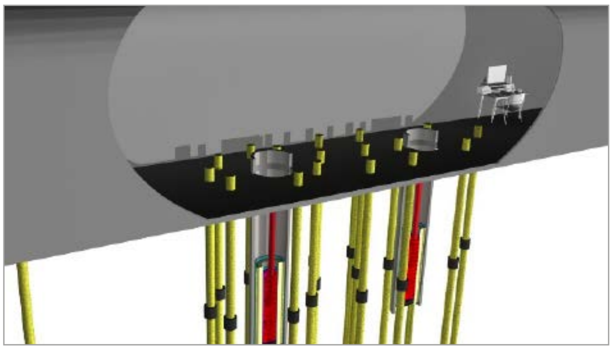

Figure 3. Layout of an experimental unit designed to study rock thermomechanics

The experiment will help to identify spatial distribution of temperature and values characterizing the mechanical parameters of rocks (stresses, displacements, seismic manifestations, speed of ultrasound transmission, etc.) and their time variations due to thermal and mechanical influences also during the drilling of wells for RW disposal. Main parameters of the rock mass will be calculated based on these data: thermal conductivity, heat capacity, Young's modulus, thermal expansion coefficient, fracturing, etc. The calculated parameters will be further used in the numerical modeling of thermomechanical processes expected in the disposal facility. Since thermal rock properties may depend heavily on its saturation level, presence or absence of water in locations subject to measurements should be detected during the experiment.

The experiment involves several stages. Preliminary stage focuses on well drilling and the initial state of the rock mass, cracks present in the rock mass are mapped. First of all, vertical instrumental wells along with sampling performed for subsequent identification of thermomechanical rock parameters in the surface laboratory. Logging surveys are performed in these wells. Upon their completion, equipment is installed there to measure the thermomechanical parameters and the initial state of the rock mass is specified. Spatial distribution of thermophysical rock characteristics near well surface is considered as another point of interest during such exploration. For instance, optical scanning method [18] can be used for these purposes, nevertheless requiring the development of appropriate equipment enabling the application of this method under URL conditions. Thus, uncertainties associated with thermal rock properties will be identified considering several scales: a core fragment, separate well, an area within the rock mass. Comparison of the resulting values will enable the development of extrapolation approaches allowing to extrapolate the figures measured for individual samples to extended areas of the rock mass, which is necessary for numerical modeling.

The instrumental wells layout should provide the opportunities for ultrasonic exploration of EDZ formed during the drilling of wells for heater installation. Figure 4 shows such a possible layout implemented under APR experiment [10]. Thus, the speed of ultrasound propagation both in the immediate vicinity of the well intended for heater installation (for example, between IBs 1 and 3) and at a distance (between IBs 1 and 2) can be measured. A dotted line in the figure shows the paths along which the ultrasound propagation speed was measured. Several instrumental boreholes should be also drilled in the unheated part of the excavation to monitor possible non-heat related changes occurring in the rock mass. Wells are then drilled to accommodate the heaters. Parameters of the rock mass are measured afterwards by geophysical methods to assess the impact produced by the construction of large-diameter wells. Another thing to consider is the possibility of drilling several horizontal small-diameter instrumental boreholes from the boreholes intended for heaters, as well as some vertical ones stretching along the axis. Figure 5 shows a possible layout of such boreholes according to APR experiment [10]. Mockup containers fitted with heaters are loaded into boreholes after sensor installation. Final location and the size of the boreholes will be determined based on preliminary numerical simulation of the experiment. In addition, it will depend on the DDF RW layout.

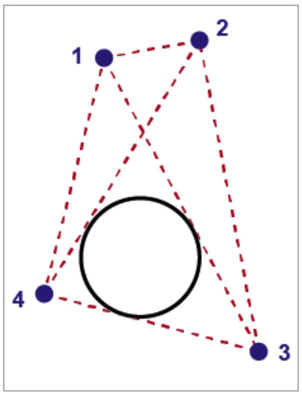

Figure 4. Layout of vertical instrumental boreholes (1–4) in the APR experiment [10]

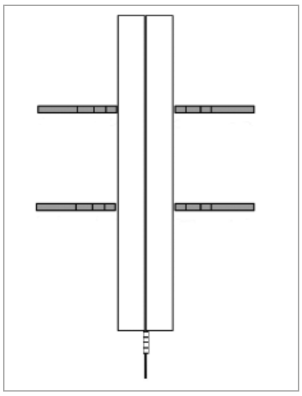

Figure 5. Layout of instrumental boreholes drilled following the completion of wells intended for heater installation in the APR experiment [10]

The first stage, lasting 1—2 years, involves the assessment of main thermomechanical rock parameters: heating is enabled in one well only resulting in a fairly simple and predictable temperature and stress fields. Measurements performed at this stage allow to estimate the thermomechanical parameters of the rock mass at a macroscale. Multivariate numerical thermomechanical calculations will involve varying property values used as input data. Heuristic optimization methods [19] will help to find such values corresponding to the calculated temperature and stress fields being as close as possible to the experimental ones similarly as in case of hydrogeological and geochemical models [20, 21].

At the second stage that would last for 3—5 years, both wells will be heated. It will investigate time-dependent evolution of spatial stresses distribution caused by three-dimensional temperature gradients. Thus, the rock mass state will be studied under conditions similar to those expected in the DDF RW. The results obtained (temperatures, stresses, and displacements) can be used to validate the calculation tools used for the numerical simulation of thermo-mechanical processes expected in the DDF RW, in particular the FENIA code [22]. At this stage, measurements in the heated and unheated parts of the experimental unit should be compared to distinguish between the heat-induced effects on the stress-strain state of the rock mass and its evolution caused by other factors, for example, URL construction process in general.

The total duration of the experiment will be 5—7 years. Heat-induced mechanical stress can affect fracture configuration, especially near the wells causing subsequent changes in the thermal and strength properties of the rock. To assess these changes, upon experiment completion, studies of thermal rock properties by optical methods should be carried out again with samples taken for further research in the surface laboratory. Thereafter, the resulting values should be compared to those obtained before the experiment was started. Fracture should be mapped again to assess the heat-induced effects of the fracture evolution in the rock mass. In addition, measurements allowing to monitor the rock mass state during its cooling and the associated saturation of the rock mass should be continued.

Integral experiment

Upon completing the experimental program focused on individual groups of phenomena (rock thermomechanics, EBS behavior, hydrogeology, microbiology, etc.), an integral experiment should be implemented with the considered phenomena to be studied in aggregate taking into account their mutual influence. In this case, the final layout of the experimental unit (the depth of the wells, their location and distance between them, EBS materials and layout, etc.) will be specified based on the adopted HLW disposal concept.

From the viewpoint of thermomechanics, the integral experiment can be viewed as an extension of the previous one both considering its scale and the spectrum of the studied phenomena. In particular, heat-induced effects on the rock mass state will be studied along with the effects produced by bentonite swelling during its saturation on the stress-strain state of rocks and EBS, the mechanical strength of EBS, including insulating containers (IC), in natural conditions. In this case, IC designs should be similar to those intended for HLW disposal. The robustness of computational tools in simulating the processes expected in DDF RW using coupled models should be verified and demonstrated which is seen as an important part of the study. Along with thermomechanics, other processes will be studied as well: hydraulic, chemical, etc.

To come up with a fully-fledged three-dimensional spatial picture of the studied processes being as much as possible similar to the one expected in the DDF RW a system of 4 wells was proposed (Figure 6). Since the heating of the rock mass to a depth of 10—20 m as expected in the DDF RW requires considerable time, it was proposed to reduce the distance between the wells. The final flowsheet for the integrated experiment should be set based on the experiments focused on individual phenomena taking into account the engineering capabilities for the development of the experimental unit.

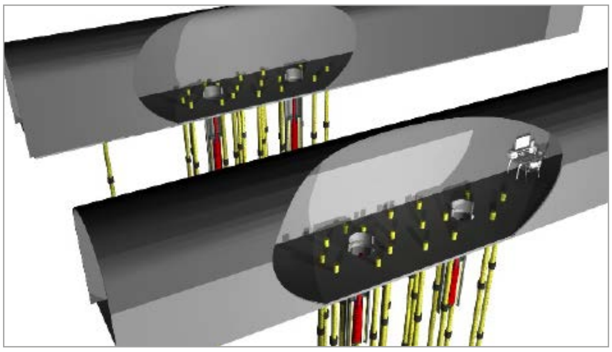

Figure 6. Possible layout of the integral experimental unit

Experiments of this kind reflecting future RW disposal concept and relevant testing methods are also implemented in URLs around the world. In particular, in the Äspö HRL under the Äspö Prototype Repository (APR) experiment [23], the behavior of EBS and near field rocks is studied to investigate thermophysical phenomena, water and gas flows, chemical and microbiological processes. The experimental unit consists of a tunnel section with six vertical wells being 1.75 m in their diameter and about 8 m deep (4 in the inner section and 2 in the outer one). Containers with heaters are accommodated inside the wells with the containers themselves corresponding to those that are supposed to be used for actual RW disposal purposes. The gaps between the containers and the walls of the wells were filled with buffer blocks made of compacted bentonite. The measurement tools applied allow to monitor the pressure of the rocks and the pore water, the saturation with water and drying of the buffer materials, the temperature of EBS and the rock, accumulation of gases in the buffer material, chemical and biological processes. The experiment was started in 2001, the outer section was dismantled in 2010—2011 and the inner section will be monitored at least through 2020.

Conclusions

Based on the experiments described above and proposed for implementation in the Nizhnekansk URL thermal and mechanical parameters of the host rocks can be estimated on a large scale (several meters). This will enable the refinement of previous estimates based on small samples and performed in surface laboratories and the development of scaling techniques allowing to extend such values over large areas of the rock mass. Moreover, evolution of rock properties due to heating and tunneling operations with corresponding changes in the mechanical stress field will be also investigated under natural conditions. Water saturation of rocks under realistic conditions and considering different saturation modes (intensive heating as at the beginning of DDF RW operation and during subsequent cooling) is viewed as another important aspect of the research since the saturation of rocks can produce a noticeable effect on their thermal and physical properties.

Under the integral experiment, the behavior of all disposal system components will be studied under conditions being as far as possible similar to the actual disposal ones. From the viewpoint of rock and EBS thermomechanics, EBS evolution under a combined impact produced by heating, hydrostatic pressure and bentonite swelling, as well as the behavior of the rock mass under inhomogeneous heating conditions is seen as the most interesting point of this experiment. In this case, complex temperature gradients will arise resulting in high stresses potentially marginal to the ultimate strength of the rocks [24]. Findings of the experiment will be used both to test and refine HLW disposal approaches and methods and to validate the calculation tools used to simulate the processes occurring in the DDF RW.

This article has summarized the planned experiments and did not touch upon the issues related to the selection of measuring tools and their location in the instrumental wells. These will be addressed based on numerical modeling, including the uncertainties and sensitivity analysis, similar to the decision made on the other characteristics of the experimental unit. Such a numerical analysis was overviewed in [25] serving a basis for subsequent ranking of the impacts produced by individual parameters of the unit and rock characteristics on the temperature and stress field under rock thermomechanics experiment. Under the experimental program, particular consideration should be also given to the development of approaches for core sampling purposes allowing further core studies in the surface laboratory. In addition, the experiments will require the development of purpose-designed equipment: heaters, remote tools for thermal measurements of rock, etc.

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