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ANALYSIS OF THE PERFORMANCE OF A THERMAL SPALLATION DEVICE FOR ROCK DRILLING

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Abstract. The use of the thermal spallation technique for rock drilling was first considered as an effective way of perforating hard and deep rocks (granites). In this technique combustion generated high pressure, high temperature, supersonic jet is impinged over a hard rock surface perforating it upon impact. The discharge nozzle is kept away from the rock surface, thus delaying a probable tool blunting. The present work presents and discusses the results of tests of that equipment performed on granite samples dealing with, in a first phase, the study of the drilling rate evolution for several operational conditions. In a second phase the influence of the combustion chamber nozzle diameter was examined. This increase in nozzle diameter is accompanied by an increase of mass flow rate and by a corresponding increase of the drilling rate.

Keywords: *thermal spallation, rock drilling*

1. Introduction

The use of the thermal spallation technique for rock drilling was first considered in the eighties and early nineties as an effective way of perforating hard and deep rocks (granites) for setting up geothermal energy production plants. In this technique, combustion generated high pressure, high temperature, supersonic jet is impinged over a hard rock surface perforating it upon impact. The discharge nozzle is kept away from the rock surface, thus delaying a probable tool blunting. This technique is in use nowadays in surface iron ore mining fields to effectively open small orifices for installing explosive charges (Rauenzahn, 1986, Williams et al., 1988).

The feature that turns the use of this technique attractive for use in granites is the rock fracture mechanism, which occurs when submitted to high thermal loads. This leads to compressive loads in the neighborhood of the exposed surface, causing the coalescence of cracks parallel to the face of the material, and its consequent failure. Two ways of achieving this high thermal input have been studied: employing high power lasers and using hot supersonic jets. Although both techniques possess nearly the same efficiency, the spalls produced by the first one tend to obstruct the exposed rock surface, while the gas flow from the burner carries away the removed material, exposing a new surface to be attacked. For a given value of the heat flow input into the rock, the spallation rate increases with the product of its thermal diffusivity with its thermal dilation coefficient and the Young modulus (Rauenzahn, 1986, Rauenzahn and Tester, 1991).

Note that simply melting the rock is not necessarily an efficient manner to remove it. To achieve melting is necessary to yield a higher heat load than the one needed to obtain spalling. Hence it seems more interesting to operate with moderate supersonic jet temperatures, higher than those required to obtain spall, but below the rock melting point. For this to occur the needed heat flux is of the order of $1MW/m^2$, which can be achieved through the burning of propane or natural gas with oxygen or air

In the case of hard rocks, this technique would lead to costs smaller than those required using the conventional rock drilling procedure. The cost of the thermal spallation drilling technique in granitic rocks is estimated as being of US$ 9.00/m, i.e., two orders of magnitude less than the conventional drilling procedure for depths ranging from 3 to 7 km (Wilkinson and Tester, 1993).

Besides, this drilling cost technique would increase linearly with the drilling depth, contrary to the conventional approach whose costs are an exponential function of the drilling depth (Tester et al., 1994). As far as drilling rates are concerned, advance rates up to 10 m/h were measured in surfacing granites (Rauenzahn, 1986, Williams et al., 1988, Wilkinson, 1989, Rauenzahn and Tester, 1991, Wilkinson and Tester, 1993). Further, the drilled holes diameters are from 10 to 20 times larger than the burner discharge diameter.

The development of this drilling technique was interrupted in the US in the early nineties. However, only recently the mechanisms involved in the actual destruction of a rock submitted to a large concentrated heat load have been analyzed and understood, leading to a renewed interest towards its use to achieve deep cavities in crystalline rocks.

Within this framework, in order to further investigate the viability of the use of this technique for drilling hard rocks of interest to the oil industry, a project funded by Petrobras, was awarded to PUC-Rio and INPE. This led to the design, building and testing under multiple conditions, of a model of a thermal spallation rock drilling system. The modeling of the compressible flowfield and its interaction with a cavity was also investigated (Figueira da Silva et al., 2004). This work presents and discusses the results of tests of that equipment performed on granite samples. These tests dealt with, in a first phase, the change of the tool relative advance progress rate, the initial distance between the discharge nozzle and the rock surface and the burning time while measuring the chamber pressure, the fuel and oxidizer volumetric flow rates, the drilling depth and the removed rock volume. In this phase it was also estimated the rock penetration rate (i.e., the ratio between the drilling depth and the testing time). In a second phase the tool advancing rate, the initial distance between the discharge nozzle and the rock surface, the testing time and the O/F (Oxidizer/Fuel) volumetric flow ratio were kept constant, while the chamber pressure, the fuel and oxidizer volumetric flow rates, the drilling depth and the removed rock volume were measured.

2. Process Fundamentals

The rock spalling mechanism achieved through the surface application of high heat fluxes has been described by Freeman et al. (1963), Soles and Geller (1964), and Rauenzahn and Tester (1991) that focused at the thermo-mechanical rock characteristics and the probable fracture. Besides these analyses other studies were also performed also by Calaman and Rolseth (1961) and Rauenzahn (1986), which led to considerable advances in this drilling technique. Successful results in large scale experiments at the Los Alamos Laboratories were obtained by Williams et al (1988).

According to these studies, heat fluxes generated by the hot jet acting on the rock surface lead to high thermal stresses. A statistical approach on stress induced failures behavior suggests that these internal stresses are enough to relay the growth of micro fractures in non homogeneous rock regions. These micro fractures can develop into unstable conditions leading to surface ruptures into small plates (spalls). This continuous spalling process then leads to the desired rock drilling action.

2.1. Fracture Modes

The rock fracture mechanism due through thermal stresses generated by the incidence of a hot jet has been described by Rauenzahn and Tester (1991) based on the work of Dey (1984) and Preston (1934).

The rock surface exposed to the hot jet has its temperature raised through heat conduction. A small portion of this surface undergoes high temperature gradients leading to large thermal stresses in layers parallel to the surface. Any pre-existing fracture in the material propagates under compressive stress along the direction of the applied stress. In this way, existing micro cracks parallel to the rock surface open under the influence of the compression stresses that act parallel to it. The inexistence of any opposition normal to the surface layer, leads it to undergo buckling (Boley and Weiner, 1960). Finally, under the effect of stresses, the ends of this layer rupture, generating the spalling. Hence under each generated spall, fresh layers are exposed to the hot jet and the mechanism is successively repeated generating drilling action as suggested in Fig.1

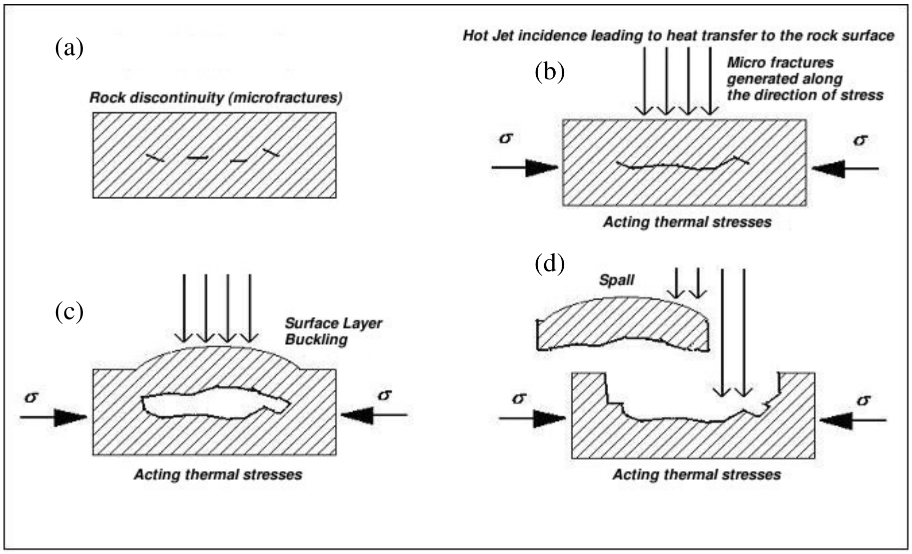

Figure 1. Schematic representation of the rock spalling process.

3. Experimental Set Up

To develop the capability of testing under multiple conditions the thermal spallation effects on granite samples, the facility sketched in Fig. 2 was designed and built at INPE's Combustion and Propulsion Laboratory. In this facility natural gas and oxygen are burnt in a pressurized combustion chamber. The volumetric flow rates of fuel (natural gas) and oxidizer (Oxygen) are set, measured and recorded. These flow rates are a priori adjusted by needle type valves and distance controlled by solenoid valves. Local regulators at the cylinders adjust the feeding pressures and manometers measure the pressure between the solenoid valves and the drilling unit.

Ignition is triggered by the action of a spark plug. The reading of the combustion chamber pressure assures the correct system pressurization or of any possible leaks. Finally, a nitrogen based purging system exists for the sake of the overall operation safety.

An overall view of the drilling tool and of a sample of granite is shown in Fig. 3. Note that the granite samples were chosen based on their fine granulometry on a purely tentative basis. The mechanical and thermal properties of these samples are unknown, which hampers a full quantitative comparison to previously published data. As it can be verified in Fig. 3, the testing sample (made of granite) is supported by a fixed metallic frame bench which also holds the supersonic gas generator, also referred here as the drilling unit. The rock sample to be drilled is set on a scaled rail track in which the initial distance between the nozzle exit area of the gas generator and the testing sample surface can be adjusted. The drilling unit is held in two degrees of freedom support to allow for a fine tuning of the jet incidence angle.

This facility allowed, in a first phase, the measurement of the change of the tool relative advance progress rate, the initial distance between the discharge nozzle and the rock surface and the burning time while measuring the chamber pressure, the fuel and oxidizer volumetric flow rates, the drilling depth and the removed rock volume. The rock penetration rate (i.e., the ratio between the drilling depth and the testing time) was also estimated. In a second phase, the tool advancing rate, the initial distance between the discharge nozzle and the rock surface, the testing time and the O/F volumetric flow ratio were kept constant, while the chamber pressure, the fuel and oxidizer volumetric flow rates, the drilling depth and the removed rock volume were measured. The advance rate is defined as the speed with which the drilling apparatus moves with respect to the rock sample, whereas the drilling rate is the actual measured value of the cavity depth, i.e., the drilling depth, divided by the firing duration. Obviously in steady state operations the drilling and the advance rates should be identical. The total tool displacement is the product of the firing duration and the advance rate.

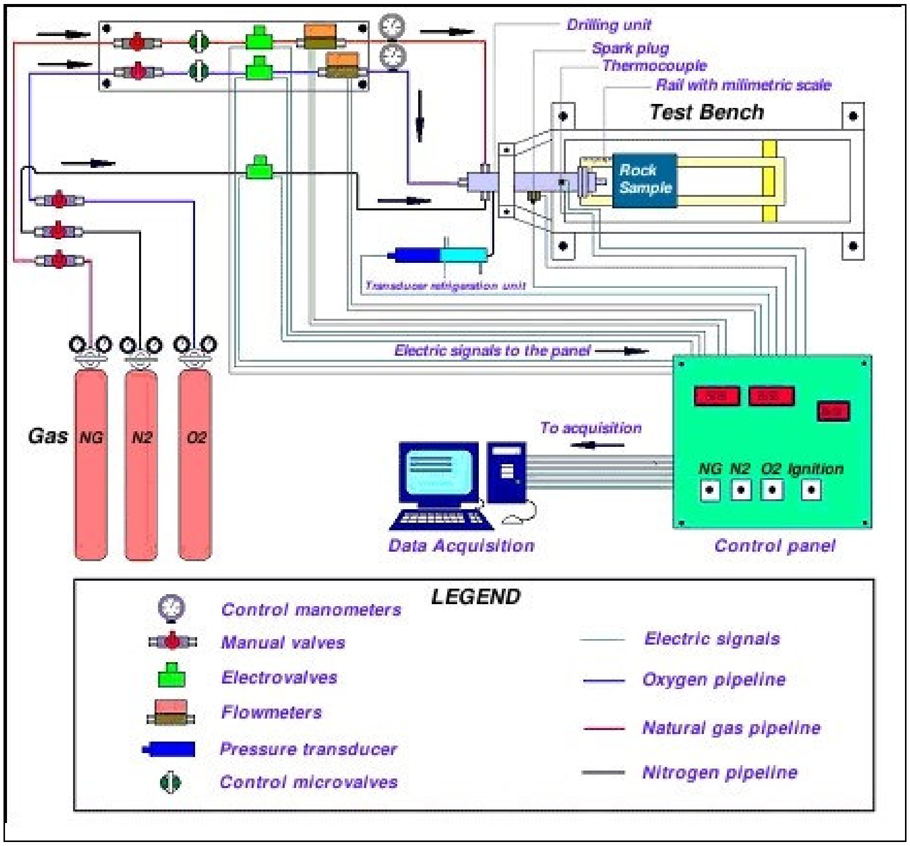

Figure 2. Overall system assembling scheme.

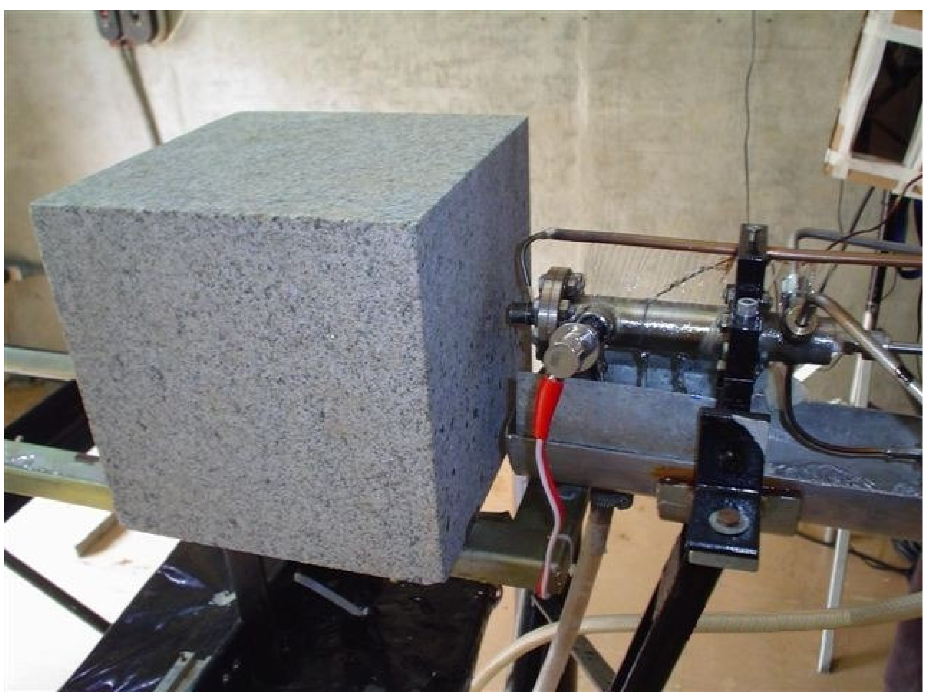

Figure 3. Partial view of the drilling apparatus.

3.1 Data Acquisition

During the test procedure the following data are acquired and stored: the chamber pressure, the natural gas (NG) and oxygen flow rates and the temperature at the drilling unit surface. These parameters are continuously presented and available on the control panel and at the data acquisition system. The control panel also possesses the NG, O_2 and N_2 solenoid valves open/close switches and the ignition switch. The whole system is shielded by a master switch, which operates simultaneously the solenoid valves, closing them at once to abort the test.

The data acquisition system, based on the LabView program, transfers and records in real time all measured parameters which can be recovered as files in ASCII for later analysis. Figure 4 shows the display for this system.

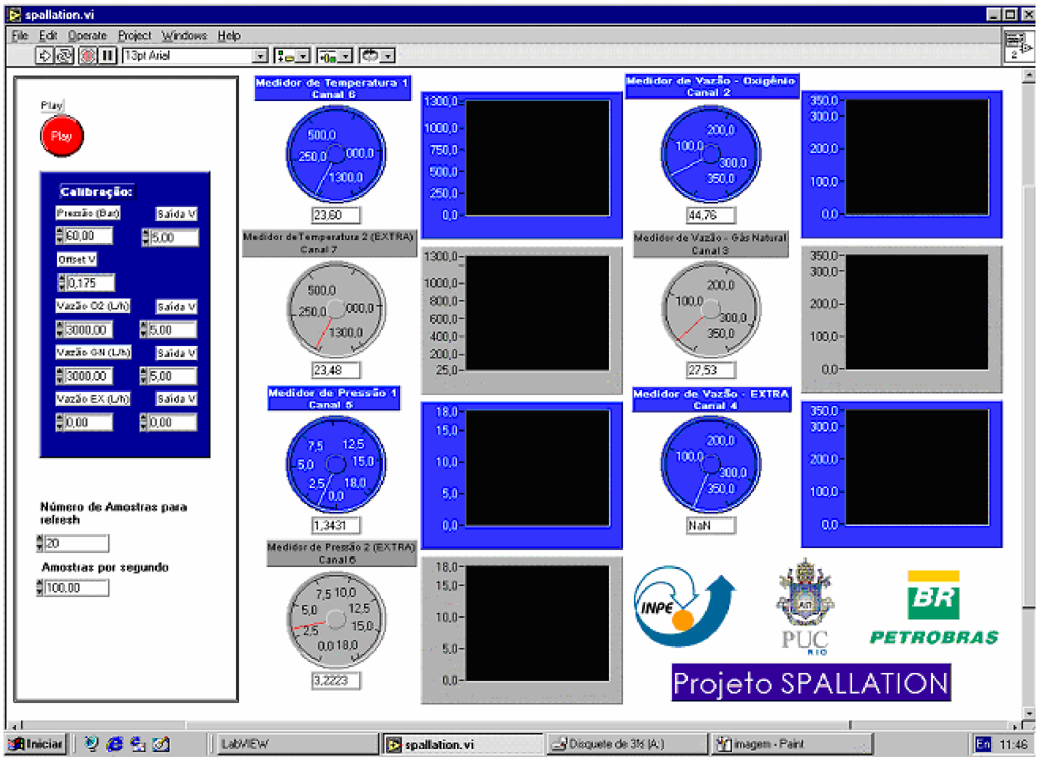

Figure 4. Data acquisition system display.

4. Testing Procedures and Results

The testing procedures were defined in order to achieve meaningful relations among the main operation parameters. To do so, it was decided, in a first phase, to run tests using several previously defined but different mixture ratios and distances between the drilling unit exit section and the rock surface. In a second phase all tests were run keeping the O/F volumetric flow ratio, the firing times and the advance rates constant, while varying the dimensions of the drilling unit nozzle (i.e., its throat and exit diameters). Figures 5, 6 and 7 show the results obtained in both phases, whereas the raw test data can be found in Tables 1 and 2.

Measurements were taken using volume flowmeters for NG and O_2 using Contech Model DMY- 2030 equipment with ± 2% full scale precision. The chamber pressure was measured using a GE Druck strain gage pressure transducer, model PMP 1400, with full scale precision of ± 2%. The drilling depth and the removed rock volume were estimated using a Mitutoyo caliper with ± 0.02 mm precision and a Pirex Beaker with ± 0.5 mL precision respectively.

Figure 5 shows that, despite the large number of parameters which were allowed to vary during this initial testing phase, both the removed rock volume and the drilling rate exhibit a decreasing trend with increasing firing time. The values of these parameters seem to undergo certain stabilization for large firing durations around the figures of 0.5 and 40 dm^3/h, respectively. These values are an order of magnitude smaller than those previously obtained (Rauenzhan and Tester, 1991, Wilkinson and Tester, 1993). Note, though, that these works were conducted using larger diameter drilling apparatus. The initially larger values of the drilling rate could be explained either by the larger relative value of the experimental accuracy of the measured rock removed volume that prevails for small volumes or by the effect of the large thermal shock at the rock surface upon the beginning of the spallation process. This initial thermal shock would lead to larger penetration rates than those observed at the steady state operation. Furthermore, it was observed that, for the smaller stand-off distances between the nozzle exit and the rock surface, and the longer firing times, molten rock seemed to form at the outer edge of the cavity. These high surface temperatures are connected to the chosen combustible mixture, i.e., natural gas and oxygen, which had not been previously used. The formation of the molten rock layer would soften the surface of the sample, thus halting the spallation process. Therefore, in order to achieve a balance between achieving steady state and melting the rock surface, the firing time during the second test sequence was limited to 20 s. Furthermore, tests were conducted with leaner mixtures with the aim of reducing the stagnation temperature of the burned gases.

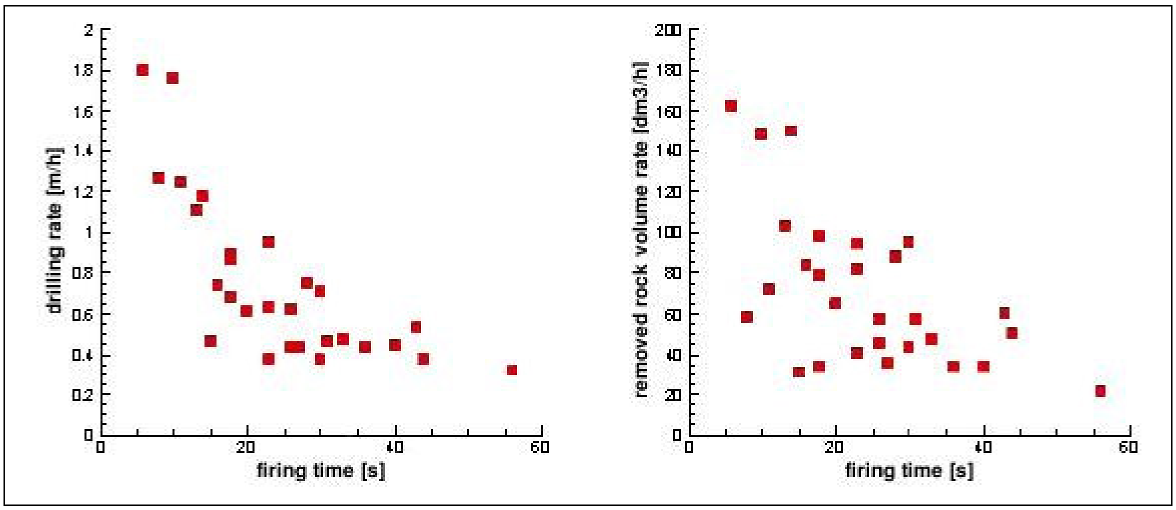

Figure 5. Drilling rate and rock removed volume rate vs. firing time.

Figures 6 and 7 show the drilling depth and the removed rock volume as a function of the nozzle throat diameter for a firing time of 20 s. The details of the experimental conditions are given in Table 2. These figures allow to verify that a three-fold increase on the nozzle throat diameter leads to an order of magnitude increase of both the removed rock volume and the perforated depth, and thus on the drilling rate. For the larger throat diameter, i.e., 6 mm, a drilling rate of the order of 3 m/h is obtained. This value is in accordance to those previously published (Rauenzahn and Tester, 1991, Wilkinson and Tester, 1993).

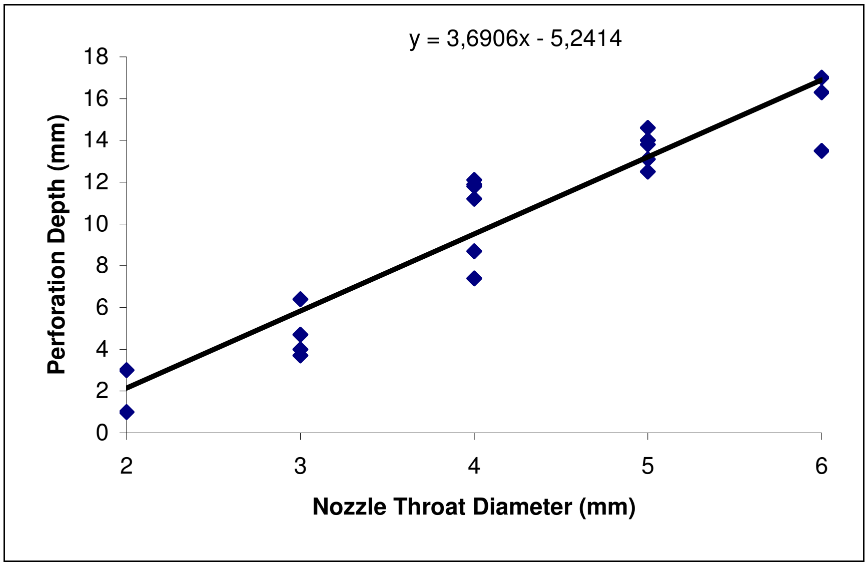

Figure 6. Drilling depth vs. nozzle throat diameter.

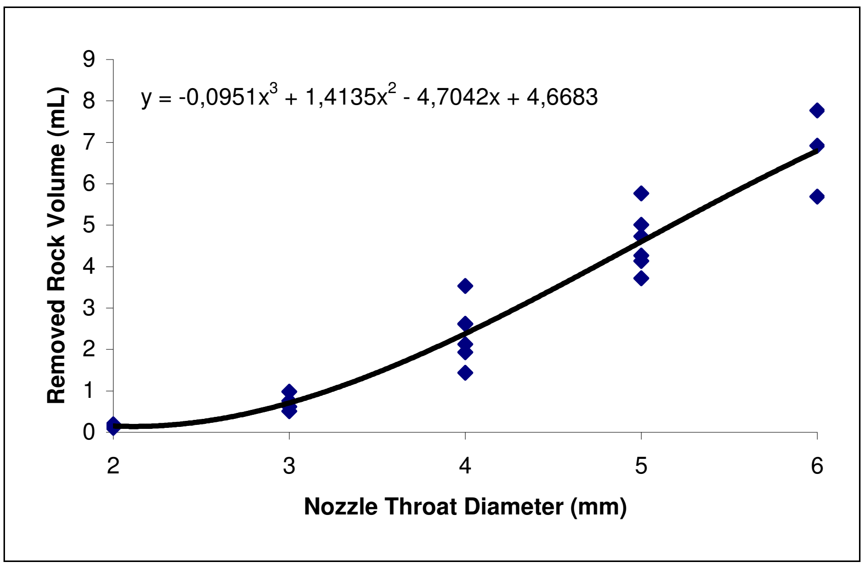

Figure 7. Removed rock volume vs. nozzle throat diameter.

5. Concluding Remarks

Thermal spallation drilling of granite samples has been demonstrated by using a pressurized combustion drilling tool. The initial testing showed that the large energy content of the natural gas/oxygen mixture used led to partial melting of the rock surface. In order to preclude this effect, which impeaches the spallation process, the fuel/oxidizer ratio has been decreased, so to decrease the combustion temperature, and the firing time was limited to 20 s. This short duration is by no means a limitation of the process *per se*, and will be improved in the near future. As a consequence of these operating conditions, and by progressively increasing the combustion chamber throat diameter, drilling rates from 1 to 3 m/h were measured.

Based on the obtained results, the drilling system is now being strongly improved. The on going phase 3 work will includes designing, building and testing a drilling unit with a 10 mm nozzle throat diameter, which will operate at 30 bar, with mean mass flow rates of 500 g/s (compressed air) and 20 g/s (natural gas). The whole system will stand vertically as expected in a real oil well drilling operation and it will be cooled by the feeding compressed air, thus increasing the operation time capability. These improvements are being accomplished with the financial support from Petrobras and in partnership with IEAv/CTA.

6. Acknowledgement

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Table 1. Experimental data from Thermal Spallation on a Granite Surface, phase 1.

Advance Rate (m/h)	Tool Initial Distance from surface (mm)	Firing time (s)	Tool total displacement (mm)	Chamber pressure (Bar,g)	O/F (vol.)	Drilling Depth (mm)	Drilling rate (m/h)	Removed rock volume (mL)
1,80	10,00	18,00	9,00	7,91	5,66	4,30	0,86	0,39
1,80	10,00	20,00	10,00	7,85	3,88	3,40	0,61	0,36
1,80	10,00	30,00	15,00	7,84	2,98	3,15	0,38	0,36
1,80	10,00	40,00	20,00	7,83	3,33	4,90	0,44	0,37
1,80	15,00	26,00	13,00	7,87	4,98	3,10	0,43	0,33
1,80	15,00	27,00	13,50	7,93	6,09	3,20	0,43	0,27
1,80	15,00	43,00	21,50	9,85	5,04	6,30	0,53	0,71
2,00	10,00	16,00	8,89	9,89	4,53	3,30	0,74	0,37
2,00	15,00	31,00	17,22	7,72	4,70	4,00	0,46	0,49
2,00	20,00	36,00	20,00	7,67	5,38	4,25	0,43	0,34
2,00	25,00	44,00	24,44	7,61	5,01	4,65	0,38	0,61
2,00	30,00	56,00	31,11	7,71	5,81	4,95	0,32	0,33
3,60	10,00	8,00	8,00	7,16	2,97	2,80	1,26	0,13
3,60	15,00	13,00	13,00	7,16	3,94	4,00	1,11	0,37
3,60	20,00	18,00	18,00	7,12	3,57	3,40	0,68	0,17
3,60	25,00	23,00	23,00	6,93	4,16	6,05	0,95	0,60
3,60	30,00	28,00	28,00	6,94	3,83	5,85	0,75	0,68
3,60	35,00	33,00	33,00	6,93	3,79	4,30	0,47	0,43
5,00	10,00	6,00	8,33	6,06	3,57	3,00	1,80	0,27
5,00	15,00	11,00	15,28	6,66	3,48	3,80	1,24	0,22
5,00	20,00	14,00	19,44	6,72	3,44	4,55	1,17	0,58
5,00	25,00	18,00	25,00	6,82	3,44	4,45	0,89	0,49
5,00	30,00	23,00	31,94	6,81	3,44	4,00	0,63	0,52
5,00	25,00	26,00	36,11	6,84	3,40	4,50	0,62	0,41
5,00	40,00	30,00	41,67	6,79	3,33	5,95	0,71	0,79
6,00	15,00	10,00	16,67	6,15	3,04	4,90	1,76	0,41
6,00	20,00	15,00	25,00	4,86	2,27	1,90	0,46	0,13
6,00	35,00	23,00	38,33	5,73	2,67	2,45	0,38	0,26

Table 2. Experimental data from Thermal Spallation on a Granite Surface, phase 2.

Removed rock Volume (mL)	Drilling Depth (mm)	Nozzle Throat diameter (mm)	Firing Time (s)	Mean Flow Rate O2 (L/min)	Mean Flow Rate NG (L/min)	O/F (vol.)	Mean Chamber Pressure (Bar, g)
0,11	3,0	2,0	20	629,99	170,67	0,27	2,35
0,19	1,0	2,0	20	633,89	172,01	0,28	2,32
0,51	3,7	3,0	20	1092,99	203,44	0,19	1,05
0,76	4,7	3,0	20	1126,09	201,23	0,18	1,26
0,98	6,4	3,0	20	1154,29	197,65	0,17	1,45
0,62	4,0	3,0	20	1160,71	194,29	0,17	1,41
1,44	7,4	4,0	20	1422,72	312,16	0,22	1,07
2,62	11,8	4,0	20	1442,69	298,69	0,21	1,55
2,13	11,2	4,0	20	1450,56	291,27	0,20	1,52
3,53	12,1	4,0	20	1446,14	287,60	0,20	1,48
2,61	11,9	4,0	20	1451,83	294,42	0,20	1,45
1,93	8,7	4,0	20	1444,65	300,86	0,21	1,40
4,73	14,0	5,0	20	1611,82	398,06	0,25	1,19
4,14	14,0	5,0	20	1656,78	382,61	0,23	1,38
3,72	12,5	5,0	20	1657,68	385,49	0,23	1,34
5,77	14,6	5,0	20	1662,39	379,14	0,23	1,35
5,01	13,1	5,0	20	1667,43	387,41	0,23	1,33
4,27	13,8	5,0	20	1673,74	386,67	0,23	1,30
6,92	16,3	6,0	20	1790,69	565,34	0,32	0,78
7,77	17,0	6,0	20	1803,89	496,42	0,28	0,78
5,69	13,5	6,0	20	1752,82	598,43	0,34	1,25