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Lead author	Simon Hahn (HBO)
Contributors	Volker Wittig (HBO), Sarah Jasper (HBO), Dennis Schwarz (HBO), Dhafir Albadroui (WSG), Koos Hoogland (WSG), Richard R. Bakker (TUD)
Change History	

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1. Executive Summary

Deliverable D5.2 presents the experimental outcome of jetting experiments at simulated reservoir conditions. Different rock types are tested under various conditions with the use of three different types of test bench. At first jetting experiments are conducted under submerged conditions in order to derive a better understanding of the governing erosion mechanism. Therefore pitting tests are combined with PIV measurements in order to derive and explain the erosion pattern of the occurring cavitation erosion and why the rock is more like to be eroded by the stagnation pressure of the impinging jet. Second, jetting experiments under pressure controlled conditions are performed. Rate of penetrations (ROP) of up to 100 m/h can be achieved which proofs the successful application of RJD technology especially in sand stone reservoir rock types. Especially the rotating nozzle design bears the highest potential for jetting operations where the static nozzle designs tend to fail, especially when pore pressure increases. The third experimental series under application of a bi-axial stress field show that the current RJD technology, as being used by project partner WSG, is not able to penetrate harder sandstone rock types (e.g. Dortmund sandstone) when field operating conditions are applied. The induced stress in the specimen does not initiate or enhance ROP. A second experiment thereby shows that higher nozzle exit speeds can lead to massive breakouts. Fourth, experiments are performed under a tri-axial stress field in collaboration with TU DELFT. Rock cubes are tested under different and very severely stress regimes while jetting into them. Compared to tests at atmospheric conditions it can be stated that the application of a stress field does not enhance the erosion of rock. At last experiments are conducted with the project partner WSG in order to determine the jetability of the Icelandic Basalt rock type and Icelandic inter basalt sediment layer. The experiments show that already higher pump pressures result in higher jetting performance, hence making them jetable as previously not expected. Furthermore the experiments approved the feasibility of the planned field test in Iceland when the soft sediment layer is the target zone. All in all the experiments conducted with the RJD technology show different results at simulated reservoir conditions compared to those at atmospheric which are described in deliverable D5.1 (Hahn & Wittig, 2017). Therefor, further testing at conditions representing the reservoir conditions more closer are needed in order to better understand and analyze the jetting process downhole.

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2. Introduction

Jetting experiments under simulated reservoir conditions are essential to understand the jet-rock interaction and thereby develop an estimation for successful jetting operations in the future. In deliverable D5.1 (Hahn & Wittig, 2017) jetting experiments are performed under atmospheric conditions only which includes the rock not being affected by a differential stress field acting on it or internal pore pressure. As in a real reservoir these two aspects occur it is mandatory to simulate them in lab experiments in order to get closer to the physical process of rock destruction and extraction downhole. Initially these tests should be conducted in the iBOGS test bench ("in-situ borehole and geofluid simulator") located at the International Geothermal Centre Bochum. Three experiments with dedicated samples were planned initially while applying real reservoir pressures and temperatures. During the ongoing work in the preceeding deliverable D5.1 (Hahn & Wittig, 2017) it turned out that more parameter variations are needed for the experiments in order to differentiate the effects interacting within the complex system of high pressure jetting, rock parameters and reservoir conditions. Therefore, the initially experimental plan is split up between three different devices that can vary the differential stress field acting on a specimen or the pore pressure. By this procedure the effect of parameter variation can be differentiated clearly and finally conclusions made more precisely. The application of a bi-axial differential stress field and application of pore pressure is realized by GZB and the application of a tri-axial stress field by TU DELFT.

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3. Submerged jetting experiments

In order to better understand why a radial jet drilling operation is successful in terms of eroding the formation and creating a lateral, the erosion process itself needs to be understood. In D5.1 (Hahn & Wittig, 2017) several nozzle designs are described in more detail that represent the current state of technology in RJD. All of them follow the same design specifications. At least one nozzle outlet is forward oriented which has the task to erode the formation and at least one is backward oriented in order to create pulling force. In order to reduce the complexity of the jetting process downhole, during the submerged jetting experiments only one single jet is analysed in terms of rock destruction and flow field. The assumption behind this simplification is based on the different tasks of the nozzle outlets. The main objective of the forward oriented nozzle jets is to erode the borehole front while the backward oriented ones create pulling force and widen the borehole. The erosion mechanism behind it remains the same independent on their number and orientation.

3.1 Test setup and equipment

The jetting experiments are performed at atmospheric conditions in two different test benches. The first part of the experiments investigates the erosion pattern on a highly cavitating water jet and its contribution towards rock destruction. Therefore pitting tests are performed as well as experiments with sandstone rock specimen. These experiments are conducted in a water tank in order to derive submerged conditions, meaning that the nozzle, the high pressure water jet and the target specimen are under water. The second part of the experiments take a closer look at the flow regime of the high pressure water jet itself and directly on the specimen surface. For this purpose a PIV measurement system is used that can track the velocity field of the jet by enlightening tracer particles within the fluid by a pulsed laser. By applying simple vector geometry the velocity components can be derived within the recorded area. As the nozzle is of highly cavitating character, the occurring gas bubbles make it impossible to apply PIV measurements. Consequently the creation of these bubbles must be suppressed by simultaneously enabling optical access. For this purpose the iBOGS mini is used. In the following figure 1 a picture of that device is presented. The operating conditions for the PIV measurements in part 2 are the same like those for the submerged jetting experiments in part 1. The optical access to the inside of the high-pressure vessel is given by three sapphire windows that are position rectangular to each other with a diameter of 35 mm each. A 16 bit sCMOS camera (LaVision sCMOS, 2560x2160 pixels) with a Zeiss Yashica macro lens is equipped with an optical filter to separate the fluorescent signal from the laser light reflections. The framerate of the camera is 50 Hz and it can capture two images within few microseconds. The time delay between the two recordings can be adjusted to the

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actual fluid flow in the experiment. The images are illuminated by a Nd:YAG double-pulse laser (QuantelEvergreen 200) with a repetition rate of 15 Hz, a wavelength of 532 nm and a pulse length of 5 ns. Camera and laser are synchronized by a timing unit. The area of interest in the recorded image is 8,0 x 4,7 mm with a scale factor of 0,0064 mm per pixel.

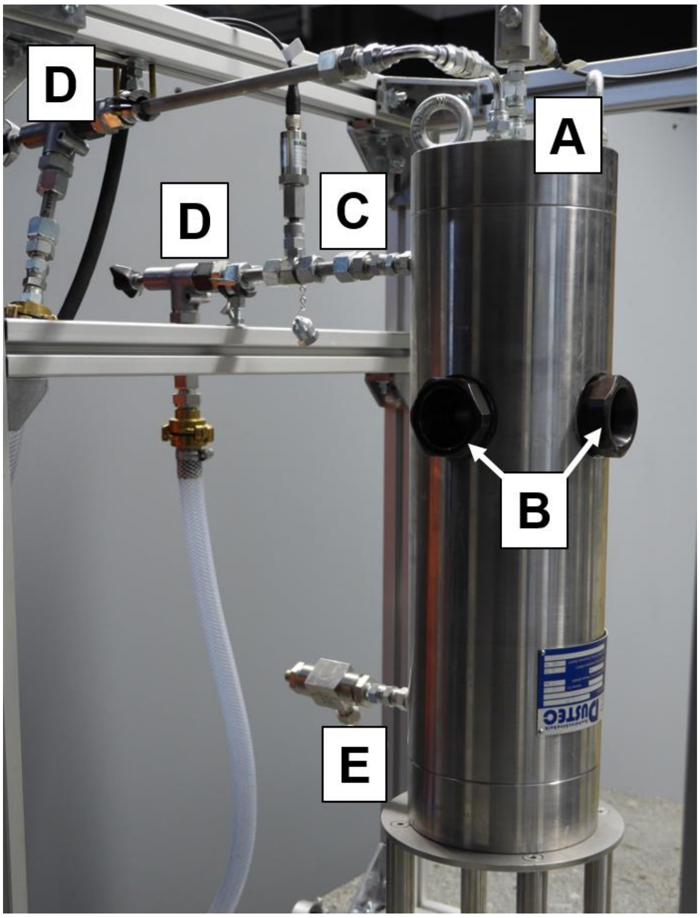

figure 1: iBOGS mini high pressure vessel with fluid inlet (A), saphire windows (B), pressure sensor (C), relief valves (D) and additional fluid outlet (E)

3.2 Nozzle and specimen design

The pitting tests are conducted with Aluminium specimen which are simple plates with a length of 40 mm each and a thickness of 1 mm. The rock specimen are of sandstone type from Bad Dürkheim quarry location (IGSN GFTRE0035). The cubes are saturated before testing, of cubic form with 40x40x30 mm (WxLxH) and treated the following way. The first experiments are conducted with rock cubes which have a thin layer of glue in the center of the top surface where the high pressure water jet is supposed to work on. The layer is of cylindrical form and has a diameter of 5mm. The following experiments

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have an Alumina plate with a pin hole on top, also with a diameter of 5mm. Idea behind this setup is the following: due to the nature of an imping jet on a flat surface, a stagnation zone will develop where no cavitation bubbles are able to implode and therefore erode the material. Only pure stagnation pressure of the jet is acting in that region. Therefore the rock cubes with the thin layer of glue on top are only facing cavitation erosion, the rock cubes with the Alumina plates only stagnation pressure. Depending on the outcome of the experiments qualitatively the influence and share of each erosion mechanism to the creation process of a cavity can be judged. In the following figure 2 and figure 3 photos of the rock specimen before testing are presented.

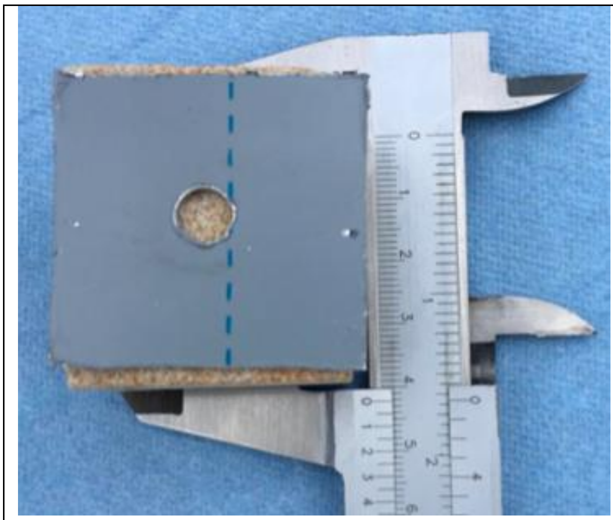

figure 2: rock specimen with Alumina plate

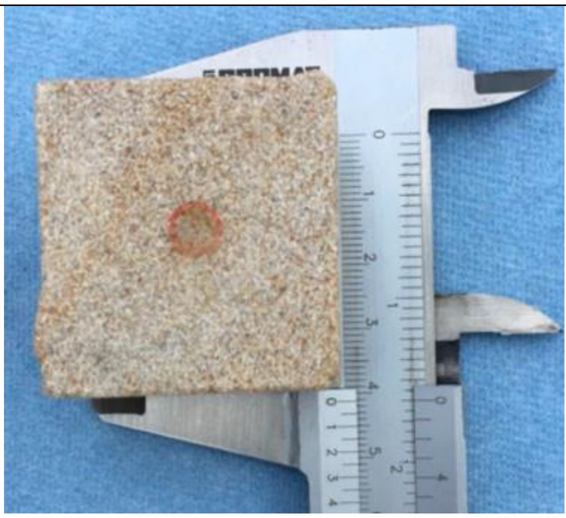

figure 3: rock specimen with plugged pores

The chosen nozzle design is of highly cavitating character has it uses 2 chambers to create the cavitating bubbles. In the following figure 4 a technical sketch of the nozzle design is presented.

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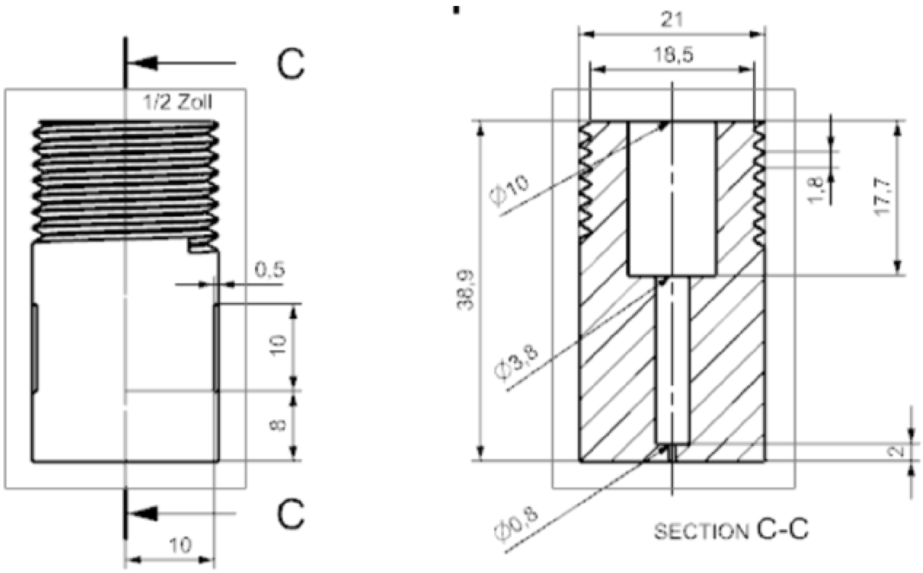

figure 4: technical sketch of nozzle design

3.3 Experimental results

The results of the pitting tests show the typical erosion pattern as expected: in the center of the Alumina specimen the surface looks untreated while the cavitation erosion is acting only in a ring shaped area around it. Around 80 experiments are conducted testing different standoff distances ranging from 2.0 mm to 5.0 mm in order to derive a strong statistical basis. For the chosen nozzle design with an outlet of 2.00 mm and the operating conditions of 160 bar pressure resulting in 18 l/min flow rate it turns out that the inner untreated zone shows an average diameter of 5.5 to 5.6 mm. In the following figure 5 a photo is presented that shows an Alumina specimen after the pitting test.

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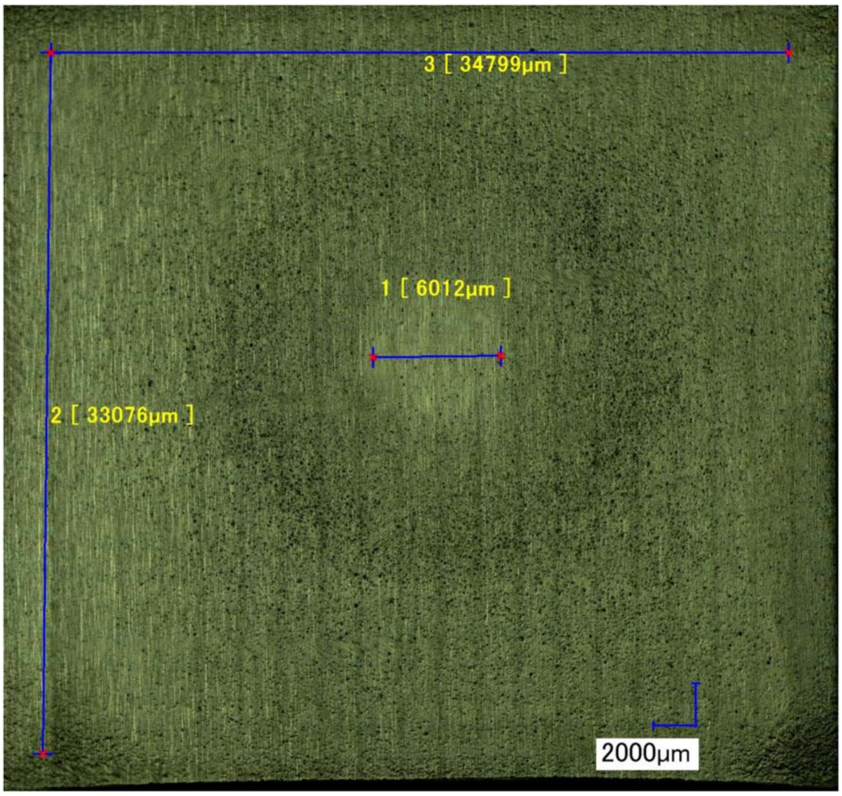

figure 5: Alumina specimen after test

The results of the experiments with the rock specimen are different for each setup. When only the cavitation erosion is removing material from the rock surface no cavity is created in the specimen and it stays mostly intact. Only a thin layer on the surface shows damage and material is eroded in exactly the same area as indicated by the ring shape area during the pitting tests. In the following figure 6 a 3d topography image of a dedicated specimen is shown which shows the erosion pattern. All in all 8 tests are conducted with this setup in order to derive reproducible results and the jet exposure time is 2:00 min.

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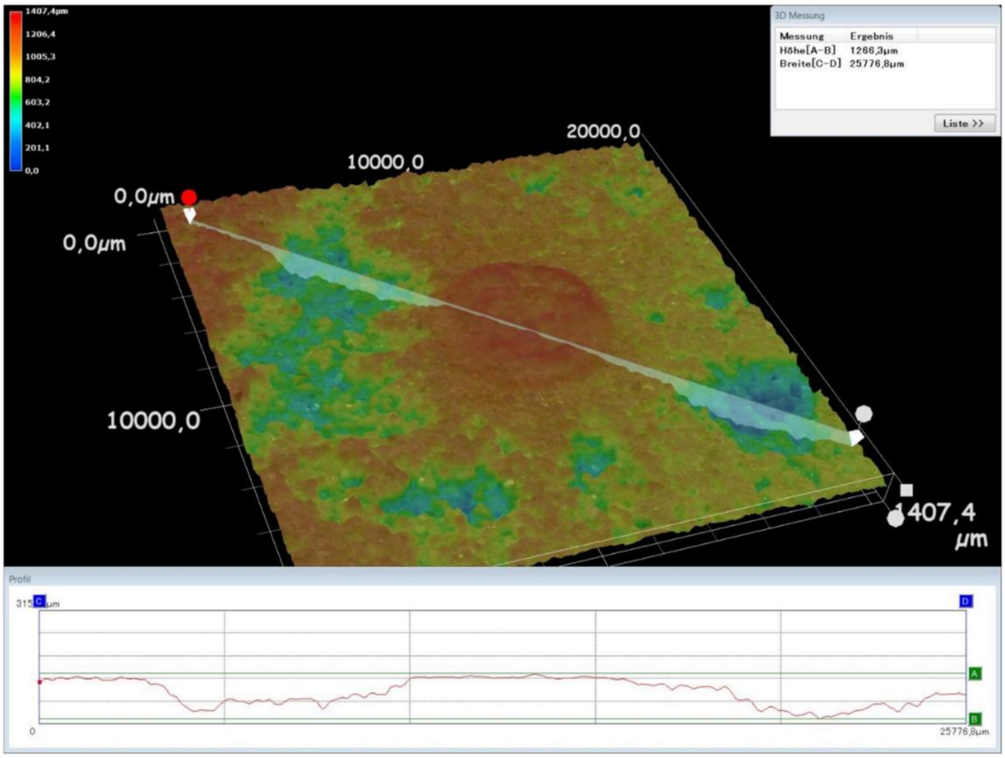

figure 6: surface measurement of rock specimen with plugged pores

When rock specimen is covered by Alumina plate on the top surface it shows quick response to the stagnation pressure acting on it. In less than a second a cavity is created and often also the specimen fractured. In the following figure 7 a photo of the specimen after the test is presented. All in all these types of experiments are conducted 5 times.

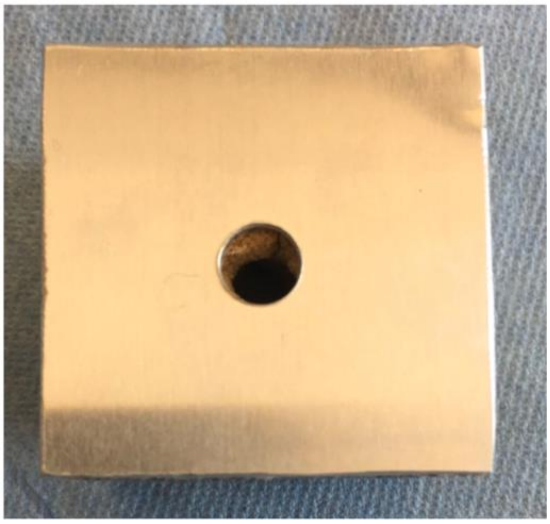

figure 7: rock specimen with Alumina plate after test

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The experimental results of the PIV measurements show that a stagnation point is created on the target surface directly below the nozzle outlet. An illustration of the recorded images for PIV analysis is given in figure 8. The figure shows a typical raw image of the conducted experiment. The tracer particles are shown in white color. In addition to the tracer particles, the raw image also shows few gas bubbles originating from outgassing and cavitation. Therefore, the raw images are preprocessed before they are analyzed to avoid inaccurate velocity distributions. The high-pressure nozzle is located at the top of the image, the aluminum sample at the bottom. The arrows in the image illustrate the water flow schematically. The water jet exits the nozzle and is deflected by the aluminum sample resulting in an impinging water jet flow with a stagnation point.

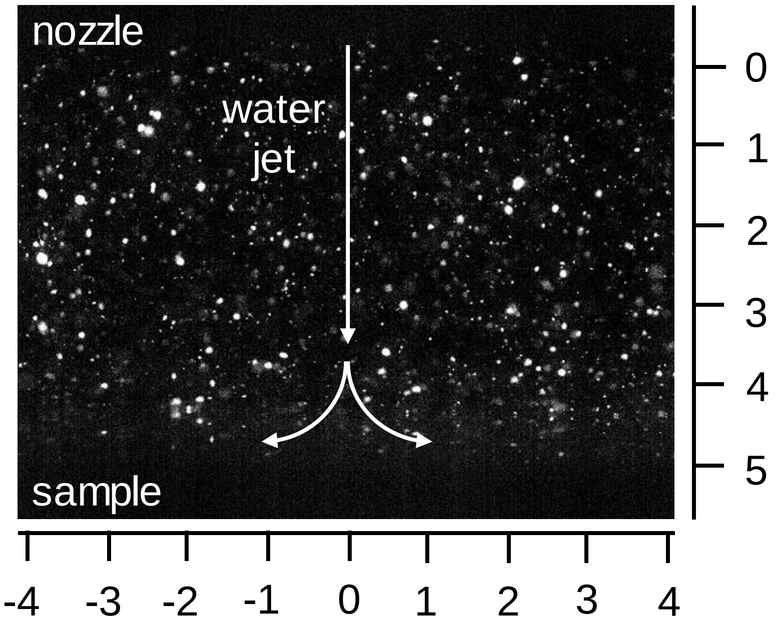

figure 8: Raw image of a typical PIV recording, scales in (mm)

The transient position of the stagnation point is analyzed by clustering 15 images for each evaluation point, meaning the transient behavior is analyzed with a temporal resolution of 1 Hz. According to the recorded data this is the maximum possible resolution for which the average result at each evaluation point has a statistical robustness. Although the time resolution might be rough for very detailed analysis, it is sufficient enough to evaluate this preliminary test. The experiment is conducted for 33 s recording 500 measurement points in total and resulting in 33 evaluation points as stated above. The transient position of the stagnation point over this time is

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illustrated in figure 9. The position of the stagnation point from the overall averaged result is marked as 0.

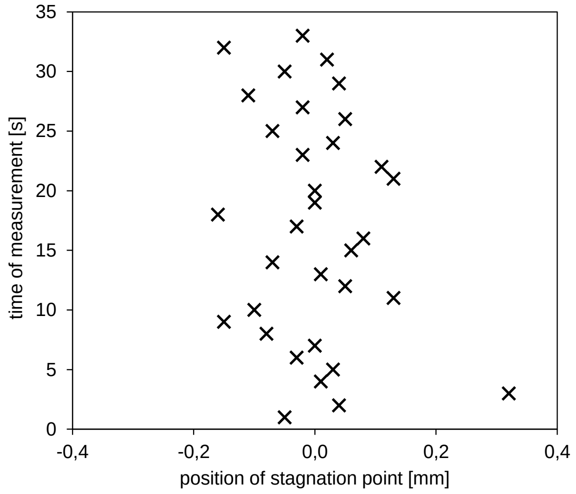

figure 9: Transient position of the stagnation point

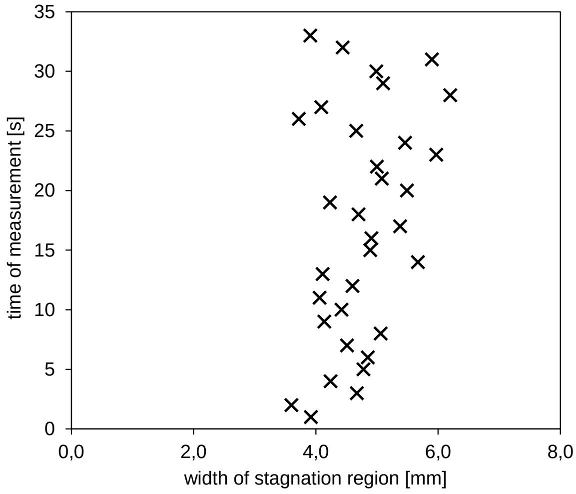

figure 10: Width of the stagnation region

It can be seen from figure 9 that the stagnation point position varies in a range of -0.16 - 0.13 mm with one outliner of +0.32 mm. This indicates that the erosion mainly induced by high stagnation pressure of the water jet is in the range of +/- 0.2 mm of the average impingement point in this experiment. The transient behavior of the stagnation point is an indication that the jetting process is highly unsteady in small scales and that the water jet including the surrounding flow in front of the nozzle have a turbulent characteristic. Referring to the applied nozzle outlet diameter of 2.0 mm, the fluctuation of the stagnation point position is about 10%. That can be concluded to be almost stationary for the given experimental conditions.
In addition to the stagnation point position the width of the stagnation region can be identified from the recorded data. Again, one evaluation point for the stagnation region is drawn from an average of 15 images representing 1 s of measurement, respectively. In figure 10 the measurement results are presented. The width of the stagnation region varies from 3.6 – 6.2 mm for the conducted experiment with an average of 4.8 mm. This is in a same scale with the aforementioned experiments stating that the inner untreated surface from the jetting experiments on alumina plates is between 5.0 – 6.5 mm. Meaning, that the cavitation bubbles are deflected from the stagnation region having no effect on the erosion of the material.
The result of this preliminary experiment shows that it is possible to detect the transient position of the stagnation point during the jetting process. Even with a relatively low temporal resolution of 1 Hz the transient behaviour of the stagnation point can be detected.

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4. Pore pressure controlled experiments

In deliverable D5.1 (Hahn & Wittig, 2017) jetting experiments with the current RJD technology are performed under atmospheric conditions, meaning that the surrounding pressure is 1 bar and the specimen are not saturated. This is not the case in a real reservoir. In depths of several hundred meters of depth the formation is usually saturated with reservoir fluid, oil or water, and a differential stress field is acting. Both characteristics and their effect on the performance of a jetting operation can be tested simultaneously to some extent in the 'iBOGS mini'.

4.1 Experimental Setup

The 'iBOGS mini' is a facility that has been designed in order to investigate jet drilling technologies in general under simulated reservoir conditions. The experimental device consists mainly of a pressure vessel of about 12.5 cm of diameter and 50 cm of height that can handle entire rock specimen of approximately the same dimensions. In order to apply real field RJD equipment the test bench has a feed system to guide the nozzle while it is penetrating into the rock. The vessel has one inlet and two outlets where one of them acts as a safety line and the other one as pressure control line. The pressure control line is connected to a valve which can reduce manually and continuously the flow path and thereby generated back pressure in the vessel. By this the pore pressure in the saturated specimen can be controlled and mechanical stress induced in the specimen to some extent depending on the Biot factor. According to the Biot theory, pore pressure induces mechanical stress in the rock specimen. In the following figure 11 and figure 12 a photo and a technical sketch of the vessel is presented.

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figure 11: photo of ‘iBOGS mini’

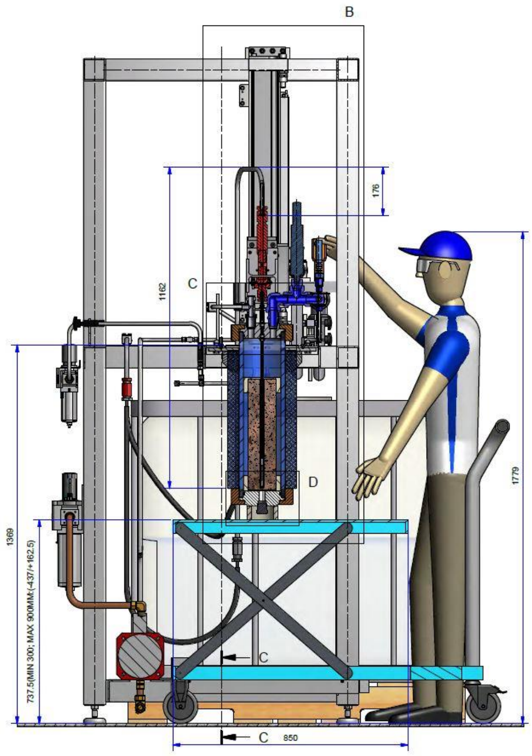

figure 12: technical sketch of ‘iBOGS mini’

The entire test bench has a height of about 2.5 meter, the specimen is lifted from the bottom side into the vessel and the jetting nozzle is guided from above by a thin steel tube that enters the pressure chamber.

4.2 Experimental procedure, nozzle design and specimen

At first the specimen are generated by coring rock blocks available in GZB’s rock library. The specimen have a diameter of 12 cm and a height of max. 40 cm. Before testing all rock specimen are saturated by submerging them in a water tank for long enough time and a flat surface is generated on top and bottom of the core. For the jetting experiments being conducted in work package D5.2 6 different rock types are chosen by GZB in order to be tested.

- Gildehaus SST (IGSN GFTRE0065)
  The sandstone from Gildehaus quarry location is chosen as it bears a high possibility for successful jetting operations and therefore as well to relate the jetting results conducted in D5.2 to those ones in D5.1 (Hahn & Wittig, 2017).

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Next to this for the experiments performed in the true tri-axial cell at TU DELFT the same rock type is used.

- Kohlenkalk KK (IGSN GFTRE0000)
  This limestone rock type was initially chosen as it represents a typical and hard accessible geothermal reservoir rock which is not able to be successfully jetted with the current RJD technology and its inherent limitations. The use of acid is seen as mandatory as jetting fluid but the effect of additional back pressure resulting in induced tension in the rock matrix might enhance the initiation of ROP.

- Bad Dürkheim SST (IGSN GFTRE0035)
  The sandstone from Bad Dürkheim quarry location is chosen as it has not been jetted successfully during the experiments at surface conditions during D5.1 (Hahn & Wittig, 2017). Therefore it is more than reasonable to evaluate its jetability under different ambient conditions, in this case under higher ambient pressures that cause higher pore pressures inside the specimen. Next to this its high anisotropy makes it furthermore an interesting candidate for the experiments.

- Friedewald SST (IGSN GFTRE0057)
  During D5.1 (Hahn & Wittig, 2017) the sandstone from Friedewald quarry location has been tested under atmospheric and dry conditions for evaluating its jetability. On the one hand it turned out that this rock type has one of the lowest threshold velocities to start the erosion process but on the other hand jetting with RJD equipment was not as successful as with the Gildehaus SST rock type. Therefore experiments under saturated conditions are scope of interest as well as the influence of increasing pore pressure on the jetting performance.

- Dortmund SST (IGSN GFTRE0099)
  The sandstone from Dortmund quarry location has already been tested in D5.1 (Hahn & Wittig, 2017) concerning its jetability. Numerous experiments have been executed to found out that for unsaturated specimen a minimum nozzle exit velocity of about 160 m/s is needed to initiate the erosion process. With saturated specimen this threshold velocity can be lowered significantly. The jetting experiments with real field RJD were not successful using dry Dortmund

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sst specimen. Therefore testing the equipment with saturated specimen and back pressure in the vessel is of interest.

- Icelandic sedimentary layer
  In GZB's rock library there are currently four different types of islandic basalt and one sedimentary layer available which represent different target layers for the jetting operation planned in late October 2018. One selected rock type will be tested which is supposed to bear the highest potential to create a hole inside with the current RJD technology. Therefore these experiments are seen as complementary to the big field test carried out in Island on a real geothermal well site.

The operating conditions during the experiments are chosen in such a manner as that they are comparable to real field operating conditions. This includes a flow rate of up to 20 to 25 l/min and both Radial Jet Drilling nozzle designs, including the rotating and static nozzle design. Pressure and flow rate are supplied by a 3 piston triplex pump from the manufacturer Hammelmann that can deliver up to 900 bar of operating pressure. The nozzles are connected to the steel pipe of the feeding system and the the test bench via commonly high pressure hose to the pump. In the following figure 13, figure 14 and figure 15 technical sketches of all three tested nozzle designs are presented. More detailed descriptions can be found in D5.1 (Hahn & Wittig, 2017).

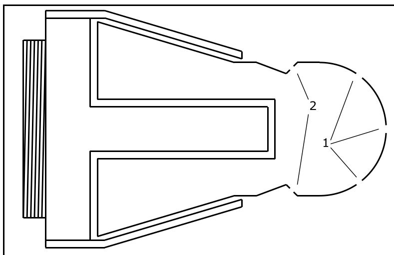

figure 13: technical sketch rotating nozzle design

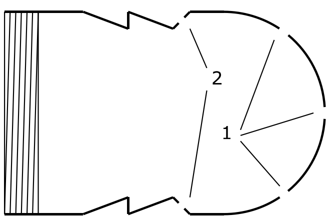

figure 14: technical sketch static nozzle design WSG

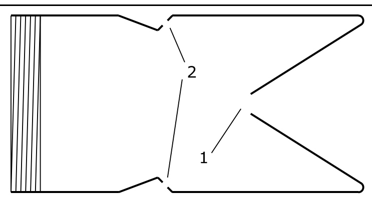

figure 15: technical sketch static nozzle design Buckman©

In each sketch presented in figure 13, figure 14 and figure 15 the forward and backward oriented outlets are indicated referring to 1 and 2. It can be seen that the Buckman© nozzle design has only one forward oriented outlet, where the other ones have multiple ones. Next to this the Buckman© nozzle designs uses a wider diffusion angle of the forward oriented jet to erode material. In order to evaluate the influence of water temperature during the tests, the temperature of the jetting fluid at the outlet of the test bench is tracked and referred to the ROP during the experiments.

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The initially planned experimental procedure during the tests follows a basic guide line which is adjusted for each test individually. Scope of the experiments and therefore also of the experimental procedure is to find out the influence and dependency of pore pressure increase or decrease on the performance, meaning ROP, of the used jetting system. Therefore the experimental procedure is as followed:

- At first the saturated sample is placed in the pressure vessel for 5 minutes and then a distance of 10 cm is tried to be jetted.
- Then the pressure in the vessel is ramped up to 50 bar of total pressure and another 5 minutes are taken to let the pressure in the pores increase to the vessel pressure. After that again a distance of 10 cm is tried to be jetted.
- At last stage the pressure in the vessel is further ramped up to 150 bar of total pressure and again 5 minutes are taken to let the pressure in the pores being increased. Then again a distance of 10 cm is tried to be jetted.
- After all three stages of the experiment are conducted the pressure is released and the sample is taken out of the vessel.
- During all jetting phases the nozzle has direct contact to the rock specimen and no contact when the pressure is ramped up. This is controlled by the 2 hydraulic pistons adjusting the nozzle standoff distance.

In the following figure 16 the experimental procedure is illustrated.

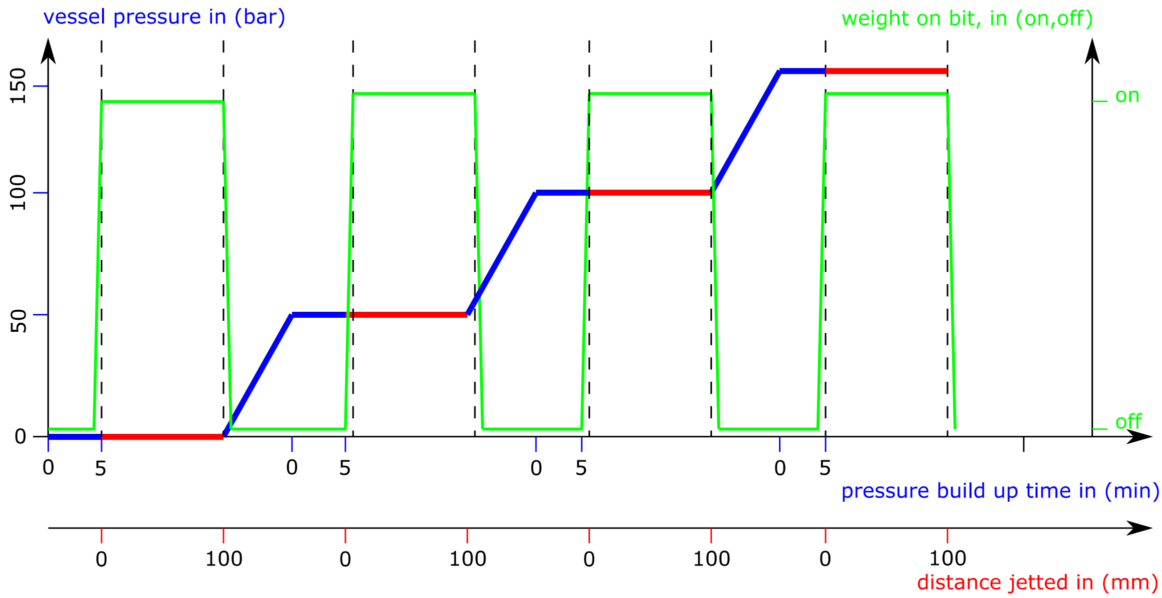

figure 16: experimental procedure of submerged and pressure controlled jetting experiments

The green graph indicates the weight on bit, meaning if the nozzle has contact to the specimen or not. The red graph and the according axis shows the jetted distance and the blue graph the increase of back pressure, hence absolute pressure in the vessel. On the according y-axis the scalar value can be seen and on the x-axis the pressure build up time. All in all the experimental procedure of ramping up the back pressure and hence the specimen pore pressure is shown.

4.3 Results and Analysis

Numerous experiments have been carried out according to the proposed procedure or a modified version of it. The results are summed in the following table 1 including used nozzle type, jetting bit and back pressure and flow rate as well as jetting time and generated ROP. The results are discussed for each rock type separately.

- Gildehaus SST
  The sst from Gildehaus quarry location is tested with both static nozzle designs, Buckmann© and WSG, as well as with the rotating one. The increase of back pressure up to 150 bar does not initiate ROP using the static nozzle with multiple forward oriented outlets. Although a uniform cavity is created out of the single jets, it is not big enough in diameter to enable the nozzle to enter in the rock. A photo of cavity created by the static nozzle is presented in figure 17.

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figure 17: Gildehaus sst, photo of cavity by static nozzle design of WSG

Also when the static nozzle of type Buckman© is used, higher back pressures of more than 20 bar stop the creation process of a borehole. A decrease of the surrounding pressure during the experiments to less than 20 bar resulted in a ROP of up to 12 m/h and the typical star shape borehole could be create. A photo of a successful jetting experiment using the Buckman© nozzle is presented in figure 18.

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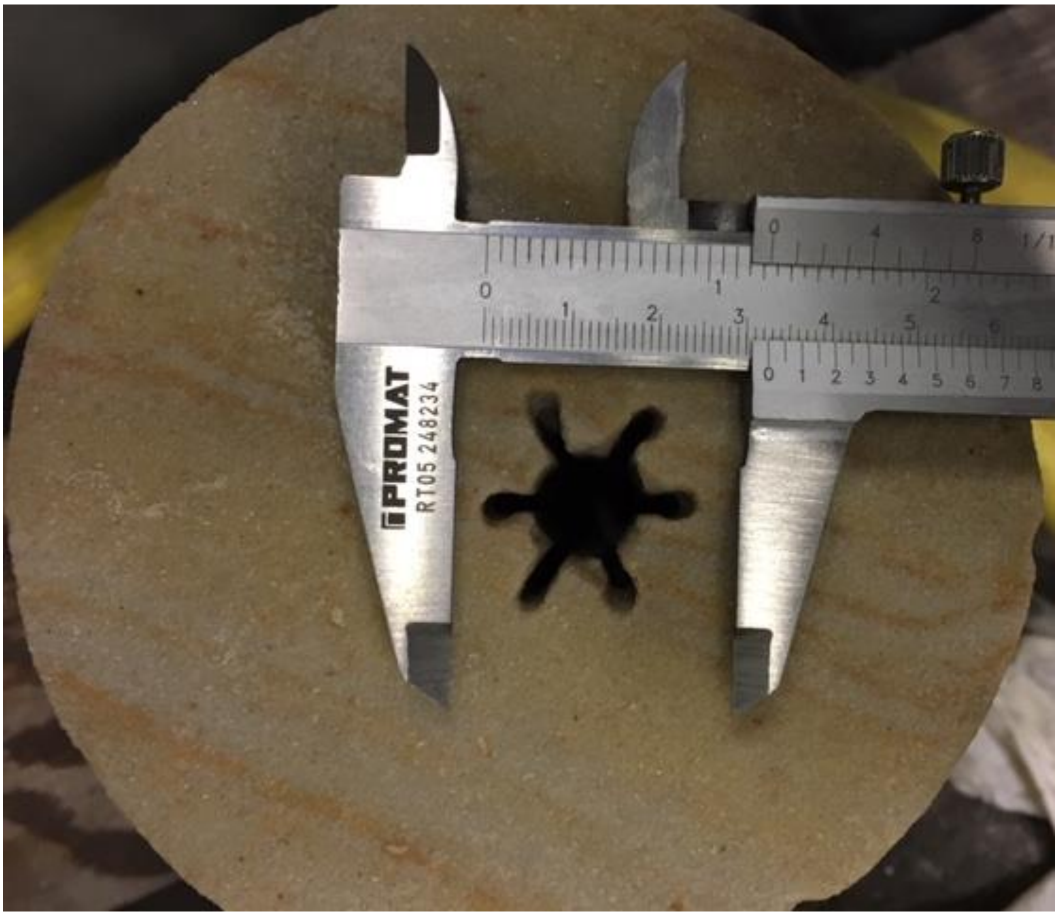

figure 18: Gildehaus sst, star shape borehole by static nozzle of Buckman© nozzle design

Using the rotating nozzle design jetting into the Gildehaus sst rock type is no problem. Rate of penetrations up to 100 m/h can be realized at 0 back pressure conditions inside the ‘iBOGS mini’. The borehole wall is of circular shape with its typical wavy curvature which can be seen on the photo presented in figure 19.

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figure 19: Gildehaus sst, lateral created by rotating nozzle StoneAge© Beetle tube spinner

- Bad Dürkheim SST
  Jetting experiments with the Bad Dürkheim sst rock type were only successful using the rotating nozzle design. Similar to the Gildehaus sst ROPs of up to 100 m/h could be reached which resulted in a very short experiment time. But in contast to the Gildehaus rock type, the diameter of the lateral is smaller. Experiments using the static nozzle design of type Buckman© were not successful. A photo of a succesfull jetting experiment using the rotating nozzle design is presented in figure 20.

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figure 20: Bad Dürkheim sst, lateral created by rotating nozzle design

- Friedwald SST
  The Friedewald rock type also bears huge potential when jetting with the rotating nozzle design. Under saturated conditions the experiment lasts only a few seconds resulting in a ROP of 100 m/h. Similar to the Bad Dürkheim sst the final diameter of the created lateral is lower than that one of the Gildehaus sst. A photo of the experimental outcome using the Friedewald sst is presented in figure 21.

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figure 21: Friedewald sst, lateral created by rotating nozzle design

- Dortmund SST
  The sandstone from Dortmund quarry location is tested only with the rotating nozzle design with back pressures up to 150 bar. Also under these conditions and being saturated it was not able to create a hole in the rock. Additionally a mechanically assisted jetting bit was tested which is supposed to erode the rock by high pressure water jets and cutting plates. But also this tool was not able to successfully penetrate the rock.

- Iceland sedimentary layer
  The rock specimen of Iceland was tested using the rotating nozzle design. The jetting bit entered the rock and created a lateral but with a very high deflection which finally lead to breakage of the specimen. A photo of the broken rock core is presented in figure 22.

figure 22: Iceland sedimentary layer, fractured specimen after test using rotating nozzle design

- Kohlenkalk
  Finally the Kohlenkalk was tested as well with the rotating nozzle design but it was not possible to successfully create a borehole or lateral.

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Exp.#	Rock type	Nozzle type	Flow Rate (l/min)	Bit (bar)	Back Pressure (bar)	Jetting Time (min)	ROP (m/h)
1.a	SGH6-GI	static	26.5	500 +/- 20	0	05:00	0
1.b	SGH6-GI	static	26.5	500 +/- 20	50	05:00	0
1.c	SGH6-GI	static	25.5	500 +/- 20	100	05:00	0
1.d	SGH6-GI	static	25.0	500 +/- 20	150	05:00	0
2.a	SGH6-GI	static	26.5	500 +/- 20	0	05:00	0
2.b	SGH6-GI	static	26.5	500 +/- 20	50	05:00	0
2.c	SGH6-GI	static	25.5	500 +/- 20	100	05:00	0
2.d	SGH6-GI	static	25.0	500 +/- 20	150	05:00	0
3.a	SGH6-GI	static	26.5	500 +/- 20	150	05:00	0
3.b	SGH6-GI	static	0	500 +/- 20	100	00:00	0
3.c	SGH6-GI	static	0	500 +/- 20	50	00:00	0
3.d	SGH6-GI	static	0	500 +/- 20	0	00:00	0
4.a	SGH6-GI	rotating	26.5	450 +/- 20	0	00:05	100
5.a	SBS6-BD	rotating	27.0	450 +/-20	0	00:05	100
6.a	SBS6-BD	rotating	27.5	450 +/-20	0	00:05	100
7.a	SQZ6-FR	rotating	27.5	460 +/-50	0	00:05	100
8.a	SRS6-DO	rotating	28.5	500 +/- 20	0	02:00	0
8.b	SRS6-DO	rotating	28.5	500 +/- 20	50	02:00	0
8.c	SRS6-DO	rotating	28.0	500 +/- 20	100	02:00	0
8.d	SRS6-DO	rotating	27.5	500 +/- 20	150	02:00	0

9.a	SRS6-DO	rotating*	25.5	500 +/- 20	0	10:00	0
10.a	SBS6-BD	static*	32.5	300 +/-20	0	05:00	0
10.b	SBS6-BD	static*	32.5	300 +/-20	0	01:00	0
11	SGH6-GI	static*	34.0	300 +/-20	0	00:30	12.84
12.a	SGH6-GI	static*	33.8	300 +/-20	100	00:30	0
12.b	SGH6-GI	static*	33.8	300 +/-20	100	01:00	0
13.a	SGH6-GI	static*	29.4	400 +/-20	100	01:00	0
13.b	SGH6-GI	static*	29.4	400 +/-20	50	00:30	0
13.c	SGH6-GI	static*	29.4	400 +/-20	40	00:30	0
13.d	SGH6-GI	static*	29.4	400 +/-20	30	00:30	0
13.e	SGH6-GI	static*	29.4	400 +/-20	20	00:30	0
13.f	SGH6-GI	static*	29.4	350 +/-20	10	00:30	0.82
13.g	SGH6-GI	Static*	29.4	350 +/-20	0	00:30	0.82
14	IC#5	rotating	34.0	400+/-20	0	5:00	0
15	KK	rotating	34.0	400+/-20	0	5:00	0

table 1: overview jetting experiments at pressure controlled conditions

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5. Bi-Ax Jetting Experiment

In order to estimate the influence of reservoir conditions on the performance of the radial jet drilling technology, in this case differential stress in the formation, an experiment is carried with a test bench that can apply such a stress field on a cylindrical rock specimen.

5.1 Basic assumption

The experimental approach is based on the assumption that the direction of jet nozzle in the reservoir is always in direction of the least horizontal stress. This results from the following relationship of horizontal and vertical stress field in the formation that is shown in the following figure 23.

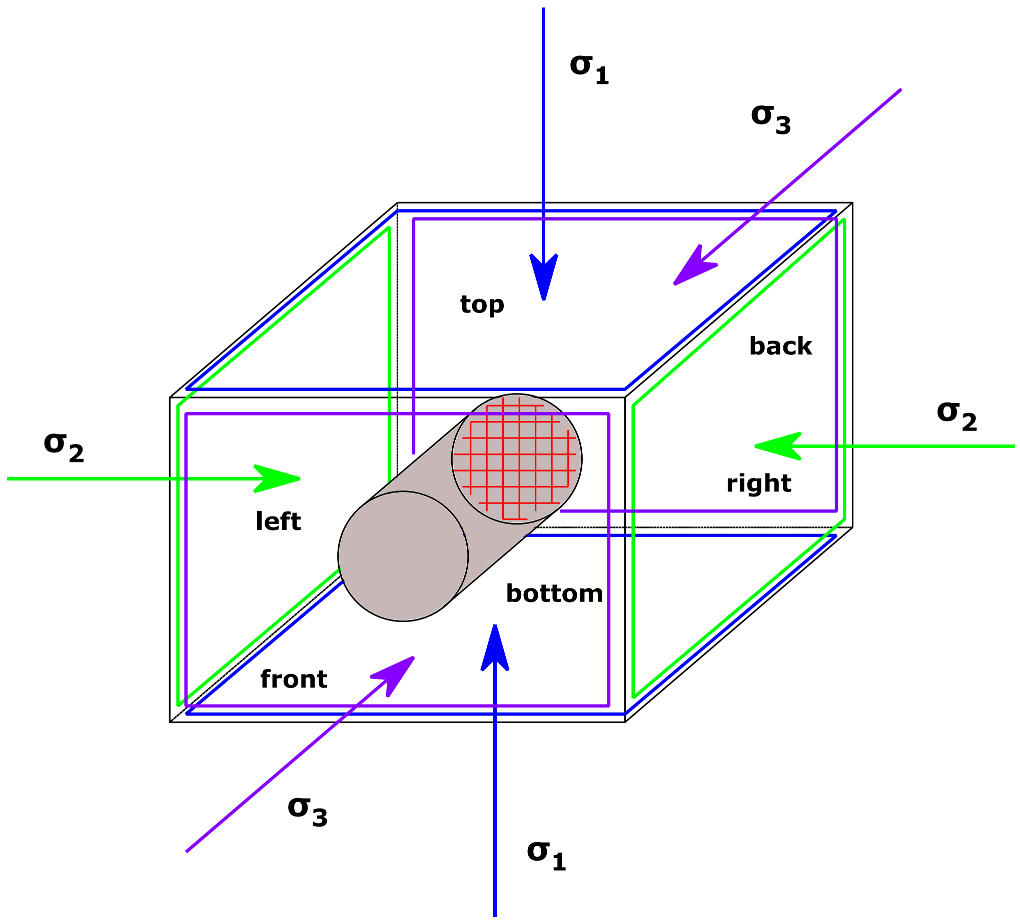

figure 23: schematic sketh of stress distribution in reservoir

Considering a rectangular control volume in the rock formation, stress is applied on the surfaces from three directions: vertical stress from top and bottom (blue, σ_1), horizontal stress from left and right (green, σ_2) and horizontal stress from front and back (lila, σ_3).

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In the formation the horizontal stress can be divided into the maximum and minimum horizontal stress acting on an arbitrary control volume. The grey cylinder in the center of the control volume indicates an already created lateral with red lines at its front. The basic assumption of the experiment now is that the orientation of jetting nozzle is towards the minimum horizontal stress σ_3, as in this direction the stress distribution on the borehole wall (marked with red crossed lines in figure 23) is maximum and therefore the solid can be extracted most effectively. The vertical stress results from the hydrostatic pressure of the rock column above the control volume and the horizontal stresses from tensions within the formation due to defective relaxation of formation layers. In order to apply such a differential stress field related to the vertical stress σ_1 and one horizontal stress σ_2 a special test bench is needed.

5.2 Test bench and specimen

Test bench

An appropriate facility for this kind of mechanical load on rock specimens is provided by the Institute of Engineering Geology & Rock Engineering of Ruhr Universität Bochum. The concept of this test bench is to apply pressure on the outer surface of a cylindrical sample with oil filled pressure pads, which is then converted into stress inside the specimen. The pressure can be adjusted in two directions independently from each other with more than 500 bar. The test bench consists mainly of a ring shaped casing with a high wall thickness and it includes oil pads and oil supply lines. The increasing pressure in the pads acts against the steel case (assumed to be non-deformable) of the test bench and on the rock specimen (assumed to be deformable). The pressure in the pressure pads is applied by a small hand pump which is able to apply max. 500 bar of pressure. Inside the test bench a cylindrical rock specimen is set that needs to have a diameter of 142 mm and a length of 700 mm. In the following figure 24 a sketch of the test bench is shown to visualize the principle of the facility and the test setup.

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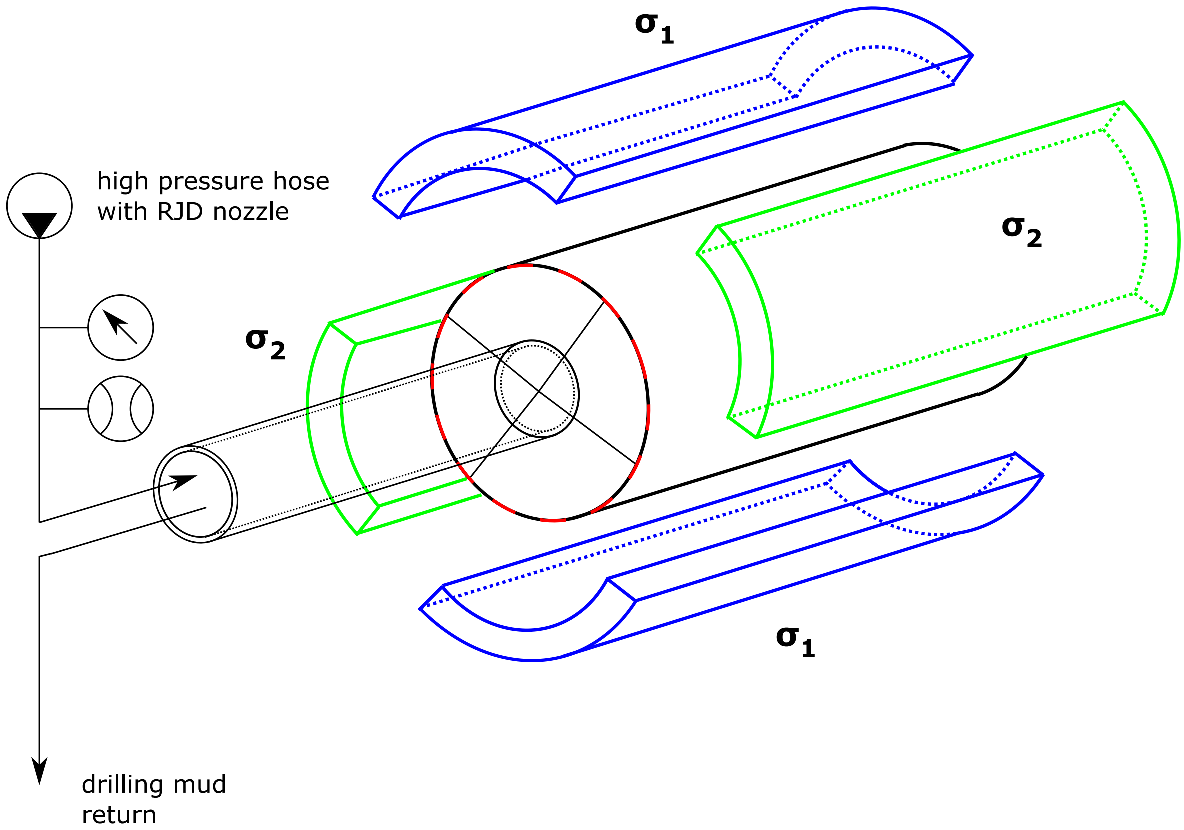

figure 24: sketch of the test bench with specimen and pressure supply

The pressure pads that induce the differential stress field σ_1 and σ_2 are marked in blue and green, the cylindrical specimen in black. In order to guide the jetting nozzle with the connected high pressure properly to the rock surface and to provide a controlled back flow of the mud (water plus eroded material), a steel tube is cemented at the surface of the front plane of the specimen (red dashed line). The forward movement of the jetting nozzle is not enforced by a mechanic device as the backward outlets create already enough pulling force inside the steel tube to push the nozzle towards the rock. The steel tube has an inner diameter of about 40 mm and has therefore almost the same diameter like the jetting boreholes created in the Gildehaus sandstone during the experiments at atmospheric conditions in D5.1 (Hahn & Wittig, 2017). In the following figure 25 a photo of the experimental setup is shown.

<u>Specimen</u>

The experiments are conducted using a sandstone from Dortmund quarry location as it represents the toughest one of all 4 tested. In D5.1 (Hahn & Wittig, 2017) it is already stated that it needs the highest nozzle exit velocity at atmospheric conditions and during the experiments in chapter 3 it shows as well the highest resistance against current RJD technology even under saturated stated and increased pore pressure.

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Therefor the induction of higher mechanical stresses in the rock skeleton are assumed to improve the jetting performance, hence enables the erosion process. The specimen has a diameter of 142 mm and a length of 700 mm. A saturation of such a big specimen is not possible, therefore it remains dry during the test. A quick saturation in the near wellbore area due to the stagnation pressure of the jet can be observed and makes it therefore possible to relate the outcome of the experiments to D5.1 (Hahn & Wittig, 2017) and to the experiments reported in chapter 3.

figure 25: test bench before start of experiment

Nozzle design

Similar to the experiments at atmospheric and pressured controlled conditions under D5.1 (Hahn & Wittig, 2017) and chapter 3 several nozzle designs of radial jet drilling technology are used. In order to ensure comparable results with the previously conducted jetting experiments at atmospheric and pressure controlled conditions the operating conditions cover also a flow rate from 20 to 25 l/min with a pump pressure ranging from 200 to 230 bar provided by a small 3 piston plunger pump. For providing

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more pump pressure a high pressure pump of the manufacturer KAMAT is used that allows pressures up to 1500 bar and flow rates up to 120 l/min. The fluid is transported through a high pressure hose of field specifications (Parker Tough, 200MPI) that is shortened to reduce the pressure losses. Hence the test setup represents real field conditions applied in a jetting operation with the possibility of going even beyond. For the rock specimen the sandstone from the Quarry location in Dortmund is used. As this sandstone represents the hardest one of all four tested ones and it has not been successfully jetted yet, it is expected to create a borehole with the support of a differential stress field. For this purpose a core with the adequate coring device is taken and accordingly prepared for the experiments. In order to exclude mistakes and uncertainties in using the radial jet drilling nozzles correctly a forth nozzle type is used. This type has already been in use for the jetting experiments under atmospheric conditions in D5.1 (Hahn & Wittig, 2017). This nozzle type is characterized by a high efficiency concerning rock destruction. A sapphire insert is used to focus the high pressure water jet more precisely and in the following figure 26 a technical sketch of the nozzle is presented.

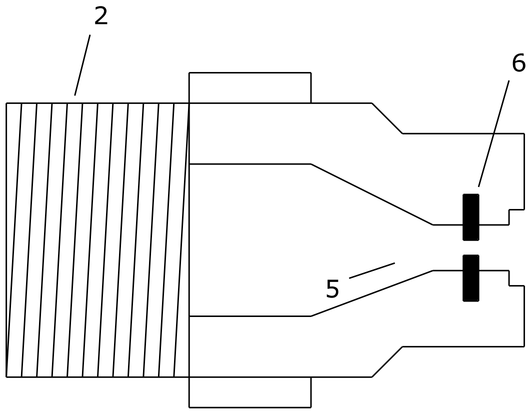

figure 26: industry standard nozzle

The nozzle is also connected with a thread connection (2) to the high pressure with an adapter in between and only has one forward outlet (5), in this case an orifice. The sapphire inlets improve the spray characteristic of the high pressure water jet by reducing the diffusion angle to 1° to 5°, depending on the operating pressure. The minimum outlet diameter is about 1.1 mm.

5.3 Test procedure

The test procedure is quite similar to that one of the experiments at atmospheric conditions without the differential stress field in D5.1 (Hahn & Wittig, 2017). The sample

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is prepared and put inside the test bench. When the high pressure hose is equipped with the radial jet drilling nozzle the pump is turned on and the pressure increased in order to increase the flow rate. At first the usual static nozzle with the multiple forward oriented outlets is used. At second the rotating nozzle design and at third the Buckman© nozzle. Initially for all nozzles the operating pump pressure is limited to 250 bar which delivers a maximum flow rate of 25 l/min. After this stage the pump is changed and the pressure is increased in several stages up to 820 bar and a flow rate up to 35 l/min. The differential stress field is varied in all stages of the experiment. Initially a differential stress of $p_{\sigma_1} = 400\ bar$ and $p_{\sigma_2} = 200\ bar$ is installed. After that a homogenous distribution of $p_{\sigma_1} = 300\ bar$ and $p_{\sigma_2} = 300\ bar$ is set and finally only one stress direction is induced with $p_{\sigma_1} = 300\ bar$ and $p_{\sigma_2} = 0\ bar$. The experiments with the radial jet drilling technology are done on the front plane, the experiments with the single nozzle from Spraying Systems on the back plane.

5.4 Results and analysis

With all nozzle designs referring to radial jet drilling technology no boreholes can be created, even under the maximum operating conditions of 820 bar pump pressure and the differential stress field of $p_{\sigma_1} = 300\ bar$ and $p_{\sigma_2} = 0\ bar$. Even if manually an entrance in the rock specimen is created by using a normal drilling device, the jet drilling nozzles are not able to extract rock cuttings from the borehole wall and to create a lateral. In contrast to that the single nozzle is able to create holes in the back front of the rock surface under any operating and differential stress conditions. In the following figure 27 photo is presented after three jetting tests with the single nozzle.

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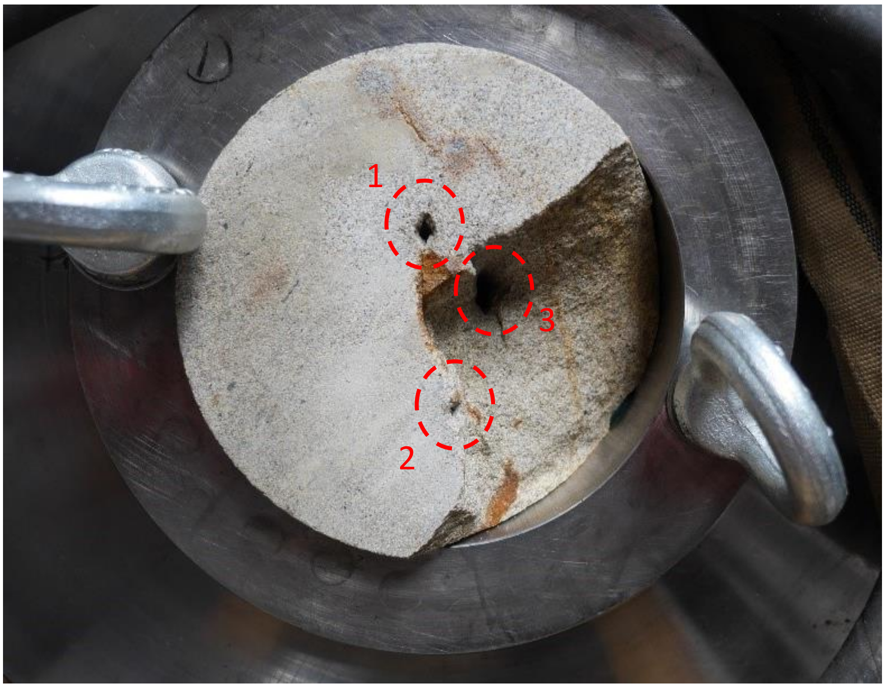

figure 27: rock breakout and holes using single nozzle design from Spraying Systems

In figure 27 the created boreholes are marked with red dashed lines and numbered. The depths of each cavity are almost the same, up to 45 mm with a diameter of about 4 mm. The intensity of the high pressure water of the third cavity is so high, that in addition with the differential stress field of $p_{\sigma_1} = 300\ bar$ and $p_{\sigma_2} = 0\ bar$, a big part of the back plane broke out.

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6. Tri-axial jetting experiments

In the previous chapter 3 the jetting experiments are performed under application of a biaxial stress field on the rock specimen. As mentioned already the stress state in a real reservoir is 3 dimensional. Therefore experiments being conducted with a specimen under tri-axial stress state is one step closer to jetting under simulated reservoir conditions. In order to carry out those experiments a true tri-axial compression cell is used located at the Geophysics laboratory at TU DELFT. Scope of the jetting experiments is to evaluate the influence of the acting stress state within the rock specimen, or in big scale the reservoir, on the jetting performance, meaning ROP, and orientation of the created lateral as the current RJD technology is not steerable. The experimental setup and procedure, specimen and nozzle design as well as the experimental outcome are briefly described in the following.

6.1 Experimental Setup

The true tri-axial compression cell is able to handle rock specimen of cubic shape with an edge length of up to 30 cm. The rock cube is placed inside the cell and compressed from all 6 plane surfaces independently for each direction in space. In the following figure 28 a photo of the test bench is shown with a rock specimen positioned inside.

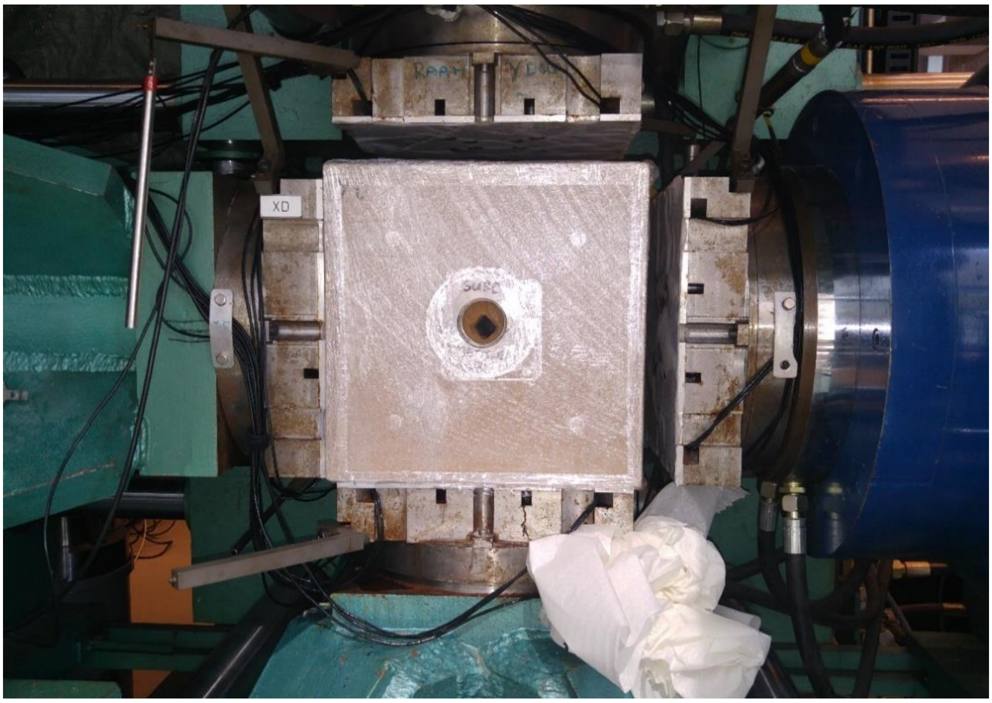

figure 28: photo of tri-axial cell test bench at TU DELFT

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The plates at the left and west side of the cube apply stress in x-direction, the plates on top and bottom stress in z-direction and the plates in the front and back stress in y-direction. All plates are planar and of the same type except the front plate, missing in figure 28. This plate has a hole in the center with a diameter of 40 mm in order to connect external periphery to the specimen under load during the experiment. In case of the jetting experiments this periphery includes a steel pipe that is connected with a thread connection hydraulically sealed to the rock specimen inside the cell. This steel pipe serves on the one hand as mud return path and on the other hand as guidance for the jetting nozzle. In the following figure 29 a photo is presented that shows the front plate including the external periphery.

figure 29: photo of tri-axial cell front plate and connected steel tube

In figure 29 the steel tube can be seen as well as the black high pressure hose from Parker (A) that is of field specifications and connected to a high pressure pump supplying flow rate for the jetting nozzle. The back flowing water including the eroded

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rock cuttings are guided through the annulus of the steel pipe and through a low pressure hose (B) to a settling tank without any back pressure. Consequently the flow path is a closed system: fresh water is supplied by the pump, guided through the jetting hose and nozzle to the inside of the cell towards the lateral wall and from that point on through the annulus of the steel pipe and the low pressure hose to a settling tank. Using this setup enables one to accurately measure flow rates and pressures during the experiments. Additionally the movement of the jetting nozzle is tracked during the experiments in order to derive rate of penetrations. The stresses acting on the rock surface is constantly adjusted and measured directly by the test bench itself.

6.2 Specimen and nozzle design

As already mentioned the rock specimen are of cubic size with an edge length of 30 cm. As rock type Gildehaus sst is chosen as it bears the highest potential for successful jetting experiments proven by the numerous experiments already conducted with this rock type. In order to connect the steel pipe with the rock specimen and thereby generate a hydraulically sealed system a thread connection is glued into the rock. In figure 28 this thread connection can be seen on the front face of the rock specimen and in figure 30 more detailed picture is presented.

figure 30: thread connection in rock specimen for steel pipe

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For this connection a small entrance is created, then placed and finally connected to the rock by glue. This step is done before the specimen are saturated by storing them in a water tank until no gas bubbles are evaporating anymore out of it, approximately for 2 to 3 days. Most of the experiments are conducted using the rotary nozzle design, again because of its good performance during the already conducted jetting experiments at atmospheric as well submerged conditions. Once also the static nozzle design of WSG is tested as a reference case. In the following figure 31 an unused rotating nozzle of type StoneAge© Beetle Tube Spinner is presented.

figure 31: rotating nozzle design, unused before experiment

Most of the experiments are conducted with an unused nozzle but maximum 2 experiments are conducted with the same one if it is not worn out too much.

6.3 Experimental procedure

The experimental procedure for each test is basically the same. At first the rock specimen is placed in the test apparatus and the desired stress field installed. Then the steel pipe is connected to the rock with the thread connection as well as the periphery including pump and mud return path. Then the jetting operation is started and the operating parameters ROP, pump flow rate and pressure recorded. Afterwards the stress is released from the rock surface and the jetting nozzle and specimen

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analysed with regard to the created lateral and borehole. In the following table 2 the applied stress state $\sigma_{x,y,z}$ for each experiment is given as well as pump pressure p_p and volume flow rate Q_p, nozzle type and specimen number.

Specimen number	Nozzle type	Pump pressure, in (bar)	Flow rate, in $\left({}^{l}/_{min}\right)$	Stress x, in (MPa)	Stress y, in (MPa)	Stress z, in (MPa)
GI-02	rotating	340 - 360	24 - 25	35	5	5
GI-03	rotating	340 - 360	24 - 25	5	35	5
GI-04	rotating	340 - 360	24 - 25	10	10	30
GI-05	rotating	340 - 360	24 - 25	10	30	10
GI-06a	rotating	340 - 360	24 - 25	10	30	10
GI-06b	rotating	340 - 360	24 - 25	30	10	10

table 2: experimental schedule

6.4 Results and analysis

In the following the experimental result of each individual jetting experiment is reported and analysed.

Jetting specimen GI-02

In the first jetting experiment the highest stress is applied in x-direction with a magnitude of 35 MPa resulting in a perpendicular jetting direction. The other sides are loaded with a stress of 5 MPa each. After the rotating nozzle has entered the rock it is moved manually in an oscillatory mode in order to prevent stalling of the nozzle head. The nozzle entrance time can be estimated in figure 32 from 0 to about 400 seconds of experimental time. Then the jetting operation starts, rock mass is eroded and the lateral created. The gained rate of penetration is about 750 mm/h which is indicated in figure 32 by the red marked slope of the displacement graph. After the experiment the shape of the lateral is analysed with a camera and a picture is presented in figure 33. It can be seen that the lateral wall is not of uniform shape. Basically it shows a circular shape as in those laterals created under atmospheric and pore pressure controlled conditions. But on top and bottom of the borehole wall deep fractures can be observed

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that lead to massive breakouts it the near vicinity. Consequently the shape in those regions is not uniform.

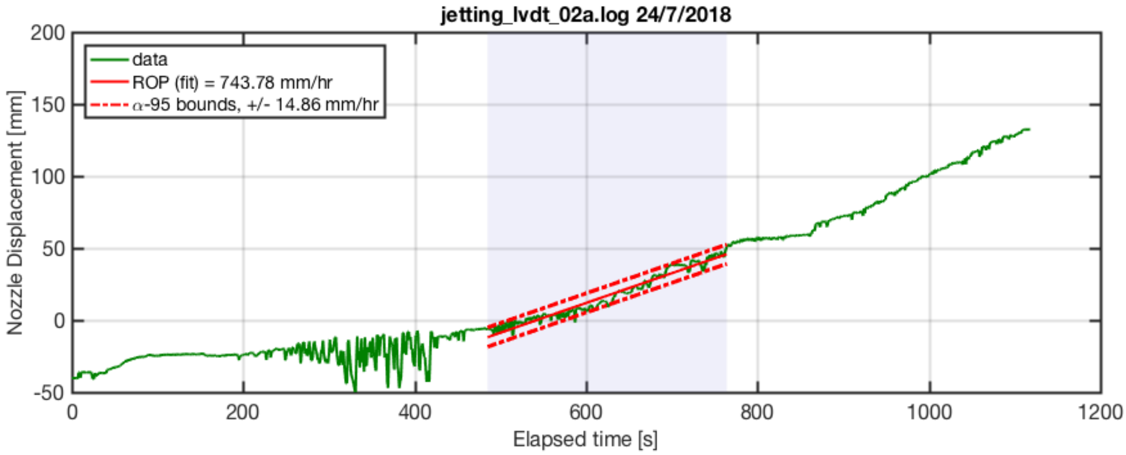

figure 32: ROP during jetting experiment with GI-02

figure 33: lateral shape after jetting experiment with GI-02

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Jetting specimen GI-03

In the second jetting experiment the highest stress is applied in y-direction hence in parallel to the jetting direction. The absolute value of stress applied on the front and back surface of the specimen is 35 MPa, the other sides are loaded with 5 MPa each. After a short entrance distance of the nozzle inside the rock specimen the jetting operation is started and ROP generated. The according graph presented in figure 34 shows displacement of the nozzle vs. the ongoing time of the experiment. It can be seen that the mean value for rate of penetration is about 180 mm/h and therefore much less compared to the stress state applied in the first experiment. The analysed lateral wall presented in figure 35 shows a round shaped and regular borehole wall without any visible cracks or breakouts.

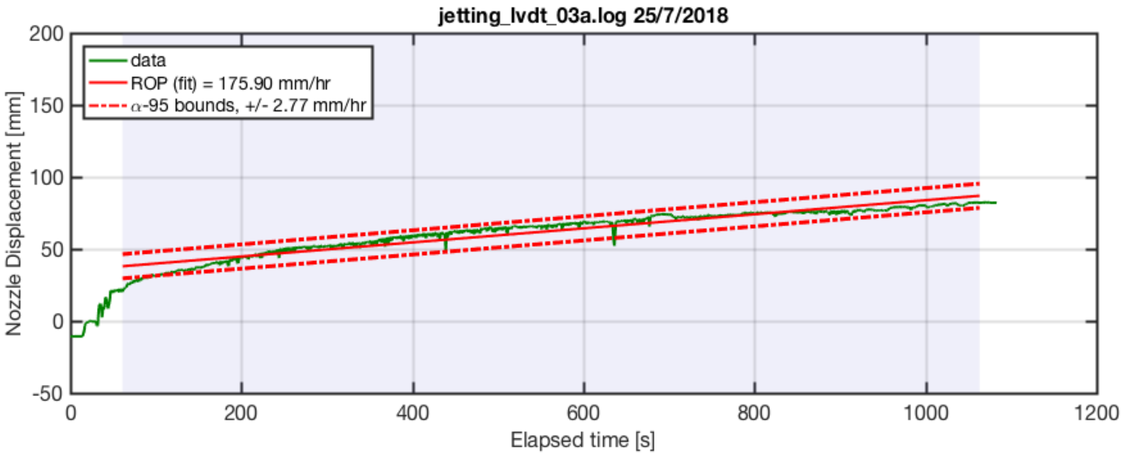

figure 34: ROP during jetting experiment with GI-03

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figure 35: lateral shape after jetting experiment with GI-03

Jetting specimen GI-04

In the third experiment jetting into specimen GI-04 the highest load is applied again perpendicular to the jetting direction. On top and bottom plate a stress of 30 MPa is applied in z-direction and on the other sides of the specimen a stress of 5 MPa each. Immediately after the nozzle enters the front side of the specimen the jetting operation is started. The slope of the ROP can be seen in figure 36 revealing that about 320 mm/h can be jetted with the applied operating conditions. In figure 37 a photo is presented that shows the visual inspection of the lateral wall after the experiment. Similar to the shape presented in figure 33 the borehole wall a uniform cylindrical shape can be assumed but due to breakouts it is more of rectangular form. In contrast to figure 33 no fractures of comparable depth can be observed.

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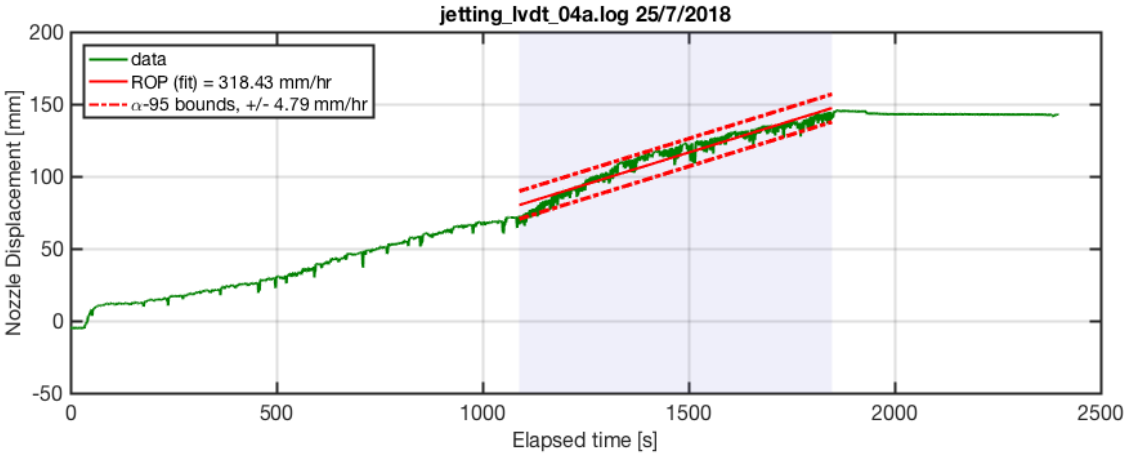

figure 36: ROP during jetting experiment with GI-04

figure 37: lateral shape after jetting experiment with GI-04

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Jetting specimen GI-05

In the jetting experiment with the specimen GI-05 the highest stress is applied in jetting direction, hence in y-direction, with a magnitude of 30 MPa. On the other sides of the rock a stress of 10 MPa is applied each. According to the slope of the nozzle displacement curve presented in figure 38 shows that during the experiment an average ROP of about 100 mm/hr is achieved. The optical inspection of the lateral shows similarities with that one of experiment 3 with specimen GI-03. The oscillations recorded of the displacement measurement device seen in figure 38 occur due to the forward backward movement of the nozzle in order to prevent stalling.

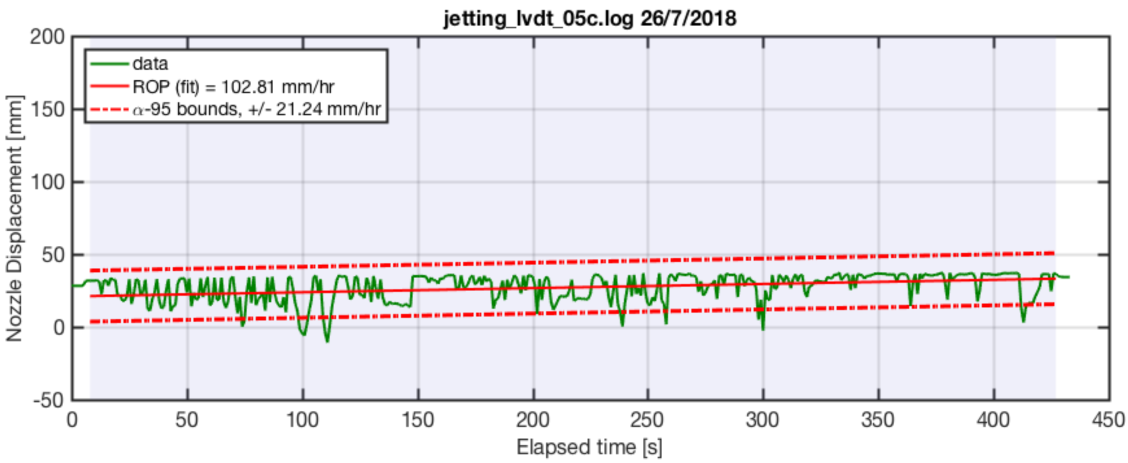

figure 38: ROP during jetting experiment with GI-05

Jetting specimen GI-06a

In the first part of experiment 6 with specimen GI-06 again a stress field is applied on the rock specimen with the highest magnitude of 30 MPa parallel to the jetting direction. The other sides are again load with 10 MPa each. After the nozzle enters the rock cube a distance of max 10 cm is drilled and ROP recorded. With this setup an average rate of penetration of about 210 mm/hr can be achieved. In figure 39 the measurement data can be seen with the recorded ROP marked in red. The first part of the experiment takes 700 seconds and the nozzle is kept in place after finishing.

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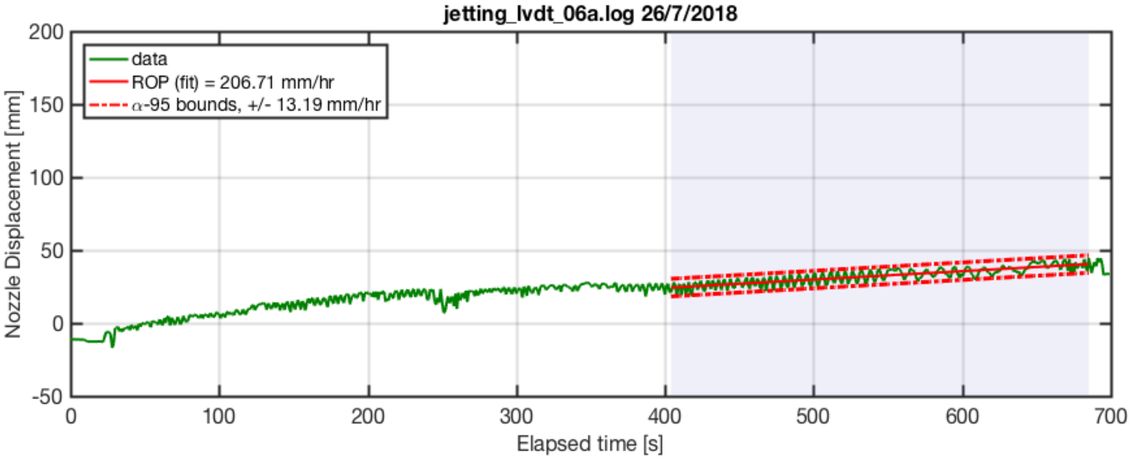

figure 39: ROP during jetting experiment with GI-06a

Jetting specimen GI-06b

After completing the first part of the experiment with specimen GI-06 the stress field is varied while keeping the rock specimen inside the tri-axial cell. The differential stress field is rotated by 90°, meaning that the highest stress is now acting perpendicular to the jetting direction in x-direction. The magnitude of 30 MPa is not changed as well as the load being applied in y- and z-direction. Each direction applies 10 MPa of stress on the according specimen faces. Once the stress field is applied the jetting experiment restarts directly from the last stop of jetting experiment GI-06a. In the following figure 40 the rate of penetration recorded during the second half of the jetting experiment is presented. Along the slope of the graph marked in red, it can be seen that an average ROP if about 600 mm/hr can be achieved with the current setup. Pressure and volume flow rate are not changed compared to the previous setup.

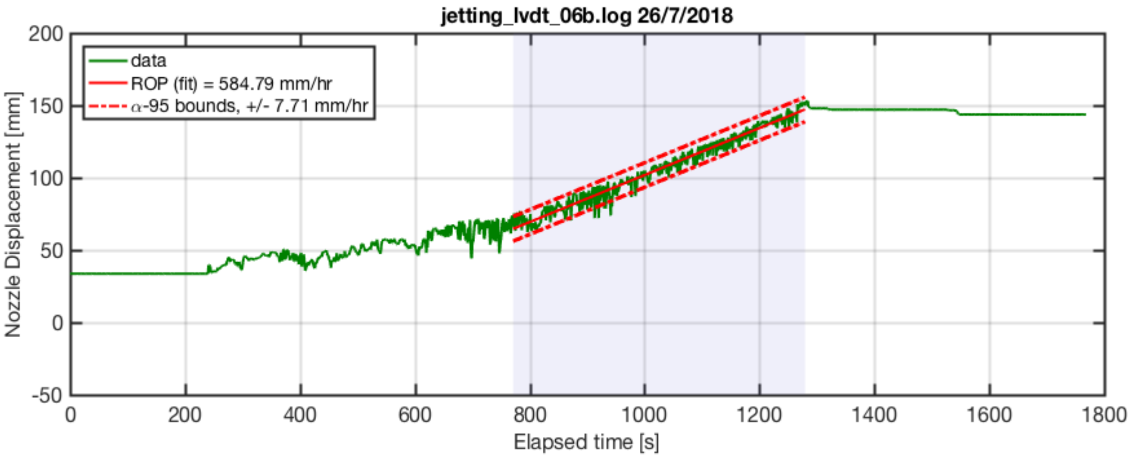

figure 40: ROP during jetting experiment with GI-06b

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In the second half of the experiment with specimen GI-06 a distance of about 9 cm is drilled inside the rock within a time of about 500 seconds. After the experiment is finished, the rock specimen is unloaded and the created inspected. In the following figure 41 a photo is presented that shows the combined lateral shape of experiment GI-06a and GI-06b.

figure 41: lateral shape after jetting experiment with GI-06

The first part of the lateral results from the experimental setup of the experiment GI-06a. Same as in the experiment GI-04 and GI-02 a non-uniform shape of the lateral wall can be seen. The curvature of the wall tends to be more rectangular than cylindrical while no massive breakouts or fractures can be seen. The second part of the lateral shows a smaller diameter but it is almost of perfect round shape. A transition between both later wall shapes and hence experiments can be assumed as well.

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7. Atmospheric Jetting Experiments

In order to further plan the field test jetting operation at the Iceland drill site within WP6, experiments are conducted at atmospheric conditions with the project partner WSG in Emmen, NL. The test procedure is similar to that one usually performed before a radial jetting operation is started in the field in order to evaluate its effectiveness (jetability). For this purpose, cores of the respective target horizon are provided and prepared by GZB. A positive test result under surface experimental conditions will normally lead to successful creation of laterals downhole.

7.1 Test bench and setup

The WSG jetting test-stand is made up of closed box with a removeable lid on top with approx. dimensions of 80x50x50 cm (L x W x H). There is a small opening at the front end which allows a thin high pressure (hp)-pipe to be inserted into the tank. A small piece of flexible hp-hose with threaded connections at its ends is used to connect the pipe with the jetting nozzle. Inside the box, the hp-pipe and nozzle is radially guided with relatively small clearance of 2…3mm (radially) inside another tube, which is used to simulate shape of the later borehole. The sample is placed on top of a metal frame directly in front of the nozzle. It should firmly touch the guide tube’s outlet. A rather flat contact surface is recommended. Additional contact force should be applied by adding wooden planks at the backside of the specimen. Optional, strong glue can be used to seal and connect the rock to the tube. The sample is additionally tied to the metal frame with a tension belt in order to prevent slipping and tilting. In the following figure 42 a sketch of test setup is presented followed by photos in figure 43, figure 44 and figure 45.

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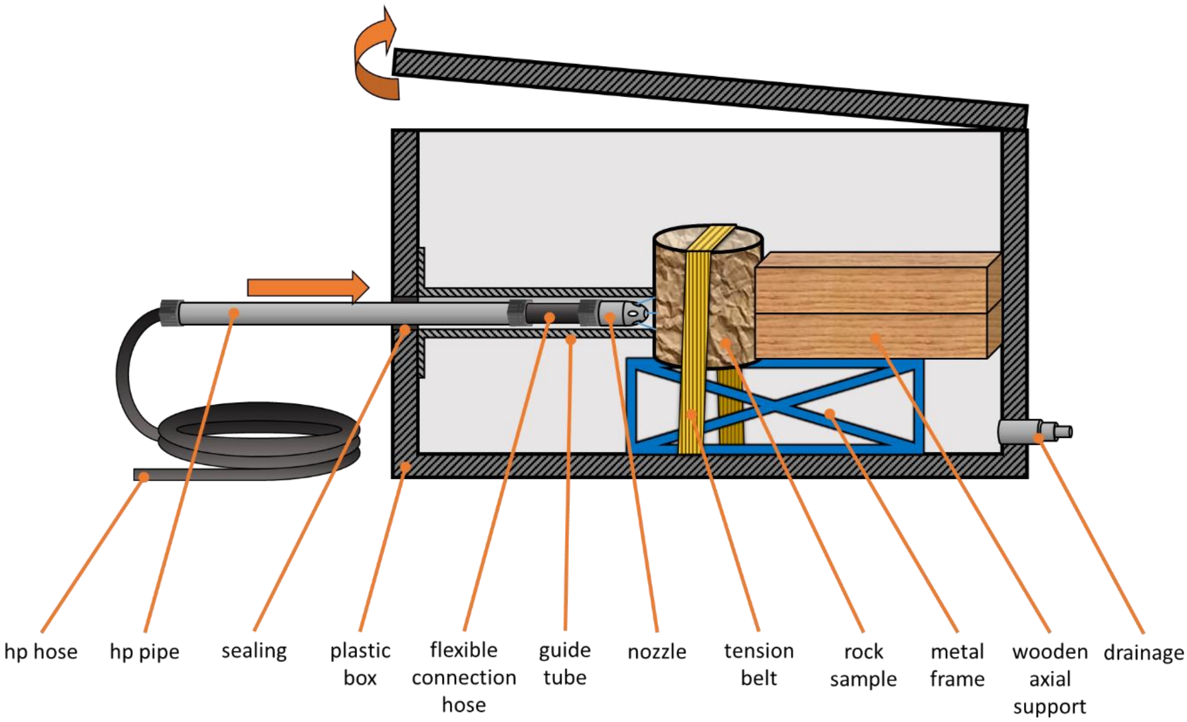

figure 42: sketch of the test bench including labeling of the components

figure 43: Guiding tube in front of hard rock sample (left) | Jetting box with hp-pipe as inlet from the front side (right)

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figure 44: Rock sample firmly attached to the guiding tube with nozzle inside. Additionally the sample is strongly tied to the metal frame beyond

figure 45: HP-pipe with flexible hose and threaded connection for a nozzle at its end guided with little radial clearance inside the outer tube

7.2 Test execution

All experiments are conducted with a speed-controlled high pressure pump. After its start, the pressure is quickly (5 – 10 sec.) raised up to approx. 500 bar and stays

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constant. The flowrate ranges around 22 l/min for the static nozzle and 26…27 l/min for the rotating nozzle. During the tests, the high-pressure pipe with the nozzle at its end is manually re-adjusted to the rock at short intervals by pushing it carefully into the box by hand. Especially in case of the rotating nozzle, only a little force is allowed to prevent it from getting stalling. In the following figure 46 a photo of the jetting operation is presented.

figure 46: Pump setting (left) and re-adjustment of the hp-nozzle by slightly pushing it against the rock surface

Two types of Iceland basalt rock types are tested. One is internally labelled as VBA6-IC01 and of very porous and brittle or soft character (figure 47, left). The other one labelled as VBA6-IC03 is a highly dense rock type, very hard and almost no porosity is visible (figure 47, right). Next to the Island basal rock types a sediment layer is tested as well that is assumed to bear higher potential for a successful jetting operation at the field test. This sediment layer shows less porosity than VBA6-IC01 but higher strength.

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figure 47: Iceland basalt rock specimen, VBA6-IC01 left, VBA6-IC03 right

The experiments are completed after 5 min of jetting time or early when the jet is no longer penetrating into the rock anymore, meaning that the back thrusting jets are washing out the sides of the created hole instead of further penetrating into the rock.

7.3 Experimental observation

As water is splashing out of the guide tube to all sides, the box lid is closed for most of the time and only sometimes opened for short visual inspection in order to see if the backward oriented nozzle outlets are only washing out the lateral instead of penetrating further into the rock.

<u>Island Basalt VBA6-IC01</u>

In case of the rather porous basalt, the rock can be jetted very gradually. Each time a peace of rock breaks off, significant movement of the nozzle is possible. The test ends after 3:00 min of total jetting time and the static as well as rotating nozzle are tested. In the following table 3 the experimental results are presented for each test including one picture showing the specimen afterwards.

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#	Rock	Nozzle	Pump	Time	Outcome	
1	Soft	Static	500 bar 22 l/min	3 min	1cm deep hole + crack	
2	Soft	Static	500 bar 22 l/min	2 min	1cm deep hole + crack	
3.1 **3.2**	Soft	Rot.	500 bar 26 l/min	2 min + 2 min	No crack, 2 cm deep hole Bigger washout	

table 3: experimental results jetting tests with VBA6-IC01

Island Basalt VBA6-IC03 (1)

In case of the rather tough basalt, no significant rate of penetration is possible. Each test is stopped after 5 minutes and only the rotating nozzle design is tested. In the following table 4 the experimental results including photos of the specimen are presented.

#	Rock	Nozzle	Pump	Time	Outcome	
4	Hard	Rot.	500 bar 26 l/min	5 min	No significant progress; slight nozzle wear	

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#	Rock	Nozzle	Pump	Time	Outcome	
5	Hard	Static	500 bar 22 l/min	5 min	Washout* (left)	
6	Hard	Static	500 bar 22 l/min	5 Min	No progress (right)	

table 4: experimental results jetting tests with VBA6-IC03

<u>Island inter basalt sediment layer</u>

The jetting experiments with the sediment layer rock type are conducted with the rotating and static nozzle design, once with water and once with acid as jetting fluid. The first experiment using the static nozzle design shows good penetration after 10:00 min of jetting time, similar like the second experiment using the rotating nozzle. In the third and fourth experiment using acid the penetration of the rock cores is successful for both rock specimen as well and but no significant increase in ROPs can be achieved. In the following table 5 the experimental results are presented for each test including one picture showing the specimen afterwards.

#	Rock	Nozzle	Pump	Time	Outcome	
7	Sedi ment	Static	500 bar 22 l/min	10:00 min	Good penetration towards end of experiment	

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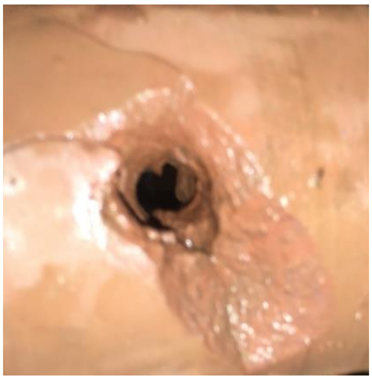
#	Rock	Nozzle	Pump	Time	Outcome	
8	Sedi ment	Rot.	500 bar 21 l/min	3:00 min	Complete penetration	
9	Sedi ment	Rot. + acid	500 bar 21 l/min	2:00 min	Complete penetration + core broken	
10	Sedi ment	Static + acid	500 bar 22 l/min	10:00 min	Complete penetration + core broken	

table 5: experimental results jetting tests with Iceland inter basalt sediment layer

<u>Island Basalt VBA6-IC03 (2)</u>

The second series of jetting into the hard Iceland basalt rock type is done with much higher pump pressures of up to 800 bar resulting in flow rates of max. 35 l/min. In case of these more intense operating conditions a significant rate of penetration is possible. In the following table 6 the experimental results including photos of the specimen are presented.

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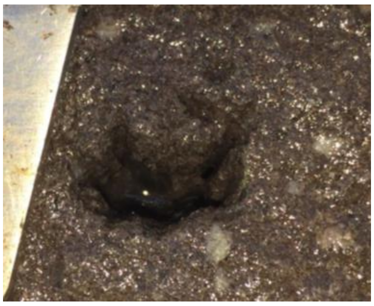
#	Rock	Nozzle	Pump	Time	Outcome	
11	Hard	Rot.	700 bar 27 l/min	15:00 min	No full bore hole, but 30 mm deep	
12	Hard	Rot.	800 bar 29 l/min	15:00 min	No full borehole, same shape as exp. 11, but slightly deeper 32 mm	
13	Hard	Rot.	800 bar 35 l/min	6:00 min	Full penetration, lateral 150 mm long	
14	Hard	Rot.	700 bar 33 l/min	10:00 min	Full borehole, but not jetted through, lateral 117 mm deep	

table 6: experimental results jetting tests with VBA6-IC03 with extreme high pressures

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8. Conclusions

8.1 Submerged jetting experiments

The experimental outcome of the submerged jetting experiments show that at first that cavitation erosion can be neglected as governing erosion mechanism. The volume of removed material as well as the local occurrence of this erosion mechanism is completely different than those ones while only stagnation pressure acting on the rock. Furthermore, also the time needed for the cavitation erosion to remove material is magnitudes higher compared to the erosion initiated by the pure water pressure of the jet. The PIV measurements underline this statement by giving a well suited explanation why the cavitation bubbles are not entering the target center zone. Also the measured width of the stagnation point shows good agreement with the later diameter of the cavity.

8.2 Pore pressure controlled jetting experiments

The experiments clearly reveal that the rotating nozzle design works best for most of the rocks. It is able to create the most uniform boreholes with fastest time resulting in highest values for ROP. Under these given hydraulic conditions the static nozzle design from WSG is not able at all to create a borehole which enables the nozzle and subsequent hose to enter the rock specimen. Only the Buckman© type nozzle is capable of successfully jetting a lateral with a non-rotating nozzle design. But the experiments also show that this type of nozzle is quite sensitive towards the applied back pressure, meaning pore pressure inside the rock specimen. Furthermore it can be seen that the increase of back pressure has no effect on ROP of harder and less permeable rock types like that one from Dortmund quarry location. It might even decrease the jetting performance.

8.3 Bi-ax jetting experiments

The results of the experiments under the applied hydraulic conditions clearly show that the current RJD technology is not able to successfully penetrate the harder sandstone rock types like the tested one from Dortmund quarry location. Although the specimen is not saturated it can be assumed that the near wellbore area is filled with the jetting fluid relatively soon. Therefore, the experimental results in this chapter are comparable with those under pressure controlled conditions. Both experiments do show that the Dortmund sandstone rock type needs much higher nozzle exit velocities in order to initiate the erosion process that is needed to create a lateral.

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8.4 Tri-ax jetting experiments

The experimental results of the tri-ax jetting experiments enables one to give two conclusions. The first one refers to the overall ROP itself. During the tests a maximum ROP of 750 mm/hr can be achieved which is magnitudes less than those achieved at atmospheric and dry conditions reported in D5.1 (Hahn & Wittig, 2017) and during the experiments under pore pressure controlled conditions. Although the differential stress field applied during the experiments is more of an extreme character that might be unlikely to occur in nature, it shows that a high differential stress locally does not enhance the rate of penetration in general. This is convenient with the experiments reported in section 4. During the application with a bi-axial stress field the sandstone from Dortmund quarry location was still not jet-able. The second conclusion can be made referring to the orientation of the differential stress field itself. The experimental data, meaning the ROP values, show a tendency indicating that jetting perpendicular towards the highest stress enhances the speed of the jetting nozzle creating a lateral and vice-versa. This statement is underlined especially by the experiments GI-06a and GI-06b where exactly the same rock specimen is used for both stress states without varying the experiment setup concerning pump pressure, flow rate and nozzle design.

8.5 Atmospheric Jetting Experiments

The additional guide tube, which simulates the closed environment of a created borehole, could be a key factor for successful jetting experiments and operations. Additionally, the high pump pressure while using the static nozzle design is contributing as well, resulting in higher nozzle exit speeds. The small annulus inside the guiding tube creates a thin and narrow flow path resulting in very high and extremely turbulent velocities and thus, high pressure losses. Due to that fact this may lead to an extreme pressure concentration directly at the borehole front acting uniformly on the wall. This may to some extent, equal the hydrostatic pressure of a water column in a real borehole and have a positive effect on the jetting result itself. Therefore, the flow regime directly at the borehole front differs from that one during the pore pressure controlled jetting experiments and, thereby gives a possible explanation for the significant difference between the results of both setups.
The jetting performance on the porous basalt is, in contrast to the hard non-porous rock, sufficient enough to proceed the planned field test at the Iceland drill site within WP6. Furthermore, the effectiveness of the rotating nozzle was not significantly higher compared to the static one. On top during the experiments it turns out that the static nozzle is the preferred one as the rotating nozzle may get stuck more easily in the hole. During the experiments stalling of the rotating nozzle is often a problem that occurred frequently during the tests while the pressure readings on the surface are not able to

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indicate that. Therefore a constant forward backward movement of the nozzle is required in order to maintain its rotational movement. The use of acid does not really result in a significant increase of rate of penetration for the tested sedimentary rock type layer. Still a difference between both nozzle types being used can be observed. The test series using more intense high pump pressures and flow rates shows that also quite hard rock types like the Iceland basalt are accessible with the current, slightly improved RJD technology. Nozzle pressures of at least 750 bar are needed to penetrate into these rocks. This observation matches with the experimental results of the surface experiments conducted to the Iceland rock types already reported in D5.1 (Hahn & Wittig, 2017). During this former test series with just one single nozzle it turned already out that outlet velocities of more than 300 m/s are needed by applying at least 800 bar of nozzle pressure as well. Therefore, such a significant increase in the jet nozzle pressure downhole can already be seen as an improvement of the current RJD technology in order to access geothermal reservoirs of hard rock formation types.

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References

Hahn, S., & Wittig, V. (2017). *D5.1 - Jet drilling at ambient conditions.* H2020 SURE.

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