Feasibility of Spallation Drilling in a High Pressure, High-Density, Aqueous Environment: Characterization of Heat Transfer from an H_2-O_2 Flame Jet

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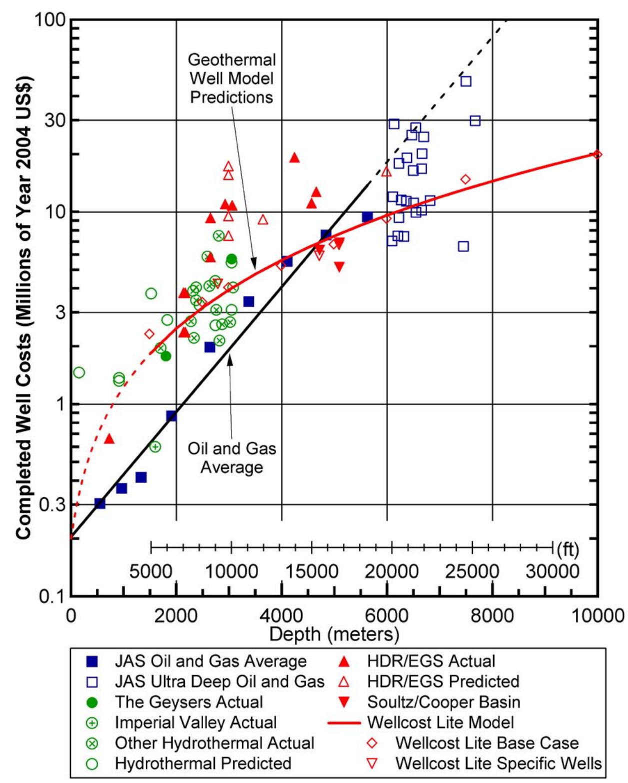
Keywords
Spallation drilling, heat transfer, jets, impinging, high pressure

ABSTRACT

Due to the high costs associated with drilling deep wells with conventional rotary drilling, novel drilling technologies could be a key to implementing engineered geothermal technologies on a global scale. One such technology, flame jet thermal spallation drilling, uses high heat fluxes to rapidly heat the surface of rock, inducing thermal stresses that cause rock fragments, or "spalls," to be ejected from the rock surface. To date, all field and laboratory tests investigating jet flame drilling have been performed in air-filled holes at near ambient pressures. In order to drill deep wells in practice with this technique, stable flames will need to be created in aqueous media over a range of pressures. As a first step, we have experimentally investigated a hydrogen-oxygen flame jet in water at a pressure of 100 bar (1500 psi) in a lab-scale apparatus that replicates conditions that would be found in a fluid filled borehole at a depth of about 1 km (3300 ft.). The heat flux from the jet flame to a brass block was determined by measuring the steady state temperature profile within the brass block. Estimated maximum heat fluxes on the order of 0.5 MW/m^2 (44 BTU/ft^2-s) were observed, which should be high enough to induce thermal rock spallation.

Introduction

The cost of drilling and completing wells is a major factor in determining the economic feasibility of developing geothermal resources for energy production. This is especially true for Engineered Geothermal Systems (EGS) in lower grade regions where depths of greater than 3 km (10000 ft.) are needed. For example, if the average geothermal gradient is 40 °C/km (2.2 °F/100 ft.), holes must be drilled to depths greater than 4 km (13000 ft.) to encounter commercially useful rock temperatures for producing electricity. Under these conditions, drilling and reservoir stimulation costs can represent over 50% of total capital investment (Tester et al., 1994). As gradients decrease further, the fraction of total costs contained in the subsurface components (drilling, completion, and stimulation) increases. This is due to the tendency of conventional rotary drilling costs to increase non-linearly with depth, as shown in



1. JAS = *Joint Association Survey on Drilling Costs.*
2. Well costs updated to US$ (yr. 2004) using index made from 3-year moving average for each depth interval listed in JAS (1976-2004) for onshore, completed US oil and gas wells. A 17% inflation rate was assumed for years pre-1976.
3. Ultra deep well data points for depths greater than 6 km are either individual wells or averages from a small number of wells listed in JAS (1994-2000).
4. "Other Hydrothermal Actual" data include some non-US wells (Mansure 2004).

Figure 1. Completed oil, gas, and geothermal well costs in year 2004 US$ as a function of depth (adapted from *The Future of Geothermal Energy*, Tester et al., 2006).

Figure 1. In order to make geothermal energy universally accessible in areas of low thermal gradients, new technologies will be needed to lower drilling costs and/or increase well productivity.

A technology that has seen recent renewed interest is thermal spallation drilling. Thermal spallation drilling is a drilling method in which the surface of a rock is rapidly heated to the point where thin flakes of the rock, called "spalls," are violently ejected from the surface. Heat is normally delivered to the rock by a flame jet directed at the rock surface. Thermal stresses, caused by differential expansion of the rock due to temperature increases, induce failure in the rock surface. Typical spalls are 0.1 to 2 mm thick and have diameters 10-20 times their thickness (Dey and Kranz, 1985). Spallation is typically used in hard, crystalline rocks such as granite, taconite, quartzite, and hard sandstones.

Thermal spallation drilling was commercially developed for drilling blast holes in the mining industry starting in 1947 by the Linde Air Division of Union Carbide. These systems used a flame jet-piercing tool to drill blast holes for mining ore. By 1961, the tool had been used in the production of 140 million tons of crude taconite ore, as well as 25 million tons of granite, quartzite, syenite, and sandstone (Calaman and Rolseth, 1961).

A truck mounted flame jet thermal spallation system for drilling vertical boreholes was developed and tested by Browning Engineering in the early 1980's. The system delivered fuel, oxidant, and cooling water to the jet burner via a series of rubber hoses. During tests performed at Conway, NH in granite, Browning (1981) drilled a 20-25 cm (8-10 in.) diameter hole 335 m (1100 ft.) deep at an average rate of penetration of 15.8 m/hr (52 ft./hr). Near the end of this experiment, instantaneous drilling rates of over 30 m/hr (100 ft./hr) were achieved. Similar tests at Barre, VT achieved an average drilling rate of 7.6 m/hr (25 ft./hr) in a 35-40 cm (14-16 in.) diameter hole to depths of 130 m (430 ft.). A flame jet drilling system was developed and tested at Pedernal Hills, NM by Los Alamos National Laboratory. This system drilled 35-45 cm (14-18 in.) diameter holes to depths of 30 m (100 ft.) at average penetration rates of 6-7 m/hr (20-23 ft./hr), and also successfully demonstrated the ability to achieve downhole ignition and the use of drill pipe as a burner support and conduit for combustion air (Williams et al., 1988).

The heat fluxes at the rock surface associated with jet flame thermal spallation drilling range from 0.5-10 MW/m^2 (44-880 BTU/ft^2-s). Although the jets themselves have nozzle exit temperatures of about 1800 °C (3300 °F) and higher, the temperature of the rock surface during spallation is much lower. The actual surface temperature during spallation is still debated. Lab scale studies by Rauenzahn (1986) calculated rock surface spallation temperatures of 500 °C (932 °F) or less for surface heat fluxes less than 1 MW/m^2 (88 BTU/ft^2-s), which is in line with conclusions reached by Dey (1984) and Geller (1970). Later studies by Wilkinson (1989) confirmed similar temperatures measured by infrared scanner for spallation induced by both flame jets and lasers at heat fluxes of ~1 MW/m^2 (~90 BTU/ft^2-s), but recorded temperatures as high as 750 °C (1400 °F) for Westerly granite and 900 °C (1650 °F) for Barre granite at heat fluxes approaching 3 MW/m^2 (264 BTU/ft^2-s).

Although thermal spallation drilling is a promising technology, it does have several limitations. Only certain types of rock spall readily. These are usually hard, crystalline rocks such as taconite, quartzite, jasper, diorite, granites, and hard sandstones. Some rocks, such as limestone, shale, basalt, and soft sandstones are thought to be "non-spallable" (Wilkinson and Tester, 1993), although in an experiment by Williams et al. (1996), a hard limestone that was placed on a turntable and alternately heated with a flame jet and then cooled did undergo a spallation-like process.

A current limitation of the thermal spallation drilling tests conducted so far is that they were performed in air-filled holes in a low density, gaseous environment at near ambient pressures. This limits the depth to which an open, uncased hole can be drilled, due to a number of factors including borehole stability and concerns about effective spall removal. In deep drilling applications, boreholes must be filled with fluids of liquid-like density to provide a hydrostatic force to stabilize the borehole in the presence of in situ stress that increases with increasing lithostatic pressure. In conventional rotary

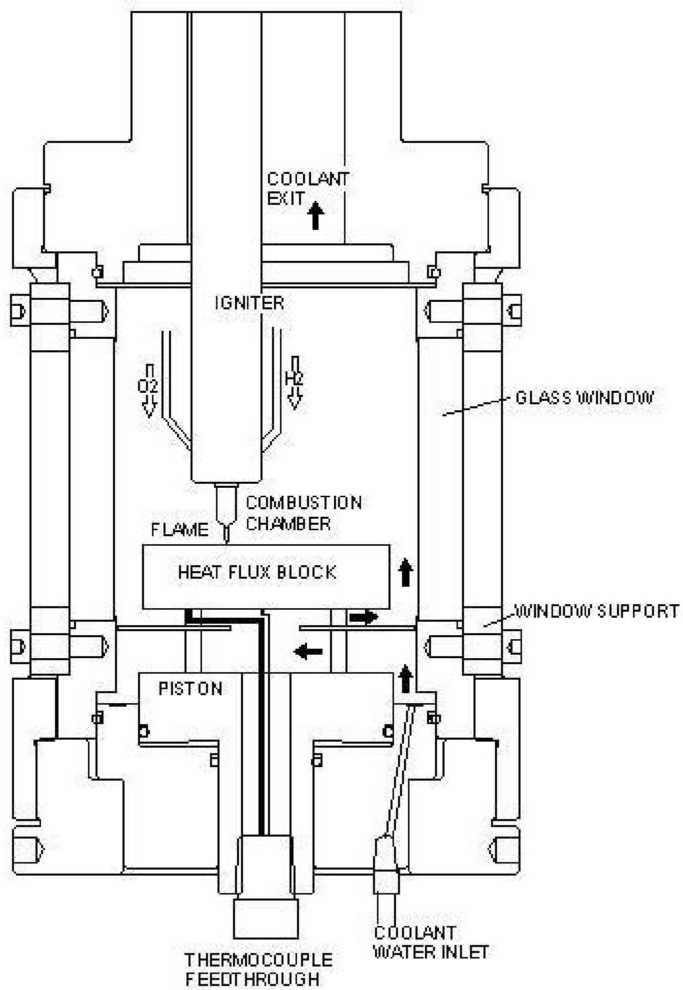


Figure 2. Cross section of experimental pressure cell used to create hydrogen-oxygen flame jet in water at 100 bar (1500 psi).

drilling, a dense fluid (drilling mud or water) also is used to entrain and remove drill cuttings from the hole, to control or eliminate pore fluid inflow from the borehole walls, and to provide buoyancy for any drill string system, lessening its load carrying requirements. In order to use flame jet thermal spallation drilling to drill deep wells, it would be necessary to create a jet flame in a liquid-like density, aqueous environment as discussed in U.S. Patent 5771984 (Potter and Tester, 1998). As in low density thermal spallation drilling, the jet flame in the high density environment would have to be capable of achieving high heat fluxes to the rock surface on the order of 1 MW/m^2 (88 BTU/ft^2-s), and rock surface temperatures of 500 °C (932 °F) and higher.

Testing high density thermal spallation in the field would be technically challenging and prohibitively expensive. A more viable early approach is to perform controlled experiments at a lab scale. The purpose of our initial research is to produce jet flames under laboratory conditions that simulate the deep borehole environment, and to measure the heat flux from a jet flame impinging against a flat surface. A pre-mixed hydrogen-oxygen flame jet issuing into water at 100 bar (1500 psi) impinging against a bronze block was used to measure heat flux from the jet to a flat surface. Steady-state temperature measurements in the block were used to fit parameters to an assumed heat flux profile from the jet. The results from experiments at multiple stand-off distances are presented and discussed along with implications for continued experimental work.

Experimental Set-up

Experiments were carried out using a specially designed apparatus shown in Figure 2. The apparatus consists of a combustion chamber and jet nozzle mounted in a 140 mm (5.5 in.) diameter by 136.5 mm (5.375 in.) long water-filled cylindrical chamber capable of operating at pressures in excess of 150 bar (2200 psi). The chamber has two large quartz glass windows mounted on opposite sides of the chamber wall so that the jet flame can be observed during operation. Hydrogen and oxygen rates are precisely controlled to the correct stoichiometric ratio and supplied separately to the apparatus prior to mixing in the combustion chamber. Ignition of the gases is achieved using a high voltage spark. The combusted gases exit the jet through a nozzle with a diameter of 1.0 mm (0.040 in.). The combustion chamber and jet nozzle are offset from the chamber centerline, and can be rotated around the chamber, scribing a circle with a diameter of 31.75 mm (1.25 in.). Pressurized cooling water enters the chamber from the bottom of the apparatus at a continuous rate, passes by the heat flux block and exits through the top of the chamber to a dome loaded back pressure regulator.

The flame jet impinges against a cylindrical brass block 99.0 mm (3.9 in.) in diameter by 25.4 mm (1 in.) thick mounted on a piston in the base of the combustion chamber. Measurement of the heat flux from the impinging jet to the brass block was made using a plug-type heat flux gauge, shown in Figure 3. The heat flux plug is a 25.4 mm (1 in.) diameter by 25.4 mm (1 in.) long brass rod with 6 holes drilled to the center of the plug at various depths. K-type thermocouples 0.80 mm (1/32 in.) in diameter were inserted into the holes and used to measure the steady state temperature along the plug's centerline during the experiment. The larger brass block was cut in half and a hole was machined for the heat flux gauge plug, so that when the plug and block are assembled, they fit tightly, providing good thermal contact. The sides of the block were insulated, and the bottom of the block is continuously cooled by flowing water during the experiment. The block and plug were then mounted on a movable piston at the bottom of the chamber of the experimental apparatus using stand offs. The piston travel can be controlled during a test, allowing heat flux from multiple stand-off distances to be studied during a single run.

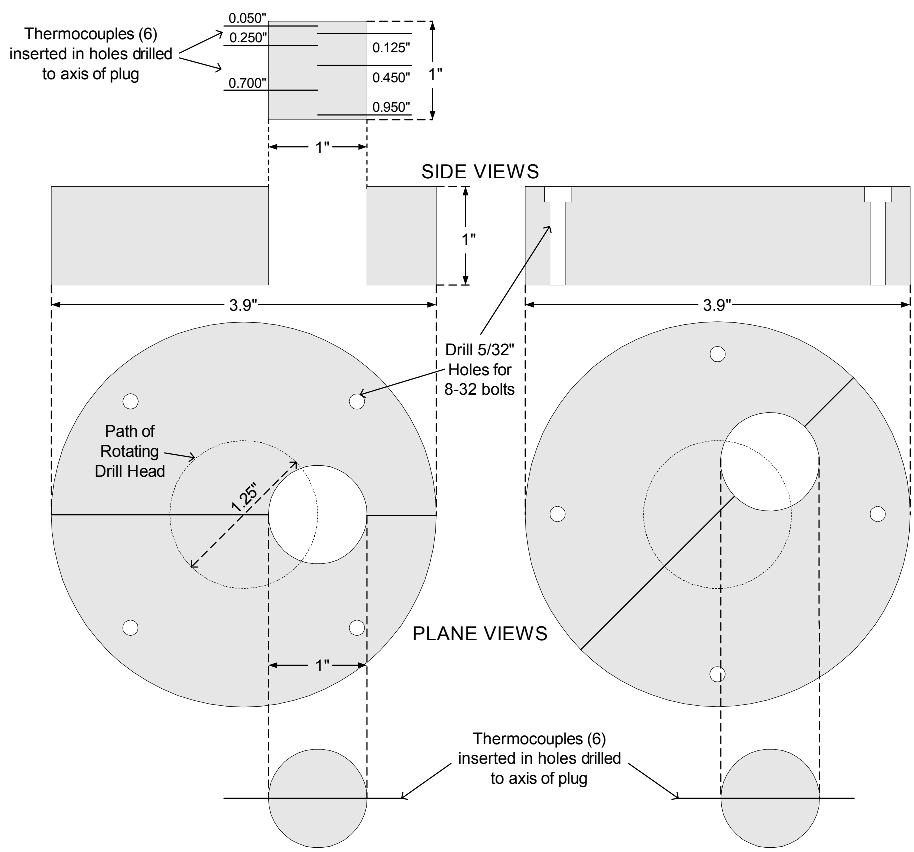


Figure 3. Plug type heat flux gauge contained in a brass block. Temperature measurements from thermocouples inserted at various depths along the centerline of plug are used to determine the heat flux from an impinging jet to the block.

Two experimental runs at similar combustant flow rates were conducted. During each run, the jet nozzle was centered over the heat flux plug and the temperature in the brass block was allowed to equilibrate. The jet nozzle was then rotated approximately 15° along its circular path of travel and the temperature was allowed to equilibrate again. This was repeated two more times, so that temperature data at jet nozzle positions of 0°, 15°, 30°, and 45° were collected. Precise angular measurements were made using an indicator mounted on the rotating assembly outside of the apparatus. In this way, temperature data along the center axis of the heat flux gauge at multiple distances from the impinging flame could be collected during a single run. The jet stand-off distance was then decreased by about 2.5 mm (0.1 in.), and the process repeated. During each run, data was collected for 2 stand-off distances. The flow rates, jet nozzle positions and stand-off distances studied for each run are listed in Table 1.

Table 1. Conditions studied during experimental runs. A cell pressure of 1500 psi was maintained during each run.

Run	H_2 Flow	O_2 Flow	Stand-off Distance	Distance between Point where Jet Impinges on Block and Thermocouple Array			
	(lpm_n)	(lpm_n)	(mm)	~ 0° (mm)	~ 15° (mm)	~ 30° (mm)	~ 45° (mm)
1	46	25	14.9	1.5	4.5	8.6	12.5
			12.2	1.5	4.2	8.5	12.5
2	46	28	14.6	1.8	5.5	10.1	13.6
			12.1	1.7	5.3	9.4	13.6

Theory and Modeling

The steady state heat flux from the impinging jet to the brass block was determined by modeling heat conduction within the block and matching simulation results with experimental data. A 2-D axisymmetric geometry for the block, with the jet flame centered on the block, and steady state behavior was assumed. The governing equations for the heat conduction in the block are shown in (Eq. 1).

$$\begin{aligned} 0 &= \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2} \\ -k\frac{\partial T}{\partial z} &= Q(r) \quad @\ z = 0 \\ T &= T_o \quad @\ z = Z \\ Q &= 0 \quad @\ r = R \end{aligned} \qquad \text{(Eq. 1)}$$

The thermal conductivity of brass was assumed to have a constant value of k = 115 W/m-K (66.4 BTU/ft-hr-°F). FEMLAB was used to carry out the simulations and generate a temperature profile, $T(r,z)$, for an assumed heat flux distribution, $Q(r)$, on the surface of the block at z = 0, where r and z are the radial and axial positions, respectively. A heat flux profile shown in (Eq. 2) was based on experimental work on convective heat transfer in non-isothermal, variable density impinging jets by Kataoka et al. (1985).

$$Q(r) = Q_{max}\left[1+0.414\left(\frac{r}{r_o}\right)^2\right]^{-2} \qquad \text{(Eq. 2)}$$

Optimum values for the parameters $Q_{\max}$ and r_o in (Eq. 2) were found by minimizing an objective function, f, based on the sum of the square of the errors between experimental temperature data and simulation results for the experimental data points at each stand-off distance. The modified simplex method of Nelder and Mead (1964) was used to make successive guesses for the parameters being optimized until a local minimum value of f was found.

Results and Discussion

Representative simulation results compare favorably with experimental measurements as seen in Figure 4. Table 2 shows the optimized parameters for all the cases considered here. The preliminary results given in Table 2 are not sufficiently reproducible. The temperatures at the surface of the brass block, where the jet is impinging, were significantly lower in the second run than in the first run despite being run at similar conditions. The maximum measured temperatures near the surface decreased by 8-17 °C (15-30 °F) between Runs 1 and 2. One possible explanation for this lack of reproducibility is a buildup of an oxide layer on the brass surface, but the brass block did not appear to be heavily oxidized, so this is unlikely. More likely, the difference was due to incomplete combustion during the second run, reducing the heat output of the jet. Hydrogen sensors at the system outlet recorded excess unburnt hydrogen in combustion products during Run 2. The most obvious change between runs was the use of a new combustion chamber in Run 2. Although the chambers were built to the same specifications, it is possible that slight changes in nozzle configurations between runs led to incomplete mixing and only partial combustion during Run 2. Work is continuing in our laboratory on nozzle design to produce more consistent results.

The steady state temperatures measured at the surface of the brass block were lower than those normally found at a rock surface during spallation drilling. This is due to several

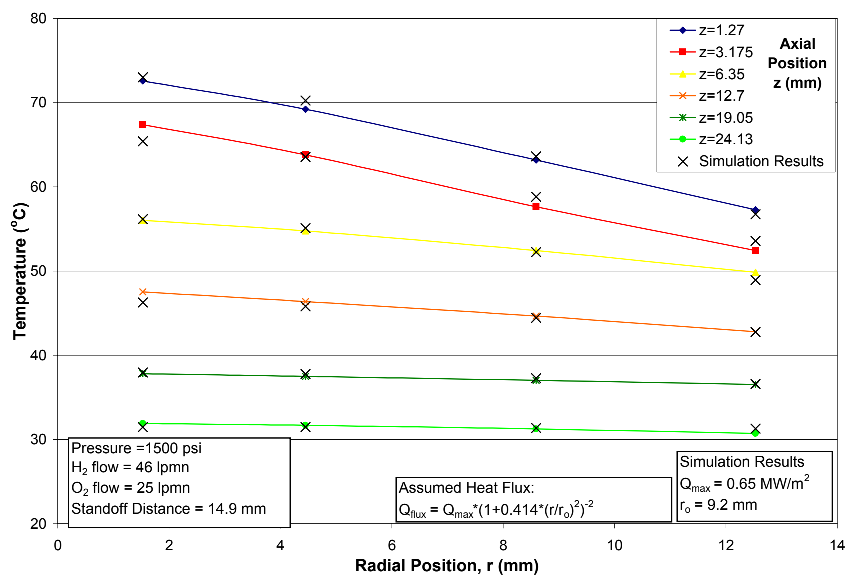


Figure 4. Representative results of experimental and simulation temperatures within the brass block resulting from a flame jet impinging against a flat surface, assuming a 2-D axisymmetric profile with the jet impinging the surface at r=0 mm and z=0 mm. Data shown is from Run 1, with a jet stand-off distance of 14.9 mm (0.571 in.).

Table 2. Optimized parameters for heat flux from experimental data.

Run	H_2 Flow	O_2 Flow	Stand-off Distance	Q_{max}	r_o	Error, f
	(lpm_n)	(lpm_n)	(mm)	(MW/m^2)	(mm)	(K^2)
1	46	25	14.9	0.65	9.2	12.1
			12.2	0.63	9.4	34.3
2	46	28	14.6	0.37	12.0	14.8
			12.1	0.63	8.2	60.9

factors, including the high thermal conductivity of brass, the continuous cooling of the brass block from below, and the entrainment of cold water into the jet stream as it exits the nozzle. A rock surface, with its lower thermal conductivity, would likely experience much higher steady state surface temperatures for the high heat fluxes measured. Maximum heat fluxes at the point of jet impingement on the order of 0.5 MW/m^2 (44 BTU/ft^2-s) were measured. During actual thermal spallation drilling, in which a cavity would be formed, the confining environment of the borehole would likely result in re-entrainment of combustion gases, resulting in significantly higher jet temperatures and higher heat fluxes.

Conclusions

The heat flux of a stable H_2-O_2 flame jet impinging against a flat surface in a high pressure, high density aqueous environment was measured for the first time at several stand-off distances. The conditions replicate those that one would expect to find during thermal spallation drilling of rock in a water-filled borehole 1 km (3300 ft) deep. Although the results showed considerable variability, maximum heat fluxes on the order of 0.5 MW/m^2 (44 BTU/ft^2-s) were observed for all runs. These are comparable to the heat fluxes needed to induce spallation in rock at ambient pressures in air-filled holes. The heat flux distribution estimated using a non-isothermal, variable density, impinging jet model showed excellent agreement with experimental data.

As a result of this preliminary work we have demonstrated that heat fluxes of sufficient magnitude necessary for thermal spallation to occur in high density environments can be sustained. In future experiments we plan to study configurations more like those that will be encountered during actual drilling, such as confined flow in a cylindrical volume (borehole) where heated fluids are re-entrained into the flame jet.

Acknowledgements

This work was supported in part by funds from the US Army Research Office under contract no. W911NF0510522 (with special thanks to Dr. Robert Shaw for his technical supervision), the Department of Energy through the National Renewable Energy Laboratory under contract no. DE-AC36-99-6010337, and by fellowship support from Shell International Exploration and Production, Inc.

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