Ultrasonic/sonic drill for high temperature application

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ABSTRACT

Venus is one of the many significant scientific targets for NASA. New rock sampling tools with the ability to be operated at high temperatures of the order of 460°C are required for surface in-situ sampling/analysis missions. Piezoelectric materials such as $LiNbO_3$ crystals and Bismuth Titanate are potentially operational at the temperature range found on the surface of Venus. A study of the feasibility of producing piezoelectric drills for a temperature up to 500°C was conducted. The study includes investigation of the high temperature properties of piezoelectric crystals and ceramics with different formulas and doping. Several prototypes of Ultrasonic/Sonic Drill/Corers (USDC) driven by transducers using the high temperate piezoelectric ceramics and single $LiNbO_3$ crystal were fabricated. The transducers were analyzed by scanning the impedance at room temperature and 500°C under both low and high voltages. The drilling performances were tested at temperature up to 500°C. Preliminary results were previously reported [Bao et al, 2009]. In this paper, the progress is presented and the future works for performance improvements are discussed.

KEYWORD: High Temperature actuators, Piezoelectric Drill, Rock sampling, Venus.

1. INTRODUCTION

The current NASA mission planning efforts have identified Venus as a significant scientific target for a surface in-situ sampling/analyzing mission. The Venus environment represents several extremes including high temperature (460°C), high pressure (~90 Atm), and potentially corrosive (condensed sulfuric acid droplets that adhere to surfaces during entry) environments. This technology challenge requires new rock sampling tools for these extreme conditions.

For this purpose, a high temperature Ultrasonic/Sonic Driller/Corer (USDC) [Bao, et al., 2003; Sherrit et al., 2004, Bar-Cohen et al, 2009] that is driven by piezoelectric stacks is being developed. This penetrator requires very low axial load for is drilling action and it operates percussively (see **Figure 1**). Generally, the USDC consists of three components: actuator, free-mass and a bit. A schematic diagram of the USDC mechanism is shown in **Figure 2**. The actuator of the USDC operates as a frequency transformer converting 20-kHz ultrasonic vibrations to a 60-1000 Hz sonic hammering action (percussion). The tip of the ultrasonic horn impacts the free-mass creating a sonic resonance between the horn and the bit. The USDC has been demonstrated to drill rocks that range in hardness from basalt to soft sandstone and tuff. Other media that were drilled include soil, ice, diorite, and limestone.

A piezoelectric drill has the potential to be operated as a sampler at Venus conditions. The piezoelectric crystals, like $LiNbO_3$, have a Curie temperature higher than 1000°C and the Curie temperature of some piezoelectric ceramics, like Bismuth Titanate (BT), is higher than 600°C. We studied high temperature properties of piezoelectric ceramics with different formulas and doping. In addition to the crystal $LiNbO_3$, a commercially available BT ceramic, Ferroperm Piezoceramics PZ46 and the lab-made BT ceramic with Tungsten (W) dopant were selected as the actuation materials for our test drills.

A study of the feasibility of producing piezoelectric drills that can operate in the temperature range up to 500°C was conducted. Three breadboard drills were fabricated and assembled using single $LiNbO_3$ crystal and the two types of high temperature piezoelectric ceramics. The transducers were analyzed by scanning the impedance at room temperature and 500°C under both small and large voltages. The drilling performances were tested at temperature up to 500°C.

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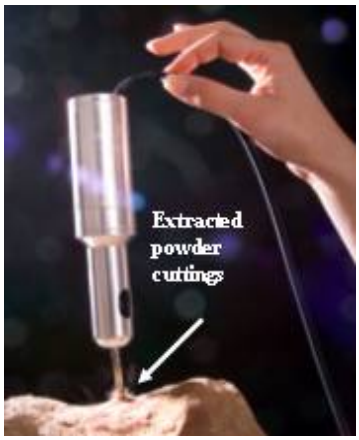

Figure 1: The USDC requires relatively small preload to drill a rock.

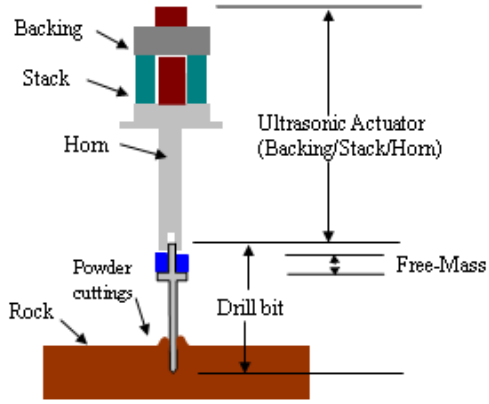

Figure 2: A schematic view of the USDC components

2. High Temperature Piezoelectric Materials

The piezoelectric material that is used to produce the sampler is the key to its ability to function in Venus environments. New HT piezoelectric ceramics were developed for high temperature (HT) applications. One candidate piezoelectric ceramic material is Bismuth Titanate. Samples of different formulas and doping were made. To evaluate the samples, we used an Agilent 4294A precision impedance analyzer and a d_{33} meter and measured the electrical characteristics at both room and at temperatures up to 500°C. The data were tabulated for the various samples and are documented in Tables 1 with 36° Y-cut $LiNbO_3$ crystal. The data imply that the thickness coupling coefficient at 500°C is about 15 to 20%. The test results are very encouraging and the material with a Tungsten (W) dopant was selected because of its relatively high Q, low loss, high Tc and high d_{33}. Piezoelectric ring elements were made for drilling tests using hot isostatic pressure to insure the production of robust ceramic compositions.

TABLE 1: The electromechanical measured properties of the $LiNbO_3$ crystals and the Bismuth Titanate with various doping contain.

Material	T_C (°C)	K	loss	d_{33} (pC/N)	Q_p	k_p	500°C			
							K	loss	Q_p	resistivity
Modified $Bi_4Ti_3O_{12}$	666	118	0.5%	16 (16)*	3000	3.7%	300	41%	200	$7.4x10^6$
$Bi_{3.887}Ti_{2.866}W_{0.146}O_{12}$ - Fe_2O_3	~620	154.6	1%	14 (13)	2900	3.3%	590	62%	50	$1.5x10^6$
$Bi_{3.9}Ti_{2.85}W_{0.15}O_{12}$- Fe_2O_3	~620	156.8	1%	11.5 (11)	2000	3.1%	670	67%	46	$1x10^6$
$Sr_{0.8}Ca_{0.2}Bi_4Ti_4O_{15}$- Fe_2O_3	595	143.7	0.4%	12 (11.5)	5600	2.9%	461	42%	360	$1.9x10^6$
$Sr_{0.6}Ca_{0.4}Bi_4Ti_4O_{15}$- Fe_2O_3	644	146.8	0.25%	8 (8)	5800	2.6%	463	100%	120	$2.9x10^5$
$Bi_{3.93}Ti_{2.9}W_{0.1}O_{12}$- MnO_2	657	158	0.5%	17 (11)	3700	4.3%	421	44%	45	$3.6x10^6$
$Bi_{3.96}Ti_{2.9}W_{0.1}O_{12}$- MnO_2	~650	145	0.3%	18 (12)	3900	4.3%	370	40%	40	$5.6x10^6$
W doped $Bi_4Ti_3O_{12}$	637	165.7	1.5%	17 (15.5)	1800	3.4%	309	16%	1000	$\sim 5x10^6$
$LiNbO_3$ (36° Y-cut)	1150	62	0.5%	40 (40)	1500	46%	104	6%	500	$3.8x10^6$

* The value in parenthesis is the data obtained after 500°C.

3. Finite Element Analysis of Breadboard Transducers with HT Piezoelectric Materials

In addition to the effort to improve the performances of piezoelectric materials, we are also investigating the proper transducer design that will allow for using relatively low performance piezoelectric materials and still drill effectively. As a first step we investigated the performances of the transducers using the HT piezoelectric materials to replace the piezoelectric ceramic PZT-8 in a "baseline" USDC transducer that was developed for operation at room temperature. Finite element models were used to analyze these transducers [Bao et al, 2003]. The modeled transducer consists of a piezoelectric stack, a horn, a backing block, a pre-stress bolt and a Belleville (see **Figure 2 and 5**).

The primary results for the baseline transducer using Lithium Niobate single crystal are shown in **Figures 3** and **4**. **Figure 3** illustrates the mode shape of the first resonance. It is a longitudinal mode with maximum displacement at the tip of the horn. **Figure 4** is the input admittance curve at the frequency range around the resonance.

These results suggest that using Lithium Niobate in the baseline transducer will have a resonance frequency and mode shape similar to that using PZT-8. However, the maximum conductance is much lower, which implies that the electrical power delivered to the transducer under the same voltage will be much lower. Increase the driving voltage will partially compensate for the disadvantage of the high input resistance but this is ultimately limited by electric break down. Further, the high loss at high temperature as shown in the **Table 1** may result in a rapid overheating when operating the drill in a high temperature environment and operating with duty cycling may be required. We are continuing to investigate possible designs to increase the power capability of the transducer using the model analysis.

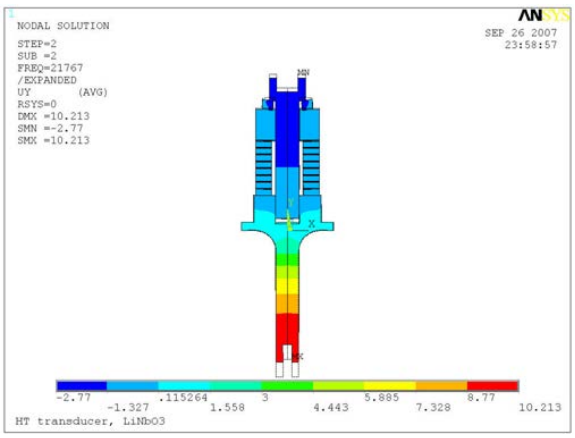

Figure 3: First longitudinal mode shape for the $LiNbO_3$ material. The color scale shows displacement in the vertical direction. The resonance frequency of the transducer is 21.767 kHz

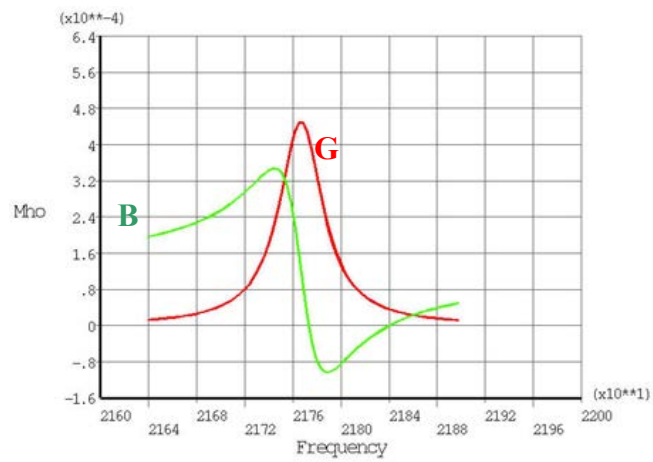

Figure 4: The input admittance response around the first resonance frequency for the $LiNbO_3$ material. G is the real part (conductance) and B is the imaginary part. The mechanical Q was set to 500.

HT USDC breadboards were produced using 1-in diameter $LiNbO_3$, PZ46 and PSU Bismuth Titanate transducers The detailed stack dimensions are listed in **Table 2** and an example photo of the PSU BT transducer is shown in **Figure 5**.

Table 1: The dimensions of the transducer rings using $LiNbO_3$ single crystals, as well as PZ46 and Bismuth Titanate ceramic

Xducer #	Material	No. of rings	Out diameter	Inner diameter	Thickness
			mm	mm	mm
1	$LiNbO_3$	10	25.4	12.7	2.0
2	PZ46	10	25.0	13.0	2.0
3	PSU BT	10	25.4	12.7	2.1

Figure 5: The HT transducer with PSU Bismuth Titanate stack that we constructed as one of breadboards.

4. Impedance Analysis at High Temperature with Low and High Voltage

To analyze the performances of the breadboard transducer, impedance scans were performed. The scans were performed using small signals by an Agilent 4294A precision impedance analyzer with voltage level of 0.5V and large signal with a setup established in our Lab. The setup consist of a function generator generating a linear frequency modulated sine signal, an amplifier amplifying the signal to high voltage level close to the operating voltage, and a digital oscilloscope recording the applied voltage and the voltage on a 1 Ω resistor which was connected to the transducer in series. The latter is actually equal to the current though the transducer. The impedance at the scanned frequency range was found by the recorded voltage and current data. The large signal level was of the order of hundreds of volts. The scans were done at both room temperature and high temperature of 500ºC. An example of the raw data of the screen of the oscilloscope is shown in **Figure 6**.

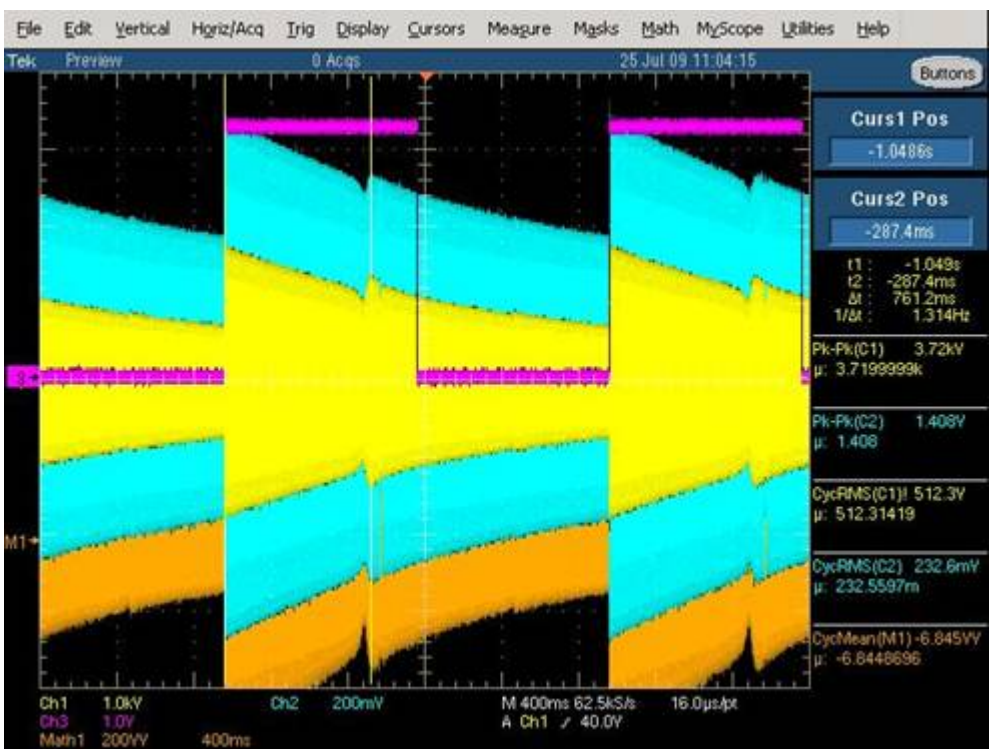

Figure 6: The voltage (yellow) at high level of 3.7 kVpp with modulated frequency of 18-25kHz and corresponding current (cyan) were recorded by a multichannel digital oscilloscope for impedance measurement. The orange trace is the instantaneous power.

The parameters of equivalent circuit were extracted from the measured data. Although the Agilent 4294A impedance analyzer has the function to extract the parameters, the error in the extracted values are very large when the electric loss of the piezoelectric elements are relatively high since the equivalent circuit model used by the analyzer

neglected the loss. Actually the electric loss of these piezoelectric materials at high temperature is quite high, much higher that at room temperature. A model including the electric loss was established and a computer program was developed to extract the parameters from the measured data. The modified model is shown in **Figure 7**. The C_0 is the static capacitance of the transducer and the added resistor R_0 represents the electric loss of the piezoelectric material. The L_1, C_1 and R_1 form a dynamic breach which represents the resonance of the transducer. The program was used to process both the data obtained by the Agilent 4294A impedance analyzer and the setup of high voltage scan.

An example of the experimental data obtained by the setup of high voltage scan and the corresponding admittance of the equivalent circuit with the extracted parameters are presented in **Figure 8**. The agreement between the two data sets is an indicator of the accuracy of the model. The modified model greatly improved the accuracy.

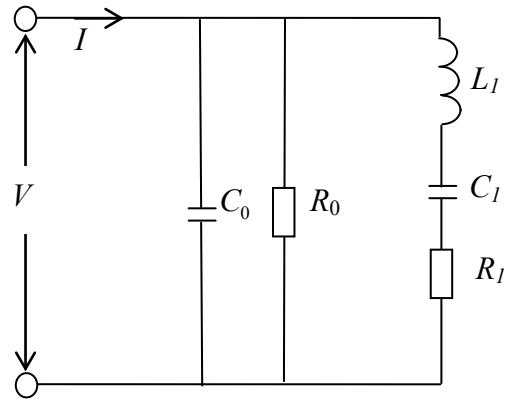

Figure 7. Schematic of the equivalent circuit of the transducer around resonance.

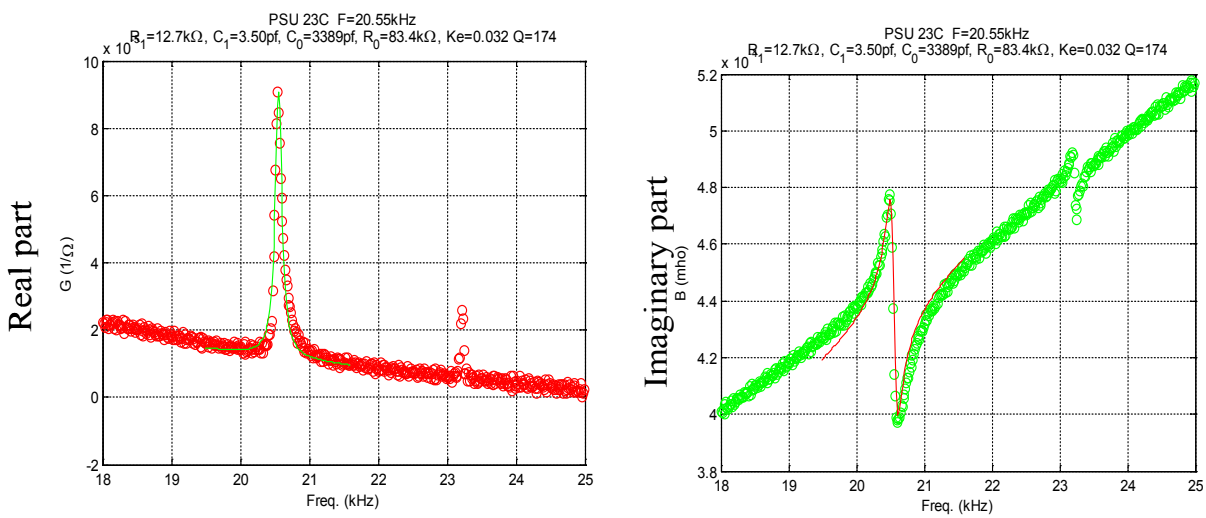

Figure 8: Example of large signal impedance scan: the complex admittance and parameters extracting. Circles – experimental data; Line – fitted curve with the equivalent circuit parameters shown in title.

The data in **Table 3** is a summary of impedance analysis results for transducers using Pz46 and PSU BT ceramic with high and low voltage at room and high temperature. In the table the resonance frequency Fr, static capacitance C_0 and its lose resistance R_0, dynamic capacitance C_1 and resistance R_1 are the extracted parameters of the equivalent circuit. The dynamic inductance L_1 can be determined by the resonance Fr and C_1. The Qm is the mechanical Q value and K is the dielectric constant of the material. Ke is the effective coupling factor defined as the square root of mechanical energy over the total (mechanical and electrical) energy of the oscillating transducer at the resonance frequency. The "Vtip at applied V(voltage)" was estimated by using the equivalent circuit and the normalize mode shape computed by the finite element model.

Both PZ46 and PSU BT transducers worked at 500°C with increased capacitance and higher electric loss compared with room temperature results. Under high voltage both have higher electric and mechanical loss (lower Qm) compared with low voltage values. At high temperature and high voltage, the PSU BT transducer exhibited better overall

performance than the PZ46. It is easier to reach higher tip velocity with the PSU BT material than using the PZ46 material as the "Vtip data at applied V" in the table shows.

Table 3: Summary of impedance analysis for transducers made of Pz46 and PSU BT

Transducer	#2 Pz46				#3 PSU			
Temperature	23C		500C		23C		500C	
Voltage level	0.5V	1100Vp	0.5V	850Vp	0.5V	1000Vp	0.5V	570Vp
Fr (Hz)	22996.88	22678.2	20805.25	20480.57	20830	20555	19384.1	19082.851
C0 (F)	1.84E-09	2.17E-09	2.75E-09	3.07E-09	3.46E-09	3.39E-09	4.20E-09	5.70E-09
R0 (Ohm)	1.00E+07	187318	48780.488	52423	1.00E+07	83400	15038	8319
C1 (F)	2.40E-12	4.03E-12	3.62E-12	4.58E-12	4.15E-12	3.50E-12	4.82E-12	3.79E-12
R1 (Ohm)	2359	24391	2968	20012	1446	12699	1152	7900
Qm	1224.32	71.38	711.29	84.83	1272.06	174.21	1479.70	278.86
K dielectric	116.18	136.99	173.72	193.92	216.05	211.57	262.19	355.75
Effec. Coup. Ke	0.0360	0.0430	0.0362	0.0386	0.0346	0.0321	0.0338	0.0258
Transformer M/E (n)	0.2237	0.2861	0.2488	0.2753	0.2668	0.2416	0.2673	0.2333
Efficiency M/E	1.000	0.885	0.943	0.724	1.000	0.868	0.929	0.513
|Z| at Fr (Ohm)	1998	3210	1971	2490	1209	2237	938	1376
Gme/|Y|	0.8467	0.1316	0.6641	0.1244	0.8364	0.1761	0.8148	0.1742
Vtip at applied V (m/s)		1.6552		1.6198		3.4221		3.2473

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5. Drill Test at High Temperature

The testbed consisted of a furnace and an assembly that allowed the HT USDC to be evaluated both internal and external to the furnace and a retaining structure for the rocks used in the drilling tests at temperatures as high as 500ºC. The furnace itself is capable of operating temperature of up to 1200ºC allowing, if needed, to conduct higher temperature tests of the USDC and the piezoelectric stacks. To test the operation of this horizontal tube shape furnace we procured customized insulating side caps that have a center hole and we used one of these holes (see on the right in **Figure 9**) for insertion of a high temperature bit that we produced. Initially, the USDC was placed outside the chamber and it was pushed pneumatically to drill with controlled preload to investigate the rock/bit interactions at high temperature.

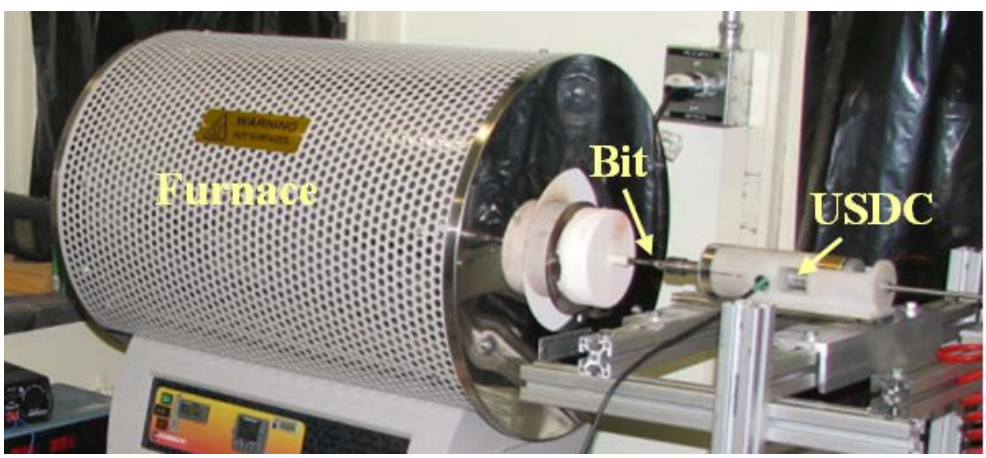

Figure 9: Photographic view of the furnace that was developed as a HT testbed. This photo shows an initial test with a rock sample inside the chamber while the USDC was placed outside.

To test the USDC with the HT piezoelectric stacks inside the chamber we constructed a fixture that is shown schematically in **Figure 10**. This fixture allows sliding the USDC while drilling as well as securing the position of the drilled rocks along the bit path. The USDC is pushed from outside the chamber using the controlled preload system that was developed and tested for this apparatus.

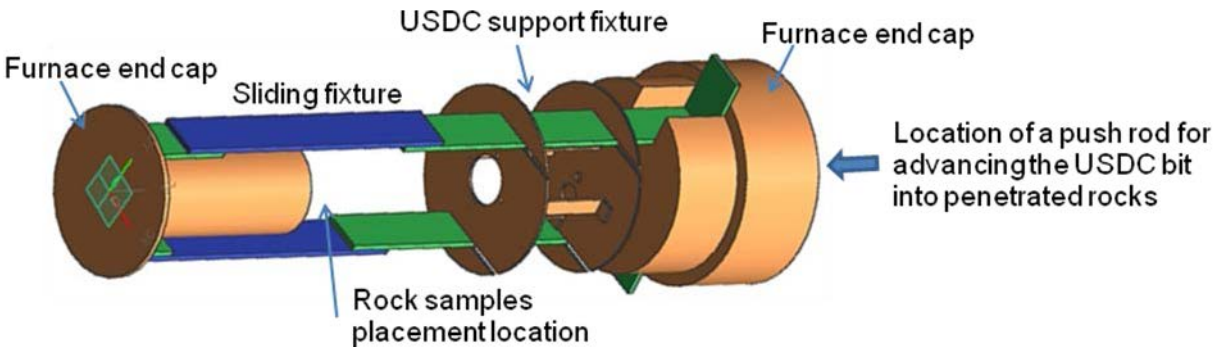

Figure 10: Schematic view of the support fixture for testing the USDC and its drilling performance inside the HT chamber.

Using the analytical model a breadboard was designed using ten piezoelectric discs that were held in compression by the stress bolt to prevent fracture of the discs during operation. The impendence characteristics of the actuator at RT and 500°C were tested using the HT chamber shown in **Figure 9**. The first HT bit, which was made of Crucible CPM-3V hardened to HRC 63, degraded as a result of drilling at 500°C (from outside the chamber). To improve the drill performance, Tungsten Carbide WA-2 (HRA 92) was used. The breadboard USDC was test drilling limestone from room temperature up to 500ºC. The drilling rate dropped from ~ 5 mm/min at room temperature to almost zero at 500ºC. The properties of limestone at 500ºC are not known and therefore no relevant conclusions could be made. Further, while drilling a brick, the drilling rate of the USDC actuated by $LiNbO_3$, was observed to be around 1 mm/min at 500ºC compared to 3 mm/min at room temperature. The test results are summarized in **Table 4.** As can be seen the $LiNbO_3$ demonstrated the highest drilling rate. However, the $LiNbO_3$ crystals are not robust. Cracks perpendicular to the electrode surface developed quickly and resulted in electric breakdown. Both PZ-46 rings and PSU BT elements worked at 500ºC with relatively low performance. They were mechanically much robust than the $LiNbO_3$ crystal. The PSU BT showed superior capability over the PZ46.

Table 4: Drilling test results

	23C				500C			
	V rms	A rms	Minutes	Drill Rate (mm/min)	Voltage	A rms	Minutes	Drill rate (mm/min)
PZ46	1320	0.4	12	1.94	830	0.37	10	0.02
PSU	900	0.35	7	1.1	460	0.3	4	0.14
$LiNbO_3$	216	0.054	4	3	580	0.041	2	1.27

5. SUMMARY

In an on-going study, we are developing piezoelectric USDC drills that can be used to sample rocks in high temperature environments corresponding to the surface of Venus (460°C). The high temperature properties of a variety of piezoelectric materials including $LiNbO_3$ single crystals and piezoelectric ceramics were evaluated and a high temperature piezoelectric ceramic PSU BT was developed. High temperature USDC breadboards were constructed using $LiNbO_3$ crystals and two ceramics of PSU Bt and PZ46 to compare to the standard piezoelectric material PZT-8. A test setup to perform large signal impedance analysis was established and used to characterize the HT transducers. Three breadboard HT USDCs were built and tested in a furnace at 500°C. All worked at the high temperature on brick samples with relatively high or low drilling rate.

The transducer using Lithium Niobate crystals showed the best performance so far. However, the cracking of the crystal is still a challenge that needs to be solved. We are planning to use thicker elements to increase the strength and use high temperature fiberglass to wrap the crystal. A transducer of larger diameter (1.9”) will also be designed and fabricated for evaluation.

Both PZ-46 rings and PSU BT rings worked at 500°C and were relatively robust. The PSU BT material is better than the PZ46 although the performance was still relatively low. To improve the drilling performance of the BT sampler a transducer using larger diameter (1.5”) rings will be designed and fabricated for evaluation.

ACKNOWLEDGMENT

Research reported in this manuscript was conducted at the Jet Propulsion Laboratory (JPL), California Institute of Technology, under a contract with National Aeronautics Space Administration (NASA).

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