Rock Sampling using the Ultrasonic/Sonic Driller/Corer (USDC) for In-situ Planetary Exploration

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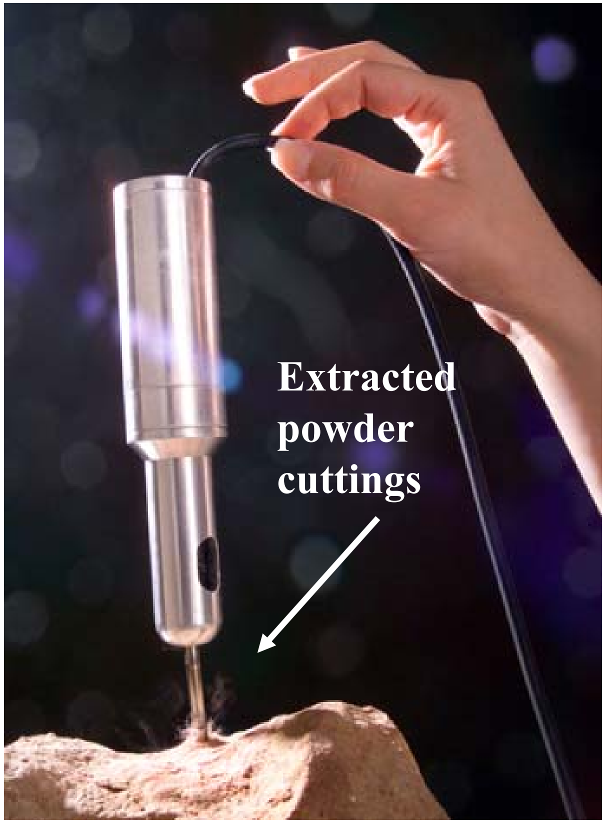
Introduction

- Sample return and in-situ sampling is one of the major objectives of future NASA's planetary exploration missions.
- A novel USDC mechanism was developed for sampling.

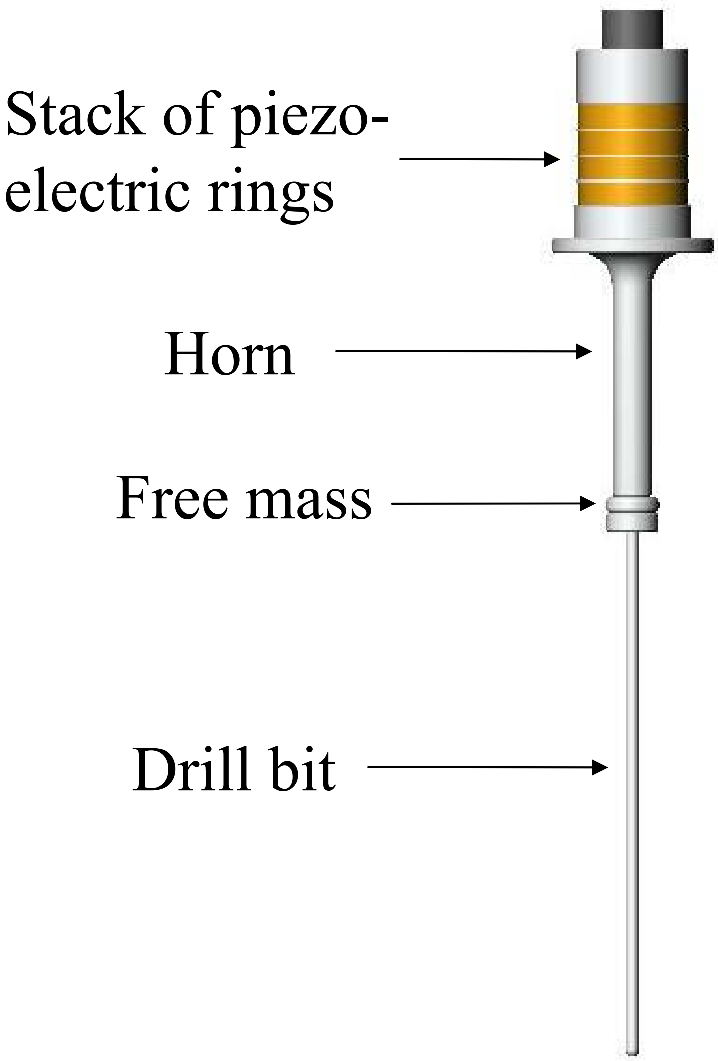
✓ Small reaction force
✓ Compact design
✓ Light weight
✓ Low power

2000 R&D 100 award



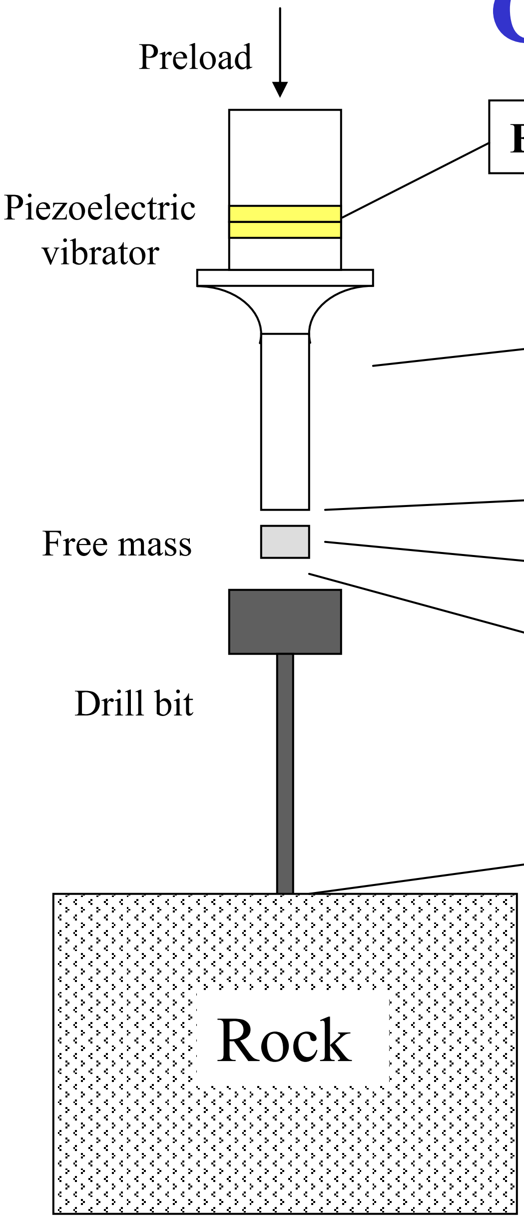
Simple feasibility tests was made operating the USDC from the Sojourner frame.

Analysis of the USDC mechanism



- An ultrasonic horn transducer that is driven by a piezoelectric stack.
- The horn transducer in the USDC drives a free flying mass (free-mass), which bounces between the horn tip and a drill stem at sonic frequencies.
- The impacts of the free-mass create stress pulses that propagate to the interface of the stem tip and the rock.
- The rock fractures when its ultimate strain is exceeded.
- This novel drilling mechanism has been shown to be more efficient and versatile than conventional ultrasonic drills under a variety of conditions.

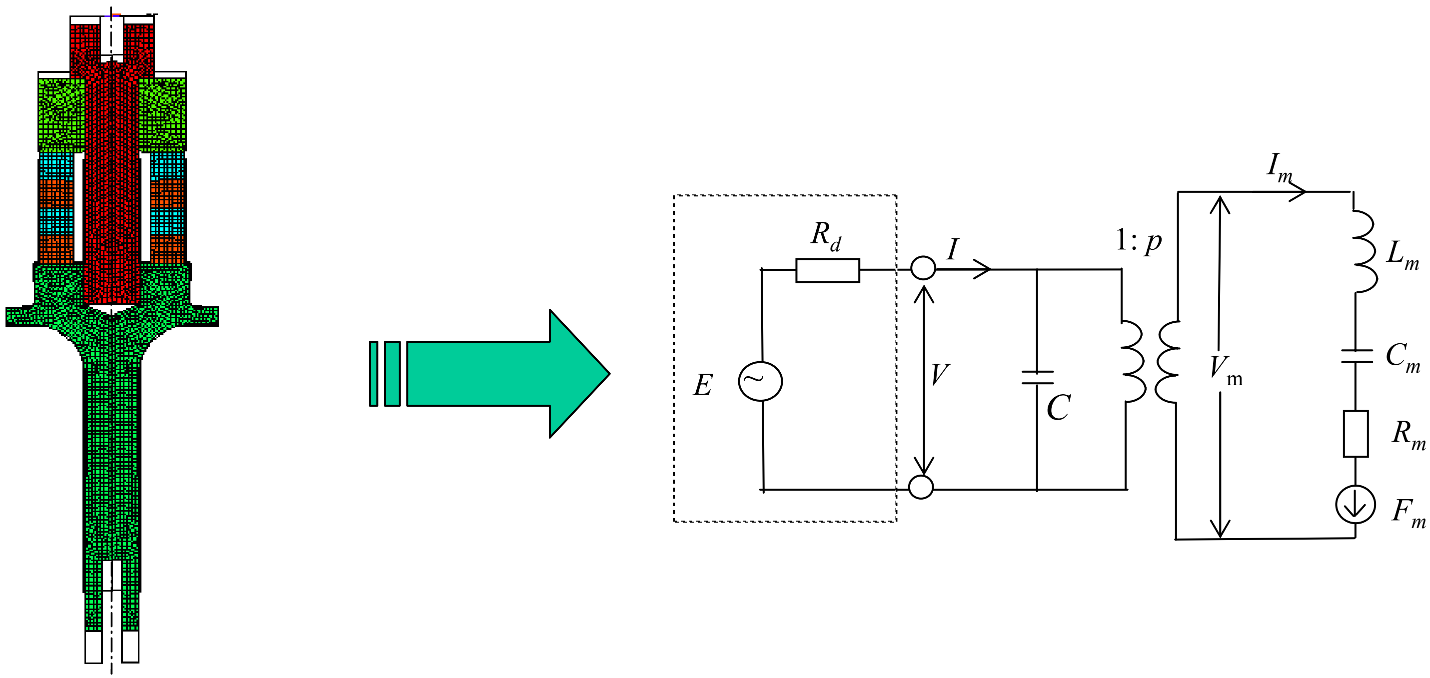
Computer Modeling



1. Piezoelectric vibrator with horn
2. Vibrating horn tip driving free mass
3. Free mass bouncing between the horn tip and drill bit
4. Free mass-drill bit impact
5. Strain/stress in rock induced by drill bit impact

Modeling and Computer Simulation of Ultrasonic/Sonic Driller/Corer (USDC), Bao, X, et al, IEEE UFFC Vol. 50, 1147-1160(2003)

Piezoelectric transducer



FEM Modal Analysis. Figure shows calculated modal shape at resonance of 22.668 kHz. The outline is the un-deformed.

Schematic of the equivalent circuit of the transducer around resonance.

Reaction of free-mass impacts

Impact force on the tip

$$F_c = f_I \delta(t - t_I)$$

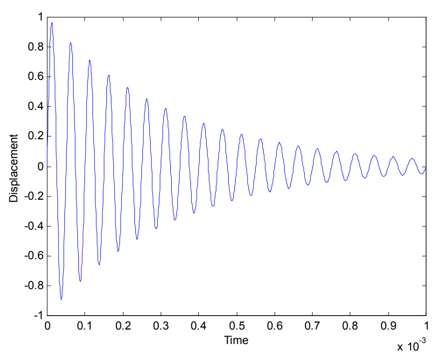
Translation velocity change

$$f_I = -m\Delta v_I$$

$$\Delta U_I = \frac{-m\Delta v_I}{M} H(t - t_I)$$

Induced vibration

$$U = U_0 + at + \sum_I \Delta U_I$$

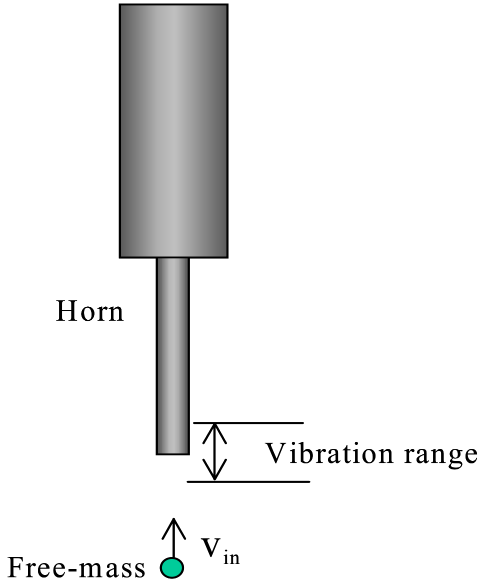


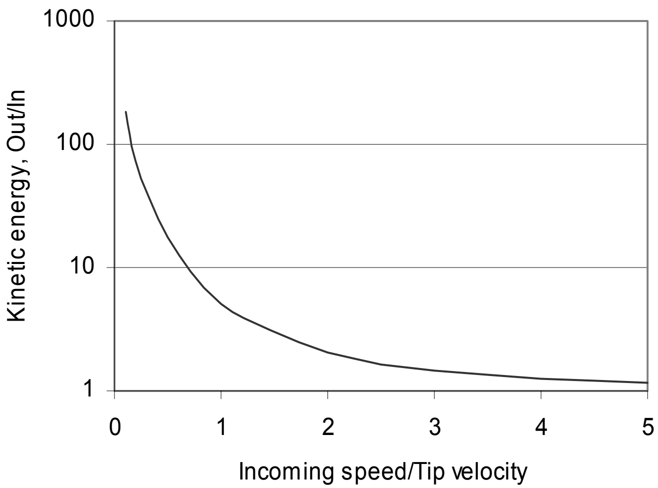
$$I_{mI} = \dot{a}_I = -\frac{m\Delta v_I \xi_t}{L_m} \exp[(-\alpha + j\omega_f)(t - t_I)]$$

$$t > t_I$$

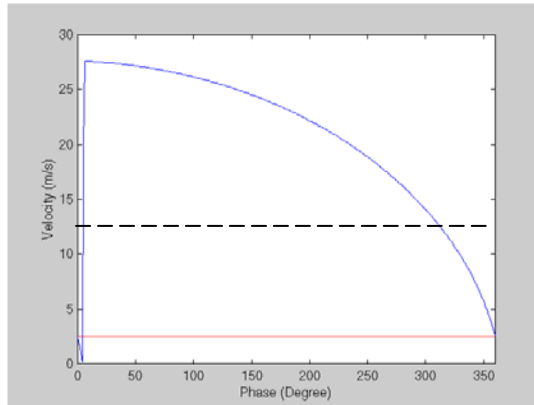
Free-mass Driven by Vibrating Tip

Simple collision model

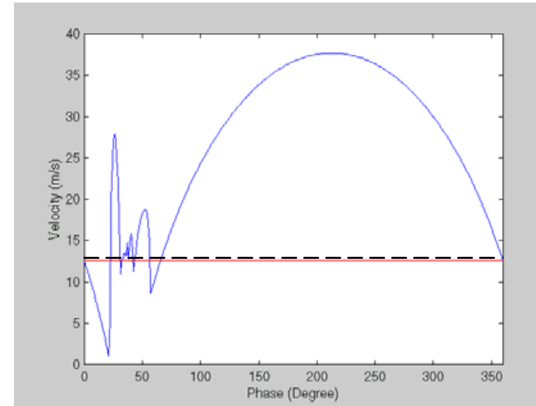




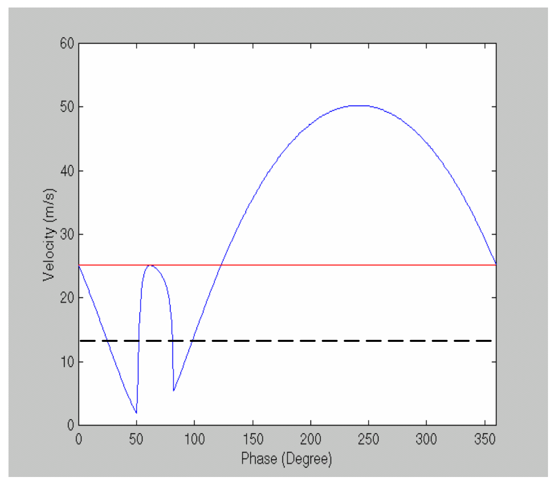
Average increase of the free-mass energy



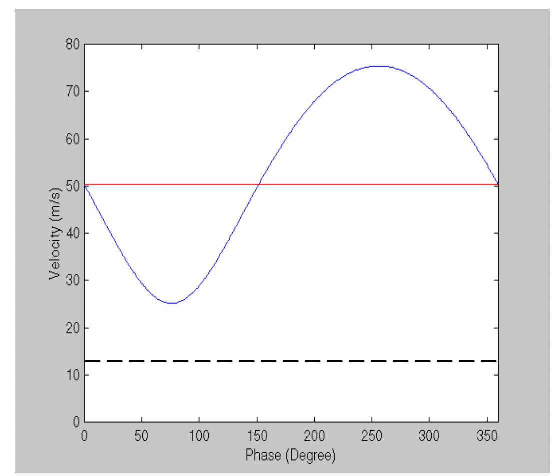
Vin = 0.2 Vtmax



Vin = 1.0 Vtmax



Vin = 2.0 Vtmax



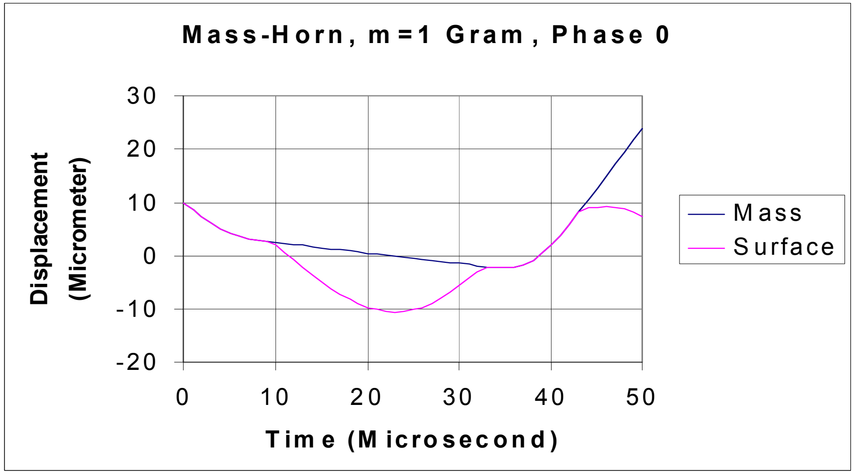
Vin = 4.0 Vtmax

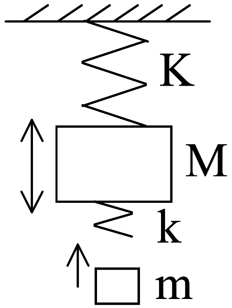
——— indicates the free-mass coming velocity.

- - - - indicates the tip maximum velocity.

Free-mass Driven by Vibrating Tip

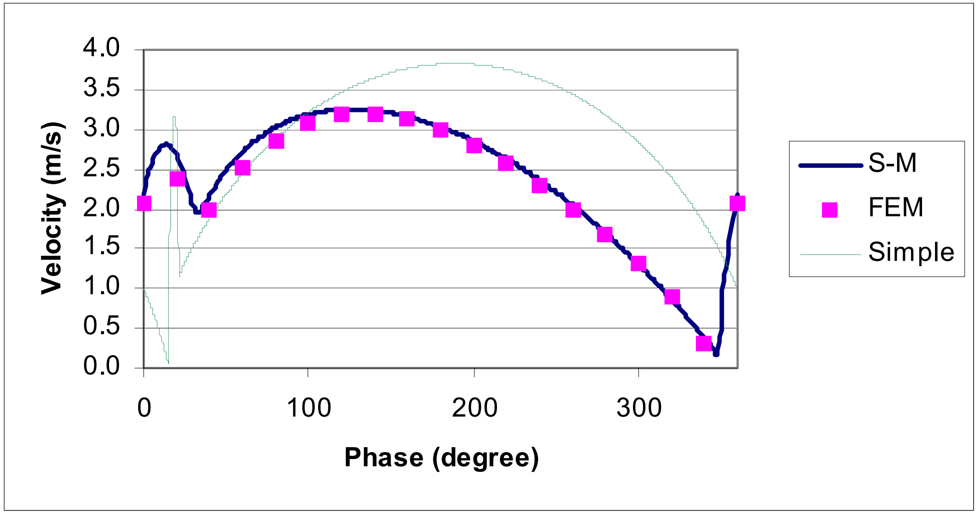
FEM & Spring-mass model





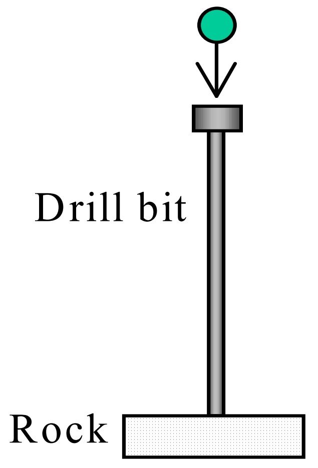
Spring-mass model

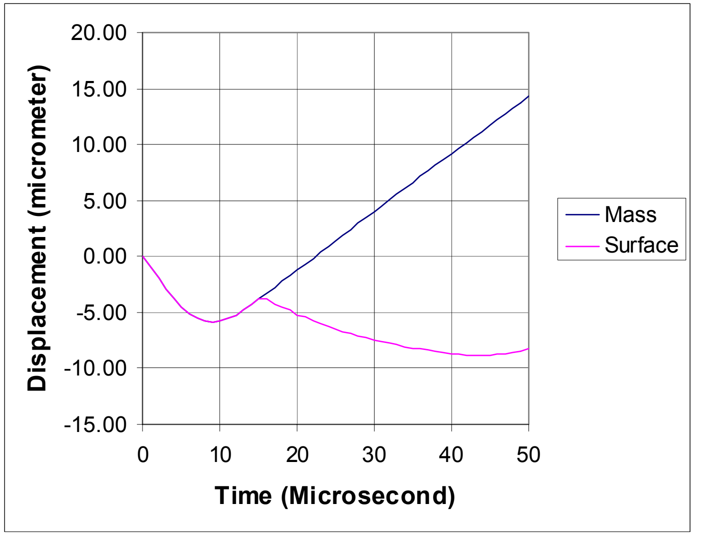
FEM: The free-mass and surface displacement as a function of the time.

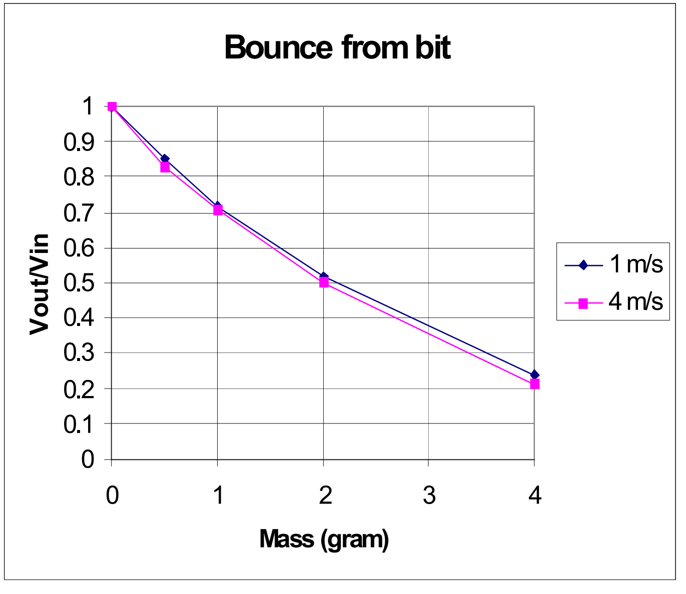


Comparison of the three models

Free-mass bounce from the bit





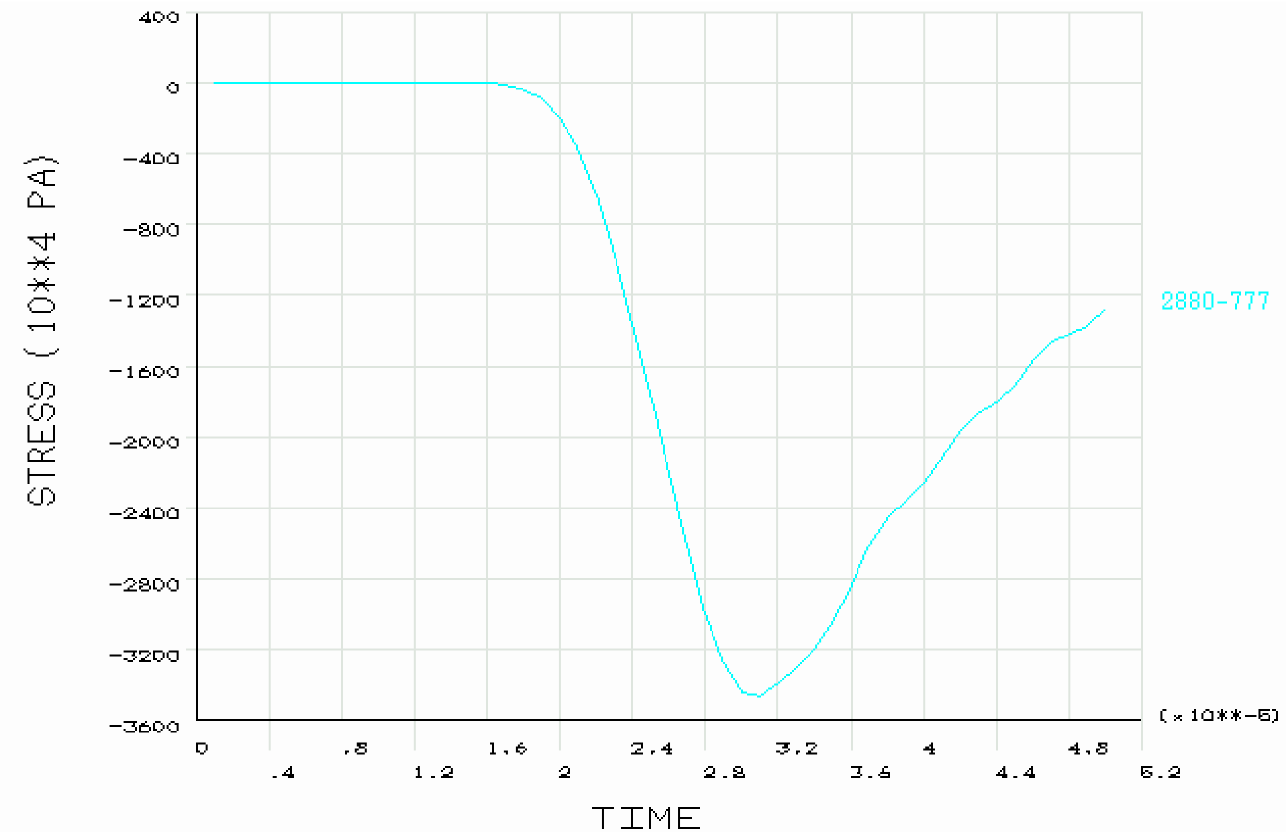


FEM results of the free-mass bounce from the drill bit. The free-mass is 2 grams and the incoming speed is 1 m/s. The rebound speed is 0.53 m/s and contact time 16 μs.

The rebound speed is dependent to the mass of the free mass.

Free Mass - Bit Impact

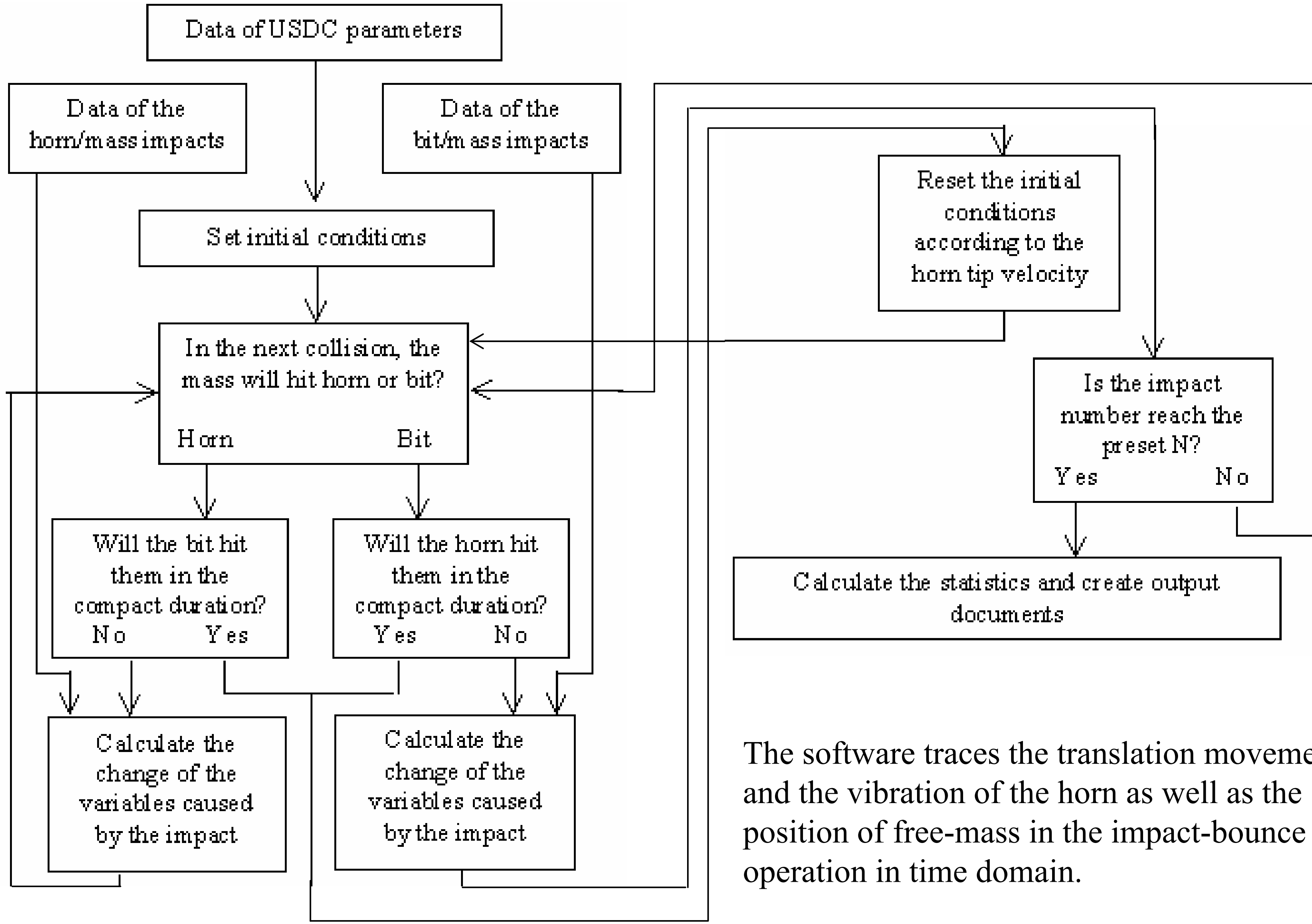
Finite Element Solution



Impact stress at the root of the bit

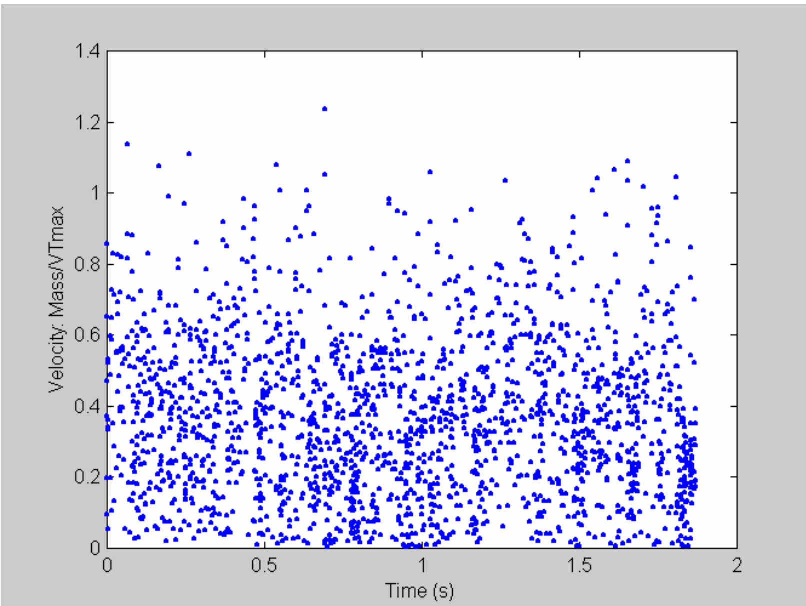
Free mass of 1 gram with 1 m/s hits drill bit D3mm x 100mm with a head of D12mm x 6mm

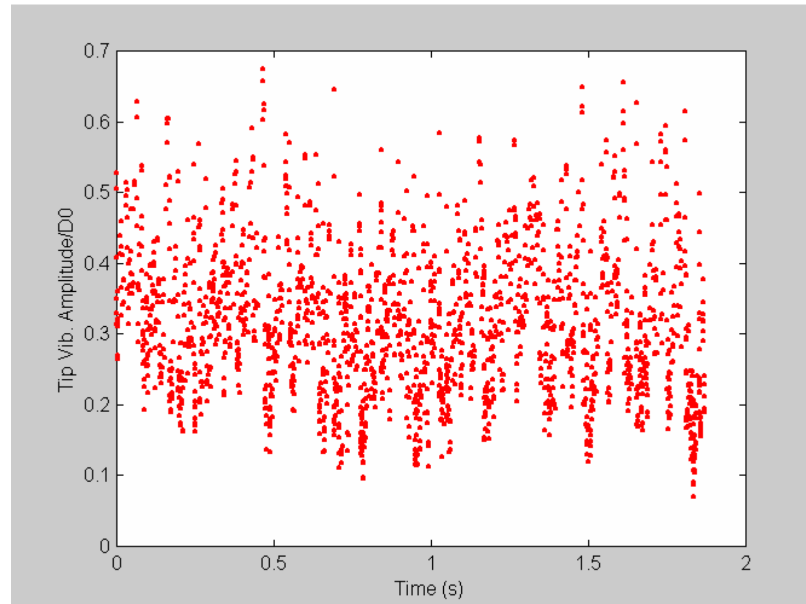
Simulation program



The software traces the translation movement and the vibration of the horn as well as the position of free-mass in the impact-bounce operation in time domain.

Samples of Results

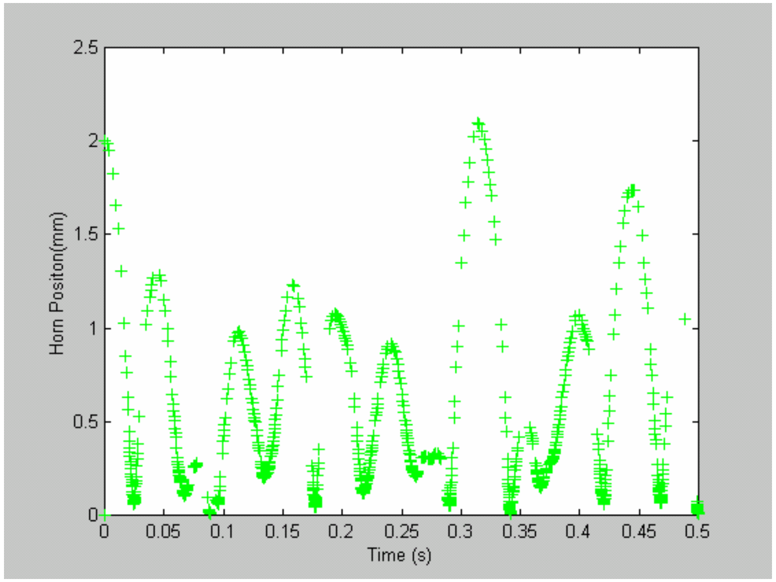




Free-mass velocity after impact with horn normalized by the horn tip vibration velocity without loading of 6.67 m/s

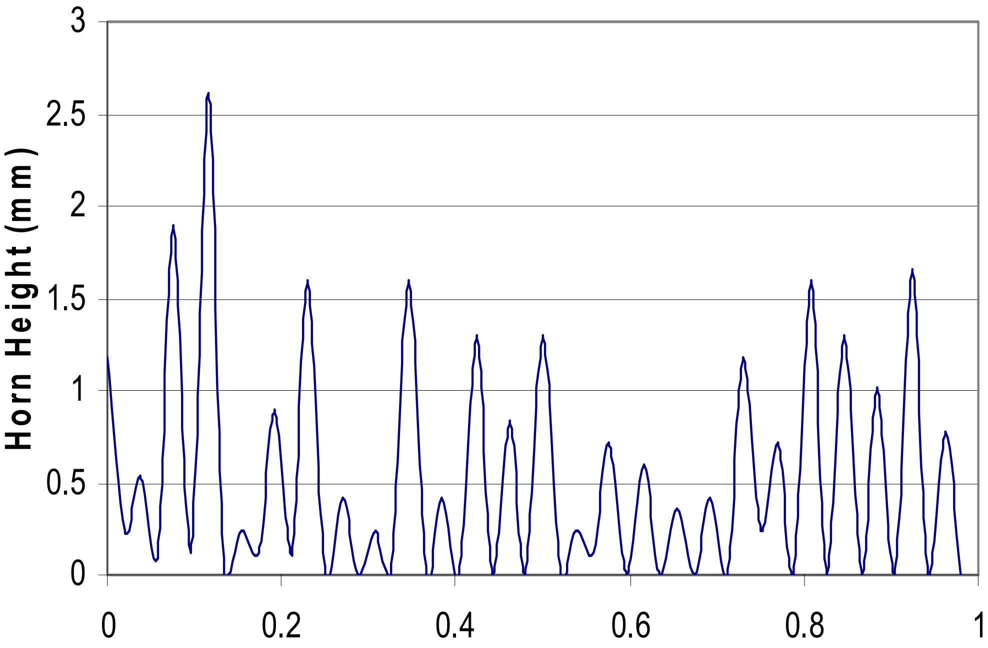
Horn vibration amplitude after impacts with free-mass normalized by the amplitude without loading

Motion of the Horn



Simulation Results

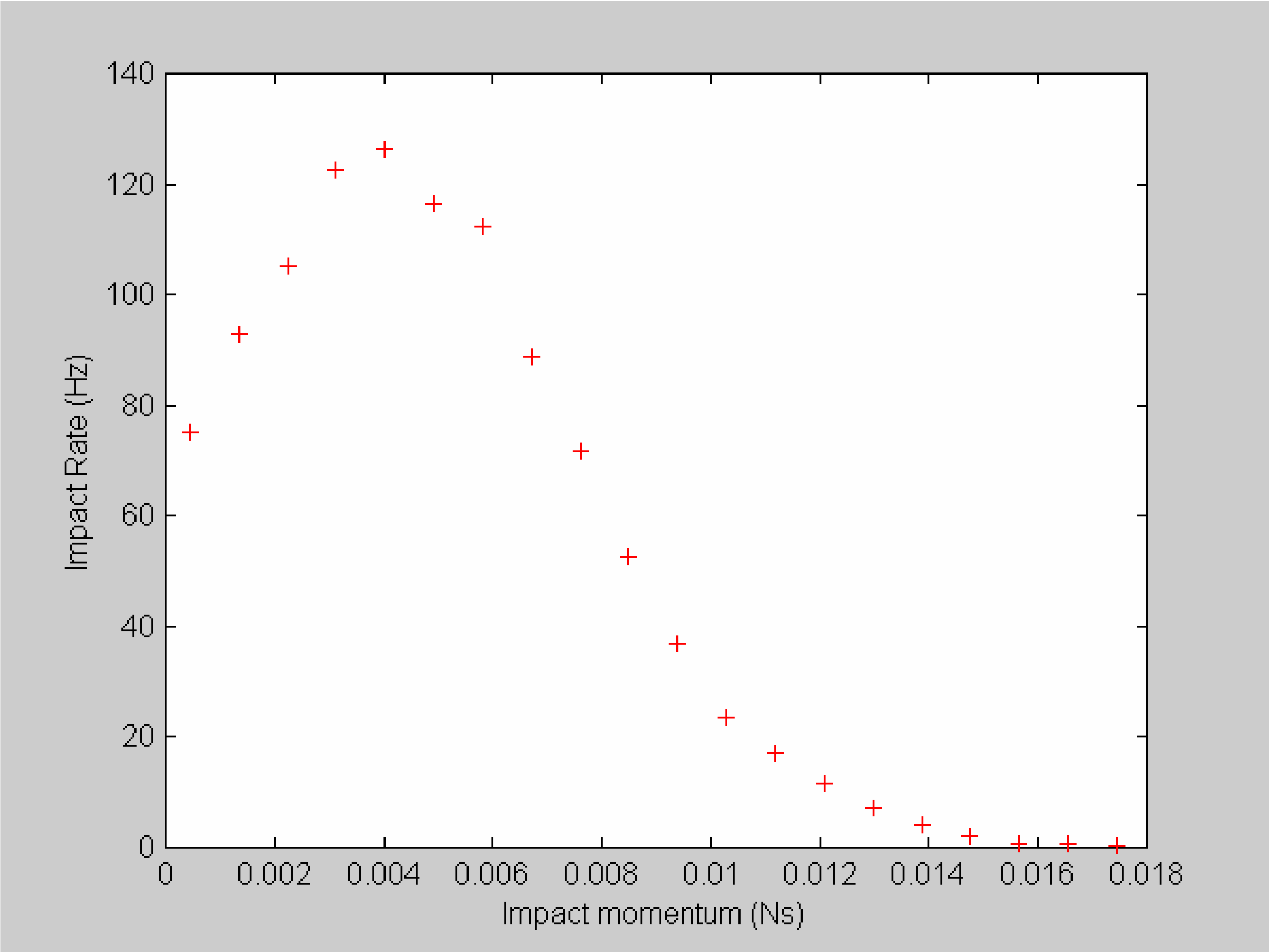
+ indicates the impacts with free mass



Experimental Data

The simulation results are confirmed by the experimental data with the random characteristics of the horn jumps and the ranges of frequency and heights of the jumps.

Statistics of Free-mass/Bit Impacts



The impact frequency versus momentum

Strain and stress in rocks

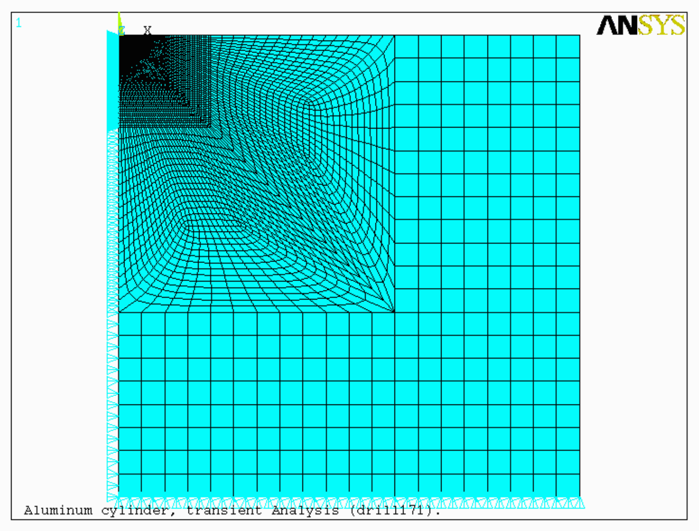


Fig. 15. The mesh used to solve the bit rock interaction.

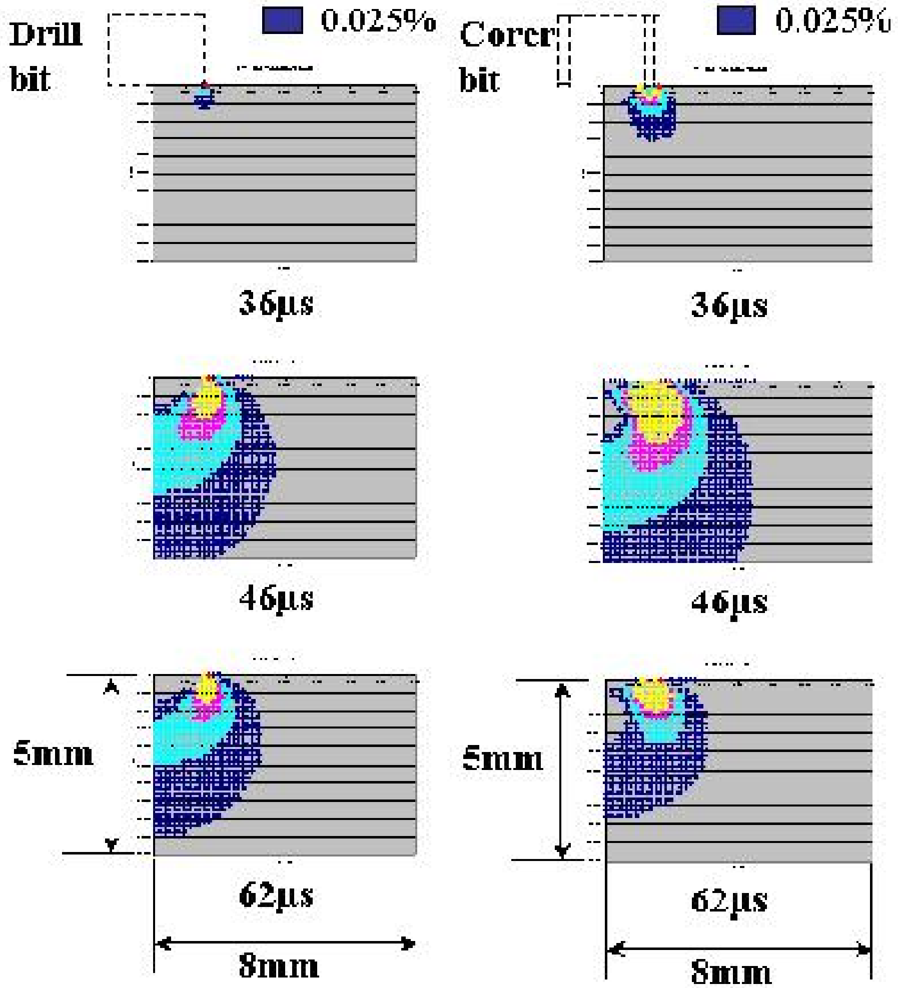


Fig. 16. The principle strain profile.

Estimation of drilling rate

Drilling rate:

$$R = P/E$$

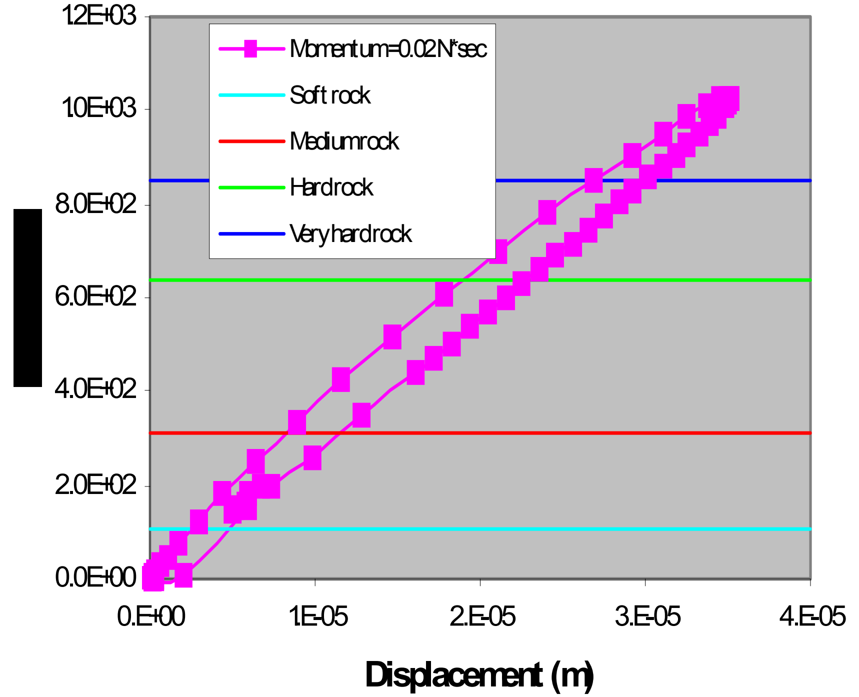
where P = power input to the rock, joules/sec

E = specific energy, joules/cm^3.

Table Specific energy and compression strength of rocks*

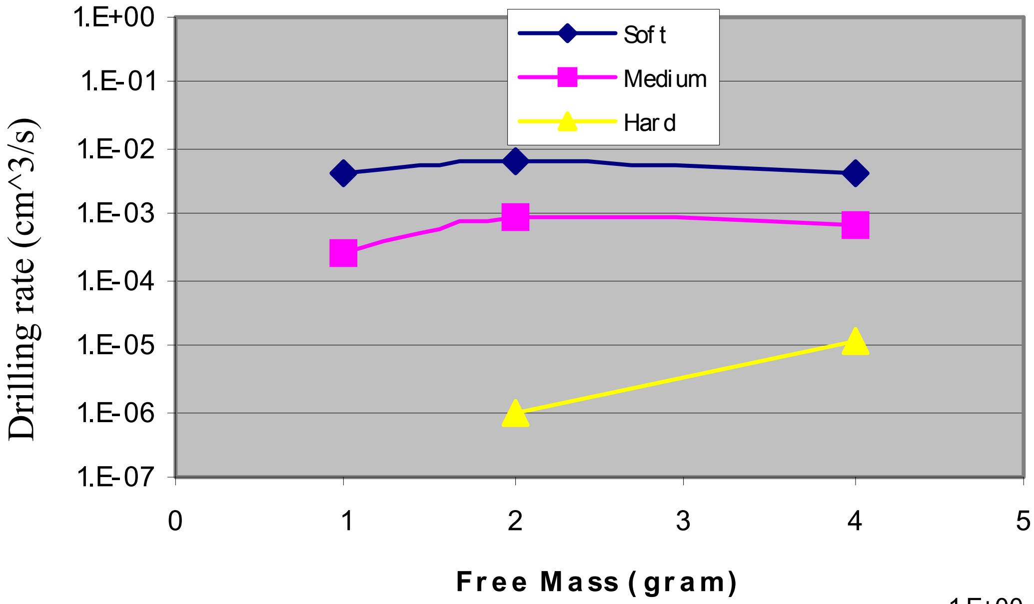
Rock type	Compression strength (MPa)	Specific energy (joules/cm^3)
Soft	< 50	30
Medium	50 – 100	50
Hard	100 – 200	260
Very hard	> 200	390

*W. Maurer, Novel Drilling Techniques, Pergamon Press, 1968

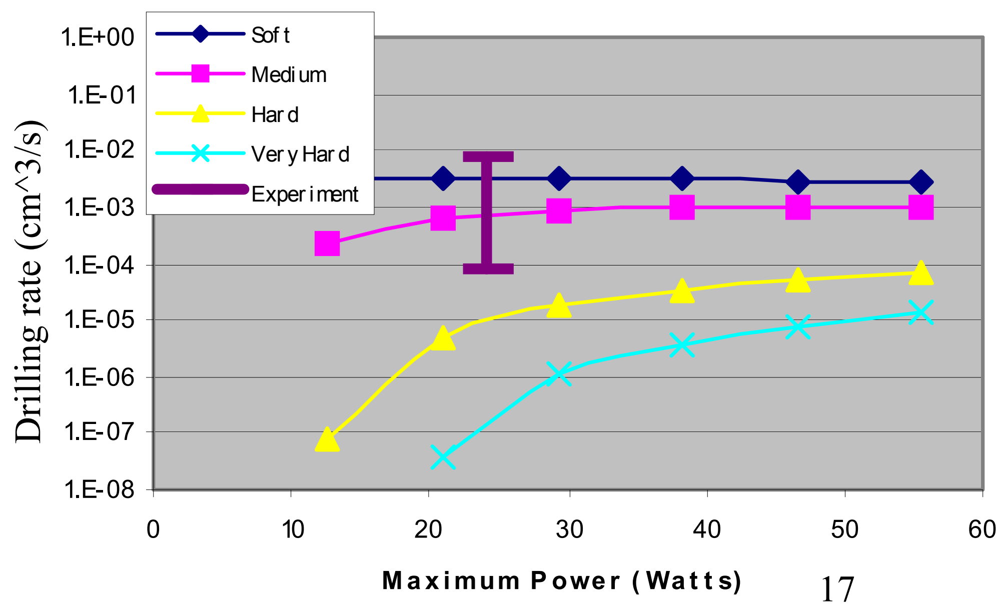


Force-displacement curve of rock surface under the drill bit.

Estimation of drilling rate

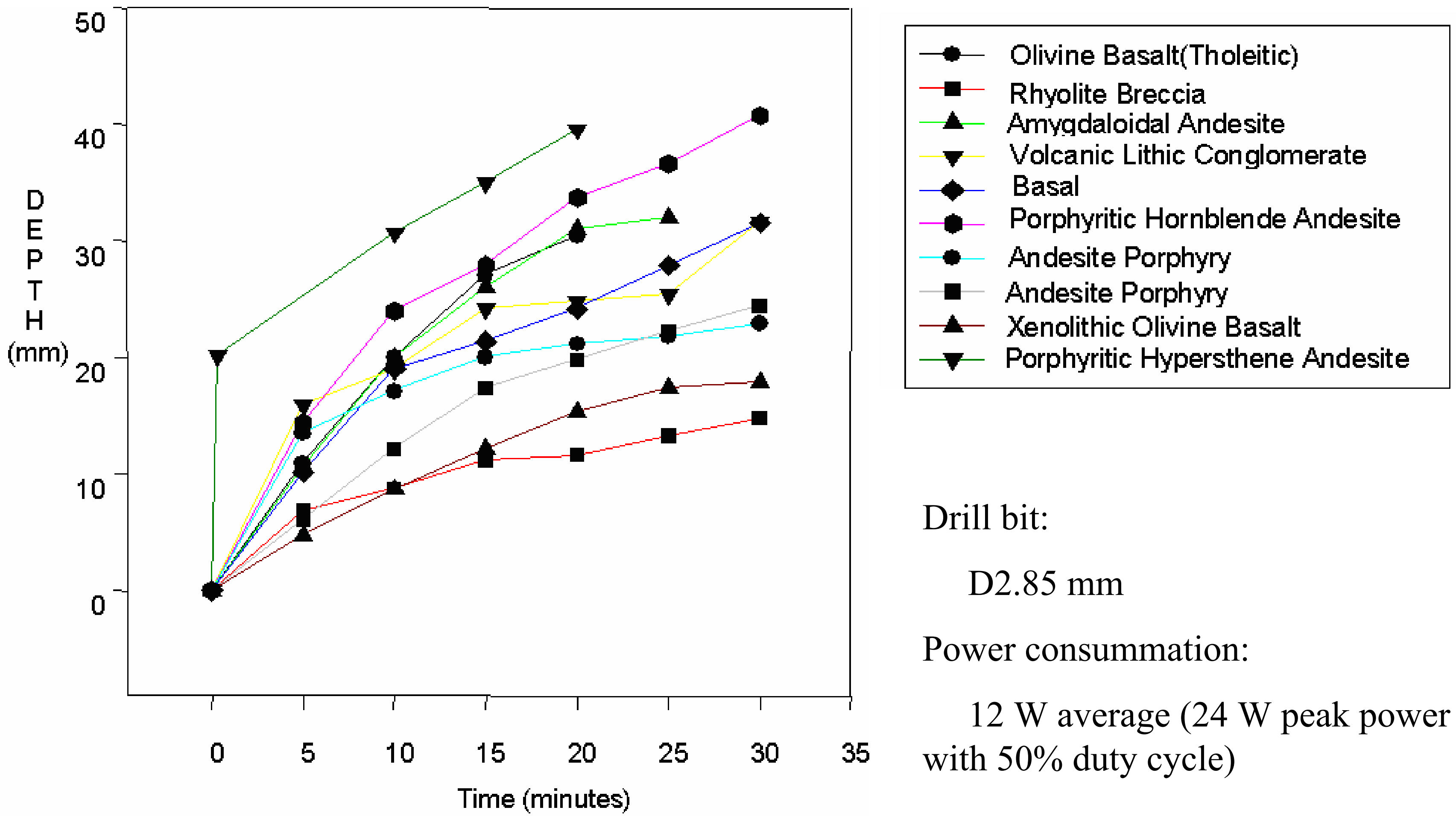


Drilling rate for different free-masses.



Drilling efficiency for different maximum power (the average drilling rate for average power of 10 watts with duty cycling the power supply). The brown bar indicates the range of experimental data for a variety of rock samples.

Experimental Data of Drilling Rate



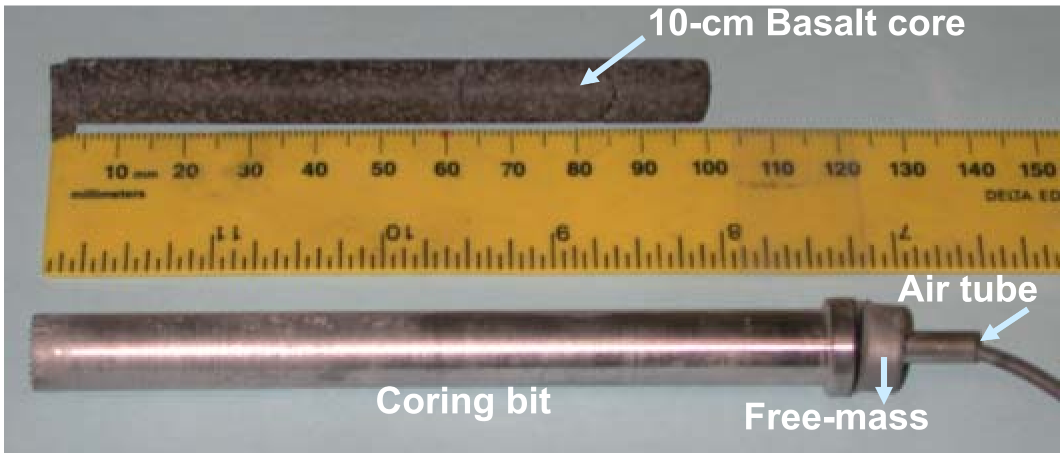
Drill bit:

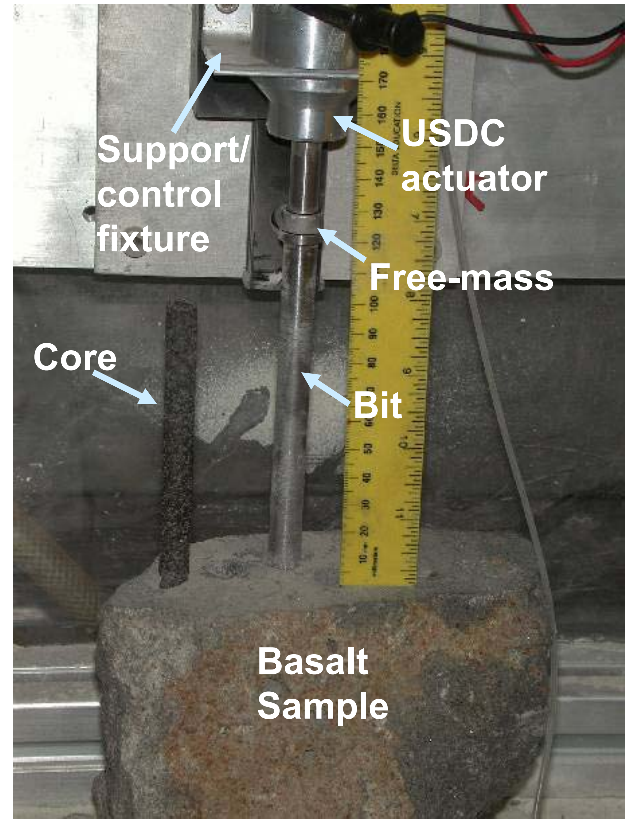
D2.85 mm

Power consummation:

12 W average (24 W peak power with 50% duty cycle)

Coring basalt via the USDC

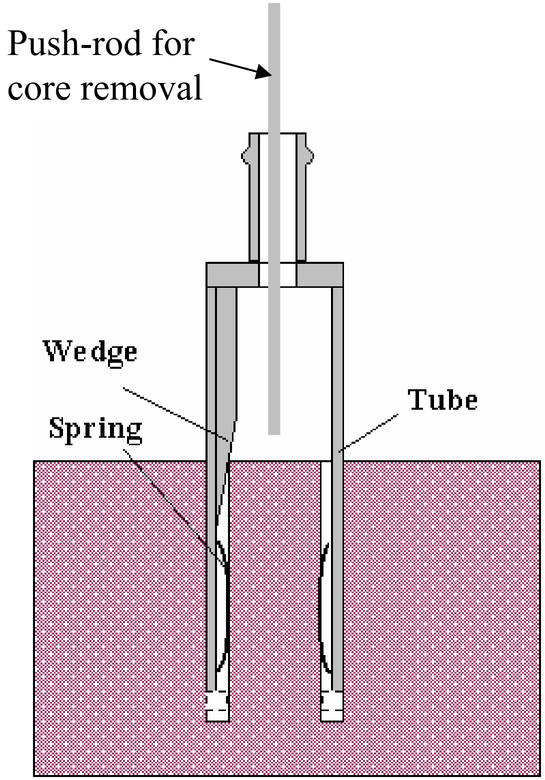




Coring set-up

USDC Core Breaking/Holding/Extracting

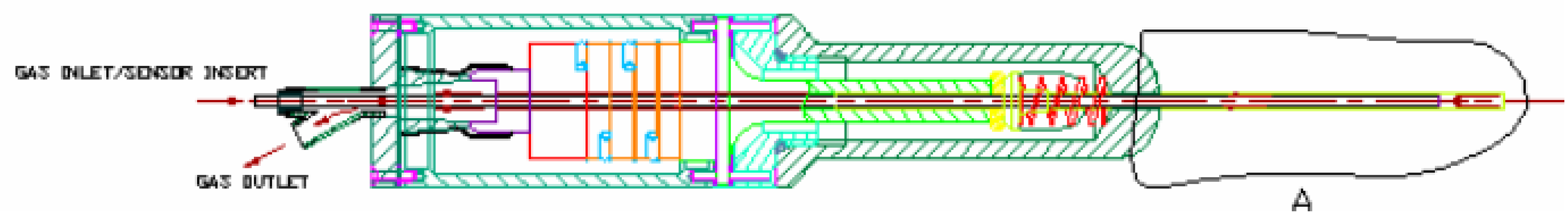
All-in-one bit using an internal wedge and side springs



Retaining spring and a grabbed core

Two created cores (out of two attempts)

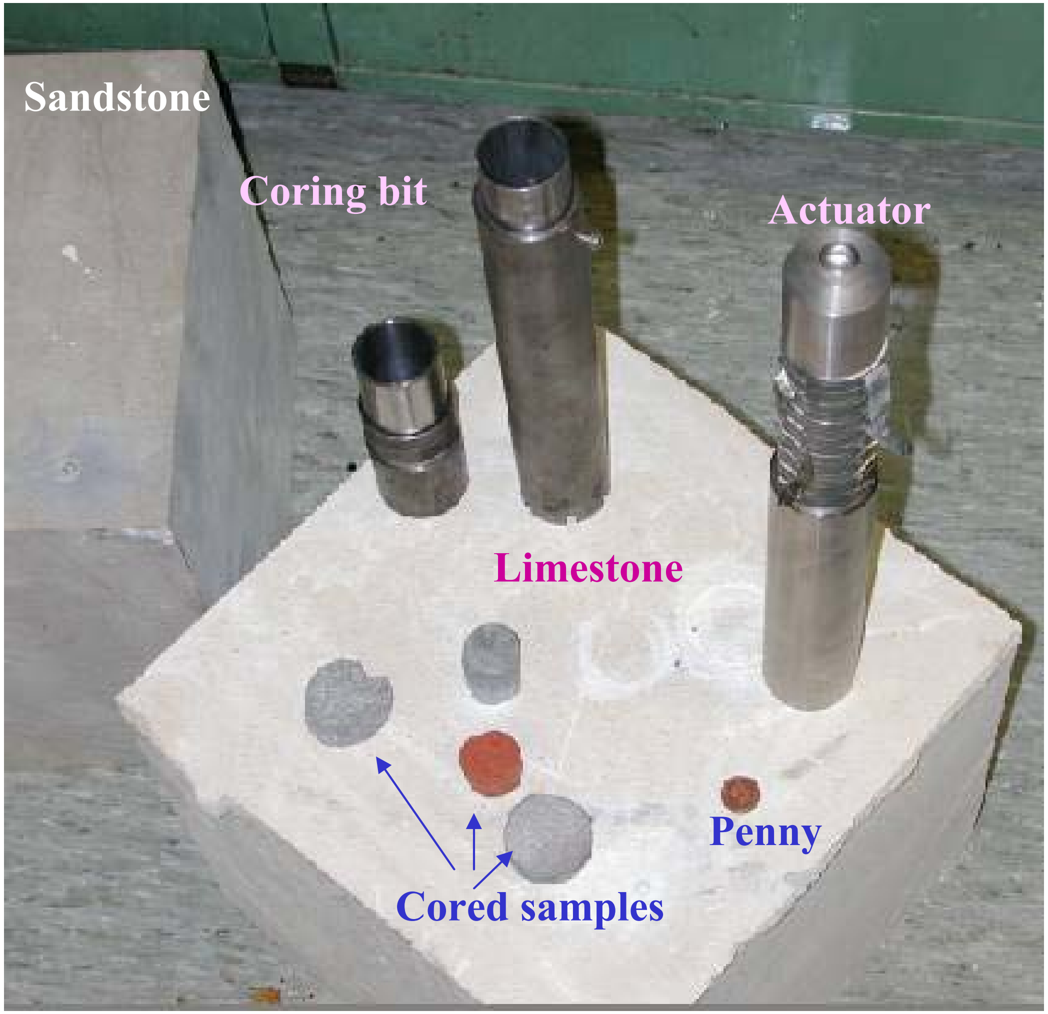
Powder sample acquisition

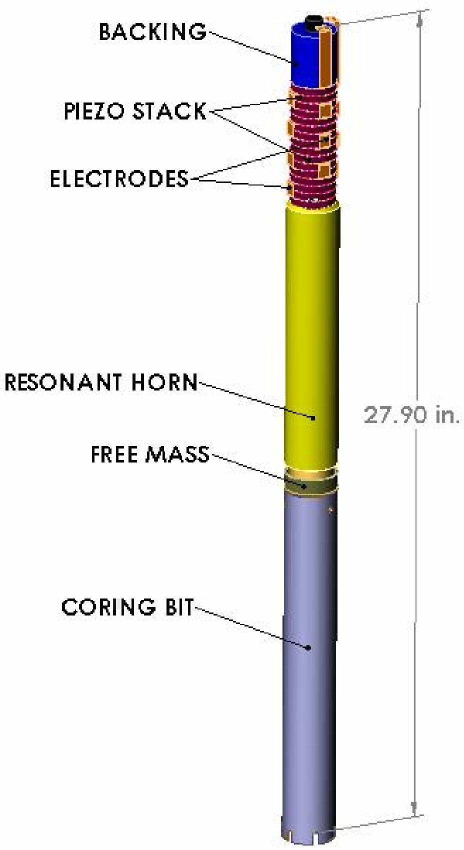


USDC with tubing and pressurized CO2 are being integrated to allow extraction powder.

Compressed air brings the powder sample through the tube to the paper.

Ultrasonic Gopher





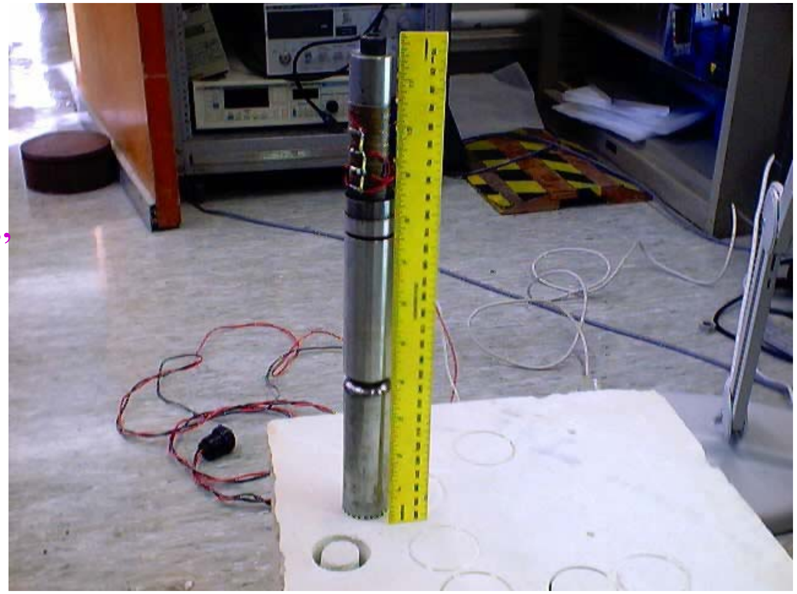
D1.75"

Ultrasonic Gopher

Another design

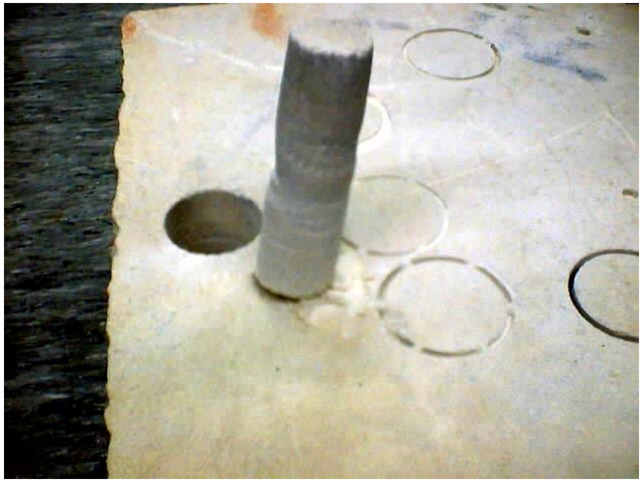
- **The Gopher**

  Size: D1.125" x 12"
  15 kHz

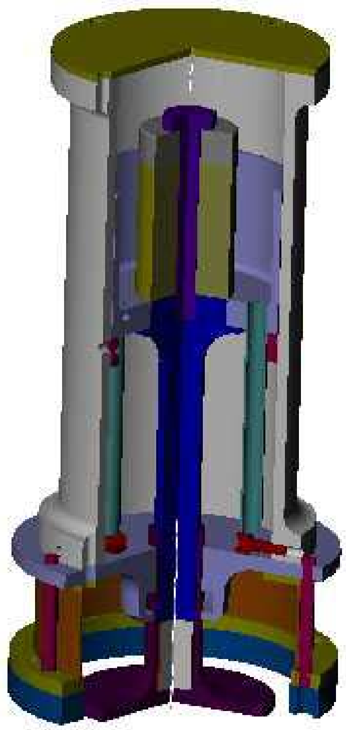


- Core and the hole on limestone

  Core D1" x 4"



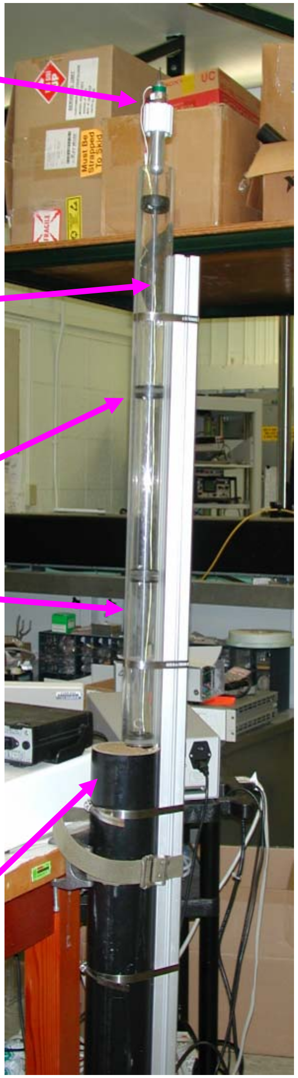
URAT: Ultrasonic Rock Abrasion Tool



URAT Schematic and Disassembled

Abrading
brick

Soil penetrator and test bed

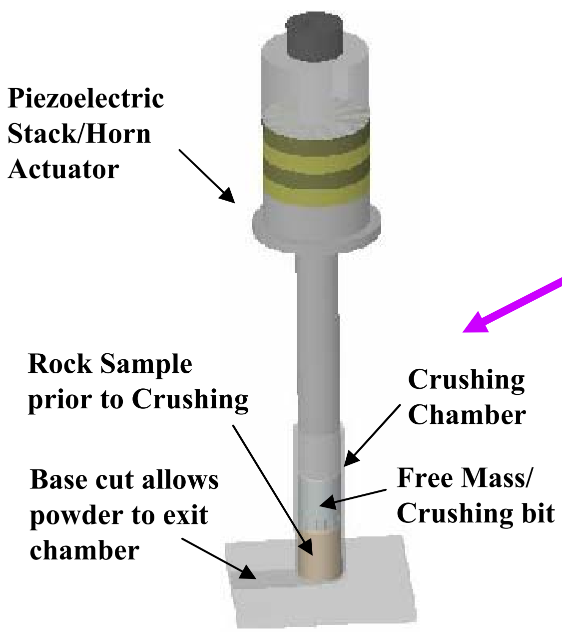


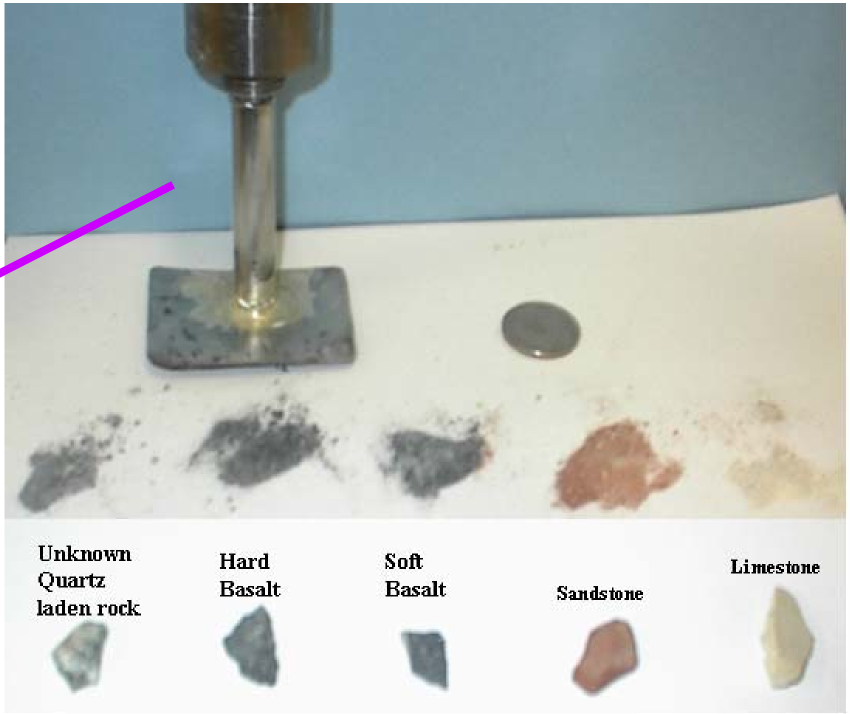
- Using 7 lb preload at ~70W and 20% duty cycled power, we reached a depth of 3-ft (~90-cm) in 30-40min.
- Since we used duty cycling the net drilling time is only about 6-8 minutes.

Powdered Cuttings

USDC crusher

- The USDC is used as a rock crushing, milling, and powdering device.
- Its actuator harmonic motion creates a series of low frequency impacts that grind the sample into powder within a short time period.
- A crushing chamber confines the free-mass to movement in one direction only leading to a very efficient milling.
- The grinding effect can be enhanced by making a free-mass with teeth on its interface with the sample.





Powder Sampling

USDC generates quality XRD powders

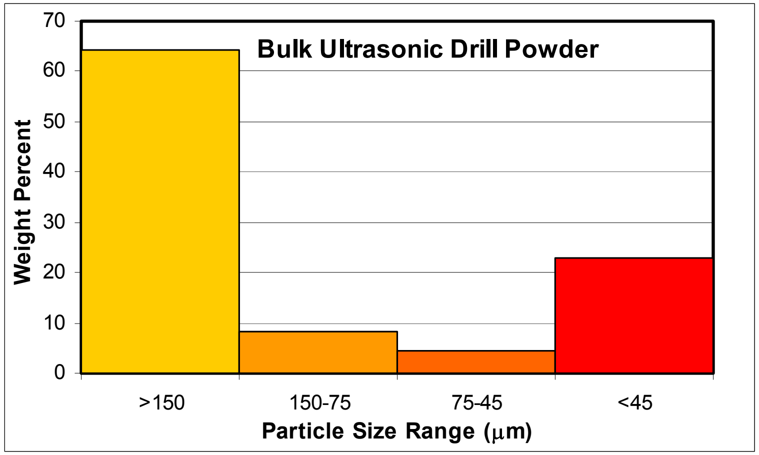


Fig.1 The size distribution of bulk powder generated by ultrasonic drill from the basal limestone of the Todilto Formation (Echo Amphitheater, New Mexico).

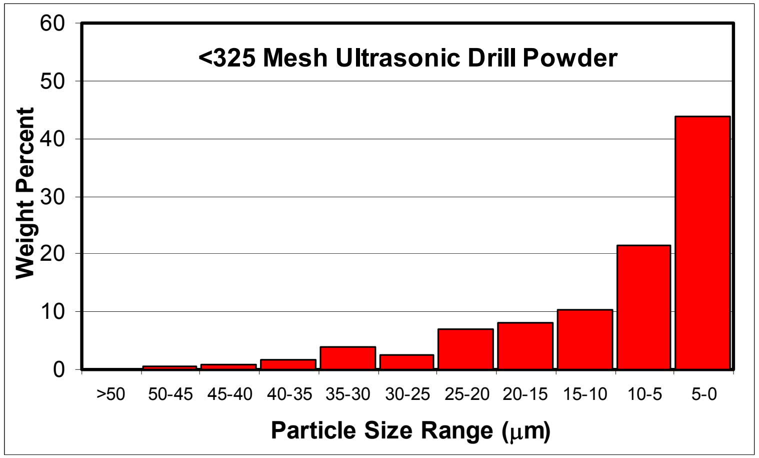


Fig. 2 The size distribution of the powder screened with 325 mesh

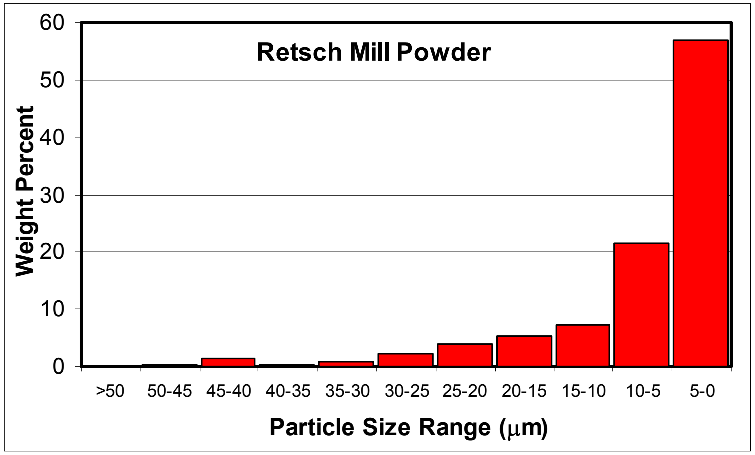
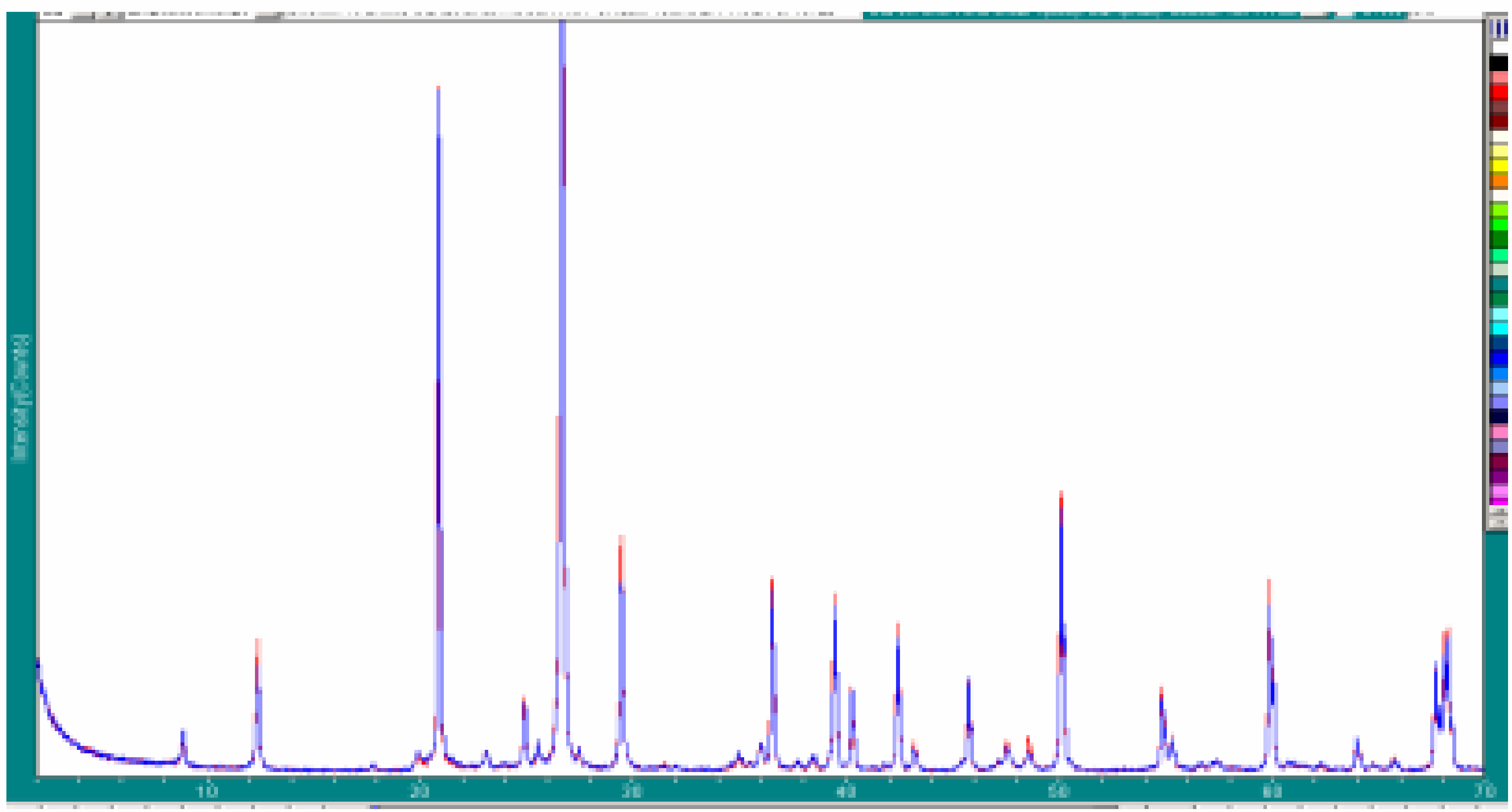


Fig. 3 The size distribution of the powder obtained from a laboratory Retsch mill

USDC creates large portion of fine powder that qualified for XRD analysis

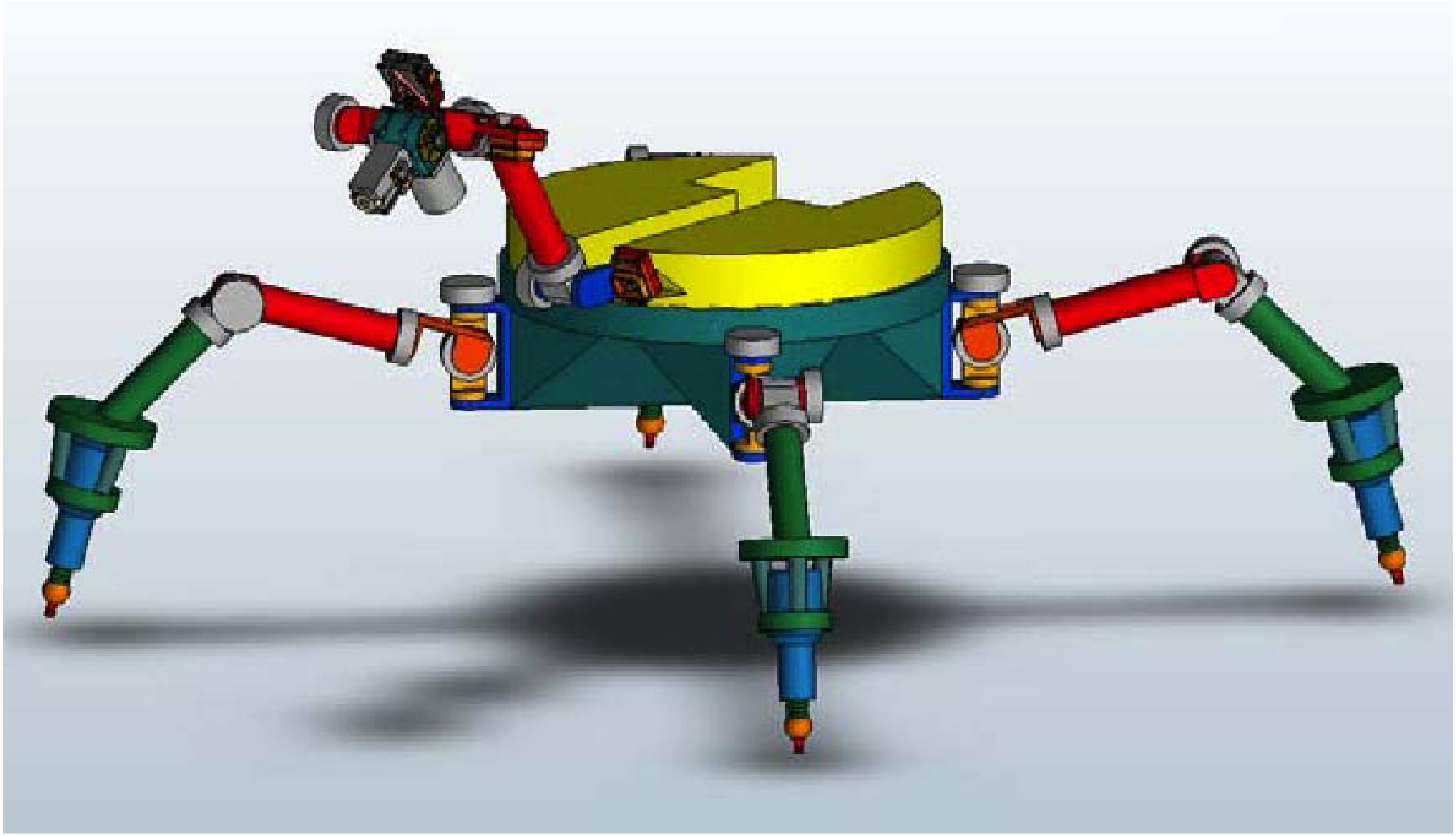
CHEMIN Sample #1 – Chinle Sandstone



LANL's Lab XRD patterns of the <45 µ m USDC powder (blue) compared to the Retsch milled <5 µ m powder (red).

Note: The patterns compared extremely well.

Steep Terrain Access Robot

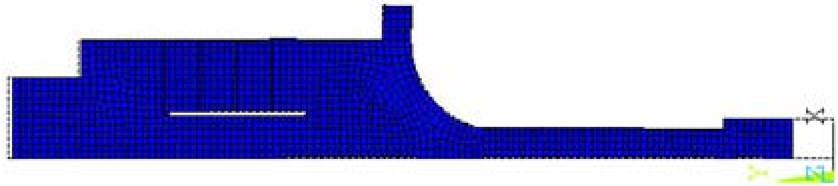


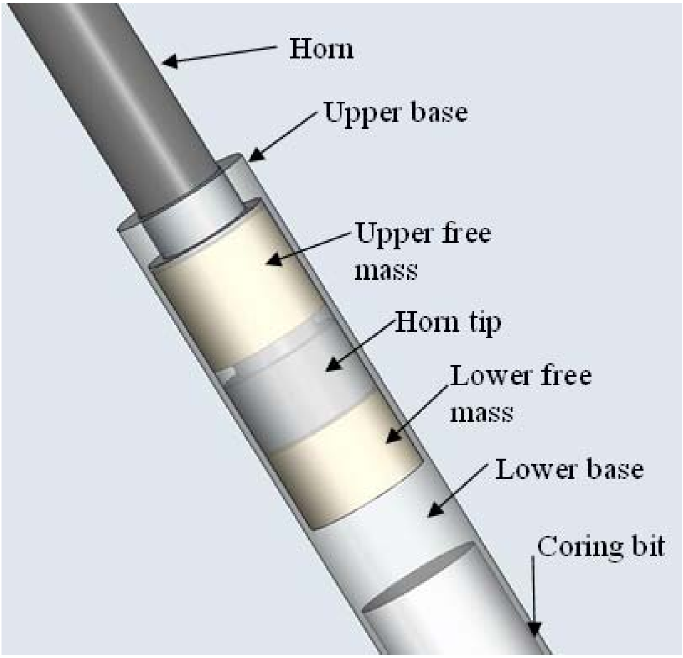
Steep Terrain Access Robot

Dog-bone horn and dual direction actuation

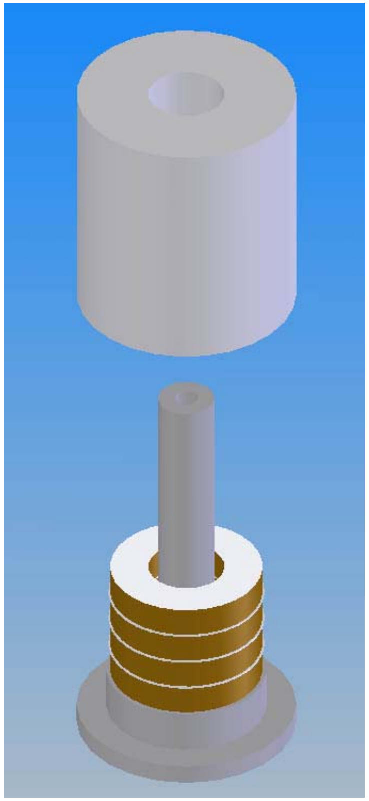
Free masses in both sides of the protruding tip.

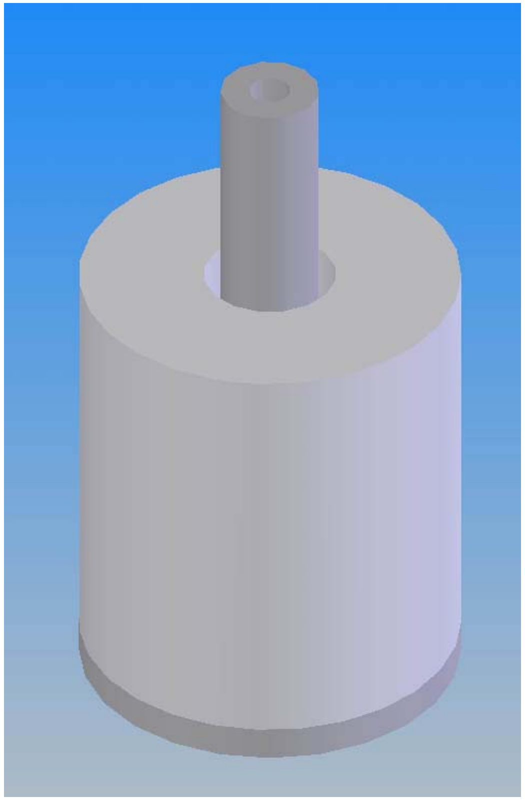
Neck Diam: 7.5 mm, Length: 75.5 mm, Freq.: 19.3KHz





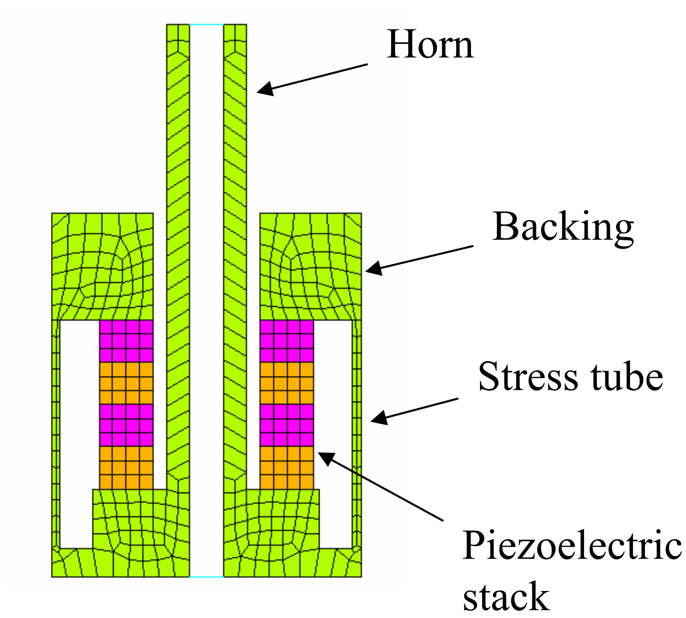
The Flipped and Planar Folded Horns

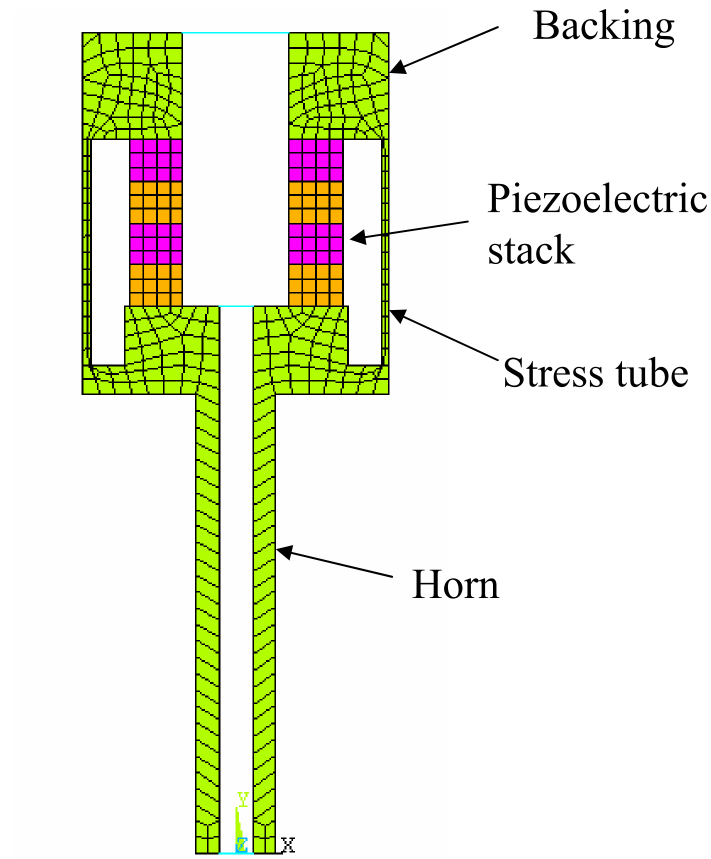




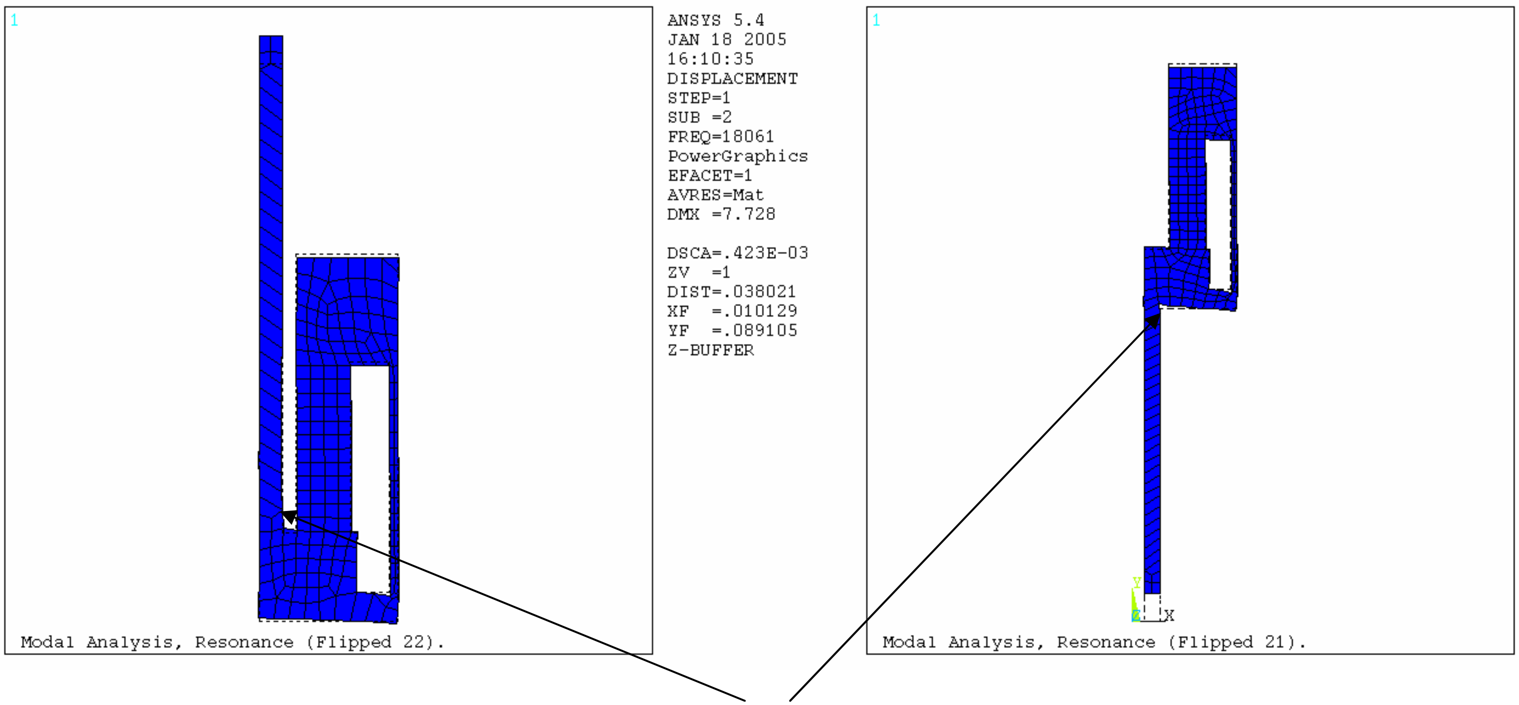
Flipped Horn

The Standard and the Flipped Horns





Analysis of the Standard and the Flipped Horns

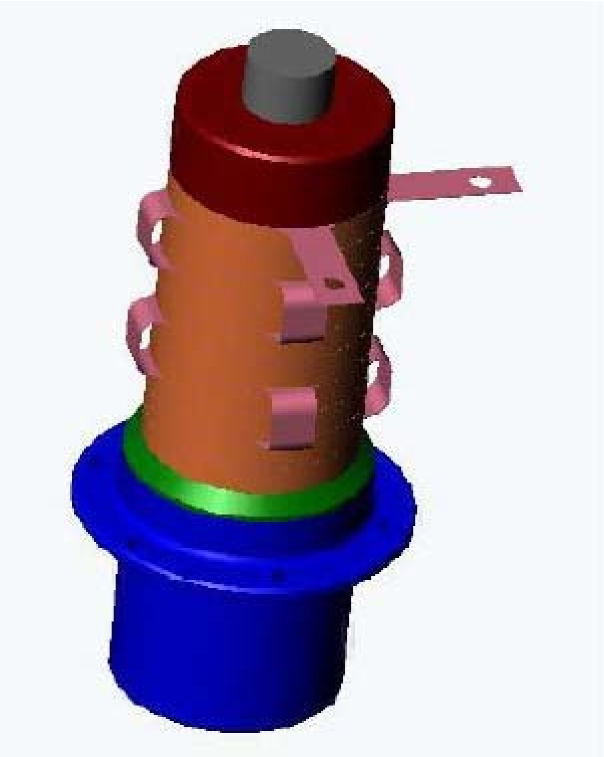


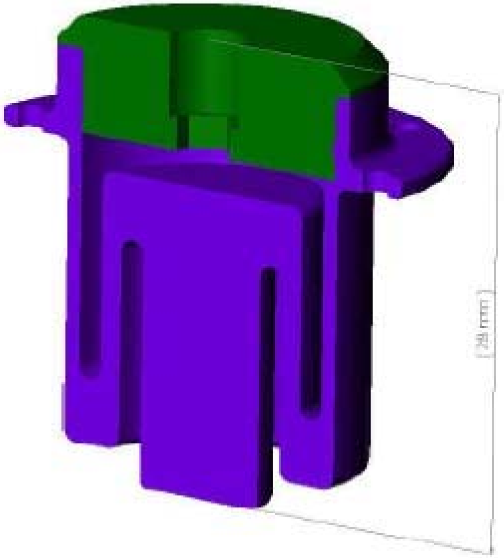
Maximum Stresses

Analysis Results of the Standard and the Flipped Horns

	Flipped horn	Standard horn	Difference (%)
Resonance frequency (Hz)	18061	17950	0.61
Horn-tip disp. (m), 1 volt	4.62×10^{-7}	4.63×10^{-7}	0.22
Electric current (amp), 1 volt	1.05×10^{-2}	1.04×10^{-2}	0.95
Max. stress (Pa), 1 volt	2.50×10^{6}	2.24×10^{6}	10.4
Horn-tip disp. (m), 1 watt	4.51×10^{-6}	4.54×10^{-6}	0.67

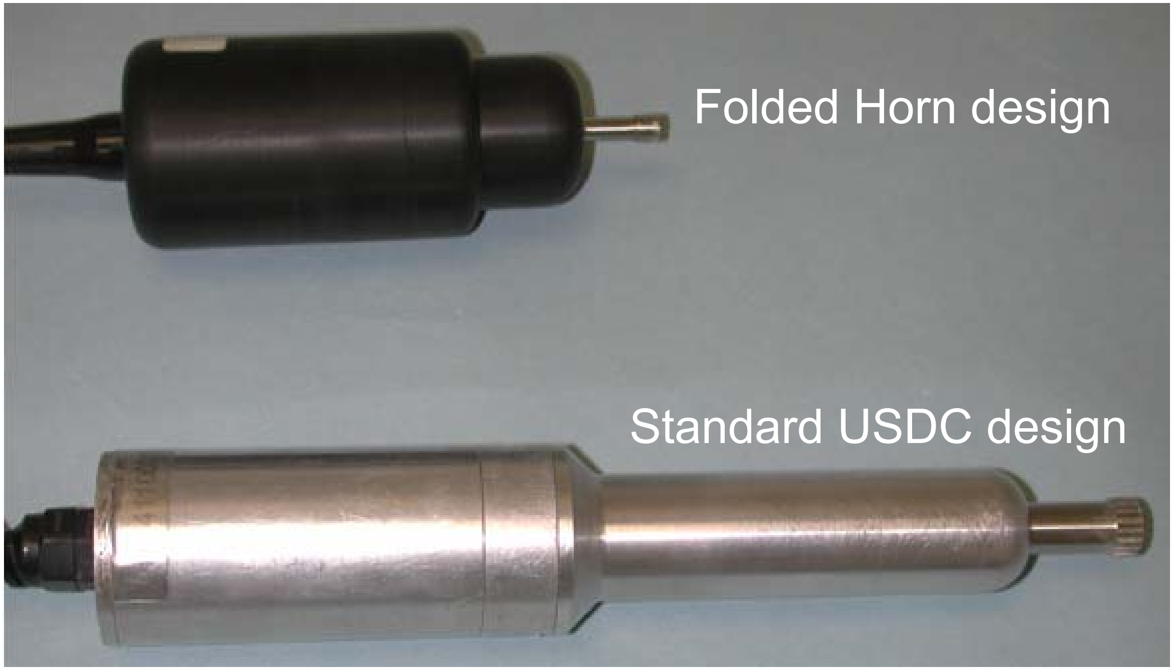
Folded Horn

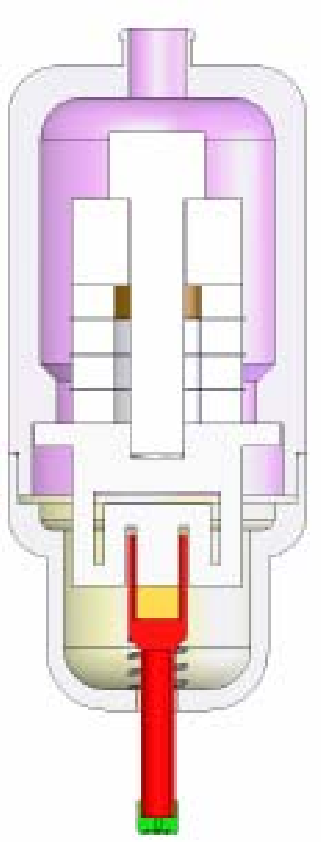




Dimensions reduction

- Using a folded horn the length of the powdered cuttings sampler was significantly reduced.





Powdered Cuttings Sampler

A view of the bit cutting edge

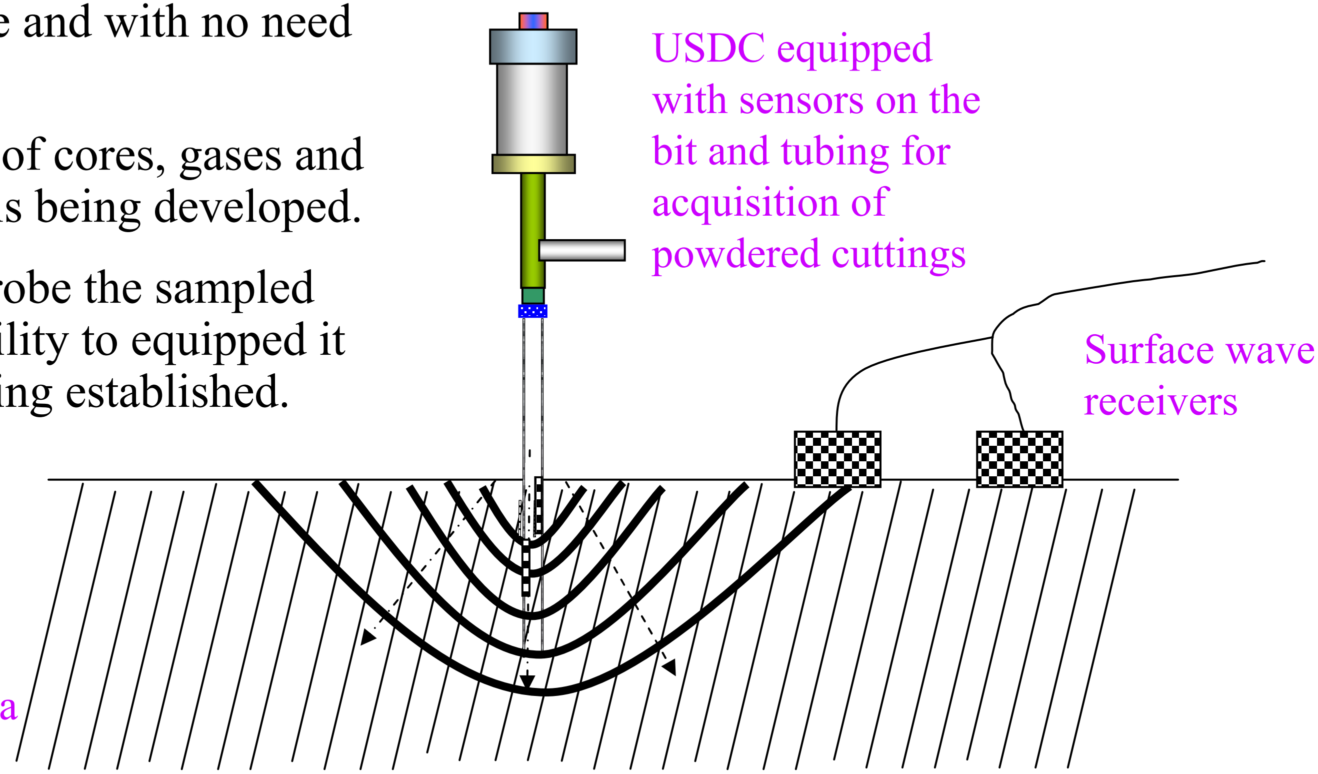
Sampled powder

The sampler in action drilling limestone and accumulating powdered cuttings inside the bit

Sensing

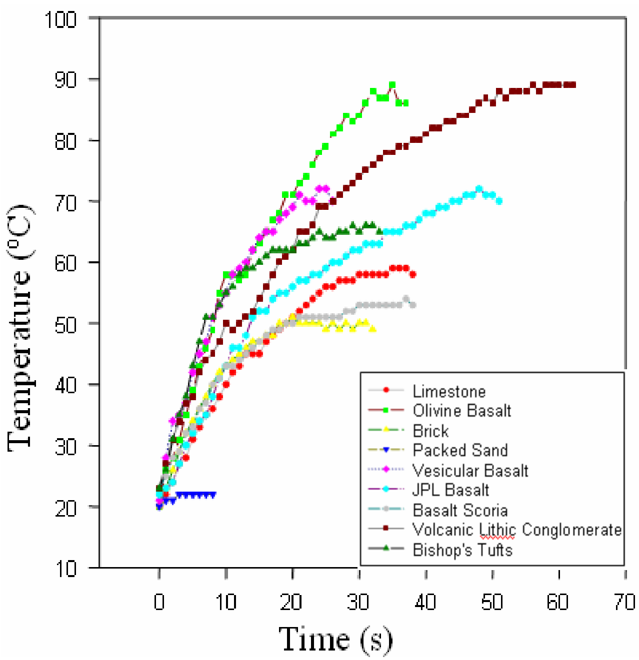
The Ultrasonic/Sonic Driller/Corer (USDC) as a probing, sampling and sensing system

- The USDC was demonstrated to core samples from rocks that range in hardness from soft to very hard using very low axial force and with no need for bit sharpening.
- Effective sampling of cores, gases and powdered cuttings is being developed.
- The capability to probe the sampled medium and the ability to equipped it with sensors are being established.



Bit Temperature measurements

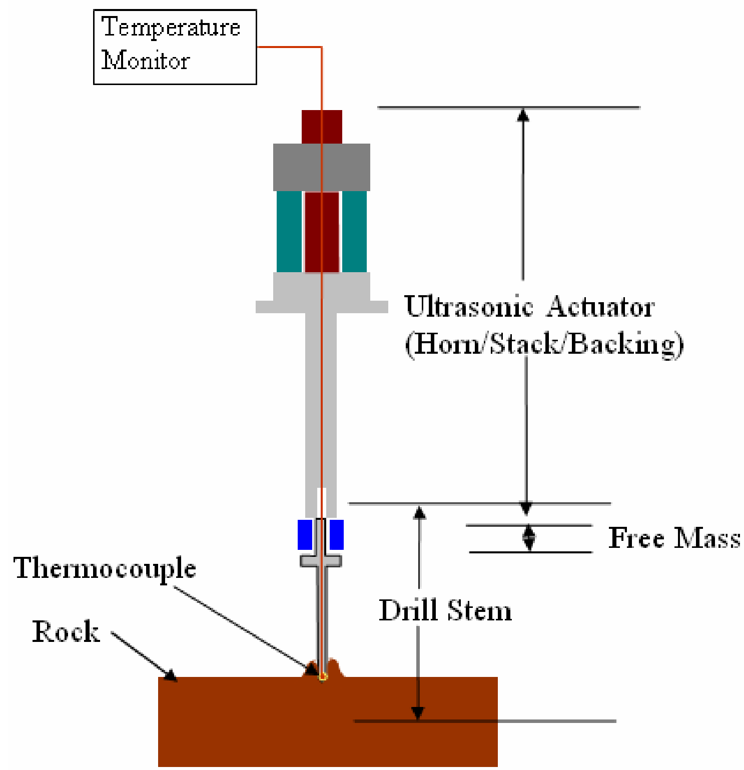
A thermocouple was integrated into the USDC bit to allow real time monitoring the temperature during drilling.



Temperature rate of rise and maxima as a function of time for drilling variety of media

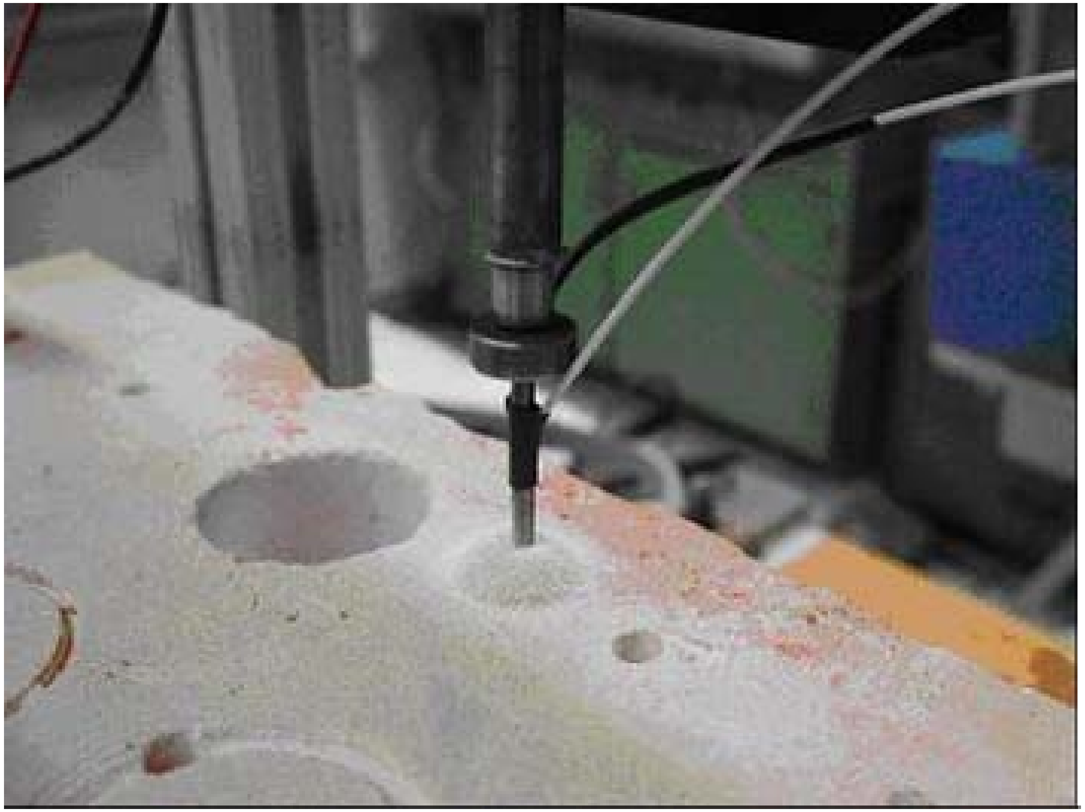
Power < 40 watts

Bit diameter = 3.6 mm



Experimental Setup

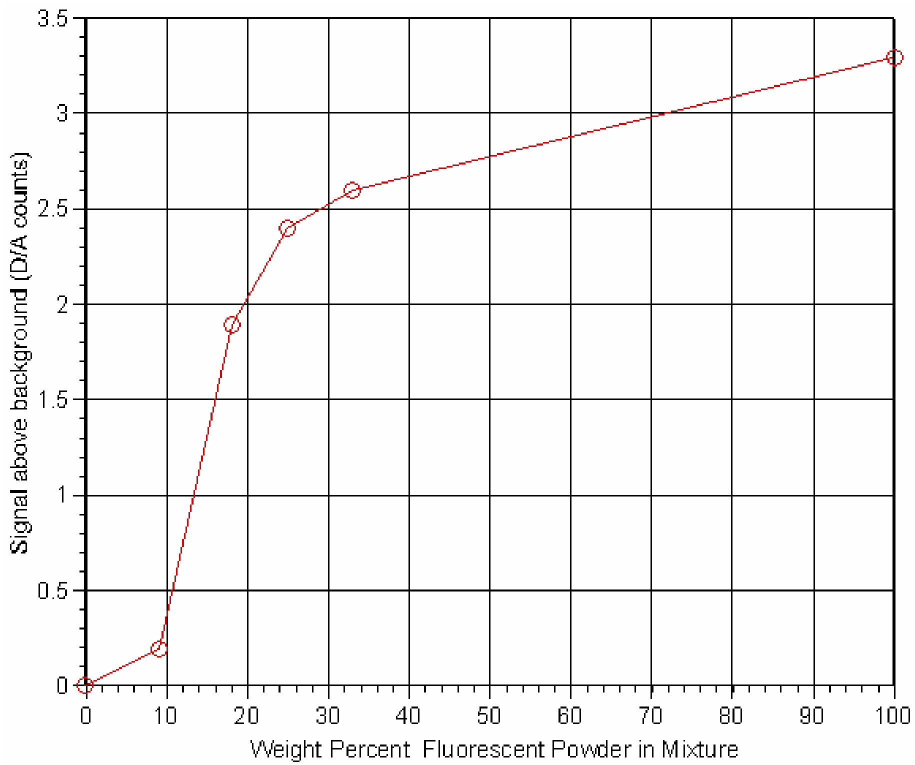
Drill with integrated fiberoptics

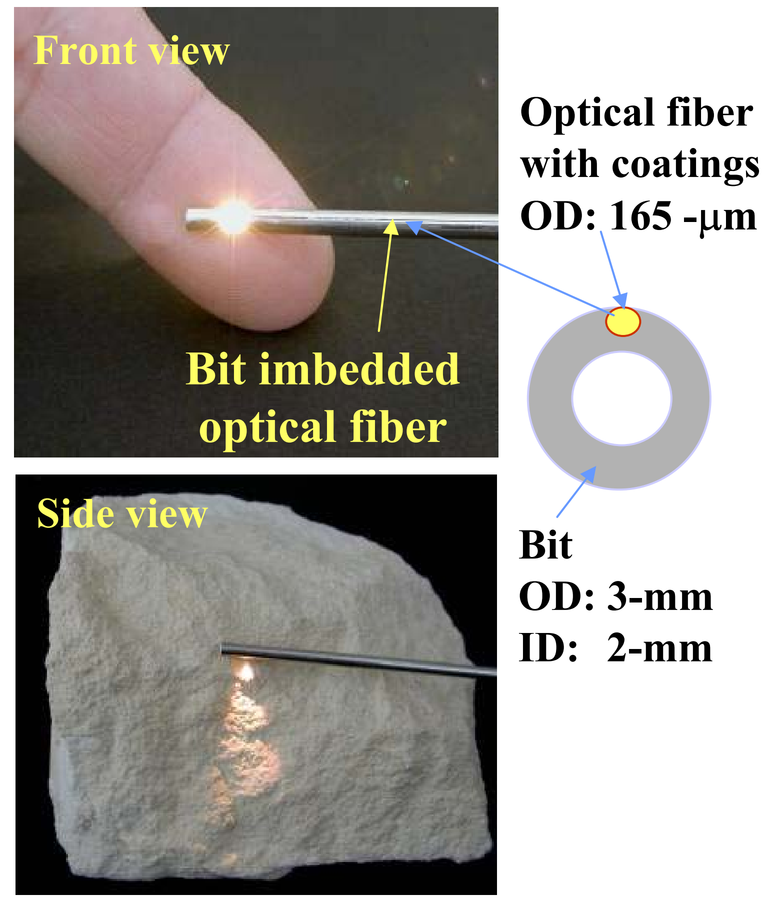


Drilled 1.1-inch deep hole on limestone, no damage integrated fiber optic was found.

Integrated fiberoptics and measured reflectivity

Preliminary study jointly with Research International, Inc



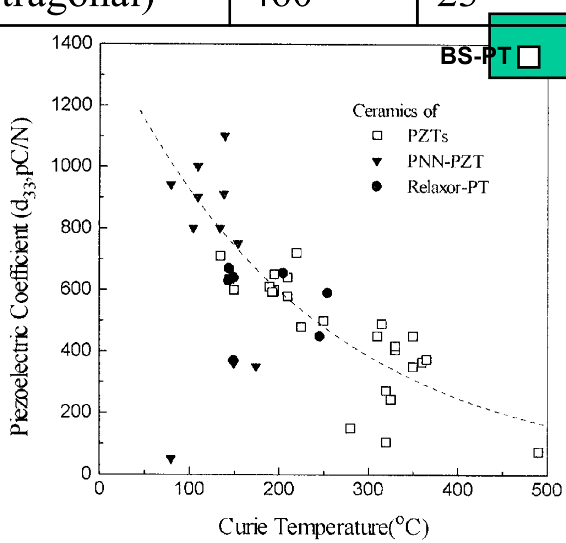


Increase of response signal in the range of 545nm to 700nm with fluorescent powder percentage (Magnaglo, MG-410). The light source was 415 nm UV.

Operation in extreme environments

Comparison of various Piezoceramics with $BiScO_3$–$PbTiO_3$

Material	Structure	T_c (˚C) (C/cm^2)	P_r	E_c kV/cm	d_{33} pC/N
PZT-5A (soft)	Perovskite (MPB)	330	36	~ 10–12	~ 400
PZT-8 (hard)	Perovskite (MPB)	330	25	> 15	~ 225
$PbNb_2O_6$ (modified)	Tungsten Bronze	~ 500	—	—	~ 85
$Na_{0.5}Bi_{4.5}Ti_4O_{15}$	Bismuth Layered	~ 600	—	—	18
$BiScO_3$– $xPbTiO_3$ x=62	Perovskite (rhombohedral)	420	28	17	290
$BiScO_3$– $xPbTiO_3$ x=64	**Perovskite (MPB)**	**450**	**32**	**21**	**465**
$BiScO_3$– $xPbTiO_3$ x=66	Perovskite (tetragonal)	460	23	25	260



Ref: T. Shrout, Penn State U.

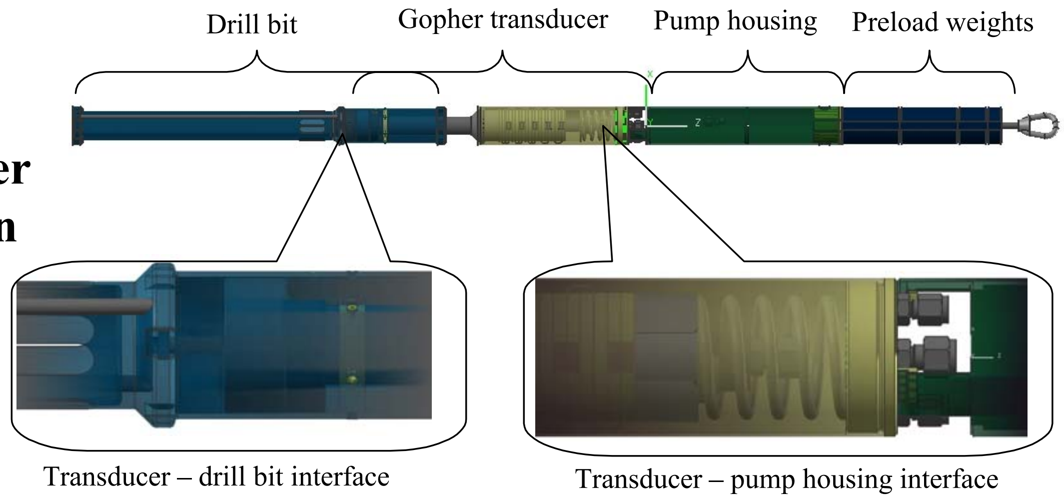
High temperature USDC for Venus

HT-USDC

A USDC that can operate at 450°C would be applicable for the exploration of Venus.

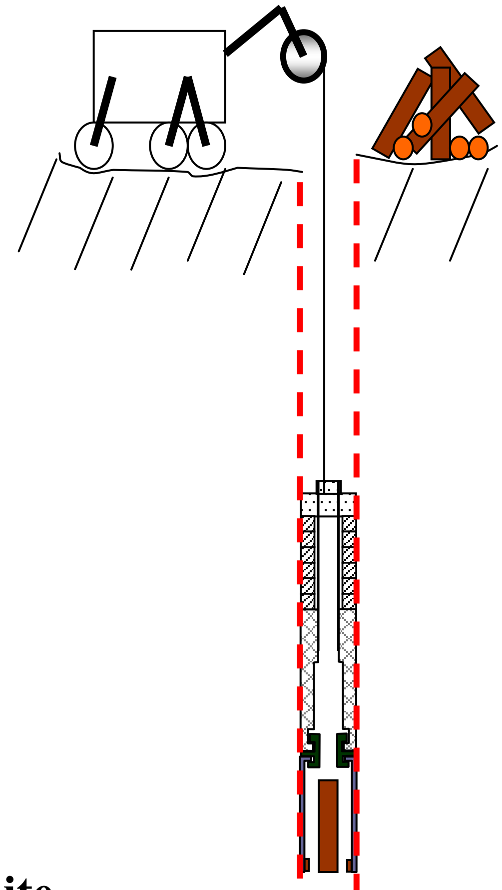
Gopher

Gopher design



Mt. Hood test site

Close up view of the drill site

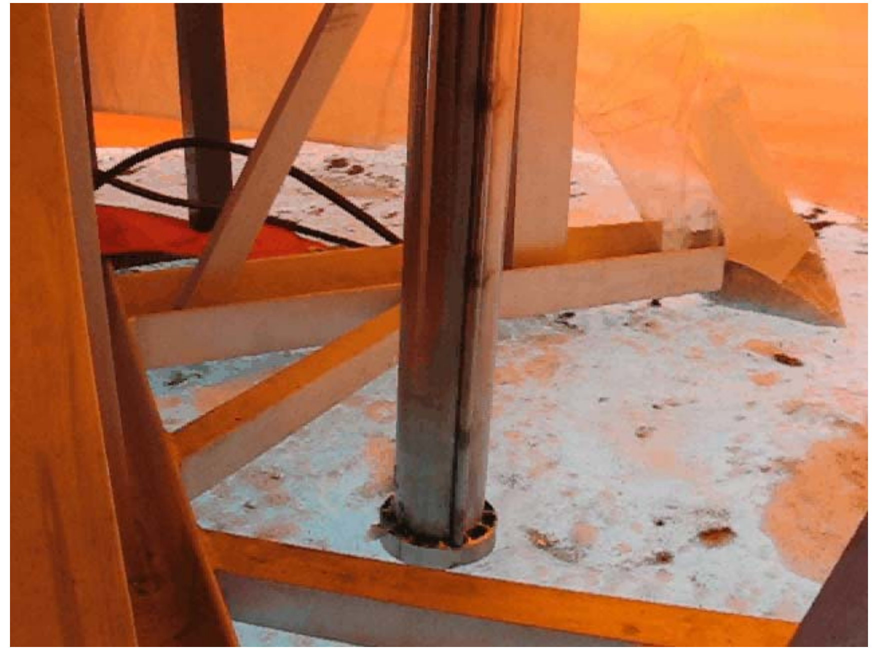


A total of 1.25-m was accomplished in a total drilling of 5 hours with an average drilling of 0.25 m/hr.

Field test in Lake Vida, Antarctica

A total depth of 176cm was reached

Lake Vida test site.



Inside the drilling tent.

The gopher in the drilled hole

SUMMARY

The USDC has been studied as a probing device that can sample cores, powdered cuttings as well as operate as a platform for sensors

Sampling techniques

– Methods of operating the bit as an all-in-one unit for extraction of cored rocks (including basalt) with maximum integrity were developed.
- Devices for the acquisition of powdered cutting and cores of various materials were developed and being studied including powder sampler, gopher and many others.

Noninvasive probing

- The reflection and transmission of imparted elastic waves (bulk and surface) were measured to establish means of rocks characterization. Also, the effect of loading the actuator by the sample were monitored by measuring the change in impedance and resonance frequency.
- Surface wave velocity measurements were the only reliable quantitative data that was obtained.

Integrated sensors

– An integrated thermocouple showed great potential in determining the hardness of drilled rocks using the heating rate and maximum temperature rise. Assuming relatively similar heat transfer to rocks, this should provide an effective sensing technique. It can also help protecting cored samples from thermal damage.
– We demonstrated the integration of an optical-fiber into a bit and the the measurement of reflectance and fluorescence levels in the wavelength range of 400 – 1150 nm.