ESTIMATION OF MARS REGOLITH TEMPERATURES UNDISTURBED BY THE INSIGHT HP^3 PROBE PENETRATION BY EXTRAPOLATION OF COOLING CURVES RECORDED DURING SCHEDULED STOPS IN PROBE PENETRATION.

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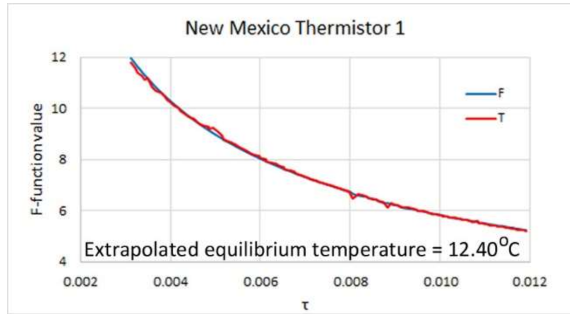
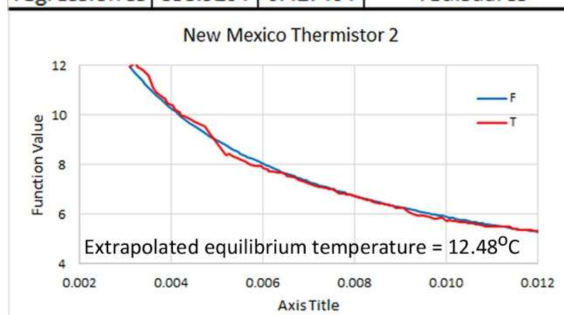
Introduction: Prior to launch of the DS-2 penetrator mission to Mars in 1999 calculations and experiments were made to determine the feasibility of extrapolating equilibrium regolith temperatures from the cooling of the DS-2 penetrator from kinetic and frictional heating of penetration [1]. Extrapolations were based on conductive heat transfer theory of an infinite region bounded internally by a circular cylinder of a perfect conductor [2-4], with the introduction of dimensionless parameters $\tau = \kappa t/a^2$, $h = K/AH$, and $\alpha = 2\pi a^2 \rho c/S$, where K, ρ, c, κ are the thermal conductivity, density, specific heat and diffusivity of the region outside the cylinder, S is the thermal capacity of the perfect conductor, per unit length of the cylinder, and t is time. The contact resistance across the surface of the cylinder is given by $1/H$ per unit area. The function that describes this cooling is commonly called the F-function. An example of results of one of the cooling penetrator experiments and theoretical fits to the data are shown in Figure 1. One parameter required for the technique is the thermal diffusivity of the medium that is penetrated. This parameter can be estimated by using an assumed diffusivity and refining the assumed value based on the quality of the fit to the data.

During the penetration of the InSight HP^3 mole, stops are scheduled at approximately 0.5 m depth intervals to allow the mole to cool before the initiation of an active heating experiment. Temperature data will be recorded during this cooling period and the possibility is being investigated of using these data to extrapolate the regolith temperatures prior to disturbance by the mole penetration and to estimate regolith thermal properties. These data will complement equilibrium temperatures measured and calculated from data collected in the mission and data from the active heating experiment.

Preliminary Information: The HP^3 mole differs from "cylinders" that were considered for cooling bodies in the DS-2 mission with respect to its surface contact resistance. The analytic models shown in Figure 1 were run with the assumption that the contact resistance between the steel projectile and the dry sand target was zero. This assumption may not have been valid with the DS-2 penetrators in the Mars regolith,



Linear Regression to fit temperature data to F-Function			
Slope (A)	1.936373	-24.0089	intercept (B)
±	0.0064	0.104142	±
R^2	0.998811	0.062619	s(y)
F	91534.8	109	degrees of freedom
regression ss	358.9204	0.427404	redisual ss



Linear Regression to fit temperature data to F-Function			
Slope (A)	1.671776	-20.4928	intercept (B)
±	0.011037	0.184351	±
R^2	0.995531	0.120638	s(y)
F	22943.01	103	degrees of freedom
regression ss	333.9022	1.499015	redisual ss

Figure 1: *Plots of probe cooling temperature data converted into F-function space, and F-function fits to the data with linear regression parameters used to shift the shift the temperature data. These data were recorded from the cooling to a hollow steel projectile approximately 50 mm in diameter fired from a very large air gun into a dry sand target at White Sands Missile Range, NM, USA. The data are from two thermistors at the surface of the projectile at two different positions along its length. Best fit assumed a thermal diffusivity for the sand of* $2x10^{-8}$ mm^2/s.

but, as no data were returned from the mission, there were no data to test the assumption. The HP^3 mole is sheathed with heating foils (TEM-A) that are protected from abrasion by aluminum half shells [5]. The heating foils, very close to the surface of the mole, will reduce the general thermal properties of the mole from those of a "perfect conductor", and their effect may be included in the F-function model as surface contact resistance. The magnitude of this contact resistance must be deduced in the curve-fitting process.

The HP^3 instrument is scheduled to start penetration at the InSight landing site at the beginning of February, 2019. Cooling data will be available for analysis before the 2019 LPSC. Many testbed simulations have been run with the HP^3 instrument and temperature data from one of these penetrations is shown in Figure 2. Attempts to model the cooling portion of the curve in Figure 2 have been unsuccessful. The reason for this lack of success is thought to be that the initial conditions for the model, uniform "zero" temperature in the medium surrounding the cooling cylinder, is not met with the HP^3 probe because the medium is heated by the probe during penetration. Possibly the penetration heating may be dissipated sufficiently to use the F-function curve when times are large, but the temperature record shown in Figure 2 did not continue long enough for the heating pulse to become sufficiently dissipated to allow use of the F-function (in Figure 2, time of heating >> time of cooling; need time of heating < time of cooling for use of the F-function). Limited time records of probe cooling should not be a problem with the actual HP^3 penetration data because a period of at least 2 sols is scheduled each time the probe is stopped before the active heating experiments to allow heat deposited in the regolith to dissipate [5]. It is not certain at this time whether using the later part of the cooling curve will allow the extrapolation of undisturbed regolith temperatures, but with the long cooling periods scheduled, useful information should be recovered from the cooling data.

Alternative Solutions: Two alternative solutions to the direct application of the F-function method are being investigated. The first is to use a similar method to fitting the F-function to the cooling data, but to extract information from the heating curve. As shown in Figure 2, the heating curve is somewhat similar in form, but inverted with respect to the cooling curve. A fit to these data, using the same conductive heat transfer model of an infinite region bounded internally by a circular cylinder of a perfect conductor, could be used to determine similar information to the cooling model. Jaeger [3] gives the heating solution for a perfectly conducting cylinder in an infinite medium and reports that this solution may be approximated by the I-function, similar in concept to the F-function [6].

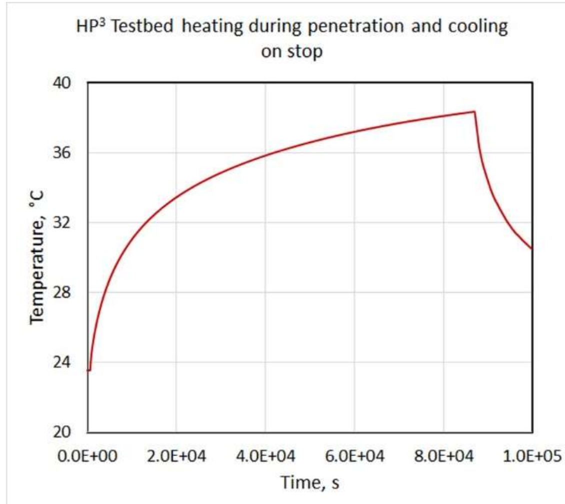


Figure 2: *Plot of temperature of outer probe foil (TEM-A) for HP^3 probe during testbed penetration simulation. Penetration, which resulted in heating, continued for about 24 hours, followed by recording cooling for about 3 hours and 20 minutes*

The second solution under investigation is to model the heating and cooling curves using a commercial finite-element code (COMSOL®) and to determine undisturbed temperatures and the thermal properties from the model parameters that give the best fit to the data.

Concluding Remarks: Temperature data recorded by the HP^3 during penetration and cooling before active heating experiments will be used to provide estimates of undisturbed temperatures of the regolith and thermal properties of the regolith to complement more formal determination of these parameters.

References: [1] Mosshamer, C.L., *M.S. Thesis, Northern Ariz. Univ*., AZ, USA, 33 pp + 2 appendices, (May, 1998). [2] Bullard, E.C., *Proc. Roy. Soc.,* **A222**, 408-429 (1954). [3] Jaeger, J.C., *Aust. J. Phys*. **9**, 167-179 (1956). [4] Carslaw, C.S., Jaeger, J.C., *Heat Conduction in Solids*, Oxford, 2nd edn. p. 342 (1959). [5] Spohn T. et al., *Space Sci. Rev*., **214**.96 (2018). [6] Jaeger, J.C., Clarke, M., Proc. *Roy. Soc. Edinburgh* **A61**, 229- (1942)