PRECURSOR ACTIVITIES TO SOLVE PLUME CRATERING PROBLEMS FOR HUMAN-CLASS MARS LANDERS.

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Introduction: It is unsafe or too risky to land human-class landers (>40 MT) on Martian soil without first constructing a mechanically competent surface, a landing pad. This drives requirements into the precursor mission program to gain the scientific knowledge and develop the technologies needed to make terminal landing safe. The need for landing pads is the consensus of the plume/soil research community after a decade of concentrated research, including experiments, physics-bases simulations, and mission analysis. This finding has not yet been communicated widely outside the community of researchers because the consensus has been achieved only recently, so both space architects and mission planners may be unaware of the seriousness of the problem. The successful landings of prior missions is deceptive because there are several distinct regimes in cratering physics, and different regimes occur for different conditions, producing vastly differrent results. Prior missons to the Moon and Mars all successfully avoided the worst cratering regimes owing to their smaller size landers and/or environmental conditions where they were landing. What the plume/soil community has concluded is that the worst cratering regime – deep penetration and deep fluidization of soil beneath and around the lander – will be impossible to avoid when we land human-class vehicles on unconsolidated Martian soil, and that it will be too uncontrollable to land safely with any type of vehicle conceived so far. The depth of the fluidizationn is what makes it so dangerous, because while its engines are shutting off, the deep cylindrical jet hole is collapsing, and the surrounding soil is returning chaotically to a solid state, then the vehicle will be settling into this highly dynamic solid/fluid mixture and tipping unpredictably. Large rocks and smaller gravel will also strike the bottom of the vehicle at high velocity during the cratering process. It seems unlikely that Skycrane will adequately scale to human-class landers. It seems that schemes to redesign the vehicle and reduce this plume problem all reduce the mass of payload that can be landed on the surface while exaggerating the entry and descent challenges by making the propulsion system non-optimum or the vehicle too heavy. So far, no reasonable method to land humans safely has been identified except for sending a smaller robotic mission prior to the arrival of the human-class lander, and robotically constructing one or more adequate landing pads from native materials. This is a new paradigm for Mars missions and there are many technologies that must be developed, beginning from TRL1, before a Mars mission can proceed. Also, it is unlikely that such a major paradigm change can be adopted without extremely good justification, so the physics-based simulation codes that predict the plume/soil interactions must be improved beyond their current capabilities and validated for the Mars environment on appropriate energy scales. We must accelerate acquisition of the scientific knowledge and development of the technologies related to plume/soil prediction and landing pad construction if we are to maintain the option to develop architectures and mission hareware in time to support human Mars landings by 2033.

Possible Mission Scenario: To build a landing pad prior to human arrival, a smaller spacecraft with MSL-class mass could land first. It would include grading and boulder-removing capabilities, with sufficient automation to operate at a 40 minute time delay efficiently. It would also carry a soil stabilization device, which could be a microwave or convective radiation sinterer or something else. The robotic paver would build a pad that is adequately large for landing accuracy errors, and then travel some tens of kilometers to begin constructing a second pad. By building several pads in the landing elipse, the cross-range needed to get to any pad can be reduced, lessening the demands on the EDL system and improving the chances of safe landing if a problem occurs during entry and descent. Both ascent and descent vehicles could arrive next, landing on two of the constructed pads. Or, the ascent vehicle could arrive two years before the human-tended descent vehicle, but that requires the paver vehicle be sent four years before the humans.

Near-term Precursor Activities: To develop this capability and to verify that landing pads are truly needed, we must acquire a greater knowledge of the regolith down to a depth of several meters as explained in the next section. We need to know the permeability of the soil, the particle size distribution, chemical cohesion, bulk characteristics such as friction angle and density, and the size distribution of embedded gravel and rocks.We also need to know the moisture content of the soil as a function of depth and the depth to solid ice at some sites and develop confidence that we can predict this for other sites. We need to know how the regolith characteristics may vary from site to site within the typical types of terrain that may be selected for landing.

We will also need a knowledge of the mineralogy of the soil so that we can develop simulants for sintering tests. We need to know the susceptibility of the soil to microwaves and its thermal conductivity. If we wish to develop a martian concrete instead of sintering the soil, we need to identify a source of sulfur or some other binder in the local region near the pad and identify methods to excavate and process it.

A precursor mission may therefore include a deep diging capability to obtain core samples to two or more meters depth, and a suite of instruments to measure permeability of the undisturbed sample, moisture content, particle size distribution, and mechanical properties. It may also include the ability to sift the sample to isolate and photograph gravel and rocks. Cores should be obtained at multiple sites. The mission may also include prospecting capability to locate binder materials, and an experiment to make a small sample of Martian concrete. A subsequent mission may include a sintering device, after we better understand how to tune the sintering to the martian minerals. Both concrete and sintered coupons should be tested mechanically and thermally in situ.

It is also highly desirable to observe actual cratering events in the Martian environment and compare them to the predictions of physics simulation software (which has not yet been develop adequately). The precursor mission would then need a video camera operating during descent, and a method of measuring soil ejecta during the event and a method to measure crater size after the event, perhaps. Flying the vehicle multiple times to repeat the experiment is highly desirable.

Terrestrial Experiments: Terrestrial experiments are needed to augment the limited data we can obtain from planetary precursor missions. The exhaust jet of a human-class lander is believed to be capable of digging a jet hole many meters deep, all the way to the length of the supersonic core of the jet (estimated to be about 10 m for Mars cases), and the physics that might ultimately limit that jet hole to a shorter distance cannot be modeled at the present and so cannot be predicted. It can be observed experimentally on Earth if we fly very large vehicles over soil, but physics-based simulation software is needed to extrapolate to the planetary case. An example of a mechanism that might limit the depth of the jet hole to less than the length of an unperturbed rocket exhaust jet is the collapse of the side-walls of the jet hole in the soil, creating a fluidized mixture of soil and turbulent gas so that the supersonic core is broken up and does not reach the full 10 m into the soil. The lack of predictive simulation capability for soil behavior in these extreme conditions, includeng aggregative, turbulent fluidization physics, especially in rarefied atmosphere and reduced gravity, makes it impossible to know how deep the hole will be and how wide the area of collapsing soil and fluidization under and around the lander. The goal of the experimental program will be to identify and understand the relevant physics and to formulate ways to simulate them accurately in a flow code. Tests should first be performed at the lab scale, continuing work that has already occurred at the Kennedy Space Center and the Jet Propulsion Lab over the past decade, including in vacuum chambers such as the Planetary Aeolian Lab and in reduced gravity flights. Tests should also be performed with larger, flying platforms on Earth such as proposed by Red Dragon mission and the XEUS lander development team. Data should also be obtained from the actual Mars environment including larger-scale, more energetic cases. A similar test program has been ongoing for the lunar case, which is dominated by the viscous erosion regime.

Physics Simulation Tools: Physics simulation tools are presently inadequate because soil is difficult to model. An effort to develop simulation tools has been ongoing for 7 years continuously through STTR contracts, SMD-funded LASER projects, and in-house funding at KSC. This work has primarily focused on the lunar case for the needs of the Constellation program and to support protection of the Apollo sites as the Google Lunar X-Prize missions begin to visit them. The ability to model the visous erosion regime around the circumference of the jet is therefore relatively mature, with some remaining knowledge gaps. Deep cratering and fluidization beneath the jet is not mature.

Landing Pad Construction: Grading technologies are being developed with autonomy by JSC and KSC in collaboration with Caterpillar, Inc. A microwave sintering capability has been developed recently through a phase 1 SBIR contract, but it was focused on lunar soil, which has a different microwave susceptibility than martian soil. Convective sintering was developed by Hintze and field tested on the tephra of Mauna Kea. The sintered material demonstrated limited success when subjected to a small scale rocket exhaust, but it did fracture and flake unacceptably if it were an actual mission. Microwave sintering is a difficult process because or runaway melting and because the depth of penetration is difficult to control. Other sintering techniques have similar challenges. Developing a reliable sintering technique requires better knowledge of the microwave susceptibility and thermal conductivity of the soil at a typical future landing site. Another possibility is to locate a source of sulfer and process it into a binder for martian concrete. Other concepts need to be explored, as well.

References: Metzger et al, J. Aero Eng **22**, 24-32; Metzger et al, Craters Formed in Granular Beds by Impinging Jets of Gas, Powders & Grains, Golden, Colorado, July 13-17, 2009. Metzger and Mueller, "Landing Plume Effects," in Mars Design Reference Architecture 5.0, NASA SP-2009-566-ADD, pp. 234-248; Metzger et al, JGR – Planets 116, E06005.