Rocket Exhaust Cratering:
Lessons Learned from Viking and Apollo

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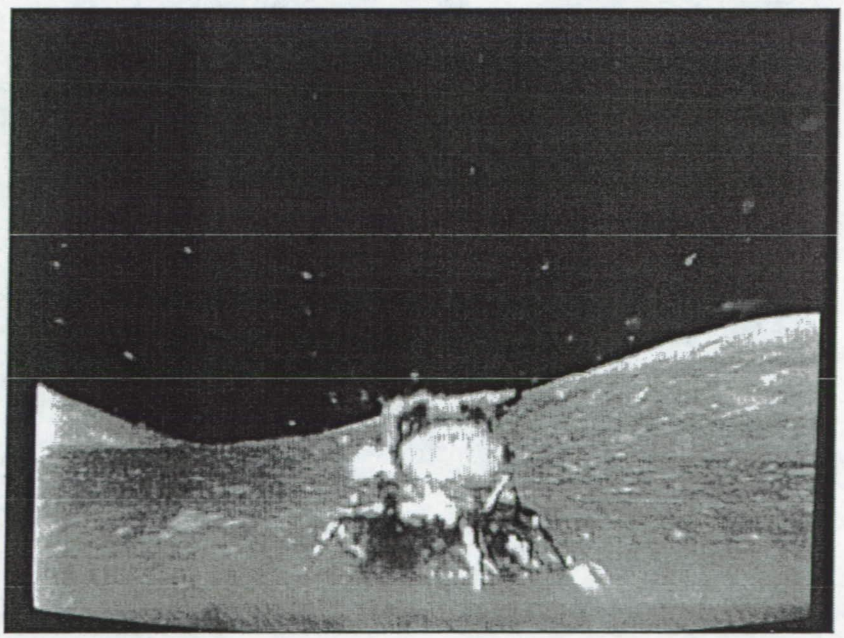

1. THE SIGNIFICANCE OF THE TOPIC

During the Apollo and Viking programs NASA expended considerable effort to study the cratering of the regolith when a rocket launches or lands on it. That research ensured the success of those programs but also demonstrated that cratering will be a serious challenge for other mission scenarios. Unfortunately, because three decades have elapsed since NASA last performed a successful retro-rocket landing on a large planetary body – and ironically because Apollo and Viking *were* successful at minimizing the cratering effects – the space agency has a minimized sense of the seriousness of the issue.

The most violent phase of a cratering event is when the static overpressure of the rocket exhaust exceeds the bearing capacity of the soil. This bearing capacity failure (BCF) punches a small and highly concave cup into the surface. The shape of the cup then redirects the supersonic jet – along with a large flux of high-velocity debris – directly toward the spacecraft. This has been observed in terrestrial experiments but never quantified analytically. The blast from such an event will be more than just quantitatively greater than the cratering that occurred in the Apollo and Viking programs. It will be *qualitatively* different, because BCF had been successfully avoided in all those missions. In fact, the Viking program undertook a significant research and development effort and redesigned the spacecraft specifically for the purpose of avoiding BCF [1]. (See Figure 1.) Because the Apollo and Viking spacecraft were successful at avoiding those cratering effects, it was unnecessary to understand them. As a result, the physics of a BCF-driven cratering event have never been well understood. This is a critical gap in our knowledge because BCF is *unavoidable* in the Martian environment with the large landers necessary for human exploration, and in Lunar landings it must also be addressed because it may occur depending upon the design specifics of the spacecraft and the weakening of the regolith by gas diffusion.

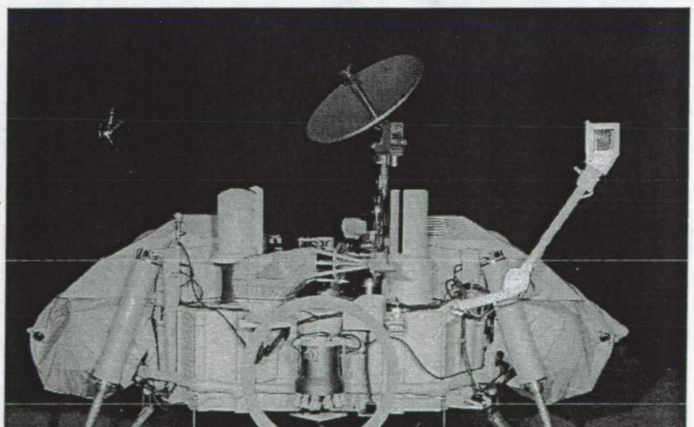

Figure 1.
Each of the three retro-rockets on a Viking lander had 18 small nozzles instead of one large nozzle. The multi-nozzle engine was developed specifically to prevent bearing capacity failure of the regolith beneath the exhaust jets.

Furthermore, cratering (with or without BCF) will be a serious issue when we attempt to land multiple mission-critical spacecraft within short distances of one another, whether on the Moon or Mars. It is possible that the first spacecraft to land may be damaged by the blast from the second spacecraft's landing. The co-landing of critical hardware has never been done before, but we do have some relevant experience because the Apollo 12 Lunar Module (LM) landed 155 meters away from the deactivated Surveyor 3 spacecraft. Portions of the Surveyor were then returned by the astronauts to Earth for analysis. It was found that the surface of the Surveyor 3 had been sandblasted by a high-speed shower of sand and dust particles during the LM's landing. The sandblasting cast very sharp, permanent "shadows" onto the spacecraft which very accurately pointed away from the point on the regolith directly beneath the LM. Judging by the sharpness of the shadows and the lack of curvature allowable for the particles to fit the trajectory, the particles must have been moving in excess of 100 m/s. Furthermore, every cavity and opening in the spacecraft was filled with grit by the high-speed spray. Co-landed spacecraft must be designed to withstand the blast and contamination of the cratering.

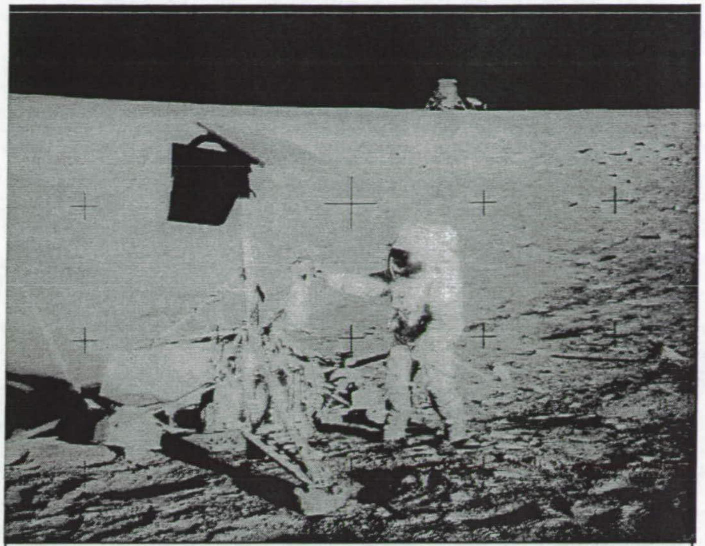

Figure 2.
Surveyor 3 spacecraft with Apollo 12 LM in background. The Surveyor spacecraft experienced substantial blast effects from the LM landing 155 meters away.

Whether or not BCF occurs, and whether or not multiple spacecraft are to be co-located on the surface of the Moon or Mars, we must be able to predict and control the blast effects from both launching and landing the spacecraft. We cannot seriously imagine landing humans on either body without first tackling this problem. To date, however, much of the physics of the cratering phenomena have never been explained (or even adequately observed), and this makes the task of predicting and controlling the phenomena presently impossible.

It is important that the program begin solving this problem now – rather than later in the design cycle of a spacecraft or mission – for two reasons. First, the problem is very complex (as discussed below in this paper) and may take a significantly long period of time to solve. Second, the solutions to this problem are likely to become major drivers of the overall architectures of mission and spacecraft. NASA-generated images such as Figure 3 illustrate this statement. The image shows a large spacecraft that landed on the flat regolith while supposedly making no craters beneath it – nothing more than a little smoothing of the surface. In fact, a spacecraft as large as the one depicted in this image would need such a large thrust to control its descent that it would make very deep craters that would have grown very wide by the time of engine cutoff. Even in the Lunar case with lower surface gravity and an uncollimated exhaust plume it is possible that a

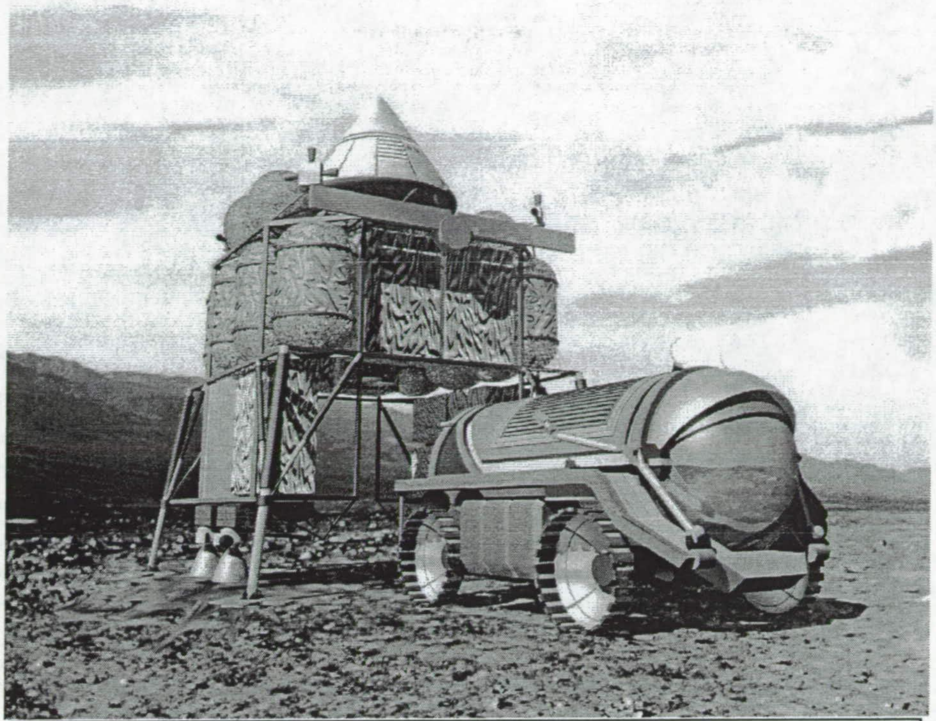

Figure 3.

The lack of craters in this image is unrealistic. The four large diameter jets would impinge upon the surface directly during landing – especially because the engines are mounted almost touching the ground – thereby inducing bearing capacity failure and the vertical jet of soil noted during terrestrial experiments. The spacecraft would likely be damaged by ejected material. Furthermore, the footpads would dig into the sides of the resulting craters, making the spacecraft unstable.

spacecraft this large may induce significant cratering. Exacerbating the problem, the rocket nozzles shown on this spacecraft are few and have large diameters (and therefore very long jet core lengths) and are located very low to the regolith and very close to the spacecraft's footpads. It is doubtful that a spacecraft of this design could be level and stable when its footpads are digging into the sides of the deeply excavated craters that would certainly result. Furthermore, the high velocity debris exiting vertically from the craters would severely damage.the unprotected wheels on the rover and the unprotected rocket nozzles, cryogenic tank, and thermal insulation materials on the lander. This spacecraft is clearly not tenable without significant modification, if BCF and its after-effects are taken into account.

As another example, Figure 4 shows two spacecraft landed some distance apart. Presumably, the spacecraft were drawn so far apart to indicate the safety measures needed to protect them from debris viscously scoured from the surfaces by their neighbor's rocket exhaust gases. However, the image shows no deep craters such as would realistically result from BCF beneath the overpressure of the jets. A soft landing with a spacecraft this size should have effected BCF that is both extensive and violent.

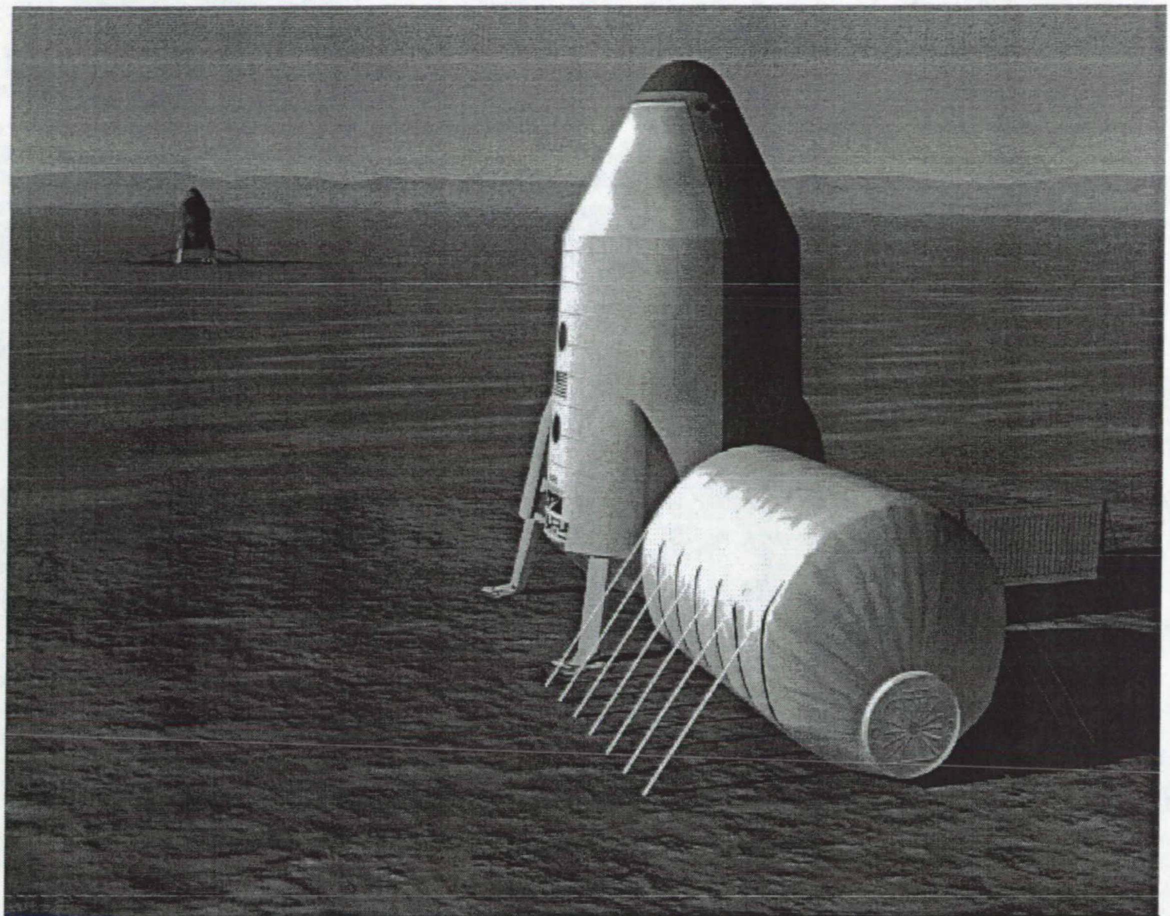

Figure 4.
The lack of deep craters in this image is unrealistic, because BCF would certainly occur with spacecraft this size. Large distances between co-landed spacecraft (as shown or even greater) is necessary to prevent intra-site blast damage. When BCF occurs, the ground jets are deflected upward by its concavity so that particles are swept into steep, high-energy ballistic trajectories. Due to the high terminal velocity of the Martian atmosphere (or it absence on the Moon), blast damage may occur at large distances. Note also that a spacecraft this tall and narrow may not be able to land safely on the cratered terrain.

Considering (1) the size of the spacecraft and the scale of the resulting blast, (2) the high angle of ejection for the entrained debris after BCF occurs, (3) the high velocity of the ejected material, and (4) the low aerodynamic drag of the Martian atmosphere, it is not unreasonable that high velocity debris strikes may occur even at the distance shown in the image. Unfortunately, the distance between spacecraft affects the overall architecture of the mission, because a nuclear reactor or an In-Situ Resource Utilization (ISRU) fuel-production unit on one spacecraft will need umbilicals that reach to its co-landed neighbors, and the mass of the umbilicals may become excessive as the spacecraft are placed further apart. On the other hand, placing the spacecraft closer together may increase the need for blast shielding or blast doors to protect critical hardware, antennas and optics. It is important therefore to determine the necessary spacing of spacecraft as an integral part of the design of the mission.

Figure 5.
A Viking footpad completely buried in the weak soil. This indicates the low shear strength of the soil at this particular location on Mars. Deep cratering would result if a human-scaled lander attempted a retro-rocket landing on this material.

Additionally, one must question whether such a tall spacecraft with a narrow base as shown in Figure 4 can safely land and stand upright on the uneven terrain that will result from the cratering. The cratering may be relatively unpredictable on spatial scales comparable to the base of these spacecraft, depending on the size of heterogeneities hidden within the Martian regolith (such as included boulders or rough bedrock features that lie hidden beneath the layer of loose material). The larger the spacecraft thrust, the more its blast will uncover those heterogeneities and produce an uneven landing surface. This is exacerbated by the fact that Mars has undergone dramatic climatic cycles in the past, and that the quantity of ice in the regolith may have varied appreciably. If the upper layer had been impregnated by ice in the recent geologic past, but now is desiccated to the depth of a meter or two, then it is likely that the desiccated region has low mechanical strength [2] and will be easily stripped away by the cratering. (See Figure 5.) The spacecraft will then be left to land on whatever features have been exposed. In fact, this desiccated layer is the predicted state of the regolith for significant portions of the surface of Mars even at moderate latitudes. It may therefore be important for many proposed landing sites to keep lander spacecraft shorter with a wider base. Of course this is speculative and perhaps overstating the case, but if cratering considerations *do* affect the shape of the lander, then that may in turn drive requirements for the launch vehicle that places the lander into Earth orbit, and it may also drive requirements for on-orbit assembly.

The findings of cratering research may not only affect the design of the spacecraft, but also the profile of the mission because CO_2 ice content or lack of shear strength in the regolith may place limits on the latitudes or regions to which a mission may be directed during particular Martian seasons. Further research may also show us that certain operations should be undertaken by the astronauts on the surface of the Moon or Mars to modify the regolith in the launch environment in order to minimize the damage caused to the nearby ISRU hardware, habitation modules and rovers left behind for future returns to the surface, and to sensitive experimental apparatus that had been setup in the vicinity. This may also drive out the need for particular technology that must be developed prior to these missions, such as a special lightweight mat and anchoring system to serve as the launch pad or as the liner of a trench beneath the rocket.

These examples illustrate that cratering considerations are integral to many other elements of spacecraft design and mission architecture. Clearly some of the concept images generated by NASA in recent years reflect a naive view of cratering phenomena, and this unrealistic view is being incorporated into mission and spacecraft architecture studies. It would be a mistake to allow this trend to persist. Before we land anything larger than a Viking spacecraft on Mars or an Apollo LM on the Moon, and before we co-land any mission critical hardware on either body, we must first understand cratering physics and then include *realistic* predicted cratering effects into the earliest stages of the mission and spacecraft architecture studies. To place this in proper perspective, NASA's experience launching rockets from terrestrial launch pads has shown that ejected debris is a very serious and life-threatening concern, and so the Kennedy Space Center expends significant effort to control this hazard with every launch. Compared to the controlled environment of a terrestrial launch pad, the launching and landing surfaces of the Moon and Mars are completely *littered* with uncontrollable debris, and even far worse their surfaces will become fluidized and interact dynamically with the rocket's plume in ways that are currently unknown and unpredictable because the physics have not yet been driven out. This is a serious safety challenge to NASA's program of planetary exploration. However, it is our conviction that this is a solvable problem given adequate attention. The safety standards of the manned space flight program have evolved such that we will not be allowed to put any less effort into the blast hazards of landing on the Moon or Mars than we put into launching from a controlled launch pad environment on Earth. Eventually the safety standards of manned spaceflight will be enforced. It is important to our planning that they be enforced early in the planning stages because they will have a major impact on the architecture of the program.

2. TECHNICAL BACKGROUND

During the Apollo Lunar program and the Viking Mars program, considerable effort was invested in understanding and controlling the cratering phenomena [1, 3-27]. The problem is more severe on Mars than on the Moon because the gravity is greater, requiring a greater thrust and a lower altitude at engine cutoff, and because the thin Martian atmosphere collimates the supersonic jet of exhaust gas so that it is focused onto the regolith below. The problem is most severe when the length of the jet core (the length at which it is extincted through turbulent mixing with the surrounding atmosphere) reaches the regolith. Then, the static overpressure of the impinging supersonic core exceeds the regolith's shear strength and so BCF presses it down into a concave cup. Experiments on Earth show that the cup then enlarges and explodes. A geyser of rocks and soil are redirected by the concavity of the cup into the vertical direction directly towards the spacecraft, rising as high as 40 feet during the terrestrial experiment. The crater then continues to enlarge while blasting the surrounding area with rocks and sand that have been entrained into the gases that are flowing outward at supersonic velocities.

It was originally predicted that the small pressure caused by the Viking lander's retro-rocket exhaust would have indeed been sufficient to cause BCF, even though the engines were to shut down early and allow the lander to freefall the last 10 feet or so. As a result, the nozzles were redesigned specifically for this reason, to reduce the static overpressure on the regolith [1]. The nozzle of each of the three Viking lander's engines was replaced by 18 little nozzles to enhance turbulent mixing and extinction of the supersonic cores at a length shorter than the lander's height above the surface at engine cutoff. The violent cratering process was therefore successfully avoided and the mission was a success. With the vastly larger spacecraft needed to land humans on Mars and launch them again from the surface for the return to Earth, it will be impossible to avoid these energetic cratering phenomena.

These violent BCF-related phenomena had been observed during terrestrial experiments conducted during the Viking and Apollo eras [3], but the tools that were available to investigate them were very primitive compared to what is available today. As a result, the processes that occur inside a cratering event have never actually been observed or described, and we have not identified some of the organizing principles which result in the timing and scale of the various processes. Nevertheless, the investigators pieced together a rough description of the processes, which follows. A detailed review of those previous studies is found in Appendix A.

As illustrated in Figure 6, a standoff shockwave sets up just above the surface of the grains and the gases form a stagnation region beneath this shockwave. The gases entering the stagnation region then move radially outward across the surface and the flow eventually becomes supersonic again at some finite radius (the sonic line). The gases and granular medium interact at least three ways: (1) radial flow of gas across the surface of the grains, (2) static pressure of the gas upon the grains directly beneath the jet, and (3) diffusion of gases through the pores of the grains. These all contribute to setting in

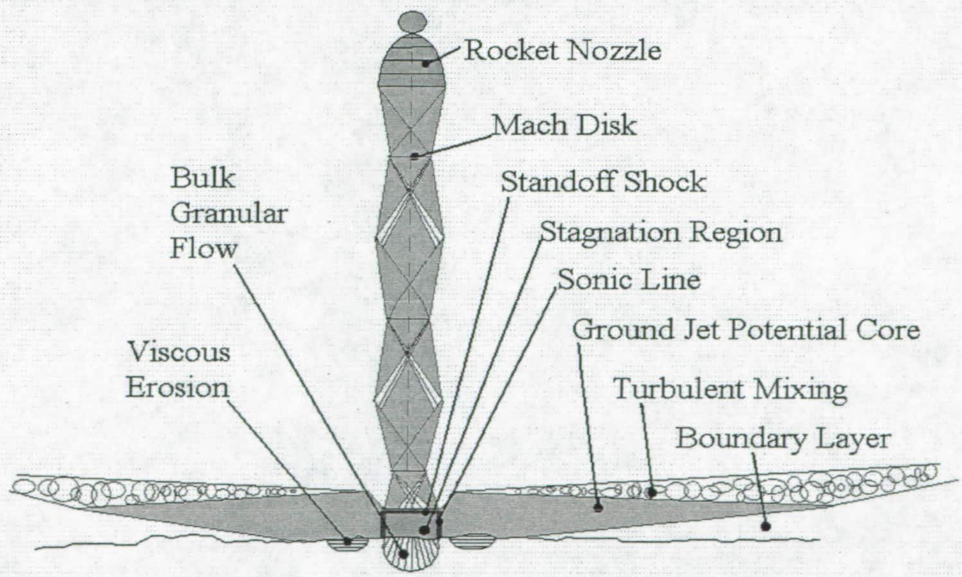

Figure 6.
Plume interactions with the regolith for the Martian (atmospheric) case.

motion two competing granular flows which interact dynamically during the subsequent evolution of the shape of the granular surface.

First, the surface erodes viscously as the surface grains are entrained into the flow and carried radially away. This process by itself causes a shallow annular depression to form in the region of maximal traction, and left to itself this ring will grow outward and inward until it becomes a shallow crater.

Second, if the static overpressure is sufficient to exceed the bearing capacity of the granular surface, then the grains begin a bulk flow by shearing according to a geometry that is determined by the distribution of pressure on the surface and the propagation of these stresses beneath the surface. This pushes the initial cup down into the surface. Simultaneously, the shear strength and bearing capacity of the granular matrix is reduced as the static pressure drives the gas between the grains, increasing the granular pore pressure and helping to lift the grains up and over one other. This is illustrated in Figure 7. Therefore, the onset of the granular flow is dependent upon both the magnitude and duration of the impinging jet, and also upon the mechanical properties and porosity of the grains. Furthermore, not just the onset but also the geometry of the granular flow is determined in part by the properties of the gas diffusion through the grains, because the mechanical properties of the granular matrix are modified locally in terms of the pressure gradient and flow field of the diffusing gases.

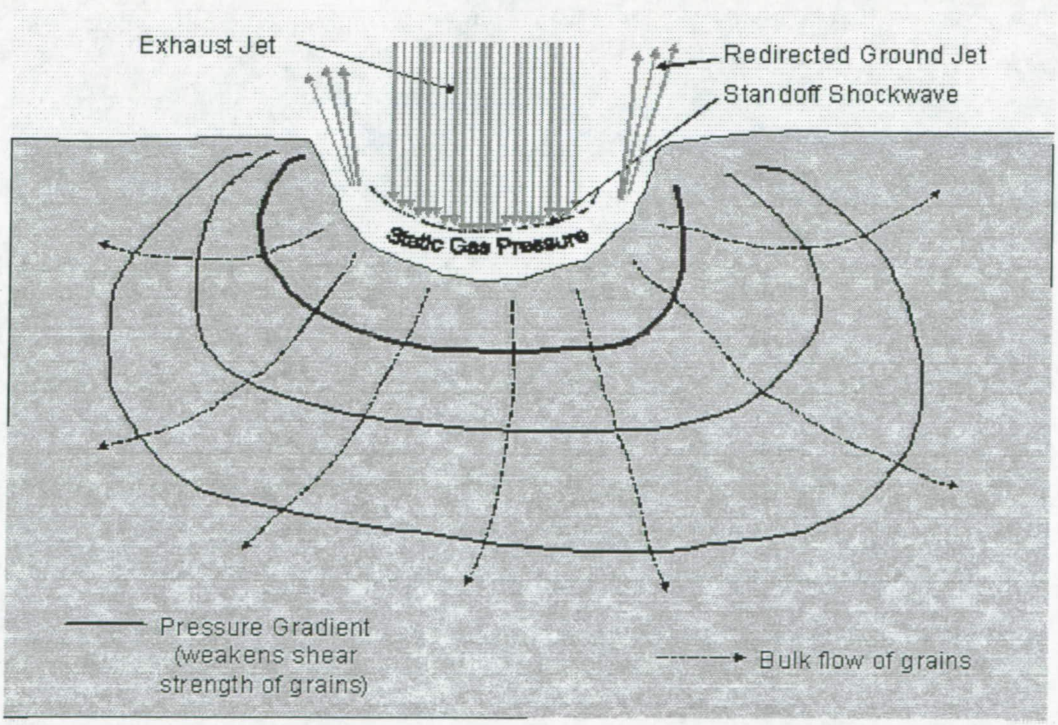

Figure 7.
Diagram of gas diffusion enhancing bearing capacity failure.

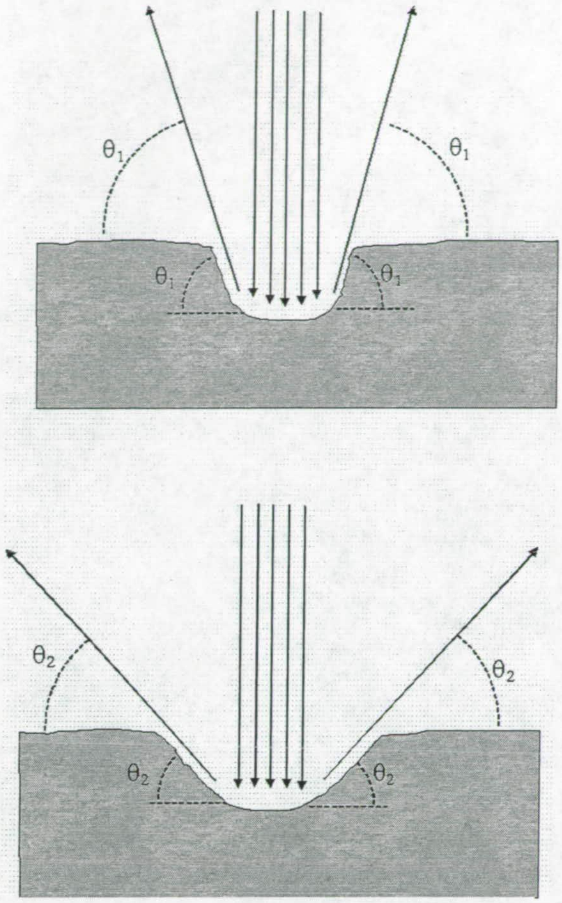

Figure 8.
Ejection angle depends on crater shape.

These two flow processes then, one a viscous flow of surface grains and the other a mechanical flow of grains in the bulk, interact with one another dynamically along the interface as mediated by the gaseous flow field setup by the shape of the interface. Experimentally it has been shown that the granular flow due to the bearing capacity failure results in the formation of a small cup in the surface, and this cup is complete in less than 300 msec. This disrupts the radial flow field by redirecting the jet upward and dramatically changes the regions of surficial shear stress so that a fast vertical flow of material ensues. Experiments have shown a geyser of soil ejected 40 feet into the air. It is unclear to us whether the static pressure inside this cup enlarges the cavity until it blows the sides out and up (some researchers [3] have assumed that this happens), or whether the observed geyser of soil is driven entirely through viscous entrainment along the surface.

Next, the explosive spray of material abruptly stops and viscous entrainment continues at a much slower pace, so that the hole that formed in the first 300 msec is only doubled in the next 5 seconds. The physical cause of this abrupt change of rates has not been determined, and the effects have only been roughly measured in terms of the quantity of soil ejected and the timing of the cessation of the fast event.

The flow that viscously entrains the ejected material must certainly be a function of the shape of the crater and therefore the ejecta flow field evolves with the crater as illustrated in Figure 8. Predicting the damage to surrounding hardware therefore depends upon the prediction of the evolution of the shape of the crater. Likewise, determining the safe distance away from a landing rocket depends upon the evolution of the crater shape.

Furthermore, the diffusion of gases between the grains has also sometimes caused an annular eruption surrounding the central impingement site of the jet. This is because the diffusing gases set up pressure gradients in the medium which on their own are sufficient to lift the grains against gravity. When the jet is extinguished a central eruption sometimes occurs, as well, due to the diffused gases rushing back out through the pores of the medium. Molecular contamination noted on returned portions of the Surveyor 3 spacecraft had a different spatial distribution than the physical damage from cratering ejecta, and we believe its spatial distribution reflects the occurrence of a central eruption after engine shutdown.

Landing a spacecraft on a regolith with a shallow sub-surface layer impregnated by CO_2 and/or water ice, such as we expect to find between the mid-latitudes and poles of Mars, will result in sublimation of the ice into the pores of the grains due to the transfer of heat from the diffusing rocket exhaust. As a result, we expect there to be a severe reduction of the shear strength of the surface in the desiccated layer of soil overlying this ice and a dramatic enhancement of the cratering process [See Appendix A, section A.6]. On the other hand, the existence of ice may tend to cement grains together and plug the pores against diffusion of the exhaust gases, which would tend to reduce the cratering effects. As a result, until further research is performed we cannot yet predict the effects on cratering due to carbon dioxide and water ices adsorbed into the regolith. We do not know the microstructure of the ices, whether they coat the grains, cement the grains together, or completely fill the pores. We do not know how the microstructure may vary with depth into the regolith or with season, latitude, or specific terrain characteristics. Furthermore, we do not know how the ices will affect the engineering properties of the soil when frozen or when sublimating or melting. Finally, we do not know how the timing of sublimation will be related to the cratering process as a function of location below and around the crater, and so we do not know how the sublimation will contribute to the overall process.

We also have little understanding of the composition of the regolith at the scale of 1 to 2 meters depth. We have excavated the top several centimeters at five specific locations during the two Viking missions and beneath the wheels of three rovers, and we may obtain data on much larger scales through the use of ground penetrating radar on orbiting spacecraft, but I do not know of any plans in the program to really investigate and characterize the engineering properties of the regolith at the scale relevant to exhaust cratering.

3. RECOMMENDATIONS

The NASA exploration program should undertake the following elements of focused research to understand, model, predict and control rocket exhaust cratering:

1. Research and development of a modeling/prediction capability for gas/regolith interactions in the Lunar environment. This should include the gas diffusion blowout and BCF enhancement effects that have been observed experimentally and which will be a critical component of the cratering if the spacecraft uses pulsed thrusters (e.g., the 2007 Phoenix lander). The goal should be to develop a blast effects prediction tool that will be used by spacecraft and mission designers.

2. Basic research aimed at understanding the interrelationships of the several phenomena that occur inside a BCF event, to understand the interrelationships of their scaling and timing and to understand dependencies upon relevant parameters such as grains size, gravity, atmospheric pressure, jet core diameter, etc. It is probably necessary to perform numerical simulation in order to "see inside" the cratering event under a variety of conditions in order to deduce causal and scaling relationships and to map the parameter space. Experimentation is also needed to benchmark and validate the analysis and simulation. KSC was pursuing funding (Code-U Fluid Physics) for similar research under a partnership with Sandia National Laboratory, which has expertise is the numerical simulation of explosive blasts in geomaterials. However, because Code-U has been restructured there is no longer any provision within NASA to pursue this line of research outside of Code-T.

3. Basic research to understand the mechanical properties of Lunar (and Martian) soil simulant with adsorbed water (and carbon dioxide) ice and how those mechanical properties change as heat transfers and the ices sublimate. Note that civil engineering for cold regions has experience studying soil with water ice, but there is no scientific heritage in studying soil with carbon dioxide ice. There is furthermore no experience in studying soil with ices adsorbed in the manner they shall be found on Mars. This could be performed at a facility such as the several Mars Atmospheric Chambers at KSC or at other similar facilities in the agency. KSC is currently pursuing funding for related research (Code-S, Planetary Geology and Geophysics) under a partnership with the U.S. Army's Cold Regions Research and Engineering Laboratory, which has extensive experience studying frozen soils.

4. A sequence of hot-jet cratering experiments with ices adsorbed in soil simulant in order to demonstrate the integrated cratering / ice sublimation and verify that the relevant processes have been identified for the sake of developing a software model.

5. Develop a generalized software model to incorporate all the relevant physics (including BCF and ice) effects so that predictions can be made for various spacecraft designs and landing sites. Development of the model should be evolutionary and parallel the other parts of the research program. This model will then become a spacecraft design tool and mission development tool. It will also be a critical resource to formally certify that the risks of losing of life and vehicle are acceptable and to certify that the mission is ready to proceed. Due to the long time needed to develop this tool into a truly useful resource, the basic development should begin 10 years or more before the planned mission.

6. Planetary science research to characterize the regolith at several potential landing sites in the relevant scale of depths aimed at understanding its composition and mechanical properties and the seasonal variability of its adsorbed volatiles. This may involve the addition of instrument packages, shovels or augers on existing missions or the development of a dedicated mission – possibly a sample return. These data would then serve as input to the software model to make realistic predictions. It may also serve to uncover some previously unknown features that could exacerbate cratering at particular landing sites. However, the results of the above items will determine whether this item is critical.

7. A series of hot-fire cratering tests should be done with the qualification unit rocket engines designed for the Mars landing. These will calibrate the predicted effects to the actual hardware to validate the modeling.

8. Computational Fluid Dynamics of the full configuration of the landing spacecraft in order to understand the interactions between engine jets and the composite flow field beneath the spacecraft.

9. Scale model landing tests of the flight configuration spacecraft onto scale model soil simulant and comparison with the software model predictions

10. If the results of the previous effort confirm that cratering is a serious problem, then it will probably be necessary to perform a full-scale but unmanned landing on Mars of the final flight version of the spacecraft intended to carry humans. (It is difficult to see how the program will buy-down the risk of landing in any other way if we know that the cratering will be violent and severe, since landing failure will probably be fatal.) This landing would occur in the presence of instrumentation previously emplaced during a robotic mission. Instrumentation on the lander and on the surface of Mars would document and measure the cratering to validate the predictions, to ensure that the spacecraft does not lose attitude control due to asymmetrical impulses from the ejected regolith striking its bottom surfaces, to verify that the damage to the bottom of the spacecraft is acceptable, to verify that the spacecraft does not tip due to its legs settling into uneven craters, and to measure the airborne debris flow field for the purpose of protecting surrounding hardware in the actual mission.

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APPENDIX A: REVIEW OF PREVIOUS RESEARCH

A.1 Surveyor 5 Lunar Soil Erosion Experiment

The Surveyor 5 spacecraft executed a firing of its vernier engines for 0.55 seconds to study the effects upon the lunar surface. There was evidence of both viscous erosion and gas diffusion blowout, as expected. The report describes the observed effects upon the surface and the locations of observed ejecta. The authors note that gas diffusion blowout is expected to eject soil in a vertical direction, whereas viscous erosion (in the absence of pressure cratering or other surface distortions) should tend to move it in a mostly horizontal direction [4].

A.2 Apollo-Era Studies

During the Apollo and Viking programs, NASA undertook a series of investigations to understand and quantify some of these physical phenomena. These studies discovered that the cratering event is not a single process, but a complex set of solid/fluid interactions which to this day have not been accurately described or explained. Even a very basic, qualitative physical explanation is lacking for some aspects of the cratering event. During the Apollo and Viking missions it was not necessary to fully understand these phenomena because the spacecraft engines were designed to prevent the most energetic of these processes from occurring. That is, the pressure developed upon the Lunar or Martian regoliths in the stagnation region of the impinging jets was kept sufficiently low to prevent the bearing capacity failure of the sand which otherwise would have occurred. This was possible in the Lunar landings because in the absence of an atmosphere the exhaust gases spread out significantly before striking the surface, and because the small size of the Lunar Excursion Modules and the weak Lunar gravity made it possible to use a lower thrust. The Viscous Erosion mechanism was therefore the only important mechanism for these landings, because the exhaust pressure on the lunar regolith was not very high relative to the regolith's strength. It turned out that the lunar regolith has a very loose layer of dust which is a couple inches thick, and beneath this is a much stronger layer which was more or less unaffected by the lunar landings. This was the suspicion at the time, based on observations from the Surveyor landings and from the theoretical understanding of the moon's history.

Leonard Roberts of NASA/LaRC authored a number of papers on the subject of viscous erosion of the lunar dust between 1963 and 1966 [5-8]. His method was adopted in 1966 by J. S. Dohnanyi of Bellcomm, Inc., to apply analytically to the Lunar Excursion Module (LEM) engines [9]. Norman S. Land, Leonard V. Clark and others published a series of experimental studies of this viscous erosion between 1963 and 1966 [10-13] Roberts derived a set of equations which calculate the region of maximum shear force on a flat dust-grain layer, and calculated the quantity of material which would be entrained into the gas flow as a function of radial distance from the center of the exhaust. The region of maximum shear force turned out to be a ring some distance out from the center of the exhaust. This is far enough out that the gases have a large radial component of their velocity, but are not yet too widely spread so as to reduce the density too much. This method predicted that some quantity of grains would be kicked up during the landing, but that astronaut visibility would not be too seriously affected. During the Apollo program, the theoretical predictions turned out to be largely accurate. However, because the Apollo Lunar Modules (LM's) did not follow a straight vertical path but traveled horizontally across the terrain while descending, the amount of dust kicked up depended upon how long the LEM stayed over any one spot (horizontal velocity) as a function of altitude. Some landings kicked up more dust than others did, with Apollo 12 being the worst.

Very few studies have been done on the other exhaust cratering mechanisms besides viscous erosion. Nevertheless, probably the most complete and best study to date, "Soil Erosion by Landing Rockets," was published during this Apollo-era in 1966 [3]. This study discussed viscous erosion but focused primarily upon bearing capacity failure (BCF) with some emphasis also upon gas diffusion (but only insofar as it modified the soil characteristics that affect pressure cratering). A large amount of experimental work was performed, although the methods of measuring and quantifying the results were very primitive by modern experimental standards, and due to the theoretical and computational limitations of that time the work was largely oriented toward an estimation of the magnitude of the effects rather than an analytical description of the physical relationships. Cold gas jets and hot engine firings were used to create craters in sand and clay, and the resulting craters were measured for various dimensions. The data were compared to identify significant parameters and relationships. Several approximate methods or models to analytically estimate crater dimensions and compared them to the experimental data. Only crude approximations and very rough models were used to analyze the physics because the actual equations were too difficult to solve analytically at the time. These rough models included an analogy to the classic civil engineering cone penetrator test, a refinement in which the gas diffusion was assumed to have reached steady state to weaken the soil for the cone penetrator, a purely elastic model of the sand to provide an order-of-magnitude estimate of the width of sand that would fail and be removed in the initial crater formation (probably more like a guess than an estimate), and a yield-strength analysis using the equations of soil mechanics to calculate the stresses as a function of distance beneath a point load to estimate crater depth. The approximate methods were valuable at the time because they provided physical insights into the cratering process which contributed to the description presented in the introductory section, above. However, they were not able to observe or measure the actual physical processes inside the crater-forming event.

A.3 Gas Diffusion Blowout Studies

Another important study in this Apollo era was authored by Scott and Ko [14] in 1968. It was apparently the first paper to identify the gas diffusion blowout which occurs in an annular region around the main crater and also centrally when an engine abruptly shuts off. The Hayes report (described above) was concerned only with how gas diffusion enhances the pressure cratering mechanism, but this paper treated the gas diffusion as a separate cratering mechanism, independently capable of ejecting material from the regolith. Investigators first performed experiments with actual rocket exhaust impinging on a bucket of rocks and soil as a high-speed camera photographed it. They discovered that radial diffusion of pressure could eventually blow out a toroidal region around the exhaust jet, because the high pressure would diffuse outwardly to a region where the static exhaust pressure on the surface was less. They also found that when the rocket was shut off a blast of soil shot up the center of the crater toward the rocket nozzle.

This phenomenon derives from the existence of the surface itself, resulting in a discontinuity in the gas flow characteristics afforded by the media on either side. The gas above the surface propagates relatively unhindered through the ambient atmosphere, and so it crosses a sonic line and travels away supersonically. It is constrained by the ambient pressure to travel along the surface as a ground jet. This ensures the existence of a low-pressure boundary condition along the top of the soil everywhere beyond a short radial distance from the impingement point. Meanwhile the gases beneath the surface propagate slowly and viscously through the soil's pores and are not constrained to travel just along the surface. This allows a three-dimensional pressure gradient to develop and grow, subject to the two-dimensional boundary conditions along the surface and the requirement that it approach hydrostatic equilibrium toward infinite depth. Thus, pressure will decrease in the downward direction directly beneath the jet, but some distance radially away from the impingement point it will first increase and then decrease again. If the gas viscosity in the soil's pores allows the vertical pressure gradient to actually exceed the weight density of the soil, then there may be some point at which the absolute pressure exceeds the vertically integrated weight density, the downward pressure from above the surface, and any cohesive stresses in the soil all combined. If that condition is achieved, then the regions above all such points will be lifted out by the pressure.

Scott and Ko took a numerical, finite-element approach in their research to model these effects. Whereas the Hayes report sought a solution of only the steady-state pressure to see how it enhances BCF, the gas diffusion blowout mechanism is inherently transient. As with the Hayes study, the gases are assumed to flow isothermally, and the result is Darcy's Law. This reduces to Laplace's equation in the steady state case, which is what the Hayes report had derived and solved. The numerical iterations demonstrate that pressures develop in such a way that certain regions of soil near the surface become unstable. That is, their weight is less than the upward force due to the gas pressure. The calculations successfully demonstrate instability over a toroidal region during jet firing and over a large central region after jet cutoff.

A later paper by Hon-Yim Ko [15] in 1971 provides an improved analysis of how gas diffusion enhances BCF. Ko also describes a finite element program to analyze both gas diffusion and BCF, but apparently the program did not yet produce sufficiently accurate results due to the iteration intervals that had to be used in the calculations with the limited processing capabilities available at the time.

A.4 Surveyor 3 Analysis

When Surveyor 3 landed on the Moon, its vernier engines thrusted at 90% of the spacecraft's lunar weight during the final descent. They failed to cutoff due to a hardware failure, and as a result, the spacecraft rebounded from the surface twice, translating about a foot in distance with each hop. The engines were shut down by a ground command about a second before the third (and final) touchdown. [16] Two and a half years later the Apollo 12 Lunar Module (LM) landed 155 meters away from the Surveyor 3 spacecraft [17]. The Apollo astronauts retrieved parts of it and returned them to Earth for analysis Surveyor 3 to understand the effects of its exposure to the lunar environment. Several studies [18-23] revealed two interesting features. First, a polished aluminum rod had been pitted by particles during the Surveyor landing. A number of the pits still contained the lunar particles including plagioclase, possibly some clinopyroxene, and a mixture of glass and fines. The same rod was also coated with a molecular contamination which investigators concluded was not of lunar origin, and therefore must have consisted of some unburned hypergolic engine reactants (although this was not directly confirmed). Interestingly, while the pitting and the engine reactants were distributed similarly in terms of their circumferential orientation on the rod (that is, peaked highest on the side facing the regolith), they were not distributed similarly in terms of their position along the rod's length. The molecular contamination was concentrated toward the inboard end which was higher and therefore further away from the regolith, but closer to the spacecraft's engine. The pitting was concentrated toward the outboard end which was lower and therefore closer to the regolith, but further away from the spacecraft's engine. This difference was a mystery to the investigators, because the same exhaust which propelled the particles also contained the molecular contamination, and there is no lunar atmosphere to make the ballistic trajectory of a small molecule different from that of a very large piece of sand. We have hypothesized, based on the above studies, that invoking two different cratering mechanisms explains this. Since the spacecraft bounced twice, the engine came very close to the ground two times, and the lower portion of the rod would have been sandblasted by the viscous erosion both times. Particles ejected by viscous erosion would be concentrated in solid angles close to the ground, thus blasting mostly the lower end of the rod. There should not have been sufficient pressure for BCF to occur, and the gas diffusion blowout mechanism would not hurl particles with sufficient velocity to pit the rod, so the pitting would reflect the spatial distribution of viscous erosion, not BCF or gas diffusion.

The molecular contamination, on the other hand, should reflect the distribution of the gas diffusion blowout. It would have occurred gradually two times as the spacecraft rebounded from the surface, thus translating the center of the exhaust pressure and allowing the previously loaded regions to depressurize, and it would have occurred one time more dramatically when the engines were suddenly cut off. We do not know how high the spacecraft was at engine cutoff, but regardless, the exiting gas from all three events would have dispersed nearly isotropically within the half-sphere above the regolith, emanating from the small circular regions which had been subjected to the most static pressure. This would preferentially contaminate the end of the rod that was closer to the spacecraft, because it was oriented more normally to the pressurized part of the regolith (and it was probably closer to that region, as well). There would actually be less contamination at the end of the rod that was lower and nearer to the regolith since that part of the regolith was further from the engine nozzle and had not been highly pressurized with gas. That lower end of the rod was oriented obliquely toward the region that had been pressurized (and was probably farther from it, too). Thus, we have hypothesized that the interrelated jet-induced cratering phenomena is responsible.

A second interesting feature of the hardware brought back from moon is that the Surveyor had been sandblasted by a high-speed shower of sand and dust particles during the LM's landing, too. The sandblasting cast very sharp, permanent "shadows" onto the spacecraft which very accurately pointed away from the point on the regolith directly beneath the LM, 155 meters away. Judging by the sharpness of the shadows and the lack of curvature allowable for the particles to fit the trajectory, the particles must have been moving in excess of 100 m/s. Some particles were captured in a cavity of the Surveyor's camera when they entered through an inspection hole, and the particles are available for analysis so that grain size distribution may be calculated. This would provide data to fit to an analytical model of Lunar viscous erosion if it were deemed important to do so.

A.5 Viking-Era Studies

A series of papers were authored in response to the need to land spacecraft on Mars. These papers were primarily interested in the engineering question of spacecraft design with the goal of avoiding BCF altogether and keeping gas diffusion blowout to levels that could be safely ignored. Thus, the physical understanding of exhaust cratering was not advanced much during this impetus.

Roberts had derived the model for viscous erosion for the case of lunar landings where there is no atmosphere. Hence, every exhaust jet is necessarily underexpanded at all times. In contrast, rockets designed to launch from Mars will probably be optimized for some altitude above the surface, and hence the jet exhaust at the time of launch would be overexpanded and tightly collimated by the thin Martian atmosphere. Roberts' model therefore needed to be modified to some degree before it could be applied to Mars.

When Mariner IV discovered that the Martian atmosphere is far thinner than scientists had previously believed, K. M. Forman authored a paper [24] which was apparently the first to discuss the feasibility of using retro-rockets instead of parachutes on Mars. It discussed the characteristics of the rocket plume impinging upon the surface and included the collimating effect of the Martian atmosphere.

A second paper [25] described an experimental study that was done in the 60-foot vacuum sphere at the Langley Research Center. A scaled Viking lander was lowered over a soil composed of uniform glass beads. The lander fired cold gas jets that were scaled to produce the same relative interference between the gas jets that would have occurred if they had been hot exhaust jets. No theoretical work was done, but craters sizes and cratering onset times were measured as the lander descended along a realistic flight profile. The investigators determined that thrusters canted inward would produce less cratering than thrusters pointed straight down. A weakness in the study is that the investigators did not increase the jet thrusts with each increase in cant angle. Such increases would be needed to make up for the corresponding loss of lift that result from vectoring the thrust away from the vertical direction. This puts some doubt into the results of the study, but the author noted that analytical work may be done to account for it.

There were several other experimental investigations done by various researchers during this period, and there were some analytical investigations of viscous erosion and the BCF onset performed at the Martin Marietta Corporation and the University of Colorado. This includes Ko's paper, mentioned earlier. A Viking-related study performed by the Martin Marietta Corporation and authored by G. L. Romine, T. D. Reisert, and J. Gliozzi [1] addresses exhaust cratering both theoretically and experimentally. The paper may be divided into three parts. The first is background. It begins by reviewing the known mechanisms behind the exhaust cratering phenomena, by summarizing previous analytical and experimental studies, and by describing the authors' experimental study of the existing Viking lander nozzle design. The background review described all three known cratering mechanisms but the rest of the paper focuses on viscous erosion. This is because the goal of the Viking program was to keep surface pressures low enough to avoid the other two cratering effects. The authors performed the experimental study of the existing lander nozzle in order to get a baseline of its cratering effects so that comparisons could be made after the nozzle was redesigned. We discern the following characteristics in the data as the rocket engine was translated lower or higher above the impingement surface:

1. a cyclic pattern of pressure spikes due to the Mach diamond structure in the jet;
2. diminishing amplitude of the pressure spikes due to a weakening of the Mach disks further from the nozzle;
3. increasing amplitude of the pressure spikes over time due to increasing ambient pressure in the test chamber which better constrains the jet;
4. a phase inversion of the pressure patterns at some fixed radius from the jet axis and which allows the width of the Mach diamonds to be inferred;
5. shortening of the Mach diamond structure as the ambient pressure increases;
6. narrowing of the Mach diamond structure as the ambient pressure increases; and
7. a decrease in core length as the ambient pressure increases.

Because the lander design had originally used a conventional bell nozzle for each of its three engines, but the previous analytical and experimental studies showed that a conventional bell nozzle would affect the surface too much beneath the lander, the second part of the paper was a trade study to pick an alternative nozzle that would drastically reduce the amount of surface pressure on the ground. A multiple-nozzle design with 18 canted nozzles (along with two other candidate nozzles which are not described in the paper) was chosen for the third part of the study. The multiple nozzle design breaks the jet into many little independent jets which are shorter due to the smaller individual nozzle scales. The jet exhaust cores die out by mixing with the ambient atmosphere before reaching the Martian surface. Thus, only turbulent air impinges the surface instead of the high-speed jet core, and this vastly reduced the pressure on the surface. The third section of the paper then is a detailed experimental study of the multiple-nozzle design. The authors described in detail how the two types of simulated Martian soil were prepared and instrumented. They compare the results that were obtained with the analytical predictions and note that the comparison is favorable. Along slopes facing the engine, the smaller grained material was removed leaving only material with grain sizes above some cutoff value. The resulting "armor" of course material on the surface prevented further erosion. Nevertheless, it is the larger particles, among all those below the cutoff size, which are the ones to erode most quickly. The material largely follows the streamlines, flowing significantly upwards only if a surface crater deflects the flow upwards (as would happen if BCF could not be prevented). The authors also note that subsurface heating seems to be entirely due to diffusion of the hot gases between the grains rather than conduction across the grains, and they provide a modified version of Roberts' analytical description of viscous erosion. Their analysis is based on lifting of a bulk mass of material rather than the lifting of individual particles. They base this on physical reasoning that when the entire layer is lifted, then the jet flow will winnow out the particles below the cutoff size, allowing the larger ones to drop back to the surface. This physical insight allows the analysis to include realistic soil models by summation over a distribution of grain sizes.

Finally, A paper by R. E. Hutton, H. J. Moore, R. F. Scott, R. W. Shorthill, and C. R. Spitzer [26] described the observed disturbances that were actually caused by the Viking retro-rockets landing on Mars. The paper makes conclusions about grain size for some of the types of surface materials on Mars by comparing the observed erosion with the experiments that had been previously conducted on Earth.

A.6 Mars Polar Lander Studies

Due to budget restrictions, little work was done to characterize the expected exhaust cratering during the Mars Polar Landing mission despite requests from the Lockheed Marietta Astronautics propulsion group [27]. One paper by LMA and Primex Aerospace employees [28] describes the MPL retro propulsion system and briefly discusses the possible alteration of the landing site. The paper explains that the MPL project is not concerned about site alteration to the same degree as the Viking project because the MPL's science objectives will not be as adversely affected by it. For MPL, it was thought that the MARDI camera might produce one or two pictures of the landing site during final descent and this implies that the actual cratering effects might be quantifiable after the fact. The paper notes that the carbon dioxide and water ices which were expected to cover the surface would sublime under the hot rocket exhaust, and "the overall cratering effect of MPL 98 is expected to be greater than that of Viking, but it is considered an acceptable risk to the mission" [28]. The analysis was not very detailed, however, for the MPL failure report says, "No work was done on this potential threat to MPL." [27]

Also, LMA performed a CFD analysis [29] of the MPL's engine plumes to understand how the exhaust jets would interact beneath the spacecraft. While the MPL thrusters were pulsed in order to control the average thrust, this study analyzed the case where all thrusters were firing simultaneously, as this was considered to be the worst case. However, the authors also used a transient-analysis modeling technique to estimate the overshoot in the surface pressure each time an engine is started and then stopped. The startup spike is actually two quick spikes and is the result of shock wave impingement upon the ground before reaching its steady state above the ground. The shutdown spike is a concentric collapse of the jet flow. These spikes are on the order of only 15 milliseconds in duration but are three to four times the steady state pressure during engine firing. Perhaps the high pressure is the reason that the JPL Special Review Board considered the use of steady state pressures to be optimistic instead of worse case [30].

We have also analyzed some informal calculations that compare the scaling of the MPL spacecraft to the Viking nozzle selection study discussed above. We concur with the predictions that, unlike the effects of the Viking mission, BCF should have occurred (had the MPL made it to that stage in the landing) or did occur (if it did make it to that stage). The jet cores were long enough to impinge directly upon the Martian surface and the pressure in those cores was nearly two orders of magnitude higher than Viking's predicted BCF threshold. However, this may have been limited to very small volumes of soil due to the transient nature and spatial variability of the overpressure on the soil. Further analysis would be needed to quantify whether this was an important concern.

We have also identified ice adsorbed into the regolith as an exacerbating factor which potentially may have lowered the BCF threshold to a value far below that of the Viking landing sites. H. Houben predicted [31] that the steady-state concentration of adsorbed water in the regolith near the Mars Polar Lander site (75 degrees South, approximately) is 0.2 to 1 kg per cubic meter. Even at the lower limit, we can calculate that just one cubic meter of soil would outgas about 10,700 liters of steam (at 10 deg C and 6.1 mb) when subjected to a hot rocket exhaust. This would undoubtedly enhance the cratering effect to say the least. Given this order of magnitude, moisture content of the regolith ought to be considered, even for landing sites at mid-latitudes or locations that are more equatorial. In fact, if the adsorbed water is converted to vapor by the impinging exhaust gases, and if it is confined to the pore space between the grains, then it would create approximately 26.1 – 130.7 kPa of pressure multiplied by the inverse of the porosity. For example, if the porosity is 40%, then the pressure is 65.4 – 326.8 kPa. This compares to a mere 5.6 kPa at a 1 meter depth due to the weight of the soil, or only 56 Pa at a 1 cm depth. (This assumes a soil density of 1.4 g/cm^3, which is based on Viking measurements.) Therefore, the effective normal stress, which is stress minus pore pressure, will completely vanish and the grains will be lifted apart by the water vapor. The soil will be blown out or will at least shear freely wherever its adsorbed water has been converted to vapor (neglecting any chemical cohesion between the grains). This has the potential for deep cratering.

If the pores are closed due to the ice itself, then the gases will not be able to diffuse into the regolith and heat the subsurface ice. (Tests for Viking show that heat transfer was predominantly by gas diffusion, although those tests used an iceless soil.) In that case, only the top layer of ice will melt allowing the top layer to viscously erode. Thus, the soil will be removed in layers, and the effectiveness of this removal will depend upon the rate at which thermal energy is transferred to the ice. On the other hand, if the Martian season is such that water is in the process of desorbing from the regolith, then the pores will already be open to some depth, and the diffusion of hot gases into those pores will vaporize the remaining ice and assist the viscous removal of the soil – if not blowing it out entirely. For the case of the Mars Polar Lander, this may have been the case. The MPL arrived at Mars very near perihelion when porosity should have been increasing. Again, however, the quantity of blown-out soil might have been very small due to the transient nature of the overpressure. Further analysis would need to be performed to quantify it.

A.7 Phoenix 2007 Lander

This section has been removed from the paper to avoid possible disclosure of proprietary data. No insight into the phenomena has been omitted by removing this section.