SPACEX STARSHIP LANDING SITES ON MARS. M. Golombek[1], N. Williams[1], P. Wooster[2], A. McEwen[3], N. Putzig[4], A. Bramson[5], J. Head[6], J. Heldmann[7], M. Marinova[8], and D. Beaty[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, [2]SpaceX, Hawthorne, CA, [3]University of Arizona, Tucson, AZ, [4]Planetary Science Institute, Lakewood, CO, [5]Purdue University, W. Lafayette, IN, [6]Brown University, Providence, RI, [7]NASA Ames Research Center, Moffett Field, CA, [8]M[3] Interplanetary, Santa Monica, CA.

Introduction: Building on work with a broad spectrum of the Mars community, SpaceX began working with scientists at JPL for the past several years to consider landing sites for initial Starship Mars missions in the 2020's. This activity has progressed through definition of preliminary engineering constraints, ice resources, and initial considerations for future human habitation. Two workshops have been held, prospective landing sites were identified, and orbital images have been acquired of these sites, and a preliminary downselection of potential landing sites has been made. This abstract summarizes: a) the engineering constraints, safe surfaces, and ice at the sites, b) identifies areas that have been judged to be likely safe for landing, and c) describes the downselection of prospective landing sites.

Engineering Constraints, Requirements and Considerations: Engineering constraints on potential landing sites are mostly related to elevation, latitude, surface slopes, rocks, and the presence of a load bearing surface. Starship uses terrain relative navigation to attain a small landing ellipse (circle) less than 200 m in diameter. An elevation below -2 km with respect to the MOLA geoid that can support the delivery of large payloads, with <-3 km preferred for increased performance. Latitude must be $\leq$40° for solar power and thermal management, and closer to the equator is desirable. Multiple separate landing locations spaced within a few km of each other, to support the multiple missions needed to grow an outpost, are required as retro-rockets used during landing may modify the surface (or damage pre-existing infrastructure). Slopes should be <5° over a 10 m length scale and the chance of impacting a rock greater than 0.5 m high (1 m diameter) should be <5%. Finally, the landing site must be radar reflective to enable measurement of the distance to the surface, and it must be load bearing to support the spacecraft at touchdown.

The landing site must be close to significant deposits of water/ice, a required resource for in situ propellant production and a consumable to support habitation. Mid-latitude ground-ice has been observed by neutron spectroscopy [1], radar reflections [2], analogous ice-related morphologies including polygonal patterned ground [3], ice in fresh crater ejecta [4] and has been observed just below the surface by the Phoenix lander [5]. Hundreds of meters thick local ice deposits expressed as lobate debris aprons (LDAs) adjacent to Montes exhibit viscous flow morphologies and have radar reflectors with dielectric constants similar to nearly pure ice [6].

Safe Landing Surfaces: The latitude, elevation and load bearing requirements quickly reduced available areas to Arcadia Planitia, Phlegra Montes, Utopia Planitia and Deuteronilus Mensae. Hazards are estimated from experience with previous Mars missions for rocks >1 m in diameter. Rock counts in High-Resolution Imaging Science Experiment (HiRISE) images [7], together with modeled size-frequency distributions of Martian rocks [8], were used to extrapolate from >1.5 m diameter rocks to 1 m diameter rocks. Using the area sampled by the landing legs indicates that rock cumulative fractional areas of <10% would yield <5% chance of landing on a 1 m diameter rock.

Comparison of landed surfaces with rock cumulative fractional areas of <10% (Viking Lander 1, Spirit, Phoenix and InSight) shows that few to no rocks must be visible in HiRISE images in the landing ellipse. Digital Elevation Models (DEMs) from stereo HiRISE images of sample surfaces in Arcadia Planitia show that smooth, flat surfaces with polygons (as opposed to crenulated or brain terrain) meet the reference <5° slope/tilt constraint. Following previous landing site selections, areas with very low thermal inertia (<100 J m^{-2} K^{-1} $s^{-1/2}$) dominated by potentially thick dust deposits that may not be radar reflective or load bearing are excluded [9].

Potential Landing Sites: A workshop was held in January 2019 attended by members of the science community and SpaceX personnel to discuss regions that meet the latitude and elevation constraints and had evidence for substantial ice deposits. Areas of interest in Arcadia Planitia, Erebus and Phlegra Montes, Utopia Planitia and Deuteronilus Mensae were identified as areas that were worth evaluating to better understand their potential suitability as Starship landing sites. HiRISE images were evaluated in these areas to see if suitably smooth and rock free areas existed. Potentially safe surfaces were identified in Arcadia Planitia, and Erebus and Phlegra Montes, but Utopia Planitia and Deuteronilus Mensae appeared too rocky in available images. In May 2019, more than nine new HiRISE stereo pairs of prospective landing sites had been acquired. By May 2020, 15 potential landing sites in Arcadia Planitia and northern Erebus Montes had been identified along with one site in Phlegra Montes [10] (Fig. 1).

At a workshop in August 2020, these sites were discussed with members of the science community, SpaceX and other NASA and industry personnel. Six other landing sites in Phlegra Montes were also defined. Properties of the prospective landing sites that were evaluated include elevation, latitude, rocks, slopes, roughness, expanded secondary craters, nearby LDAs, thermal inertia, albedo, dustiness, polygons, and assessments of subsurface ice based on Subsurface Water Ice Mapping (SWIM) scoring of neutron, thermal, shallow radar, dielectric, and geomorphic analyses [11].

Downselection of Landing Sites: The 22 prospective landing sites that were defined are on three different terrain types with access to different types of ice deposits (Fig. 1). Seven Phlegra and three Erebus Montes sites are adjacent to or on LDAs. The 12 sites in Arcadia Planitia are on plains beneath which there is evidence for thick deposits of relatively pure ice [2]. Of these sites, six are on a sinuous geomorphologic unit with smooth, flat rock-free surfaces, relatively high thermal inertia and evidence for flow that could be glacier related [12]. The remaining six are on terrain adjacent to the sinuous unit.

Phlegra Montes Sites: Of the seven Phlegra Montes sites, several were higher than -3 km elevation (and two exceeded the maximum elevation) and/or appeared slightly rough and rocky. The Phlegra Montes site, PM-1, has the lowest latitude and elevation of the group, a clear association with LDAs, well developed polygons, and has the highest SWIM score for geomorphic indicators of ice. The PM-7 site is adjacent to lineated valley fill (attributed to glacial flow) and appeared the safest of the Phlegra sites.

Erbeus Montes Sites: Of the three Erebus Montes sites, EM-16, has a clear association with an LDA with nearby brain terrain and the strongest radar return for shallow ice and the highest combined SWIM score. Site EM-15 is associated with a prominent but less extensive LDA, has well developed polygons, nearby brain terrain and appears smooth.

Arcadia Planitia Sites on Sinuous Unit: Of the six Arcadia Planitia sites on the sinuous unit, AP-9 has the thickest ice from radar returns and geomorphology indicating shallow ice. It has the highest combined SWIM score for ice, but appears slightly rocky and rough. AP-1 appears to be the safest site and has a moderate combined SWIM score for ice.

Arcadia Planitia Sites adjacent to Sinuous Unit: Of the six Arcadia Planitia sites adjacent to the sinuous unit, three lack the radar reflector interpreted to be the base of thick (>~20 m) ice. Of the remaining three sites, AP-8 appears the safest and has the highest neutron and combined SWIM scores for ice.

Downselected Sites: The four primary sites selected for further study (in no priority order) are: PM-1, AP-1, AP-9 and EM-16 (Table 1, Fig. 1). Two are LDA sites (PM-1, EM-16) and two are on the sinuous unit in Arcadia Planitia (AP-1, AP-9). The three secondary sites in priority order are: AP-8, EM-15, and PM-7. Two of these are LDA sites (EM-15, PM-7) and the third site (AP-8) is adjacent to the sinuous unit in Arcadia Planitia.

To further assess these landing sites' suitability for human missions and persistent human presence on Mars, additional site characteristics should be considered. For each location these include: further understanding the location and safety of the landing sites, the extent and characteristics of the ice deposits, the methods and difficulty by which the ice could be extracted for in situ resource utilization, the proximity and trafficability to the landing site(s), and the near-surface materials that could be utilized for the outpost.

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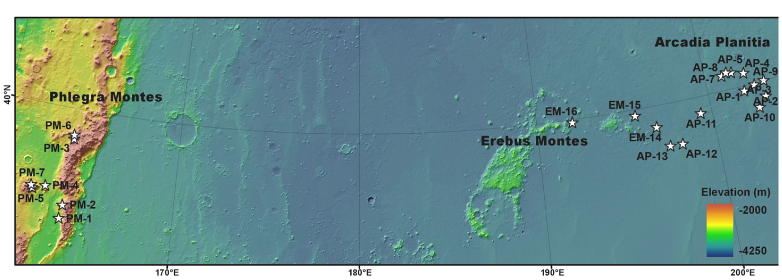

Fig. 1. Topographic map of Arcadia Planitia, Erebus and Phlegra Montes show landing sites considered for SpaceX Starship. Topography with respect to the MOLA geoid.

Table 1. Downselected prime (first 4) and secondary (last 3) landing sites

Land-ing Site	Lati-tude °N	Longi-tude °E	Eleva-tion* km
PM-1	35.23	163.95	-3.2
AP-1	39.8	202.1	-3.9
AP-9	40.02	203.35	-3.9
EM-16	39.89	192.03	-3.9
AP-8	40.75	201.3	-3.9
EM-15	39.75	195.62	-3.9
PM-7	36.43	162.16	-2.3

*with respect to the MOLA geoid.