TransFormers for Ensuring Long-Term Operations in Lunar Extreme Environments. J.G. Mantovani[1], A. Stoica[2], L. Alkalai[2], B. Wilcox[2], and M. Quadrelli[2]. [1]James.G.Mantovani@nasa.gov, NASA Kennedy Space Center, UB-R1, Kennedy Space Center, FL 32899, [2]Adrian.Stoica@jpl.nasa.gov, NASA Jet Propulsion Laboratory, MS 198-219, 4800 Oak Grove Dr, Pasadena, CA 91109.

Introduction: "Surviving Extreme Space Environments" (EE) is one of NASA's Space Technology Grand Challenges [1]. Power generation and thermal control are the key survival ingredients that allow a robotic explorer to cope with the EE using resources available to it, for example, by harvesting the local solar energy or by utilizing an onboard radioisotope thermoelectric generator (RTG).

TransFormers (TFs) are a new technology concept [2] designed to transform a localized area within a harsh extreme environment into a survivable micro-environment by projecting energy to the precise location where robots or humans operate.

For example, TFs placed at a location on the rim of Shackleton Crater, which is illuminated by solar radiation for most of the year, would be able to reflect solar energy onto robots operating in the dark cold crater. TFs utilize a shape transformation mechanism to unfold from a compact volume to a large reflective surface, and to control how much–and where–the energy is projected, and by adjusting for the changing position of the sun. TFs would enable in-situ resource utilization (ISRU) activities within locations of high interest that would normally be unreachable because of their extreme environment.

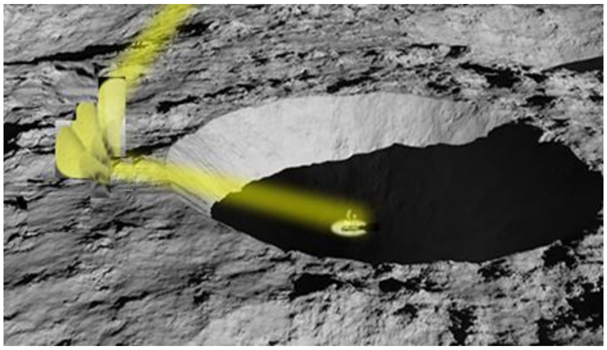

Fig. 1. Scientific and ISRU target for TransFormers-permanently shaded craters such as Shackleton crater on the Moon.

Discussion of the NIAC Phase I Study: In the Phase I study [2], a high-level comparative assessment was performed for missions to craters on the Moon and Mercury, as well as lava tubes/caves on the Moon and Mars. For a mission deep inside the Moon's Shackleton crater, a more detailed analysis was performed, looking at mission trade-offs, and optical and thermal analyses for providing sufficient power for charging the solar panels and maintaining the rover warm while working at the 40–70K crater temperatures. These analyses were conducted for three classes of rovers, the sizes of the three generations of Mars rovers: the Sojourner Rover, Mars Exploration Rover (MER), and the Mars Science Laboratory (MSL) Rover.

A rover with MSL technology is able to satisfy the full set of target scientific exploration requirements with 300 W of power. An MSL-sized rover would carry a sampling arm and a drill; a mass spectrometer for detecting ice, chemicals, and carbon; an X-ray diffractometer (XRD) for mineralogy; and ground-penetrating radar (GPR) for subsurface structures. This allows for a full geological and mineralogical exploration and for ice/mineral sampling, as well as for subsurface structure analysis. A possible cave exploration mission might require a stereo camera, a spectrometer for ice/mineral detection, an ultraviolet (UV) fluorescence instrument for organics detection, a seismometer for interior structure, a GPR for assessing cave stability, a sampling arm, and a mass spectrometer for carbon detection.

The TF solution has been found sufficient to power rovers such as described above. Some of the robotic missions described can be done using RTGs, but TFs have advantages over an RTG solution in several situations, for example: use of smaller robots; lower cost missions (Discovery-size), with increasing cost benefits for repeated missions in the same area; and powering/warming multiple rovers/vehicles. It is also a more desirable solution for human operations on the Moon.

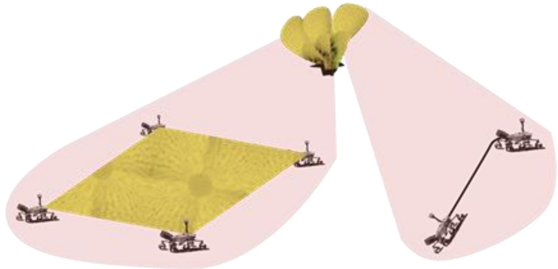

Fig. 2. Illuminating a solar oasis, where multiple rovers operate, e.g. performing ISRU, and where prospector and excavation rovers come to warm up and recharge batteries (left beam). Exploratory rovers could receive controlled beam illumination, for short duration during excursions, filtered light, or in emergency cases only.

Calculations were performed on the needed TF area to project solar power 10 km into Shackleton crater (20-km diameter). A preliminary evaluation was conducted of the effect of solar illumination in causing ice sublimation, and explored means to reduce/limit the spill of energy around the rover so it does not heat and sublimate volatiles (a RTG must also eliminate almost 2 kW of thermal power). We also looked at the needed functions and the ability to integrate the package into a mass below 100 kg and a volume less than 1 m^3 . We considered built-in functions including pointing, Sun tracking, and a means to compute and actuate to the needed shape. The designs examined require compact packing and light weight for the flight to the Moon and the surface transport by the rover to the rim.

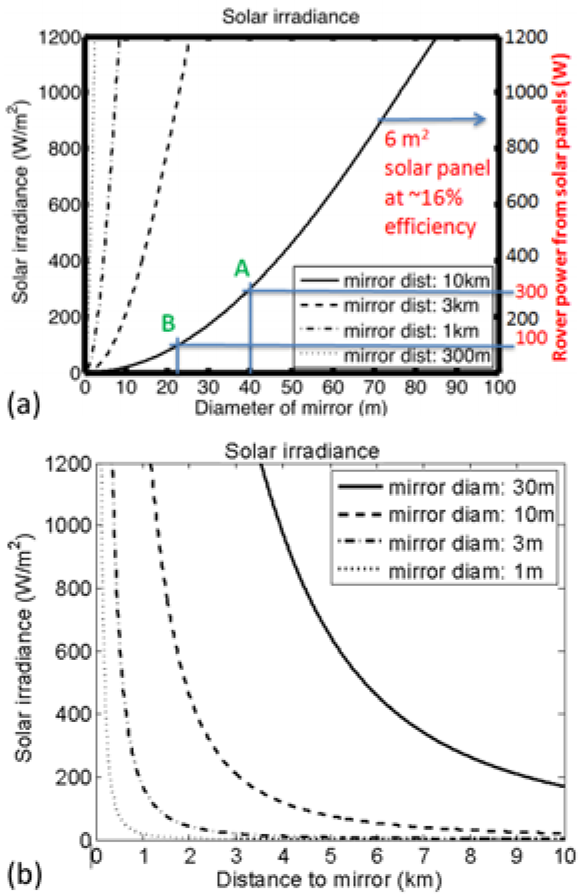

Fig. 3. (a) Solar irradiance vs diameter of mirror. (b) Solar irradiance vs distance to mirror.

Main Findings: In the short term, the highest return on investment for science and ISRU, and in preparation of manned missions, comes from a TF mission at the Lunar South Pole. A 40-m diameter (~1200 m^2 surface) TF is sufficient to project 300 W/m^2 10 km into Shackleton crater for a MSL class rover (~300 W from 6-m^2 solar panels). A 10-m-diameter TF is able to provide nearly full solar irradiation to a 1 km distance. This supports affordable exploration of lava tubes and would support a permanent base-projecting sunlight inside caves would require multiple reflections, beyond the line of sight (BLOS) of the TF on the skylight. This will require further study.

The component technologies for implementing a 1200-m^2 autonomous TF are at TRL 3 and higher. Integration is between TRL 1 and 2. A 1200-m^2 surface could be packed into a volume of 1 m^3, with a mass less than 100 kg. The Phase I study offers promise that large surfaces can be compactly packed and unpacked, for example, in origami style. The RTG mass prevents its use by MER or smaller rovers. TF cost is projected to be much lower than RTGs (~$45M); multiple rovers and multiple missions require no additional cost. Short-duration (hours) illumination of regions containing volatiles appears to have no major effects. Alternatives have been considered to avoid longer exposures, which need further refinement.

TFs show considerable advantages for repeated missions in the same region, and for the simultaneous powering of multiple platforms, enabling new classes of missions at relatively close in currently inaccessible places of interest.

Conclusions: The TF concept can be advanced in the context of a mission scenario at Shackleton crater by:

(1) focusing on a polar volatiles mission-with a detailed mission concept analysis, eliminating remaining high risks, increasing to TRL 3, providing: (a) robust solutions to dust, radiation and meteorites; (b) option of multi-hop reflections to project beyond line of sight, helping to control the focus of power and hence reduce the influence on the explored area; (c) conduct a design study targeting a scalable TF unit of 1000 m^2 and mass of 10 kg;

(2) tap into the potential of new classes of missions: (a) simultaneous powering/warming of multiple robots for effective mining, construction, and large-scale exploration; large area projection for a lunar base; (b) permanent multi-mission resource in the polar area of value to NASA and its partners.

The 2014 NIAC Phase I TransFormers study showed that TFs can enable long-term surface operations in Lunar extreme environments. The current NIAC Phase II study targets the risks identified in the Phase I study and addresses possible challenges to the advancement of the concept.

References:

[1] NASA Office of the Chief Technologist, *Space Technology Grand Challenges*, http://www.nasa.gov/offices/oct/strategic_integration/grand_challenges_detail.html.

[2] Stoica, A. et al. (2014) *NIAC Phase I Final Report: TransFormers for Extreme Environments*, https://www.nasa.gov/sites/default/files/files/Stoica_2013_PhI_Transformers.pdf.

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