Technology development for lunar thermal applications and the next generation of space exploration

E A Silk[1]* and **R Creel**[2]

[1]Thermal Engineering Technology Development Group, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
[2]Apollo Lunar Roving Vehicle Thermal Control Engineer, Ryan Associates, Inc., Gloucester, Massachusetts, USA

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Abstract: In recent years, NASA has shown a renewed interest in Lunar exploration. This renewed interest is expected to spawn a new era of exploration into the solar system, as well as generate new residual technologies for earth application. A review of experiences on the prior Apollo missions shows that there are significant challenges associated with returning to and establishing a base for humans in the harsh Lunar environment. The present article is a high level overview of the effort to return to the Moon, in the context of a larger effort towards human expansion farther into the solar system. Also included is a review of technical challenges associated with returning to the Moon.

Keywords: lunar exploration, advanced thermal control

1 INTRODUCTION AND BACKGROUND

In 2004, a new vision for NASA's space exploration programme was announced. This vision embodied a commitment for the return to flight of the space shuttle, the development of alternative power systems and enhanced on-board systems (i.e. lasers and electronics) for earth-oriented missions, as well as manned and unmanned exploration farther into the solar system. Among these three objectives, manned exploration is of particular interest. The extension of manned exploration beyond low Earth orbit (LEO) presents unique opportunities for learning about the origins of our universe. Flight missions such as the Apollo era programme, the Russian Lunokhod robotic Moon rovers, as well as the more recent unmanned rover missions to Mars (Pathfinder, Spirit, and Opportunity), provided many engineering procedural insights regarding successful methodologies for travel to and operation on extra-terrestrial bodies. They also allowed the Lunar and Martian surfaces to become technology classrooms for us and build upon our aspirations of extending exploration deeper into the solar system.

The ability to conduct manned exploration beyond LEO to the Moon (and ultimately farther into our solar system) presents many technical challenges. These challenges are thrust upon the vanguards of Earth's technology advancement and development through our current level of understanding of math, science, and the universe we live in. The following is a discussion of the goals, current direction, and challenges associated with NASA's space exploration programme as well as a review of some currently progressing technology efforts that are aimed at addressing these challenges.

2 GOALS AND CHALLENGES

The long-term goal of the current exploration effort is to extend a human presence farther into the solar system. Targeted locations for exploration may include celestial bodies such as the Sirius Star System and/or Alpha Centauri. Human technological capability for travel to such locations currently has not been harnessed. However, the path to

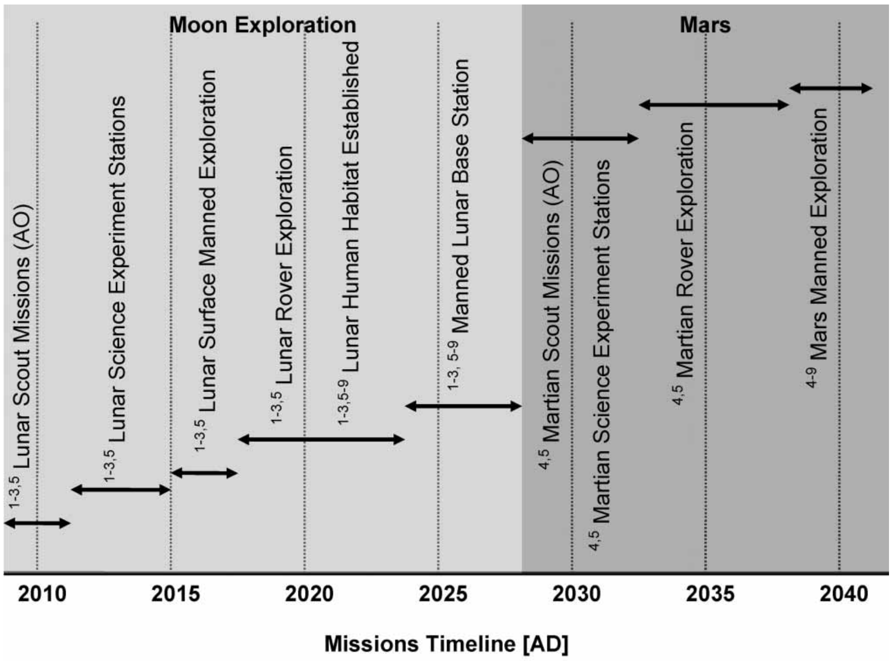
*Corresponding author: Thermal Engineering Technology Development Group, Thermal Engineering Branch/Code 545.0, NASA Goddard Space Flight Center, Building 7, Room 215, Greenbelt, Maryland, USA. email: eric.a.silk@nasa.gov

attaining such a goal must begin with the establishment of a roadmap for success. The current exploration technology roadmap (Fig. 1) has been devised according to the principles of patient gradualism where incremental steps leading to the desired end goal are taken over a selected period of time. Mission enabling technologies and methodologies that feed into the success of the desired end goal are to be gained during the intermediate stages of the process with the attainment of strategic interim goals. One targeted interim goal for this process is human travel to and exploration of Mars. However, a more near-term practical goal is the return to and establishment of a human base on the Moon. The establishment of a Lunar base would provide scientific opportunities for continuous research in a lower gravity environment. While the legacy work of the Apollo era has provided a template for human travel to and exploration of the Moon, the Lunar environment still poses significant challenges regarding sustained human habitation.

3 LUNAR ENVIRONMENTAL CHALLENGES

Since the Moon has no atmosphere (unlike the Earth), there is no shielding from harmful short wavelength solar radiation incident upon the surface. Practical designs for human habitats on the Lunar surface must provide shielding from this adverse radiation environment. The lack of an atmosphere similar in constituents to that of planet Earth also presents a need for oxygen production (as well as carbon dioxide elimination) for the yet to be designed habitat enclosures. Since the Lunar regolith is predominantly comprised of metal oxides, oxygen may be produced as a byproduct of the melting of Lunar regolith [**1**]. This work is currently under investigation at the NASA Goddard Space Flight Center. Issues such as food supply/production and waste management also need to be addressed.

Another environmental challenge is that of extreme temperatures. Figure 2 is an example plot of Lunar surface temperatures observed by the



Mission Requirements

1 Advanced thermal control hardware for Lunar surface temperature changes
2 Radiation Shielding
3 Scaleable power system viable for Lunar night cycle application (minimum of 50 kWe)
4 Scaleable power system for Martian environment
5 Dust mitigation for mechanisms and hardware coupled to respective environment
6 Base location selection (Lunar or Martian surface)
7 Oxygen production
8 Food Production
9 Waste Management

Fig. 1 Exploration missions roadmap

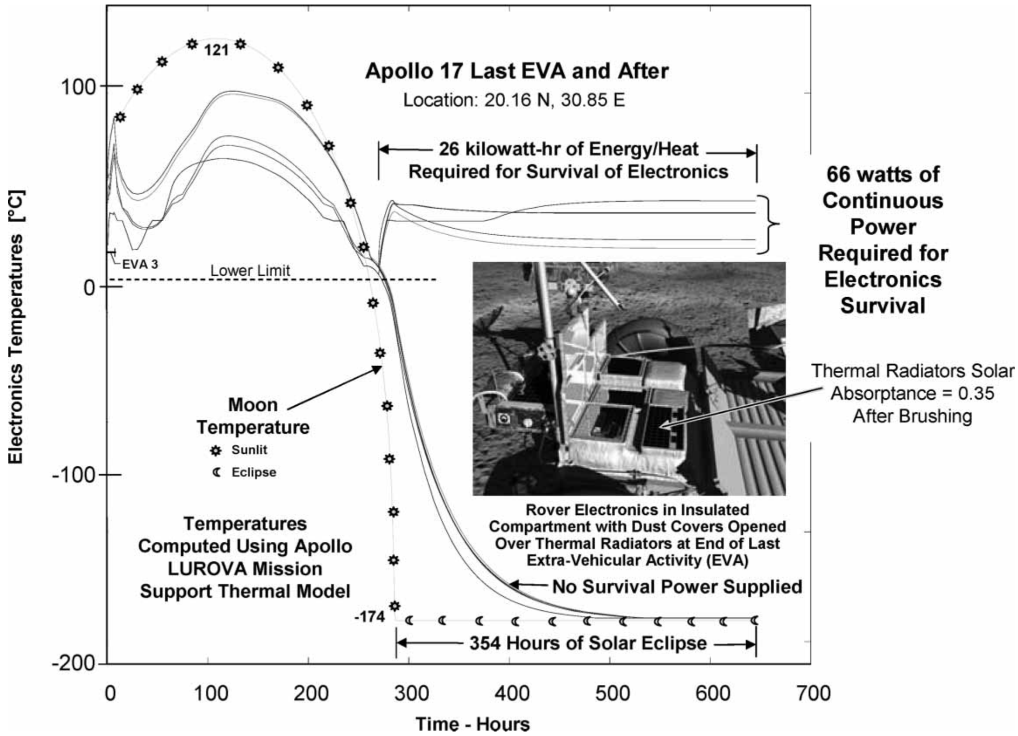


Fig. 2 Example Apollo LRV electronics temperature profile during Lunar environment cycle

Apollo 17 Lunar Roving Vehicle (LRV) electronics during Lunar morning. Also shown in Fig. 2 is the heater power that would have been required to maintain the electronics above cold limit temperatures during the postsurface operations period of Lunar night. The Lunar surfaces' hot and cold temperature extremes (depending on location) can vary between 130°C during Lunar day and −180 °C during Lunar night [**2**, **3**]. Since Lunar night, like Lunar day, has a duration of 14 Earth days, sensitive insulated electronics will require additional heating during this long eclipse period. Artificial habitats must provide sufficient heating and cooling to sustain human life during the full Lunar day/night cycle. This will require energy. The energy needed to create and maintain habitable conditions for humans is theorized as being generated by usage of advanced power systems designed for the Lunar surface. Projected capacities required for Lunar night are on the order of 50 kWe (minimum) continuous power. Power system design efforts to meet this need also are currently underway at the NASA Goddard Space Flight Center.

One of the most formidable challenges in the Lunar environment is that of dust. Lunar dust samples collected during the Apollo missions showed the dust to be very fine and powder like with the ability to carry electrical charge. The majority of regolith particles collected during the Apollo missions were smaller than 10 μm. However, larger particles up to a length of 1 mm were also present and comprised the majority of the collection sample weight [**2**, **4**, **5**]. During the Apollo 12 mission, Lunar dust was cited as the cause of false velocity tracker readings during descent to the Lunar surface, as well as false radar outputs at low altitude on Apollo 15 [**6**]. Lunar dust was also shown to clog and jam numerous mechanisms exposed to ambient on several LRV components. The pervasive dust compromised seal integrity on astronaut space suits as well as environmental gas and regolith sample containers prior to their return to Earth [**6**]. Because of one-sixth gravity condition on the Lunar surface, the dust was easily agitated and attracted to all surfaces (e.g. space suits, radiators, etc.). Once deposited on these surfaces, attempts by astronauts to clean the Lunar dust away yielded very little success due to the strength of the attraction forces.

Dust on Apollo LRV radiators increased the solar absorptance of the radiators, thereby increasing the absorbed heat and limited the ability to reject stored heat to the environment. As a result, the LRV batteries exceeded their upper temperature limits and required power switching for continued operation. Similar dust concerns have been expressed regarding Martian dust and thermal impact to the rovers on the Martian surface. Although dust effects and mitigation testing was conducted prior to the Apollo LRV missions, the characteristics of *in situ* Lunar dust were not completely understood at the time. Proper dust mitigation techniques are required and essential for the success of future missions on the Lunar surface [**3**, **5**]. Dust mitigation techniques are currently under investigation at the NASA Glenn Research Center, NASA Goddard Space Flight Center and Jet Propulsion Laboratories.

4 PARADIGM FOR SCIENTIFIC ADVANCEMENT

Science is based on physical relationships in nature. The current level of human science and technology is based on the ability of human intellect to ascertain and comprehend these physical relationships. As such, human technologies have primarily been based on the physical relationships inherent to planet Earth. This is exemplified through heat transfer and applied thermodynamics machinery such as ground-based heat pumps and heat exchangers (liquid/vapour) that are often used in vapour compression cycles for space heating and cooling in residential and commercial buildings. These ground-based heat pumps and external heat exchangers rely upon energy exchange with the immediate environment for operation.

The space programme is predominantly rooted in technologies that have been developed relative to the earthly reference frame and then modified for extra-terrestrial applications. The laws of physics are constant in our solar system. However, the framework and fundamentals regarding relationships in nature are dependent upon reference frame, and change when transitioning from one reference frame to another. The Lunar environment, which has large surface temperature excursions, low thermal conductivity soil, and no gaseous media at the surface available for convective heat exchange, makes direct application of thermal technologies that operate by means of conductive and convective energy exchange with the ambient environment invalid for use with human habitations on the Lunar surface. Earth-based power generation systems that require consumables are invalid as well because of the lack of readily available consumable resources in the extra-terrestrial environments.

Successful human expansion to another celestial reference frame requires a paradigm shift in thinking regarding the creation and development of new thermal technologies tailored for the new task and reference frame. As the primary heat transfer mechanism associated with the Lunar surface is radiation, advanced thermal control hardware for energy capture, storage, and transport in a radiation dominated environment is in need of development. Technologies such as thermally powered Stirling engines and Photon engines, that practice energy harvesting of the local thermal environment and the electro-magnetic wave scale, respectively, are more appropriate to the Lunar surface and worthy of investigation [**7**, **8**, **9**]. Other power system options may include regenerative fuel cells (RFC) and/or nuclear fission power systems. NASA missions such as Cassini have shown the ability of radioisotope thermoelectric generators (RTGs) to provide upwards of 855 kWe via a network of RTGs. Another benefit of Fission reactors is that they can provide continuous thermal energy for thermoelectric conversion during Lunar night, as was previously done on the Apollo Lunar Surface Experiments Packages and the Russian Lunokhod rovers. While failure mode scenarios during launch of nuclear payloads raise international concerns regarding health and safety of earth citizens, these systems provide flexibility in settlement location on the Lunar surface due to the lack of dependence on incident solar energy for survival.

5 CONCLUSIONS

The exploration systems mission begins with a return to the previous destination of the Moon and is anticipated to end with a heightened level of understanding of our solar system. Technology development for Lunar thermal applications will be vital for future extra-terrestrial survival and exploration. It is also anticipated that the journey will generate human advancements in science and engineering that will benefit man regardless of the reference frame. As shown, the challenges are great. However, the benefits of success will be reaped by future generations for years to come.

DISCLAIMER

The ideas and opinions expressed in this document are solely those of the authors and do not represent official NASA policy.

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