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ATMOSPHERIC RE-ENTRY ENERGY STORAGE (ARES)- A NOVEL CONCEPT FOR UTILIZING ATMOSPHERIC RE-ENTRY ENERGY

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As the aspirational goal of Mars settlement starts to slowly materialize, it is apparent that its viability hinges on the utilization of its energy and material resources. Although Mars has a thinner atmosphere than Earth, it still exerts large amounts of heat on entry vehicles, generating temperatures around 1500°C. Therefore, the entry vehicle is covered with a thick layer of ablative heat shield to protect the inside from reaching undesired temperatures. However, the temperature on the Martian surface is significantly cold. It varies between -140°C and 30°C. One of the critical challenges in developing a settlement and operating equipment on Mars is to find adequate heat sources on its surface.

The envisioned heat sources are solar energy, geothermal energy, greenhouse gases and Radioisotope Thermoelectric Generators (RTG). Although solar and possibly geothermal energy are the preferred sources for their unlimited supply, they are localized and require an elaborate infrastructure. Trapping greenhouse gases also requires extensive infrastructure. RTGs require a large amount of radioactive fuel and both the equipment and fuel have to be transported from Earth. Due to its hazardous nature, disposal/reprocessing of the fuel will be challenging. Interestingly, little to no effort has been spent to study the possibility of utilizing the large heat generated during vehicle entry.

This paper proposes a novel concept to collect, store and utilize the atmospheric entry heat energy using Phase Change Materials (PCMs) obtained from the Martian moons. Mars settlement architectures suggest that, Phobos and Deimos can be used to set up preliminary base camps. These moons are potentially trapped C-type asteroids and have the possibility to contain rich Lithium reserves. Lithium and its alloys have a relatively high latent heat of fusion and low density, making them an ideal PCM for this application. This concept takes advantage of the undesired heat generated during atmospheric entry to melt the PCMs. A storage system would store and insulate the melted PCM as it solidifies and heat energy is released. The utilized PCM could then be reused and consumed for a variety of purposes.

With current technology limitations, the heat storage system could only store the heat energy obtained using PCMs for a few hours. While the results from ongoing research could considerably increase its efficiency, PCMs could be used as a temporary energy source in landing sites where no other energy generation infrastructure is available. Alternatively, the heat generated from PCMs could be converted to electricity using thermoelectric generators.

Keywords: Space Resources, In-situ Resource Utilization, Atmospheric Entry, Mars Exploration

1. Introduction

Mars has continued to enthral humanity ever since Galileo Galilei first observed it through a telescope in 1610. It is the most accessible planet from the Earth that possibly retains answers to the origin and evolution of humankind and the solar system. There have been almost 50 uncrewed exploration missions to Mars so far, beginning with “Mars 1M No. 1”, the first mission intended to explore the red planet in the 1960s. Aside from understanding our solar system, the main driving force of these monumental efforts is to investigate whether a life off of Earth is plausible. The complex geology of Mars, the presence of an atmosphere and historical climate change are comparable to Earth's. There are numerous missions planned to explore and research the martian resources, and the race has already begun to land the first crew on Mars as early as 2030.

Moreover, establishing permanent settlements on Mars is the 'horizon goal' for numerous space agencies and private entities. No matter how aspirational the goal, it is ambitious without bridging the technology gap. Substantial technological advances in Radiation Protection, In-Situ Resource Utilization (ISRU), Life Support System enhancements, Entry, Descent & Landing Systems, Surface Power and Heating are the critical enabling technologies necessary to achieve this goal [1].

This paper proposes a novel concept for harvesting the energy during atmospheric entry to be used as a heat source on the Martian surface. The paper provides an overview of the challenges in establishing settlements on Mars, focusing on its thermal environment. It introduces Phase Change Materials (PCMs) operation and the energy obtained from atmospheric entry to utilize PCMs as a potential heat source. Finally, it explains the proposed idea and presents a Concept of Operations (CONOPS) before concluding.

2. Graphical Summary

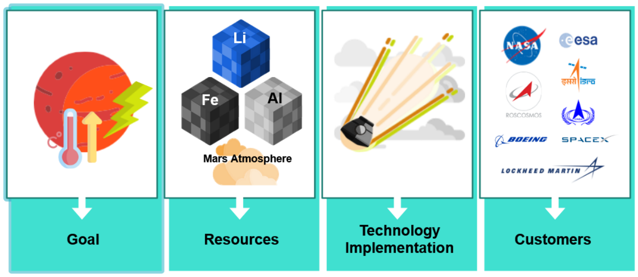

Fig. 1: Proposed plan to utilize Phase Change Materials and Martian atmospheric entry heating for generating a localized energy source

3. Mars Settlement Challenges

Settlement on the red planet poses various economic, legal and ethical challenges[2]. However, some critical technological challenges create barriers taller than the Olympus Mons. For instance, novel technologies to provide sufficient power and appropriate thermal environments for crew and equipment on Mars. Because of Mars's location in the solar system, the surface on Mars is colder than Earth's surface. It ranges from -140° C to 30° C with an average temperature of -63° C. While instruments and equipments are designed to endure the harsh environment, crewed missions need active temperature control to maintain levels preferably around 22° C.

There have been numerous efforts to produce a constant supply of power to maintain the desired temperature inside the martian bases. Solar panels to produce electricity[3] is an obvious choice. However, the sunlight on Mars is only 43% as intense as on Earth. This relatively low solar intensity doubles the number of solar panels required on Mars to produce the same amount of electricity on Earth.

With its undependability on the Sun, wind turbines have a distinct advantage on Mars over solar panels, producing uninterrupted power during the day and nights [4]. Nevertheless, wind turbines are generally large, and the lower atmospheric density on Mars requires an even larger turbine to meet the demand. Therefore, solar panels and wind turbines are best suited as an auxiliary power source rather than a primary one.

Nuclear fission power generation is the most promising technology to solve this problem so far as it is a self-sufficient energy source and satisfies all the power needs [5]. However, due to its hazardous nature, it requires extensive infrastructure, technology to prospect, mine and purify a large amount of nuclear fuel, and a safe disposal plan on Mars to protect the crew from accidents.

An alternative to nuclear plants is the utilization of geothermal energy on Mars [6]. The geothermal heat emanating from the martian subsurface reservoirs harvested using steam turbines is an excellent intrinsic and harmless energy source. Furthermore, the heat generated shall be directly used to meet the thermal requirements. On the other hand, similar to nuclear plants, geothermal plants require elaborate infrastructure to harvest energy. Moreover, without any power transmission systems on Mars, the energy from nuclear and geothermal plants are highly localized in the established area.

Although the various sources mentioned above are feasible for many applications once a large infrastructure is in place, they employ high installation cost, time and effort. Therefore, they are not a suitable choice for the initial exploratory stages or for temporary, localized energy needs.

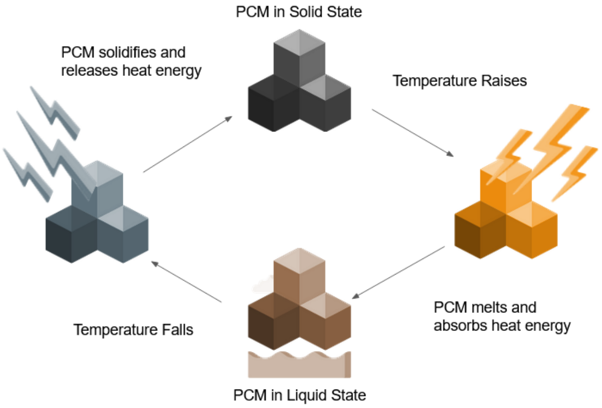

Fig. 2: The Phase Change Material (PCM) cycle

4. Phase Change Materials

A PCM is a material that provides effective heat/cooling by thermal energy transfer that occurs when it changes from one state to another. A PCM can undergo phase transformation only within two states of matter and allows repeated switching between the states [7, 8]. Figure 2 shows a schematic representation of a PCM's life cycle. PCMs differ from conventional storage materials in that it can store more heat per unit volume [9]. Additionally, PCMs absorb and release heat at an almost constant temperature.

Because of these unique advantages, PCMs are already used in numerous terrestrial and space applications such as smart drug delivery, HVAC, information storage, thermal control and energy storage in space systems [10–14]. Furthermore, they are investigated for many diverse applications such as data storage[15], building and construction[16], textiles[17, 18], passive-cooled shelters[19] and transport containers[20]. As PCMs exhibit relatively higher reliability by not involving moving parts or extra energy consumption in between cycles, hence they make a more effective use of space[14].

On the other hand, PCMs are not mature enough to solely replace the conventional thermal control system in space systems and often requires additional systems to satisfy the system's thermal requirements. Other caveats that hinder the widespread application of PCMs include their design complexity, system size, cost, and time. As a result, most spacecraft designers do not use PCMs unless it is necessary[21]. Analyzing that the choice of the PCMs can have a substantial impact on the system design, various research efforts are being directed to discover new PCMs and unleash a new potential of these materials[22–24].

PCMs, in general, are classified into organic, inorganic and eutectic based on the material composition. Organic PCMs such as Paraffins having a low melting point and high latent heat of fusion are preferred for most terrestrial and space applications. Low melting point metals such as Gallium and Sodium are being investigated for spacecraft thermal energy storage applications[14]. Although metals such as Lithium and Aluminium have large latent heat of fusion, they do not gather much attention due to their high densities and high melting points. They require a substantial amount of energy to undergo a phase transition. However, these materials could foster interest where a large amount of energy is inadvertently available.

5. Atmospheric Entry Heating

Due to several factors, Mars Entry, Descent and Landing (EDL) is highly challenging. The atmosphere on Mars is thinner compared to Earth which imposes lesser drag to the entry vehicles. Consequently, Mars entry vehicles tend to decelerate at much lower altitudes and may never reach subsonic terminal velocity[25]. Even this less dense upper atmosphere of Mars generates substantial heating on the entry vehicle. As the spacecraft enters the Martian atmosphere, a bow shock is formed at the leading edge of the vehicle. The shock waves generate heat energy as a result of aerodynamic friction between the vehicle and the air molecules, exciting them from their dormant state.

A Thermal Protection System (TPS) or heat shield is in place to protect the vehicle from overheating. Generally, there are three different approaches to thermal protection system - Heat Sinks, Radiative cooling and Ablation [26]. The Heat sinks approach employ additional layers of low thermally conductive material covering the vehicle to lower the vehicle's peak temperature. The Radiative Cooling approach uses a high emissivity material shield to emit most of the energy that it receives. The Ablation approach uses a thick layer of material with a high latent heat of fusion as a sacrificial material that melts away to protect the vehicle. Most of the past successful missions have relied on Viking heritage technologies that use an ablative material(SLA-561V) in the thermal protection system.

At high temperatures, ablative materials decompose and release hydrocarbon gas mixtures that may cause potential contamination of instruments on the vehicle. Later, Suzuki et al. proposed a nonablative lightweight thermal protection system concept to address this technical difficulty [27]. With the advancements in material science, new promising materials and innovative landing techniques are continuously emerging. The Inflatable Aerodynamic Decelerator (IAD) made from flexible, lightweight materials is one such technique. IAD is folded before launch and inflated during entry [28, 29]. The main advantage of this technique is the reduction of the ballistic coefficient and peak heating rate on the vehicle. However, once inflated, the IAD cannot be reused. O'Driscoll et al. [30] proposed mechanically deployable aeroshells, which can be repeatedly retracted and deployed with thermal protection panels in between them [30]. Becket al.[31] developed a tiled TPS with phenolic-impregnated carbon ablator (PICA) that successfully protected the Mars Science Laboratory during entry.

All these approaches try to avoid vehicle heating by employing systems that are either sacrificial or circumventing. Even though it is clear that heat energy is a rare resource on the Martian surface, little to no effort has been taken so far to harvest the heat produced during entry. Ali et al. [32] investigated the effects of using a magnetohydrodynamic energy generation system to harness the shock layer and utilize electric current via in-situ magnetohydrodynamic power generation. It is an unconventional approach that reclaims some of the vehicle's dissipated kinetic energy. The generated current operates a flow control system to modulate drag and peak heat. Although a part of the reentry energy is utilized in this case, it only lasts for a short duration.

6. Atmospheric Re-entry Energy Storage (ARES)

The immense heat generated on a landing vehicle during the atmospheric entry/reentry to a planet is profoundly undesirable. However, the abundant unrecompensed energy in the form of heat may actually be of use for a variety of applications on planetary surfaces. Instead of just shielding the entry vehicle as accomplished in the conventional approaches, Atmospheric Re-entry Energy Storage (ARES) is a proposed novel concept to protect the vehicle and capitalize from the generated heat energy. It uses PCM rather than regular ablative heat shields. When a vehicle enters the planet's atmosphere, heat loads generated on its exterior surface melts the PCM heat shield. The melted PCM is isolated and stored in an insulating container. Later, after landing, the PCM releases the stored heat energy to provide the desired temperature where needed. After its utilization, the PCM may be reused by re-energizing it through subsequent atmospheric reentries or re-purposed for other applications. Figure 3 is a graphical illustration of ARES's Concept of Operation.

6.1 PCMs for ARES

The PCMs needed for ARES application need to exhibit a set of desirable thermophysical properties such as comparatively high melting point, moderate density, small volume change and adequate latent heat of fusion. To avoid containment problem and for practicality, only solid-liquid PCMs are considered for ARES. Although ARES aims to replace conventional bulky heat shields, high-density metal PCMs and their enabling components still make the entry vehicle very heavy. Therefore, use of local resources and in-space manufacturing technologies are the key to positively benefit from ARES. This requirement imposes additional criteria in selecting the PCM, such as their availability and abundance in space. Based on this, we narrowed down on metal PCMs. The commonly preferred Paraffins cannot be used as they have a low melting point. Table 1 shows the lists of metal PCMs considered for the ARES concept.

6.2 Potential PCMs for ARES

ARES is suitable for spacecraft entering any planet with an atmosphere. However, this paper primarily analyses ARES for its use in Mars. Therefore, for this application, Phobos and Deimos are the possible sites to acquire PCMs. Apart from that, Mars is at an interesting location that has easier access to the asteroid belt. Table 1 shows the lists of possible metal PCMs and their source. The C-type asteroids contain Lithium[33], S-type asteroids consist of Aluminium[34], and M-type asteroids being the parent body of iron meteoroids is rich in Iron[35]. Additionally, the spectral characteristics and density of Phobos and Deimos are similar to primitive C-type asteroids [36, 37].

Since ARES uses atmospheric entry, the collection, storage, processing and integration of PCM to the vehicle is assumed to take place in a Mars-bound operation centre. For example, a more likely scenario is to have an outpost in the Martian moon, Phobos. Various Mars settlement architectures propose the "Phobos First" scenario, and the establishment of an outpost on Phobos is considered a precursor for a future mission to Mars [38–43]. Phobos is the largest moon of Mars with a radius of 11.1 km and orbit at 6000km from the martian surface. It has a brief orbital period of 7 hours and 39 min. Its small size and proximity to Mars make it an ideal option to create an outpost to assist in the Mars settlement missions. Hence, Lithium mined in Phobos is the preferred PCM for ARES.

Metal	Source	Properties			
		Density (kg/m^3)	Melting Point (°C)	Latent Heat (kJ/kg)	Thermal Conductivity (W/mK)
Lithium	C-type Asteroid	534	181	432.2	84.8
Aluminium	S-type Asteroid	2700	660	396.6	237
Iron	M-type Asteroid	7874	1538	247.3	80.4

Table 1: Metal PCMs considered for the ARES concept

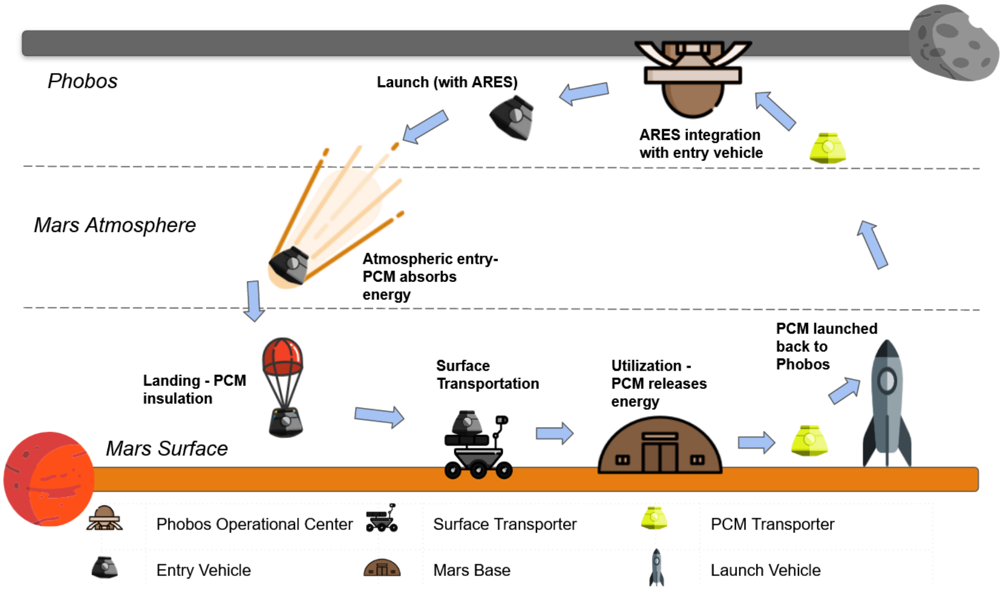

Fig. 3: Atmospheric Re-Entry Energy Storage (ARES) – Concept of Operation

6.3 ARES Heat Storage

Research done on metal PCMs is relatively scarce due to its high melting point and energy needed for phase transition. Wang et al.[24] analysed inorganic and eutectic high-temperature heat storage materials. The research results show that Al and Si-based materials are potentially good candidates for Thermal Energy Storage (TES) application. Fernandez et al.[44] presented the requirements for metal alloys to use as PCMs. Wei et al.[45] reviewed current efforts and the prospects of high-temperature PCMs. Limited investigation and the lack of vital information about metallic and high-temperature PCMs are the recurring critical limitations pointed out in these researches. Therefore, further studies are required to fully investigate metallic PCMs.

The following equation is used for a preliminary estimation of the heat storage capacity of the metallic PCMs. Using this formula, the heat energy required to melt 100 kg of lithium is approximately 138 MJ, while Al and Fe are 106 MJ and 98 MJ, respectively.

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta h_m + \int_{T_m}^{T_f} mC_p dT \qquad [1]$$

$$Q = m\left[C_p\left(T_m - T_i\right) + a_m \Delta h_m + C_p\left(T_f - T_m\right)\right] \qquad [2]$$

where Q is the Heat storage capacity, m is the mass of Lithium, C_p is Specific heat capacity of Lithium = 3.5816 kJ/kg K, ΔT is the change in temperature, T_i initial temperature is 210K which is the average temperature of the Martian thermosphere, T_m is the melting point of lithium and T_f is the final temperature and L_f is the latent heat.

From previous missions, the duration from entering the Martian atmosphere to deployment of parachutes is found to be approximately around 5 minutes and the heating rate is about 2MW/m^2 [46]. Therefore, the resultant energy available for enabling PCM's phase transition is 120MJ(per minute).

The heat generated during entry is greater than the heat required to melt the PCMs listed in Table 1. Conversely, with the average heating rate, the produced energy(600MJ) can phase transform approximately 435

Kg of Lithium, 564 Kg of Al or 615 Kg of Fe. However, these are based on the properties of pure metal. Its alloys or eutectic combination may result in better values and must be investigated in the future.

6.4 ARES utilization

The stored heat energy in the ARES system can directly be used for thermal management or as electricity by using thermoelectric generators. Some of the advantages of ARES are given as follows.

- Harvest, store and utilize the enormous energy produced during atmospheric entry.
- Vehicles with ARES can be landed anywhere on the planet's surface and would benefit from the energy generated by PCMs for its operation and that of other equipment deployed for a variety of exploration purposes.
- ARES uses metallic PCMs and the metals in it could be utilized for secondary purposes such as Li-Ion batteries and various applications of Al and Fe.
- ARES utilizes PCMs mined in space and is only integrated with the spacecraft before entry. Hence the overall weight of the spacecraft launched from Earth could be significantly lowered.

Nevertheless, there are some shortcomings that need to be addressed to fully realize the ARES concept. It requires an extensive understanding of metallic PCMs, especially for high-temperature variants and an efficient TES is required. With current technology limitations, the heat storage systems could only store the heat energy obtained using PCMs for a few hours. While the results from ongoing research could considerably increase their efficiency, PCMs could be used as a temporary energy source in landing sites where no other energy generation infrastructure is available. Alternatively, the heat generated from PCMs could be converted to electricity using thermoelectric generators. Additionally, a thorough identification of materials available on Phobos, Deimos and near-Mars asteroids is required. However, the use of the heat of entry along with PCMs should be further investigated to evaluate its potential benefits for Mars exploration.

7. Conclusion

This paper presents a concept that identifies the energy of entry as a valuable resource and utilizes it for a variety of applications on the Martian surface. This early conceptual assessment showed the viability of ARES, identified its usefulness in terms of power availability and determined the technological advancements needed to successfully implement the concept. The work presented in this paper is not exhaustive but the intent is to foster the thought of utilizing entry heat energy and to promote discussions that can lead to the development of technologies that fully leverages this energy.

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