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Introduction: The design, construction and operation of safe and comfortable habitations is one of humankind's oldest activities. Millennia of experimentation and planning have brought the creation and maintenance of habitats on Earth to a high degree of sophistication. However, humankind is now faced with new challenges as we begin to move beyond the Earth's relatively benign surface and out into Space.

The design of sustainable, long-term human settlements represents a multidisciplinary engineering and scientific grand challenge for humanity. Beyond the protection of Earth's atmosphere, future space explorers and colonists face new threats stemming from the lack of air pressure, oxygen, extreme temperature fluctuations and hazards such as meteorite impacts and intense particle radiation. Countering these challenges to provide livable conditions in Space will require the highest applications of engineering and technology.

In the context of extreme environments, there is much experience gained in terms of an approach to designing and constructing habitats that are resilient to disturbances, usually in the form of natural and man-made hazards. It is especially important to design buildings whether for habitation, laboratory or manufacturing, that are capable of responding to prevailing conditions—not only as a protective measure, but also to enable future generations to thrive under such conditions. As the civil engineering design community has learned from past disasters, the methodologies have evolved and matured, leading to present performance-based and consequence-based approaches. It is crucial to integrate this vast experience and adapt to meet these new challenges.

We are establishing a new interdisciplinary effort at Purdue University to perform the science and establish the knowhow to build resilient extraterrestrial habitats. In this document, we outline our plans and accomplishments to date towards addressing the challenges associated with designing permanent human settlements outside Earth.

Approach: There is growing interest from Space agencies (e.g. NASA, European Space Agency) in establishing permanent human settlements outside Earth. The idea has caught humanity's imagination and its appeal will only grow in the near future. There have been even preliminary conceptual ideas for permanent lunar bases, to "serve science, business, tourism and even mining purposes" [1]. However, even a cursory inspection of the proposals uncovers fatal flaws in their conceptual design. The buildings may not be able to support the load demands, which should include potential impact from meteorites and/or the seismic motions induced by such an impact, and perhaps most importantly, the materials used as cover for radiation protection may be radioactive themselves. Ongoing research has neglected the largely unexplored needs regarding the habitat and infrastructure required on extraterrestrial bodies.

To undertake this effort, our program consists of three main activities: Building Knowledge, Concept Settlement, and Enabling Partnerships. *Building Knowledge* is geared towards identifying the needs for human habitation on a planet or moon, with particular emphasis on the Moon and Mars; identifying and quantifying risks, and in particular those not found on Earth; identifying and quantifying sources of energy and other resources to sustain life; and identifying the research questions that need to be addressed. *Concept Settlement* includes conceptual analysis and design of a permanent human settlement on the Moon and Mars, aiming to have a preliminary proof of concept and feasible design for a permanent habitat. *Enabling Partnerships* is intended to engage a wide swath of stakeholders from the professional and academic communities.

Lava Tubes: NASA's GRAIL mission mapped the Moon's gravity field to unprecedented precision [2,3]. One of the more recent discoveries from this mission was the existence of a network of large, empty tubes in the lunar lava flows. Based on measurements of the gravity field, these lava tubes are more than 1 kilometer in diameter, and tens of kilometers long [4-6].

Opportunity. The discovery of these lava tubes on the Moon offers an unexpected opportunity [7]. Lava tubes may form the basis for ideal habitats on the Moon or Mars, offering instant protection to astronauts from temperature variations, radiation and meteorite impacts. If they can be pressurized, they might be rendered suitable for habitation almost immediately. Otherwise, smaller habitats can be built inside their safe havens.

Further, new technologies are needed to exploit these huge caverns. It will be necessary to move people and material from the surface into their depths, or to construct surface habitations with traditional cut-and cover methods is ripe for development.

Stability. These lava tubes are breached to the surface in several locations to form so-called "lunar skylights". Similar skylights have also been detected on Mars. Further studies are currently underway to validate the existence of these huge tunnels [8]. However, before any serious thought can be given to their use as habitats, it is essential to answer some fundamental questions: Are they structurally stable? How were they formed? Will additional meteorite impacts weaken a stable condition? What additional risks might these subsurface formations hold over time?

Based on a preliminary stability analysis, the large sizes (more than 1 kilometer in diameter, tens of kilometers long) inferred from the gravity field are stable under lunar gravity [7]. More recently, we have been investigating the possible geological formations of the lava tubes and estimating the size of the tubes given the properties of the lava flows on the Moon [9]. In addition, we have been examining the stability of the lava tubes by conducting numerical simulations considering different factors including: i. Size and shape [9]; ii. State of stress that implies changing the lateral coefficient of earth pressure (k); and iii. The material constitutive model. Those analyses were conducted using the finite element commercial software ABAQUS [10]. Our preliminary results show that as the height to width of the tube cross-section increases, the stability increases [9]. Also, lithostatic state of stress (k=1) predicts a more stable structure. In addition, the tension cut-off of the material model may change the failure shape and behavior of these tunnels. Next steps will include modeling the effects of extreme pressures and temperatures, meteorite impacts and other different factors on the stability of these lava tubes.

Hazard Quantification: Before we can establish appropriate procedures to design habitats that provide livable conditions beyond the protection of the Earth's atmosphere, it is critical to understand and characterize the prevailing conditions and the hazards that the habitat will be exposed to. Conditions include the lack of air pressure and oxygen, and the extreme temperature fluctuations. Hazards include meteorite impacts, seismic activity and intense particle radiation. When meteorites impact the lunar surface, the kinetic energy from the impact is partitioned into three forms of energy as, cratering excavation, visible light, and the production of seismic waves [11]. We have been working to develop methods to characterize these conditions and hazards and later incorporate them into the design of extraterrestrial habitat systems. For instance, we have used available photometric calibration of lunar flashes data [12] to estimate luminous energy via a velocity-dependent luminous efficiency. For a specific area of interest, we have developed an exponential distribution to estimate the return period of an impact. Also, the seismic events have been extensively studied in terms of spatial and temporal characterization. With the available data, response spectra have been developed despite the limited frequency content of the records. Potential structural or components failures due to these hazards should be included in the design process because they can result in injuries and loss of life.

Any human settlement in space will require excavation, construction and transportation of large masses of material from one place to another. Accomplishing these tasks in the Space environment, on nearly or completely airless bodies with less gravity than the Earth such as the Moon, Mars or asteroids is not beyond our current capabilities, but will require extensive planning combined with both theoretical and experimental studies long before we even begin to construct in situ pilot projects.

Summary: This abstract provides a brief overview of our vision for and accomplishments to date towards the challenges of engineering permanent extraterrestrial habitats. The results of these studies are being integrated into a system resilience framework for permanent extraterrestrial habitats [13]. This framework provides a systematic approach to designing of space structures considering their operational dependencies and disruptive/degrading conditions. An international workshop is being planned at Purdue University in the Fall of 2018 to bring together leading experts in the relevant fields to discuss the research questions and necessary technical steps for making Resilient Extraterrestrial Habitats a reality.

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