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Results of the AIAA Phobos Base Student Design Competition

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Abstract

The AIAA Life Science and Systems Technical Committee (LSSTC) and the AIAA Space Architecture Technical Committee (SATC) jointly organized and sponsored the Phobos Base Student Design Competition. The design brief conveyed a dual focus on the Environmental Control and Life Support Systems (ECLSS) engineering and the Space Architecture for design of the base and habitability for the space living and working environments. This paper presents the results of the winners in the undergraduate and graduate student categories. The purpose of the Phobos Base design competition was to develop an integrated solution for the next step in developing Mars exploration architecture: The Phobos surface base. Phobos base will support exploration of Phobos, the remote exploration of Mars, and the eventual staging of human expeditions to the Mars surface.
Keywords: Space Architecture, Habitability, Environmental Control and Life Support System (ECLSS), Aerospace Engineering, Life Science, Architectural Design.

Nomenclature—Acronyms/Abbreviations

Δv	=	"Delta Vee," Change in Velocity
ECLSS	=	Environmental Control and Life Support System
EUS	=	Exploration Upper Stage
EVA	=	Extravehicular Activity
ICES	=	International Conference on Environmental Systems
ISS	=	International Space Station
LMO	=	Low Mars Orbit
LSSTC	=	Life Sciences and Systems Technical Committee
MDAV	=	Mars Descent-Ascent Vehicle
SATC	=	Space Architecture Technical Committee
SLS	=	Space Launch System
TU	=	Tribhuvan University
UH	=	University of Houston
UVM	=	University of Vermont
WUT	=	Wroclaw University of Technology, Pennsylvania State University, AGH University of Technology, Lund University

1. Introduction

Phobos Base Student Design Competition presented two foci to the participants: to design the architecture for a habitable base in deep space and to design the environmental control and life support system to support the crew in that base. The two AIAA Technical Committees each contributed expertise to their respective portions of the design brief. The aim was to encourage future life support engineers and space architects to learn to work together on a common project or mission.

The major mission design challenge in staging humans to Mars concerns what to do when a spacecraft carrying a crew, a habitat, or other payload arrives in cis-Martian space. The two conventional options are to circularize into low Mars orbit (LMO) before landing or to attempt direct atmospheric braking, entry, descent, and landing. This design competition addresses the alternative of creating a logistical and scientific base on Phobos, the larger and closer of Mars' two moons. This base would host and support crews in transit to Mars and returning from Mars to Earth.

The major human support challenges of long duration microgravity flights include the effects on human systems adapting/deconditioning including pressure in the eyes from body fluid redistribution, bone demineralization, loss of muscle mass, and general deconditioning. Thus, a major focus is to provide human health and habitability maintenance regarding microgravity and surface environments while minimizing health risks through enhanced radiation shielding and microgravity countermeasures. As a probable captured carbonaceous chondrite asteroid that may contain as much as 13% water by mass, Phobos may also provide a source of life support and propellant consumables, including fuel for a reusable Mars Descent/Ascent Vehicle (MDAV). A critical advantage of Phobos Base would be its contribution to making a strong interplanetary infrastructure in deep space, which would make Mars exploration more sustainable over a long-term of 50 years or more.

In order to make the reports from the student teams as readily comparable as possible, the Competition Design Brief prescribed the outline in which they should write their submission, with a 100-page limit. The students would decide how much text and illustrative figures to place in each title or subtitle within the outline.

In presenting this overview of the results, the objective is not to show a rigorous, side-by-side comparison, but rather to illustrate the wide variety of strengths that the student teams displayed in what they learned. In this way, these results illuminate the many different areas of inquiry they pursued during their design project. This approach also helps to show the many complex dimensions of staging a human mission to Mars or Phobos, that often do not appear in the abundant advocacy-driven studies.

2. The Undergraduate Winners

The two undergraduate winners were the University of Vermont, Burlington VT USA for first place, and the Institute of Engineering, Tribhuvan University, Kathmandu, Nepal. The participants from the University of Vermont were Emmie Bolt, Greg Castaldi, Sami Connoley, Cam Ru_e-Deignan, Duncan Hacker Moritz Thali, Jacob Wainer, and Matthew Walton. The participants from Tribhuvan University, who called themselves Team Phobians, were Arjun Magar, Raj Kumar Gurung, Rajan Bhandari, and Sanjeev Adhikari. Their Faculty Advisor was Prof. Sudip Bhattrai.

2.1 University of Vermont

The submission from the University of Vermont (UVM) displayed a significantly higher level of insight, sophistication, and understanding than the undergraduate submission. It begins with an elegant discourse on the waiting period before departing the Earth and cis-lunar space. They describe the elliptical orbit about the Earth, its precession, and departure with excellent trajectory diagrams. FIGURE 1 shows the UVM departure trajectory Δv estimates table.

The trajectory adjustment upon arrival in the Phobos vicinity is even more impressive. The following passage explains the UVM approach and it relates to the calculation that follows in FIGURE 1 for the spacecraft to maneuver close to Phobos.

In order to compensate for the angular discrepancy between the capsule and Phobos the craft will perform a phasing maneuver. In orbital mechanics it is well understood that satellites orbit slower when they are further from the central body. The capsule will take advantage of this fact to adjust its trajectory and approach Phobos. By _ring an impulse normal to the orbit, away from Mars, the craft will experience a Δv of 0:0374974 km/s and enter a slightly elliptical orbit with a larger semi major axis than Phobos' orbit. While in this orbit, the spacecraft will travel with a slower angular velocity allowing Phobos to approach from behind.

After 8:08592 hours Phobos and the craft will have the same true anomaly. This time of flight is calculated from Equation 5 where r0 is initial position and v_1 and v_2 are the true anomalies in degreed of Phobos and the craft respectively. At this point the craft will again make a Δv maneuver of 0:0374974 km/s, this time back towards Mars. The gravity of Phobos will begin to act on the craft and draw it in. As the capsule is slowly being accelerated towards Phobos it will use attitude control nozzles to control speed and guide itself to the appropriate landing location. The total Δv requirements for the entire process from Mars capture to Phobos rendezvous are outlined in Table 3.

The UVM ECLSS calculations deserve notice; it appears that they developed their approach *from first principles* on their own and made some reasonable estimates. FIGURE 2 shows a detail from their report, detailing the calculation to estimate the required mass of water per day to generate enough O_2 to support crew respiration.

For the Phobos Base Architecture, UVM proposed automated assembly, with a simple configuration based largely upon the TransHab-derived Bigelow Aerospace "Olympus" inflatable module. In addition to this single very large pressurized environment, the UVM Phobos Base would incorporate an observation tower. FIGURES 3 and 4 show the base configuration side by side.

Although the UVM engineering work showed originality, sophistication, and subtlety, their architectural design and drawings appear very simple, and in some respects simplistic. This contradiction suggests that the UVM team consisted predominately or entirely of engineers, with few if any architects. The floor plan for "Module 1" the berthing module that the

UVM configuration would anchor to the Phobos surface provides an example of outward simplicity in the rendering but with some sophisticated thought behind it

$$t_{phase} = 2\pi\sqrt{\frac{r0^3}{\mu}}[1 + (\frac{\nu2 - \nu1}{360})] \quad (5)$$

Table 3: ΔV requirements from Mars capture to Phobos rendezvous.

Maneuver	**ΔV Required**
Elliptical to Parking Orbit (Shaping)	0.403464 km/s
Parking to Phobos Altitude (Hohmannn Transfer)	0.552202 km/s
Phobos Rendezvous (Phasing Maneuver)	0.0749948 km/s
Total	**1.03066 km/s**

FIGURE 1. Δv requirements from Mars capture to Phobos rendezvous.

An average person requires 550 liters of oxygen per day.[13] For twelve astronauts, this becomes 6600 liters. By the ideal gas law:

$$m = \frac{MPV}{RT} \quad (10)$$

$$m = \frac{0.032\frac{g}{mol} * 101.3kPa * 6.6m^3}{8.3144621\frac{J}{mol*K} * 293} = 8.75kg \quad (11)$$

This means that 9.02 kilograms of water will be required per day to provide oxygen for the crew.

FIGURE 2. UVM calculation of the amount of H_2O necessary to process to produce one day's worth of breathable O_2 for the crew.

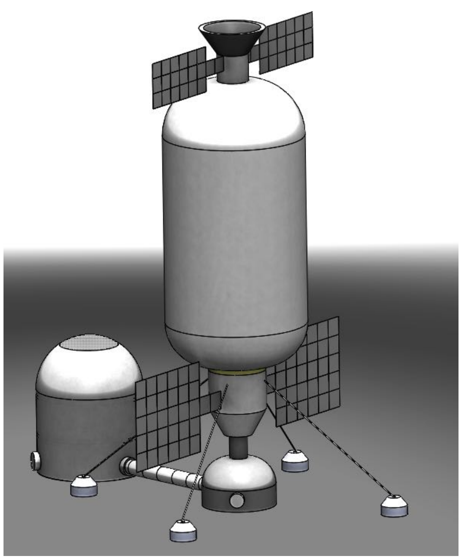

FIGURE 3. View of the UVM Phobos Base, showing the Olympus Module, Observation Tower and docking node.

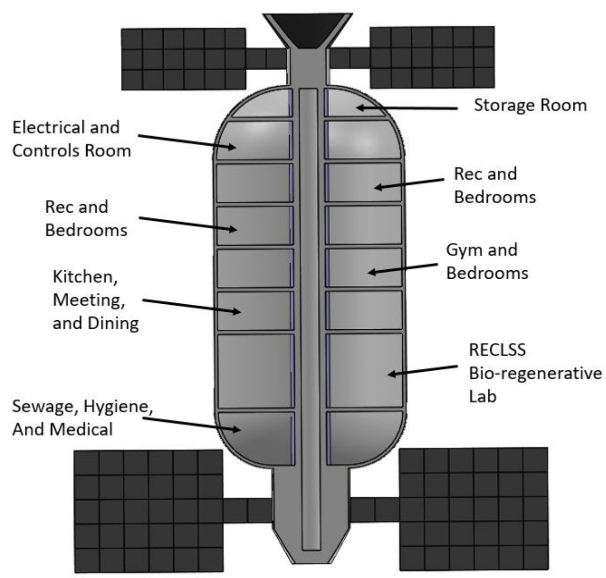

FIGURE 4. Transverse section of the UVM Olympus inflatable module, designating the various functional volumes.

FIGURE 5 presents the floor plan of this foundational module. FIGURE 12 shows Module 1 providing three radial ports penetrating the pressure vessel wall. These radial ports can accommodate berthing connections such as the tunnel to the Observation Tower, and EVA airlock, or docking to a pressurized spacecraft. The UVM design logic makes this module both a science laboratory for Astrobiology and a workshop for fabricating whatever the crew may need to make or replace on Phobos. It appears to include a separation wall between these two key functions.

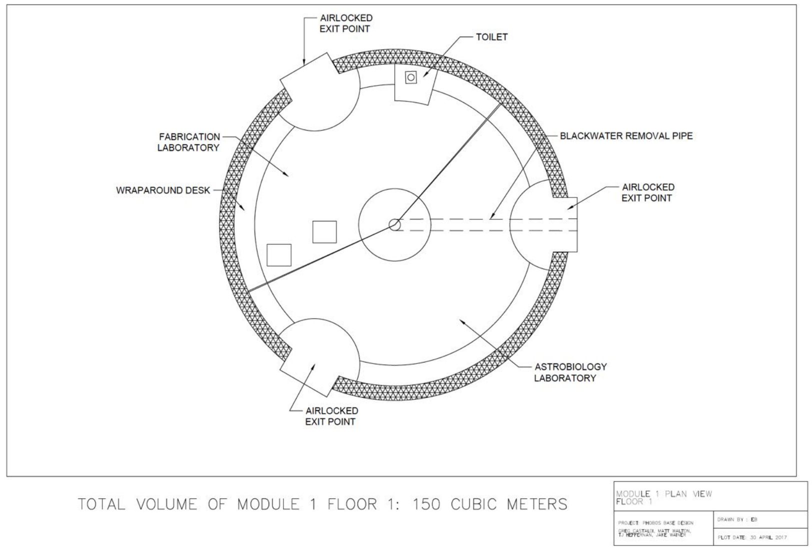

FIGURE 5. Floor plan of the UVM "Module 1" foundation module.

2.2 Tribhuvan University

The Phobians from Tribhuvan University (TU) focused more on the engineering side of the project, providing detailed calculations for the astrodynamics and trajectories of the spacecraft taking their Phobos Base to cis-Mars orbit, including the calculation of velocity to enter and maintain Mars orbit before rendezvous with Phobos. TU engaged in numerous discussions of the cost, mass, technical suitability and technology readiness, starting from the launch vehicles, continuing through the astrodynamics of the trajectory and the maneuvers at Mars and Phobos, and finally detailing the engineering for the ECLSS. This passage describes their reasoning for selecting the Space Launch System (SLS) Block 1B with the Exploration Upper Stage as their launch vehicle of choice.

Considering this Payload capacity, the whole base transportation completes in six launches. Since, in a single launch window all six launches is impossible to occur due to inability to develop six rockets within the given time as well as the difficulty in maneuvering of these launch trajectory such as they don't intercept each other. Thus, the whole base transportation extends between 2018 to 2026 with the first launch on May 2018 and arrival of last base module on Phobos on early 2026. Increase in payload for minimum fuel consumption and minimum dry mass of rocket is the primary issue in the development of the rockets. SpaceX is making rockets on minimum budget constraints with its maximum payload to mars being 13.5 metric tons by Falcon heavy. Since this Payload capacity is much lower than demanded by our mission plan, SLS was chosen. SLS Block 1B uses a more powerful second stage called the Exploration Upper Stage (EUS). On January 2015, test firing of RS-25 engines began for use on SLS and continued in 2016 and 2017 showing positive test results. This signifies the availability of SLS Block1B for the Phobos Base Transportation.

TU's habitable architecture centered on a variation of the NASA/Bigelow Aerospace TransHab-type module. FIGURE 6 shows a transvers section-elevation of the Phobian base, revealing the "docking volume" below the surface of Phobos and the TransHab-derived inflatable modules above the surface. These modules radiate from a central, spherical hub.

FIGURE 7 presents a perspective view of the TU Base, showing the layout of the TransHab-derived inflatable modules berthed radially around the central spherical hub. What appear to be solar arrays stand on the surface in a circle around the Phobian site. A structure that looks like a multi-bay radio antenna projects upward from the central hub. Spacecraft or utility modules dock to the ports at the distal ends of the inflatable modules.

FIGURE 8 Shows a larger, transparent view of the Central Hub, showing three locations for observation stations. Although FIGURE 8 shows the Central Hub as appearing to incorporate pressurized berthing ports around the equator, they do not appear in this view. The internal division of the spherical volume suggests a separation of the observation functions; certainly, the astronomical and Mars-facing positions require pointing in different directions. Why the Rover Operation Station does not share the same hemisphere with the Mars Observation Station, since they are both focused on Mars, is not explained.

FIGURE 9 presents the TU table of ECLSS Mass, Power, and Volume Estimates, apparently derived in some fashion from comparable numbers from the ISS. This table shows an important effort to investigate, understand, and calculate the ECLSS requirements for the crew in the Habitat.

TU did a heroic job of addressing all the engineering parameters of the Phobos Base design brief. They covered the Astronautical and ECLSS calculations. They made an effort at providing a micro-g countermeasure using a lower body negative pressure system. Their entry in the competition is a promising start for the participants' careers.

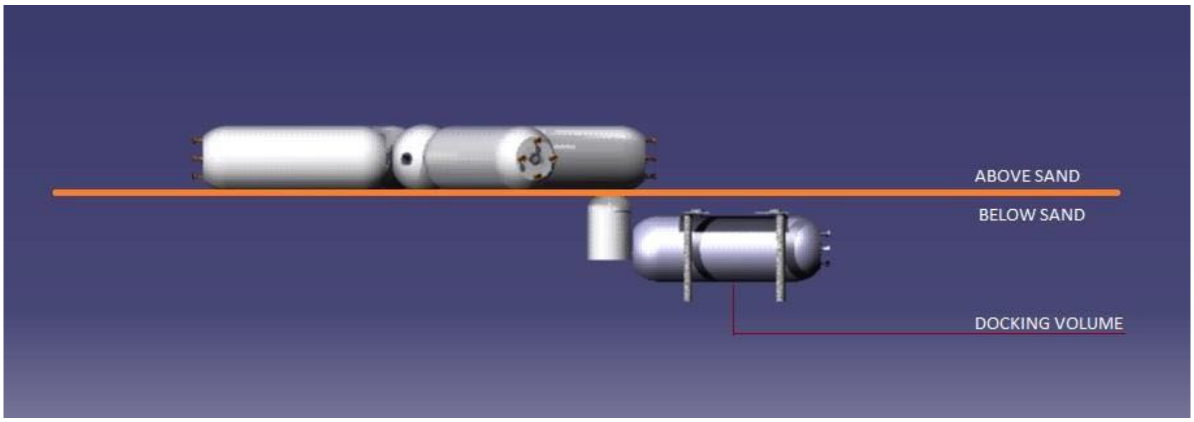

FIGURE 6. Transverse section-elevation of the Phobian Base, revealing the location of modules above and below the surface.

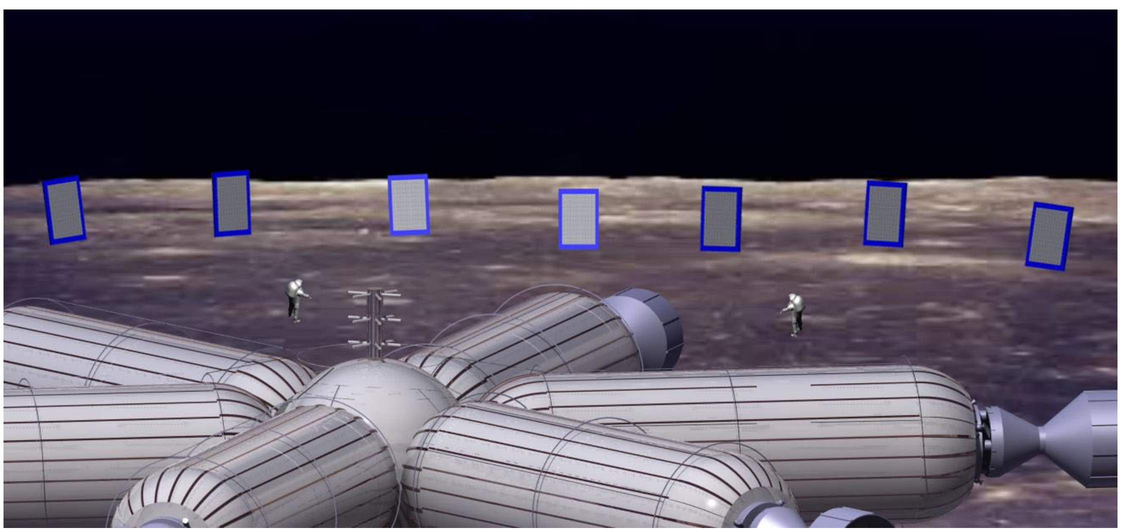

FIGURE 7. Perspective view of the Phobian Base, showing the radial arrangement of the pressurized modules around the spherical central hub, and spacecraft docked to ports at the distal ends of the modules.

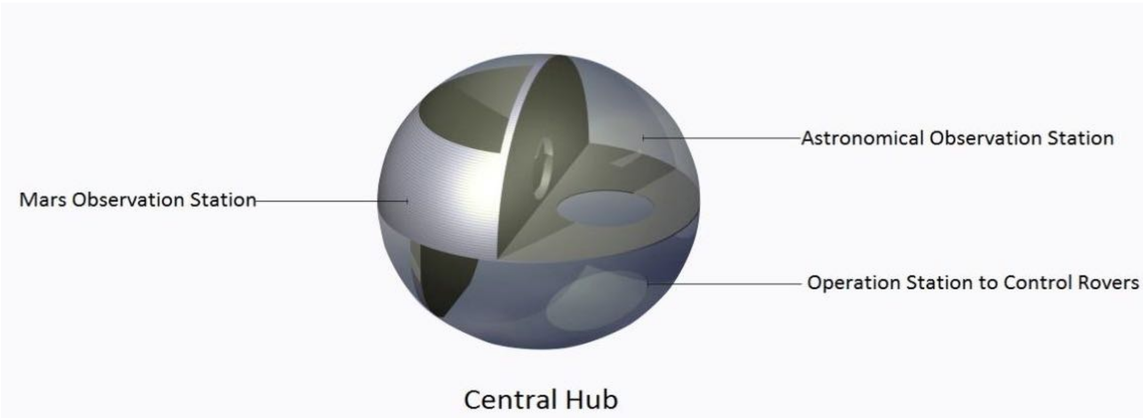

FIGURE 8. Transparent View of the Phobian TU Base Central Hub

System	Heat Generated(KW)	Power (KW)	Volume(m^3)	Mass(kg)
Water	1.999	2.211	3.255	890.935
Waste	0.363	0.363	2.063	277.765
Food	4.18	4.18	5.28	3028.63
Atmosphere	3.8643	3.8863	16.588	5897.3
ECLSS system total	10.406	10.64	27.186	10095.3

Table: ECLSS Total Mass, Power, and Volume Estimates/ISS

FIGURE 9. TU Phobian Base Table of ECLSS estimates.

3. The Graduate Winners

The two graduate winners were the University of Houston, Sasakawa International Center for Space Architecture, for first place, and Wroclaw University, of Technology, Poland for second place. The participants from the University of Houston were: Timothy Bishop, Victor Kitmanyen, Thomas Lagarde, and Zachary Taylor. Their Faculty Advisor was Assoc. Prof. Olga Bannova, Ph.D. The participants from Wroclaw University were Aleksander Gorgolewski, Anna Jurga, Leszek Orzechowski, Joanna Kuzma, Jan Popowski, and Bartosz Wasik. In addition, three individual students from other universities joined the Wroclaw team: Gordon Wasilewski from AGH University of Technology, Poland, Monika Lipinska, Lund University, Sweden, and David Conte, Pennsylvania State University, USA.

3.1 The University of Houston

The University of Houston (UH) team named their project “Phari Base,” for reasons they did not explain. The UH project displayed a strong familiarity with recent and current space exploration hardware and technology. Their approach showed an understanding of established system engineering approaches popular with NASA. The UH team saw their design concept as analogous to the International Space Station (ISS):

> The crew at Phari Base must be prepared to receive both crew and supplies from a multitude spacecraft that may arrive at almost any time to Phobos. This is analogous to the crews onboard the ISS where there are multiple supply visiting vehicles and crew transfer vehicles that dock with the ISS on a regular basis. The same can be assumed for Phari Base, where visiting vehicles carrying supplies will be sent periodically and may use any class of mission that is the most efficient method of delivery. Mars bound crews may arrive less frequently, however, since the base is assumed to expand its capabilities at some point in the future, crews can expect more traffic to flow through the base and thus should be prepared for these operations (p. 11).

Despite this analogy to the ISS — or perhaps because of it — the UH team did not appear to recognize that these launches of cargo and crew to Phobos would depend upon the Hohmann minimum energy transfer orbit windows that open up every 22 months between the Earth and cis-Mars space, including its two moons. This Phari analogy to the ISS carries through to the structural organization of Phari Base around a segment of truss:

> The transfer of the Phari Base infrastructure will happen in two stages. The first stage will be to launch the truss assembly to Phobos. The rationale behind this activity is to ensure Phari Base has an established structure on Phobos that is secured to the bedrock. Furthermore, the truss assembly itself is cheap relative to the entire base and will only require one SLS Block 2 launch. This makes the truss assembly expendable in the event the system fails; if that were to happen, telemetry would be sent back to ground control in order to engineer a more robust system. Such measures are justifiable considering how unpredictable Phobos is, even with reconnaissance probe mapping the surface (p. 23).

FIGURE 10 shows an exploded axonometric view of the Phari Base concept with its central truss. The crew quarters module was based upon the TransHab inflatable module concept.

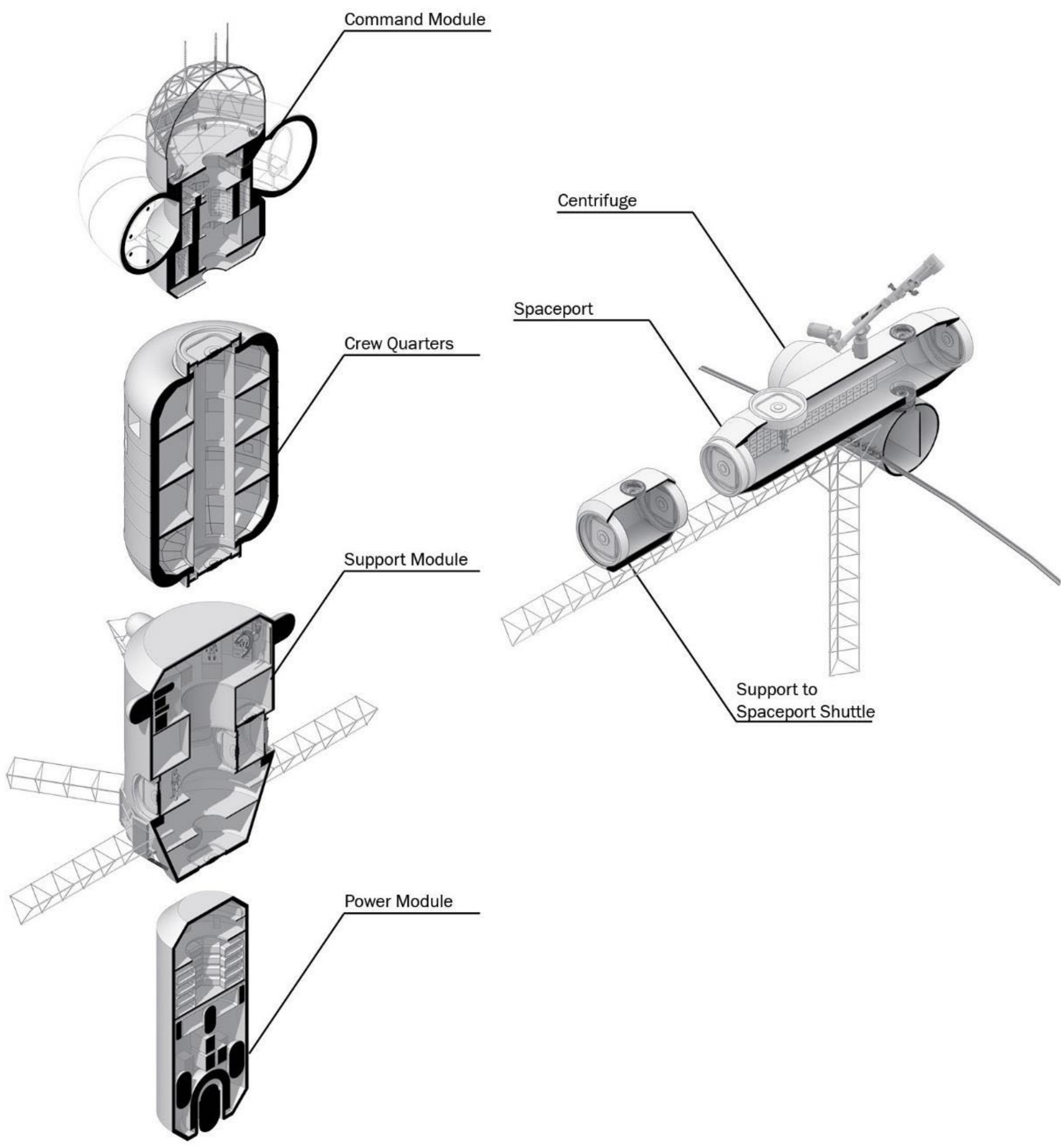

FIGURE 10. Exploded view of the *Phari Base* architecture, showing the centrality of the tetrahedral truss structure for anchoring and connecting the modules.

The UH team provided a countermeasure against microgravity in a torus wrapped around the crew module. Their countermeasure scheme involved rotating the Phari Base configuration, and the crew would enter the torus to experience higher gravity levels. FIGURE 11 shows three views of this configuration, along with some details of the dome and galley area.

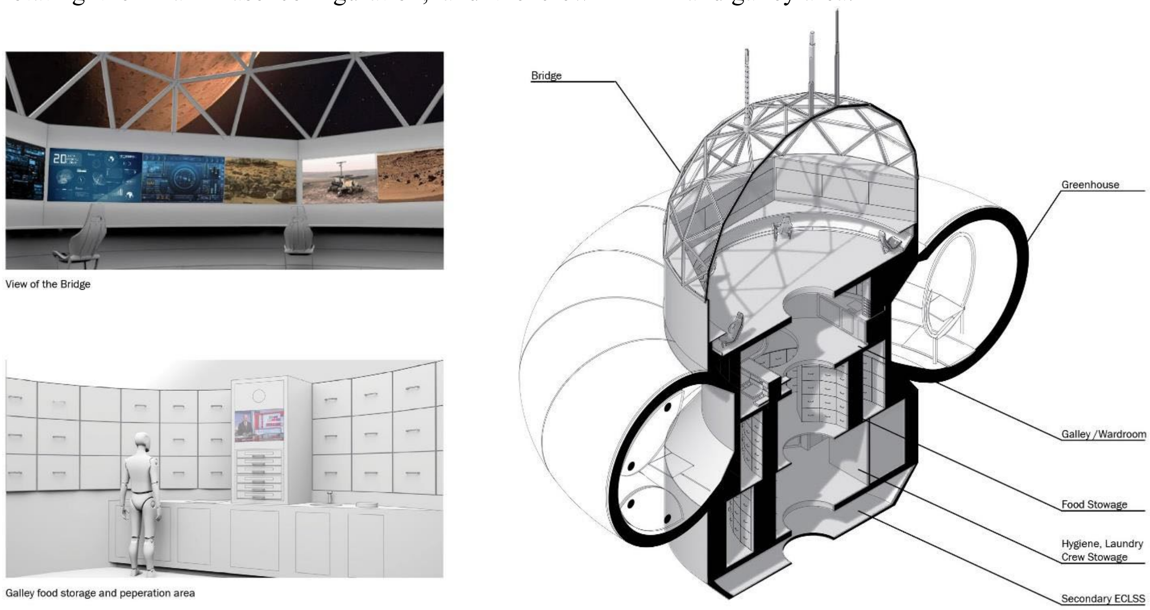

FIGURE 11. Crew module of the *Phari Base* with the "artificial gravity" torus around it. The crew module includes the geodesic dome area, galley, and all the other crew accommodations.

Overall, the UH team concentrated far more on the Space Architecture than upon the life support engineering, although they made a valiant attempt at micro-g countermeasures. The design and presentation of the habitable architecture was clear and sophisticated. What is more remarkable, the Space Architecture aspects are almost self-explanatory. UH included some estimates for ECLSS, but they were not nearly up to the level of the Architecture, which showed true professional capability.

3.2 Wroclaw University of Technology

The Wroclaw University (WUT) team brought a wide range of capabilities to the Phobos Base design problem. They named their project *Phobos Base Fearless,* negating or refuting the name of Phobos, which means fear in Greek. So, here it shall be Base Fearless. These capabilities appear to include structural and mechanical design engineering. In the mechanical engineering efforts, the students to produce their results including in structural and architectural engineering, they designed a cable-restrained holding the atmospheric pressure over a foundation. One key element of the WUT design is a fission reactor, for which they performed detailed calculations.

FIGURE 12 shows an overview rendering of the complete WUT Base Fearless. The cable-restrained roof of the inflatable stands out as the central feature. In addition, there are a variety of smaller outlying utility structures and subsystems. At a smaller scale there appears a wealth of subsystems.

FIGURE 13 shows a detailed structural cross-section of the cable-restrained inflatable roof. Although the students did a credible job on how the tension cables would help restrain the roof fabric and maintain its shape, they are nearly silent on how to attach the roof in a leak-proof manner to the foundation. What they say is:

> Construction is attached to the ground using prefabricated carbon fiber elements anchored to the ground by meter long steel screws. Cushions are connected to plate using "zipper" technology.

That roof to foundation connection will prove critical to maintain the integrity of the atmosphere containment, and it is unlikely that the arrangement in this brief description would be sufficient. Since this roof covers the largest pressurized volume, the ability to secure it in a pneumatically sealed manner will be critical to protecting the health, safety and lives of the crew.

The WUT students went into considerable detail on the design of the fission reactor and the mass of its constituent elements. FIGURE 14 shows their mass table.

Towards the end of the WUT report, the students pull together all the diverse elements into one site plan/axonometric (FIGURE 15) that goes a long way to explain their concept. They separate and distinguish three major activity areas: The Mining Site coupled with the Nuclear Power Station, the Mars Observatory, and finally, the Base Fearless core itself. It makes good sense to locate the mining site close to the nuclear fission reactor because mining will surely consume more power than any other part of the base. Separating the Mars Observatory some distance away from the activities at Base Fearless would help in minimizing contamination from dust kicked up or propulsive gases released in the vicinity of the base core and the mining site. The base core proves more complex than FIGURES 13 and 14 may suggest.

In the two frames on the left are axonometric views of parts of the WUT concept. The upper frame shows a radiator system to cool the fission reactor. In front of it are several versions of the Base Fearless lander and utility vehicles. Some are equipped with drills, some with robotic arms, some with other tools. The ones with the spherical bubbles can serve as pressurized spacecraft. In the lower frame appears the excavation for the "basement" or lower volume. This area is not pressurized; it accommodates the landing pad, which would be sintered or otherwise compacted and solidified. Connecting to this volume sits a passage or tunnel leading to three cylindrical modules. These three modules presumably provide the main living and working areas for the crew at Base Fearless, covered by the cable restrained inflatable roof.

This FIGURE 15 site plan conveys a contradiction. The students took great cares to move the nuclear reactor and the Mars observatory far from the Base Fearless core. However, they located the greatest threat to safety, the landing pad where a fuel-laden propulsive vehicle will touch down only a few meters from the living quarters for the crew. A misguided descent of a bad landing could cause an explosion, wiping out everyone at the base. That would be something to fear. Nevertheless, the students did an admirable job in putting together the most complete and sophisticated site plan in the competition.

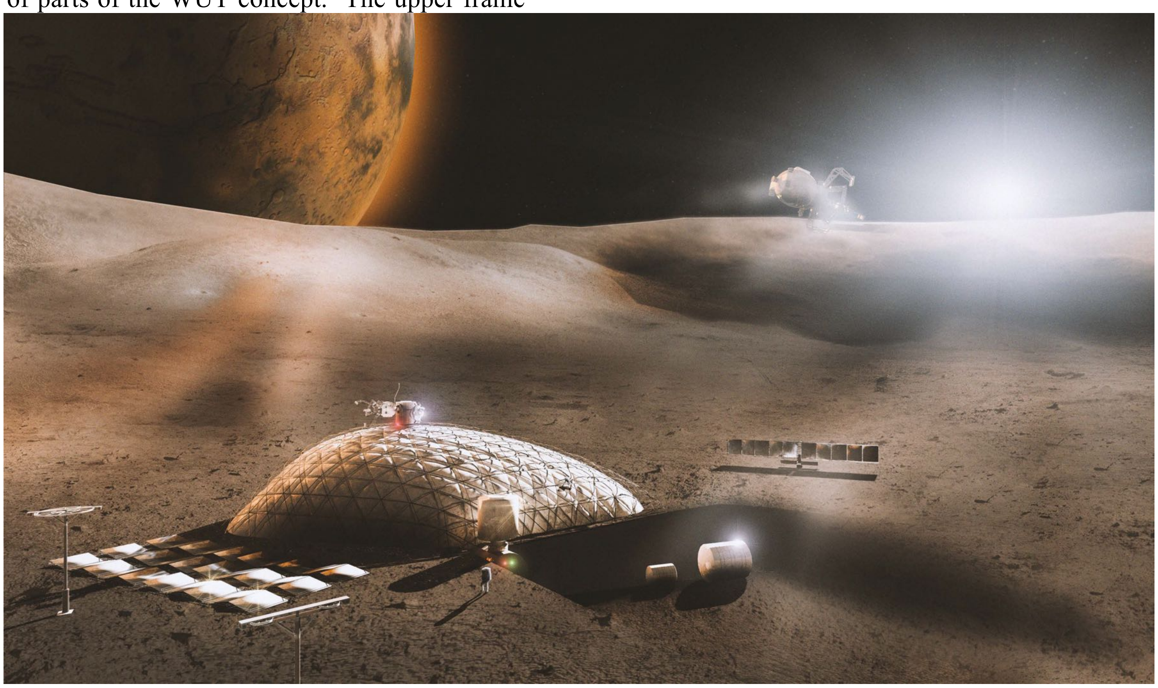

FIGURE 12. Overview rendering of the Wroclaw University team's *Base Fearless.*

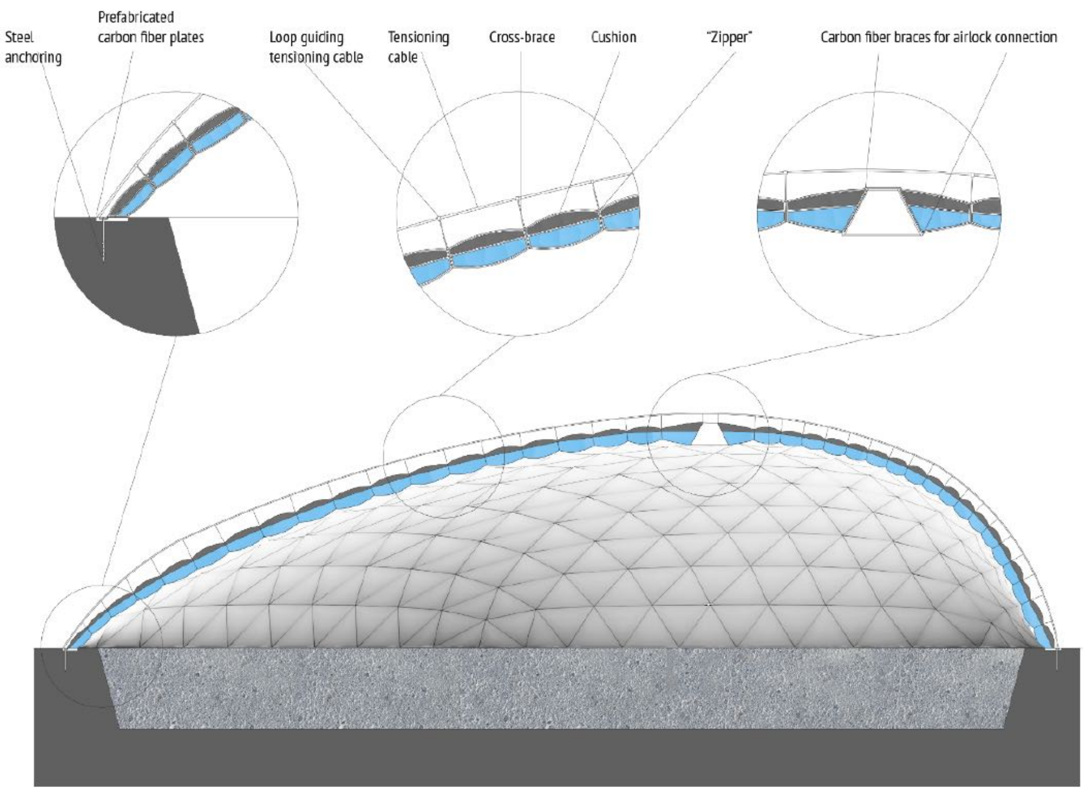

FIGURE 13. Structural cross-section of the WUT *Base Fearless* inflatable, cable-restrained roof.

Part	Main system	
	Mass, kg	Comment
Reactor	913	93 percent enriched UO2, NaK coolant, SS–316 cladding/structure, Be drum reflectors, 1 primary and 2 intermediate loops, 6 EM pumps, 175 kWt, 900K peak clad temp, cavity radiators
Shield	1676	B4C and SS–316, 1.2-m-thick axial plug, 1.2 by 1.5 m elliptical face, <2 Mrad and 1×10^{14} n/cm^2 at Stirling converters, Phobos regolith augmentation, <5 rem/yr at 100m radial distance
Power conversion	344	Free-piston Stirling, 4 dual-opposed converters, 8 linear alternators × 6 kWe, 100 Hz, T_H = 830 K, T_C = 415 K
Heat rejection	615	Pumped H_2O coolant, 4 independent loops, 400 K inlet temp, composite radiator panels with Ti/H_2O heat pipes, scissor deployment, mylar surface apron, 175 m^2 total area
Power conditioning and distribution	559	400 Vac distribution, 100 m cabling, 120 Vdc user bus, parasitic load control, comm/telemetry link, 5 kWe solar array, 10 kWh battery
Subtotal	4107	
Marigin	821	20%
Total	4928	

FIGURE 14. Table of masses of the components of the *Base Fearless* Fission Power System.

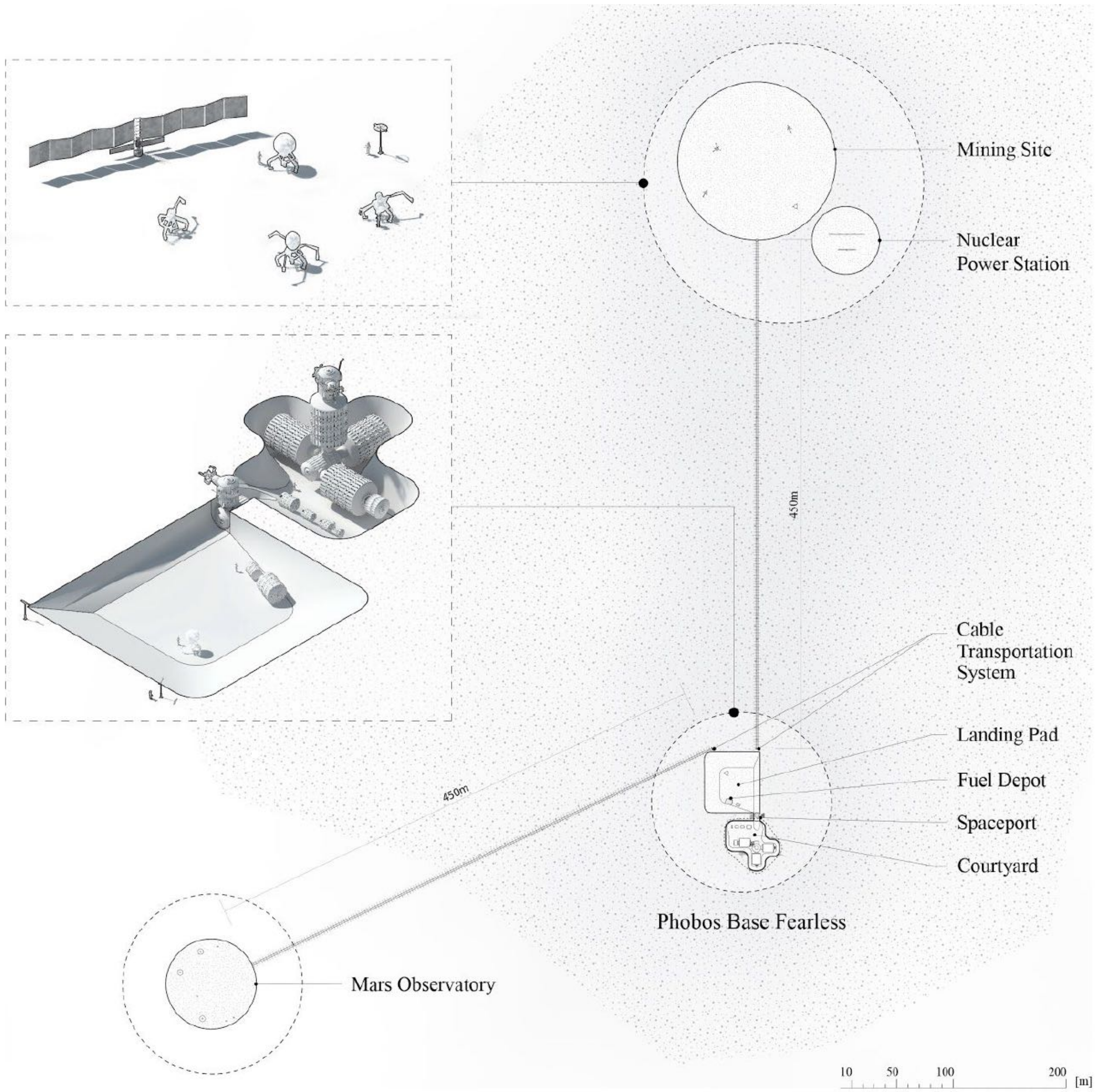

FIGURE 15. WUT *Base Fearless* site plan and axonometric view of the module assembly.

4. Discussion

This discussion of the Student Design Competition results appears in three sections: Section 4.1 discusses the student Life Support (ECLSS) Engineering. Section 4.2 discusses the student design of the habitable architecture. Section 4.3 discusses the managerial, administrative, and procedural aspects of conducting the Student Design Competition.

4.1 Discussion of the ECLSS Engineering

Each of the design teams made some effort to address certain aspects of the ECLSS, but these attempts were only partial or very selective at best. In general, the discussion of environmental control and life support systems was not the strongest aspect of either the graduate or undergraduate design proposals. Some teams put forth interesting ideas, but they were not, for the most part, well characterized in terms of their system impacts and integration requirements. System issues with operation in micro-gravity environments in transit and on the surface of Phobos went frequently unaddressed Back-up information and analyses to establish the suitability of novel ideas for the Phobos mission were generally not presented. Because each of the winning proposals offered some interesting technology choices and presented sound analyses and evidence of background research in some areas as well as significant weakness in other areas, ECLSS did not become a major discriminator in selecting the winners or in differentiating among them.

Bio-regenerative life support offerings, driven by the RFP goal of growing 50% of the crew's food needs, provided most of the teams' innovative ECLSS offerings including provocative suggestions for crew diets based in part on growing insects (e.g. cockroaches) and cyanobacteria. In two of the proposals these suggestions were backed up with data characterizing expected yields and nutritional characteristics, but unfortunately none carried these suggestions to the point of suggesting how these dietary elements would be prepared and integrated into palatable and appealing crew meals. Similarly, a suggested rotating garden technology in the UH offering was justified by a rationale of plant growth benefits from reversing gravitational fields that seemed disconnected from the microgravity environment anticipated during transit from Earth to Phobos and on Phobos' surface, and suggested dimensions and rotation rates seem inconsistent with any really useful artificial gravity forces on the growing plants (e.g. 30 micro-g at 22 min/rotation).

Composting plant wastes and crew wastes was a significant element in nearly all the bio-regenerative offerings. This reflects the clear need to recycle biomass that is not consumable by the crew if significant food growth is going to be viable in missions like the targeted Phobos base and the evident desirability of closing the loop on consumed nutrients as well. However, none of the proposals really addressed the impacts of composting as an aerobic process on the sizing, design, and operating conditions for physical / chemical atmosphere regeneration systems like CO2 separation and reduction, humidity control, trace contaminant control and oxygen generation, or the compatibility of proposed composting processes with anticipated crop planting / harvesting cycles. Finally, there was a notable absence of discussion of the impacts of large-scale plant growth on base water supply and water treatment systems.

4.2 Discussion of the Habitability Design

The Habitability portion of the discussion addresses the undergraduate and graduate winners as separate sections.

4.1.1 Undergraduate Teams' Habitability Designs

Phobos Base Design submitted April 2017 by Greg Castaldi, Jacob Wainer, Emmie Bolt, Matthew Walton, Moritz Thali, Cam Ruffle-Deignan, Duncan Hacker, Sami Connoley, University of Vermont, Burlington VT, USA. (UVM)

Human Spaceflight: Phobian Base submitted April 2017, by Arjun Magar, Raj Kumar Gurung, Rajan Bhandari, Sanjeev Adhikari, Institute of Engineering, Tribhuvan University, Kathmandu, Nepal. (TU)

Both undergraduate teams, UVM and TU, proposed vertical volume structures with habitable and working spaces stacked producing a consolidated series of compartmentalized units.

UVM proposed adequate room for all activities though the storage capacity may be small, and the design allowed for smaller groups to operate by separating areas not only horizontally but vertically. Most habitat areas were reasonable in size except for the electrical/controls room in the Bigelow Olympus Tower. UVM illustrated isolated sections that could operate independently and considered emergency situations related to any failures or damage to life support systems in terms of crew health and safety, isolating crews in compartments until the environment was stable, which was mostly a mechanical/structural intervention while TU introduced a human focused concept of a Crew Health Care System as a software suite for medical/environmental feedbacks for health and safety.

TU focused on the regimentation of activities of daily living and exercise at the same time each day, building routine. This team stood out suggesting how and when crews would perform activities of daily living tasks. The team understood crew discipline for repetitive, same tasks, day in and day out, and how routine was important for crew health and in fact, crew safety. The habitat values were difficult to determine for the TU team as they appeared to value tasks and performance within a disciplined crew and didn't spend time presenting their work in terms of human factors and ergonomics of the interior space and overall the allocations of crew space appeared insufficient. UVM identified the communal kitchen as home-like and having a familial value, while TU appeared to view nutritional and dietary parameters as simple satisfying an appetite rather than being a communal activity that had high social value and that could also include gardening as a recreation/relaxation activity however focused on the production of food as the function purpose. UVM provided a specific module for a garden to be integrated in the living quarters of the crew, appearing to embrace the aspect of garden as having a therapeutic value.

The habitat values were difficult to sort out in TU proposal; some were missing. There appeared to be a lack of consideration of human factors and ergonomics in terms of space required to navigate around equipment in microgravity. Overall, the allocations for the TU base appeared to be insufficient. In terms of habitability innovation, of the two undergraduate teams, TU appeared to a bit further advanced and courageous. The TU team proposed introducing the Crew Health Care System (CHeCS) as a software suite to provide medical and environmental feedbacks to ensure health and safety of the crews. This team also highlighted concepts for the extraction of water from Phobos with a unique solution of using a microwave beam to heat up the water to a certain extent so that it can be converted to vapor.

4.2.1 Graduate Team Habitability Design

Human Spaceflight Phobos Base submitted April 2017, by Timothy Bishop, Victor Kitmanven, Thomas Lagarde, and Zachary Taylor, Sasakawa International Center for Space Architecture (SICSA), Cullen College of Engineering, University of Houston. (UH)

Phobos Base Fearless: Concept of Operations and Architecture for a Permanent Human Presence on the Martian Moon Phobos submitted April 2017, by Leszek Orzechowski, Davide Conte, Aleksander Gorgolewski, Jan Popowski, Anna Jurga, Bartosz Wasik, Joanna Kuzma of Wroclaw University of Technology, Poland; Pennsylvania State University, USA; Gordon Wasilewski of AGH University of Technology, Poland; and Monika Lipinska of Lund University, Sweden. (WUT)

Not considered: University of Southern California – "The Space Trojans" an Interplanetary Mission Sketch but not a design habitat for the Phobos Moon.

Of the two graduate teams to complete and submit a 'habitability' proposal, the UH team provided and demonstrated an exceptional understanding of human factors, human physiology and psychology in terms of the configuration and use of space to live in. Two of the featured mechanisms proposed would significantly improve the habitability of the Human Spaceflight Phobos Base (HSPB): 1. a rotating, green-house, and 2. a centrifuge exercising/recreation facility that provide health solutions to counter effects of micro-gravity on the human body, radiation, dust and contaminants in the habitat.

The UH design provided for a range of solutions to the problems posed by the extreme environment and by including their understanding of interior lighting to address human circadian rhythm. They also indirectly addressed the perception of safety, of free and open access between spaces so 'obstruction' did not become an annoyance nor expenditure of energy. Creating a 'safe room' in the Command Module was good, designed to contain crew for a maximum of four days as an added redundancy.

The UH investigation into visual perception of the environment encompassed lighting and the curvature of the habitable volumes, LED lighting technology and its ability to provide specific spectrums for day and night, was well illustrated as well as an analysis on color for navigation, presenting a case for the psychological support the crew for orientation, sense of up and down, and mental health. Curved spatial configurations can be disorienting on Earth, and the UH team alluded to that condition for this space habitat as the floors of both modules would be slightly curved with respect to the curvature of the base. Interestingly, the team argued that this would help 'prevent the perception of slopes (inclines and declines) and promote the feeling of a flat environment.'

The UH team also understood the importance of eating, diet, caloric, fat, and protein intake, and did provide details on planting growth systems and comparisons between possible alternatives. Feeling that traditional exercise required a change of environment for such a long-duration mission to Mars, the team proposed creating an exercise area with treadmill, bike and weights to be used in artificial gravity (AG) via centrifugation, with the caveat that this solution may still pose harm to crewmembers due to the impacts of rotation and acceleration within the structure.

The calculations, logistics and planning features of the WUT proposal while incomplete due to time management constraints, was detailed and consumed much of the paper, and it focused on advanced tele-operations bringing materials, frames and integrating habitat modules over years. The analysis of power requirements showed that this team identified lack of sun light at the site which would immediately impact habitability and functionality of systems.

Using robotic agents, the WUT team appears to have decided to reduce the activity of crews engaging and being exposed in the open and on the surface of Phobos. Three reasons would be: enhancing crew safety, attempting to ensure infrastructures and human engagement avoided contamination of the habitat, and lastly, the attempt to simulate an Earthlike relationship with the outside environment.

The crew could operate in a semi-pressurized courtyard, under a membrane, giving astronauts the possibility to experience being 'outside', without full EVA equipment. They suggested that astronauts needed only light space suits and breathing devices. This approach certainly would provide an alternate habitable environment. it also appears that this crew will be operating in shifts and sharing sleeping arrangements.

The habitat does not appear to have adequate room for all health-related lifestyle activities and appears to encourage working in isolation or in a cramped situation where it may be necessary to share work. The galley kitchen was small for a crew of two to prepare a meal for a crew of 12. The provision of a table for a crew of 6 to sit together outside of the galley was good. The recreation space beside the food production space in the Green Module was also demonstrating that the team understood the therapeutic value of seeing green spaces color, and plant textures. Space in the Green Module was adequate for 1 crew member only.

There was an effort to provide information on their biomass production. Fully aware of the need for fresh food for the crew, oxygen production, removal of carbon dioxide, the WUT team investigated parts of the nutrition and dietary requirements of crew, the introduction of insect species for protein, and listed plant species with caloric value compared to surface area the plants would require to grow. The Private Module did provide a favorable interior for psychological health and wellbeing of crew members as it was set apart from group activities and noisy equipment. This would help to reduce the 'mechanical noise' and vibration sensations often commented about by astronauts. This team did approach the design highlighting functional areas and divided the modules into private, activity, group activity, food production (green module) and the dirty module. The interior space was designed to provide transit between spaces, and they did mention in their paper a concern for the physical and psychological health and wellbeing of the crew. Several ideas were offered with respect to accommodating human factors and they did look at the cognitive concerns for moving about the modules. They proposed creating an artificial orientation by locating stronger lighting on 'ceilings' and beside frequently used pieces of equipment put on 'walls. These measures were proposed to give a sensation of vertical 'up' and 'down' and right and left sides while moving within the modules. The main feature this team highlighted was the outside space for exercise and recreation by providing the semi-pressurized courtyard with its protective membrane. The team felt that the membrane would be 'an additional layer protecting astronauts from the external environment, giving them sense of security, while the semi-pressurized courtyard contributed to visual perception of the microgravity countermeasures. Having Phobos subgrade on 'bottom' and membrane structure above distinguished 'up and down', very desirable in the microgravity environment.'

4.2.3 Summary of the Habitability Designs

The Phobos Design Competition garnered attention from five teams, two undergraduate teams and 3 graduate teams. One of the graduate teams, the team from the University of Southern California, elected not to address habitability in their proposal, approaching the call with an interplanetary base design that didn't address the criteria for the competition that included a base on Phobos. The UVM and the TU team both combined vertical and horizontal configurations for a habitat base.

Several teams embraced the concept of robotics and humans working together. The prospects of mining the moon's surface for a water supply was introduced in a variety of ways by WUT and TU. The most outstanding part of the WUT team is a semi-pressurized courtyard space to serve as a space haven for the crew. Its function goes further in terms of offering radiation protection for the habitable functions. The semi-pressurized courtyard gives astronauts the possibility to experience being 'outside', without the full EVA equipment. It brings storage area; composting, a potable water tank, an excavated water tank and grey water tank. The area also allows for more convenient conditions of many works and repairs which usually would consume working spaces inside. To stay in that area, astronauts need only light space suits and breathing devices. Repeatedly in all the proposals, storage was limited for mission, quarters would be cramped, and the courtyard space helped eliminate some of those negative conditions of habitability in this exercise.

One of the concerns that repeated itself in all the proposals was the combining of the medical units with areas meant to handle waste or personal hygiene. The concern for this author is the sharing of the sewage space with the medical and hygiene functions in some of the designs. While understanding that sharing the infrastructure to transport grey and black water in common areas where waste products in terms of excrement, or bodily fluids will require efficient removal, it also creates a vulnerability to contamination of the medical care unit where an astronaut may be sick or injured or dying. Containment in the event of a crew epidemic, separating contaminated space from the 'cleaner' habitable areas, was challenging and in some cases lacking in consideration. These elements also tended to be located close to the ventilation system supplying the entire habitation unit. The teams combined the gym or exercise units near sleeping quarters, this too may be disruptive for crew members trying to rest or relax in their private quarters while outside a team member is on a treadmill or using weights.

Most of the papers did not address the gym environment qualities, perhaps because this activity was not required as a separate functional area or volume in the proposal call for the design competition. The TU team did not provide material on recreation or relaxation activities though space was allocated within the food storage compartment. They believe the relaxation area should be quiet and isolated. While the UH did not identify the value of the Cupola on the ISS where crews go to as prospect refuge viewing the Earth and some degree of relaxation.

The TU appeared to recognize the requirement for privacy and perhaps even the activity of meditation. This may be a culture consideration for this team from Nepal and there are some interesting parallels for where they located the recreation space within the food storage area, perhaps with a similar consideration like the other teams, who placed greater value to the accessing of plant materials or the view to modules with plant materials as therapeutic.

In the end however, TU determined that gardening or food production spaces were designed strictly for ECLSS functions (working and to meet simply feed crew) and there wasn't the attempt, as in the other teams' papers, to integrate such spaces for the purpose of increasing comfort, aesthetics, or mental health support for the crews. TU, unlike other teams, however, emphasized the need for food storage from Earth which including storing 15,000 kilograms on the Phobos base as well as continued resupply of food from Earth.

TU referred to the risks of the space environment to human safety and health but made a statement in their analysis that risk 'is generally benign once the launch is successful'. While true that risk is extremely high at launch and landing, for a Mars expedition, the risk patterns may be dramatically different, and this undergraduate team did not demonstrate insight. One concern in the TU design was their 6th module, proposed to contain fuels, hydrogen, stored water, materials and supplies plus the energy cells for running the base. With respect to crew safety and psychological support, this storage solution of highly flammable materials combined and located in close proximity to the habitat module, despite its containment underground, would likely result in an underlying and ongoing psychology concern for the crews.

As with the other teams, WUT mentioned the microgravity effects on crew physiology. They were unique in their examination of women's health issues in terms of menstruating in space. The TU team referenced including females in their crew complement, and they appeared to have cultural sensitivity to separating the capacities and privacy needs of two genders. WUT team also illuminated the different sanitary needs between male and female crews.

Interestingly UH did not present significant information on the use of the washrooms by crew, or their personal hygiene concerns. [seems most of the teams did not approach this aspect of habitability]. Most of the teams considered the standard solutions for waste management, through an awareness of the sanitary systems that are in place in ISS. The TU team proposed both a commode and a urinal as separate units and appeared to have dealt with the perpetual issue of foul smells, contamination, and separating solid waste from liquid waste.

4.3. Discussion of Managerial, Administrative, and Procedural Aspects of the Design Competition

The team from the AIAA LSSTC and SATC commenced discussions about holding a joint student design competition in the Human Spaceflight category at the 45th International Conference on Environmental Systems (ICES) in Bellevue, WA in July of 2015. Shortly thereafter, we produced the first draft of the design brief. The joint team went through many revisions. When the team felt the draft was ready, they presented it to the staff of the AIAA Foundation that organizes and runs multiple student design competitions each year.

However, the AIAA Foundation staff had just undergone a reorganization that cast into doubt the schedule for when they would review the proposals from the Technical Committees to select the design competition proposals for the 2017 competition year. Not surprisingly, seen in hindsight, there was a considerable amount of confusion concerning what the competition proposal needed to say, what were the criteria for selection, and the extent to which these criteria may have changed from previous years. The joint TC team appointed Donna Rodman as the single point of contact with the AIAA Foundation. Donna spoke at length to the staff and attempted to interpret for the Joint TC team what the staff told her. However, that interpretation was difficult because it consisted of literally playing telephone. Donna would talk to the staff, and then she would write what she thought she heard in an email. Finally, the Joint TC Team was able to elicit from the staff the written competition proposal template. From that time, it was possible to move ahead with composing the competition proposal to the AIAA Foundation.

The two TCs agreed that ideally the design competition should consist in equal weight of Life Support Engineering and Life Science Countermeasures on one hand and Space Architecture, habitability and the design of space living and working environments on the other. The teams completed and agreed upon the competition proposal and submitted it to the AIAA Foundation. A paper at the 46th ICES in 2016 reported on this progress (Cohen, 2016). The AIAA Foundation selected the Phobos Base proposal from the Joint TC Team in the summer of 2016. They said it was their turn to carry the ball; we could relax and let them do the rest.

Early in the process of communicating and coordinating with the AIAA Foundation, it became clear that it would be necessary to name one of the TCs as the lead organizer and to name a single point of contact. Since Donna Rodman was the person who volunteered to be the point of contact with the AIAA Foundation and she belonged to the LSSTC, and that settled it.

The AIAA Foundation staff packaged the Phobos Base design brief into their RFP format that went out via email to all the AIAA student chapters. It also appeared on the AIAA Foundation website along with other design competition RFPs such as aircraft design. One of the incentives the AIAA Foundation provides is a prize: $500 for first place, $250 for second place, and $100 for third place. However, for reasons unknown, the advertisement for the Phobos Base competition did not mention the prizes. So, it looked to would-be student teams like it was the only student design competition lacking the endowment of prize money. The Joint TC Team did not discover this omission until long after it was too late for adding the prize money to make any difference.

Consequently, other student design competitions received up to 15 entries. The Phobos Base competition received only four valid entries; and these were the four that won places in the design competition. The Phobos Base design competition received one more entry from the University of Southern California that consisted largely of a polemic about why putting a human base on Phobos was a mistake. The judges ruled that because this submission did not actually include a design project it was non-responsive and therefore, they could not evaluate it.

A further complication arose for the 2017 ICES when the TC Joint Team wanted to establish or reserve presentation time slots for the winning teams to present their work at the conference. The ICES Steering Committee did not vote to approve such an arrangement. The conference chair for that year insisted that only papers that passed successfully through the standard abstract approval and manuscript approval process could be published or presented. The only alternative would seem to be to invite the winning student teams to submit an abstract by December and then come back the next July to present their work of a year earlier.

The entire design competition design cycle took two years, from the beginning of the idea in 2015 to the announcement of the competition in September 2016, to the receipt of entries in April 2017, judging, and announcement of winners in June 2017. The Joint TC Team's plan had been to award the prizes at the 47th International Conference on Environmental Systems (ICES), 16-20 July, 2017. However, that approximately one-month period was far too short notice to allow the teams—especially the ones from Nepal and Poland—to travel to the USA by mid-July to accept their awards.

The Awards themselves proved a bit of a puzzlement. The Design Competition consisted of two divisions, one for graduate students and one for undergraduates. However, the AIAA Foundation allocates prize money for three prizes. Although it was relatively straightforward to select the first place winner in each division, it was difficult to decide upon the "third place" winner, since that meant that one division would rate two winners but the other would rate only one. This mismatch between the divisional structure and the number of prizes suggests a need to reconsider the assignment and allocation of prizes.

A final, unexpected problem was that the Joint TC Team was unable to obtain the judges' written evaluations and comments about the design submissions from the AIAA Foundation. It would have been very helpful to the Joint TCs to understand how well the students rose to the competition challenge in the judges' estimation.

5. Lessons Learned

The deliberative design requirements process to create the competition design brief began two years before the AIAA announced the student design competition. Most of the TCs' efforts in the process went into preparing the competition and working with the AIAA staff to do so. Preparing the design brief was the fulcrum about which the whole effort turned. It required participation and buy-in from the members of both TCs to ensure there was a balance between life support engineering and space architecture design. Even so, the students put much more effort into the space (mission) and habitat architecture design than into the ECLSS engineering. That outcome raises not so much a lesson as a strategic question: should there be a mid-competition submission and review so the TCs can give a commentary and course correction if needed to ensure the student teams cover all the bases sufficiently and equitably? Such an intervention would require a major revision to the competition procedure and would require extensive discussions with all the stakeholders before making such a change for a future design competition.

So, besides this one big strategic question, here are the lessons learned:

5.1 Get everything in writing

If anyone refers to a document, a guideline, or a template, make sure to get it in written form as soon as possible. Do not try to rely upon a recitation of a text over the telephone.

5.2 Keep communicating with the AIAA Staff

Stay in active communication with the AIAA Foundation Staff throughout the process, even when they seem to say, "Please stop bugging us, we will take it from here."

5.3. Clear point of contact

Pick a single primary point of contact to communicate with the AIAA Foundation, but also provide a lot of back up, including having multiple members of the TC team participating in teleconferences.

5.4 Check everything from the AIAA staff whenever there is something new.

If there is one new item that is announced, there may be others that were not announced. Check all the correspondence carefully and follow all the links to make sure everything is happening the way it should. It is especially important to be vigilant about the items that unknown persons in the AIAA staff post to the competition website, and to monitor them for accuracy, completeness, consistency, and timeliness.

5.5 Promote the Design Competition outside the AIAA

Make the effort to advertise the design competition outside of AIAA channels to students at universities that work with the TC members where there may be AIAA student chapters.

5.6 Uniform location of content

Use a system for uniform location of content for the student submissions so that it is easy for the judges to compare the submissions "apples to apples" and actually find all the teams' apples.

5.7 Clear evaluation criteria

Make sure that the judging evaluation criteria are clear and consistent so the student participants know what they are and so that the volunteer judges follow them.

5.8 Realistic and Practical Date for the Awards Ceremony

Schedule the award ceremonies long enough after the judges complete their work and the winners receive notifications that they can plan travel to the award ceremony and raise money to fund it. In this instance, the next AIAA meeting, the Space Forum and Exposition, typically held in September, may provide the best option.

5.9 Arrange in advance to obtain the judges' final evaluations

Arrange in advance with the AIAA Foundation staff that they will furnish the judges' final evaluations and scoring of the student design submissions to the sponsoring TC(s).

5.10 Student Papers at an AIAA Forum

Pick a conference to present the prizes to the winners where it is possible for the sponsoring TC(s) to create placeholder abstracts in a student paper track for the winners of the design competition to submit their cleaned-up reports as conference papers, thereby making them formally referenceable. This proviso means altering the traditional paper submission process to allow for the fact that the student teams will be hard at work writing materials the AIAA invited. It *should* be possible for the AIAA staff and publication system to behave flexibly enough to accommodate the student design winners.

6. Conclusion

The AIAA Phobos Base Student Design Competition was a worthwhile endeavor. The student teams did a terrific job in their design submissions for Phobos Base. The competition proved as much a challenge to the Joint TC organizing and judging teams as first-time design competition organizers as it did to the students.

Team design competitions of this type can afford a very rich and meaningful design experience for the students. Perhaps the most important factor for them is to start the competition early, during the fall quarter or semester. For that reason, it is important to get the word out to prospective student teams as early as possible — before the start of the new academic year.

Four take-aways from the competition experience deserve attention and further discussion. These findings indicate a need for the AIAA to make changes in how they conduct student design competitions, at least with respect to complex humans in space projects: midcourse correction review, awards schedule, placeholder student abstracts, and the number of winners and prizes.

6.1 Mid-course Correction

Although the student design teams all did well with their mission designs and habitable space architecture, they all suffered from a lack of attention to the ECLSS Engineering. A mid-course review could have helped to emphasize and strengthen that dimension of the design competition. It would also have informed the competition organizers that it would be helpful to provide more reference material that would be relevant in case the international competitors (e.g. from Poland and Nepal) did not have access to it.

6.2. Number of Winners

The AIAA or AIAA Foundation needs to address the mismatch between the *even* number of divisions and the *odd* number of prizes. Ideally, each division should be able to accommodate first, second, and third prize winners. In this framework, the competition judges would have been able to select up to six prize winners, up to three in each division.

6.3 Schedule Awards Ceremony Far Enough in Advance

On the AIAA's annual student design competition cycle, it announces the new competitions in September and the winners of the competitions in mid-June. As part of the prize-giving, the AIAA then presents the awards to the student teams or their representative(s) at an AIAA Forum or associated conference. Assuming that each team needs at least three months to organize their travel to the award ceremony and raise funds to pay for their trip, the soonest the award ceremony should take place is at the AIAA Space Forum in late September of that year. A fallback position might be to hold the award ceremony at the Sci-Tech Forum in January of the following year. If the organizers of an ECLSS and Space Architecture competition such as this one for Phobos Base feel very strongly that the award ceremony should occur at the ICES, then they should hold it the following year, giving the student teams time to submit their abstracts through the normal ICES submission process (due date is typically around 8 NOV).

6.4 Placeholder Abstracts are part of the awards

The amounts of the awards are almost purely nominal: \$500 for first place, \$250 for second place, \$100 for third place. The awards ceremony and the awards themselves would be much more meaningful and significant if as part of the prize experience, each team presents an executive summary of its design entry when receiving the prize. To make this event possible, it would require that the ICES or the AIAA Space Forum — or whatever conference hosts the awards ceremony — provides placeholder abstracts as part of the award for each winning student team. Sponsoring the students in this way to present their work at the awards ceremony would be much more meaningful for all involved.

7. Acknowledgments

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8. References

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