Self-Assembling and Self-Regulating Space Stations: Mission Concepts for Modular, Autonomous Habitats

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The field of space architecture must contend not only with the environmental challenges of operating in the vacuum, but also with constrained physical dimensions in rocket payload fairings, risky astronaut space-walks, and limited robotic mobility for assembly. To address these challenges, we propose a new construction paradigm—one that moves beyond aluminum cylinders in orbit to build towards larger volume, modular space stations that still meet the mandates of life support systems and safety. Our TESSERAE (Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments) research platform builds on principles from biomimicry: self-assembly from discrete nodes following a certain "coded" growth pattern. We also introduce redundant and reconfigurable parts for robustness and adaptability. Our work focuses on autonomously self-assembling and self-regulating space structures, without requiring a human EVA or robotic agent. Overall, the TESSERAE hardware platform includes a series of functions for *self-aware* self-assembly and maintenance that allow for in-space construction and reconfigurability of orbiting, multi-module space architecture. Our research platform integrates magnetic docking, sensor technology and control code to bond common base units into modular structures. An early, miniaturized hardware testbed for this platform was deployed successfully on the ISS over 30 days in 2020 and is slated for further missions. Our paper for ICES 2021 presents a vision for integrating this structural, in-space self-assembly with interior livability, including a new ECLSS integration plan for the modular structures. We also point forward to a dual mission concept for TESSERAE, merging A) microgravity self-assembly and in-orbit operation with B) the ability to self-disassemble and re-purpose structural tiles for use on a planetary surface.

Nomenclature

ConOps = Concept of Operations
ECLS = Environmental Control and Life Support
ECLSS = Environmental Control and Life Support Systems
EPM = Electro-Permanent Magnets
EVA = Extravehicular Activity
LIFERAES = Life-support Integrated Electromagnetic Reconfigurable Adapative Environment Systems
MSM = Module System Manager
MBR = Membrane Biological Reactors
TESSERAE = Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable Adaptive Environments

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I. Introduction

As the space industry plans for semi-autonomous and seasonal crew activity in platforms like Gateway, and as the ranks of astronauts expand to include space tourists and other visitors, we anticipate a need for reconfigurable and adaptive habitat architecture. The TESSERAE platform offers a new approach to the construction of exo-shells in orbiting contexts. Rather than relying on prefabricated, uni-body modules that are sent to orbit in a predominantly finished configuration, such as the approach with most current ISS chambers like Destiny,[1] our approach defines modular surface tiles that join together to form a closed topology or chamber geometry (see figure 1). We have focused our shell-based research work on one prime example, the "buckyball"—a closed geometric surface comprised of 20 hexagonal and 12 pentagonal tile segments. We do not subdivide these sections further into a triangular tessellation, for the initial TESSERRAE prototype development, due to the need to minimize additional seams and reduce the number of distinct tiles that must self-assemble to close the 3D structure.[ǂ] For now, TESSERAE is therefore not a standard "geodesic dome" and will rely on additional clamping between gasketed tile seams to provide the structural rigidity and air-tight containment for pressurization.[2] In addition, we anticipate inflating an internal bladder and pressurizing the interior as an added layer of safety redundancy in certain mission scenarios.

The TESSERAE tiles each include a specialized suite of custom electro-permanent magnets (EPMs) and sensing that guides autonomous self-assembly after tiles have been released in a microgravity environment.[3,4] In our intended ConOps, TESSERAE tiles are released inside a temporary inflatable membrane to keep tiles proximate as they self-assemble through the interactions between their magnetic docking faces. With the use of EPMs coupled to an autonomously functioning state machine, the bonding execution system selectively controls the magnet torques and polarities to provide for sensor-mediated self-assembly *and* self-disassembly (for bonding error detection and correction). We have tested a series of miniaturized hardware prototypes for this platform across several microgravity environments, culminating in a successful demonstration of quasi-stochastic self-assembly in a multi-tile swarm on the ISS over 30 days in 2020.[3]

With this TESSERAE approach, we aim to define the modular, reconfigurable building blocks of flexible habitat architectures, so that:

A) large and open interior-volume habitat chambers may be constructed (larger than the widest rocket payload fairing on the market) while preserving a rigid exo-shell;

B) agile habitats of the future may respond to changing ConOps, evolving mission goals, and On-orbit Servicing, Assembly, and Manufacturing (OSAM) needs by replacing or changing out their surface shell complement with a standard suite of tiles (akin to LEGOS™ at space scale); and

C) entire space stations can be self-assembled in short order, deployed for use, then de-pressurized, disassembled and packed flat again for shipping to a new destination, thus creating a generation of reusable habitat technology that could serve both government and commercial needs in LEO and at near-Earth Lagrange points, in addition to NASA's Moon to Mars focus.

Building on our prior work that explored the mechanism of modular, autonomous self-assembly from a structures perspective, we now consider the applicability of the TESSERAE platform for the industry's broader framing of "smart spacecraft" and present a vision for integrated, autonomous, modular systems across both exo-shell construction and interior livability. Through this smart spacecraft lens, we use this paper to present cutting edge environmental control ideas that should be considered for inclusion in next-generation habitat design, as we explore beyond the current ISS station paradigm. This holistic approach integrates the TESSERAE self-assembly construction paradigm for exo-shells with additional work at the MIT Media Lab Space Exploration Initiative on responsive interior environments that can optimize occupant happiness or performance ("Mediated Atmospheres"). We also present new, collaborative work with Axiom Space on an ECLSS integration plan for the TESSERAE modular structures.

ǂ While the current TESSERAE prototype approach does not make use of triangular tessellations, due to the points shared above, we are considering triangle-based tessellations for extensibility to closed geometries other than the buckyball. While this paper soley considers shell-based habitat self-assembly and the associated ECLS integrations, a separate TESSERAE research thrust also explores volumetric-unit self-assembly of pre-fabbed, plesiohedron ("space filling") modules.

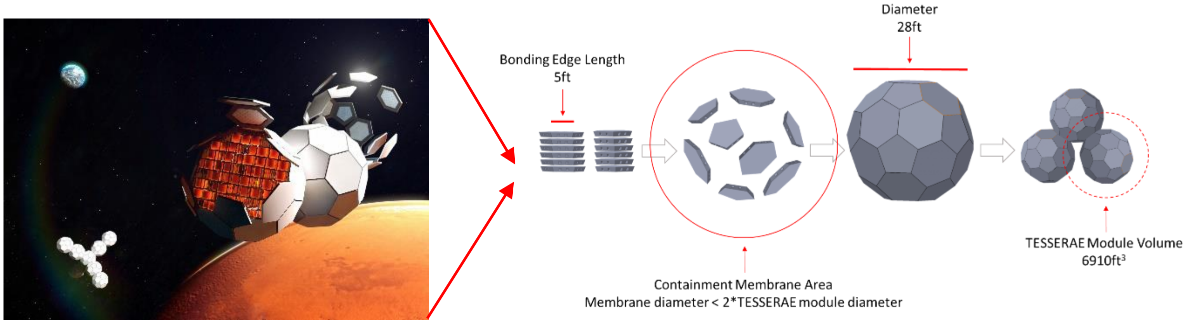

Figure 1. Overview of TESSERAE Self-Assembly Concept. From left to right: TESSERAE render, courtesy of TU Dortmund Fraunhofer Institute, decomposed into a staged operations diagram. TESSERAE tiles are first packed flat for launch; upon release at orbit insertion, tiles circulate in microgravity for self-assembly inside a flexible containment membrane; as tiles self-assemble they form the buckyball shell module; finally, entire TESSERAE modules are docked for larger space station configurations. These preliminary dimensions are prospective; we expect to develop a suite of TESSERAE modules with variations on the physical scale.

ECLS systems play a critical role in human space exploration. However, many of the functions that ECLS systems provide in human spaceflight architectures also satisfy mission requirements for a variety of non-human spaceflight architectures, such as thermal control for sensitive spacecraft systems. Additionally, while many spacecraft subsystems have played a critical role in satisfying government-defined mission requirements, the thought of monetizing the functions provided by subsystems is still fairly new in the implementation of spacecraft. As the private space market grows, mission flexibility for both cost and utility will be essential for providing solutions that meet customer demand. The modular TESSERAE approach can open the trade space around the idea of operationally responsive missions that cross boundaries between human and non-human spaceflight architectures, serving varying government and commercial mission architectures. Specifically, TESSERAE ECLS systems or Life-support Integrated Electromagnetic Reconfigurable Adapative Environment Systems, LIFERAES, could provide maximum utility around mission flexibility and prospective ECLS monetization through the various, "remixable" utility functions provided. In addition to describing the TESSERAE technology and integration of new autonomous systems across construction and livability, this paper will describe how LIFERAES support modular ECLS functionality in a variety of mission scenarios. We close with a brief, initial presentation of economic prospects around monetization efforts so that ECLS systems may transform from a value-sink to a value-source.

II. Literature Review

Modular assembly of space habitats has been explored by de Weck et al., including use of innovative geometric base units.[5] The literature review in de Weck's 2005 analysis points us to a rich history of standardization, interoperability design, and modularity in space structures. We present a condensed version of their review here, including Frisina's work on densely packing space structures for launch based on triangular faces,[6,7] and the interoperability and interchangeability with other models from the early work of Baily et al.,[8] Harwood et al.,[9] and Abbot et al.,[10] for standardization of interfaces, docking systems and reconfigurable spacecraft, respectively. Scott Howe has pioneered an approach to modular panels for the construction of space structures, notably the TRIGON system and several related applications.[11,12,13,14] While the TESSERAE system uses a different mechanism for self-assembly (quasi-stochastic EPM docking) and targets different final geometries, we build on Howe's notion of modular self-assembly and reconfigurability. Modular self-assembly has been shown in many smaller scale earth-based robotic swarm systems,[15,16,17,18] a field that TESSERAE draws on to extend agent-less self-assembly into microgravity environments. We also build on fundamental concepts from chemistry in the energy activation and energy favorability considerations to drive stochastic self-assembly of modular parts to a deterministic final structure.[19,20] In the applied aerospace realm, numerous robotic docking considerations for in-space assembly have been considered,[21,22,23] though TESSERAE takes a new approach by avoiding traditional propulsion or jet-powered GNC systems in favor of quasi-stochastic self-assembly through controlled magnetic torques.

On the topic of systems-level requirements and design considerations for aerospace vehicles and larger structures, Newman et al. discuss how to incorporate principles of flexibility into aerospace system design[24] and Coen establishes the range of requirements that ECLS functions must meet in an interplanetary habitat.[25] Highly networked, best-in-class modern connectivity and IoT-like systems have been proposed for augmenting space habitats,[26] and we build on this work by showing how environmental control systems can be part of this networked paradigm in the future. An integrated, networked approach to space habitats can benefit from shell structures that are themselves "smart infrastructure," with natively embedded sensor and tile-tile communication networks that can support livability functions, as we are proposing for TESSERAE. Finally, we draw on the trenchant observation that cost, rather than strictly performance or engineering ingenuity, now drives the space program[27] after the geopolitical motivators of the Apollo era waned and the calculus of political budget planners changed. We intentionally offer TESSERAE as a platform for iterative, incremental growth with only modest resources required for each additional tile or shell set, in an explicit attempt to jumpstart progress on sustainable expansion of human activity in space that does not depend on political whims.

ECLSS is a critical, core functionality for human spaceflight because it keeps humans alive. While much work has been performed to study and enhance robustness, spacecraft programs are still working on roadmaps that would help define modularity in the context of vehicle design. [28,29,30,31,32,33,34] Modularity in ECLSS systems may help to decrease costs and enhance reliability while promoting more flexibility in mission objectives. Vehicle-ECLSS integration will be a key feature for future stations, habitats, and transport vehicles when considering how to reduce cost and decrease complexity while enhancing reliability. Escobar, Nabity and Klaus note that the forefront ideas and analysis for decreasing overall mission costs while enhancing reliability have revolved around concepts of sparing and increasing robustness: reliability, resilience, and survivability.[35] Much work is needed to apply these principles to real systems and build out the integrated hardware and software control models for modular, resilient and properly-redundant ECLSS components.

Paragon Space Development Corporation began some of this work in 2009 via the Commercial Crew Development program where they advanced ECLSS modularity with the development of an "all-in-one" ECLSS air revitalization system, CCT-ARS (Commercial Crew Transport – Air Revitalization System).[36] UTC Aerospace Systems (UTAS) joined the field in developing modular or "palletized" ECLS systems with the work they were doing in the NextSTEP program in 2016.[37] The work performed by these two life support system companies has helped to advance the notion of modularity through the framework they developed for enhancing serviceability, increasing the ease of integration, and reducing costs through interchangeability.

Future concepts for modularity that could add flexibility involve bioreactor membranes. In recent years, there have been studies that focused on Membrane Biological Reactors (MBRs) as a viable means to remediate wastewater in the microgravity environment of human-tended space exploration missions. The biological water processor (BWP), built as part of the Alternative Water Processor (AWP) system located at NASA Johnson Space Center, serves as one such example of space-based membrane bioreactor research.[38] Instead of relying on settling tanks as in terrestrial systems, the BWP utilizes a series of membrane aerated biological reactors (MABRs) to reduce the carbon and nitrogen loads in wastewater. MABRs are hollow cylinders that contain bundles of tubular gas-permeable membranes inoculated with wastewater microbes that establish biofilms to mediate carbon oxidation and nitrogen removal from the influent waste streams.[39] The flow of wastewater through these membranes must be maintained to ensure homogenous mixing of the microbial environment and prevent inert biomass from collecting on internal substrate surfaces. Although not currently deployed in space, membrane bioreactors represent an actively researched water processing technology for future human space exploration missions. Intended as a vital component of a larger life support system architecture, MBRs are not a stand-alone technology, and are best suited as modular components to larger wastewater processing systems. Modular MBR applications could function as part of a sand-substrate nanoparticle biofilter,[40] an upstream waste removal element to an osmotic membrane system,[41] or even as a yeast-bacteria bioreactor in multi-stage space farms.[42] Like all microbial-based biofilms, MBRs will likely show future vulnerability to environmental perturbations, especially in smaller digester systems,[43] but if incorporated as a modular component to an expandable wastewater treatment system, such vulnerabilities could be mitigated through added redundancy.

Serviceability, ease of integration, and interchangeability are key tenets for spacecraft architectures of the future and preventing gaps in ECLS architectures.[44] Overall reliability and adoption of modular systems will also be critical. Principals such as buffering while utilizing sparing to enhance reliability[45] and in-space resource utilization, coupled with applied development of modular, next-generation ECLS modules such as bioreactor membrane systems, will aid in increasing adoption rates for modular ECLS. We anticipate that such adoption will in turn result in enhanced reliability and reduced mission cost.

III. Integrating Self-Assembling and Self-Regulating Systems: TESSERAE livability vision

A. Livability: Next generation goals with Mediated Atmospheres in Space

Designing the "atmosphere" and sensorial qualities of physical space can have a remarkable influence on human experience and behavior. The original Mediated Atmospheres project[46] (figure 2) envisioned and built a smart office that is capable of dynamically transforming to enhance occupants' work experience and cognitive ability, via both subtle and overt customizations tailored to closed-loop bio-signal inputs. The workspace prototype is equipped with a modular real-time control infrastructure, responding to biosignal sensory input from occupants (such as heart-rate, IR facial analysis, galvanic skin response, etc.) with controllable lighting, image projection, heat, smell, and sound. This technology (from customizable individual elements to the entire room or building scale) can be applied to a space exploration habitat or crew cabin context to address behavioral health risk reduction and cognitive performance improvement for human life in deep space.

Manipulating light, sound, smell, and visual-field objects can have a powerful effect on cognitive performance, mood, and physiology. We envision a holistic, data-driven approach to the "envirome," an optimization of built-environment space experiences meant to supplement and interact with human physiology. This notion of the envirome builds on the "microbiome," by building an ecosystem of linked bio-digital interfaces that interact with human occupants to deliver a holistic environmental experience. We expect these built environment interfaces to also work in tandem with robotic agents that support human crews. Shelhammer emphasizes the importance of integrating physiological sensing of astronaut crews with environmental controls and "smart spacecraft" systems that can respond dynamically to these signals.[47] In the future, we expect IVA (IntraVehicular Activity) space suits and aerospace-grade fabrics will also natively embed physiology and piezo-electric sensing technology[48,49] that can serve as additional inputs to this system. Planning now for space architecture "smart shell" infrastructure that can integrate with natively embedded networking and crew-sensing systems will enable us to realize responsive, controllable interior environments. From both well-established and recently undertaken Astronaut ethnography work,[50,51] we expect that such personalization and customization of interior environments can both protect and delight human crews, while also effectively monitoring their health signals.

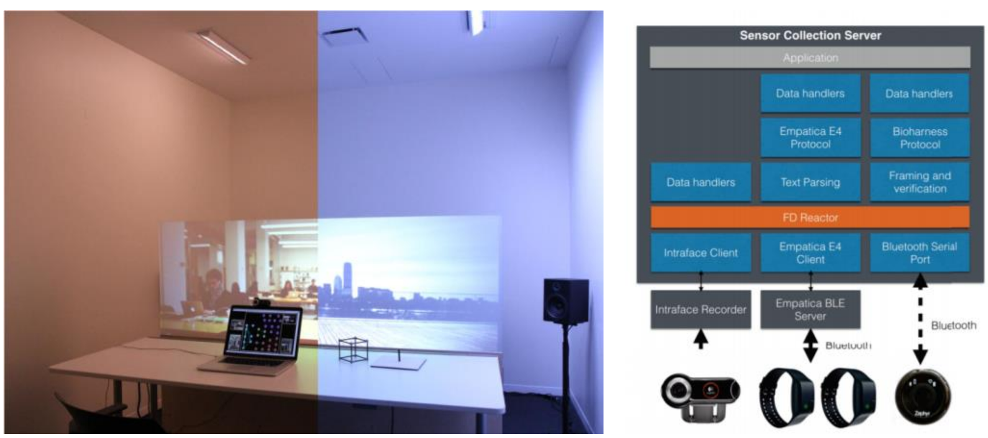

Figure 2. Depiction of the terrestrial Mediated Atmospheres responsive interior (left), with data collection and live-control loop method for occupants (right). Image Credit: Nan Zhao (2017).[52]

B. Anticipated Mission ConOps

The TESSERAE exo-shell offers the flexibility to build and reconfigure habitats in-orbit and respond to changing mission needs. The next step is to outfit these modular, self-assembling shells with ECLSS platforms to service and protect crews. As their mission scenarios vary, the ECLSS platforms will incorporate appropriately closed or open-loop, flexible hardware. Below, we consider several of the space industry's target mission scenarios and discuss how varying combinations of interchangeable TESSERAE tiles and modular ECLS sub-systems could be brought to service these contexts in the future. Additional technology development is still required to improve the feasibility and longevity of both closed and open-loop systems. Closed systems will need to explore bioregenerative and fully recyclable resource consumables, building on notions of "Controlled Ecological Life Support Systems" (CELSS) such as Biosphere2 (with much development still needed to prove out these concepts successfully).[53] Open systems still nominally rely on an Earth-based supply chain, but as the space industry prepares to support steady-state habitation around the moon and Mars, the need for effective In-Situ-Resource-Utilization (ISRU) and local sourcing of ECLS resources will grow. Projections in the NASA "Life Support Baseline Values and Assumptions Document" (BVAD) will guide requirements for these new technologies, as well as our integration of modular ECLS functions into TESSERAE. We present the classic mission scenario tables from the BVAD in Table 1 and 2, as contextual references grounding the TESSERAE ECLSS approach.[54] We anticipate designing a TESSERAE exo-shell with a LIFERAES ECLS tile set for mission reconfigurability across Options 1 (Very Short) through 4 (Long) (e.g., multiple missions could share or re-use the same original, but modified, infrastructure). For Options 5-6, however, we would anticipate best servicing occupant needs via dedicated shell structures that would be augmented along capacity dimensions for seasonal or steady-state increase in population (rather than full reconfigurability). BVAD's Option 7 (permanent habitat) is beyond the scope of this paper, but could be considered in future work, in concert with other settlement architectures.

Table 1. Mission scenarios of interest for TESSERAE ConOps planning: very short to long missions[54]

<table>
<tr><th>Designator</th><th>Duration</th><th>Air Subsystem</th><th>Habitation Interface</th><th>Waste Subsystem</th><th>Water Subsystem</th><th>Food External Interface</th><th>Thermal External Interface</th></tr>
<tr><td>Opt 1: Very Short</td><td>~30 hours</td><td>Stored Commodities w/ Consumable Waste Removal Hardware</td><td>Launch-Entry Suit w/ Wipes Only</td><td>Waste Storage Only; Minimal Restrictions on Inputs</td><td>Stored / Consumables</td><td>Stored Food Only</td><td>Rejection w/ Consumables</td></tr>
<tr><td rowspan="2">Opt 2: Short</td><td rowspan="2">~20 days</td><td>Stored Commodities w/ Consumable Waste Removal Hardware</td><td>Launch-Entry Suit +/- Other Clothing w/ Wipes & Bags for Toilet</td><td>Waste Storage Only; Minimal Restrictions on Inputs</td><td rowspan="2">Stored / Consumables</td><td rowspan="2">Stored Food Only</td><td rowspan="2">Non-Consumable Rejection Supplemented by Consumables</td></tr>
<tr><td>Regenerable Physicochemical Hardware w/ Consumables & Make Up, If Necessary</td><td>Pre-Packaged Clothing; Limited Water for Oral Hygiene; Wipes for Body Hygiene; Dedicated Toilet, Semi-private/temporary sleep areas; Smoke Detection and Fire Suppression</td><td>Waste Stabilization w/o Water Recovery; Minimal Restrictions on Inputs; Source Separation</td></tr>
<tr><td rowspan="2">Opt 3: Medium</td><td rowspan="2">~20 weeks</td><td rowspan="2">Regenerable Physicochemical Hardware w/ Consumables & Make Up, If Necessary</td><td rowspan="2">Pre-Packaged Clothing; Limited Water for Oral Hygiene; Wipes for Body Hygiene; Dedicated Toilet, Private Sleep Areas, Temporary Radiation Storm Shelter; Smoke Detection and Fire Suppression</td><td rowspan="2">Waste Stabilization w/o Water Recovery; Minimal Restrictions on Inputs; Source Separation. 25% logistics carrier waste reuse</td><td>Stored / Consumables</td><td rowspan="2">Stored Food Only</td><td>Non-Consumable Rejection Supplemented by Consumables</td></tr>
<tr><td>Recovery / Reuse of Some Waste Water w/ Other Waste Water Stored; Make Up from Stores; Consumables Supplied</td><td>Non-Consumable Rejection</td></tr>
<tr><td rowspan="2">Opt 4: Long</td><td rowspan="2">~10-20 months</td><td>Physicochemical Hardware & Regenerable Consumables w/ Negligible Bioregeneration & In-Situ Oxygen, If Necessary & Available</td><td></td><td rowspan="2">Waste Stabilization w/ Water Recovery; Wet Wastes Accepted w/ Others Stored 50% logistics carrier waste reuse. 50% Waste processing residuals used for shielding or converted to methane propulsion for station keeping</td><td>Recovery / Reuse of Some or All Waste Water w/ Any Other Waste Water Stored w/o Brine Recovery, If Produced; Consumables Supplied</td><td>Stored Food w/ Fresh Vegetable Production Unit</td><td>Non-Consumable Rejection Supplemented by Consumables</td></tr>
<tr><td>Physicochemical Hardware & Regenerable Consumables w/ Minor Bioregeneration & In-Situ Oxygen, f Necessary & Available</td><td>Limited Clothing Laundry; Water for Oral & Body Hygiene; Dedicated Toilet, Private Sleep Areas, Dedicated Radiation Storm Shelter</td><td>Recovery / Reuse of All Waste Water w/ Brine Recovery, If Produced; Consumables Supplied; ISRU Make Up Possible</td><td>15 % Bioregeneration w/ Stored Food</td><td>Non-Consumable Rejection</td></tr>
</table>

Table 2. Mission scenarios of interest for TESSERAE ConOps planning: very long to permanent missions[54]

<table>
<tr><th>Designator</th><th>Duration</th><th>Air Subsystem</th><th>Habitation Interface</th><th>Waste Subsystem</th><th>Water Subsystem</th><th>Food External Interface</th><th>Thermal External Interface</th></tr>
<tr><td rowspan="2">Opt 5: Very Long</td><td rowspan="2">~10 years</td><td>Physicochemical Hardware & Regenerable Consumables w/ Minor Bioregeneration & In-Situ Oxygen, If Necessary & Available</td><td rowspan="2">Clothing Laundry; Free Water for Oral & Body Hygiene; Dedicated Toilet Private Sleep Areas, Dedicated Radiation Storm Shelter</td><td>Waste Stabilization w/ Water Recovery; Wet Wastes Accepted w/ Others Stored >75% logistics carrier waste reuse. >75% Waste processing residuals used for shielding. Production of methane (combined with ISRU) or oxygen/water</td><td>Recovery / Reuse of All Waste Water w/ Brine Recovery, If Produced; Consumables Supplied; ISRU Make Up Possible</td><td>Stored Food w/ Fresh Vegetable Production Unit</td><td rowspan="2">Non-Consumable Rejection</td></tr>
<tr><td>Significant Bioregeneration w/ Physicochemical Hardware & In-Situ or Regenerable Consumables; Wastes Vented or Stored</td><td>Reclamation of Life Support Commodities w/ Consumables, Mineralization, & Storage</td><td>Recovery / Reuse of All Waste Water w/ Brine Recovery, If Produced; ISRU Make Up & Consumable Manufacture</td><td>15 % Bioregeneration w/ Stored Food</td></tr>
<tr><td rowspan="4">Opt 6: Multi-Generational</td><td rowspan="4">~2-10 decades</td><td rowspan="2">Integrated Bioregeneration w/ In-Situ Commodities for Minimal Losses & Some Hardware Manufacturing</td><td rowspan="2">Clothing Laundry; Unlimited Water for Oral & Body Hygiene; Dedicated Toilet</td><td>Reclamation of Life Support Commodities w/ Consumables, Mineralization, & Storage</td><td rowspan="2">Recovery / Reuse of All Waste Water w/ Brine Recovery, If Produced; ISRU Make Up & Consumable Manufacture</td><td>50 % Bioregeneration w/ Stored Food</td><td rowspan="4">Non-Consumable Rejection</td></tr>
<tr><td rowspan="2">Reclamation of Life Support Commodities w/ Mineralization, & Storage w/o Consumables</td><td>75 % Bioregeneration w/ Stored Food</td></tr>
<tr><td rowspan="2">Integrated Bioregeneration w/ In-Situ Commodities for Minimal Losses & All Hardware Manufacturing</td><td rowspan="2">Clothing Laundry; Unlimited Water for Oral & Body Hygiene; Dedicated Toilet; Clothing Manufactured Locally</td><td rowspan="2">Recovery / Reuse of All Waste Water w/ Brine Recovery, If Produced; ISRU Make Up & All Hardware Manufacture</td><td>Essentially Complete Bioregeneration w/ Protein from Plant Products</td></tr>
<tr><td>Reclamation of All Commodities w/ Mineralization w/o Consumables w/o Permanent Storage (No Waste)</td><td>Complete Bioregeneration w/ Protein from Animal Products</td></tr>
</table>

If we continue in the current space infrastructure paradigm of creating custom, one-off habitats for each of the above mission scenarios (e.g., habits like Salyut, Tiangong, Skylab, Mir, ISS, and Gateway that are tuned for the specific needs of a particular orbit or crew size), our human presence in space will scale slowly. Akin to how the space industry has benefited from the rise of re-usable rockets,[55] we hope to contribute to an era of re-usable and reconfigurable space habitats that adapt to changing mission needs. Through a modular ECLS infrastructure, we aim to create a suite of TESSERAE tiles that can free mission planners from the over/under 30-day mission dichotomy, and allow originally short-term mission infrastructures to be retrofitted with higher-capacity ECLSS units or "resupply" units that can extend mission life and scale for increased crew size as needed. Future work will analyze how many multiples of a 32 tile set, and with which individual functionalities, are required to address these multiple mission scenarios. In the long view, we also anticipate integrating our open-loop ECLSS tiles with in-situ resource extraction, as suggested in section C, figure 6 under "Space Utilities Architecture," below. TESSERAE's overall goal in the environmental control domain is to enable dynamic and adjustable ECLSS capacity based on inclusion of more or less ECLSS tiles of varying functionality—air exchange systems, contaminant filters, traditional and MBR water filters and production systems, et cetera.

C. ECLSS and LIFERAES Concept

Each vehicle subsystem is best described by its set of functions and defined by its requirements. Functions are derived from mission needs. As a result, mission architectures vary from one mission to the other as needs differ. The DoD, NASA, and the private space community alike could benefit significantly from ECLSS architectures that adapt to changing needs. As needs change from mission to mission, design requirements follow. Therefore, one of the key areas to ensuring an adaptable spacecraft architecture is in the capture of functions. If the functions of spacecraft or mission architecture are appropriately captured, design envelopes provide the flexibility for systems to carry out various missions.[56]

A general set of ECLSS' functions have been distilled as follows[57]:

1. <u>Control cabin pressure</u>: The cabin control capability maintains a habitable total pressure and oxygen concentration within the habitable module(s). Specifically, cabin control will consist of venting and relief, storage, and distribution of the O_2 / N_2 gases to manage the atmosphere. Inherent to this function is the control of pressure control system(s) including monitoring of cabin total pressure and partial pressure oxygen, and the provision of health, status, and monitoring telemetry.
2. <u>Remove air contaminants</u>: The air contaminant removal capability ensures that the habitable atmosphere is free of pollutants that might harm the crew. This capability includes removal of metabolic, trash, and equipment generated contaminants in gaseous and particulate (solid) phases within the pressurized volume and controlling them to concentrations below prescribed physiological limits. Inherent to this function, is the control of contaminant removal system(s) such as the CO2 removal system, including monitoring of airborne contaminants, and the provision of health, status, and monitoring telemetry.
3. <u>Condition cabin air</u>: The condition cabin air capability provides a habitable and comfortable environment by managing the atmospheric temperature and by removing humidity. This capability does not include the addition of moisture into the air. Included in this capability is the circulation of air for proper thermal distribution, and a uniform breathable atmosphere. Inherent to this function is the control of air conditioning systems, including monitoring of atmospheric temperature and relative humidity, and the provision of health, status, and monitoring telemetry.
4. <u>Provide water</u>: The provision of water capability provides water for direct crew consumption, medical needs, hygiene applications, and downstream payloads and EVA systems that require water reservoirs. This capability includes storage, distribution, dispensation, and quality control. Inherent to this function is the control of water management system(s) including monitoring water quality, and the provision of health, status, and monitoring telemetry.
5. <u>Mitigate Fire Hazards</u>: The ECLSS should provide a capability to mitigate the effects of a fire. This capability includes monitoring for combustion products and providing a fire suppression capability. As part of the function to protect crew and vehicle from a hazardous environment, crew protection equipment and post-combustion recovery of the habitable environment are also within this ECLSS function's scope.
6. <u>Body waste management</u>: Management of crew body waste functions consists of collection and isolation of crew body waste. If body waste is not transferred to a resource recovery system (such as a water recovery

system) or immediately discarded via venting, then waste will be stabilized and transferred to systems for long term storage and disposal.

These functions are critical to ensuring an ECLSS supports a variety of missions. Within the context of spacecraft systems, they interact with physical subsystems, and ultimately the crew. A block diagram showing these interactions is provided in figure 3.

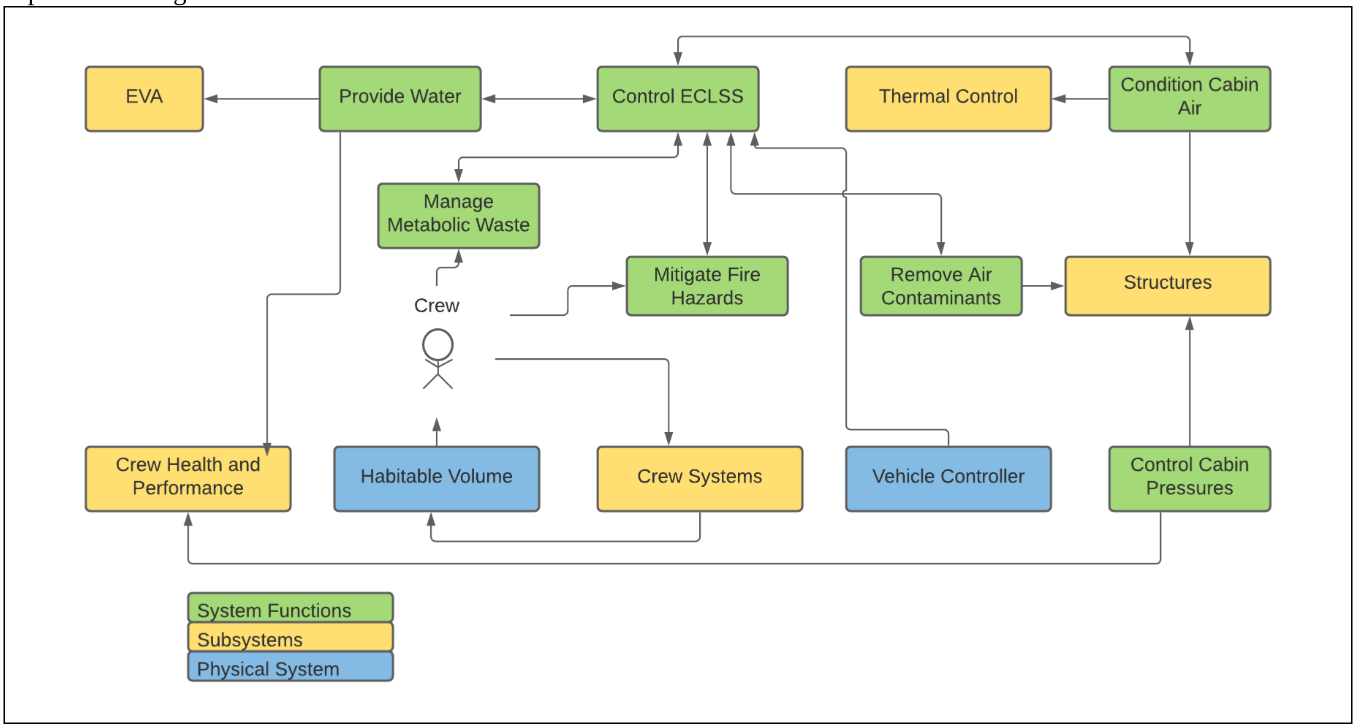

Figure 3. Typical ECLS Function Interaction Diagram

The interaction between subsystems and ECLSS functions is important as it highlights the other implied spacecraft functions that must be supported when integrated with the vehicle. Several of the other subsystems that are inherently supported by ECLSS are: EVA, Crew Health and Performance, Crew Systems, Thermal Control, and Structures. The following list provides a summary on the subsystem to ECLSS function interaction for context.

1. EVA systems enable astronauts to perform operations outside of a spacecraft. These operations are conducted utilizing spacesuits. ECLS systems currently interact with EVA systems on the ISS via the provisioning of water.
2. Crew Health and Performance systems are critical in human spaceflight as they support the crew's health and performance through the provisioning of monitoring and retention of health and performance via exercise machines. These exercise machines introduce heat loads into the cabin as crews utilize them. ECLSS is also responsible for the measurement of oxygen in the cabin environment. These measurements are often cross correlated to monitoring that is directly related to the astronaut.
3. Crew Systems consist of the crew's quarters, bathroom facilities (consumables), and utilities that interact with crews such as water dispensing systems. ECLSS is responsible for providing the plumbing necessary to ensure cabin pressure is maintained via isolation from the vacuum environment during toilet usage, and that waste is properly vented from the spacecraft when needed. Therefore, crew systems are needed to ensure the crew has a set of utilities to be able to utilize the toilet that are compatible with the plumbing architecture.
4. Structures are a critical component to ensuring the spacecraft pressure can be maintained within the tolerances that ECLSS is responsible for (associated with supporting pressure control for various ConOps).
5. Thermal Control and ECLS systems are connected via the cabin heat load. Cabin heat loads are handled via ECLSS hardware in a thermal control loop that circulates through the spacecraft, and ensures that all system

heat loads (primarily from crew and avionics) can be dissipated into the external space environment. The rejection capabilities of the thermal control system directly relate to the number of crew, and crew activity. Crew activity is determined through the crew health and performance group. Crew health and performance is also a critical stakeholder as exercise loads define dew points that impact condensation on surfaces, and heat loads within the cabin environment.

Since the relationships between spacecraft subsystems and ECLSS functions are so coupled, intertwining a spacecraft level subsystem and subsequent system level function is an important aspect to consider in vehicle design. LIFERAES has specifically been conceptualized to capture this dependence. The LIFERAES concept envisions that TESSERAE tiles carry ECLSS functionality, and support the subsystems at the spacecraft level as shown in figure 3. The vision is that each tile carries ELCSS functionality, and can therefore be constructed to create an ECLSS architecture that is tuned to the mission needs. Much like TESSERAE, LIFERAES scale in ECLSS performance as a function of the number of tiles that are assembled. For instance, fans are necessary components in removing contaminants. The LIFERAES concept proposes that one tile will be able to carry the fan performance needed to support the contaminant removal function of one crew member. Similarly, CO_2 control is a sub-function in the contaminant removal function, and can be executed via physiochemical processes or packed bed reactors. In this instance, a single packed bed reactor is fitted onto a single tile. Thermal control inside the habitable environment is carried out similarly via a dedicated heat exchanger per tile. An exploded view of LIFERAES and a brief summary of the tiles is shown below in figure 4.

While certain ECLS tile functionalities motivate a multi-unit stacked system with clear, open-air access on both "ends" for intake and outflow, as shown in figure 4, certain resource processing or regeneration functionality (such as the MBRs and MABRs discussed previously), could be integrated directly into structural tiles that have only one tile side exposed to the interior and the other side exposed to the exterior vacuum environment. In this case, the elements of a LIFERAES stack may be implemented in-line with the habitat exo-shell, rather than installed perpendicular to the habitat wall. This allows for flexibility in use of interior space and better optimizing the physical profile of ECLS hardware systems that extend into habitat operating interiors.

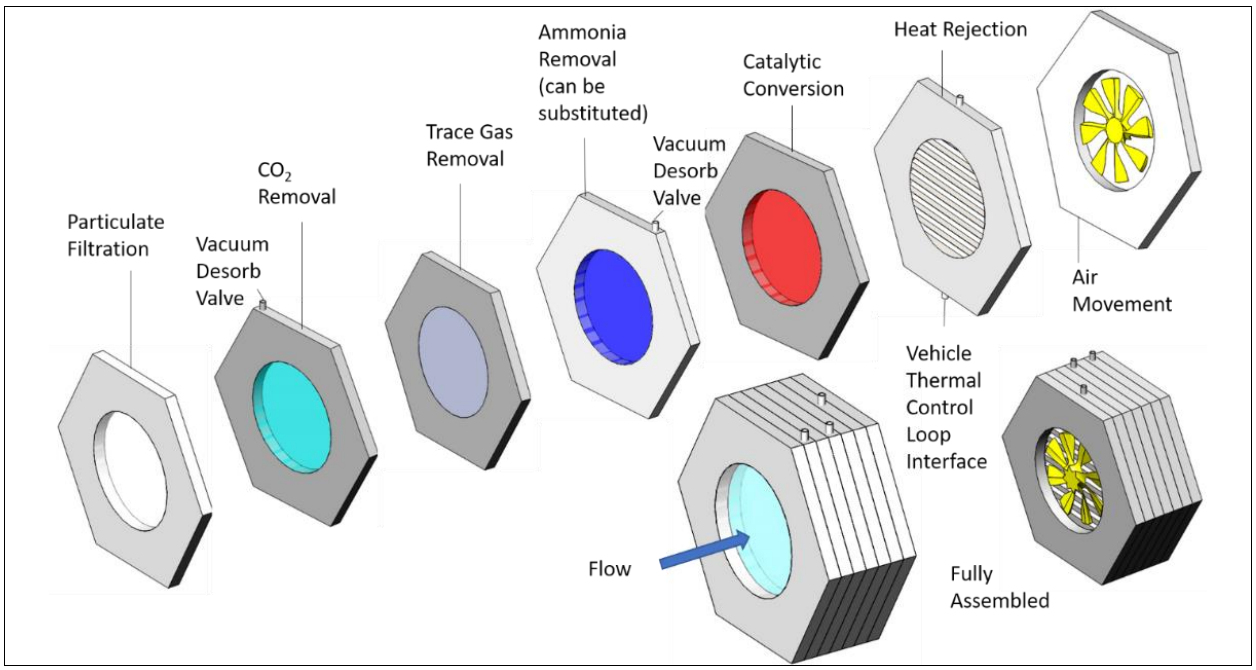

Figure 4. Exploded view of LIFERAES concept with sample functional tiles labeled.

LIFERAES not only has utility in expanding for varying mission sizes, but the individual tiles also have functionality in expanding into various mission architectures or spacecraft that are not necessarily human spaceflight missions. The DoD has a well know program, Operationally Responsive Space (ORS),[58] in which they are interested in being able to deploy various missions with reconfigurable spacecraft. One of the largest hurdles in redirecting a spacecraft is that it may need to be redirected in an environment in which it lacks functionality or exceeds its performance requirements. Given the large demands for power on small spacecraft, LIFERAES can conceptually support reconfigurable missions through utilization of the thermal control (heat rejection) tile. Turndown ratio, or the ability for a spacecraft radiator to change its emissivity based on its environment and thermal rejection needs, is often a challenge found in spacecraft as they maneuver through space. TESSERAEs can be reconfigured with the LIFERAES interchangeable raft to provide thermal rejection to an external radiator that can increase and decrease in size to provide more or less heat rejection capability. The tiles can also be coated with various emission paints to provide re-configurable turndown ratios as shown in Figure 5.

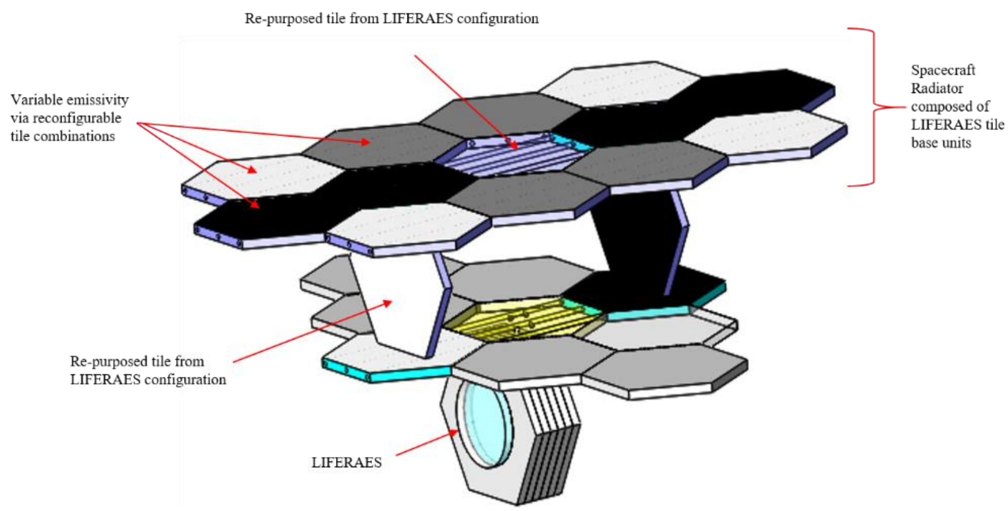

Figure 5. TESSERAE and LIFERAES combined to provide flexible radiative surfaces

If spacecraft or nearby neighbor vehicles have these interchangeable tiles, assets may be able to redeploy in space without the need for ground intervention. This flexibility also helps avoid the over-designed, over-provisioned expensive architecture that simultaneously meets all conceivable mission needs. LIFERAES provides flexibility in mission design, with an opportunity to start with a modest functionality complement and expand as needed.[59] We have kept the hexagonal profile for LIFERAES to ensure that they pack and stack in the same rocket payload holster housing that is being designed for TESSERAE exo-shell structural tiles. Furthermore, the hexagon shape is a useful tiling geometry that allows us great flexibility in expanding functional arrays over time.

Last but not least, LIFERAES plays a critical role in the concept of buffers for increased reliability. As systems continue to be developed with further loop closure in mind, redundancy and excess commodities in ECLSS architectures help to offset reliability challenges posed by systems that attempt to fully "close the loop." As buffers increase in size, reliability for closed loop systems increases proportionally.[60] If LIFERAES becomes a standard part of vehicle architecture and ecosystems in space, the system would offer buffering technology to help offset any unplanned downtime or failure downtime of technology already in place.

For LIFERAES to integrate effectively with the exo-shell layer, connector and tubing approaches must either couple natively through the self-assembling interface (posing interesting challenges for robust, no-leak self-connecting connectors at flush interfaces) or rely on out-of-tile-plane flexible connectors that can be serviced by astronaut crews on the interior side of the habitat shell. We will pursue future work for both approaches, as the pros and cons vary with mission contexts—we may need fully autonomous coupling in non-crewed contexts such as storage depots, but prefer to have manually-coupled tubing between tiles in the crewed context where astronauts may need to quickly access tubing in life-critical emergencies. Candidates for the autonomous, self-closing tubing connectors are drawn from precursors in the oil and gas industry,[61, 62] and candidates for the out-of-tile-plane connectors will draw on flexible tubing. Candidates are currently under material performance consideration for spaceflight.

While this paper has considered the integration of LIFERAES for a single TESSERAE habitation module, our concept for the TESSERAE station assumes we will one day dock multiple buckyball exo-shells together. To do so, we will pursue thickened hexagonal tiles that can house airlocks and docking ports (akin to the Common Berthing Mechanism[63] on station). Future work will consider how to share ECLS functions and optimally distribute LIFERAES across multi-module stations.

D. Space Utilities Architecture

In addition to providing mission flexibility for operational responsiveness, LIFERAES has the ability to fit within mission architectures where commodities for future explorers can be monetized. The TESSERAE exo-shell architecture, while primarily designed for reconfigurable use in microgravity, has also been stipulated for on-surface use to supplement regolith or fabric HAB structures in lunar or martian contexts (figure 6). Additional maneuverability tools (pulleys, ladders, etc.) may be needed in the surface assembly context, and construction will also have to contend with uneven terrain, thus requiring half-domes for stability or structural modifications for adjustable stand-offs.

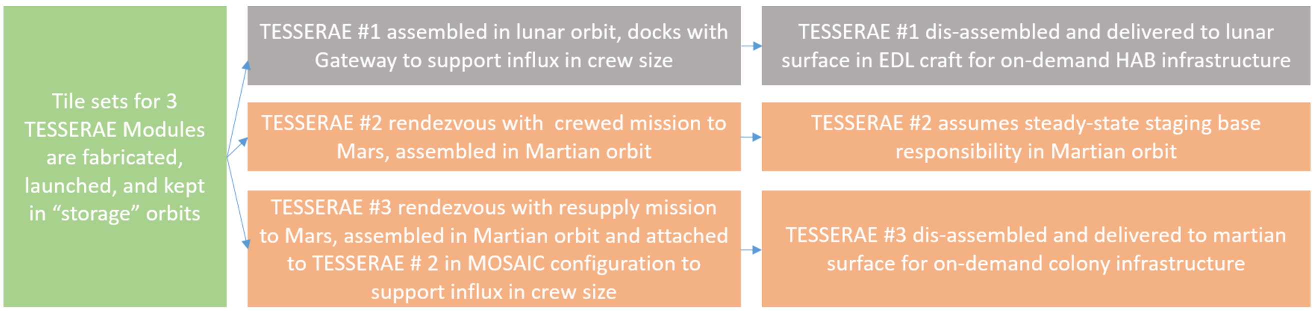

Figure 6. Mission Multiplicity with TESSERAE Shell Units. Originally presented at AIAA in 2019[64], updated here for Artemis mission plans and NASA's Moon to Mars focus.

Future lunar mission architectures may consist of systems that provide utilities such as fuel, electricity, water, and oxygen to residents or users. One such architecture is shown below in figure 7. LIFERAES tiles have direct overlap with the functions shown in the space utilities concept in figure 7. LIFERAES could present a significant stepping stone in the commercialization of space. Rather than assuming that life support system functionality serves a purely passive role from the value chain perspective, it can serve as an active participant in producing value that can be exchanged for goods, services, or currency. While the economic model is not the primary driver for showing interchangeability utilizing LIFERAES, this concept provides the foundation for future work in the area of in-space resource utilization and commerce.

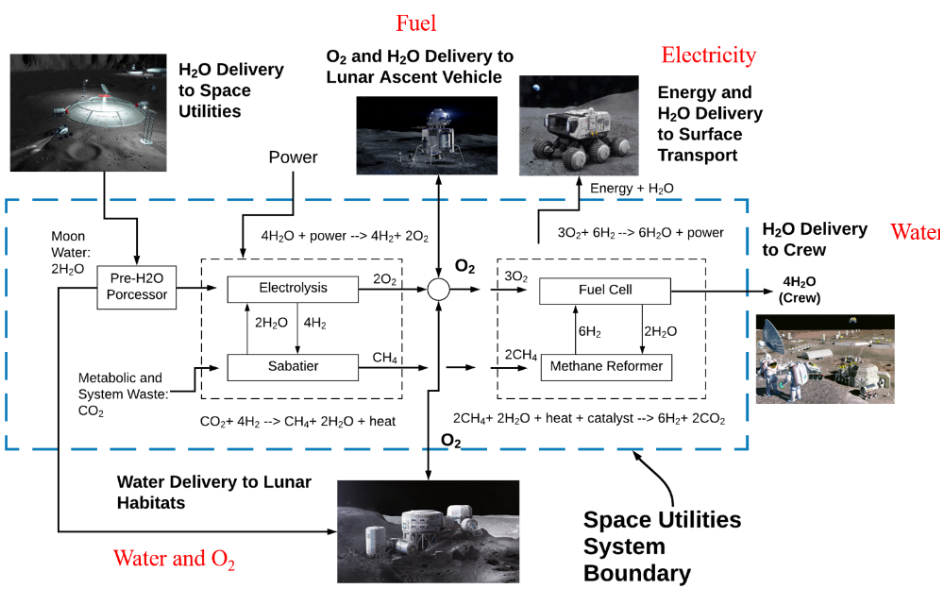

Figure 7. Space Utilities Architecture. The generation of these marketable outputs (Fuel, Electricity, Water, O2) could be driven within modular, remixable ECLS tiles that produce extra capacity for sale.

IV. Conclusion

From reconfigurable LIFERAES, to modular MBRs, to entire crew cabins with physiologically-responsive, controllable sensory interiors like Mediated Atmospheres, we have established a deep technology portfolio to pull from for holistically integrated, next-generation environmental control. This paper has presented several concepts for applying the TESSERAE exo-shell modularity principle to similarly modular and reconfigurable ECLSS, as we develop a technology roadmap to bring the TESSERAE habitat concept online. The TESSERAE exo-shell architecture allows us the structural flexibility to remodel the ConOps of in-space infrastructure to meet changing mission needs, and may one day provide the architectural modularity basis on which to deploy these flexible, modular ECLS concepts. With the flexibility for various architecture and mission constraints, LIFERAES have the potential to support environmental control and life support for a wide range of near-term commercial habitation and deep-space exploration goals.

Future work will prepare specifications for the prospective generation and/or filtering capacity of each LIFERAES stack (by functional area), and the radiative properties of each thermal array, to enable a trade study of ECLS tile needs across the various mission scenarios presented in Table 1. We intend for this to build towards a "menu" of modular LIFERAES systems that can be chosen by mission designers for inclusion in habitat architectures, with the intent of storing redundant units in-orbit for ease of mission reconfigurability beyond the designer's original conception. This model will be included in a forthcoming space supply chain analysis for self-assembling, modular space infrastructure. Additional work is also underway for designing and characterizing pressure control across varying internal volumes with TESSERAE's current clamping and pressurization designs, and designing reliable thermal control conduits.

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