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ECLSS-First Space Habitat Architecture

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The conventional approach to designing space habitats imposes substantial inefficiencies upon the Environmental Control and Life Support System (ECLSS). The design and dimensions of these accommodation spaces are often completely arbitrary in relation to the optimal form, configuration, location, and size of the ECLSS elements. The limited availability of rack- or compartment-based accommodation space forces the ECLSS distribution to spread out suboptimally among multiple modules, or, to centralize into a single rack. Compelling this complex equipment to squeeze into *a priori* sized rack volumes makes system design and operations much more difficult for ECLSS equipment. It increases failure rates. This "bash to fit, paint to match" philosophy leads invariably to profound dysfunctionalities in the design, distribution, engineering, and installation of crucial life support elements. The underlying "Don't size the box/fit the box" doctrine leads to serious difficulties in cleaning, maintaining, and servicing the ECLSS equipment. This paper argues that the design of the ECLSS takes precedence over all the other systems and subsystems.

Figure 1. US ISS ECLSS Racks at NASA MSFC from the left: test racks versions of Water Processing, Urine Processing, and O₂ generation racks in ISS Node 3 Tranquility. Credit: NASA MSFC.

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Nomenclature

AIAA = American Institute of Aeronautics and Astronautics
BEAM = Bigelow Expandable Activity Module, an inflatable module attached to the ISS
ECLS = Environmental Control and Life Support (Functions)
ECLSS = Environmental Control and Life Support System (Hardware)
ESA = European Space Agency
EVA = Extra-vehicular Activity
ISRU = In Situ Resource Utilization
ISS = International Space Station
JSC = NASA's Johnson Space Center
LDAC-1 = Lander Development Analysis Concept One
MSA = Multispectral Analyzer
MSFC = NASA's Marshall Space Flight Center
MVA = Moon Village Association
NASA = National Aeronautics and Space Administration
PLOC = Figure of Merit: Probability of Loss of Crew, also known euphemistically as "Safety"
PLOM = Figure of Merit: Probability of Loss of Mission, also known euphemistically as "Mission Success"
PLSS = Portable Life Support System
PSR = Permanently shadowed region
RH = Relative Humidity
SMAC = Spacecraft Maximum Allowable Concentrations
SWEG = Spacecraft Water Environmental Guidelines
Tiangong = Chinese space station

I. Introduction

The international partnership of space agencies supporting the Artemis program has identified the South Pole of the Moon as the preferred region on which to build the first lunar base. Compared to the ISS or even the proposed Lunar Gateway Station, the logistics chain will stretch much longer. It will consist of many more flight segments with a complex descent and landing of hardware to the surface. This spatial-temporal paradigm means that life support systems sustainability will become more critical. It will have far more stringent reliability requirements on redundancy, reusability, operational life-time, safety, and sustainability than used on ISS today. Due to the large launch masses and vehicles, it may not be feasible to send an *unscheduled* cargo lander on short notice to replenish depleted or lost consumables or to replace broken-down equipment. Additionally, designers must take into account the lunar environmental constraints that differ from the ISS' microgravity. One driver for this tenet is that the Environmental Control and Life Support System (ECLSS) involves fluid mechanics. Low-gravity environments affect fluid mechanics and do not scale linearly either with volume or crew size. Figure 1 shows an example of the tightly-packed ECLSS equipment installed on the International Space Station (ISS) in Node 3.

Conventional approaches to developing habitat concepts for long duration space missions share a common weakness. They do not provide for efficient or logistically cost-effective ECLSS because the packaging constrains those functions to fit into an overall habitat architecture. The system engineers already made the decisions to prioritize structural efficiency, propellant production, solar power integration, external access points, computing, and other competing concerns. Furthermore, the more mature discipline of space vehicle design can influence space habitat design. The ECLSS influence ranges from non-existent for uncrewed spacecraft to highly modular and evolvable (e.g., ISS). The consequence of this conventional approach is that these spacecraft designs treat the human crew's life and health as a function to provide somehow, in part via intense logistical support. Instead. the spacecraft design should treat human life and health as the overall system's core purpose. State-of-the-art orbital space stations (ISS and Tiangong) rely upon frequent resupply missions to replenish ECLSS consumables. They also depend on logistics to supply tools, parts, and orbital replacement units for ECLSS equipment. Prior research(Russell, Klaus, 2007, pp. 808-820; Bagdigian et al, 2015) indicates that maintenance of ECLSS hardware and housekeeping are two of the leading demands on crew time.[1-2,19] These demands directly impact the crew's ability to achieve mission objectives (e.g., research and exploration). For permanent lunar and deep space habitats, the ECLSS functions become more dominant in terms of physical resources and mission risk. They must operate continuously while crew are present, potentially for years. ECLSS is the most consumables-reliant function after propulsion. ECLSS enjoys less opportunity than propulsion to rely upon in-situ resource utilization; the crew cannot burn or eat lunar material. The ECLSS, Power System, and Thermal Control System must function almost independently of any resupply due to round-the-clock operations necessary for these critical functions. Therefore, to support and ensure the safety and health of the crew sustainably, the design of the ECLSS must occur early — at the outset of the design process — ***before designing all other habitation systems and subsystems.***

This paper argues that the best remedy for this situation is — given a schematic architectural plan — to design the complete ECLSS system first, then mold the design of all other habitat systems around the ECLSS. Long-duration human missions will last hundreds or thousands of days. The greatest determinant of long duration success or failure will be the self-sufficiency of the ECLSS, distinct from the supply chain that supports it. The more robust the ECLSS, the less critical will be the temporal uncertainty of the supply chain. Logistics would consume less of supply capabilities, allowing more capacity for commercial and scientific payloads. Design and integration in the best possible configuration for long-duration service would ensure this ECLSS robustness. That means using the design process to make the ECLSS immune to unviable system engineering trades and inefficient interfaces. To make that immunity possible, the design of the ECLSS must precede the design of all other systems of the habitat, which will then take shape around the ECLSS.

Figure 2 shows a schematic of the ECLS functions in a spacecraft or space habitat. The design of an ECLSS needs to capture and accommodate all these functions to provide the critical O_2 supply, CO_2 removal, water processing, urine processing, and water recovery to the habitat. The operational and physical integration of ECLS functions as hardware is the vital step to ensure that the ECLSS performs at its optimum level of production with a high degree of reliability and self-sufficiency.

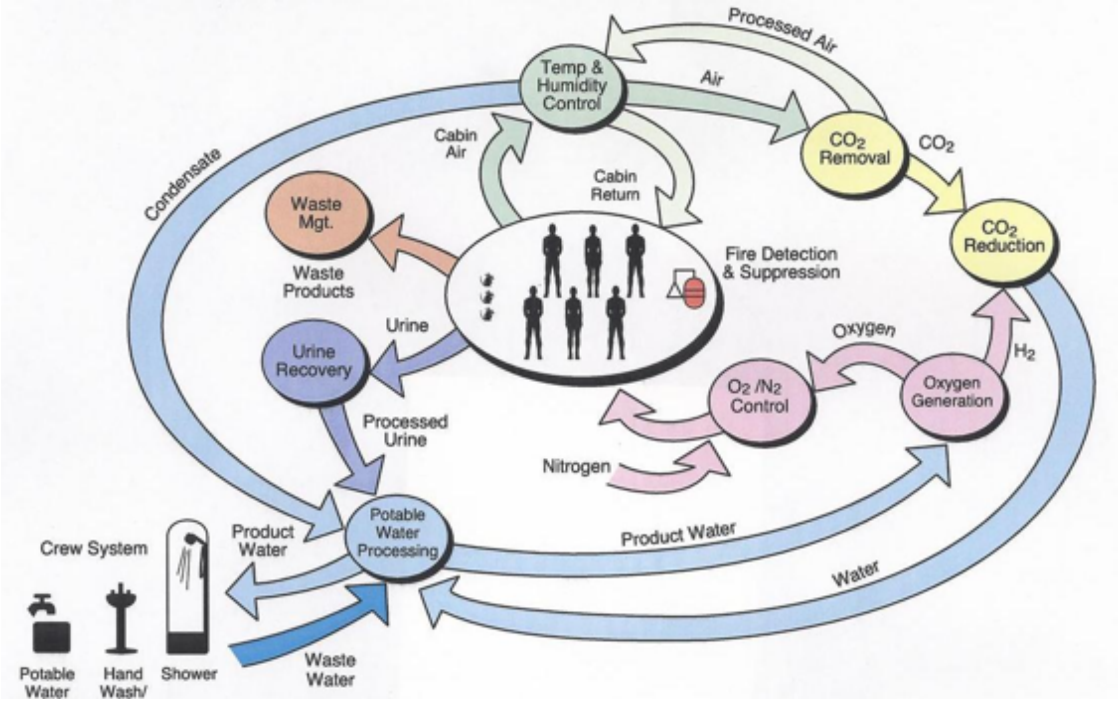

Figure 2. Space Station Regenerative ECLSS flow diagram. It is accurate for the ISS except for the shower, which was not launched to ISS. Credit: NASA.

II. ECLSS and Its Discontents

Sigmund Freud begins Civilization and its Discontents (1930) with the statement:

> "It is impossible to escape the impression that people commonly use false standards of measurement — that they seek power, success and wealth for themselves and admire them in others, and that they underestimate what is of true value in life."[10]

The same observation applies to Life Sciences and Life Support Systems. System Engineers evaluate "system integration" based on how well systems and subsystems can be packaged. This packaging, or quantizing, drives major subsystems into modular racks that allocate power, data, cooling, and other services without interference among adjacent racks. *Packaging alone becomes a false standard when it serves as the exclusive measure of system integration success.*

The fundamental discontent for accommodating ECLSS equipment in a conventional structures-first space habitat is the demand to shoehorn that equipment and all its utility and distribution connections into an arbitrarily predetermined box, rack, or panelized compartment. This engineering demand means that few — if any — of the ECLSS equipment elements can assume their optimal configuration, packaging, shape, or size. For the purpose of this design analysis, the primary structure "shell" is just a thermally insulated envelope that encloses an atmosphere.

Historically, system integration engineering practices do not prioritize ECLSS operating in its most efficient, maintainable, reliable, and safe manner. Instead, the ISS architecture prioritized inter-compatibility and standardization, in part due to the international collaboration required to build, supply, and operate the station. Initially, the ISS ECLSS was an open-loop design, dependent upon frequent consumable resupplies of H_2O and O_2. Over the decades, NASA and its partners added more sustainable, regenerative capabilities. Unfortunately, an evolvable architecture tends to forgo optimization because much of the physical sizing parameters are required to match pre-existing interfaces and standardized configurations (e.g. rack module volumes). This practice degrades the efficiency, maintainability, operations, performance, reliability, and safety of that equipment.

For example, the Water Processing Assembly on ISS contains filters and treatments with capacity limited by the rack module's volume. This limited volume constrains the size of filters and thus increases the frequency of manual maintenance. Another example is ducting, which is routed within the pressurized cabin and thus competes with all other equipment for volume and access. This competition constrains the number and location of air supply and return registers, which can lead to certain regions of the pressurized cabin as BEAM (Morgan et al, 2023) having marginal air mixing, so cannot be inhabited for extended durations.[12a]

Figure 3. Four Stand-off rack arrangement of a "baloney slice" through an ISS module. The standoffs are the yellow arc segments at the corners. Credit: NASA.

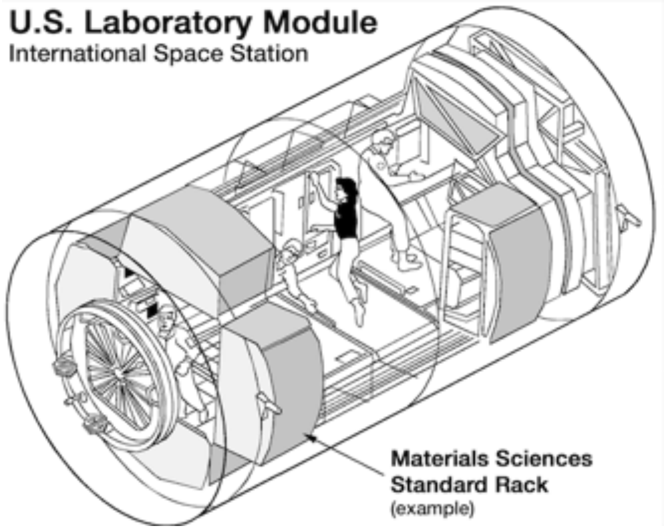

Figure 4 Transparent, cutaway view of the US Destiny Lab module showing quad rack installations and the utility "crossovers" at the distal end. Credit: NASA.

Inevitably, these trade-offs are often not distributed equitably among the disciplines and the hardware they affect. The oft-cited justification that "all systems must make some compromises" is small comfort if those compromises increase risk of system or mission underperformance or failure. Increasing those risks can drive up the *probability of loss of mission* (PLOM) and *probability of loss of crew* (PLOC). Figure 3 and 4 show the Four Stand-off/Quad Rack System into which most ISS ECLSS hardware is *required to fit*.

Figure 5. The US Destiny Lab early in its utilization on the ISS. Most of the rack faces exposed with blank cover panels. Credit: NASA.

Figure 6. Astronauts Christina Koch, Anne McClain, and David Saint-Jacques work in the (almost) fully-equipped US Destiny Lab. Credit: NASA.

One essential lesson from ISS is how important it is to plan for growth internally from the addition of new capabilities, equipment, operations, and utilities. Figure 5 shows a "before" view of the US Destiny Lab soon after it was launched and berthed to the ISS. The stand-off utility channels at the "corners" between the racks proved inadequate to carry all the utilities, which led to crowding and made the standoffs difficult to access due to all the clutter (Smitherman et al, 2012).[20] Figure 6 shows an "after" view of Destiny's interior with the proliferation of accessories, cables, computer screens, mechanical devices, and tubing, Who knows what is where and how all this hardware is functioning? The impact on ECLSS hardware means that all this crowding, congestion, and confusion makes access much more difficult, especially quick access in case of an emergency.

This clutter increases the difficulty of disconnecting the rack utility connections to free the rack to swing out into the central "corridor" as it was designed to do. In contrast, ECLSS should locate in a volume that will be — and will remain — a clutter-free zone. Crew members need access to control debris and dust, which can foul, clog, and damage ECLSS hardware.

III. Life Support Imperatives

To maintain human health, life, and wellbeing in an off-Earth habitat, the ECLS functions serve with the utmost importance. Key among these functions is maintaining a breathable and safe atmosphere, providing clean and safe water, and disposing of biological wastes in a safe and sanitary manner. Note that the adjective *safe* appears in each of these clauses. There are many ways in which ECLSS may fail, and each of these failure modes may pose risk to crew health, safety, and life.

This section introduces two key life support imperatives for the lunar base and habitat: the "site" configuration and the design. The first imperative — site analysis — is ubiquitous to all architecture and construction. The second imperative is resources (Barker, 2020) such as water, the universal solvent, the key to life.[3]

Figure 7 presents a diagram of the distribution of all the major ECLSS hardware among the ISS Modules. It illustrates both decentralization and centralization of the ECLSS equipment. Three modules provide accommodations for centralization of hardware: Zvezda Service Module, US Destiny Lab Module, and Node 3. The decentralization appears primarily where the temperature and humidity control locates in those three modules plus four more modules. The ISS architecture that prioritized other core functions, such as vehicle mating interfaces and power generation, drove the centralization and decentralization of ECLSS functions. In an ECLSS-first approach to habitat design, the application of centralization would apply more deliberately to optimize ECLSS capabilities.

A. Human-Centered Design of ECLSS

Human-Centered Design originally referred to the human-machine interface in aircraft cockpits, especially the nascent efforts at automation of aircraft controls and displays. (Billings, 1991).[5] This essay applies an expanded definition of Human-Centered Design to include the Human-Environment interface. ECLSS provides the machines that mediate this Human-Environment Interface. The machines control the environmental conditions including air quality, temperature, pressure, and humidity. They also handle waste including urine recycling to produce potable water and solid waste disposal. The astronauts devote substantial time and effort to maintaining and adjusting the ECLSS equipment, so that constitutes a human-machine interface as well.

Please refer to Figure 7, which shows the location of this equipment and its ECLS functions. The following subsections indicate the baseline ECLSS element hardware units. It shows the assembly-complete plan with all the modules installed in place. Figure 7 illustrates the many parts of the ECLSS hardware distributed throughout the ISS. Although the ISS ECLSS is approaching obsolescence, it remains the most complete example available of a physical/chemical life support integration. In this plan, the ECLSS equipment appears distributed quite unevenly among the modules.

ECLSS for human-centered habitat design demands efficient resource collection, storage, cleaning, treatment and distribution. This efficiency enables uniform and consistent provision of air, water, and food. It also ensures microbial mitigations and waste management that complies with environmental use and safety regulations such as the Spacecraft Water Exposure Guidelines (SWEG, NASA, 2017) and the Spacecraft Maximum Allowable Concentrations (SMAC, NASA, 2020).[15,17]

An experimental, human-rated centrifuge for artificial gravity built at JSC could deliver improved health outcomes for astronauts and open a new field of physiological research. However, it had no dedicated cabin volume and so could not be integrated safely into the existing crew exercise zone. It never launched.

These examples demonstrate how not leading with ECLSS can result in limited capabilities, inefficiencies, and impaired reliability for ECLSS functions. These functions are all-important to sustain the crew on a long-duration mission, (e.g. a permanent lunar habitat or 1000-day human mission to Mars).

Noise has been a constant irritant in spacecraft such as the Space Shuttle and the ISS. On the ISS, the "background noise" puts out about 72 dBA more or less continuously during the working day, with intermittent peaks around 85 dBA(Limardo et al, 2021, p. 4).[12] Noise will probably emerge as a problem in a lunar base or habitat. Crew-adjacent ducting also exposes astronauts to high levels of flow-induced noise, an issue exacerbated by ventilation fans running at high power to service lengthy duct routes. Writing in 2013, Limardo et al described measured hearing loss among space crew members (Limardo et al, 2013, p. 10):

> “The data suggests an improvement in the ISS acoustic environment; although hearing loss has been documented in long-duration spaceflights, to date, clinically significant permanent threshold shift (PTS) have not been documented for ISS crewmembers. However, cases of temporary threshold shift (TTS) with subsequent recovery has occurred and have been documented.”[11]

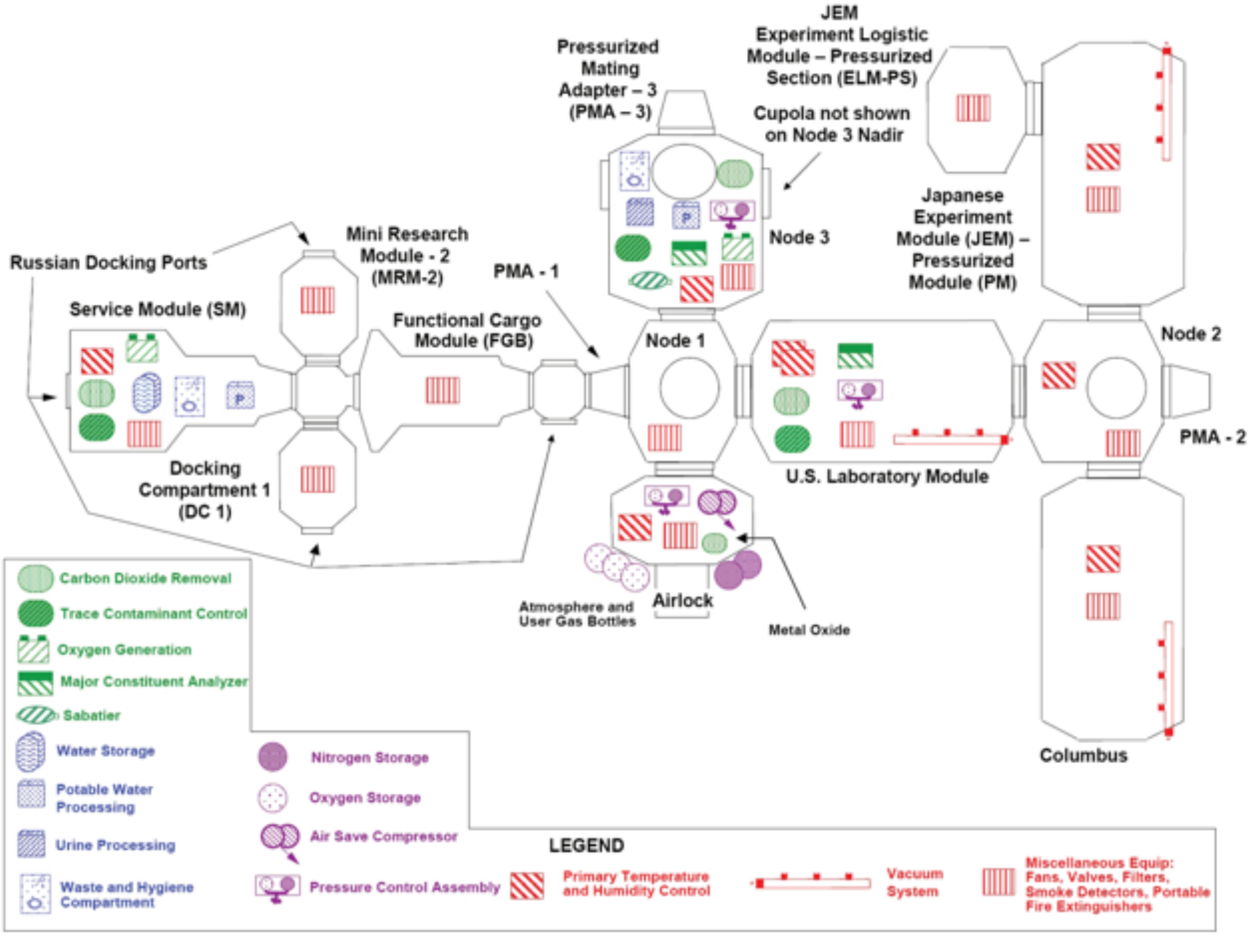

Figure 7. Diagram of ECLSS Hardware on the ISS, circa 2010. Courtesy of ESA: ESA-HSO-COU-030. (Barratt, Baker, Pool, 2019; NASA, 2017; NASA, 2020).[4,9,15,18]

A further complication arises when vehicle or habitat planning demands that major pieces of ECLSS equipment be located remotely from each other, even separating them into different pressurized modules. Separating ECLSS hardware that functions best in close proximity creates unnecessary and punitive mass and volume penalties. These penalties undermine the ECLSS whole. However, for a lunar habitat or lunar base, neither the Space Shuttle cargo bay nor a rocket fairing diameter constrains the volume of Class 2 inflatable pressure vessels, i.e. deployable so that after arrival in space, some work is required to set it up to become ready to operate. Neither are such primary structures constrained to limiting them to Class I pre-integrated habitats, i.e. pre-integrated on Earth so that it is ready to operate upon arrival in space (Cohen, Kennedy, 1997)[6].

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[6] Cohen, Kennedy, 1997: Class 1 Habitat: Pre-integrated on Earth so that it is ready to operate upon arrival in space. Class 2 Habitat: Deployable (e.g. inflatable) so that after arrival in space, some work is required to set it up to become ready to operate. Class 3 Habitat: ISRU-based so that it incorporates some elements of native materials or structures on the lunar or planetary surface.

Table 1. Distribution of ECLS Functions Among the ISS Modules as shown in Figure 7.

Major ECLSS Modules	**Russian Service Module**	**Joint Airlock Module**	**US Lab Module**	**Japanese Experiment Module**	**ESA Lab Module**	**Node 2**	**Node 3**	**Number on ISS**
Names	***Zvezda***	***Quest***	***Destiny***	***Kibo***	***Columbus***	***Harmony***	***Tranquility***	**7**
ECLS Functions:								
CO_2 Removal	**X**	**X**	**X**				**X**	**4**
Trace Contaminant Control	**X**		**X**				**X**	**3**
O_2 Generation	**X**						**X**	**2**
Major Constituent Analyzer			**X**				**X**	**2**
Sabatier CO_2 Removal							**X**	**1**
Water Storage	**X**							**1**
Potable Water Processing	**X**						**X**	**2**
Urine Processing							**X**	**1**
Waste & Hygiene	**X**						**X**	**2**
N_2 Storage		**X**						**1**
O_2 Storage		**X**						**1**
Pressure Control Assembly		**X**	**X**				**X**	**3**
Primary Temperature & Humidity Control	**X**	**X**	**XX**	**X**	**X**	**X**	**X**	**8**
Vacuum System			**X**	**X**	**X**			**3**
Number per Module	**7**	**5**	**7**	**2**	**2**	**1**	**10**	

Table 1 complements Figure 7 by enumerating the equipment and indicating its location in the ISS. Table 1 displays the extent of ECLSS centralization and decentralization on ISS. Reading down the columns shows the extent of centralization in each module. Reading across the rows shows the extent of decentralization in the distribution of ECLS functions. Thus, the two most centralized modules are the Russian Service Module Zvezda and the American/ESA Node 3 Tranquility. The most decentralized function is temperature and humidity control. The least decentralized functions are those that occur in only one location such as water storage in Zvezda or O_2 and N_2 storage on the Quest Joint Airlock.

Table 2. Criteria for an ECLS/Space Architecture Trade and Analysis Study. [4,14,18]

Criterion	CENTRALIZED ECLSS Architecture	DECENTRALIZED ECLSS Architecture
Crew Health	Resource collection, storage, treatment and provision to meet crew metabolic needs. Consistent or uniform quality possible due to single centralized source for ECLSS provision.	Resource collection, storage, treatment and provision to meet crew metabolic needs. Module-to-module quality may vary depending on performance of each ECLSS unit.
Size	Large ECLSS unit size – Designers size ECLSS subsystems & components for the maximum crew size and habitat pressurized volume.	Designers size small ECLSS unit size –ECLSS subsystems & components to serve *X* number of crew members and *Y* pressurized volume. Replicate the ECLSS unit and locate as needed to serve the entire crew and habitat pressurized volume.
Power	Power demand is commensurate with unit size.	Power demand commensurate with unit size and number of ECLS units in use.
Cost	Low production rate. High unit cost.	Higher production rate. Lower unit cost.
Efficiencies of Scale	Alternative technologies become feasible with increased habitat size. Component efficiencies can approach theoretical limits of thermodynamic processes and/or biochemical reactions when unconstrained by packaging, although distribution losses likely increase due longer distribution distances.	The suite of feasible technologies is influenced by unit size. Component efficiencies depend upon the unit size. Distribution losses expected to be constant.
Complexity	Driven by technologies selected for provision of ECLS. Regenerative ECLS inherently requires system complexity to perform the required functions. Network to distribute ECLS functionality throughout the habitat increases with size.	Driven by technologies selected for provision of ECLS. Regenerative ECLS inherently requires system complexity to perform the required functions. Network complexity remains constant with ECLS unit size.
Redundancy	Must be intentional during centralized ECLS design.	Similar redundancy provided via multiple units, when pressurized compartments are interchangeable. Dissimilar redundancy must be intentional during ECLS design. Several dissimilar designs would help ensure safety.
Maintenance & Repair	One (or two with redundancy) ECLSS to maintain and repair. Centralized location within a single service module simplifies access. Fewer spares?	Greater number of ECLS units to maintain and repair. Must provide service access to each ECLS location. Access may vary from one module to another. Variation in ECLS units is also possible. Increased number of spares? The design should be simpler as the units serve a smaller volume.

References: Barratt, Baker, Pool, 2019; NASA, 2021; NASA, 2020; NASA, July 2017.

In Table 2, the authors suggest the criteria and rationale within a system level trade study to assess these architectures for implementation of ECLS *functions* within the space habitat. Table 2 presents the criteria by which to evaluate the success of ECLSS design elements and layout.[7] In Table 2, the independent variable consists of the degree to which the design centralizes or decentralizes the ECLSS. ECLSS should be robust enough to provide for the metabolic needs of the crew, which the system must meet regardless of the architecture employed. Other metrics include size, power, cost, efficiencies of scale, system complexity, functional redundancy, maintenance, and repair. All these metrics connect to other systems' and sub-systems' follow-on implementation. Since this approach is novel, Table 2 provides an overview of design criteria mapped to centralization and decentralization.

B. ECLSS Centralization versus Decentralization

Figure 9. The Waste and Hygiene Compartment with space toilet in Node 3 Tranquility. NASA photo.

Figure 8. Russian Elektron O_2 Generator in the Zvezda Service Module. Courtesy of James Oberg.

A centralized ECLSS architecture can benefit from efficiencies of scale and offers potential to simplify the maintenance and repair. In comparison, a decentralized architecture can provide greater layers of redundancy by allowing for replication of a lower cost, common unit to support modular buildup of the habitat and more opportunities for functional adjacency in less crowded volumes.

ISS ECLSS provides for the metabolic needs of the crew through food provisioning, atmosphere revitalization and temperature/humidity control, water recovery and treatment, and waste management. The philosophy for ISS ECLS hardware shown in Figure 7 follows the modular design for the station. For example, US

Node 3 houses key functional elements of atmosphere revitalization (CO_2 removal, trace contaminant control, oxygen generation, oxygen recovery via a Sabatier reactor and gas analysis). Some of these functions occur in the Destiny US Laboratory Module, adjacent to Node 1 and in the Zvezda Russian Service Module . Figure 8 shows the Russian Elektron O_2 generator in Zvezda. Although it is part of a centralized installation, it was not integrated with other ECLSS hardware. Neither was it jammed into one of the panelized compartments in Zvezda.

1. Centralization

Centralization offers the potential to implement effective and efficient integration of ECLSS hardware. ISS Node 3 presented an opportunity for such integration. Unfortunately, the available rack space was very tight.

Most modules directly support temperature and humidity control to ensure crew comfort. All modules have ventilation and fire detection/suppression for crew safety. The distribution of some ECLS functions throughout the station provides redundancy in certain scenarios. Yet, that multiplicity does not automatically or necessarily translate into improved reliability. In some cases, decentralization of equipment that perform the same function, by virtue of different manufacturers, assures dissimilar redundancy. However, maintenance and repair of these disparate subsystems may require additional training and an increased cache of spares.

Two key “centralized” functions are the space toilets in the Zvezda Service Module and in Tranquility Node 3. In Zvezda, the toilet is largely a stand-alone system. In Node 3, the Waste and Hygiene Facility is integrated to some extent with other centralized functions, particularly the provision of wash water and the recycling of gray water. There is no recycling of human solid waste. Figure 9 shows a view into the Waste and Hygiene Facility in Node 3.

Figure 10 shows a diagram of the ECLS functions integrated within Node 3. Such a complex system integration can provide a basis for ECLSS centralization, provided there is sufficient volume both for the equipment and for easy access to it.

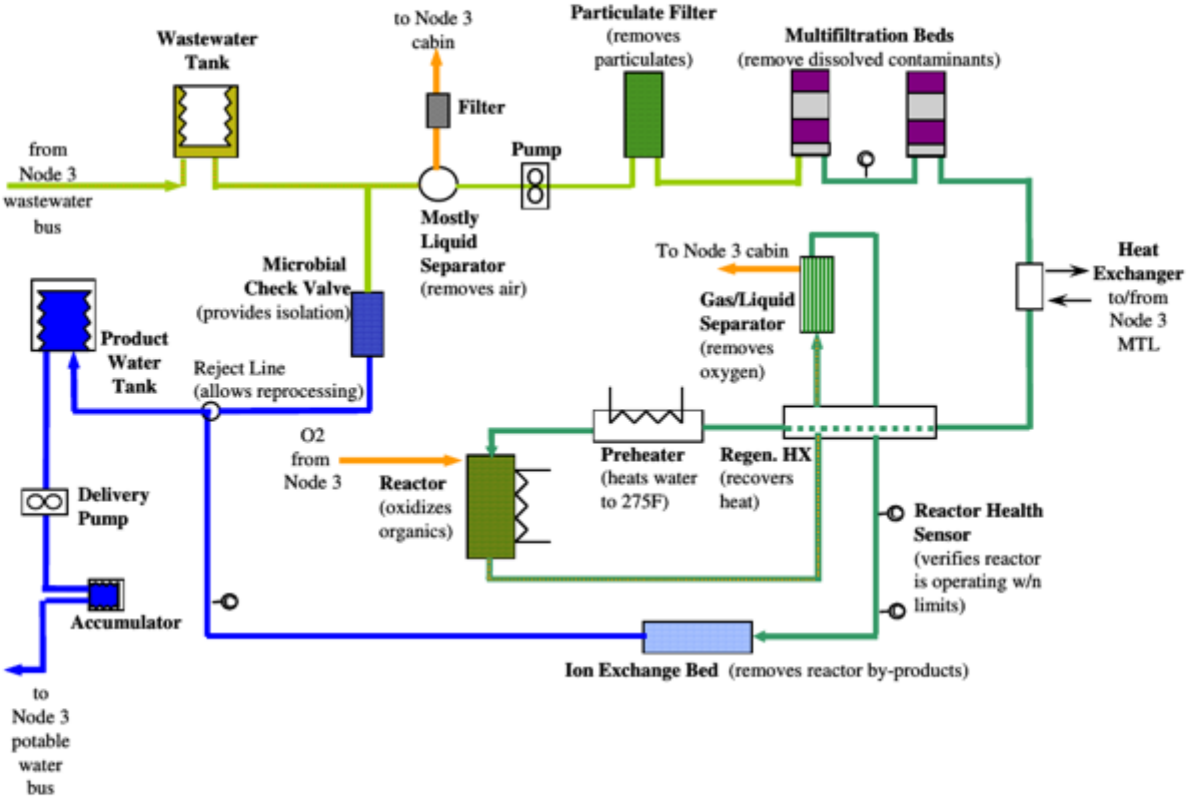

Figure 10. Flow Diagram of the ECLS functions in Node 3. This hardware integration accounts for what occurs in the three rack units shown in Figure 1. Credit: NASA.

2. Decentralization

In part, this architecture for decentralized or distributed ECLSS hardware stemmed from the international collaboration for design, build, and assembly of ISS. The latter began with launch of the Zarya Module (also known as the Functional Cargo Module) in Nov 1998. It has continued to this decade with the most recent installation of the

NanoRacks Bishop Airlock in Dec 2020(NASA, 2020, 16 Nov).[18] The canon of life support includes familiar concepts such as atmosphere revitalization, water purification, and waste removal. To understand the impacts of structure-prioritized design engineering upon ECLSS, it is essential first to comprehend these processes and how they interact within the flow of the internal environment. Only in this way can one hope to recognize what it would mean to optimize these ECLSS processes through physical configuration and system integration.

Table 1 presents criteria for assessing the layout and installation of ECLSS equipment in a pressurized spacecraft or space habitat. This analysis is more complex than just centralization versus decentralization. Centralization can, in some cases, offer advantages in terms of efficiencies of scale. However, generally decentralization offers greater advantages and lesser disadvantages than centralization. Decentralization implies lower per/unit cost and higher production of units of each type. Decentralized ECLSS can also translate into better and easier access to the ECLSS equipment for servicing, maintenance, and repair. Decentralization is predominately the route to optimize the network (i.e., interdependency) of ECLS functions and their distribution. If designers do not correctly distribute the decentralized ECLSS, the corresponding "pain" derives from multiplying command structures, leading to a mass penalty. Table 2 presents the pros and cons of centralization and decentralization at a general level. However, the issues of what is centralization and what is decentralization of ECLSS hardware become much more complex when multiple modules are involved. Surdyk et al in 2017 proposed an approach to objectively compare and trade qualitative criteria such as crew health and maintainability. Morrow et al expanded it in 2019.[13,21]

All ECLSS equipment should provide sufficient clearance volume to allow maintenance, repair, and servicing. That clearance volume should allow the crew to open up all equipment, do "tear-downs" in which they pull the inner cores or mechanisms out, and can remove them from the immediate vicinity for more precise work. Ideally, several units of equipment may share the same teardown volume to minimize the allocation of "unoccupied" spaces or areas.

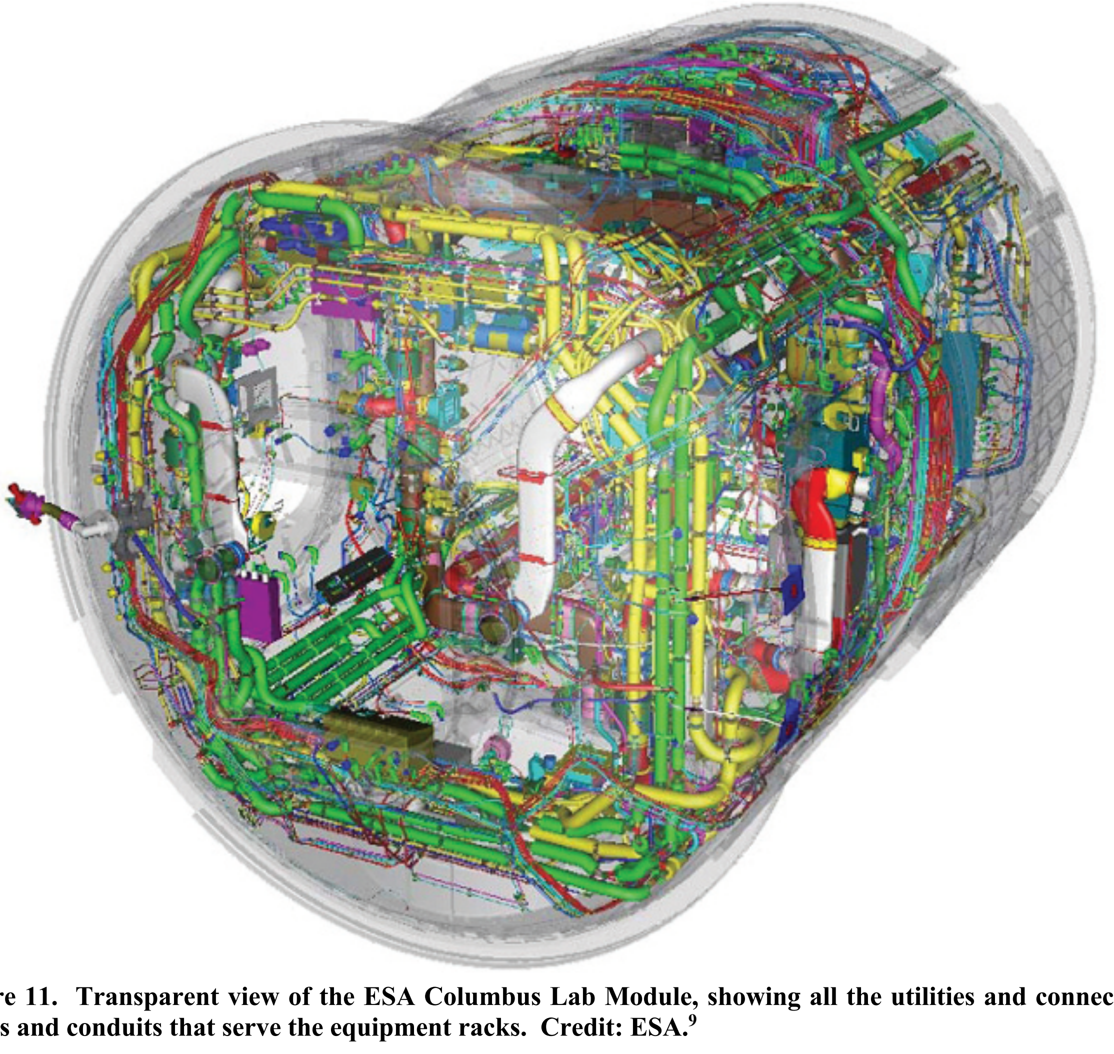

Figure 11. Transparent view of the ESA Columbus Lab Module, showing all the utilities and connecting cables and conduits that serve the equipment racks. Credit: ESA.[9]

C. Access Clearance for all Equipment to Enable Maintenance, Repair, and Servicing

Although it may seem self-evident, the need for satisfactory access clearance to all ECLSS equipment leads to neglect in favor of system engineering packaging demands. Access clearance may seem like an obscure starting point for this discussion, but it is a true measure of the success of functional-, physical-, and system-integration. How else would it be possible for a crewmember to disassemble and repair a compressor "on site*?"*

Figure 11 shows a transparent view of the ESA Columbus lab module. This illustration shows the dense-packing and complexity of all the systems and subsystems that connect and serve the equipment racks. ECLSS equipment in Columbus includes the Primary Temperature and Humidity Control, ventilation fans, air ducting with HEPA filters, smoke detectors, and fire suppression.

D. ECLSS Reliability

Once a consolidated and optimized ECLSS engineering design is well-defined, it becomes possible to discuss how many complete units and subsystems are ideal for redundancy that improves reliability. For example, while working on the Northrop Grumman design for the Constellation Program *Altair* Lunar lander(Cohen, Houk, 2010) it was necessary to meet NASA's target Figures of Merit of 1/500 for Probability of Loss of Mission (PLOM) and 1/1000 Probability of Loss of Crew (PLOC).[7] NASA provided the Lander Development Analysis Concept One "LDAC-1" model for the Altair, a single-string, "minimum design" model that they believed contained one of everything necessary to perform the mission — *if nothing went wrong*. The Northrop Grumman evaluation of PLOM and PLOC for the single-string LDAC-1 came out at PLOM = 1/39 and PLOC = 1/89 for the designated "Go Anywhere/Return Any Time" Altair lunar mission(Cohen, 2009).

> *1.* For the Northrop Grumman response to LDAC-1 during the Lunar Lander Development Study (2008, not published) it would not do to follow the conventional method of cramming the ECLSS piecemeal into nooks and crannies throughout the Altair configuration. It was necessary to formulate an architectural design strategy to achieve PLOM = 1/500 and PLOC = 1/1000. The key features of the design solution for Altair/LDAC ECLSS were that:[7*] *The air revitalization system, including all system redundancies, resided in the Crew Ascent/Descent Module, from which it was distributed to the Habitat Module and the EVA Airlock,*
>
> *2. The Multispectral Analyzer was tripled over the NASA LDAC-1 "minimal design," single-string specification, with one Multispectral Analyzer in each of the three pressurized modules above.*
>
> *3. The thermal loops were doubled over the LDAC-1 single-string, with double valve-sets, throughout the complete configuration including to and from the external radiators.*

This example shows that when the designers establish an ECLSS architecture early in the vehicle conceptualization, they can meet the challenge of safety and mission assurance requirements, including probabilistic risk assessment. It also suggests the limits of "single string minimum design" as a procedure to scope out a spacecraft or habitat design. Unlike the pressure vessels' typical "design for minimum risk" that can enable single string for that type of hardware, ECLSS invariably requires redundancy to ensure reliability.

IV. Discussion

This discussion addresses several topics of potential controversy. This paper does not necessarily settle the big issues; its role and intent are to ask questions. These issues arise from the foregoing exposition, to frame the design context and subtext as key questions.

A. Reprise: Is it truly necessary for the design of ECLSS to precede all other design disciplines?

YES. In many institutions, the engineering disciplines continue to be stove-piped such that that the lack of communication between them has spawned a whole new shadow discipline within system engineering, just to interpret among all the other disciplines. Until aerospace design engineering becomes truly interdisciplinary and egalitarian

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[*] Full disclosure: Marc Cohen served as Human-Systems Integration Lead for NGC's Altair, including ECLSS, EVA, habitability and their reliability. He was a member of the team that estimated these probabilities.

between disciplines, it will be necessary for far-distant and long-duration missions that ECLSS design comes first, before all others.

B. Logistics: To what extent does the much longer logistics chain affect the design and operation of the lunar base and habitat?

This situation is similar to military logistics in history, but the battle is against:

1) Continuously consuming or leaking resources with no local resupply, and

2) Handling emergencies. Emergencies are akin to battles.

The design challenge is not so much about mission duration as "WHERE" the mission occurs. Is resupply possible? Are spares available?

C. Single Volume: If the default design for the habitat was one huge volume (e.g. an inflatable dome), which would be more advantageous: a centralized or decentralized ECLSS?

In terms of safety, the view of a big unitary dome is not acceptable, leading to very important constraints on subsystems as "structure, inflatable volume, etc." In this case, a centralized ECLSS would not be acceptable.

D. Growing Food: If growing food at the lunar base is a major constituent of the food supply, what are the interface issues between the physical/chemical ECLSS and the implicitly bioregenerative agriculture?

Growing food leads to considering plants' needs. Some plants may not thrive in an open huge volume. Moreover, again for safety, we cannot envision a single large greenhouse growing all food. Given the risk that any problem arising may jeopardize all food. So, plant segregation into separate pressurized volumes is a safety precaution.

E. ECLSS Room: Should ECLSS equipment receive its own room(s) as dedicated accommodations or should they occupy interstices or plenums between rooms?

ECLSS equipment should be installed first din its own designated place and maintenance volume. Other equipment should be installed after ECLSS with respect for these constraints.

F. Centralization vs. Decentralization of ECLSS: Are they incompatible?

Centralization is good for the mass budget. Decentralization allows more redundancy, a better space occupation, and a better chance for astronauts' survival, assuming the decentralized parts are not built on the same pattern.

G. Why do these problems arise? Why do they persist?

These problems arise because the space business is done in a such a way that humans enter the loop at the very end of conception. More emphasis is given to structure, thermal, power, etc., as usual in a conventional spacecraft. For example, a car is made to roll, a plane is made to fly, etc. The crew always comes after the machines.

H. Prioritization of Systems and Subsystems

Another way to frame why these problems arise is that the prioritization of systems and subsystems reflects the power dynamics within the agency or corporation. Typically, for example, the "Structures Division" that takes responsibility for the pressure vessels occupies a much more powerful position within the organization than the Human Factors group who try to advocate for the crew. Similarly, the Data Systems, Power, Propulsion, and the Guidance, Navigation, and Control often enjoy larger budgets and more powerful positions than ECLSS and Thermal organizations. So, what happens is that the resources, budget, mass, and volume allocated to each discipline reflects their position and power within the agency or corporate hierarchy.

V. Conclusion

Given a schematic architectural layout of a space habitat, the next logical step is to design the ECLSS for the maximum efficiency, accessibility, serviceability, maintainability, and crew safety. The ECLSS-first architecture should take into account which ECLS functions benefit from centralization and which benefit from a decentralized distribution. Generally, the centralized functions that outfit the hygiene facility and its capabilities include water processing, urine processing, solid waste processing, hand-washing, and if feasible, a full-body shower. Conversely, the decentralized functions that afford wide distribution throughout the habitat include temperature and humidity control, air revitalization, CO_2 removal, and pressure control.

Overall, decentralization offers greater advantages and lesser disadvantages than centralization for most ECLS functions. Decentralization leads to higher production of ECLSS units of each type at lower cost per unit. The presence of more widely distributed ECLS functions and the equipment that serves them gives greater redundancy (via common parts and tooling, potential to interlink module functions, etc.) and hence reliability within the ECLSS architecture.

Once the design of the ECLSS is complete throughout the spacecraft or space habitat — including clearance zones that keep the ECLSS equipment accessible and uncluttered — it is time for the other disciplines to begin designing the pressure vessel shell around the ECLSS and all the other outfitting. This ECLSS-first approach to habitat architecture will improve mission assurance and resource utilization, particularly for indefinite human habitation beyond low Earth orbit.

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