Antaeus: Concept for a Sample Receiving Lab/ Planetary Quarantine Facility at the Gateway

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Antaeus will provide an integrated system in a module designed to receive samples with biological potential from the Moon and Mars to perform preliminary handling, processing, curation, storage, and analysis. Antaeus breaks the chain of potential contamination or infection with the Earth. By keeping Mars samples away from contact with the Earth, scientists can control any dangerous microbes, and if necessary, kill them without endangering the Earth or humanity. The Antaeus Architecture and technology ensemble would also serve to support with a crewed Mars base or habitat.

The Antaeus Module docks to the Lunar Gateway. Antaeus will receive "pristine" samples delivered by robotic spacecraft to its airlock, from which the robotic system will place each sample capsule into an individual sample handling and analysis chamber (SHAC). Researchers may operate the Antaeus systems tele-robotically from anywhere. Once the scientists complete their preliminary assessment of lunar samples, they may choose to send a SHAC to Earth or archive it in place. For each sample, the researchers determine the sample's biological potential and decide whether to sterilize it or observe it in its "natural" state. The Antaeus module incorporates a standalone Environmental Control and Life Support System (ECLSS) including a shower enclosure to afford decontamination.

Antaeus supports analysis of lunar biological samples (Surveyor 3 Streptococcus, Apollo 17 jettison bag E. Coli, and Space IL crash site tardigrades) and lunar ice cores for helio-physics solar history. Antaeus provides a suite of capabilities to analyze samples in a cryo-vacuum state under laboratory conditions without the necessity of returning them all the way to the Earth. The prepared sample and lunar biologicals retrievals will afford practice and testing for contaminant control and simulated handling of potentially biological samples. For Mars Returned Sample Handling (MRSH), Antaeus affords planetary protection with respect to back-, cross-, and forward contamination of the sample.

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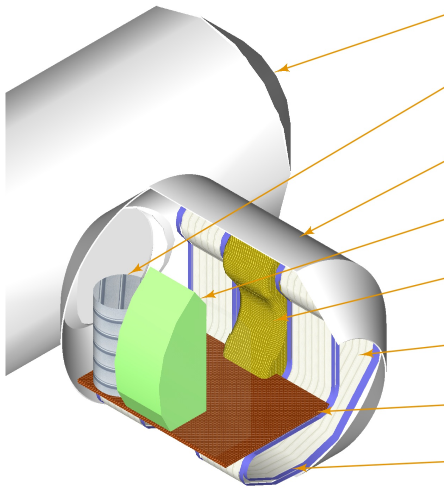

FIGURE 1. Schematic drawing for the Antaeus Sample Receiving Laboratory/Planetary Quarantine Facility core module berthed to the Lunar Gateway Station.

Key Words

Back Contamination, Biological Activity, Biosignatures, Cross Contamination, E. Coli, Forward Contamination, Helio-Physics, Lunar Gateway Station, Lunar Ice Cores, Mars Returned Sample Handling (MRSH), Mars Sample Return (MSR), Microbes, Microbial Life, Planetary Protection, Protection against contamination, Robotic glovebox, Solar History, Space Architecture, Spectroscopy, Streptococcus, Surgical Robot, Tardigrades.

Nomenclature

Δv	= "Delta-vee:" change in velocity, an analog for total propellant expended
EML	= Earth-Moon libration
Halo Orbit	= A periodic three-dimensional orbit about the EML 1, 2, or 3 Lagrange Point of gravitational stability
Gateway	= Lunar Gateway Station (Originally known as the Deep Space Gateway)
MRSH	= Mars Returned Sample Handling
MSR	= Mars Sample Return
SHAC	= Sample Handling and Analysis Chamber

I. Introduction:

THE ANTAEUS PROJECT will provide an integrated system in a module designed to receive "pristine," environmentally sensitive samples with biological potential from the Moon in Phase 1 and from Mars in Phase 2 to perform preliminary handling, processing, curation, storage, and analysis. The Antaeus module may be attached to the ISS or Deep Space Gateway for Phase 1 and to the Gateway for Phase 2. Antaeus will receive pristine samples delivered by robotic spacecraft to its airlock, from which the larger robotic system will place each sample into an individual sample handling and analysis chamber (SHAC). Researchers may operate the Antaeus systems on board ISS or Gateway, or telerobotically from anywhere.

Once the researchers complete their preliminary assessment of lunar samples, they may choose to return a SHAC to Earth or archive it in place. For Mars samples, the researchers will determine the sample's biological potential and decide whether to sterilize it in an autoclave or observe it in its "natural" state. The Antaeus module includes a standalone Environmental Control and Life Support System (ECLSS) including a shower enclosure to afford decontamination and bioisolation from the ISS, Gateway, or surface base.

A. Antaeus Mission Development

Antaeus fits into multiple mission contexts. Mission Phase 1a addresses lunar robotic exploration and sample return, providing a suite of capabilities to analyze lunar samples in a cryo-vacuum state under laboratory conditions without the necessity of returning them all the way to the Earth. Mission Phase 1b supports would support a lunar base or habitat with a surface laboratory. Phase 1 will afford practice and testing for contaminant control and simulated handling of potentially biological samples, such as the Apollo LM Jettison Bags (containing crew biological wastes). Mission Phase 2a is when Antaeus asserts its great advantage for Mars: to afford both forward contamination protection of the sample and backward contamination control for planetary protection.

B. Breaking Contact With The Earth

The story of Antaeus derives from one of the Greek myths. Antaeus was a mythical "half-giant" whom Hercules fought as one of his twelve labors. The only way Hercules could defeat Antaeus was to lift him off the ground, breaking his contact with the Earth from which he received his power. The Antaeus analogy is that by keeping Mars samples away from contact with the Earth, scientists can control any dangerous microbes, and if necessary, kill them without endangering the Earth or humanity.

The *Antaeus analogy* expresses the imperative that by keeping Mars samples away from contact with the Earth, scientists can control any dangerous microbes, and if necessary, kill them without endangering the Earth or humanity. The Antaeus Architecture and technology ensemble would also serve Mission Phase 2b, integrated with a crewed Mars base or habitat.

C. The Antaeus Concept

FIGURE 1 presents a cutaway view of the basic Antaeus concept for a "short" lab module to attach to a docking port on the Gateway. This figure shows the key features for Antaeus. The carrier spacecraft airlock is obscured behind the far pressure shell; it connects to the back of the pressurized manipulator box. The Antaeus lab stores SHACs both before and after they have been used to receive and analyze samples. FIGURE 2 shows an early CAD sketch of the full Phase 2 Antaeus module assemblage.

II. The Problem of Mars Sample Handling, Return, and Reception

Antaeus addresses the challenge of conducting the return of "pristine" samples from the Moon and Mars encounters several obstacles that to date have proven nearly insurmountable. The concept for Antaeus first emerged in a study led by Don DiVincenzi at NASA Ames Research Center, focusing on an Earth-orbiting quarantine station. This Antaeus concept includes the return of potential biological samples and frozen ice cores from the Moon, largely as preparation for returning potential counterparts from Mars. Although many relevant technologies have advanced, the fundamental challenges remain unchanged:

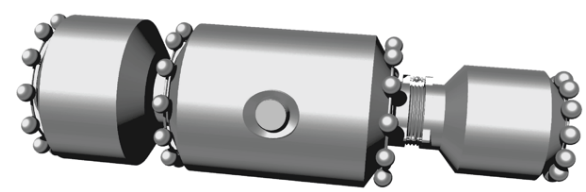

FIGURE 2. Sketch of Antaeus Phase 2 Early Concept for Mars Sample Return to the Gateway Station. The "Decontamination Section" would be launched as part of Mission Phase 1a to receive lunar samples. The larger Sample Receiving Lab and Compressor/ Autoclave section to receive Mars samples would be launched for Mission Phase 2a. Credit: Suzana Bianco.

1. Returning samples from Mars to the Earth in meaningful quantities for detailed analysis is prohibitively expensive for most researchers.
2. For samples from extreme conditions such as frozen cores from the Moon's permanently shadowed craters, the return system must maintain them in their natural cryo-vacuum state.
3. Martian samples involve the CO_2 atmosphere, temperature (average -63C), and pressure environment (average 600 pascals), which the return system must maintain.
4. Samples with biological potential need protection from forward-contamination from Earth biota while protecting humans and the Earth from back-contamination.

5. The analysis system must protect all samples cross-contamination from other samples.

A. Limitations of the Current Approaches

The current approaches – insofar as there are any -- are not suitable for a sustained and repeatable campaign of deep space sample return and analysis. During the "Mars Revival" of the 1990s, the preference was for astronauts to do sample handling on Mars in a laboratory (Hoffman, Kaplan, 1997; Cohen, 1999; Cohen, 2000). at a Mars base. The Mars Program Office at JPL has since contemplated a "Cache Plan" to collect samples on Mars in one location to pack them into a return vehicle to return them ***somewhere*** unknown, but that appears to be as far their planning goes. The NASA Ames Space Science Division published such a cache plan, but NASA had not yet defined that ***somewhere*** at the time of this study (Santos et al, 2009). Meanwhile, there are serious concerns and opposition to comparable "bioterror" research facilities in the USA, including safety, security, and accidents, all when staff are handling toxics with rubber gloves (National Research Council, 2010; GAO, 2009; Jarling, Rodak, Bray, Davey, 2009, pp. 135-143). The lack of consensus on Mars sample return to the Earth has become painfully obvious:

How and where can one "write the environmental impact statement to locate a Mars Sample Receiving Lab on Earth? (Cohen, 2002; Cohen, 2003).

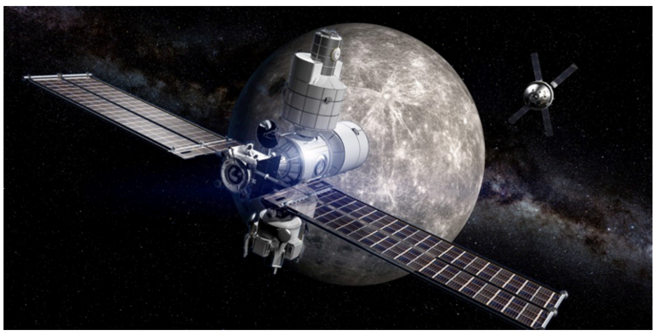

FIGURE 3. Deep Space Gateway Station in a Near Rectilinear HALO orbit at the Moon. NASA image.

B. The Antaeus System

Antaeus reduces cost substantially by not returning samples to the Earth, but handling them in lunar orbit. The **essential core of this concept** is to place samples in a Sample Handling and Analysis Chamber (SHAC) and keep them there throughout their period of analysis and retention. The researchers conduct all their scientific processes and sample analysis in the SHAC. The SHAC contains all the preparation and manipulation tools – that scientists operate robotically or telerobotically from anywhere: Earth, the ISS, or the Gateway. Antaeus minimizes the risks of moving samples from one container to another. Using the SHACs exclusively avoids the cleaning problem.

Antaeus as sketched in FIGURE 1 is a system to receive lunar and planetary samples in a space laboratory module or modules shown in FIGURE 2, and attached to the Gateway lunar space station portrayed in FIGURE 3 (Cowing, 2018). The Gateway station is in orbit about the Earth-Moon Lagrange Point 2 (EML-2) illustrated in FIGURE 4. The Gateway's orbit is a Near Rectilinear HALO orbit about EML-2 as shown in FIGURE 5.
Antaeus will receive "pristine" samples delivered by robotic spacecraft to its airlock (Downes, Crawford, Alexander, 2018), and then robotics will place each sample into an individual sample handling and analysis chamber (SHAC). Once researchers complete their study of a sample, they may return a SHAC to Earth or archive it place. For Mars samples, the researchers will determine the sample's biological potential and decide whether to sterilize it (Lupisella, et al, 2018). The Antaeus module includes a standalone Environmental Control and Life Support System (ECLSS) with a shower for decontamination.

III. The Antaeus Project

Marc Cohen, first author and PI, worked on the original Antaeus Project, specifically to develop a mockup of an on-orbit receiving lab (1980-81). The Antaeus Report: Orbiting Quarantine Facility (NASA SP-454) proposed to create an Earth orbital space station to quarantine Mars material:

> ". . .To detect the presence of biologically active agents—either life forms or uncontrolled (replicating) toxins—in the sample and to assess their potential impact on terrestrial systems. Only when the sample could be certified safe or controllable would it be transmitted to laboratories on Earth for physical analysis." (DeVincenzi, 1981, p. 1).

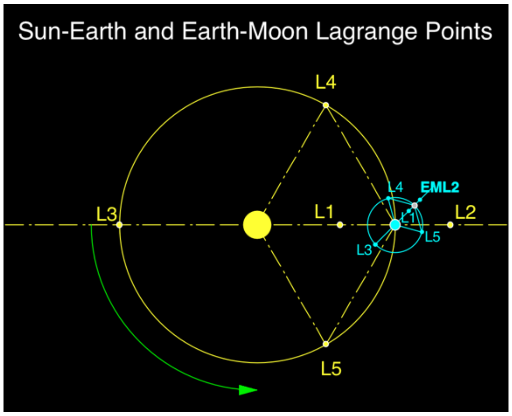

FIGURE 4. Sun-Earth and Earth-Moon Lagrange Points, highlighting EML-2.

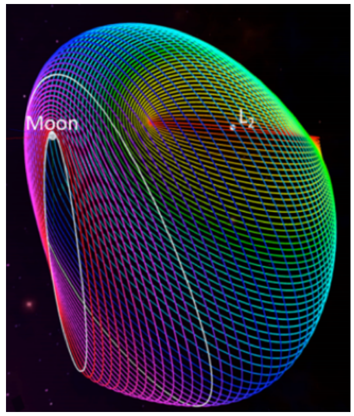

FIGURE 5. Halo Orbit about EML-2.

A. Scope of the Project

Having said all the above about handling samples from Mars with biological potential, the initial project focuses on learning how to handle the wide range of potential samples IN SPACE (and microgravity). It will require incremental progress, particularly how to maintain them in their wide range of ambient conditions, including extreme cold and hot environments, under vacuum or near-vacuum atmospheres. An intermediate step toward handling Mars samples would be to retrieve one of the 12 ***Apollo jettison bags*** left behind by the Apollo crews with their biological wastes inside as shown in FIGURE 6. That challenge would be to detect if any e. coli, for example, survived over 50 years of exposure to radiation and extreme thermal cycling. Ideally the Antaeus module will attach to the Gateway Station in a HALO orbit about EML-2, allowing a much easier delivery to Antaeus than a return to Earth.

B. Antaeus in Lunar Orbit at the Gateway.

The reasons for recovering such sample return missions to EML-2 are that it poses significant advantages compared to returning samples from the Moon, Mars, or beyond to the Earth or to the ISS in LEO. The comparatively modest ΔV requirements from the Lunar surface to EML-2 reduce the cost and mass of delivering the samples compared to recovering them back to LEO or reentering them to the surface of the Earth.

FIGURE 6. Apollo 11 Jettison Bag discarded at Tranquility Base.

IV. Technical Description

Attached to the Gateway Station, *Antaeus* will provide an integrated system in a module designed to receive samples from the Moon in Phase 1 and from Mars in Phase 2 to perform preliminary handling, processing, storage, and analysis (Cohen, Bianco, Avery, 2018). It will be capable of complying with NASA's 2002 Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth (Rummel et al, 2002), with the intention of maintaining compliance with any subsequent versions.

A. Antaeus Technology and Module Design Innovation

For Antaeus to succeed, it will require advances in both sample handling technology and space module architecture. The key points of innovation include:

1. Receive cryo-vacuum samples delivered robotically from the Moon.
2. Analyze pristine samples in a "manipulator box" at a controlled atmosphere, temperature, and pressure of their origin while preventing back-, cross-, and forward-contamination.
3. Since the most difficult task is cleaning the "box" between samples, the system will place each specimen into its own small Sample Handling and Analysis Chamber (SHAC), with an internal microsurgical robot, video, and windows to expose the sample to analytical instruments.
4. Combine autonomous, human, robotic, and telerobotic techniques to analyze the samples.

5. The Phase 1 Lunar Sample-Receiving Lab (approx. 4,000 kg, 45 m3) converts into the decontamination/buffer segment for Mars Phase 2. It incorporates a shower and other features to decontaminate the crew. Also, its atmosphere can be evacuated to the vacuum of space.
6. The Phase 2 Mars Sample-Receiving Lab is outfitted with more sophisticated "glove box chambers." Since "everything leaks," these chambers are vacuum jacketed and the air that flows through them passes through a compressor and autoclave before recycling the atmosphere.
7. This design concept protects the samples from forward organic contamination from Earth, prevents cross-contamination between samples, and protects the crew and the Earth from back-contamination.
8. Mars samples stay in their SHAC containers until determined to be inert or sterilized. Once are rendered inert, they may be returned to Earth.

B. Parametric Design

Our Phase 1 focuses on parametric design for *Antaeus* to be scalable from a mostly telerobotic technology demonstrator module to a larger, more highly automated system that offers refinements to direct human researcher management and control. It involves several trade studies including: 1) Methods of creating and maintaining the Moon-like or Mars-like environment inside the Manipulator Box and the SHAC; 2) The allocation of responsibilities among the three robotic systems 3) The competing approaches to selecting and prioritizing sample types for the technology demonstration phase; and 4) Efficiency versus Effectiveness studies, including power, conservation and recycling of artificial atmosphere gases, temperature and pressure control systems, and data bandwidth.

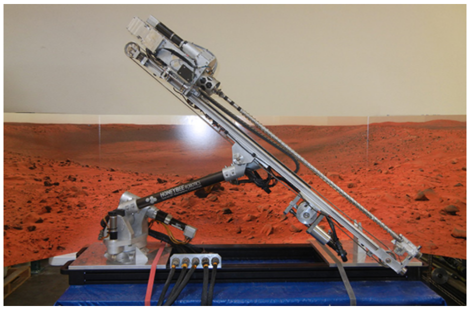

FIGURE 7. Honeybee robotics Icebreaker drill shown on Mars.

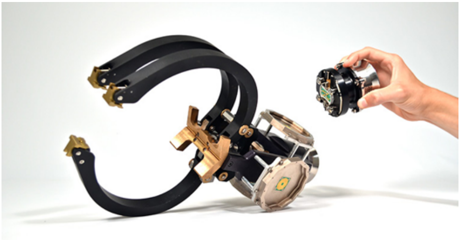

FIGURE 8. Honeybee Robotics satellite servicing manipulator.

C. Antaeus Mission Phases

Antaeus fits multiple missions, with allowances for variations in mission profile.

1. Mission Phase 1a

This first phase addresses **lunar** sample return, providing a suite of capabilities to analyze lunar samples with biological potential, notably Streptococcus, E. Coli, and tardigrades under laboratory conditions. It would include a cryo-vacuum environment capability in which to analyze lunar ice cores to study the history of the solar wind.

2. Mission Phase 1b

The second phase on the Moon would support a lunar base or habitat with a surface laboratory. Phase 1 will afford practice and testing for contaminant control and simulated handling of potentially biological samples, such as the ***Apollo LM Jettison Bags*** (containing crew biological wastes) as shown in FIGURE 5.

3. Mission Phase 2a

Antaeus can assess and hopefully assert its great advantage for **Mars:** to afford both forward contamination control of the sample and backward contamination control for planetary protection.

4. Mission Phase 2b

This phase entails the human exploration of the Mars surface from a base habitat. This phase would fulfill the original intent of MDRM 1.0, a human-tended Mars sample lab at a Mars Base.

5. Mission Phase 3

This post-Mars Sample Return phase would be to receive cryo-vacuum samples from the icy moons ***Europa and Enceladus*.** Phase 3 would be similar in many respects to handling lunar cryo-vacuum samples.

6. Mission Phase 4

This phase would handle ambient atmosphere samples from the surface of Titan and perhaps Jupiter or Saturn, which might resemble the procedures for handling Mars ambient-atmosphere samples.

D. The Three Disciplines: Geology, Robotics, Space Architecture

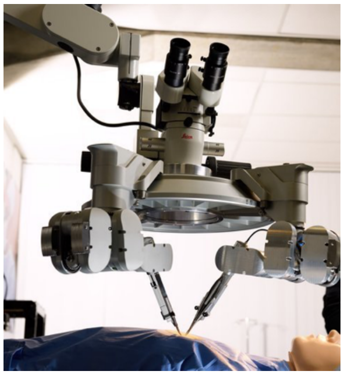

FIGURE 9. ***Microsure*** **surgical telerobot.**

This proposal represents three disciplines: Geology, Robotics, and Space Architecture. The PI and CoIs will coordinate their efforts to produce an integrated system approach to Antaeus concept formulation.

1. Geology

The science—is the primary driver to set the requirements for the capabilities Antaeus provides. Dr. Donald Barker is the CoI for Geology. The lunar sample sources map to four primary sources: cores, regolith, rocks and volcanic deposits. As most of the lunar surface has been heavily gardened through impact processes, regolith can be accessed everywhere to varying depths. Basement rock materials, either from the highlands or mare, are accessible in either outcrop, craters or through drilling. The regolith and basement rocks give insight into a variety of geological and environmental processes involved in the evolution of the Moon (e.g., lunar mantle/crust history, petrology and geochemistry). Lunar Dark Mantle Deposits (DMD) and volcanic glass provides insight into the history and evolution of the lunar mantle. Cryo-maintained materials from the lunar poles can provide insight into lunar environment evolution, impact histories and use as a barometer for historical solar activity. Lastly, many of these sample types can also be used to assess the potential for lunar resources for human habitation.

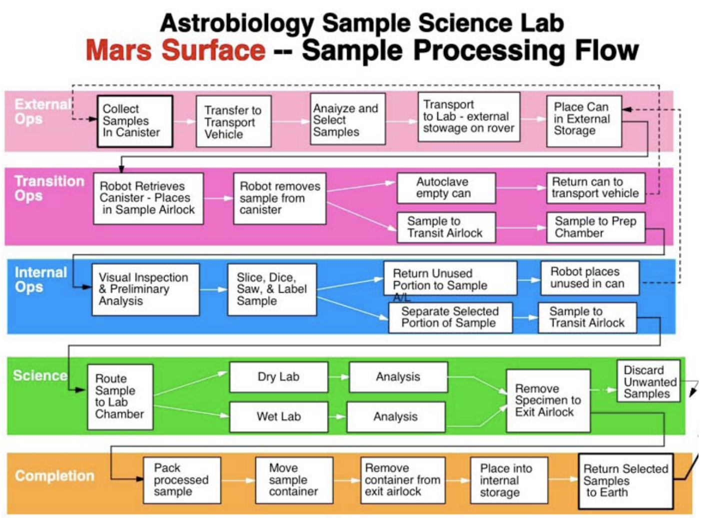

FIGURE 9. Sample handling process for the Mars surface science laboratory that provides a benchmark for the process in the Antaeus module (Cohen, 2015).

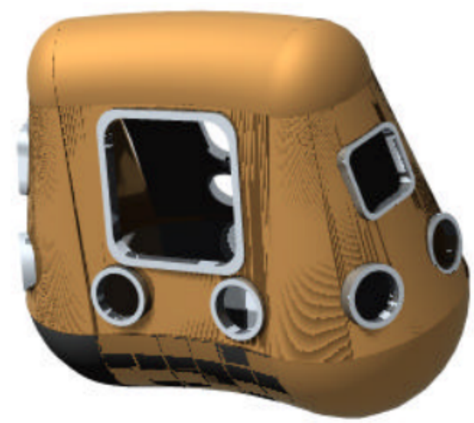

FIGURE 10. Ergonomically designed, "BSL–5" pressurizable "Manipulator Box" that can mount mechanical manipulators at the ports.

2. Robotics and Automation

The robotics for Antaeus encompasses three principal systems: The microsurgical robot in the SHAC, the larger manipulator robot in the Manipulator Box, and the automated archival inventory system. Microsurgical robots have advanced substantially in the past 20 years to where they are common in operating rooms (Mattos et al, 2016; Tan, Liverneaux, Wong, 2018). The Antaeus Team member, Honeybee Robotics, possesses world-leading expertise in space robotics. Their rock drills and abraders have been installed and used with great success on every NASA mission to Mars since Opportunity and Spirit, with an example of such a drill appearing in FIGURE 6. Honeybee has also pioneered manipulator systems for satellite servicing as shown in FIGURE 7. A further key step will be the survey of commercially available microsurgical robots, an example of which appears in FIGURE 8. The Antaeus Robotics and Automation approach includes a plan to study the existing robotic surgery technologies. The Antaeus team will evaluate which of them make the most promising candidates for installation in the Antaeus system, and what tasks lie ahead to adapt and modify these systems for sample handling, manipulation, and analysis.

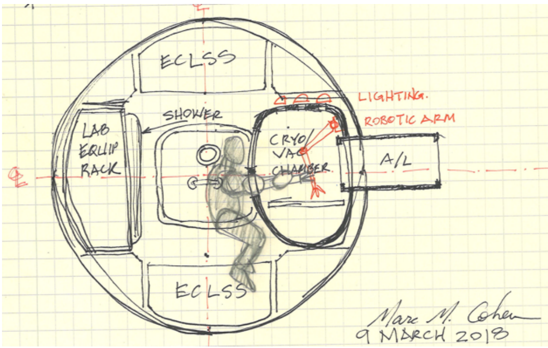

FIGURE 11. Transverse section through the Antaeus Module, showing the Manipulator Box, Airlock, and crew position to use AX-5 arms with the Jameson Prehensor.

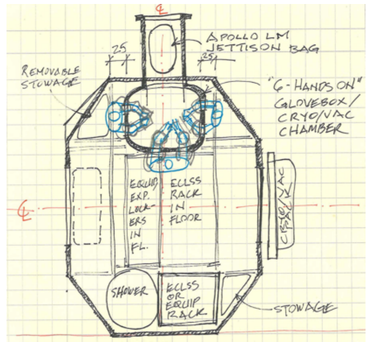

FIGURE 12. Plan View of a minimally sized Antaeus Module showing three possible crew positions to use AX-5 arms and Prehensor.

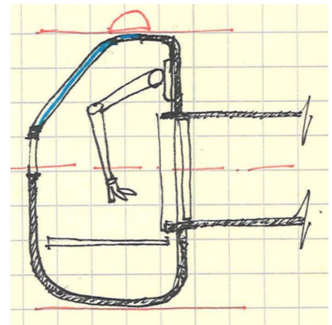

FIGURE 13. Cross-Section through a manipulator box with Robotic Arm mounted above the sample airlock.

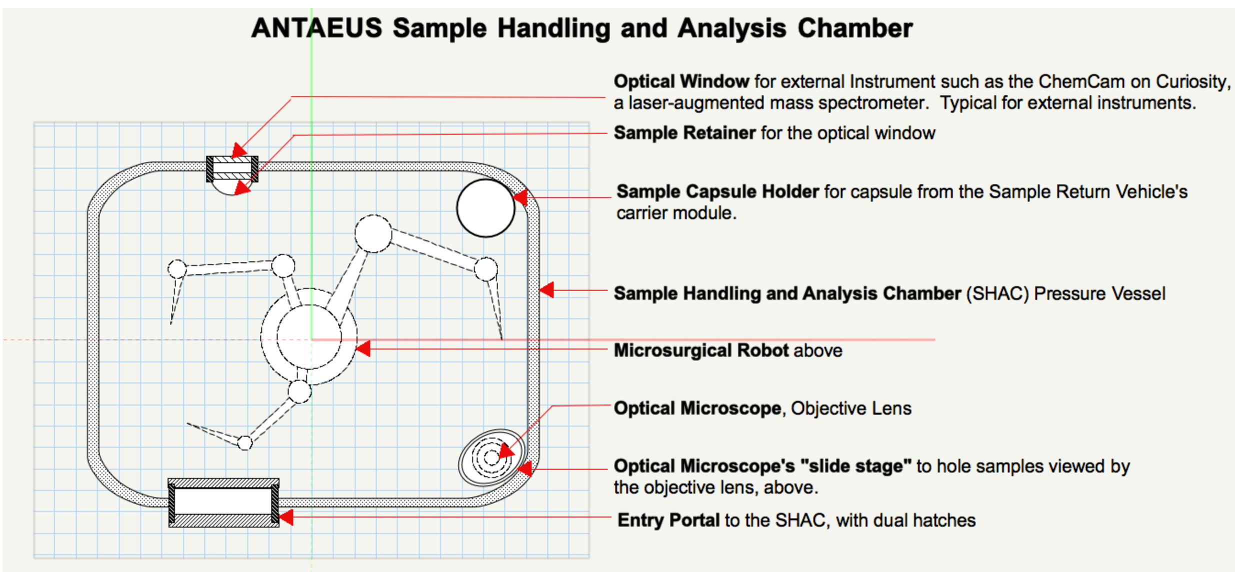

FIGURE 14. Diagram of the Sample Handling and Analysis Chamber (SHAC).

3. Space Architecture

The challenge of designing and physically integrating Anteaus means making all the systems work together in a crew-tended module. The Space Architecture design inquiry involved making many sketches and CAD drawings of the Module. "Thinking with a pencil" is a key design method illustrated in FIGURES 9 to 14. A key precept in this design effort was to not be bound by the "four stand-off" standard rack conventions from the ISS, but instead to be open to developing secondary structure and mechanical systems optimized to support the Antaeus tasks.

E. Specific Aims

FIGURE 15. The Jameson Stanford/ Ames Direct Linkage Prehensor, shown out of its pressure shell, developed by John Jameson.

FIGURE 16. The Ames Research Center AX-5 hard, high-pressure space suit, developed by Hubert C. "Vic" Vykukal.

1. Make Sample Return and Analysis Affordable and Efficient in Δv.
Significance: Eliminate the cost of Trans Earth Injection and Reentry. Eliminate the cost of a super-secure Earth-based laboratory.
Innovation: Afford inexpensive remote access to scientists and students anywhere.
Approach: Model the several structure envelopes to provide the volumes and platforms for the key functionality: Airlock, Manipulator Box, SHAC, Sample Archive System.

2. Analyze "pristine" samples in a controlled atmosphere.
Significance: Preserving the samples in their original condition is crucial for many of the scientific analyses.
Innovation: Design the Manipulator Box and SHAC as controlled environment chambers.
Approach: Adapt standard and customized ECLSS equipment to maintain a controlled Moon-like or Mars-like atmosphere, temperature, and pressure of original environment.

3. Prevent back-, cross-, and forward-contamination.
Significance: The great stumbling block for any Mars sample return is how to handle possibly biologically active samples. Antaeus solves that problem elegantly by breaking the tie to Earth.
Innovation: Antaeus confines each sample in its own SHAC, which protects it from external contaminants and contains its particles, gases and other materials.
Approach: Antaeus affords four levels of containment and protection against contamination: 1) Separation from the Earth, 2) The Antaeus Module, 3) The Manipulator Box, 4) The SHAC.

4. Eliminate the Need for Cleaning
Significance: Cleaning is difficult to guarantee and expensive to perform, especially when the requirement is to eliminate contamination.
Innovation: Don't clean. Make every SHAC a one-time use container.
Approach: Antaeus will place each specimen into its own SHAC, with an internal microsurgical robot, video, and windows to expose the sample to analytical instruments.

5. Provide diverse methods to handle and analyze the samples
Significance: The availability of these multiple modalities gives flexibility to Antaeus (Barnes, Haddock, Cruzen, 2018).
Innovation: Adapt the AX-5 Hard, High Pressure Space Suit arms and Jameson Prehensor to manipulation and servicing in the Manipulator Box as shown in FIGURES 15 and 16.
Approach: The design of the SHAC and Manipulator Box across all systems including automation, human, instrumentation, robotics, and telerobotics gives flexibility for varied ops.

6. Afford a "Head Start" for Phase 2 Mars Samples
Significance: This design provision allows the conversion of the Phase 1 module into part of the Phase 2 upgrade and expansion for *Antaeus.*
Innovation: The Phase 1 module serves a dual purpose as a quarantine/decontamination buffer.
Approach: The Phase 1 Lunar Sample-Receiving Lab (approx. 4,000 kg, 45 m^3) converts into the decontamination/buffer segment for Mars Phase 2. It incorporates a shower and other features to decontaminate the crew. Its atmosphere can be evacuated to the vacuum of space.

V. Discussion

The Antaeus project team first presented the concept at the NASA Deep Space Gateway Science Workshop on March 1, 2018, in Denver, CO and later that year at the NASA Exploration Science Forum at NASA Ames. The team put the concept together through a variety of ideas and sources. These ideas and sources had evolved over a period of nearly 40 years. While this effort clarified the design problem definition and, in a sense, prioritized the mission objectives over time, it did not produce a clean, crisp design solution. What the many sketches, diagrams, and models did accomplish was to serve as hypotheses about what the design problem is. The statement of the design problem stated above is crisp and clear.

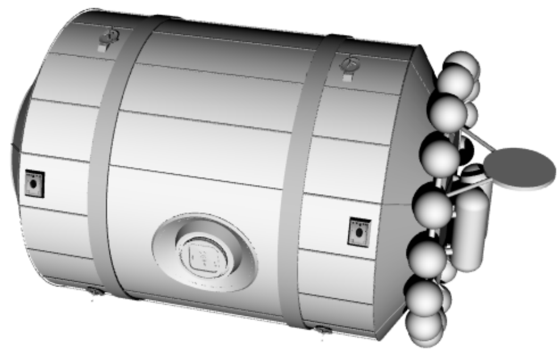

FIGURE 15. Antaeus Module concept with abundant high-pressure gas storage tanks, airlocks, and externally mounted compressors and gas autoclaves. Credit: Suzana Bianco.

A major source of ambivalence was whether to include all potential capabilities—automated, human, robotic, and telerobotic—for handling, processing, and analyzing samples, and to repair anything that might go wrong in the Antaeus systems. This emphasis on diversity of capabilities, while appealing in terms of potential versatility, also posed great penalties in terms of complexity, particularly the problem of protecting humans involved in the work from contamination.

Another source of ambiguity was the lack of a definitive "stopping rule." If the Antaeus occupies the optimal space-time coordinates to receive extraterrestrial samples and the team develops this capability for lunar samples and Mars samples, why stop there? Why not lay the foundation for a technology capable of ***safely*** receiving samples with biological potential from throughout our Solar System?

What has become self-evident is that the Antaeus project as shown in this record was too ambitious. It was trying to accomplish too many objectives with too many capabilities. Instead, the Antaeus team will need to reassess their progress as of this writing and find ways to refine and narrow the objectives and the capabilities by which to accomplish them.

Finally, at the pragmatic level, we must address the question of how large is a reasonable and affordable size for the Antaeus module? By eliminating the dual capability of human direct "hands-on" manipulation through gloves or mechanical "hands" such as the Jameson Prehensor and relying solely on robotics, it will be possible to reduce the mass and volume of the Antaeus module. How much of a reduction will be possible remains to be determined. However, the Antaeus team's goal now is to consolidate all the functions into a single module, approximately half the mass and volume of the module ensemble shown in FIGURE 2. FIGURE 15 illustrates this progress toward a consolidated module concept for Antaeus.

VI. Conclusion

All previous concepts for Mars Returned Sample Handling (MRSH) involve humans doing the majority of the work—hands on—through rubber gloves on an ongoing basis. What we have learned from the Antaeus design research is that the system can only function successfully as an entirely automated, robotic, or telerobotic system, or some combination thereof. The old paradigm for "BSL4+" bio-isolation with massive security, with dozens of researchers in full-body bunny suits stuffing their already sleeved and gloved arms into gloveboxes will be rendered moot by Antaeus.

The new concept for theaters system is that it will need crew attention only for maintenance, repair, and resupply. Researchers may operate the Antaeus systems tele-robotically and by tracking the autonomous systems telemetry from anywhere.

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