The Contained Sample Handling and Analysis System (CSHAS)

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***Abstract*-The Contained Sample Handling and Analysis System (CSHAS) system (Figure 1) is being developed to support the handling and analysis of Mars returned samples in a Sample Receiving Facility (SRF). CSHAS builds upon prior efforts for spaceborne cell culturing systems while also incorporating new technologies from related fields such as biomedical devices and semiconductor manufacturing.**

The NASA Cell Culture Unit (CCU) is used as the basis for a new instrument for automated handling and analysis of a subset (e.g., fine particles) of the sample. The CCU, an autonomous bioreactor habitat being developed by Payload Systems Inc. for NASA, was designed for use aboard the International Space Station (ISS). Although the environment in the SRF is quite different from that on ISS, the CCU nevertheless has several features—including sample segregation and containment, automated sub-sampling, video microscopy, thermal conditioning, and environmental sensing—that are applicable for use in returned Mars sample handling and analysis. The CSHAS effort adapts the CCU flight system for use on Earth to perform analysis, testing, preparation and other functions in support of defined Mars returned sample handling and analysis protocols.

The CSHAS technology development effort focuses on: (1) defining the specific role(s) for CSHAS in the Mars returned sample handling protocols, (2) determining the needed modifications to the existing CCU design, (3) implementing the appropriate modifications through subsystem design modifications and component selection, and (4) developing a breadboard system that is capable of demonstrating the applicable functions (e.g., sample handling, reagent addition/sample extraction, chemical and physical analysis, bioisolation) in a SRF-relevant laboratory environment. The result of this activity will be to bring the CSHAS technology to a maturity of TRL-4 (i.e., breadboard system in laboratory environment), setting the stage for follow-on efforts to advance the technology to TRL-6 (i.e., prototype demonstration in SRF analogue environment).

The CSHAS development is responsive to a need for systems to allow preparation and testing of a returned Mars sample. The need to protect both the Earth's population and the sample itself from contamination presents one of the most technically complex aspects of the MSR mission. The CSHAS system described herein would significantly advance our ability to perform physical and chemical analyses, life detection tests, and biohazard detection tests and other analyses to reduce the risk and enhance the scientific return for this critical MSR operation.

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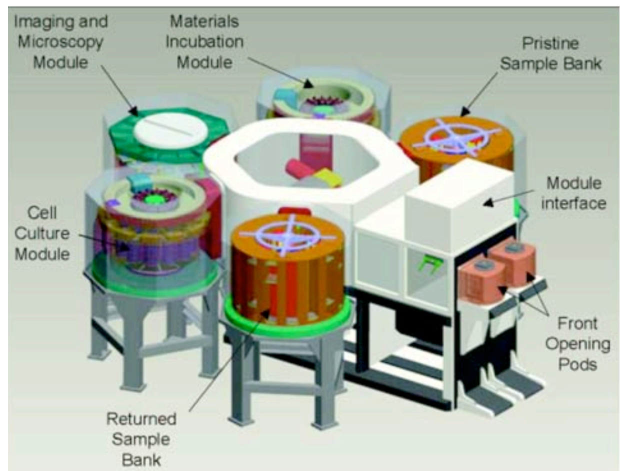

Figure 1: CSHAS system implementation

I. INTRODUCTION

Mars has proven to be a highly attractive—and yet daunting—target for exploration due to its distance from Earth, inhospitable environment, and fascinating climatological and geological (and possibly biological) history. One of the cornerstones of NASA's long-range program of planetary exploration is to bring a scientifically rich sample of Mars rock, regolith, and atmosphere back to Earth—this effort is known as the Mars Sample Return (MSR) mission. Once the sample returns to Earth, it must be treated as biologically active and hazardous until proven to be safe.

Although the MSR mission is still in the earliest stages of planning, it has been recognized that some facility must be provided to both protect the Earth from the returned sample (biohazard containment) and also to protect the sample from Earth (contamination prevention). Because of the scientific significance of the sample and the aforementioned public safety implications, efforts are already underway to develop a protocol for the handling and analysis of the returned sample.

A NASA-developed protocol for Mars returned sample handling exists today in draft form [1]. It has been a consistent theme in the draft protocol that some effort must be made to analyze the physical and chemical characteristics of the sample as a prelude to life detection and biohazard testing and subsequent release to the broader community for scientific analysis. The specific methodology for this analysis has not yet been defined, and no existing apparatus or protocol provides for both sample-to-environment and environment-to-sample isolation.

When providing for isolation and containment of a potential biohazard, it is important to minimize the interactions between humans and the sample—not just for the protection of those interacting with the sample, but because the most common causes of containment breaches tend to be associated with human handling. The ideal system would provide both sample-to-environment and environment-to-sample protection, largely or totally autonomous sample handling and analysis, and extensive analytical functions. Payload Systems Inc. (PSI) has proposed to develop a system exhibiting exactly these needed capabilities, dramatically reducing the parallel risks of inadvertent loss of Mars sample containment and sample contamination.

A. Background

The Mars Exploration Program 2003 Advanced Technologies NRA solicitation called for, among others, systems "that will allow testing and preparation of the newly received [Mars returned] samples (exclusive of biological testing) under human or robotic manipulation". In response to this call, we proposed to use the NASA Cell Culture Unit (CCU) as the design basis for a new instrument for handling and analysis of a subset (e.g., fine particles) of the returned sample.

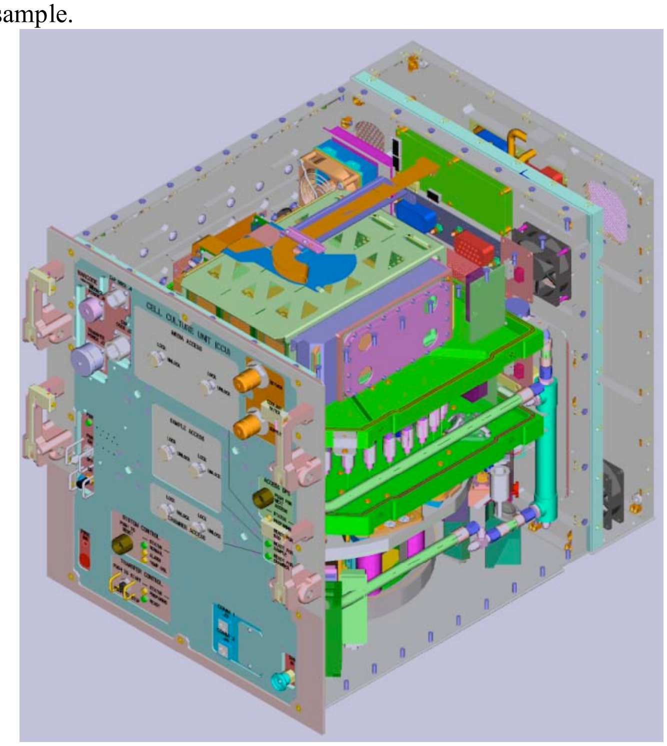

Figure 2: Cell Culture Unit (cutaway view)

The CCU (Figure 2) is an autonomous bioreactor habitat being developed by Payload Systems Inc. for NASA for use aboard the International Space Station [2]. The CCU has several core features—including multiple levels of sample segregation and containment, reagent addition/extraction, automated sub-sampling, video microscopy, thermal conditioning, precise environmental sensing and control, etc.—that are applicable for use in returned Mars sample handling and analysis.

We believe that the CCU technology is well-suited to handling and analysis of solid "fines" (unconsolidated regolith, atmospheric dust, and dust generated from coring operations) suspended in an aqueous solution. Furthermore, although not specifically requested in the solicitation, the CCU technology is also applicable for life-detection and biohazard analysis (cell culturing) activities for the same class of sample.

With these attributes in mind, we proposed to adapt the CCU flight system technologies into a Contained Sample Handling and Analysis System (CSHAS) for use on Earth to perform analysis, testing, preparation and other functions in support of defined Mars returned sample handling and analysis protocols.

The expected result of this activity is to bring the CSHAS technology to a maturity of TRL-4 (i.e., breadboard system in laboratory environment), setting the stage for follow-on efforts to bring the technology to TRL-6 (i.e., system prototype demonstration in SRF-analogue environment).

B. Project Objectives

The overall objective of our effort is to *develop a CCU-variant system optimized to support NASA Sample Receiving Facility (SRF) preparation and testing of returned Mars sample materials*. Our technology development effort focuses on: (1) defining the specific role(s) for the CSHAS in the Mars returned sample handling protocols, (2) determining the required modifications to the existing CCU design, (3) implementing the appropriate modifications through subsystem design modifications and component selection, and (4) constructing a breadboard system capable of demonstrating key functions (e.g., sample handling, reagent addition/sample extraction, chemical and physical analysis, bioisolation) in a SRF-relevant laboratory environment.

The specific objectives of the CSHAS project are:

1) *Assess the applicability of the existing CCU design to meet the needs of a handling and analysis protocol for a returned Mars sample*. The CCU was not designed with the SRF protocol application in mind. While it appears that many of the CCU design features are pertinent to this new application, a comprehensive review of the new SRF protocol requirements and a flow-down to the CCU functional and performance capabilities was essential to prove feasibility. PSI collaborated with NASA Jet Propulsion Laboratory (JPL) and NASA Ames Research Center (ARC) personnel to define the requirements associated with the sample handling protocols in the SRF. This effort (now complete) resulted in a detailed assessment of the applicability of the existing CCU design for use in sample handling and preparation protocols for physical/chemical analysis and other functions in the SRF.

2) *Define the appropriate modifications to the CCU for ground-based operation, along with those CCU functions that are not applicable for use in Mars returned sample handling and analysis*. The existing CCU design is oriented toward on-orbit operation on the space shuttle and ISS. Mass, power, and thermal conditioning are precious resources on these flight systems, and the CCU design is driven at least partially by

these factors. Some elements of the CSHAS design for the SRF may be simplified and/or made more robust in the absence of these spaceflight requirements. This effort (now complete) resulted in a definition of the modifications necessary to translate the CCU from a spaceflight multi-use cell research system to a ground system tailored to the needs of the SRF.

3) *Define the appropriate modifications for any additional CCU functions required to support Mars returned sample handling and analysis*. A detailed assessment of the anticipated SRF needs resulted in a set of additional functions or features required to make the CSHAS compatible with its new mission. For example, the two levels of containment provided in the existing CCU design does not satisfy the containment requirements for the returned sample. Additional sample conditioning, sensing, and sample segregation requirements have also inspired modifications to the existing CCU design. This effort (now complete) resulted in the definition of a set of modifications to the existing CCU design for use as a sample handling and analysis tool in the SRF.

4) *Develop a breadboard system to demonstrate relevant Mars returned sample handling and analysis procedures*. Now that the design activity described in the previous two objectives has been completed, a hardware implementation is essential to drive out subtle issues and to ensure that the integrated system concept is sound. The relevant functional testing can be performed with simulants in a standard laboratory environment. This effort (now underway) will result in a CSHAS breadboard system for sample handling and analysis, bringing the overall technical maturity to TRL-4.

C. Organization of Paper

The following sections of this paper lay out a more detailed discussion of the major technical efforts associated with the CSHAS project. These include the design and development of: (1) a conceptual design of the modular elements of CSHAS, (2) a sample handling system to transport and transfer samples safely throughout the CSHAS (and, potentially, throughout the SRF), and (3) a demonstration and TRL-4 validation program using the CSHAS breadboard system elements.

II. Module Design

A. System Description

Implementation of the CSHAS global architecture is illustrated in Figure 3. The proposed CSHAS system provides a standard interface for all modules, including those not considered a part of CSHAS. This approach reduces system complexity, increases flexibility in placing and introducing modules, and supports material transport between CSHAS modules, and between other SRF modules.

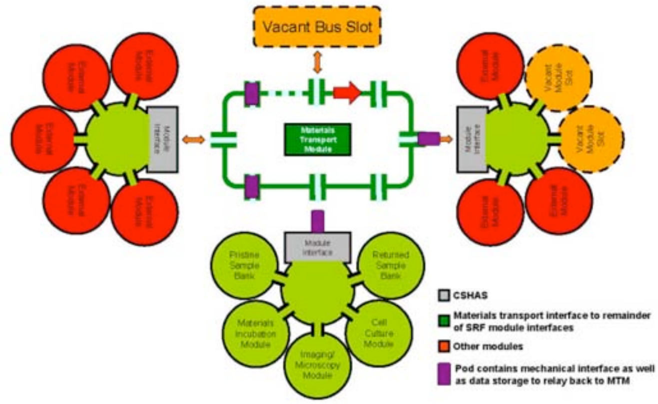

Figure 3: CSHAS system architecture within SRF

The CSHAS system concept is based on a modular bus architecture, selected to enable the evolution of the design and technologies that make it up and that will undoubtedly change by the time a sample is brought back from Mars. This approach, which maintains maximum flexibility by allowing complete module interchangeability through a minimal set of standard interfaces, sees the bus embodied in the Module Interface. This module interacts with the SRF through an exchange of materials and information, and manages their flow to and from the specialized modules on its bus.

The specialized modules, instead, are conceptualized with a modular slot architecture in mind. This maintains sufficient flexibility through functional separation and subsystem interchangeability, while enabling the design of custom subsystems and components optimized for functionality. Each module is based on a turntable layout, as is CCU, with subsystems and components slotting into place on separate sectors. After a thorough analysis of various layout options, it was determined that the turntable would minimize complexity while maximizing processing access and module utilization.

CSHAS consists of the Standard Module Interface and a number of specialized modules. Currently these modules include a Cell Culture Module, a Pristine Sample Bank, a Returned Sample Bank, and a Materials Incubation Module.

B. Standard Module Interface

The Standard Module Interface, as shown in Figure 4, provides the interface between the SRF and the specialized modules that form part of the CSHAS system. The Module Interface receives and returns information and materials through its interface with Front Opening Pods (FOPs) that travel between the various SRF modules and facilities. A front end robot operating through an airlock that separates the specialized modules from the rest of the SRF serves a back end robot that routes the materials appropriately.

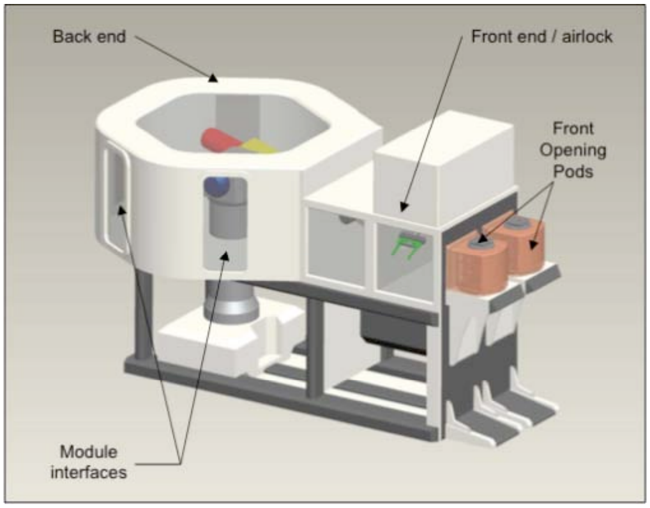

Figure 4: Standard Module Interface concept

The specialized modules interact with the Module Interface through standard interfaces. The atmosphere and temperature to which these interfaces are exposed is controlled by the Standard Module Interface and can be modified for each individual carrier that is moved through the system. This means that the environmental conditions during each transfer can be matched to those in the module sector being addressed.

C. Cell Culture Module (CCM)

The Cell Culture Module, shown in Figure 5, is the one that most closely resembles the CCU. Responsible primarily for culturing of specimens for the determination of biohazard presence and life detection, it consists of 16 chambers arranged in four separate sectors, each with its own thermal and atmospheric control capability. Access to the chamber receptacles is through a single transfer port that interfaces directly with the Module Interface. The only other external interface provides the opportunity to replace spent media cartridges without breaking the mechanical and biological containment that prevents cross contamination. The system will provide BSL-4 protection with at least three levels of containment at all times. Its operation will be fully automated.

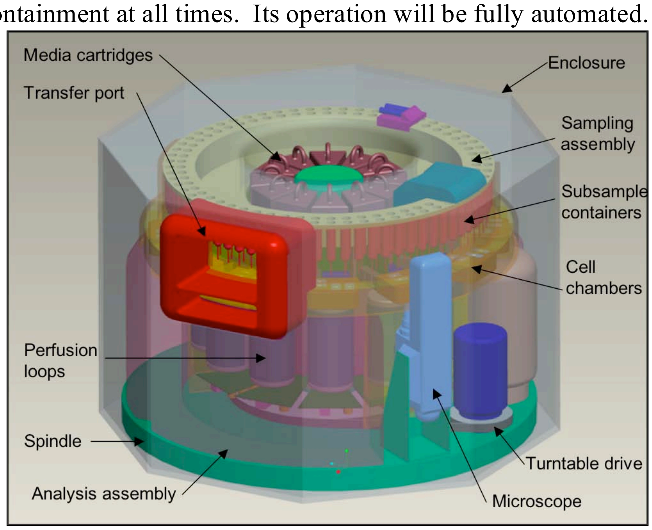

Figure 5: Cell Culture Module concept

The sector division approach was carried over from CCU because it provides the opportunity for parallel processing in four thermally independent environments. In addition, each chamber possesses its own fully controlled perfusion loop, providing additional experimental flexibility. The progress of each experiment can be observed through the onboard microscopy capability, which allows observation without disturbance. Finally, a fully automated sampling system enables the introduction or extraction of materials, additives and specimens at any time during an experiment.

D. Materials Incubation Module (MIM)

The Materials Incubation Module is similar in construction and function to the Cell Culture Module. Just like the CCM, the MIM contains four thermally independently and controllable sectors, each with four incubation chambers. The chambers can be supplied with fluid or other specimens through the fully automated sampling system. In addition, replaceable fluid cartridges can be accessed without breaching the required biological protection and containment system.

Although the MIM is simpler than the CCM (because it does not require the perfusion loops necessary for cell culturing), it does have the ability to control the individual incubation chamber atmospheres in order to enable the exposure of materials coupons to the Martian sample under a wide range of thermal and environmental conditions.

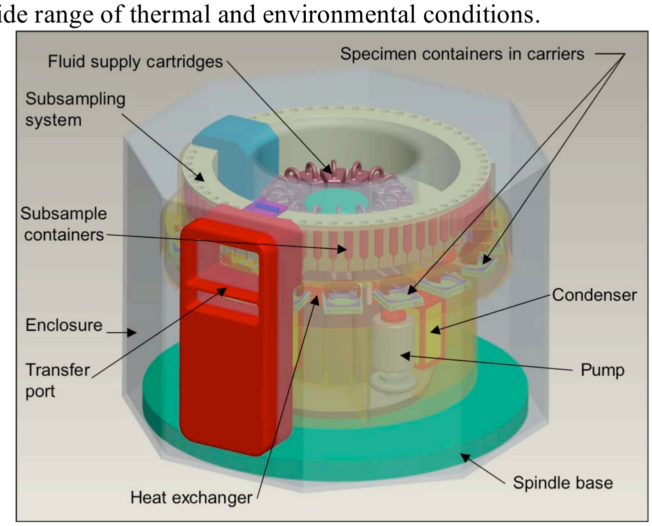

Figure 6: Materials Incubation Module concept

The primary purpose of the MIM is the determination of suitability of various materials exposed to Martian samples during their long-term storage here on Earth.

Pristine Sample Bank/Returned Sample Bank (PSB/RSB)

The Pristine and Returned Sample Banks, shown in Figure 7, are identical in basic design and function. The reason for their separate existence is the need to store the majority of the returned sample in pristine condition, separate from the portion of sample that will be subjected to testing. This implies that different materials may be used in the manufacture of these modules to ensure that long-term contact will not degrade the sample. Naturally, this could only be done once it has been determined what the best material choice is.

The PSB and RSB are also arranged in four separate sectors to provide the opportunity for different storage conditions, if required. Each bank will contain a set of racks that will allow flexible placement of carriers in storage.

The number of PSB's and RSB's in the SRF in general is not limited. It may be worthwhile to store pristine samples in multiple PSB's, for example, to lower the risk of sample being compromised should there be a module failure. The same argument is valid for the rest of the modules in the system, demonstrating the flexibility of the CSHAS architecture and its wide applicability within the SRF in general.

III. Sample Handling System

The CSHAS sample handling system takes into consideration: (1) the biological containment of the returned samples and of terrestrial organisms and materials exposed to those samples, (2) the cleanliness of the handling approach and associated equipment, environment control, and (3) materials handling, tracking, and distribution. Each type of testing or analysis of the returned samples—such as cell culturing or materials incubation—presents unique requirements that affect the handling system. These include specimen preparation, handling, packaging, and observation requirements. In addition, the system must support the storage of pristine (untested) specimens, specimens awaiting test and analysis, and specimens returned after testing—all in controlled environment conditions. Lastly, the sample handling system needs to provide inventory management, scheduling, and data management.

A. System Heritage

The proposed system for the retrieval, movement, storage, and management of the specimens between modules is based on the current best practice of the semiconductor fabrication industry. Semiconductor fabrication utilizes highly-automated robotic handling in an ultra-clean environment under strict process control, all of which are applicable to the SRF.

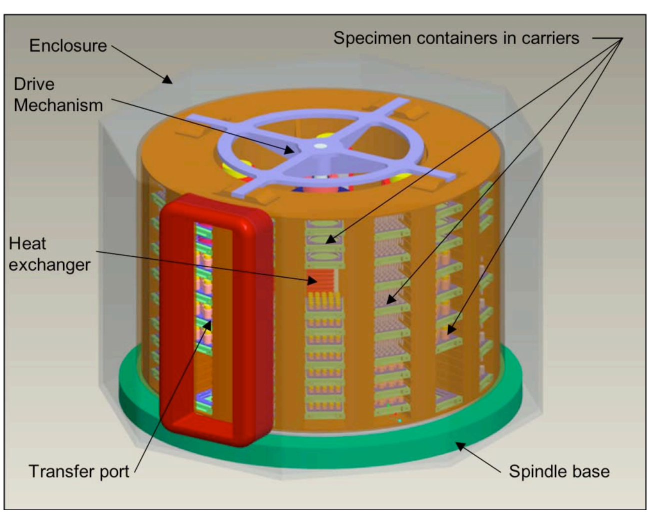

Figure 7: Pristine and Returned Sample Bank concept

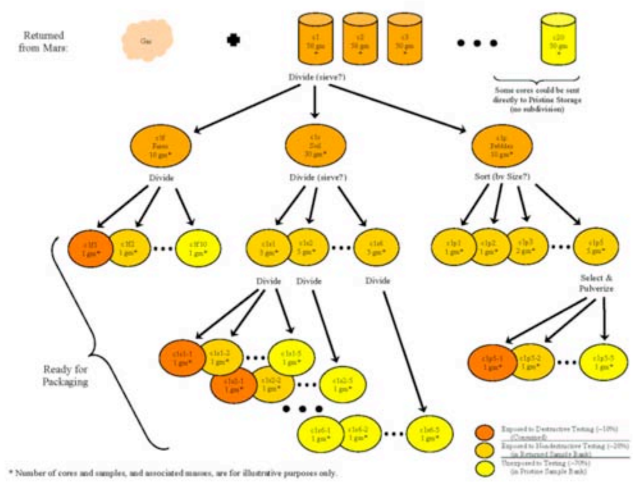

Figure 8: Example Mars sample subdivision

B. Sample Subdivision

The Mars returned sample mass of 500-1000 grams is expected to be in the form of a number of cores and gas captured in a sealed container. The cores will be physically subdivided into smaller sub-samples, herein called ***specimens***, based on soil type and particle size: dust, fines (particle size smaller than 1 mm), soil, pebbles, rocks, and gases. The subdivision will be done manually, mechanically, or in some combination of the two. A typical specimen size will be 1 gram, but can range from 0.1 gram to 8 grams or more, depending on the associated test or instrument requirements. After the subdivision, the specimens will be allocated, approximately, as 70% for pristine storage (unexposed to testing/analysis), 20% exposed to nondestructive testing, and 10% consumed in destructive testing. Figure 8 illustrates one possible subdivision of the Mars samples.

C. Specimen Packaging

Specimen packaging must be responsive to the handling requirements imposed on extra-terrestrial materials: (1) considered to be potentially hazardous material, i.e., need to maintain strict biological containment, until demonstrated otherwise; (2) keep isolated from terrestrial materials to prevent contamination; and (3) subjected to a rigorous analysis protocol to determine if hazards to earth-based life exist, if Mars-based life is present, and if residue of past Mars-based life is present.

The NASA sample handling draft protocol requires specimens to be packaged individually and to support automated, robotic handling, with minimal impact on the specimens. A survey of existing packaging methods identified drug/serum packaging developed by the pharmaceutical industry as an applicable approach. Drug/serum packaging provides containment, provides a sterile and clean environment, uses materials highly resistant to chemical interaction with its contents, and is compatible with automated processing including cleaning, sterilizing, filling, capping, and visual inspection of package contents. Serum packaging applicable to use with CSHAS includes ampules, and bottles or vials with crimp caps. Figure 9 shows the proposed specimen packaging.

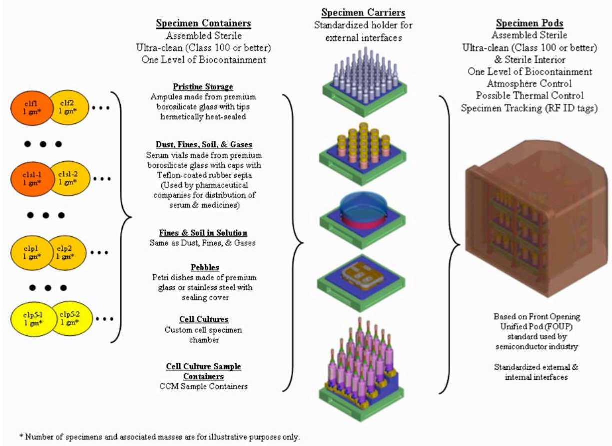

Figure 9: Specimen packaging

All recommended containers can be assembled sterile, can be cleaned to provide ultra-clean conditions, and provide one level of bio-containment. Ampules and serum vials are utilized for pristine storage and for the packing of dust, fines, and gases. Petri dishes with custom sealing covers are used for larger solids such as pebbles and rocks. CCU-related cell chambers and sub-sample containers are used for the CSHAS Cell Culture Module. All of the specimen containers are organized to use custom-developed specimen holders and carriers, allowing the use of standard transport pods from the semiconductor fabrication industry for the movement of the specimens within the SRF. Figure 10 shows prototype carrier hardware installed in a typical transport pod.

D. *Automated Handling*

The proposed automated handling system for CSHAS is shown in Figure 11. This approach assumes the development of standardized interfaces for specimen containers and associated equipment such as the holders and carriers described above. It utilizes standard semiconductor interfaces and equipment to move specimens between storage banks and specific modules within the SRF. Each module would be housed in a double-wall Class III Biological Safety Cabinet providing Biological Safety Level 4 (BSL-4).

Figure 10: Specimen handling pod

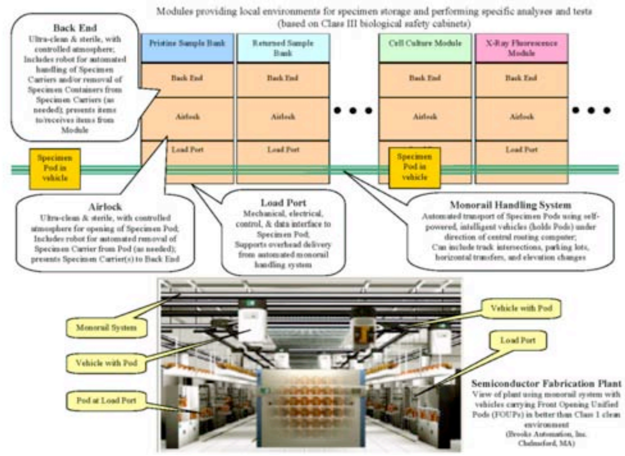

Figure 11: Automated handling of specimens

IV. DEMONSTRATORS AND TRL-4 VALIDATION

The CSHAS unique technology and designs will be verified through a series of demonstrators and NASA TRL-4 validation testing. Most of the CSHAS technology components are utilized in two CSHAS modules: the Cell Culture Module (CCM) and the Material Transport Module (MTM). Therefore the CSHAS validation can be represented and covered by the validation of CCM and MTM.

Since CCM is directly adapted from the Cell Culture Unit (CCU), the CCM validation will focus on those new elements and processes which have not been demonstrated in the CCU. As for those elements and processes already demonstrated in the CCU, analogy analysis will be used to show their applicability to CHSAS. Since the MTM is adapted from the semiconductor industry, the MTM validation will focus on the key elements that are not currently used in the semiconductor industry, such as specimen containers and carriers. Applicability of the semiconductor industry's automated robotic handling will be demonstrated for CSHAS sample handling.

Much of the technology and design of the Cell Culture Module is adapted from CCU, including the cell chambers, perfusion loops, subsampling system, microscopy, and so on. Detailed feasibility assessment was performed in the first year of this project. As expected, most of the CCU design can be directly transferred to CCM. Theefore, the CCM design effort focused on the capability not presented in CCU—including dry and solid specimen exposure to cell culture, additional sensing capability other than pH and O_2 such as glucose and lactate, humidity sensing, and high salinity cultures. Figure 12 below shows one representative cell culture single loop in CCM, with the red circles highlighting the CCM capabilities currently not present in CCU, including the inline specimen vials and offline glucose and lactate analyzer. Besides the cell culture single loop, other major CCM functional components are microscopy, subsampling, and thermal control subsystems.

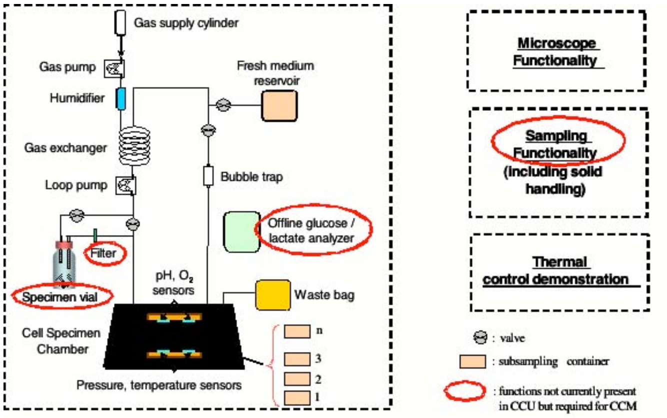

Figure 12: One CCM cell culturing loop and other major CCM functions required demonstration.

Among them, sample handling of a solid specimen is not currently present in CCU, and the microscopy and thermal control capability are extended from CCU and need additional demonstration. Cell growth tests will be performed to demonstrate the culture functionality using one mammalian and one microbial model cell systems. Besides the normal cell culture demonstration, pathogens will be introduced to the normal culture to demonstrate the CCM capability to detect toxins. In addition, tests will be performed to demonstrate the new elements including the glucose/lactate sensing and in-line specimen vial integration. Handling the solid specimen represents a new task for CCM. We propose three specimen exposure methods. One is specimen introduction through inlet line as shown in Figure 12. A second method is specimen introduction through use of a CCU subsample container, and a third method is specimen introduction directly into cell chamber. For each proposed method, specific process development work is required to achieve an efficient specimen exposure. As CCM is required to handle high salinity microbial cultures, culture tests will be performed to demonstrate CCM hardware's compatibility to high salinity. For the microscopy inside CCM, the CCU bench top microscope prototype will be used to demonstrate its functionality, especially the capability to observe the specimen when introduced directly into cell chamber. For CCM subsampling demonstration, the Engineering Design Unit of CCU will be used as demonstrator. The new demonstration will include the specimen introduction through subsample container and thermal control for subsampling. For the CCM thermal control capability demonstration, a closed volume breadboard will be built to simulate one quadrant of internal CCM hardware, and the CCU thermal control system will be adapted and integrated into the closed volume.

Various sample handling demonstrators will be built, including specimen containers, carriers, pods, standard module interface, and automated handling system. The validation test will focus on demonstrating the material compatibility of the specimen containers and carriers to the representative specimen types, and the automated sample handling, including the robotic handling of specimen carriers, containers, and robotic delivery of specimens to modules.

In summary, through the above CSHAS demonstrators and validation tests, we believe that the major CSHAS technology components will be validated in the two representative modules of CCM and MTM.

V. Project Status

The CSHAS project is approximately 2.5 years into a four-year project life cycle. The CSHAS role in the SRF has been defined, the feasibility and compatibility assessment of the various CCU components to serve in the CSHAS role has been completed, and the requirements for the CSHAS system have been defined. Design of the CSHAS overall module architecture and major modules, sample handling system, and breadboard elements has been completed, as has the definition of the testing and TRL-4 validation effort. Work remaining includes the development (procurement and construction) of the breadboard system elements, and the actual testing and TRL-4 validation effort. Project completion is scheduled for mid-late 2008.

Acknowledgment

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References

[1] Race, Margaret S.; DeVincenzi, Donald L.; Schad, P. Jackson; Stabekis, Pericles D.; Viso, Michel; Acevedo, Sara E., "A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth," NASA CP-2002-211842, 2002.

[2] de Luis, J., Vunjak-Novakovik, G., Searby, N, "Design and Testing of the ISS Cell Culture Unit," IAF/IAA-00-G.4.06, presented at the 51st International Astronautical Congress, Rio de Janeiro, Brazil, Oct. 2000.