Asteroid Redirect Crewed Mission Space Suit and EVA System Maturation

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***Abstract*—The Asteroid Redirect Crewed Mission (ARCM) requires a Launch/Entry/Abort (LEA) suit capability and short duration Extra Vehicular Activity (EVA) capability from the Orion spacecraft. For this mission, the pressure garment selected for both functions is the Modified Advanced Crew Escape Suit (MACES) with EVA enhancements and the life support option that was selected is the Exploration Portable Life Support System (PLSS) currently under development for Advanced Exploration Systems (AES). The proposed architecture meets the ARCM constraints, but much more work is required to determine the details of the suit upgrades, the integration with the PLSS, and the tools and equipment necessary to accomplish the mission. This work has continued over the last year to better define the operations and hardware maturation of these systems. EVA simulations were completed in the Neutral Buoyancy Lab (NBL) and interfacing options were prototyped and analyzed with testing planned for late 2014. This paper discusses the work done over the last year on the MACES enhancements, the use of tools while using the suit, and the integration of the PLSS with the MACES.**

Nomenclature

ACFM	=	Actual Cubic Feet per Minute
AES	=	Advanced Exploration Systems
ARM	=	Asteroid Redirect Mission
ARV	=	Asteroid Redirect Vehicle
ARCM	=	Asteroid Redirect Crewed Mission
BRT	=	Body Restraint Tether
CLB	=	Crew Lock Bag
DRM	=	Design Reference Mission
EMU	=	Extravehicular Mobility Unit
EVA	=	Extravehicular Activity
FY	=	Fiscal Year
HILT	=	Human-in-the-Loop
HUT	=	Hard Upper Torso
GSB	=	Gap Spanner Boom
ISS	=	International Space Station
LEA	=	Launch / Entry / Abort
MACES	=	Modified Advanced Crew Escape Suit
MMWS	=	Modular Mini Work Station
MPIK	=	MACES to PLSS Interface Kit
NBL	=	Neutral Buoyancy Lab
NUI	=	NBL Umbilical Interface
OML	=	Outer Mold Line
PFR	=	Portable Foot Restraint
PLSS	=	Portable Life Support System
PPRV	=	Positive Pressure Relief Valve
RCA	=	Rapid Cycle Amine
SB	=	Stabilization Boom
SWME	=	Suit Water Membrane Evaporator
TCC	=	Trace Contaminant Control

I. Introduction

The maturation of the EVA system for the Asteroid Redirect Crewed Mission in 2014 occurred on three fronts: mobility and stabilization enhancements were added to the MACES, tools were developed for the specific EVA tasks of the mission, and an interface kit was designed to integrate the PLSS (designed for the Advanced Space Suit) with the MACES. The MACES and tools were tested in the NBL on a medium fidelity capsule, asteroid vehicle, and asteroid mockups. The interface kit between the PLSS and the MACES was developed in the lab. For MACES upgrades, components were procured to allow in-house buildup for four new suits with mobility enhancements built into the arms. Boots outfitted with clips that fit into foot restraints have also been added to the suit and analyzed for possible loads. Major suit objectives accomplished during testing this year include: evaluation of mobility enhancements, ingress/egress of foot restraint, use of foot restraint for worksite stability, ingress/egress of Orion hatch with PLSS mockup, and testing with two crew members in the water at one time. For tools, work was done in the areas of mockup improvement and sample collection. Major tool objectives accomplished this year include: evaluating various methods for worksite stability, utilizing new tools for asteroid geological sampling, and improving the fidelity of the NBL mockups from previous test configurations.

Another objective was the design and fabrication of the prototype interface between the MACES and the PLSS. Testing of the interface kit will be conducted in the near future. The design will be vetted through suit and PLSS experts and, with the findings from the testing, the best path forward will be determined.

II. MACES NBL Testing

A. MACES NBL Testing Overview

The major objectives for the MACES testing included: evaluating mobility enhancements, attempting to ingress/egress Extravehicular Mobility Unit (EMU) foot restraints, accomplishing two handed tasks inside of the EMU foot restraint, testing with two crew members in the water at one time to evaluate the crew's ability to help one another, and testing on higher fidelity capsule mockups to more accurately represent an asteroid-type EVA. These testing objectives served as the building blocks leading up to a full end-to-end EVA demonstration analogous to the proposed ARCM design reference mission (DRM). Similarly, while performing ISS-centric EVA tasks, the crew members evaluated the applicability and nuances of the MACES and PLSS integrated assembly, which provided a common baseline for crew members to reference and compare the feasibility of using the MACES for EVA tasks.

EMU foot restraint ingress/egress and task performance while anchored in an EMU foot restraint was a key early objective to determine compatibility within existing EVA interfaces and performance within already existing crew training processes. The successful lab and NBL demonstrations of crew unaided ingress and egress of the EMU foot restraint allows this interface and platform to be a suit connection point on the proposed crew member boom assembly for use in the ARCM DRM. The EMU foot restraint provides a stable and well-characterized worksite for hands-free operations in a suitable work envelope for the ARCM EVA activities. Translation from the capsule to the worksite using EVA handrails and ingress into an EMU foot restraint was also performed and analyzed, demonstrating that these existing tools will meet mission objectives.

An integrated approach was taken for NBL testing. Early tests were conducted with just the MACES, showing the overall extensibility of the MACES pressure garment from a contingency-only EVA system to the suit's use as an enabler of planned asteroid short-duration spacewalks. Successive test integrated the MACES and an ISS EMU PLSS volumetric shell (approximately the same volume as the Exploration PLSS mentioned later) to show the feasibility of using these two systems together on an EVA. The test series culminated with demonstration of a full-up asteroid mission profile using progressive lessons learned.

B. Hardware Build-up for NBL Testing

For this test series four NBL versions of the MACES were constructed, two sized Medium-Regular and 2 sized Large-Regular. The nominal arm position of the MACES is configured for the seated position, but to improve EVA mobility, all of the new suits have the shoulder re-biased so the neutral arm position is higher and angled toward the center of the chest. All four of the new suits had the shoulder re-biased so the neutral arm position is higher and angled toward the center of the chest. Two of these suits (one medium and one large) also have an arm bearing along the bicep coupled with a higher mobility elbow joint. These suit sizes were selected to match the size of the intended subjects who are astronauts with extensive EMU EVA experience. Existing EMU boots were added to the suit for all of the tests in this series to allow for ISS EVA foot restraint use. In order to facilitate use of the EVA foot restraint and EMU boots, the MACES required additional reinforcement because of increased load transmission. Axial restraints were added to leg restraint, tested, and analyzed to ensure safety while performing simulated spacewalks in the NBL. The suits were received in January 2014 and fit checked with the first two NBL crew test subjects. All tests were performed with current EMU phase VI gloves.

Based upon earlier NBL events, sizing predictions were made for use of the EMU boots. NBL fit of the suit has significant differences between standing upright in the lab environment, seated in a recumbent posture, and true microgravity found in space. Standing in the lab environment compresses the air column of the legs and creates the appearance of shorter suit heel to shoulder length. In this case the head position in the helmet is determined by the subject's pelvis and armpits pressing down on the suit. When the suit is in the water, it is neutrally buoyant and expands to take its preferred shape. The weight of the subject is being offset by the buoyant force of the suit, causing the subject to hang inside the suit as the gravity vector pulls them toward the lowest point. The subject shifts or flops inside the suit when rotated into different attitudes. With all of this movement inside the suit, the head position will change (sometimes unfavorably) as the subject goes from standing/sitting upright to lying face down to lying on their back face up. Additionally, excess space in the interior of the suit increases this shifting. It can take several minutes to an hour for the shifting to settle, resulting in a perception that the length of the suit has changed. It is predicted that both the MACES and EMU soft goods do increase in length during NBL testing and that the MACES will grow more than the EMU due to the materials of construction. The exact amount of this growth has not been quantified yet.

The initial NBL run did not correctly account for the increased length provided by the EMU boots or the differences between standing lab fit and NBL fit. As a result, during the first dual suit run with EMU boots, both subject's suits were too long from both heel to shoulder and crotch to shoulder. This excessive suit length resulted in lower than desired head position. For later test runs the suit was shortened and the lab fit check was modified to focus on head position while hanging from the harness to simulate the subject hanging in the suit underwater.

To raise the head position within the suits, the suits had to be sized shorter than in previous tests which increased the difficulty of donning. Techniques were developed for adjusting unpressurized leg length with the subject in the suit allowing the test subjects to don the suit in a looser fitting configuration and preventing test subject injury. Proper indexing remains vital to maximize crewmember efficiency and comfort during EVA testing, as well as to provide valid comparisons between biased, non-biased, and arm-bearing pressure garment configurations.

Lessons learned during testing in 2013 and early 2014 were applied to ongoing hardware buildup and development throughout the 2014 test series. As the need for a PLSS volumetric mockup materialized, modifications were made to the soft goods harness connected to the NBL Umbilical Interface (NUI) and MACES. The weight loading hardware used to achieve neutral buoyancy in the NBL was refined to better integrate with the PLSS mockup and varying sizes of test subjects, including development of a weigh pouch system specifically tailored to extra-small test subjects. Ancillary hardware development, such as the refinement of padding inside the suit and expanded use of a custom-designed hydration system was a key component of enhancing the effectiveness of NBL testing while adding fidelity to test objectives.

C. Mobility Enhancement Tests

In the first two tests, the primary objective was to evaluate the mobility enhancements of the newly procured suits. The tests included two crewmember test subjects that had acquired experience in the baseline suits during the summer of 2013. For the first test, one test subject wore the suit with the bearings while the second test subject wore the suit without them. In the second test, the test subjects swapped suits. This methodology was chosen to have both systems evaluated before final design choices are made.

The test subjects performed a series of tasks, both familiar and new. The familiar tasks allowed the test subjects to compare the MACES to the EMU and the new tasks allowed them to conduct tasks applicable to the ARCM DRM. Translation, ingress/egress of hatches, and simple tool work were some of the tasks chosen to test the enhanced arm mobility. As this was also the first series of tests that included two crewmembers in the water at the same time while wearing the MACES suits, some dual operation tasks were also performed.

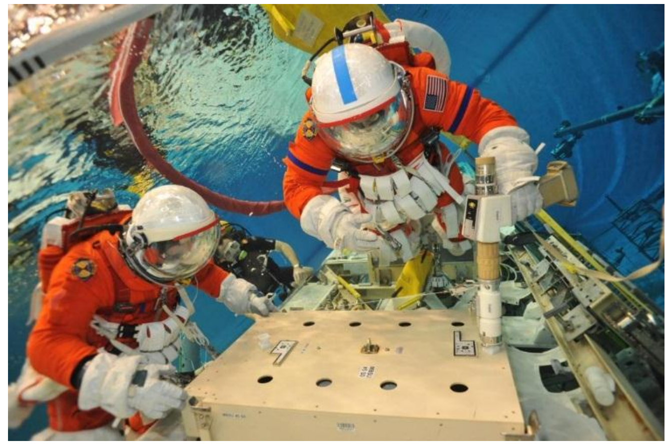

Figure 1 Crewmembers test mobility enhancements in NBL

The fit of both crewmembers in the first test was unsatisfactory and their performance was affected by the fit. They were able to complete the requested tasks but noted unacceptable levels of effort. The crew demonstrated tool use, large ORU handling, and PFR ingress/egress. In the second test, adjustments were made to the heel to shoulder length and crotch to shoulder length of each crewmember, improving the fit and therefore improving the performance. Similar tasks were completed in both tests. The opinions of both of these test subjects were that the bearings increased their performance above the suit without the bearings. Subjects commented that ingressing the PFR with EMU boots on the MACES was similar to the effort required in the EMU.

For the third and fourth tests two new astronaut test subjects with EMU EVA experience were used, increasing the data set of number of people fitted to the suits. The third test focused on training this new crew on the MACES with both ISS tasks and new asteroid related tasks. One subject commented the upper arm bearings were not very helpful while the other felt that the bearings improved his mobility. Both subjects were able to demonstrate the proposed ARCM timeline.

Major forward work for the suit includes testing with smaller female subjects, decreasing the suit shoulder breadth, and making improvements to shoulder mobility. Future suit builds will focus more on the smaller end of the sizing range and look at different options for customizing the suit to the subject.

D. PLSS Volumetric Simulator

While transitioning from 2013 demonstrations of effective MACES use in the NBL for Orion contingency EVA to evaluating the asteroid mission profile, the need for a PLSS volumetric simulator was identified. Using a volumetric analog to a PLSS outer mold line (OML) shell allowed for evaluations of safe ingress/egress of the NBL Orion mockup as well as added fidelity to mission profiles performed in the NBL. Two ISS EMU PLSS training mockups were modified by MACES engineers and technicians to interface with a Space Shuttle-era parachute harness and NUI Assembly.

The volume of the ISS EMU PLSS OML is geometrically similar to the proposed Exploration PLSS currently under development. The Exploration PLSS design falls within the volumetric constraints of the PLSS used on orbit currently, allowing for an accurate assessment of EVA performance metrics using hardware already available. The EMU PLSS simulator is shown attached to the MACES in Figure 2.

Figure 2 EMU PLSS Simulator Mounted on MACES

The PLSS volumetric simulator provided mounting for the NUI and associated umbilicals in a flight-like manner, routing supply and return ventilation gas connections under the test subject's arms. Throughout 2014, improvements were made to the PLSS simulator to optimize the front-to-back PLSS/MACES assembly dimensions and prevent test subject entanglement during NBL operations. Additionally, attachments were added to the PLSS simulator to allow for Body Restraint Tether (BRT) attachment in order to provide body stabilization during full mission profile testing.

PLSS mockup usage was a pivotal component of dual-crewmember operations in mid and late-2014, with two crew members operating in tandem to egress from the NBL Orion mockup, translate along an access boom then perform asteroid exploration activities. Outfitting both crew members with accurate PLSS mockups allowed the team to investigate the body dynamics between crew members, as well as areas of hardware interference between suited crew members and spacecraft structures. Using readily available hardware provided a cost effective approach for the NBL evaluations. It was determined from full mission profile testing that ingress and egress operations can be performed by the PLSS/MACES configuration.

E. Conclusion

By the time the project prepared for the final two tests of 2014, most of the suit modifications were complete and data was collected.

There were many findings through these tests on the operation and design of the MACES, but the most influential finding was that how important fit is to the performance of the suit for any operation where mobility is needed. The primary job of the suit is to be a LEA suit; protecting the wearer during critical events. To best accomplish this purpose, the suit needs to be comfortable for the long hours during prelaunch, launch and in-space critical events, meaning a loose fit. On the contrary, for maximum mobility during an EVA, the suit fit must be much tighter. Balancing these two opposing requirements will be the focus in the next step of development. Customization of the suits will be investigated to see if fitting the suits to a singular person will allow for an EVA fit to be comfortable enough to allow long periods of time in the suit.

III. Tool Testing in NBL

A. Background

In fiscal year 2014, the first set of prototype tools and equipment were developed specifically for ARCM. In addition to allowing maturation of tool prototypes and operation concepts, these tools were used to provide relevant tasks for evaluating the MACES as an EVA suit. This development focused on four areas: crew translation, body stabilization, geology sample acquisition, and geology sample storage.

B. Mockup

To provide the best simulation a mockup of the ARCM vehicle stack was created for the NBL. The mockup consisted of an Orion spacecraft, the Asteroid Redirect Vehicle (ARV) and a segment of a captured asteroid. The asteroid portion was comprised of pallet boxes containing various rock sizes and materials that provided a reasonable representation of a natural, rocky surface. The rocks were a combination of naturally occurring loose river gravel commonly used in landscaping, custom-made neutrally-buoyant rock simulants, and larger solid boulders. This created an overall asteroid surface with both "adhesion" and "free floating" features that would react as expected in flight when disturbed by sampling activities. Finally, to support geology sampling during the EVA the asteroid portion of the stack mockup was covered in a fabric capture bag similar to that currently under consideration for the Asteroid Redirect Mission (ARM) "Option A" vehicle architecture.

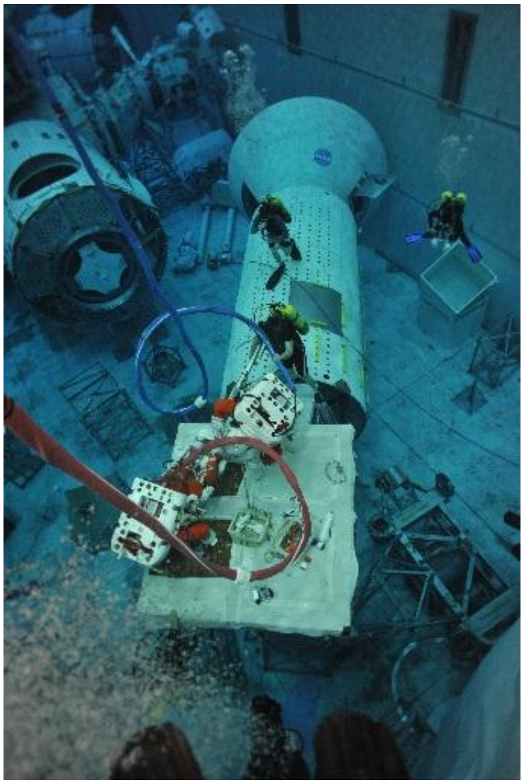

Figure 3 ARCM Vehicle Stack NBL Mockup

C. Translation

In order to accomplish mission objectives the crew members need to translate from the docked Orion vehicle at the aft end of the stack to the captured asteroid at the opposite. The first step is to egress Orion and maneuver to the ARV. However, a gap of about 5 feet between Orion and the ARV exists due to the nature of the conical backshell of Orion and the docking collar ring of the ARV. It is undesirable to place translation aides such as handrails on the external surface of Orion because of the heat shield tiles that cover much of this surface. For that reason, a crew deployed translation device called the Gap Spanner Boom (GSB) was developed. This rigid, telescoping carbon fiber pole was designed with custom end-effectors to facilitate capture and attachment on both ends of the gap. One end is a Space Shuttle Program-derived EVA self-rescue device resembling a hook while the other end provides two simple Tether Rings to interface with typical EVA Adjustable Equipment Tethers.

Figure 4 Gap Spanner Boom

After opening the Orion hatch, the EV crew member deploys the device to full extension and uses the hook end to grapple a capped peg on the ARV. Next, the crew connect a tether between a ring on the GSB and an attachment point inside Orion. The tether is then tightened to secure the boom against the Orion hatch structure with enough rigidity to provide a stable translation path for the crew. The prototype GSB was designed with limited stowage volume in mind, expanding from 32 inches stowed to 64 inches when deployed. This tool was successfully used during multiple tests and is considered a valid method for accomplishing translation between Orion and the ARV.

Known forward work for the GSB includes considerations for protection of the Orion hatch seal during EVA translation as well as identification of suitable attachment points inside the flight vehicle design for GSB tethering.

Once the crew have crossed the gap between Orion and the ARV, they must translate the path down the length of the ARV to the asteroid. ISS heritage EVA Handrails were successfully used as a means for translation during these tests. Similar hardware would need to be integrated as part of the ARV design and installed prior to launch in order to minimize the amount of setup time required of the crew during the ARCM EVAs.

The final step in the translation sequence allows for direct access to various sampling sites on the asteroid. This testing assumed ARM "Option A" which features the asteroid captured in a fabric bag. Accordingly, the mockup developed for this test series allowed for evaluation of two translation paths: one across the fabric bag using soft fabric handholds mounted directly on the surface of the bag and the other elevated above the bag surface via a crew manipulated rigid Stabilization Boom.

Translation across the fabric handholds was successfully conducted, though there is an implied requirement that the flight hardware design solution will be able to support EVA translation loads. In addition to translation, these handholds also served as local tether points and provide a small but useful amount of body stabilization capability as well as attachment points for worksite setup to secure various supporting tools and equipment during sampling tasks. Crew feedback indicated that a greater number of soft handholds than were implemented on the mockups were desired to provide a suitable work envelope as well as increasing the number of accessible worksites.

During NBL operations, the Stabilization Boom (SB) was evaluated as a translation system and worksite stability/access aide. The base of the SB was mounted to the ARV mockup and the boom's adjustable arms were extended over the captured asteroid.

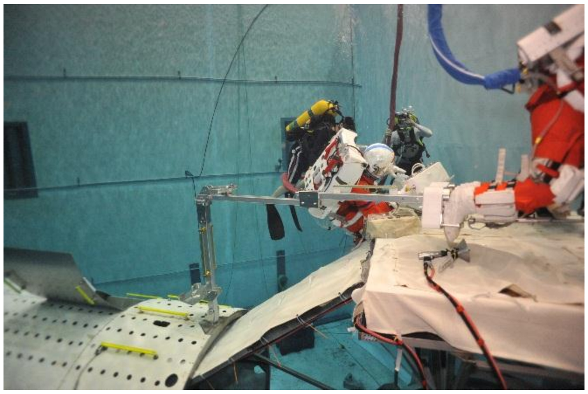

Figure 5 Stabilization Boom

The SB allows for translation using the boom structure itself or strategically placed handrails along the length of the SB. The operations concept assumed that this hardware was launched in a stowed configuration on the ARV and deployed by the EVA crew once they arrive and begin sampling operations. During the first series of NBL tests, the SB was pre-staged in the deployed configuration for simplicity and to focus evaluation tasks primarily on translation, crew ingress/egress and pitch/yaw adjustment. Future testing will investigate the feasibility of complete SB deployment and stowage operations by the EVA crew during end-to-end timeline simulations.

Lessons learned indicate the need for finer boom adjustability to increase the number of accessible geology sampling worksites. Future work will focus on providing this by increasing the number of joint combinations with improved controls for single and dual-crew operating modes.

D. Worksite stabilization

Translation, while not insignificant, is only one step in conducting a successful geology focused ARCM EVA. Body stabilization in microgravity EVA is vital to conducting meaningful work in a limited time frame. Two primary methods of body stabilization where tested with the MACES, both of which were accomplished using existing ISS hardware which included a BRT and a Portable Foot Restraint (PFR).

1) BRT

A BRT is comprised of a variable rigidity ball stack and custom end effector capable of gripping various cross sections, one of which is the ISS Heritage "Dog Bone Style" Handrail intentionally used on the NBL ARM Stack mockup in these tests. Through these handrails, the BRT rigidly couples the suited crew member to structure allowing them to perform light-load two handed tasks.

A challenge arose in selecting a mounting location for the BRT on the MACES. As a soft suit it was difficult to find a way to safely input the BRT loads without compromising the integrity of the suit fabric layers. The solution was to use the hard structure of the PLSS as the mounting point with the intention that the PLSS-to-MACES connection must already be designed to withstand all EVA generated loads.

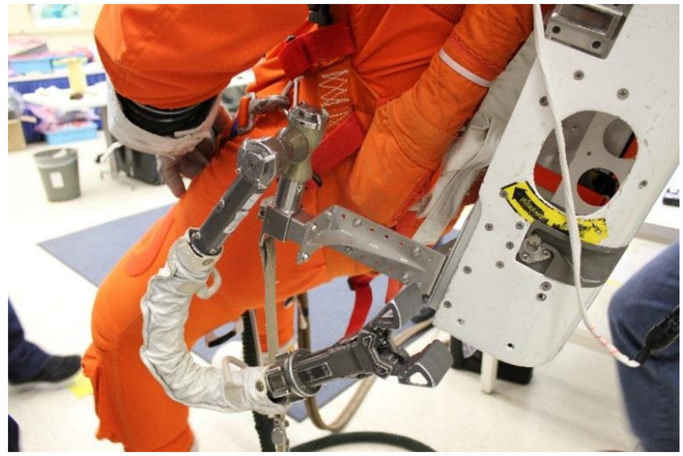

Figure 6 BRT attached to PLSS Volumetric Simulator

A bracket was designed which mounted the BRT interface to the PLSS while providing adjustability in the BRT location in free space. This allowed for quick assessment of possible interface point locations without making new brackets for each evaluation. A set of acceptable interface point locations in three-space relative to the existing forward face of the PLSS and exterior of the suited crew member were determined. These points can be carried over to a flight design as the MACES and PLSS continue to evolve.

2) PFR

Another form of body stabilization is a PFR which temporarily attaches a crew member's boots to a base plate. Loads are coupled through the suit legs, boots, and the rigid boot plate that is attached to structure, creating a closed load path. A PFR mounted to the end of the Stabilization Boom provided another way for the crew member to perform two handed tasks.

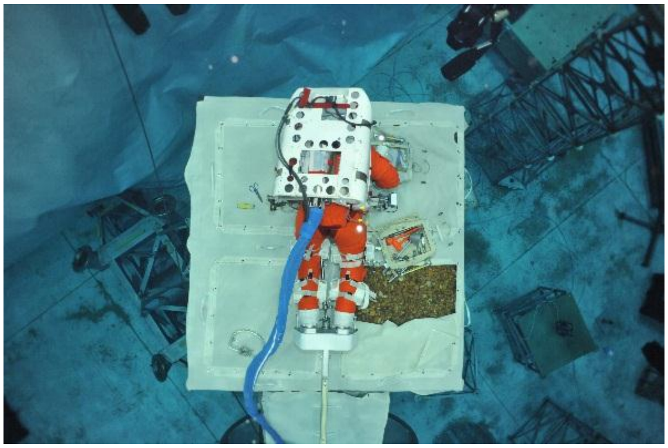

Figure 7 Crew in PFR

The version of the SB used during these NBL tests lacked a pitch adjustment near the PFR. Though the lack of this adjustment did not present an issue in testing at the NBL, crew feedback insinuated that pitch modification will be required in the flight design due to the uneven surface that may be encountered.

The crew observed no noticeable difference between the stabilization provided by the BRT and the PFR when using simple hand tools and during sample collection. This was consistent with similar light-load experiences from Shuttle and ISS tasks which, though typically construction in nature, are directly relevant to the expected ARCM EVA.

E. Geology Sample Acquisition

The science community has prepared a list of recommendations to maximize scientific return from the ARCM mission. The tools and equipment used during these tests were designed to facilitate early evaluation of these recommendations and, most importantly for this phase of mission development, the timeline feasibility of the suggested task list as EVA consumables limit the individual EVA duration to 4 hours. Though the specific sampling tool designs are expected to continue to evolve, it is known that during the mission the crew members will need to retrieve their tools, translate to the worksite and collect samples regardless of the exact features of each piece of hardware. Thus, timeline data from these evaluations will serve as a baseline with increases and decreases in timeline efficiency being a primary metric for tool design improvement.

1) Tool Management

The number of tools required for these geology tasks are substantially less than that of typical ISS construction tasks. This reduction in overhead removed the need for a Modular Mini Work Station (MMWS) alleviating the challenges associated with mounting the MMWS to the soft MACES suit (a similar challenge as mounting the BRT). Furthermore, elimination of the typical MMWS significantly reduces mass and volume needs for EVA hardware on ARCM. Alternatively, the EVA crew used Crew Lock Bags (CLBs) to organize, transport, and stow tools and collected samples during the brief EVAs. During discrete sampling tasks D-rings on the MACES provided for temporary, local tethering of tools and CLBs.

2) Tool Retrieval

The limited volume and mass allocation for tools inside Orion encourages as many tools as possible launch on the ARV. It should be noted that during these evaluations, crew members experienced difficulty retrieving some items from the ARV tool box due to the depth of the box, although the tool box would need to maintain dimensions that accommodate the limited motion of the MACES. Aside from such reach limitations, there were no issues translating with CLBs or other large objects that have been retrieved from their stowage positions.

3) Sample exposure

In these tests ARM “Option A” was simulated with the aforementioned enclosed fabric bag. With the surface covered by the capture bag, the first step in obtaining a geology sample is to gain access to the asteroid through the bag material. Access was obtained using safety cutters with an enclosed blade which precludes EVA crew access and damage to the MACES suit but allowed for relatively easy cutting of the simulated bag material. Once cut, the fabric folds were restrained with EVA forceps and Adjustable Equipment Tethers to “peel back” the partially cut panels providing a clear work area.

Figure 8 Crew Accessing Asteroid Capture Bag

Future work will increase the fidelity of the capture bag mockup and the tools used for sample exposure, including methods for reliably closing the cut seams should closure be deemed necessary to manage dust contamination concerns.

Aside from loose samples, chip samples are also of interest. These are actively broken from a larger portion of the parent body. A challenge with chip sampling in micro-gravity is capturing the flying particles created during the chipping action without the assistance of gravity to eventually slow and ground the desired piece. To address this challenge a custom tool, called the Bell & Chisel, was developed to provide containment during sampling. The Bell & Chisel is a hollow frustum with a captured chisel capable of relative motion along the frustum's center axis.

Figure 9 Bell & Chisel Sample Collection Device

The Bell & Chisel was driven by both a manual hammer and pneumatic hammer (a relatively low-overhead device for in-water testing which represented an electric hammer that would be used in flight). A manual hammer is a failsafe backup hardware item that is essential to ensure meaningful geological samples can be obtained, albeit with reduced efficiency and total number of samples.

A future challenge is to incorporate and end-to-end sample system that can prevent cross contamination, soft capture the chipped samples, and provide positive restraint of samples for transport.

F. Geology Sample Containment

In all geology sampling tasks, a significant challenge is to prevent cross contamination between samples either by the tools used during collection or the suit itself. One simple method utilized an inverted sample bag over a gloved hand to pick up loose samples. Once retrieved from the surface by either chipping or direct-pickup, the samples are generally bagged and in many cases sealed in a higher level container to prevent contamination from the cabin environment inside Orion.

G. Conclusion

The EVA tools system prototyped for the MACES testing allowed crew members to egress Orion, translate to and setup a geology sampling worksite, collect and stow geology samples; and return to and ingress Orion. The MACES testing provided an avenue for the Exploration Tools Team to increase the understanding of these tools and techniques used to complete a medium fidelity mock ARCM EVA timeline as well as gain significant insight into the unique worksite needs of the current MACES design. The crew feedback provided on prototype designs is invaluable in moving forward with an ever increasing level of confidence and fidelity.

The efforts of the prototype creation also supplied a first estimate of the mass requirements for some of the EVA hardware to be used on the ARCM mission. It is important to note that the list does not contain all the tools necessary to complete the ARCM DRM, but rather is a reasonable "lower bound" in that flight values will certainly be higher. The list totals to 75.2 kg across both Orion and the ARV:

Table 1 ARCM EVA Tools List

	Hardware	Quantity	Mass (kg)
Orion	Gap Spanner Boom	1	1.7
	Body Restraint Tether	2	7.2
	Adjustable Equipment Tether	2	0.2
	Retractable Equipment Tether	4	1.5
	Waist Tether	2	1.1
	Bell & Chisel	1	0.8
	Powered Hammer	1	2.2
	Capped Sample Container	2	0.4
	Sample Bags and Dispenser	1	1.3
ARV	Forceps	2	0.4
	Cutters	2	0.4
	Manual hammer	1	1.6
	Crew Lock Bag	2	5.6
	Stabilization Boom	1	50.8

The translation techniques and hardware evaluated during the MACES tests provided a solid framework to continue maturing the ARM EVA tools system upon. The knowledge captured and lessons learned through the MACES/ARCM testing has helped to shape the forward development path for exploration tools which will result not only in better tool prototypes, but ultimately in better space flight hardware for ARCM.

IV. MACES/PLSS Interface Kit

A. Interface Kit Overview

The MACES to PLSS Interface Kit (MPIK) serves as the structural, fluids and crewmember connection between the MACES pressure garment and Exploration PLSS 'backpack' assembly. The use of a self-contained interface serves to minimize distinct hardware changes to either the MACES or PLSS design. Minimization of design changes helps to preserve the original LEA purpose of the MACES suit while maintaining the 'suit-agnostic' PLSS development approach. The self-contained MPIK interface allows for PLSS developmental performance goals to remain unchanged in regards to flexible-mission-path PLSS as well as mitigation of potential fiscal impacts associated with designing a mission-specific life support system.

The kit contains the hardware to physically connect the MACES suit to PLSS structural and fluid connections via a common set of interfaces modelled after legacy ISS EMU PLSS-to-Hard Upper Torso (HUT) interfaces. Structurally the MACES suit is connected to the Suit Interface Pad, a curved 'cradle' that conforms to the suit's back geometry, coupled with a softgoods harness that wraps around the shoulders, chest, and waist of the pressure garment. The Interface Backbone, an aluminum 6061 frame, acts as the intermediate connection point for the Suit Interface Pad to the backplane of the PLSS. Additionally, the Interface Backbone serves as the baseline mounting interface for the Trace Contaminant Control (TCC) cartridge, low profile ventilation/water flow manifolding, and Positive Pressure Relief Valve (PPRV). Also included in the interface kit are Apollo-style umbilicals connected to the ventilation supply and return ports on the MACES. A multi-position purge valve on the return umbilical provides for high flow carbon dioxide (CO_2) washout and contingency ventilation cooling during and contingency operations. In FY14, analytic efforts were taken to quantify PPRV and purge valve sizing for the ARCM DRM, with prototype manufacturing planned in mid to late-FY15.

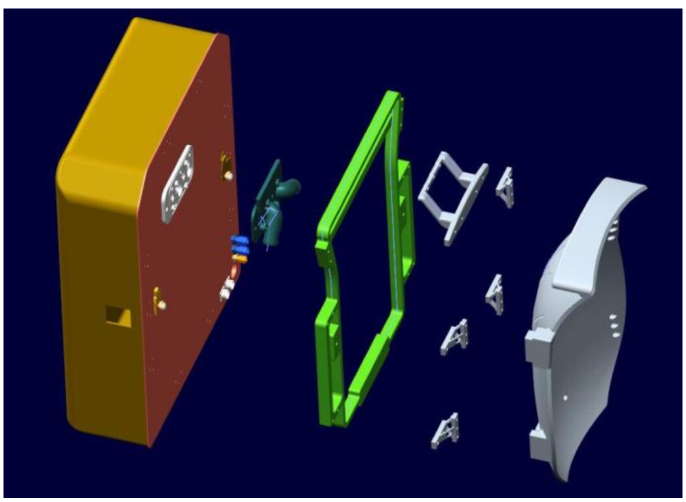

Figure 10 Pro-Engineer Representation of Prototype Structural Elements

B. Consumables Analysis

Initial efforts in fiscal year (FY) 2014 were focused on the characterization of a notional capsule-based EVA in cis-lunar space while docked to an Asteroid Retrieval Vehicle. Cis-lunar thermal environment definitions were generated and used in conjunction with METMAN and Wissler-based human metabolic models to determine the amount of primary and auxiliary feedwater needed to provide adequate crewmember cooling during nominal EVA operations and EVA contingency abort cases. MACES suit leakage rates and contingency purge requirements were used to determine the applicability of current baseline Exploration PLSS primary and secondary oxygen tanks to a four (4) hour capsule-based EVA DRM.

After determination of MACES and multi-layer insulation ensemble thermal reflectivity values during the ARCM DRM, a Thermal Desktop model was built of an asteroid contained in a retrieval 'bag'; a recovery vehicle; and an EVA astronaut in cis-lunar space. The Thermal Desktop representation was parametrically run by varying retrieval bag and MACES suit material optical and thermophysical properties in conjunction with cis-lunar orbital solar flux values to determine maximum and minimum ambient temperatures during a 4-hour EVA. The "hot-case" Thermal Desktop model is displayed in Figure 11. From analysis it was shown that the maximum environmental temperature would occur at the junction of the Asteroid Retrieval Vehicle and bagged asteroid when the vehicle assembly was in direct sunlight. In this configuration, ambient temperature would become 82.5 degrees Fahrenheit, assuming maximum solar/thermal reflectivity of the asteroid capture bag and no thermal transfer to the asteroid mass. This thermal environment corresponded to a suit heat leak of -15.6 watts (-53.2 BTU/hr). Negative heat leakage values served to define a net heat transfer into the PLSS thermal loop, impacting sizing of liquid cooling feedwater amounts.

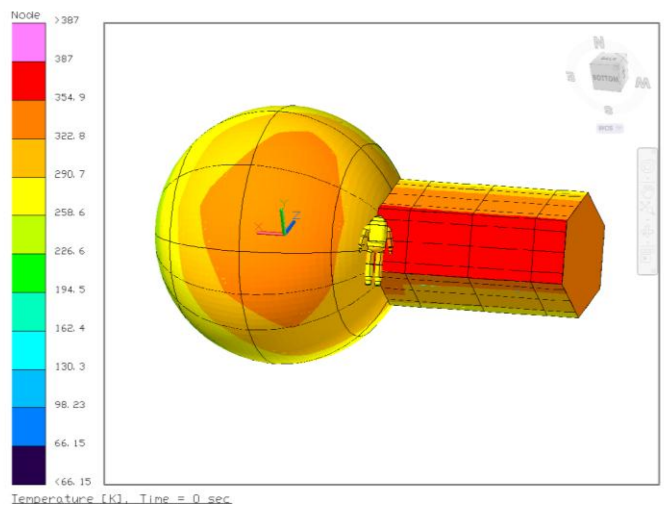

Figure 11 Hot Case Thermal Desktop Model

Operationally, this location of maximum solar lighting was preliminarily baselined as the nominal EVA operating worksite due to enhanced lighting conditions and visibility. The peak heating experienced at this location served as the upper bound of feedwater supply sizing, as the astronaut would require maximum cooling in the warmest environmental condition. Assuming a nominal 1200 BTU/hr crewmember metabolic load and 6 ACFM ventilation flow, the primary feedwater supply amount value was calculated to be 4.5 pounds of water for a 4 hour EVA. The assumed and calculated parameters are shown in Table 1 and Table 2 with the selected design point highlighted.

Table 2 Preliminary Heat Load Calculations for ARCM DRM

Metabolic Load (BTU/hr)	Ventilation Cooling Rate - Sensible (BTU/hr)	Liquid Cooling Rate (BTU/hr)	PLSS Heat Leak (BTU/hr)	PLSS Internal Heat Generated (BTU/hr)	Total Heat Load (BTU/hr)/(watts)
600	33	524	17	341	915/268
1200	24	793	17	341	1175/344
1800	25	1202	17	341	1585/464
2000	18	1683	17	341	2059/603

Liquid Cooling Rate values were determined via the use of environment-specific Wissler metabolic model runs, factoring in the maximum suit heat leak of -15.6 watts (-53.2 BTU/hr) into the thermal loop.

Table 3 Preliminary Primary Feedwater Sizing for ARCM DRM

Metabolic Load (BTU/hr)	Total Heat Load (BTU/hr)/(watts)	Feedwater for 4 hr EVA (lb_m)	Feedwater for 6 hr EVA (lb_m)	Feedwater for 8 hr EVA (lb_m)	Feedwater for 4 hr EVA (lb_m)
600	915/268	3.5	5.2	7.0	3.5
1200	1175/344	4.5	6.7	9.0	4.5
1800	1585/464	6.0	9.1	12.1	6.0
2000	2059/603	7.8	11.8	15.7	7.8

Furthermore, the ARCM DRM need for a PLSS secondary cooling loop was evaluated against the current requirement for 60 minute contingency abort cooling capability during an EVA retreat back to the crew cabin. The applicability study was part of an overall effort to ensure the Exploration PLSS thermal loop as currently designed would be adequate to prevent unsafe (greater than 300 BTU/hr) metabolic heat storage by spacewalking crewmembers. From this analysis it was determined that an auxiliary thermal cooling loop was needed for a full 60 minute abort, with metabolic heat storage exceeding a 300 BTU/hr threshold at 33 minutes following the start of a declared abort. This best-case abort duration assumed the use of purge gas flowing at 4 ACFM through a suit-mounted purge valve, showing that in order to maintain safe crew member metabolic heat retention, supplemental cooling needs to be provided. Based on this analysis, it was determined that 1.21 pounds mass (lbm) of secondary loop feedwater would meet the 60 minute abort requirement. Of note are early indications that the abort time from an ARCM EVA worksite may possibly be significantly shorter, reducing or eliminating the amount of feedwater needed for the secondary cooling loop.

Primary and secondary oxygen tank sizing was analyzed based on MACES suit leakage specifications and contingency purge valve requirements. A full spectrum of performance variables were run varying suit leakage, EVA duration time and EVA metabolic rate. Considering the current ARCM EVA design case of a 4 hour EVA at 1200 BTU/hr, it was determined that 1.239 lbm of primary oxygen storage would satisfy the requirements of an ARCM EVA. The current baseline Exploration PLSS has the requirement for 1.7 lbm of oxygen storage, showing the applicability of the current PLSS architecture to the ARCM mission in terms of oxygen consumables. Moreover, the current 1.7 lbm requirement allows for 5.48 hours of EVA time, giving margin to operational considerations.

Secondary oxygen consumables sizing was analyzed using parametric ventilation gas purge flow rates. Computational fluid analysis is currently underway to determine the proper minimum purge flow rate to ensure adequate CO_2 washout during a contingency EVA abort. Once a preliminary minimum flow rate is established, the value will be compared against earlier secondary oxygen consumables sizing tables to verify the applicability of the current PLSS secondary oxygen sizing requirement (1.7 lbm) to an ARCM EVA contingency.

Analysis over the course of FY2014 has shown the use of the current PLSS consumables requirements set and design specifications to be more than adequate to support a 4-hour EVA in the thermal environment anticipated in cis-lunar orbit. The primary thermal loop feedwater supply was determined to be 4.5 lbm of water, with the auxiliary supply calculated as 1.21 lbm of cooling water. Additionally, within the same analysis parameters and considering the MACES suit leakage rate, it was calculated that 1.239 lbm of oxygen would be needed to perform a 4 hour EVA using the MACES and PLSS. PLSS development specifications dictate 1.7 lbm of oxygen storage, adding margin to such utilization of the PLSS for an ARCM EVA.

C. *Prototype Hardware Design & Manufacturing*

Along with intensive analysis of PLSS consumables for the ARCM EVA, efforts were undertaken to model and manufacture a functioning structural and fluids prototype to demonstrate the viability of interfacing the MACES pressure garment to the Exploration PLSS. Initial design challenges were identified, including interfacing to a significantly curved pressure garment backplane; minimizing overall hardware volume for capsule egress; and tight packaging constraints for the mounting life support fluids connections from the PLSS to the MACES.

Structural elements were designed and fabricated to allow for rapid swap-out of various prototype components while providing a flight-like analog to examine different interface kit design trades. The primary structural interface between the full MPIK assembly and PLSS connections was the “Interface Backbone”; elements connecting to interfaces modelled after the current ISS EMU allowing expansion into a series of connections for life support and human interfaces. AL6061 was chosen due to the material’s prevalence in flight hardware systems and machinability. The Interface Backbone, while providing connection pickups for MPIK components, also served to dictate the separation distance between the Suit Anthropometric Pad and PLSS backplane. Adequate separation allowed for protected and proper ventilation and water umbilical routing from the PLSS fluids pad to connections on the MACES pressure garment. The Interface Backbone as mounted on the PLSS simulator is shown in Figure 12.

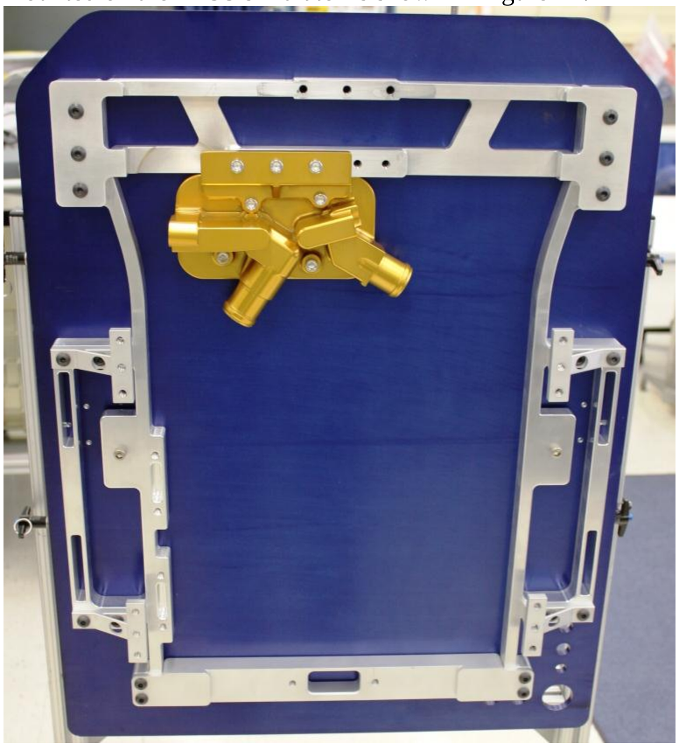

Figure 12 Interface Backbone Mounted on PLSS Simulator

Interfacing the ‘flat’ PLSS backplane to a suit with pronounced back curvature presented an initial challenge to system integration between the MACES and PLSS. The MACES pressure garment is designed primarily for use in a LEA contingency in a seated posture, necessitating the inflated curvature seen during manned use. The developmental Exploration PLSS structure maintains a flat suit-agnostic mating plane in order to allow adaption to the MACES as well as Exploration EVA suits. This common interface is less than optimal for MACES use, necessitating the creation of an anthropometrically tailored solution to allow pressurized suit interfacing as well as unpressurized suit donning and doffing of the MPIK and PLSS. The engineering development team performed 3-dimensional scanning and analysis of a range of MACES suit sizes over the course of late 2013 and early 2014 to generate models suitable for design of a custom geometry Suit Anthropometric Pad. The Suit Anthropometric Pad allows for suit softgoods harness incorporation and structural attachment of the Anthropometric Pad to the PLSS backbone structure. Additionally, designs factored in allowance of clearance for ancillary hardware such as the TCC cartridge to be mounted on the PLSS backplane. A method of discretizing the inherent curvature of the MACES suit was developed, then applied to the creation of a 3-D printed Nylon 12 structurally load-bearing Suit Anthropometric Pad for in-lab human-in-the-loop analysis. The 3-D printed pad is the largest plastic-printed piece of hardware manufactured to date at the Johnson Space Center and is shown in Figure 13.

Figure 13 Suit Anthropomorphic Pad with Softgoods Installed

3-D printing was chosen as the method allowed for large-format precision manufacturing coupled with lower mass and the opportunity for further development of crewmember-specific custom printed Anthropometric Pads. The prototype Anthropometric Pad was fit-checked with a pressurized crew member and will be further evaluated for ease of mobility and use in FY2015. Novel new methods of flight-like construction are currently under evaluation to ensure system applicability to future ARCM/asteroid DRMs.

Another overarching design driver was the need to minimize the front-to-back dimension of the MACES and PLSS hardware assembly to allow for safe egress from the current Orion cabin hatch. The front-to-back dimension was defined for the purposes of analysis and design to be the longest distance from front of the crew member’s suit ensemble to the backplane of the PLSS shell OML. Computer modelling of various PLSS backpack mating orientations was conducted to determine the maximum ‘worst-case’ front-to-back dimensions based on MACES 3D suit scans and preliminary models of the Exploration PLSS (OML). Based on this modelling, it was determined that the theoretical maximum front-to-back dimension was 34.42 inches. When compared to the most recent Orion side hatch design, this value was found to be within the minimum driving dimension of 36.57 inches between the top and bottom of the hatch opening, shown in Figure 14.

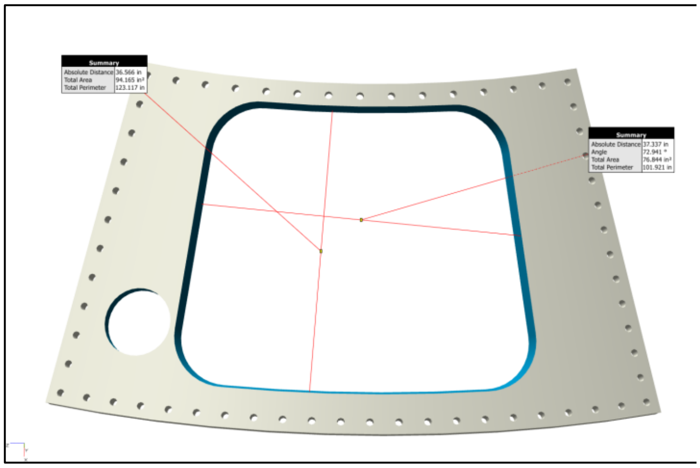

Figure 14 Orion PDR Side Hatch Dimensions

Human-in-the-loop (HILT) testing was performed using a mockup representation of the baseline Orion side hatch and the NBL MACES/PLSS configuration to determine impact points and areas for interface kit dimensional improvements. The gap between the MACES helmet and interface kit Anthropometric Pad was determined to be a critical dimension. Efforts were taken to minimize this distance while providing allocations for mounting miscellaneous ancillary hardware such as the ventilation gas interface pad on the interface kit backbone structure. Feasibility of safe cabin egress was further verified via NBL evaluation of cabin ingress and egress operations using the Orion mockup. Based on preliminary analytics and HITL testing, it was determined that that current Exploration PLSS OML coupled with optimized interface kit geometries will not pose a significant issue in regards to safe cabin egress and post-EVA ingress.

Safe delivery of breathing gas and cooling water from the PLSS f0luids interface to the MACES pressure garment was a paramount design driver in the construction of the MPIK assembly. In keeping with the ‘suit-agnostic’ design philosophy of the Exploration PLSS, a flight Exploration PLSS design would provide gas and water connections to various pressure garment systems (Z-series, MACES, EMU) via a mounting plate modelled after the current ISS EMU vent pad that connects the EMU PLSS to the ISS EMU’s HUT. The MPIK philosophy was to build off of this fluids pad to provide fluids umbilical connections leading to the supply and return points on the MACES suit. The ISS EMU-based mounting point and prototype Fluids Interface Manifold are shown in Figure 15.

Figure 15 ISS EMU-based PLSS Fluids Plate (red) & Prototype Fluids Interface Pad (Gold)

Two distinct design paths were taken to essentially parameterize possible future design trades. A low-profile, highly compact Fluids Interface Pad was 3D printed using Nylon EX build material. Concurrently, a ‘realistic’ Fluids Interface Manifold was manufactured observing conventional machining practices and limitations. Both Fluid Interface Manifold designs were integrated into a completed functional MPIK mockup and will be tested against each other in fiscal year 2015 to determine impacts on ventilation and cooling system pressure drop. By exploring emerging manufacturing technologies and practices, the MPIK team was able to build a knowledge base to be leveraged by any future MPIK flight product team.

Individual hardware elements were brought together and assembled with a MACES suit and pressurized to show the pressurized flight configuration of a crew member wearing the MPIK and PLSS for a spacewalk. This initial pressurization was the first evaluation of the overall feasibility of using an independent interface kit to bring together the Exploration PLSS and MACES designs. MACES softgoods interfaces were evaluated, as well as the pressure system interfaces between the MPIK and PLSS. From these tests, the design philosophy was proven successful and further matured. The full inflated assembly is shown in Figure 16.

Figure 16 Pressurized MACES and Interface Kit

D. EVA Cabin Egress / Ingress Ops Con Trades

The ARCM capsule baesd EVA team worked on determining operational concept trades for egressing the Orion capsule using the current Exploration PLSS design. The Exploration PLSS was designed from the onset to be used in a suitport configuration mounted on a planetary rover or with a direct vacuum access to enable usage of the PLSS's Rapid Cycle Amine (RCA) and Suit Water Membrane Evaporator (SWME). The RCA provides CO_2 removal from suit ventilation gasses, while the SWME provides metabolic heat removal to cool the crew member. Both the RCA and SWME need a 'quality' vacuum to perform their roles correctly. From analysis, it was shown that the RCA would not remove CO_2 until the cabin was reduced to below 0.267 kPa (2 torr). Furthermore, it was determined via analysis that without RCA access to vacuum, CO_2 partial pressure levels would reach the nominal EVA cutoff limit of 7.5 mmHg within 37.5 minutes based on a 400 BTU/hr metabolic rate and 6 ACFM of ventilation flow. This time decreased to 18.4 minutes if the crewmember was working at an 800 BTU/hr metabolic rate, commonly seen during EVA tool prep and egress activities. With these considerations, the need for hardware vacuum access proved to be an operational challenge faced by spacewalk from a capsule environment instead or an airlock or suitport. The MPIK team collaborated to determine two paths for operational concept trades. Historical precedents such as those seen during earlier capsule-based EVAs in NASA's Gemini and Apollo program were researched, as well as current operational procedures for nominal EVA preparation and airlock egress on the ISS.

One design trade under current analysis is the use of a set of switching valves on the MACES breathing gas inlet and return fittings to switch from vehicle-provided oxygen to PLSS-provided oxygen once the Orion cabin has been fully vented to vacuum and the RCA becomes functional. This operational concept is considered to be the most mass-efficient, as any switching mechanisms can be designed into suit hardware with no need for Orion cabin modification. The use of shared connections was done during Gemini program EVAs to allow connection to both vehicle life support and portable (chest and/or back-worn) life support systems. During EVA preparations, the crewmembers will be provided oxygen from a vehicle umbilical connected to supply and return "tees" also connected to PLSS ventilation loop umbilicals. Once the RCA becomes operational, the crewmembers will transition from vehicle to portable life support then disconnect from the vehicle to being an EVA. Liquid cooling connections would be transitioned at vacuum as well via manual swapping of liquid cooling umbilicals. This trade was identified as having multiple aspects to be evaluated, including the lack of historical precedent for life support supply switchovers at vacuum and the need for initial ammonia removal from the RCA canister before crewmembers can begin using the system. Referencing past NASA EVA experiences, during Gemini (with an open loop EVA life support system), there were no transitioning concerns as CO_2 removal was accomplished via open loop flow rather than a vacuum-dependent hardware element such as the RCA. Furthermore, disconnections could be performed in a pressurized crew module to ensure safety in the event of a valve failure.

A competing design trade also under analysis is the use of an RCA and SWME-connected vacuum pump to provide an artificial vacuum environment to allow respective hardware operations. This solution is considered to have the least impact on MACES and PLSS hardware designs, as the PLSS method of operation would differ little between a suitport EVA and a capsule-based option. During an EVA preparation, the crew would connect a vacuum pump and accumulator assembly to the PLSS's RCA and SWME vacuum ports, reducing the reference pressure on both of these hardware items and allow their operation while the cabin is still pressurized. This has the advantage of enabling PLSS checkout before cabin depressurization, allowing for troubleshooting in a safe, ambient pressure condition. A drawback of this design trade is the high quality of vacuum needed for effective RCA performance, as well as the mass penalties inherent in the inclusion of a flight-qualified vacuum pump, accumulator, and vacuum umbilical in a mission manifest.

In FY15, these trades will be more fully vetted and developed with the insight of the Mission Operations community and lessons learned from advanced PLSS development testing currently underway. FY14 Exploration PLSS testing includes the evaluation of several commercially available vacuum pumping systems to test the feasibility and sizing of vacuum systems for enabling RCA and SWME use at ambient pressures. Mass impacts and operational concerns are currently under review, with detailed egress steps and timelines being developed for community discussion in early FY15.

As an aspect of the capsule-based EVA egress operational concepts studies, a more refined MACES-to-PLSS pneumo-hydraulic schematic was developed and included in PLSS development documentation. This schematic and corresponding MPIK requirements specification were drafted in FY14 to guide closer integration between PLSS, MACES, and MPIK development while laying the groundwork for an eventual flight design and certification process. The MACES-to-PLSS pneumo-hydraulic schematic is shown in Figure 17.

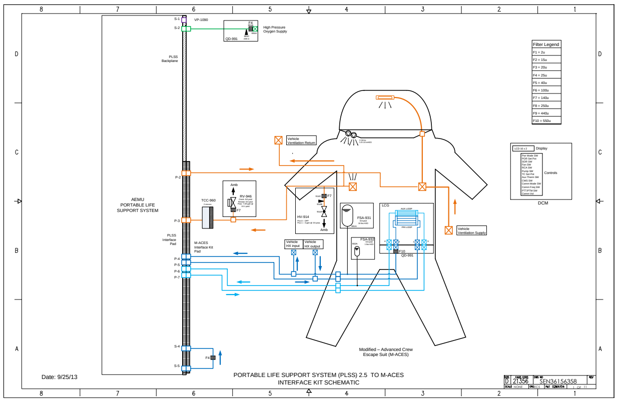

Figure 17 MPIK Fluids Schematic

E. Future Work

Following the successes of FY14, FY15 will focus on HILT testing of the MPIK assembly in the Crew Survival Engineering suit laboratory. From these manned tests, the team will be able to quantify the pressure responses of the MPIK and PLSS resulting from the use of an all soft pressure garment ensemble. The MPIK structural design will be iteratively modified based on results from manned testing, as well as lessons learned from NBL experimentation with the MACES underwater. The near-term key driving intent of MPIK development activities in FY15 is support of NASA's Mission Concept Review to determine the overall feasibility and applicability of marrying the Exploration PLSS to the MACES pressure garment for a capsule-based spacewalk.

V. Conclusion

As the Asteroid Redirect Mission matures, the suit/life support portion of the mission will mature along with it and EVA Tools & Equipment can be iterated to accommodate the overall mission objectives and compromises inherent in EVA Suit optimization. This past year, we have gained knowledge in the areas of the suit mobility and how it can be enhanced, the MACES/PLSS interface kit and how the two systems can operate together, and the tools that will make the overall system work more efficiently. The goal of the EVA architecture for ARCM is to continue to build on the previously developed technologies and lessons learned, and accomplish the ARCM EVAs while providing a stepping stone to future missions and destinations.