Replication of Segments of STS-94 as a Lunar Surface Mission

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The Artemis exploration plan will progress from initial Commercial Lunar Payloads Services (CLPS) landers to human landings to an established surface infrastructure supporting four crew for surface missions of a month or greater. NASA teams are currently working with partners to define the surface assets that will comprise this infrastructure, including habitation and laboratory facilities. However, design engineers often have limited insight into the laboratory capabilities needed inside a pressurized habitat or the demands such a facility will place upon crew availability. The Space Shuttle STS-94 Microgravity Science Laboratory (MSL-1) mission is used as an intravehicular activity science analog for the Surface Habitat. The STS-94 primary physical science instruments and crew activity in support of physical science investigations will be examined. Based on recent reference concepts for the Surface Habitat, options for incorporating the instruments and options for dividing physical science tasks among the Surface Habitat crew are discussed, based on STS-94 crew tasks and assumptions for Surface Habitat operations. Crew size considerations are raised along with recommendations to reassess some of the current assumptions. Having shown that STS-94's physical science investigations can be applied to a lunar surface mission, recommendations are made for increased attention to pressurized laboratory objectives, capabilities, and crew size.

I. Introduction

NASA's Artemis exploration plans begin with Commercial Lunar Payloads Services (CLPS) and progress towards surface mobility, [1] as shown in Figure 1. As additional missions are conducted, more infrastructure is deployed to the lunar surface to where an Artemis Base Camp is established near the lunar South Pole in the early 2030s. [1]

At this point, the lunar surface infrastructure will include the Human Landing System (HLS), Extravehicular Activity (EVA) "Suit", Lunar Terrain Vehicle (LTV, unpressurized Rover), Pressurized Rover (PR), Surface Habitat (SH), logistics, science, and technology demonstrations. [1]

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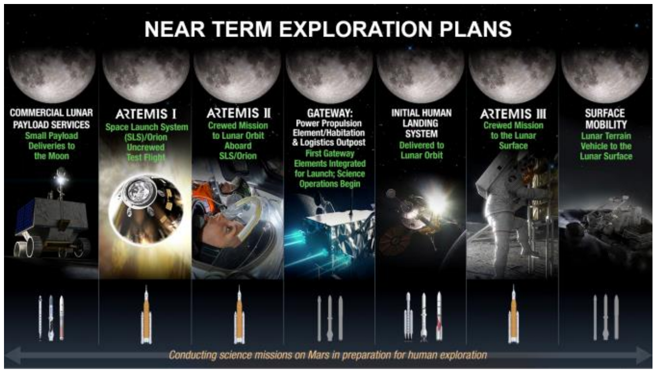

Figure 1. NASA Near Term Exploration Plans

Four-person crews will be sent to the Artemis Base Camp to support the base camp objectives of exploring the Moon, preparing for Mars, resource identification and utilization, inspiration and outreach, and international and commercial partnerships. [1] A notional Artemis Base Camp habitation area is shown in Figure 2.

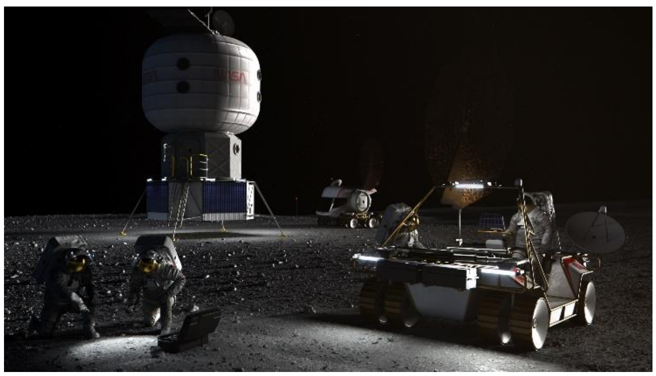

Figure 2. Notional Artemis Base Camp

Thanks to four years of field test campaigns under the Constellation Program's Desert Research and Testing Studies (DRATS) from 2008 to 2011, there are well-documented operational concepts for how Pressurized Rover crews will support Artemis Base Camp objectives. The Apollo program's Lunar Roving Vehicle and concept studies for MOLAB and LUNEX II [2] provided valuable background and were used in the early formulation of NASA pressurized and unpressurized concepts.

Additional concept development has been performed by the NASA Lunar Architecture Team, which has developed PR and LTV traverse concepts. Because these studies were performed by the exploration formulation study teams, the engineers are better prepared to define the spacecraft requirements needed to maximize each vehicle's potential.

However, the use of the Surface Habitat is not as clearly understood. At the time of the cancellation of NASA's Constellation program, a medium fidelity mockup of the Lunar Outpost was still in construction. While a portion of it was tested at DRATS it was never fully outfitted to enable the same level of science mission analog studies that had been occurring with the Pressurized Rover. Consequently, even as recently as the current year, lunar formulation team engineers have wondered if the Surface Habitat crew will be bored as compared with the Pressurized Rover crew, perceiving their work to be monotonous, tedious, dull, or perhaps even lacking sufficient activity to fill a daily timeline. This is a misconception that arises from a lack of familiarity with the breadth and depth of scientific research conducted aboard human spacecraft.

This paper will examine a portion of the Space Shuttle STS-94 Microgravity Science Laboratory mission's scientific research as a possible analog to lunar Surface Habitat science in order to demonstrate potential crew science activity in the Surface Habitat and make more accessible to design engineers the scale and pace of scientific activity aboard exploration spacecraft.

STS-94 is used as an example case of research not to imply a one-for-one mapping of experiments, but rather because it is drawn from a science mission that has been flown in space, with the specific intent to answer questions about microgravity.

Note that actual experiment selection for Artemis missions will be performed by NASA's Science Mission Directorate through its normal process of solicitations to the scientific community.

STS-94's microgravity investigation was viewed as a good comparison to the unknowns surrounding one-sixth gravity. On this basis, it is presented as a reasonable use of a human lunar infrastructure. This research is intended to illustrate the level of capability that a human lunar infrastructure might require in order to conduct research of a similar caliber.

II. STS-94 Mission Description

A. Reflight of STS-83

STS-94 mission stemmed from STS-83, a mission which launched on April 4, 1997, but was forced to land just shy of four days due to an onboard fuel cell failure. It was reflown with the same crew and outfitting, launching as STS-94 on July 1, 1997, as shown in Figure 3. STS-94 had a crew size of seven and a mission duration of 15 days, 16 hours, 44 minutes, and 34 seconds. In order to maximize the science return, the crew split into a Red Team and a Blue Team, working 24 hours a day in two shifts. [3]

Figure 3. STS-94 Launch

B. Spacelab

The primary STS-94 mission payload was the Microgravity Science Laboratory-1 (MSL-1). It was flown in Spacelab, which was installed in the Shuttle payload bay in the Long Module configuration. [3]

Spacelab is a modular space laboratory that consists of a long or short pressurized module, one or more unpressurized pallets, a tunnel (to connect the pressurized module to the Shuttle cabin), an instrument pointing system, and the Igloo – a pressurized subsystems bay used on Spacelab missions where only pallets are used. [4]

The pressurized module provides fixtures, floor-mounted racks, a workbench, and working laboratory space. Spacelab is shown in *Columbia*'s payload bay in Figure 4.

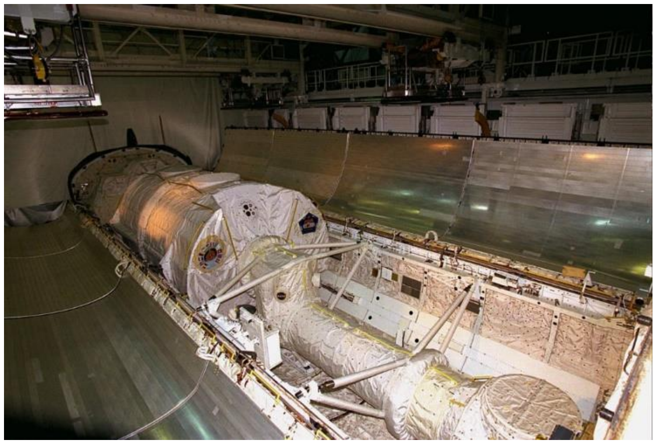

Figure 4. Spacelab Visible in Columbia's Payload Bay During Launch Processing

III. STS-94 Physical Science Investigations by Facility

Spacelab enabled the Shuttle to significantly increase the number and diversity of science investigations performed by the crew. Over the course of the 16-day mission, the crew conducted 19 materials science investigations. [3] The STS-94 crew also conducted several biological investigations, Development Test Objectives, Detailed Supplementary Objectives, and Risk Mitigation Experiments [5] but this paper is focused on the physical science activity, all of which fell within the subdomain of materials science.

The primary physical science instruments used for these investigations were:

A. Large Isothermal Furnace

The Large Isothermal Furnace was developed by the National Space Development Agency of Japan (NASDA) and used previously on STS-47 and STS-65. [3] It was used for six investigations during STS-94: the Measurement of Diffusion Coefficient by Shear Cell Method Experiment, the Diffusion of Liquid Metals and Alloys Experiment, the Diffusion in Liquid Led-Tin-Telluride Experiment, the Impurity Diffusion in Ionic Melts Experiment, the Liquid Phase Sintering II Experiment (LIF), and the Diffusion Processes in Molten Semiconductors Experiment (DPIMS). [3] The International Space Station (ISS) Destiny module currently houses its successors, the Low Gradient Furnace and the Solidification and Quenching Furnace. [6]

B. Combustion Module-1

The Combustion Module-1, in Figure 5, was developed by the NASA Glenn Research Center [3] (then named NASA Lewis Research Center). It was developed to test hardware and experiment approaches on Spacelab. It uses experiment-unique chamber inserts called Experiment Mounting Structures to receive different combustion experiments. [5] It was used to conduct the Laminar Soot Processes Experiment and the Structure of Flame Balls at Low Lewis-number Experiment (SOFTBALL). A Combustion Integrated Rack is currently aboard the ISS in the Destiny laboratory module. [7]

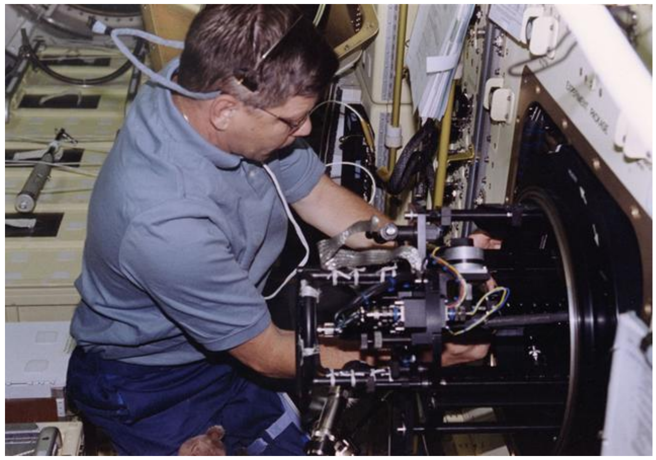

Figure 5. Astronaut Roger Crouch Performs an Experiment Change-Out in the Combustion Module-1

C. Droplet Combustion Experiment

The Droplet Combustion Experiment is an apparatus designed to test combustion properties of single, isolated 2mm to 5mm droplets under different pressure and oxygen combinations. [3] The pressures ranged from 0.25 to 1 atm. [8] The internal apparatus, shown in Figure 6, was integrated into a single-width Spacelab rack. [3] It is succeeded aboard the ISS by the Multi-User Droplet Combustion Apparatus. [9]

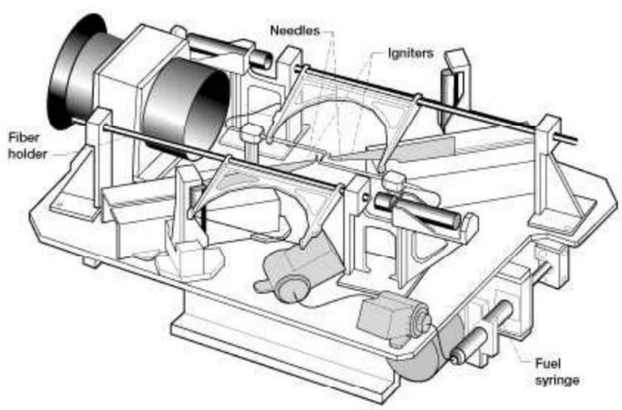

Figure 6. DCE Internal Apparatus

D. EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Rack

The size of a double-width Spacelab Rack, the EXPRESS rack housed the Physics of Hard Spheres experiment as well as a life sciences experiment. [3] At least eight EXPRESS racks are currently used on the ISS [10], four of which are shown in Figure 7, and at least one successor experiment to the Physics of Hard Spheres has flown on ISS. [11]

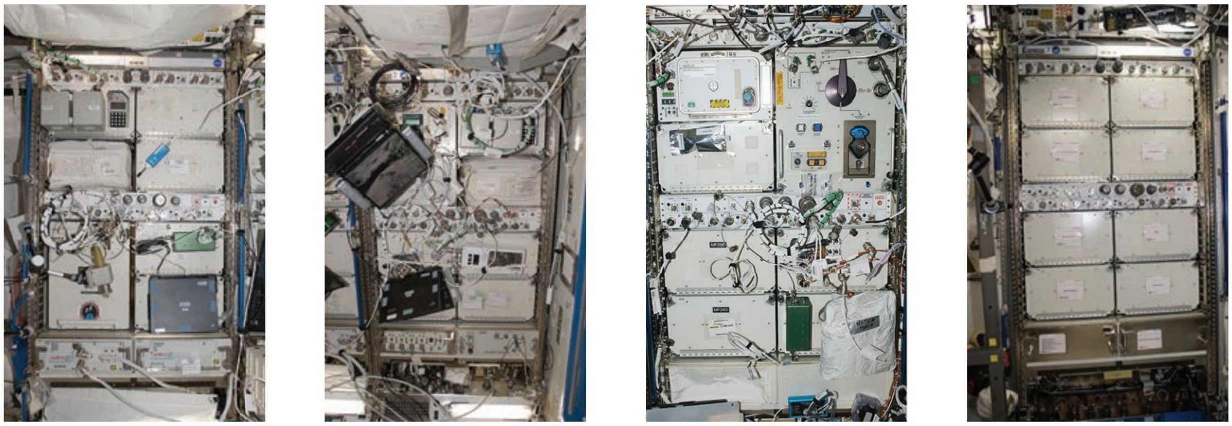

Figure 7. EXPRESS Racks 1, 2, 6, and 7 on ISS

E. The Electromagnetic Containerless Processing Facility (TEMPUS)

TEMPUS is an acronym for electromagnetic containerless processing in German (Tiegelfreies ElektroMagnetisches Prozessieren Unter Schwerelosigkeit) [12] that translates literally as Crucible-free ElectroMagnetic Processing Under Weightlessness (courtesy Google Translate). The electromagnetic levitation enables TEMPUS to heat metals to temperatures that would melt the container or otherwise contaminate the sample. TEMPUS set records for the highest temperature achieved in space (2000C). [13]

TEMPUS was used to conduct the Experiments on Nucleation in Different Flow Regimes, Thermophysical Properties of Advanced Materials in the Undercooled Liquid State Experiment, Measurements of the Surface Tension of Liquid and Undercooled Metallic Alloys by Oscillating Drop Technique Experiment, Alloy Undercooling Experiments, the Study of the Morphological Stability of Growing Dendrites by Comparative Dendrite Velocity Measurements on Pure Ni and Dilute Ni-C Alloy in the Earth and Space Laboratory Experiment, the Undercooled Melts of Alloys with Polytetrahedral Short-Range Order Experiment, the Thermal Expansion of Glass Forming Metallic Alloys in the Undercooled State Experiment, the AC Calorimetry and Thermophysical Properties of Bulk Glass-Forming Metallic Liquids experiment and the Measurement of Surface Tension and Viscosity of Undercooled Liquid Metals experiments. [3]

A successor to the TEMPUS, the Electromagnetic Levitation (EML) is currently aboard the ISS in the European Space Agency (ESA) Columbus Module [14]. The Japan Aerospace Exploration Agency (JAXA) has an Electrostatic Levitation Furnace aboard their Kibo module. [15]

F. Middeck Glovebox

The middeck glovebox shown in Figure 8 is used for experiments and materials that cannot be exposed to the open environment. The glovebox is equipped with photographic, video, and data recording capability. [5] It was used to conduct the Coarsening in Solid-Liquid Mixtures Experiment, the Bubble and Drop Nonlinear Dynamics Experiment, the Study of the Fundamental Operation of a Capillary-driven Heat Transfer Device in Microgravity Experiment, the Internal Flows in a Free Drop (IFFD) experiment and the Fiber Supported Droplet Combustion experiment. [3], [5] The middeck glovebox has been succeeded by the Microgravity Science Glovebox on the ISS. [16]

Figure 8. Astronaut Roger Crouch Working with the Middeck Glovebox

G. Gravity Measurement Devices

Four instruments were used to measure the gravity environment onboard the Orbiter: the Space Acceleration Measurement System (SAMS), the Orbital Acceleration Research Experiment (OARE), the Quasi-Steady Acceleration Measurement System (QSAM), and the Microgravity Measurement Assembly (MMA). [3]

Gravity disturbances could be created by firing the Orbiter's thrusters, crew moving about the cabin, equipment operating, and even atmospheric drag from the Shuttle flying through space. [5] The gravity measurements helped to determine how vibrations or accelerations impacted the results of microgravity experiments. [5]

Developed by NASA Glenn (at the time Lewis) Research Center, the SAMS had three sensor heads, one of which could detect accelerations up to 2.5 Hz while the other two could detect accelerations up to 25 Hz. Also developed by NASA Glenn, the OARE could sense and record accelerations as low as one-billionth of Earth gravity at a frequency of less than one Hz. [5]

The QASM, developed by the German Aerospace Research Establishment (DLR), detected steady, very low-frequency, residual accelerations between 0 and 0.02 Hz. The MMA, also developed by DLR, detected accelerations between 1 and 100 Hz. [5]

A successor SAMS also operates aboard the ISS, along with a NASA Glenn-developed Microgravity Acceleration Measurement System and a JAXA-developed Microgravity Measurement Apparatus. [17]

IV. Lunar Surface Habitat Overview

The objective of the Artemis Surface Habitat is to be a primary asset to achieve a sustained lunar presence and serve as a platform for Mars mission preparations. NASA is currently working with industry to develop conceptual designs for the Surface Habitat. A NASA reference configuration of the habitat is shown in Figure 9.

Figure 9. Surface Habitat – NASA Reference Configuration

The Surface Habitat is intended to be capable of supporting 2-4 crew for 30-60 days, including interior facilities for medical, exercise, galley, crew quarters, and stowage. It is EVA capable, including both an airlock and suit maintenance capability. It has its own power generation and offers recharge capability for surface assets. It is also a communications hub for other surface assets and can be reused for multiple missions with a 15-year design lifetime. [1]

While the Artemis mission size is four crew to the lunar surface once the PR and SH have landed, for the majority of a surface mission, only two will be present in the Surface Habitat. The other two will be deployed in the Pressurized Rover for mobility-based exploration activity up to 20 km away, leaving only the two in the Surface Habitat to conduct local exploration and laboratory operations.

A 16-17-day segment of the surface mission can easily compare with STS-94. Having the PR and SH crews swap (PR to SH / SH to PR) roughly halfway through a 33-day surface mission is one of several options being considered for Artemis lunar surface operations. This lends credence to examining STS-94 in a lunar context. A 16-17-day rotation in the Surface Habitat is approximately equal in duration to STS-94. Thus, the experience of the Shuttle crew during that mission may be comparable to the experience the SH crew will have on the lunar surface – with the obvious exception that ascent and entry for the Shuttle are both measured in minutes, and the lunar crew will experience days to weeks in other spacecraft both before and after their time in the Surface Habitat.

V. Lunar Surface Physical Science Laboratory

What would be the implications for the Surface Habitat if the physical science investigations of STS-94 were replicated on the lunar surface, i.e., not the specific experiments, but at a generalized level similar types of equipment and a similar workload? MSL-1 was flown because it was deemed important to conduct research of microgravity processes. That work did not end with the landing of STS-94; it has continued on the ISS today. Should there also be a priority given to investigate fractional gravity processes, how could they be investigated on the Moon?

There is a challenge in that the physical science outfitting associated with STS-94 is greater in terms of mass, volume, and power than the counterpart equipment currently anticipated for the Surface Habitat. The Surface Habitat instruments map closely to notional ideas for a lunar surface Physics Lab, based on Constellation-era recommendations of the Optimizing Science and Exploration Working Group (OSEWG). [18] It must, of course be noted, that the analysis that led to the Physics Lab concept also indicated a need for Biology, Human Research, and Geology Laboratories within a lunar surface habitat. [18]

The notional Physics Lab includes a Fluid Mechanics Chamber, Combustion Chamber, Multi-Purpose Glovebox, 4 middeck locker equivalent stowage, and computing/display devices. This is sufficient for the experiments conducted in Combustion-Module-1, the Middeck Glovebox, most likely the EXPRESS Rack (accounting for only the physical science experiments), and possibly the Droplet Combustion Experiment. The gravity measurement devices might also be contained in out of the way locations in the habitat. But additional volume would be needed for the Large Isothermal Furnace and the TEMPUS. If this equipment cannot be accommodated in the Surface Habitat, an option recently explored by the new Forge Innovation Team at Johnson Space Center (JSC) is to consider dedicated laboratory modules, either a stationary laboratory complex docked to the SH or a mobile laboratory. [19], [20] This research suggests that it is possible to accommodate the necessary scientific instrumentation to replicate the STS-94 physical science investigations on the lunar surface.

Based on the revised mass estimates in the JSC stationary laboratory study [20], there is an available mass margin of about 600 kg in the Biology and Human Research Lab Module and about 800 kg in the Physics and Geology Lab Module. The Large Isothermal Furnace and TEMPUS would have to fit within these allocations for delivery and could be installed in the correct location by SH crews. Optionally, the Human Research Lab could be moved into the SH post-landing to free up more volume in the lab modules. The Surface Habitat, Biology and Human Research Lab Module, and Physics and Geology Module are shown in Figure 10, Figure 11, and Figure 12 respectively.

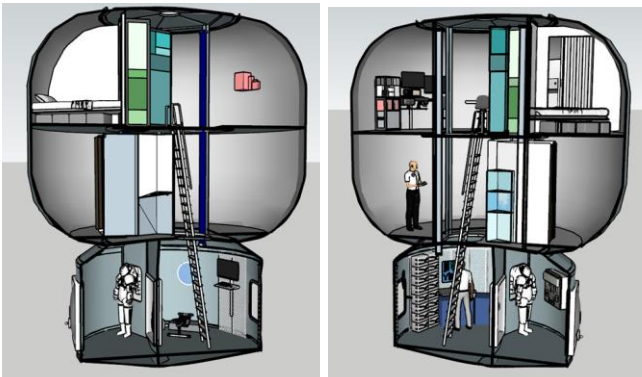

Figure 10. NASA Reference Concept for the Surface Habitat.

Figure 11. Biology and Human Research Laboratory Module.

Figure 12. Physics and Geology Laboratory Module.

It must be noted that presently only the Surface Habitat is part of the Artemis exploration plan. The laboratory modules are only a recommendation from JSC's Forge Innovation Team. As of this writing, the Lunar Architecture Team has not yet had an opportunity to consider options to incorporate laboratory modules. And even if such incorporation is desired, it would be subject to additional layers of approval at NASA Headquarters and would require Congressional support. Thus, there is no guarantee that the science instrumentation comparable to that used during STS-94 could be accommodated within the Artemis Base Camp, but this paper will continue under the assumption that it can be placed either within the Surface Habitat or in dedicated laboratory modules.

VI. Estimated Crew Availability

Published data on STS-94 crew activity is limited. Kennedy Space Center maintains a NASA Space Shuttle Launch Archive, which includes information about shuttle missions STS-1 through STS-107. [21] This archive is where much of the information about STS-94 was found. Included in this archive is a series of daily Mission Control Center status reports.

An example of the level of detail available in these daily status reports is the following day 3 task completed by STS-04 Payload Commander Janice Voss:

> *"Voss began a series of small droplet runs this afternoon to study a burning fuel droplet of heptane, part of the Droplet Combustion Experiment. The investigation is collecting information on burning rates of flames, flame structures and conditions under which flames are extinguished. Findings from this study will provide researchers with a better understanding of the combustion process and may lead to cleaner and safer ways to burn fossil fuels as well as more efficient methods of generating heat and power on Earth."* [22]

By compiling these statements for all sixteen mission days it was possible to generate some information describing STS-94 physical science crew tasks.

Team	Astronaut	# Tasks
Red	Halsell	1
Red	Still	3
Red	Thomas	49
Red	Linteris	54
Blue	Voss	26
Blue	Crouch	36
Blue	Gernhardt	3
Unspecified	Unspecified	13

Table 1. STS-94 Physical Science Crew Tasks

It is immediately apparent from this table that the Red Team had greater responsibility for the physical science investigations during STS-94. Even if all of the tasks that were reported to Mission Control without indicating the responsible crew member (listed here as unspecified) were to be attributed to the Blue Team, the Red Team still has the overwhelming majority of tasks at 107, versus a reported 65 for the Blue Team and 13 with no responsible crew member identified.

It is also apparent that within each team, two crew members were primarily responsible for physical science. Within the Red Team, most of the tasks were performed by Thomas and Linteris, 49 and 54 tasks respectively. Within the Blue Team, most of the tasks were performed by Voss and Crouch, 26 and 36 tasks respectively.

Physical science was not the only mission activity during STS-93. The crew also conducted biological research as part of MSL-1, seven Development Test Objectives, three Detailed Supplementary Objectives, and one Risk Mitigation Experiment, in addition to the activity needed to fly and operate the Space Shuttle.

Unfortunately, the Mission Control Center (MCC) status reports currently available do not indicate the amount of time spent on each task. (It is entirely possible that more detailed records exist in archives – one co-author recalls having noted start/stop times for certain Shuttle activities in the past.) In some cases, the reports do indicate that a crew member worked a morning or afternoon, for instance:

> *"During the morning period, while Linteris took time off, Thomas worked with the Large Isothermal Furnace experiment and the Glovebox unit. In the afternoon while Thomas relaxes, Linteris will work with the Combustion Module and the Large Isothermal Furnace."* [23]

But other times, there is no indication of time:

> *"Yesterday, Thomas powered up the Middeck Glovebox to conduct a study of the manipulation of bubble shape and bubble movement in water under weightlessness conditions."* [23]

Did powering up the Middeck Glovebox and conducting this study take all day yesterday or only five minutes? There simply is no basis to draw any conclusions about the relative duration of any tasks other than they were deemed of sufficient importance to include in a status report.

It is possible to review the tasks by mission day, as shown in Table 2. Here it can be seen that while there are only a couple of tasks on the first day of the mission, the crew quickly ramps up the pace of research activity and the number of tasks do not begin to fall off until day 12, though work does continue all the way up until landing day.

Mission Day	# Tasks
1	2
2	13
3	19
4	8
5	7
6	21
7	22
8	19
9	13
10	12
11	20
12	6
13	6
14	8
15	3
16	6

Table 2. Crew Tasks by Mission Day

These 185 tasks can be further inspected to identify how many tasks were assigned to each crew member on each mission day. The result is a 129-row table and is far too cumbersome to list. But the table can be sorted to provide more useful information after some preliminary analysis.

The goal at this point is to assess whether the physical science investigations of STS-94 could reasonably be applied to an Artemis surface mission. Table 1 indicates that the bulk of the work is being performed by four crew members, working two at a time. Can this work, performed around the clock over a 16-day period be instead performed by two crew working a standard day shift over a 33-day mission?

This might initially appear to be a simple assessment, but the Artemis crew does not have 33 days to use solely for research. Currently, it is assumed that the crew will spend the first 3 days acclimating to lunar gravity in the HLS. This is followed by an off-duty day and a day of habitat startup. The crew receives an additional day off once every seven days. Over the course of a 33-day surface mission there will be five off-duty days in total. Another day is lost to crew swap if/when the crews switch between the SH and PR. One day is consumed by vehicle close-out and ascent preparation; and the final day is reserved for HLS ingress and ascent. This adds up to 12 days not available for research, leaving only 21 days for Surface Habitat-specific mission activity.

These 21 days will be examined two ways, first assuming that they can be focused on physical science investigations and the second assuming other obligations that will be mentioned in the coming paragraphs.

The STS-94 physical science tasks can be mapped to an Artemis Surface Habitat mission, first by sorting them in decreasing order of the number of tasks per crew member per day. The first 21 crew-days of tasks will be examined in Table 3.

Mission Day	Astronaut	# Tasks
3	Linteris	10
6	Linteris	7
7	Thomas	6
7	Linteris	6
8	Linteris	6
11	Thomas	6
6	Thomas	5
7	Crouch	5
11	Linteris	5
2	Thomas	4
2	Voss	4
3	Thomas	4
7	Voss	4
8	Thomas	4
8	Crouch	4
9	Thomas	4
11	Crouch	4
2	Crouch	3
3	Crouch	3
4	Thomas	3
5	Thomas	3

Table 3. Top 21 Crew-Days of Physical Science Tasks

This represents 100 of the 185 tasks. Assuming for purposes of this analysis that there is no order of operation constraints that would prevent increasing the number of tasks conducted per day, the workload can be rebalanced, distributing the other 85 tasks among these 100. Each row can be treated as a mission day, and the individual astronaut can be replaced with a two-person team, thereby mapping the STS-94 physical science tasks to a daily distribution in an Artemis Surface Habitat. Using the Lunar Architecture Team's designations of Blue Team and Gold Team, this re-distribution of tasks is represented in Table 4.

Mission Day	Astronaut Team	# Tasks
1	N/A - Adaptation	0
2	N/A - Adaptation	0
3	N/A - Adaptation	0
4	Off-Duty	0
5	N/A - Hab Startup	0
6	Crew 1&2	9
7	Crew 1&2	9
8	Crew 1&2	9
9	Crew 1&2	9
10	Crew 1&2	9
11	Off-Duty	0
12	Crew 1&2	9
13	Crew 1&2	9
14	Crew 1&2	9
15	Crew 1&2	9
16	Crew 1&2	9
17	N/A - Crew Swap	0
18	Off-Duty	0
19	Crew 3&4	9
20	Crew 3&4	9
21	Crew 3&4	9
22	Crew 3&4	9
23	Crew 3&4	9
24	Crew 3&4	9
25	Off-Duty	0
26	Crew 3&4	9
27	Crew 3&4	8
28	Crew 3&4	8
29	Crew 3&4	8
30	Crew 3&4	8
31	Off-Duty	0
32	N/A - Hab Close-Out	0
33	N/A - Ascent	0

Table 4. Baseline Distribution of STS-94 Physical Science Tasks to the Artemis Surface Habitat

In actuality, the SH crew does not have this much time available to devote to physical science. Currently, it is assumed that the SH crew will assist the PR crew when they return to the SH for logistics and maintenance. This activity encompasses four days. It is also currently assumed that the SH crew will have four days allocated for EVA opportunities. These would be local EVAs conducted either on foot or with the Lunar Terrain Vehicle. The purpose of such an EVA is to conduct scientific exploration in the vicinity of the habitat. The effect of removing those eight days from the SH crew's Physical Science tasks is shown in Table 5.

Mission Day	Astronaut Team	# Tasks
1	N/A - Adaptation	0
2	N/A - Adaptation	0
3	N/A - Adaptation	0
4	Off-Duty	0
5	N/A - Hab Startup	0
6	N/A - EVA Opportunity	0
7	Crew 1&2	14
8	Crew 1&2	14
9	Crew 1&2	14
10	N/A - Logistics, Maintenance	0
11	Off-Duty	0
12	N/A - EVA Opportunity	0
13	Crew 1&2	15
14	Crew 1&2	15
15	Crew 1&2	15
16	N/A - Logistics, Maintenance	0
17	N/A - Crew Swap	0
18	Off-Duty	0
19	N/A - EVA Opportunity	0
20	Crew 3&4	14
21	Crew 3&4	14
22	Crew 3&4	14
23	Crew 3&4	14
24	N/A - Logistics, Maintenance	0
25	Off-Duty	0
26	N/A - EVA Opportunity	0
27	Crew 3&4	14
28	Crew 3&4	14
29	Crew 3&4	14
30	N/A - Logistics, Maintenance	0
31	Off-Duty	0
32	N/A - Hab Close-Out	0
33	N/A - Ascent	0

Table 5. Distribution of STS-94 Physical Science Tasks to the Artemis Surface Habitat Assuming Logistics, Maintenance, and Habitat-based EVA

As a reminder, Table 3 indicates the tasks assigned to one specific crew member on a given mission day, while Table 4 and Table 5 indicate the tasks assigned to two crew members on a given mission day. Table 6 shows calculation of the average number of tasks assigned to individual crew members per day during STS-94, as well as for both SH options.

	STS-94	SH IVA Only	SH with Logistics, Maintenance, and EVA
Thomas	3.50	4.40	7.12
Linteris	3.86		
Voss	1.86		
Crouch	2.57		

Table 6. Average Tasks per Crew Member per Day

While the average number of daily tasks is lower in all cases than the highest number of tasks ever assigned to Linteris, which occurs on day 3 (in Table 3), there is a clear increase in the pace of activity. And while in STS-94, the task loading peaked (only Thomas and Linteris had more than 5 tasks per day; Linteris only had 4 such days, Thomas only 2), the SH task loading remains constant across the entire mission. During STS-94, there was schedule bandwidth to assign other tasks to the crew on days where their physical science activities were reduced. The Surface Habitat crew will have no such relief.

It may be worth reassessing the assumptions regarding Surface Habitat-based EVAs and PR crew support. Should local EVAs be performed by the SH crew or should they keep to intravehicular activity (IVA) science and leave the EVA science to the PR crew? One might argue that the PR is equally capable of conducting EVA science, whether in the immediate vicinity of the SH or up to 20 km away and is in all cases a better operating platform for EVA activity than the SH. The PR offers shorter EVA egress/ingress time, can place the crew and any associated payloads or tools closer to the EVA activity site, supports pre-EVA direct site viewing from multiple vantage points, etc.

It may also be worth reassessing the assumptions regarding SH crew support to the PR crew for logistics and suit maintenance. Gas and fluid exchange between the PR and SH can be conducted with automated systems that merely require the PR crew to make proper umbilical connections. The PR crew can perform suit maintenance in the SH airlock, or even ingress to the SH cabin if necessary. Stowage resupply can be performed the PR crew at the same time, potentially using cranes or other mechanisms to lift Suit Port Logistics Carriers (SPLCs).

All things equal, it may be possible for a two-person SH to perform the same quantity of physical science as performed by the STS-94 crew but depending on SH assumptions it may require the crew to work constantly at a rate close to the peak rates performed by the STS-94 crew. This is especially significant considering that at the time of that peak rate, there were an additional two STS-94 crew members performing other duties. For instance, in Figure 13, Voss is assisted by Still and in Figure 14 Crouch is assisted by Gernhardt.

Figure 13. Astronauts Susan Still and Janice Voss Reviewing an Inflight Maintenance (IFM) Procedure While Astronaut Gregory Linteris Works at a Laptop Computer

Figure 14. Astronaut Michael L. Gernhardt (left), Mission Specialist, and Payload Specialist Roger K. Crouch (right) Load Boxes as They Prepare to Deactivate the Spacelab Science Module

There are no such additional crew members available in the Surface Habitat to assist. Also, the level of biological research in MSL-1, while not directly measured in this study, was clearly significantly smaller in scope than the human factors and biology research conducted in some of the life science-focused Spacelab missions such as STS-90 Neurolab. The SH will likely also see increased activity in those disciplines. Further, the Surface Habitat also has responsibility for geology science, as well as for remote sensing comparable to the STS-35 and STS-67 Astro-1 and Astro-2 Spacelab missions.

Regardless of what science is to be performed in the Surface Habitat, are two crew members enough personnel? This paper does not provide enough information to definitively answer the question, but it certainly raises concerns. During STS-94, there were seven astronauts onboard *Columbia* to conduct the mission. It does not appear that boredom of any kind was a problem plaguing the *Columbia* crew. It is conceivable that two people might not be enough to conduct the types of scientific research that require the presence of human crew, while also sustaining habitat operations.

There is a threshold at below which, crew can be present but there are not enough people onboard to conduct research as their time is fully occupied maintaining the system. Flying an insufficient number of crew may significantly reduce crew efficiency. It is, of course, far more expensive to launch crew members to the lunar surface than to low Earth orbit. Given this cost difference, is it a viable option to expect a lunar surface crew to be less efficient than a Shuttle crew?

VII. Conclusions / Recommendations

Using STS-94 as an example of a credible physical science mission, this paper has mapped the crew engagement required to support STS-94 to a Surface Habitat mission. At a generalized level, it does appear that the overall form of microgravity physics research performed during STS-94 – combustion, containerless processing, fluid dynamics, gravity measurement, etc. – has a potential role on the lunar surface.

The presence of the lunar surface and lunar gravity will invoke both opportunities for new investigations and opportunities to repeat select microgravity investigations under lunar gravity. It is therefore important that the habitable surface infrastructure support both the crew and equipment needed.

It is therefore recommended that there be increased attention on derivation of pressurized laboratory science objectives and laboratory facilities. The quality of scientific understanding achieved in the Artemis lunar missions will be directly tied to the level of investment in surface infrastructure.

It is specifically recommended that the lunar science and engineering communities work together to develop an Artemis counterpart to the Constellation-era OSEWG lunar science instrument recommendations and construct use cases to help the Lunar Architecture Team size the appropriate science laboratories for the lunar surface and ensure the needed crew sizes to make effective use of this infrastructure.

Similar work should also begin for human Mars exploration studies. While the initial human expeditions to Mars might lack the infrastructure needed to perform pressurized laboratory investigations, an expanded Mars presence with surface habitats should consider the research opportunities enabled by a human presence.

There are, of course important differences. The Spacelab was carried in the Space Shuttle cargo bay and returned to Earth at the conclusion of the STS-94 mission, shown in Figure 15. This allowed for repeated, additional maintenance and configuration of the facility.

Figure 15. STS-94 Landing

By comparison, the Surface Habitat is permanently deployed to the Moon and a very small allocation of samples will be able to be transported to Earth. This gives rise to an important architectural question. Is there value in equipping Artemis with full-up surface laboratories that can conduct the full experiment in-situ and only return data to Earth, thereby supplementing the Artemis science return above and beyond sample return capacity? If so, what are the appropriate transportation architectures, partnering agreements, and resources needed to enable such an approach?

This gives rise to the point of crew efficiency mentioned in the previous section. At a broader level than just the consideration of science or other utilization, Artemis would benefit from a finer assessment of crew number and workload. Crew sizes for lunar surface missions have been assumed to be four since the beginning of the Constellation program. However, it could be useful to examine the Artemis objectives, derive the associated workload, and then extrapolate the crew sizes needed to achieve those goals as distributed across a campaign of lunar missions.

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