
Pressurized Rover Airlocks

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ABSTRACT

The ability for crewmembers to explore the surface of the Moon or Mars effectively on foot remains a significant test of any exploration design. The availability of a pressurized rover would substantially increase the range of exploration by space suited crewmembers. The design of the airlock systems or functions will facilitate crewmembers in accomplishing these efforts. The pressurized rover for planetary exploration incorporates three types of airlocks or pressure ports: the EVA airlock, the sample airlock and the habitat docking port. This paper conducts a survey of selected precedents in pressurized rover design and then analyzes the key issues for airlock design.

INTRODUCTION: THREE ENVIRONMENTS -- THREE AIRLOCKS

The airlock is the physical interface between the three working environments for crewmembers on the lunar or Mars surface. These environments are: the pressurized habitat in which the crew will live and work; the lunar/planetary surface and its atmosphere that require astronauts to wear space suits and carry their own life support; and the pressurized rover that gives them mobility over the surface. All three of these environments intersect in the pressurized rover. Thus, the pressurized rover for planetary exploration incorporates, at a minimum, three types of airlocks or pressure port functions: EVA egress and ingress, scientific sample ingress and removal, and docking or berthing to the pressurized habitat at the planetary base.

Each of these three airlocks provides its own unique function that probably cannot be combined into a smaller number of devices. The EVA airlock enables space-suited astronauts to egress and reenter the rover. The sample airlock provides the connection through which EVA crewmembers pass samples they have collected for analysis in the Astrobiology glove box, inside the rover. The habitat docking port is the connection through which the rover "docks" to the pressurized modules at

the planetary base, and through which shirtsleeve crewmembers enter and exit the rover.

REVIEW OF ROVER CONCEPTS & REQUIREMENTS

In conducting this literature survey, the author began with the Apollo era studies such as the Lockheed MIMOSA study (1966-67) and the Boeing LESA study (1964-66). However, there was a remarkable 20 year hiatus between those studies in the mid-60s and the new flood of concepts that followed the landmark 1984 conference on *Lunar Bases and Space Activities of the 21st Century* at the National Academy of Science in Washington DC (Mendell, 1985). This Conference set the philosophical agenda for human space exploration for at least the next 15 years, envisioning the return to the Moon and going on to Mars as one programmatic continuum. Beginning this review in the 1980s makes it possible to assume a common set of mission objectives and technologies, or at least an awareness of them on the part of the designers. The different approaches to these designs and technologies are significant for understanding why particular rover designs have certain attributes and lack others.

Despite this sweep of time, the literature survey reveals surprisingly few serious studies of rover airlocks. Most airlock studies look at airlocks in general, in connection to Space Station or some other orbital vehicle. Thus, in selecting concepts from the literature for this review, it was a goal to find studies that address airlocks, while including as many science-driven concepts as possible.

From a design methodology perspective, this survey groups the pressurized rover concepts into three types of design approaches or sources: **science-driven, mission architecture-driven, and system analysis-driven**. TABLE 1 provides a comparative overview of the salient characteristics of each of the selected pressurized rover concepts that this paper discusses. These sets of requirements appear here much as they occur in the literature, with no effort to fill in

any gaps or to supplement deficiencies – only to interpret where the material may be unclear.

SCIENCE-DRIVEN APPROACHES

Science-driven design approaches consider the way to maximize the ability of the system to support scientific return on investment. Science based requirements and concepts for pressurized rovers vary considerably depending upon the people proposing them and their goals. This survey found four such sets of science requirements for rover concepts: Cintala et al (1985), Nash et al (1989), Stoker et al (1992), and ESA (2000). FIGURE 1 shows a generic science exploration vehicle.

Geological Traverse Vehicle

Cintala, Spudis and Hawke (1985) describe a proposed 4000 km lunar surface traverse one way or 2000 km round trip by a crew of up to six geologists plus two technicians in a pressurized Geological Traverse Vehicle (GTV). Although the authors do not give a timeline, this expedition would surely take months to complete. The GTV carries two smaller, unpressurized rovers that the explorers would drive on short side trips. The GTV includes space suits for all crewmembers, but it is not clear if it incorporates an EVA airlock or uses the Apollo LM method of depressurizing the vehicle when crew members go EVA.

Science Exploration Opportunities Vehicle

Perhaps the first detailed account of science requirements for a pressurized rover appears in Nash, Plescia, Cintala, Levine, Lowman, Mancinelli, Mendell, Stoker & Suess (1989, p. 31), who categorized it under “Geological and Geophysical Field Science Equipment.” They stated the rover requirements as follows:

- Vehicle:
 2. Range 500 km.
 3. Pressurized.
 4. Holds 3 to 4 people.
 5. Adaptable arm (backhoe, crane, sample stowage, etc.).

Nash et al give additional requirements for the rover to carry that include the following items, all of which suggest implications for the pressurized rover’s sample airlock, EVA airlock and other capabilities:

- Sampling Tools for dislodging, acquiring, and stowing rock and soil samples (grabbers or tongs for handling solid rocks, rakes for 1- to 4-cm rock fragments, shovel or scoop for foil and bulk regolith samples).

- Coring tools to obtain cores 5 cm diameter, 10 m deep in regolith, 2 cm diameter, 1 m deep in solid rock.
- Trenching rig for digging trenches and burying equipment.
- Major sieving operation system to prepare separated samples of loose material.
- Portable geophysical instrument packages containing magnetometer, gravimeter, active seismic array, radar/EM sounder, corner cube retroreflectors.
- Multispectral imager with close-up and telescopic capability.
 - Elemental analysis spectrometers:
 - X-ray
 - Gamma ray
 - Neutron activation.

Science Exploration Strategy Rover

In 1992, Stoker, McKay, Haberle, and Anderson published “Science Strategy for Human Exploration of Mars” in which they postulate a “Consolidation Phase” of Human Exploration of Mars.

The scientific objectives of this phase will focus on regional exploration of the areas visited earlier by teleoperated rovers. . . . Human mobility will be accomplished via a pressurized rover vehicle capable of sustaining a crew for two weeks or more in excursions over rough terrain (Stoker, McKay, Haberle, & Anderson, 1992, p. (480).

ESA Mobile Lab

A recent European Space Agency (ESA) concept poses an interesting counter-example to the long-range pressurized rover that supports a great many EVA hours. The ESA mobile lab would travel the surface without crew EVAs:

This laboratory may have [a] few days of autonomy, some 100 km range of operations, as well as external robotic arms and drilling tools, operated either by scientists inside or by teleoperations from a Mars base or from Earth. A sample airlock and a series of scientific instruments for sample analysis would allow real-time research, while a docking port on the laboratory would allow direct docking to the habitation module of the Mars base, **thus avoiding any EVA to the crew** [emphasis added] (ESA, 1999, p. 9).



FIGURE1. (Artwork by Pat Rawlings of SAIC for NASA) Concept for a pressurized rover for scientific exploration. “After driving a short distance from their Ganges Chasma landing site on Mars, two explorers stop to inspect a robotic lander and its small rover.” This image is generic in the sense that it is not linked to a particular rover concept as presented here. (Courtesy NASA -Johnson Space Center, 1995)

The ESA concept is one only a few that mention a sample airlock and a docking port to the Habitat or base. Also, it appears unique in two respects: as the only proposal for a rover that mission controllers or remote scientists can teleoperate to conduct full science operations, and unique as the only proposal to disdain EVA entirely.

None of the four science-driven pressurized rover concepts specify an EVA airlock. Only Cintala et al discuss using EVA. ESA seeks to avoid EVA. This aversion seems as if the robotic planetary science allergy to human space exploration continues to haunt them even when on Mars with humans in a rover. It seems as if the humans cannot step onto the surface it will control the costs and dominance the of human space program.

MISSION ARCHITECTURE APPROACHES

The Mission Architecture approach derives from a top-down problem decomposition in which mission architects and planners attempt to identify all the elements of the mission, the connections between them, commonality and differentiation of parts and shared or unique resources. This survey found a number of Mission Architecture design concepts for pressurized rovers, of which this section reviews four: Jones & Bufkin (1986),

Weaver & Duke (1993) Hoffman & Kaplan (1997) and Rouen (1997).

Bulldozer Traverse Vehicle

Jones & Bufkin (1986) envisioned a Bulldozer Traverse Vehicle (BTV) for Mars construction, development, exploration, and utility work. It consisted of a pressurized cabin with a “hard docking port” in the aft for docking to the habitat. In the front, it would mount a bulldozer blade and other digging attachments. It was part of a larger Manned Mars Missions Workshop study, and so declared an intention of commonality with the Mars Mobile Lab concept. There is no mention in the Jones & Bufkin concept of supporting EVA.

Mars Exploration Strategy Rover

Weaver & Duke (1993) published the forerunner of the NASA Mars Design Reference Mission. With respect to pressurized rovers, Weaver & Duke wrote with more detail and precision than the official NASA document that followed (Hoffman & Kaplan, 1997). Weaver & Duke describe the pressurized rover in sufficient detail to identify its requirement for a docking port to attach to the habitats. FIGURE 2 shows a pressurized rover docked at its aft end to the airlock “nodule” under a habitat at the

First Mars Outpost. This image shows the nature of rovers as a component of the mission architecture.

NASA DRM Rover

Hoffman and Kaplan composed a much more extensive and complete vision of the NASA Design Reference Mission (DRM) than Weaver and Duke, but they did so by treating all subjects at a higher level of abstraction. Still, Hoffman and Kaplan attach great importance on the pressurized rover. They place it in the general context of mobility for the crew on the planetary surface:

Extravehicular activity (EVA) tasks consist of maintaining the habitats and surface facilities and conducting a science exploration program encompassing geologic field work, sample collection, and deployment, operation and

maintenance of instruments.

Mobility on several scales is required by people operating from the Mars outpost. . . . Beyond the safe range for exploration on foot, exploration will be in pressurized rovers, allowing explorers to operate for the most part in a shirtsleeve environment.

Hoffman and Kaplan go on to posit more specific requirements in the DRM for the pressurized rover, but without mentioning an EVA airlock or specific EVA duties:



FIGURE 2 This rendering by John Frassanito of the Pressurized Rover docking to the First Mars Habitat is the quintessential image of the rover as a component of mission architecture. Note the airlock nodules that hang down below the habitat cylinders, to put them on a level with the rover docking port and to place them closer to the ground for EVA astronauts to descend the stair-ladder on foot. The front end of the rover resembles a giant space suit helmet facemask with metallized lens and swing-down visors (Courtesy NASA Johnson Space Center, 1993)

The requirements for long-range surface rovers include having a radius of operation of up to 500 km in exploration sorties that allow 10 workdays to be spent at a particular remote site, and having sufficient speed to ensure that less than half of the excursion time is used for travel.

One way to interpret Hoffman & Kaplan's formula is that the rover would support a total of 15 days for the crew, of which up to 5 days would be spent in traversing the surface round trip, with a ten day stay time at one or more

sites of interest. Hoffman & Kaplan describe the crew operations:

Each day, up to 16 person-hours would be available for EVAs. The rover is assumed to have a nominal crew of two people, but be capable of carrying four in an emergency (Hoffman & Kaplan, p. 1-23).

EVA Advanced R & D Road Map Rover

At about the same time in July 1997 that Hoffman & Kaplan completed the DRM, Michael Rouen of the EVA Division at NASA-Johnson Space Center completed the "EVA Advanced Research and Development Road Map." This "Roadmap calls" for a pressurized rover to accommodate three to four crew for up to 10 days. Rouen states a remarkably demanding requirement:

The operational environment will include a six person crew with significant numbers of EVAs planned. Of the six persons, two crews of two are expected to be out EVA doing exploration every day of the six day work week. Since stay times are expected to be 300 to 500 days, this amounts to a significant amount of EVA per suit system.

Rouen explains how the rover will play a key role in ensuring EVA crew safety:

When light work, health EVAs or task needs generate a significant spatial separation between crew persons, biomedical and location data will be fed back continuously to the base or pressurized rover with the people located in the habitat or rover on standby to aid an EVA crew person in distress. . . . Protection from the elements (radiation storms or local weather macrostorms) will be accommodated by having the Rover or Habitat set up as protective shelters.

Rouen mentions the airlocks for the habitat and rover only briefly:

Airlocks will be of multiple sizes with large airlocks on the base to allow transfer of large items for repair and small airlocks on the pressurized rover so that the gas resource can be conserved. All airlock systems will contain dust control provisions as well as contamination monitors to assure safe operations (Rouen, 1997, p. 2).

This mention of "small airlocks" seems to refer obliquely to such EVA airlock alternatives as the Crewlock, Transit Airlock, or Suitport, all of which are smaller than the large shuttle or ISS type airlock. Robert Trevino participated in an expedition to Antarctica, and wrote about it in terms of an analog to Mars exploration. His observation supports Rouen's point about a large airlock at the base to allow transfer of large items:

On Mars, a temporary shelter or cover may be required when repairing a vehicle in a dusty environment. A large airlock hatch will permit some equipment to be brought inside [the habitat or shelter] for repair. . . . Maintenance will be a critical function during a Mars mission, therefore, the

design of an airlock to permit equipment to be brought in and repaired will be essential (Trevino, 1997, p. 4).

SYSTEMS ANALYSIS APPROACHES

A System Analysis approach to rover design embodies a "bottom-up" view of how all the parts of a particular product or vehicle must work together. Sometimes the motive for entire system analysis derives from a desire to promote a particular subsystem as Williams et. al., where the subsystem is solar power transmitted by laser beam to a lunar rover. This literature review found four system-type studies of interest: Eagle Engineering (1988), Williams et al (1993), Clark (1996), and Arno (1999).

Lunar Surface Transportation Rover (LSTR)

Eagle Engineering, Inc. (1988) developed a lunar surface transportation rover concept for NASA-Johnson Space Center. The requirements were to accommodate a crew of four on a lunar traverse of 1500 km range for up to 42 days. FIGURE 3 shows the LSTR in the middle ground, looking rather like a train of four carriages, the first two pressurized, and the second two unpressurized. equipment or supply carriers.

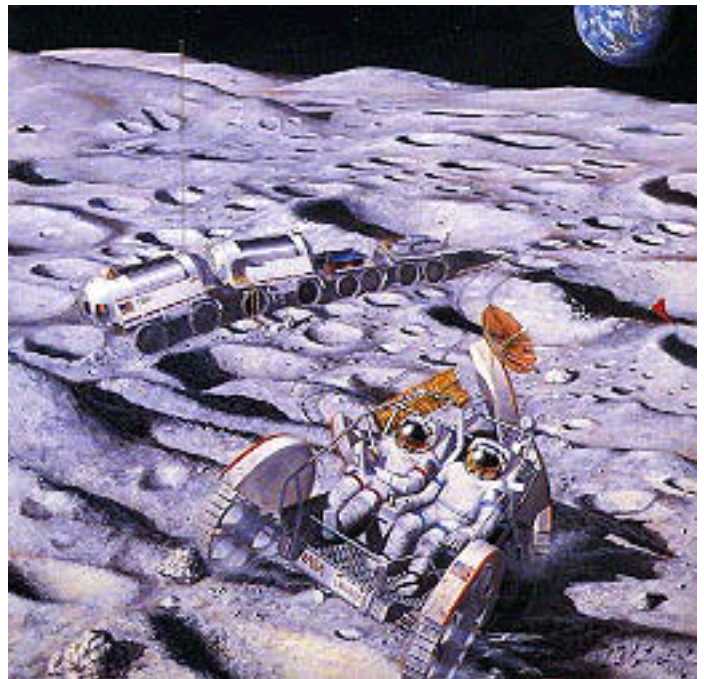


FIGURE 3. Eagle Engineering Study for a Lunar Surface Transportation Rover for NASA -Johnson Space Center (1988) which would carry unpressurized rovers with it. (Courtesy of NASA-Johnson Space Center).

For EVA, Eagle proposed to use two "manlocks," that appear to be very much like the Crewlock developed by William Haynes of the Aerospace Corporation as a single

person, conformal, minimum volume airlock. The Crewlock would normally be oriented *vertically*, but Eagle would install their manlocks *horizontally* on the lower sides of their rover, which might pose a hazard for the suited astronaut tumbling out and hitting the ground upon exiting.

Morrison & Hoffman (1993, p. 78) comment that the Eagle Engineering concept (4 crew, 3000 km) might provide the range of capability to conduct the ambitious mission that Cintala, Spudis and Hawke (1985) proposed for 8 crew members to travel 4000 km on the Moon.

Lunar Daylight Rover

In 1990, Brand Griffin developed the “Daylight Rover” concept for Boeing, which he presented to the Exploration office at NASA-JSC. FIGURE 4 shows how it incorporates two separate pressure vessels, the forward

one serving as a “driving station” and the aft one serving as an EVA airlock and solar storm shelter. The Daylight Rover scenario schedules only two buddy pair 7-hour EVAs per week. The reason for this light EVA schedule is that the plan for the manipulator arms attached to the front of the crew compartment to perform most of the geological sampling and collection. The arms pass samples to the crew compartment through a “Spacelab-type” scientific sample airlock. Griffin calls dust control during and after EVA as “critical” but does not propose solutions for it. Compared to all other rover concepts, the Daylight Rover’s wheels are extremely small. Unlike the Soviet “heavy Lunokhod” concept from the 1960s, which was the first 14 day lunar rover and incorporated solar cells (Van den Abeelen, 1999), Griffin’s Daylight Rover does not incorporate solar cells, even though he provides a nearly horizontal “parabolic sun shield.”

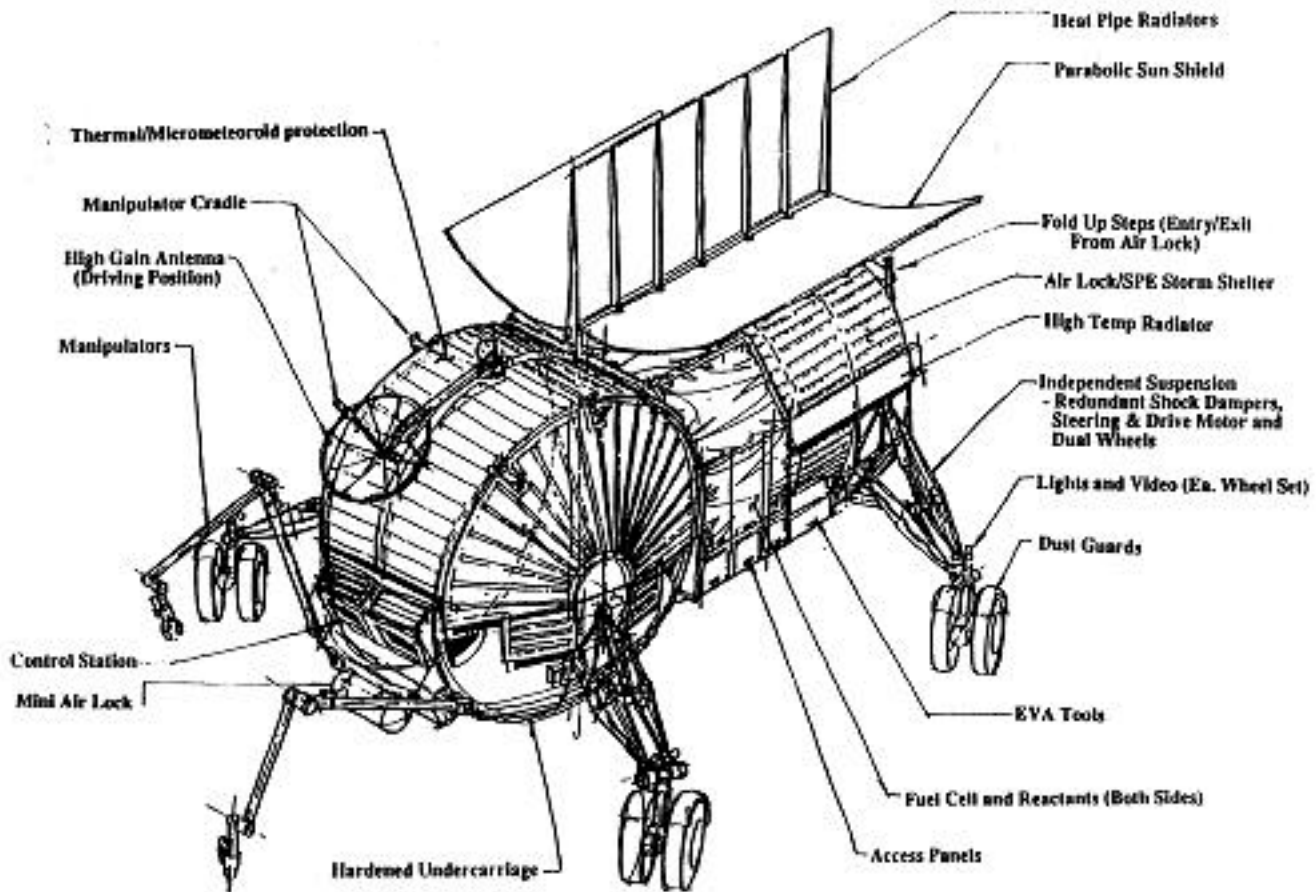


FIGURE 4. Daylight Rover for Lunar Exploration (1990), Courtesy of Brand Griffin. Note the “Airlock/SPE Storm Shelter” at the aft end of the vehicle. Two pressure vessels comprise this rover; the forward one, turned curved edge forward, with windows for navigation, and the aft one, with different proportion and turned to join the forward vessel butt-end front.

Solar Laser Beam Powered Lunar Rover & Suitports

Williams et al (1993) comprised a multi-agency team of scientists and engineers from NASA Langley Research Center and the Department of Energy’s Pacific Northwest Lab. They developed a lunar rover of which the principle feature was large antenna-like receiver to

which a solar power satellite would beam power by laser beam. With this power source, they proposed a rover that could transport a crew of four 1000 km in 30 days. Another unique feature of Williams et al’s concept is that they were the first to propose installing the Suitport “airlockless airlock” in a vehicle (Cohen, 1995). Soon after the Williams et al report, a team at NASA-Ames

Research Center installed two Suitports in the aft bulkhead of an M113 armored personnel carrier to create the Ames Hazmat vehicle. FIGURE 5 shows the aft view of the Hazmat vehicle, with one of the two Suitports visible and Jerry James in the matching suit. The

crewmembers enter or don the suit through the Suitport inner hatch in the aft bulkhead and through the portable life support system (PLSS) backpack that comprises the outer hatch (in respect to the rover).



FIGURE 5. Rear oblique view of the HazMat vehicle showing the Suitport inner hatch in the aft bulkhead and the Suitport/ Portable Life Support System (PLSS) modification to the rubber HazMat suit.

MERLIN: Martian Exploratory Rover for Long Range Investigation

Professor David Akin's team at the University of Maryland produced this concept in 1998 for the Human Exploration and Development of Space – University Projects (HEDS-UP) conference at the Lunar and Planetary Institute. It features a pressurized crew module, with an external EVA airlock connected to it by a short tunnel. The cylindrical EVA airlock stands “tuna can” fashion on its flat bottom, with dimensions of about 2m high and 2m in diameter. Like Griffin's Lunar Daylight Rover, it is comprised of two cylindrical pressure vessels of different sizes and orientations. The University of Maryland study describes an “EVA liftgate” for the EVA astronauts to lower themselves to the Mars surface.

Planetary Surface Vehicle

In 1999, Roger Arno published a systems approach to designing pressurized planetary rovers. (Arno,1999, pp. 447-476). He sized a reference rover for a crew of three

on a six day sortie of 100 km, with an average traverse distance of 15 to 20km (p. 470). As an additional safety measure, this rover would have the “ability to support three astronauts for one month while stationary (as a habitat or shelter)” (p. 464). Arno outlines a step-by-step approach for designing a pressurized rover. However, he stops short of a detailed analysis for rover airlocks. In this regard, this paper picks up where Arno leaves off. He does not address dedicated sample airlocks and he mentions the docking port/airlock only in passing as “ability to dock with other mission elements and transfer crew without EVA.” Arno's conceptual drawings appear in FIGURES 6 and 7. Arno establishes his “Design Parameter” for the largest airlock option:

EVA will be through an airlock big enough to hold two astronauts, allowing them to put on suits and take them off. It will provide equipment and space to clean and store the space suits. Pumping the airlock with each EVA will save up to 94% of the air [using the baseline Space Station pumping system] . . . Assume at least one airlock, whose hatch is compatible with the base's habitat

modules and other rovers (Arno, 1999, p. 467). . . . Assume airlock pumps, valves, and tanks of 100 kg and consume 1 kW for 15 min per EVA (Arno, 1999, p. 469)..

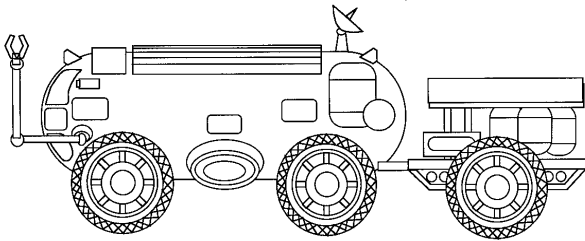


FIGURE 6. Example of a long-range pressurized rover with robotic arm and power cart. Note the EVA airlock hatch on the lower side of the rover, between the wheels (Courtesy of Roger Arno, NASA-Ames Research Center)

SUMMARY OF COMPARATIVE ANALYSIS OF DESIGN APPROACHES.

The comparative analysis of the three design approaches is instructive. Each of the three -- Science-Driven, Mission Architecture and System Analysis -- emphasize certain aspects of the design problem while neglecting others. TABLE 1 Summarizes the rovers reviewed in this survey.

Science-driven rovers

Science-driven rover concepts tend to put a premium on performance in terms of range and operating time. However, they all avoid discussing their respective EVA systems. The only mention of EVA is in the negative. In the ESA concept, the design intends to obviate the need for any scientists to resort to EVA. In this respect, the ESA vehicle with its robotic arms seems more like a deep-sea mini-submarine -- for which crew diving would be impossible -- than like a space vehicle.

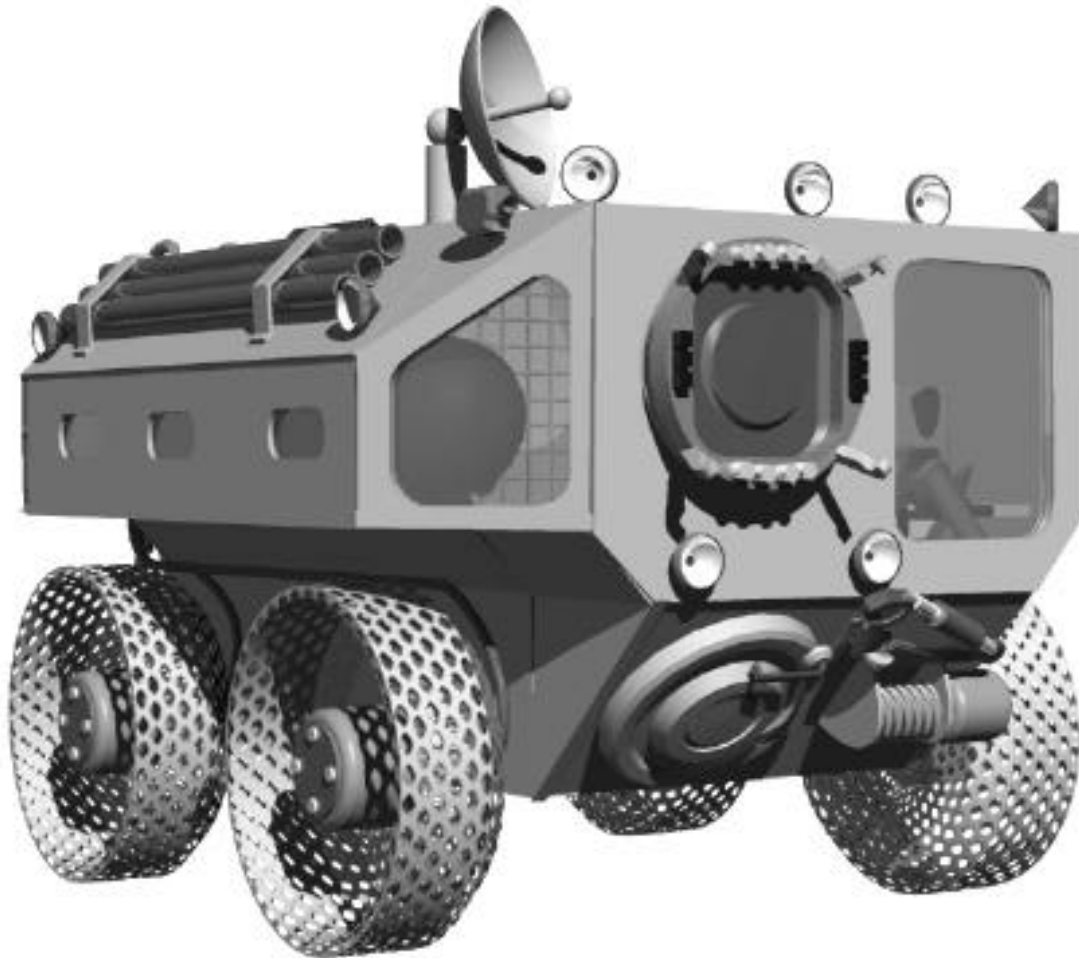


FIGURE 7. Roger Arno's concept for a pressurized planetary rover with two external hatches. The lower hatch is for EVA crew access to the cabin and the upper hatch is for the rover to mate to the habitat pressure port. Note that the EVA hatch is round and differs from the 1.25m square standard ISS-type hatch of the docking port (Courtesy of Roger Arno, NASA-Ames Research Center).

TABLE 1. Matrix of Proposed Pressurized Rover Characteristics and Requirements

Key to Design Drivers: M.A. = Mission Architecture Driven, S. = Science Driven, S.A. = System Analysis Driven

Source	Design Driver	Crew	Range in km	Range in Time	Airlock Features	Notable Requirements
Cintala, et. al., 1985	S.	6 to 8	2000 km or 4000km one way	Not stated (Months Inferred)	Not stated – (Apollo LM type depressurization inferred)	<ul style="list-style-type: none"> • “mobile base camp” • resupply or crew exchange en route
Bufkin & Jones, 1986	M.A.	2-5 (inferred)	100 km (inferred)	5 to 30 days	Aft “Hard docking port” to habitat modules; EVA not stated	<ul style="list-style-type: none"> * Move modules on the surface • Bulldozer & digging attachments • Common with a Mobile Lab as part of base
Eagle Engineering, 1988	S.A.	4	1500 km @10-15 km/h	42 days	2 “Manlocks” derived from the Haynes Crewlock	<ul style="list-style-type: none"> • Pressurized trailer for habitation
Nash et. al., 1989	S.	3 to 4	500 km	Not stated	Not stated	<ul style="list-style-type: none"> • Support extensive science requirements.
Griffin for Boeing, 1990,	S.A.	2 to 4	240 km	12 to 14 days	Airlock/solar storm shelter, Spacelab type sample airlock	<ul style="list-style-type: none"> • 14 day survival time in one place • 2 pressure vessels: cabin & “Large airlock”
Stoker, McKay, Haberle & Anderson, 1992	S.	2 or more (implied)	Not stated	2 weeks	Not stated	<ul style="list-style-type: none"> • Excursions over rough terrain
Weaver & Duke, 1993	M.A.	2 to 4	500 km	15 days:	Aft docking port to habitat external airlock	<ul style="list-style-type: none"> •10 days at remote site • 16 crew hours of EVA time per day
Williams, et. al., 1993	S.A.	4	1000 km @ 10 km/h	30 days	2 Suitports in aft bulkhead	<ul style="list-style-type: none"> • Solar satellite laser beam receiver on top • 30° max. slope
Hoffman & Kaplan, 1997	M.A.	2 to 4	500 km	15 days:	Not stated	<ul style="list-style-type: none"> •10 days at remote site • 16 crew hours of EVA time per day
Rouen, 1997	M.A.	3 to 4	Not stated	10 days	“Small airlock” in rover, “Large airlock” in habitat	<ul style="list-style-type: none"> • Very extensive daily EVA demands. • Rover is survival shelter
Clark, 1996	S.A.	2	1,000 km	2 to 4 weeks	Internal transit airlock for 2 suited crew	
Univ. of Maryland 1998	S.A.	2 to 4 (from DRM)	3000 km	24 days	Large, external, 1.1 m dia, 2.1 m high	<ul style="list-style-type: none"> •14 days at remote site • 10 days traverse • EVA “Lift-gate”
Arno, 1999	S.A.	3	100 km	6 days	EVA Airlock in rover, with port for Habitat docking	<ul style="list-style-type: none"> • Rover is survival shelter in one place for 30 days
ESA, 2000	S.	Not stated	100 km	“few days”	Sample airlock & Habitat Docking Port, No EVA	<ul style="list-style-type: none"> • May be teleoperated for science missions • No EVA requirement

Long Module Configuration

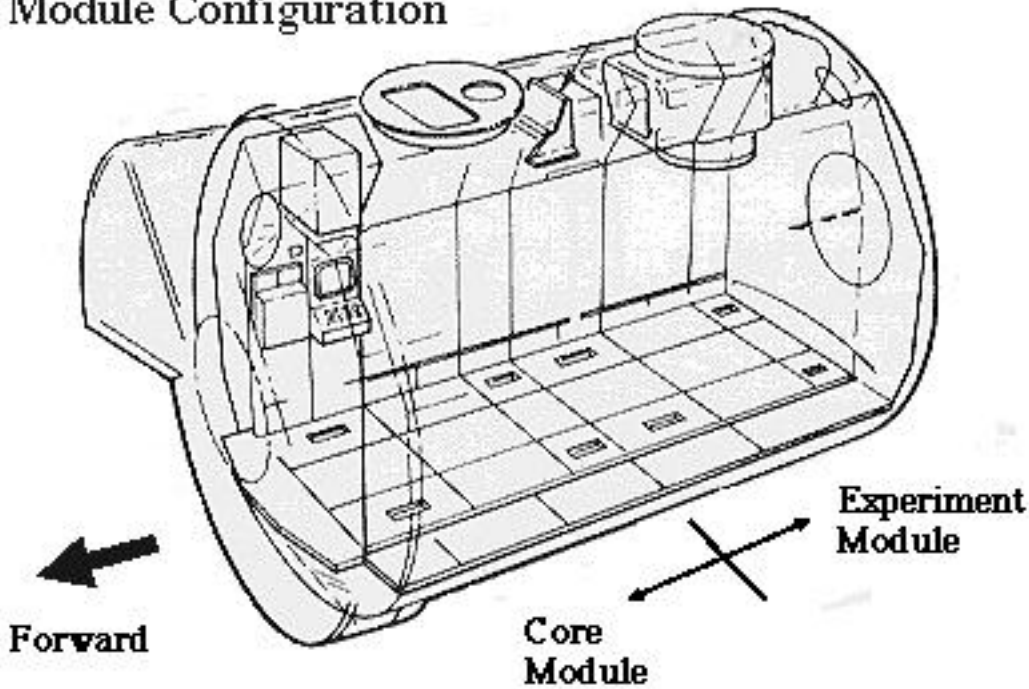


FIGURE 8. ESA Spacelab, with scientific airlock on top of Experiment Section to the right, projecting down into the volume (Courtesy of NASA-Marshall Spaceflight Center).

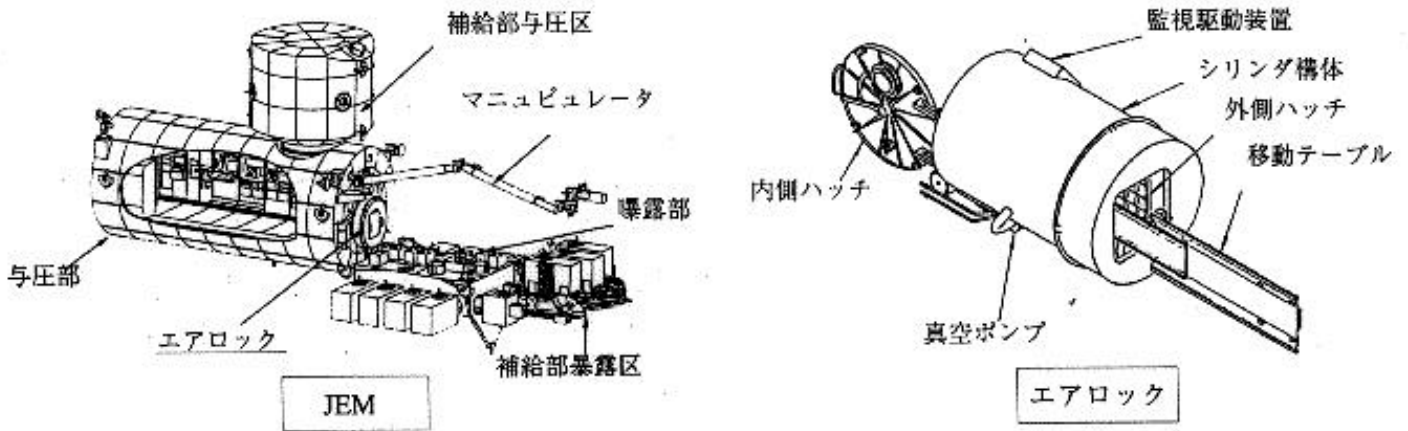


図 JEM エアロック概要
Fig. Schematic of the JEM airlock

FIGURE 9 Kibo Japan Experiment Module Airlock, to the right, showing the square outer hatch, with the slide table extended, and the round inner hatch swung open. In the image of the complete JEM to the left, the airlock appears in the front of the long module (Courtesy of Kawasaki Heavy Industries).

Mission Architecture-Based Rovers

Mission Architecture-based rovers tend to avoid any direct mention of science requirements or activities, and one can infer them only from the requirement for 10 days stay time at a remote site in both Weaver & Duke and in Hoffman & Kaplan. Mission Architecture-derived rovers

tend to pay attention on how they will physically connect with another pressurized environment – habitat or another rover element. Most tend to have a pressure port for docking with the habitat. By comparison, only one Science-driven rover (ESA) and one System Analysis-based rover (Arno) incorporate docking pressure ports. Mission Architecture concepts tend to

treat EVA activities and requirements rather lightly, typically mentioning a number of hours per day for EVA activity, but not going very far to explain how to provide and support that activity. Mission Architecture concepts also tread lightly on the idea of dedicated EVA airlocks, and do not delve deeply into particular airlock systems.

System Analysis Derived Rovers

System Analysis concepts for Rovers are the only ones that consistently treat the internal systems of rovers, particularly life support and internal airlocks. However, they tend to be so focused upon the rover and its performance that they generally ignore connections to the larger lunar or Mars mission. Only one such rover (Arno, 1999) incorporated a pressure port for docking to the habitat, as a secondary hatch on the EVA airlock. However, all these system analyses fall short of a serious consideration of EVA suit design and the ways in which it should interact with the vehicle or airlock design. Only one system-analysis driven concept – Brand Griffin’s Lunar Daylight Rover -- mentioned the scientific sample airlock.

SAMPLE AIRLOCK

The conventional wisdom about crewed rovers on a planetary surface is that the explorers will use them simply to pick up rocks and return to their base for analyze the rocks. Yet, how does the crew know if they found a “good rock” or a “bad rock;” a scientifically interesting rock, or an uninteresting rock? Imagine a crew travelling five days to a site and five days back – at a cost of millions of dollars per hour – and never knowing if the rocks they find are the samples they want. The pressurized rover clearly should have an on-board science laboratory capability to examine the samples in real-time while the crew collects them – or as soon as possible afterward. Only by providing, installing and utilizing this real-time science capacity will the crew members know if they should look for more rocks of the type they just found, or to toss out the last sample and move on to the next likely site (Cohen, 1999, p.4).

Real-time analysis will enable any needed action (e.g., gathering of additional samples) to be taken with only *hours* or *days* of delay. This timeliness compares very favorably to *months* of delay if the analytical capability is confined to the Mars Base (plus the cost and effort of returning for more of the same samples), and *years* if the analysis is carried out solely on Earth.

SCIENTIFIC SAMPLE AIRLOCKS

Given this imperative to conduct a preliminary analysis of scientific samples real time in the field, the scientific sample airlock is a peculiar but essential feature of a pressurized rover. Two of the surveyed rover concepts

included a sample airlock: Griffin (1990) and ESA (2000). In combination with an astrobiology “glovebox” research chamber (Cohen, 2000), it holds the key to examining scientific samples inside the pressurized rover while an EVA team of two or more crew members is exploring the terrain on foot outside the rover. The crewmembers collect rocks, soil, and other materials, and place it in a protective containment. This containment may vary in size, shape, design and composition from a plastic bag to a stainless steel pressure canister, and may include any manner of plastic, metal or glass boxes, jars, or other types of envelopes.

Definition of a Materials Airlock

The function of this sample airlock and its operational characteristics conform quite closely to the American Glovebox Society’s definition of an airlock:

An airlock is normally a relatively small passageway between two sealed doors that provides a path for moving materials into or out of gloveboxes without breaking containment.

Airlock size is determined by the items to be passed through and the allowable air input to the glovebox. The larger the airlock the more difficult sealing becomes. Airlocks often do not have gloveports and material transfer is accomplished by reaching through the doors. This can be facilitated somewhat by the addition of a slide tray or long handled device (American Glovebox Society, 1994, Sec. 5.2.2.2).

The needs and characteristics of a scientific airlock in Space tend to be much more extensive and challenging than the simple specimen airlock as defined by the Glovebox Society.

The First Materials Airlock in Space

Ironically, the first airlock in space to answer to this definition was not a scientific airlock at all, but the Skylab Trash Airlock (Price, 1975). The Skylab crew used the trash airlock every day to expel their accumulated wastes of all kinds into an unpressurized tank at the end of the Saturn Workshop opposite the Multiple Docking Adapter (MDA). Skylab also had scientific airlocks that served a variety of purposes, most notably astronomy (Henize, & Weinberg, 1973). Skylab astronauts conducted eight experiments, separate from the Skylab Apollo Solar Telescope, that included instruments to study the Earth’s atmosphere, particles in low earth orbit, skylight, stars, nebulae, and galaxies.

The MIR space station possesses both a trash airlock and a scientific airlock, but in the ever economical and practical Russian tradition, they are one and the same.

However, there are no reports that the MIR cosmonauts have ever mistaken a scientific experiment for trash or vice versa. One needed always to keep this duality in mind when reading or hearing that the MIR crew put an experiment out the trash airlock.

Spacelab Scientific Airlock

Perhaps the best description of these characteristics comes from W. A. den Haak in describing the Spacelab Scientific Airlock, which served as both an instrument and sample airlock. The Spacelab Scientific Airlock appears in FIGURE 8.

The Spacelab Scientific Airlock is a versatile, self-contained unit with venting and pressurization capabilities. . . . The Airlock comprises a cylindrical shell, 1 meter long and 1 meter in diameter, closed at each end by a circular honey-comb sandwich hatch which opens away from the shell. The outerhatch [sic] is hinged at the edge of the shell, and the innerhatch [sic] is removable in its entirety. Payloads are normally mounted on a sliding experiment table which can be extended into space and/or into the module. Each hatch of the Airlock is leaktight, so that module atmosphere is maintained. A passive and active control system protects the module and Airlock cavity against excessive heat loss or solar heat gain for all Airlock conditions. . . . All mechanisms are manually operated (den Haak, 1983, p. 47).

The Spacelab Scientific Airlock passed through the Spacelab Habitable module shell to which its flange was bolted. Its great advantage was that it gave the opportunity to “operate experiments in space, with human interaction, without EVA” (den Haak, 1983, p. 49). Den Haak describes the ability to operate the airlock without automated systems as an advantage in that the crew’s manual operation would be more reliable and safe. Because of the inaccessibility of the outer airlock hatch, the designers devoted particular effort to studying, testing and refining its mechanisms (ter Haar, 1979).

Scientific Airlocks on ISS

The International Space Station will have at least two scientific airlocks – one each on the European Columbus Module and one on the Japanese Experiment Module (JEM).

Columbus Scientific Airlock

The Columbus Scientific Airlock largely represents an evolution of the Spacelab Scientific Airlock, with similar dimensions and operating characteristics (Compostizo & Ariza, 1990, p. 281). However, the designers continue to devote close attention to the mechanisms that

operate the outer hatch. On Columbus, the outer hatch opening mechanism is separate from the latching mechanism. The Spacelab outer hatch was circular but the Columbus outer hatch is elliptical, which allows it to rotate 90° to pass its minor axis through the major axis of the airlock opening. The opening mechanism incorporates a translation geometry that can also move the hatch smoothly to the side of the airlock opening, rather than just swing outward on a hinge (Compostizo & de Olazabal, 1993, pp. 279-281).

Kibo Scientific Airlock

The “Kibo” Japan Experiment Module (JEM) scientific airlock appears in FIGURES 9 & 10. The JEM airlock incorporates an extensible table or slider system to move experiments and instruments out of the airlock and into the vacuum of space. The JEM robotic arm can remove objects from this slide table and reattach them to it. FIGURE 10 shows the Kibo airlock assembly before installation in the JEM.

FIGURE 11 shows the scientific sample airlock installed in a “simplified rover,” communicating from the exterior environment to an astrobiology research chamber glovebox inside. The sample airlock's internal hatch opens into the Astrobiology glovebox, which is essential to handle potentially biotic specimens in a safe manner that will protect both the crew and the sample from contamination. There are actually two airlocks connecting to the research chamber. The sample Entry airlock outer hatch appears open on the right side with its lever handle pointing up at 45°. In this concept, it is about 50 cm in chamber length and 50 cm in diameter. The Sample Exit airlock outer hatch appears closed in the center of the rover interior, with its handle pointing down. The sample exit airlock is smaller, about 30 cm long and 30 cm in diameter. It can be smaller because the sterilized samples that the crew removes from the glovebox will be small specimens sawed or chipped from the larger samples that come in the sample entry airlock.

Features of the Scientific Sample Airlock

The characteristics of the scientific sample airlock emerge from this discussion. The sample airlock consists of a (usually) cylindrical shell that spans two working environments: the exterior ambient environment of the moon or planet and the working environment inside a research chamber glovebox (Cohen, 1999 & 2000). The main mechanical parts are the inner and outer hatches, that require a high degree of reliability to ensure proper opening, closing, latching and sealing. A device such as a slide table is necessary to move samples through the airlock. The inner hatch opens into an Astrobiology glove box that accommodates operations for all forms of geological, chemical and biological science.



FIGURE10 Kibo (JEM) Scientific Airlock assembly . Note the round inner hatch swung open to the left, and the square outer hatch closed on the right. (Photo courtesy of NASDA, 1999).

DOCKING PRESSURE PORT

The ability for crewmembers to transfer from the habitat to the pressurized rover and back in a shirtsleeves environment is key to efficient and safe operations at a lunar or planetary base. Surprisingly, few design studies for pressurized rovers include this important component. The literature survey for this paper found only four:

Bufkin & Jones (1986), Weaver & Duke (1993), Arno (1999) and ESA (2000). This relative paucity of attention compares in striking contrast to the literature on orbital space module rendezvous and docking. But perhaps it is not surprising that most of the critical issues of microgravity maneuver do not apply. Axial and rotational alignment on a planetary surface are not nearly the mission-critical parameters they are in orbit.

Pressurized surface rovers present their own issues of docking, but they differ from orbital systems in the degree to which they interact with the design of the habitats or EVA support modules to which they must connect. The key question is whether the EVA airlock can double as the docking port between the mobile vehicle and the habitat.

Perhaps the most salient point on this question is *the lesson from Skylab*: that the design should not situate the airlock between the vehicle and the habitat, which in Skylab were the Apollo Command Module and the Saturn Orbital Workshop. The consequence was that whenever two Skylab crew members went EVA and depressurized the airlock, the third needed to retreat in advance to the Apollo Command Module, lest he be cut off from *escape* by the depressurized airlock (Cohen, 1983, p. 4-16 & Cohen, 1985, pp. 10 & 86).



FIGURE 11. Rear view of a simplified planetary rover, with the aft bulkhead removed. The scientific sample airlock appears on the starboard (right) side, between the two wheels, with its handle projecting up at about 45°. The sample airlock's internal hatch opens into the Astrobiology glovebox. The sample exit airlock appears in the center of the rover cabin, with its handle pointing straight down.

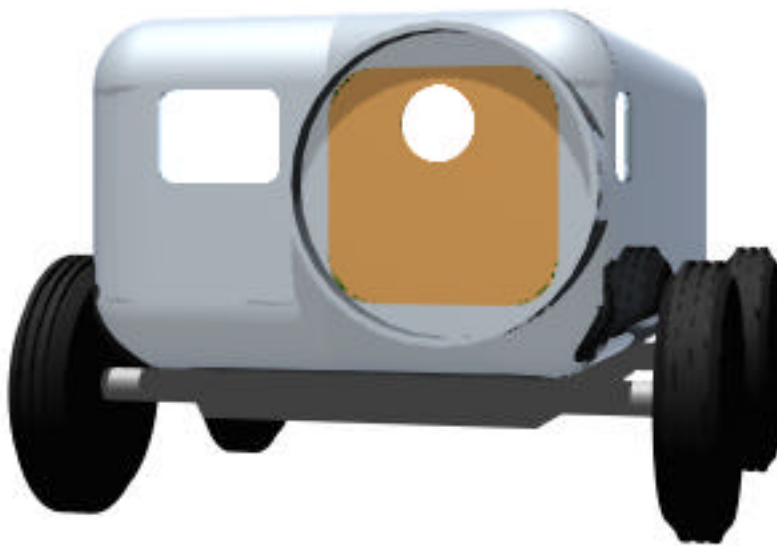


FIGURE 12. Front view of simplified planetary rover, showing the docking port at the scale of an International Space Station 1.25 m square hatchway, with the circular docking structure. This generic rover is 2 m high and 3 m wide and 5.25 m long (with the EVA airlock shown in FIGURE 14). The driver sits at the rectangular window on the left.

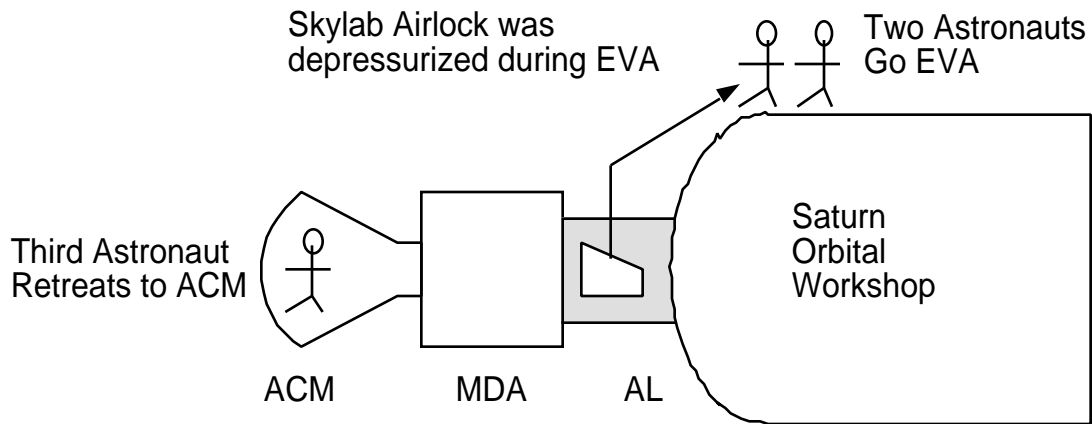


FIGURE 13. Diagram of the Skylab Configuration (1973-74) during an EVA, with the airlock depressurized so that the third crewmember is effectively cut off from the Saturn Workshop, the principle living volume. This lesson from Skylab shows very clearly that the docking port for the escape vehicle should not be located where it can be cut off from the habitat.

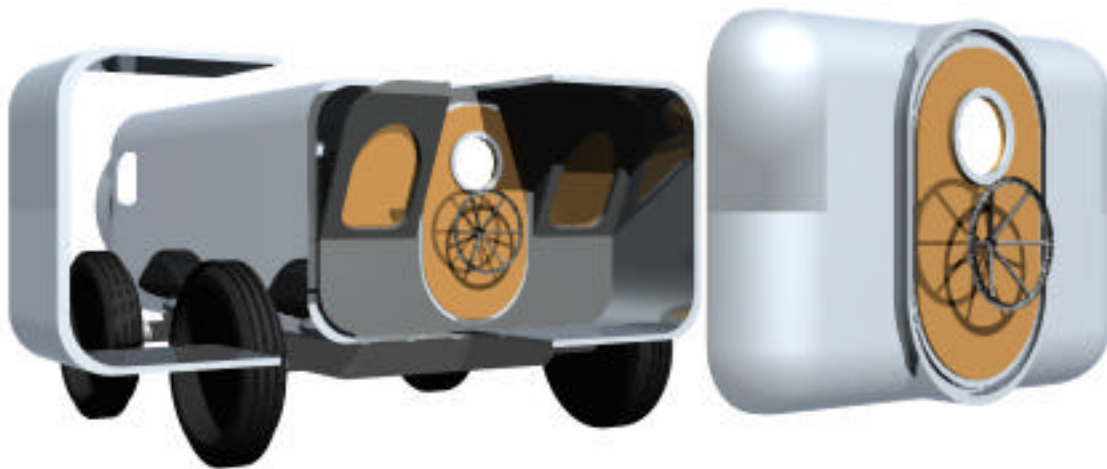


FIGURE 14. Exploded and cutaway view of Simplified Rover with two Suitports installed in the aft compartment. Between the two suitports is a crew hatch to allow access to the exterior of the suits. The aft compartment has a similar outer hatch that allows it to be sealed and pressurized for crew access to make repairs to the suits mounted at the ports.

Roger Arno is the only designer to date to actually draw a pressurized rover with a view of its docking pressure port. Arno's drawing appears as FIGURE 7. A study of this design raises some fascinating questions in the conception of his single large rover airlock with two ports: one for EVA egress/ingress and the second to mate to the Habitat, port. The questions that arise for docking pressure ports are:

- Can the entire, suited buddy pair or threesome use the airlock at one time?
- If the rover is used for an emergency evacuation of more than two crew members, how many times will it be necessary to cycle the airlock for complete transit?
- If it is necessary to equalize pressures between the rover side and the habitat side of a pressure differential, is it an advantage or a disadvantage to have an airlock in the rover between the rover crew cabin and the habitat, and its (presumed) airlock?
- Since the Habitat is likely to stand relatively high up on its landing legs, what transition or accommodation can the rover make for its docking pressure port to mate with a corresponding port from the habitat?

Berthing Versus Docking

Virtually all designs of Lunar/planetary bases and rovers assume an International Space Station (ISS) type port with the standard 1.25 m square hatch. However, the requirements of the ISS berthing port and the rover

docking port differ greatly with respect to duty cycle, alignment issues, utility connections and ergonomics. The duty cycles of the two applications differ radically.

Duty Cycle and Utility Connections

The ISS type berthing port is designed to be cycled basically just once – when a module is joined to a node or to another piece of hardware. The docking port for the pressurized rover must be designed for daily making and breaking pressure connections. The ISS type berthing port makes a permanent connection between all the ISS utilities: power, data, life support, fluids, gasses, vacuum, etc. For the pressurized rover docking port, it may be necessary to recharge batteries or renew life support consumables, but it is unlikely that the connection must carry the full suite of utilities.

Alignment and Operations

Another key characteristic of berthing and docking ports is their design for the actual docking and berthing operation. The ISS berthing port derives its inheritance from the history of Apollo Soyuz, which William Acres at NASA-Johnson Space Center designed originally to mitigate anomalies in roll, pitch or yaw -- particularly roll about the central axis of the ACM and the Soyuz. With the Lunar/Mars habitat firmly anchored on the surface, and assuming a fairly level "driveway" approach for the rover, the only likely anomaly is yaw. It would be advantageous to design a rover docking port optimized for partial gravity yaw.

Ergonomics

Finally, there arises the ergonomic consideration. The six-degree of freedom design of the berthing port led to an axially symmetric arrangement for ISS, with a central square hatch. The crew will “float” equipment racks through this square hatch top first. However, in the partial gravity of the Moon or Mars, it will be more advantageous to have a port through which

Architectural Impact of Docking Ports

The docking pressure port makes a huge architectural impact upon both the pressurized rover and the habitat module to which it docks. Please refer to FIGURE 2 that shows an airlock hanging down below the Mars Base Habitat to see the great significance of docking port height and its relationship to floor height in the habitat. The simplified rover in FIGURES 11, 12, and 14 is the size of a large delivery truck. The docking port and ring shown in FIGURE 12 obstructs a large portion of the front of the vehicle. The height of the docking port and its respective port on the habitat also present important implications as to where to place the docking port on the habitat.

Lessons for Docking Ports

The above observations yield two important lessons:

1. The docking port should not be combined with the EVA airlock because when the airlock is depressurized as the standard safe re-entry protocol for EVA astronauts, the rover and habitat become mutually inaccessible.
2. The docking pressure port requirements for a rover are radically different than the ISS. A new docking port design is necessary.

ANALYSIS OF EVA AIRLOCKS FROM FIRST PRINCIPLES

The EVA airlock or function facilitates the crew members activities in donning their suits, exiting the rover, returning to the pressurized safety of the rover and doffing the suits. The design of this airlock system takes on the utmost importance as an interface between the space suit, with its life support system, and the rover, with its atmosphere. The EVA airlock poses the greatest challenge of the three functions in terms of size, mass, power, cooling, and atmospheric requirements.

The design problem of exiting and re-entering the rover encompasses several considerations, of which the crew's safety is foremost. Safety touches every aspect of the design, and is not separable from the other

dimensions of the rover–airlock–space suit ensemble. The other dimensions of the design problem include the pressure vessel concept, atmospheric pressure regime, the conservation of consumables, the mechanical interlocks, pump down, cooling, crew timelines, mass and volume issues, and contamination control.

ATMOSPHERIC PRESSURE

The design of the rover airlock must respond to the pressure regime in the Lunar or Mars habitat, and in the space suit. The classic problem of going from a cabin atmosphere close to sea level pressure (1 bar) to a lower pressure as in the Space Shuttle EMU suit that operates at .3 bar (4.3 psi) is the threat of aerospace bends -- decompression sickness. (Nitrogen gas comes out of solution in the bloodstream and forming bubbles that collect painfully in the joints of the body). To avoid this problem, Space Shuttle astronauts “pre-breathe” pure oxygen for at least three hours before donning the suit to purge the nitrogen from their bloodstream. This pre-breathing period poses a substantial tax upon productive crew time, and may be unacceptable during a lunar or Mars mission in which EVA should to be easy, simple, routine, and safe.

The whole system-level design solutions to the pre-breathing problem include lowering the overall pressure of the entire planetary base and rover or raising the suit pressure to about .66 bar (~8.5 psi) to minimize the possibility of bends occurring.

For the rover airlock, the key questions are: 1) whether the suit should operate at the same pressure as the rover cabin, and 2) whether there should be a pressure differential between the rover and the habitat. It may be possible to develop a bi-pressure system, in which the rover operates at habitat pressure when docked to the habitat, but pumps down to a lower pressure for operations in the field. The problems with operating for long periods of time at lower pressures and novel gas mixtures are the biomedical effects and possible consequences for crew health.

The *advantage* of a multiple pressure system is that it may allow optimization of the space suit and the habitat as separate elements, with the rover/airlock ensemble serving as an intermediary environment. In fact, if lunar/Mars base planning stations a rover at the base at all times, it may be possible to make the rover/airlock combination the primary EVA support system, and avoid the expense of building a separate EVA support system installed in the habitat.

The *disadvantage* of the multiple pressure system is that it introduces a pump down—pump up protocol between different pressurized volumes. This multiple pressure situation introduces a level of complexity for crew and equipment health monitoring, as well as the time and

potential risk factors in making the transition between pressure levels. However, if the rover changes its cabin pressure -- reducing it -- only after it "casts off" from the habitat pressure port, it poses much less of an impact. When the rover returns to the habitat, it would need to increase its pressure before docking at the pressure port. For EVA use in place at the habitat, the crew would need to go through a gradual depressurization, perhaps in the rover cabin, with the rover cabin sealed off from the habitat.

EVA AIRLOCK DESIGN STRATEGIES

The goal of maximizing human productivity in supporting remote EVA from a pressurized rover does not presuppose particular design solutions or technologies. Rather, it is essential to evaluate the range of design strategies that relate to the rover/airlock ensemble. There appear to be three primary approaches to this design problem: the single volume, double volume, and the triple volume. Each of these strategies brings with it a developmental history and existing precedents.



FIGURE 15 Crew of STS-80, Thomas D. Jones (center) and Tamara Jernigan (left) suit up in preparation for going EVA through the Space Shuttle airlock (Photo: NASA).

Single Volume Design Strategy

In the **single volume** design strategy, the rover would have a single pressurized cabin that would double as the airlock. The precedents for this strategy include the Gemini, Soyuz, and Apollo LM EVAs. When the crewmembers wish to go EVA, they don their suits, start the portable life support systems, and then depressurize the rover cabin. With the rover cabin at vacuum, they egress to the lunar or Mars surface. When they wish to return to the rover, they re-enter the cabin, seal the hatch, then repressurize. In this scenario, all the crewmembers must don space suits and live off portable life support, or the rover-based equivalent, although one or more crewmembers could stay at the rover in case it was necessary to drive the rover to another location.

Double Volume Design Strategy

In the **double volume** design strategy, the rover carries with it a separate chamber to serve as an airlock so that the crew can go EVA without needing to change the pressure in the main crew cabin. The precedents for this strategy include Skylab, Salyut, Mir, and the Space Shuttle EVAs. Figure 15 shows a Space Shuttle crew suiting up in the Shuttle Middeck for an EVA, with the EVA airlock hatch behind them.

In this strategy, the crew prepares for the EVA by donning their suits either in the main crew cabin, or, if it is large enough, in the airlock chamber itself. Once suited up, and the portable life support initiated and verified, the crew seals themselves in the airlock chamber, then reduces its pressure to vacuum. They leave the airlock evacuated while walking on the surface. When they return to the rover, they seal the airlock hatch and repressurize the airlock. Once the pressure equalizes with the crew cabin, they can open the internal airlock/rover hatch. In this scenario, one or more crewmembers may remain in the rover in the shirtsleeve cabin environment. They are able to drive the rover to another location or to operate the robot arm or other systems in support of the EVA crewmembers. FIGURE 16 shows the internal view of the KVANT 2 EVA airlock on MIR.



FIGURE 16. Kvant 2 EVA airlock hatch on the MIR Space Station. (photo: NASA, 1998). The KVANT 2 airlock constitutes part of a two-volume system

The lesson from Skylab is that the crew should not enter the escape vehicle *through the airlock* from the crew habitat applies equally to the design of EVA airlocks as it does to the design of docking ports. Although it is tempting to "economize" by combining the two functions of docking port and airlock, it is a false economy. Combining the airlock and the docking port into a single unit compromises the functioning of both, to the benefit of neither.

Conformal, Minimum Volume Approaches

There are several variations on the double volume approach that include “conformal volume” pump down chambers that minimize the amount of atmosphere by shaping the free volume closely to the form of the suited crew member. Typically, these conformal airlocks accommodate only one crewmember at one time. Existing conformal airlock concepts include William Haynes's “Crewlock,” Case & Capps of Boeing's “Doorlock,” and Eagle Engineering's “Manlock”

EVA Airlock Safety Considerations

These conformal airlock concepts lead implicitly to a change in the “buddy system” protocol of EVA crews doing everything together in teams of two or three people. Instead, an individual crewmember would be alone while transiting a Crewlock, Doorlock or Manlock. Having two such devices side by side would not be the same as a true buddy system, because if a buddy in one lock was in trouble, there would be nothing the buddy in the other, separate chamber could do to help him or her. Any implementation of such a conformal airlock must first develop a credible alternative to the buddy protocol.

Triple Volume Strategy

Beyond the double volume strategy lies the **triple volume** strategy in which the airlock unit or module consists of two separate pressure vessels, and the whole unit attaches to the habitat. One volume is the depressurizable volume with the EVA hatch to the exterior. The second volume is a dedicated work environment that can support the EVA activities, with complete equipment to recharge the PLSSs and to repair and maintain the suits. If chemicals or biota contaminate the airlock or the support chamber, the crew may evacuate them to vacuum, which hopefully will purge them of any danger. Figure 17 shows the ISS Joint Airlock, which, in combination with the Node to which it attaches, has many of the characteristics of a triple volume airlock.

“Airlockless” Design Strategy

One special case of the triple-volume airlock is the “airlockless airlock.” In this case, the three volumes are 1) the larger airlock, which may operate as a conventional airlock or be maintained at vacuum for nominal operations including don/doff and egress/ingress; 2) the interstitial volume between the suit entry and the support chamber; and 3) the support chamber volume itself. In the **airlockless airlock** scenario, the rover carries with it a small interface that mates to the space suit in a fashion that eliminates the need to de-pressurize and re-pressurize any substantial volume. Instead, it becomes necessary only to pump down or bleed off a very small

interstitial volume between the space suit backpack and the “airlockless” inner hatch. The precedents for this strategy include the “Suitport” idea, the NASA-Ames Hazmat vehicle shown in FIGURE 5, and the Hamilton-Sundstrand “Ready to Wear” Marsuit (Hodgeson & Guyer, 1998, 2000).

In this strategy, the suits stow at their donning ports. When a crewmember “dons the suit” he opens the “airlockless” inner hatch and the rear entry hatch of the space suit with the portable life support pack attached. He slides feet-first into the suit, puts his arms and head in place, and then seals the rear entry hatch and inner hatch behind him. He bleeds-off or pumps down the very small interstitial volume between the rear-entry hatch and the “airlockless” inner hatch, and then separates the suit from the rover port. Upon return to the rover, he reverses this process, equalizing pressure between the interstitial volume and the cabin atmosphere before opening the two hatches.

EVALUATION FOR LONG DURATION MISSIONS

Each of these three design strategies presents a host of advantages and disadvantages that demand careful evaluation. For long duration missions, one of the major discriminators between these systems is the conservation of consumables. These consumables include electrical power, air, pump cooling, and crew time. All the precedents -- for the single and double volume approaches -- sacrificed the atmosphere to the vacuum of space, making no attempt to pump down the chamber to conserve it. For a lunar or Mars exploration system, it may not be acceptable to throw away that much air routinely with each EVA. Instead, it will become necessary to pump down the chamber as much as possible before bleeding the residual gas to vacuum.

Pumping Down the Pressure Volume

This pump down requirement for a two-person airlock imposes a substantial demand on the available electric power, thermal cooling, and the time in which to do it. Bernadette Luna modeled this airlock (Cohen, 1995). Her model shows that pumping down an airlock of 5 m³ (150 ft³) at a 10:1 compression ratio in ten minutes would require at least 15 kW of power, a very large demand on the rover systems, while still sacrificing at least .5m³ (15 ft³) of air. With less power available, say 5 kW, it would take at least 35 minutes to pump down the same volume, which would impose a penalty on crew productivity that probably would be unacceptable. The airlockless airlock offers a solution in reducing the pump down volume to .03 m³ (1 ft³) or less, so that pumping down becomes unnecessary, (compared to the much larger air volume the other strategies sacrifice even under the most aggressive conservation measures). The penalties associated with the airlockless airlock include potentially

much greater complexity in mechanical system design, and the need for exact precision in critical airlock seals, plus a more elaborate set of egress and ingress protocols (Cohen, 1995).

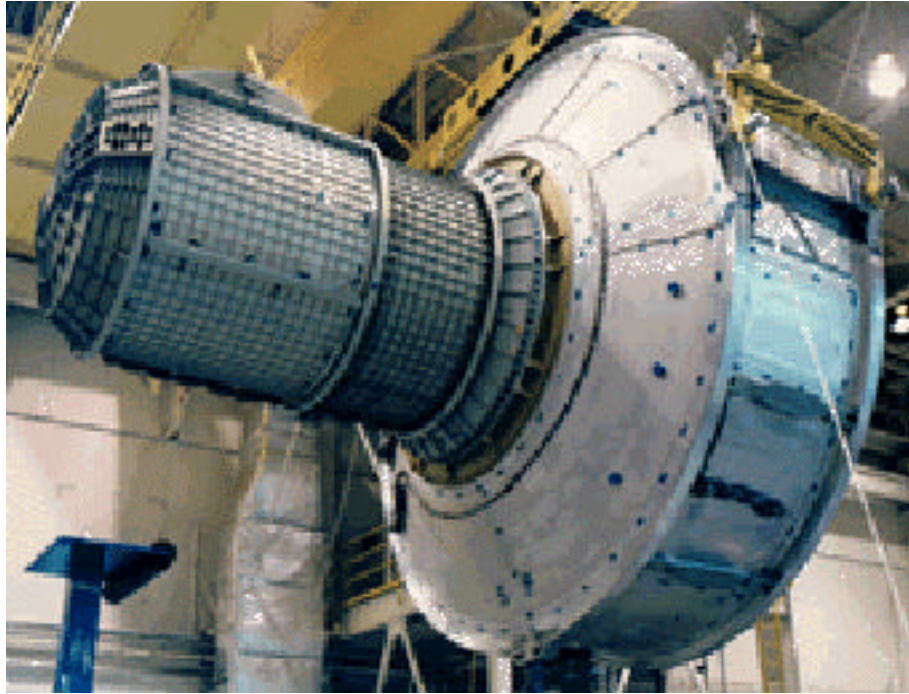


FIGURE 17 Joint International Space Station Airlock, to be launched to ISS, July, 2000, Launch Block 7A, is an example of an double chamber, external airlock. The wide diameter cylinder is the EVA support portion and the longer axis, narrow diameter section (actually about 2m diameter) is the pump-down chamber.

DUST AND CONTAMINATION CONTROL

On the moon or Mars, the most common threat of contamination comes from the pervasive dust on the surface. FIGURE 18 shows Apollo astronaut Charles Duke with lunar dust clinging to his space suit. Allton and Lauer examined the scientific sample containers that were the only items with seals returned from the lunar surface. They extrapolated from this examination to describe the problems that the Apollo program encountered with lunar dust. Dust and grit particles clinging to the seals impaired them from closing tightly and forming an “airtight” seal. Allton and Lauer assert that the ability to preserve a sample depends first upon the ability to seal that sample hermetically. They recommend that the seals on future lunar or martian sample containers should incorporate a “wiping action” to ensure that they can close properly (Allton & Lauer, 1991, p. 313).

Gordon Woodcock and his team from Boeing describe the properties of the lunar environment, especially lunar dust:

But the Moon also introduces potentially severe abrasive wear. 50% of the regolith is finer than the human eye can resolve (about 70 μm), and this highly abrasive dust sticks electrostatically to virtually everything it touches. The Apollo experience is well known. Macroscopically, the agglutinate-rich regolith clumped and built up in many places; for instance, it obscured the stair treads of the LM lander. Microscopically, the dust adhered to all kinds of equipment. Crew suits became gray from the waist down, after just a few hours of walking, riding and falling. . . . And the desiccated fines inevitably brought inside the LM cabin occasionally caused temporary breathing discomfort for the crew upon repressurization (incidentally, lunar dust in air has the odor of burnt gunpowder). (Woodcock et al 1990, p. 130)

Woodcock et al propose "overlapping countermeasures, both prophylactic and compensatory." They describe three approaches to handling dust:

1. **Keep dust off.** Design systems not to "kick up much dust."
2. **Keep dust out.** Hermetic seals against dust. Clean lenses, sensors, solar arrays and radiators periodically in situ. Remove dust with an electrostatic tool.

3. **Overwhelm the dust's effects.** "Acknowledge and address the inescapable." Let dust fall through mechanisms, preventing macroscopic accumulation. Size critical bearing surfaces robustly, treat for surface hardness, to mitigate abrasive wear (Woodcock, et al, 1990, pp 131-132).



FIGURE 18. Detail of Apollo 16 astronaut Charles M. Duke Jr. sampling lunar regolith in the lunar Descartes highlands. Very fine sediment clings to his suit, appearing gray on the suit's white outer thermal and meteorite garment. Lunar or Mars dust poses a potentially severe contamination problem (NASA Photo).

The difficulty of sealing the Apollo sample containers applies equally to all three types of airlocks. Although the greatest challenge from contamination control is probably associated with the EVA airlock, it affects all three types of airlock. It is vital to keep this dust out of the pressurized interior, and especially to protect grit-vulnerable mechanical systems such as pumps, compressors, and airlock mechanisms from it. The point at which the dust becomes the greatest threat to safety is in the donning and doffing of the space suit, ingress and egress of the EVA airlock.

Two strategies exist for donning and doffing an environmental or pressure suit without exposing the wearer to contamination. These two strategies are “decontaminate before doffing” and “exit to a safe atmosphere.”

Decontaminate Before Doffing

In the *decontaminate before doffing* paradigm, decontamination must occur while the crew member is still in the suit, and before opening the protective envelope that the suit provides.

One of the major challenges in combating a toxic material spill is how to protect the crewmember from contamination when doffing the suit after working in the contaminated environment. The traditional military approach to chemical, biological, and radioactive decontamination is to wash off the entire suit from the outside before the crewmember takes it off.

However, this decontamination approach poses many practical difficulties, especially on a dusty planet or moon with no liquid water. The considerable time that may be necessary to decontaminate the suit before a crewmember can doff it poses a significant obstacle to efficient operations. It may not be possible to decontaminate near that site, which may mean transporting the suited crew member(s) in a sealed vehicle to a separate decontamination site. This approach not only introduces a serious delay, but also potentially subjects a second site to contamination.

Current environmental suits for hazardous materials spills require decontamination before doffing. The NASA space program also uses suits that the crewmember dons and doffs without isolation from potential contamination on the suit. To doff the suit, they must leave the perimeter of a contaminated area and reenter the Space Shuttle airlock. It is not clear where decontamination would occur in the event of hazardous chemical accident on the Space Shuttle or Space Station.

Exit to a Safe Atmosphere

In the *exit to a safe atmosphere* paradigm, the wearer can exit the suit without decontaminating first. The nuclear power industry and military chemical weapons handling employ two models of *exit to a safe atmosphere* suit: the tunnel suit and the neck suit. In the tunnel suit, the crewmember crawls into the suit through a tunnel connector. The neck suit has a large disconnect at the neck that allows the crewmember to enter the suit from above, or to climb into the suit from below. The suit remains in the contaminated environment. Both the tunnel suit and neck suit have significant disadvantages for space application and for hazardous materials handling in unpredictable locations. For the tunnel suit, the length of the tunnel limits the range and usefulness of the tunnel suit. The neck suit is quite awkward and appears efficient only for use within a fairly small area.

The Suitport takes the *exit to a safe atmosphere* paradigm to an integrated systems level for both space and terrestrial applications. The Suitport emerged from the recognition that NASA was developing a new generation advanced space suit, the AX-5 suit that represented substantial improvements over the shuttle External Mobility Unit (EMU) suit, but there was little progress beyond the Space Shuttle airlock. As an airlockless airlock, the Suitport offers the additional benefit of contaminant control. By sealing the suit to the outside of the shirtsleeve environment, it is possible to isolate the contaminants from the crew. The crewmember can don and doff the suit through the Suitport without needing to decontaminate it each time. An independent evaluation by Case & Capps (1993) confirms this advantage.

From the Human Factors perspective, the Suitport presents potential improvements in the convenience of EVA and its ease of use. The suit could standby, fully assembled at the Suitport, waiting for the crewmember to “don” it by slipping in through the rear-entry hatch. Although the mechanical design is somewhat complex, the total ensemble can greatly simplify the pre-EVA and post-EVA procedures.

Conflicting or Combined Design Solution?

However, the Suitport by itself does not offer a complete solution to the needs of a space station or pressurized rover. Roger Arno offers a critique of the Suitport as follows:

“On the other hand, it makes suit maintenance and repair more difficult and requires measures to protect the suits suspended outside the vehicle. This method would also require another, large

airlock for standard transfers of material as well as emergency evacuation or entrance of the crew. (Arno, 1999, p.60)”

dust contamination of the habitat (Hodgeson & Guyer, 1998, p. 13).

To incorporate such a large airlock into the pressurized rover in addition to the suitports was more of a burden than either Eagle Engineering (1998) or Arno (1999) could accommodate, and so both picked a double volume option. Arno picked the single large airlock and Eagle conceived the Manlock conformal airlock.

More recently, Hodgeson & Guyer published their work in rear-entry airlocks in *Launchspace*, describing the associated Marssuit as “ready to wear” by virtue of its easy don/doff arrangement. Hamilton Sundstrand tested and verified a manual opening and closing system for the rear hatch assembly.

The natural desire to minimize mass, volume and mechanical complexity can sometimes obscure the advantages of operational simplicity and safety. However, the two systems of an airlockless entry and a large airlock can complement each other in an integrated system. FIGURE 14 shows an aft view of the “simplified rover” with two suitports mounted in a large airlock chamber. Between the suitports is an access hatch to the rover cabin. The aft bulkhead incorporates a similar crew hatch, large enough to allow the transfer of large pieces of equipment or bulky supplies.

CONCLUSION

This conclusion addresses the several major portions of this paper. These portions include the survey of pressurized rover airlocks; and the sections on the three types of airlocks: scientific sample, docking pressure port and EVA.

Suitport in the HazMat Vehicle

The EVA Systems Branch at NASA Ames initiated a project to apply advanced and current EVA and pressure suit technologies to disaster cleanup. The Ames team modified the rear bulkhead of a M113 armored personnel carrier (Hazmat vehicle) to accommodate two Suitport openings. Philip Culbertson, Jr developed the mechanical suitport interface between the Hazmat vehicle aft bulkhead and the Hazmat suit, for which he obtained a design patent.

The revelation of the **survey of rover and rover airlock concepts** was the very great degree to which the particular design approach or method dictated the type of airlocks the study would address or even mention specifically. None of the four Science-driven studies specified an EVA airlock, and only one mentioned a sample airlock and docking port – and that one is European. Among the Mission Architecture-driven rover concepts, most include a docking port to help “integrate” the rover with the other mission elements, but only one paper mentions EVA airlocks specifically. Among the System Analysis driven concepts, all addressed EVA airlocks but only one included a docking pressure port and one other concept included a scientific sample airlock.

The Hazmat Vehicle appears in FIGURE 5. The crewmember will be able to enter the suit rapidly from the vehicle interior, seal the suit rear hatch and the Suitport hatch behind him, detach the suit from the Suitport, and go to work. When reentering the HazMat vehicle, the crewmember backs the rear of his suit to the Suitport, and secures it to the opening. The suit rear hatch nests in the Suitport rear hatch, ideally confining any contamination that may occur of the suit hatch. The crewmember opens the two hatches together, and enters the Hazmat without coming in contact with contaminants, thus avoiding the need for decontamination procedures.

What was most surprising was that **not one study included all three airlock types**. With scientists as advocates and designers, perhaps these technical omissions are perhaps understandable. However, these surprising omissions by mission planners and system designers raise serious questions about self-styled “integrating” disciplines of mission architecture and system engineering. How could all these expensive mission architecture and system engineering studies miss such fundamental components of a mission-critical element such as a pressurized rover?

Suitport Refinements

More recently, at Hamilton Sundstrand, Hodgeson & Guyer developed a “functional mockup” of a suit system with some characteristics of the Suitport.

The key characteristics of the **scientific sample airlock** emerge as follows. The sample airlock consists of a (usually) cylindrical shell that spans two working environments: the exterior ambient environment of the moon or planet and the simulated working environment inside a research chamber glovebox. The main mechanical parts are the inner and outer hatches that require a high degree of reliability to ensure opening, closing, latching and sealing. A device such as a slide table is necessary to move samples through the airlock.

The donning station reflects preliminary concepts for air lock integration with a Mars habitat which could minimize airlock volume and help to control

The **docking pressure port** makes a substantial architectural impact upon both the pressurized rover and

the habitat module to which it docks. With a rover about the size of a large delivery truck, the docking port and its berthing ring take up a very large portion of the front (or rear) of the vehicle. The height of the docking port and its respective port on the habitat also present important implications as to where to place the docking port on the habitat. There are two important lessons here. First, the **docking port should not be combined with the EVA airlock** because when the airlock is depressurized as the standard safe re-entry protocol for EVA astronauts, the rover and habitat become mutually inaccessible. Second, it is a mistake to assume that the docking pressure port should be the same or even similar to the **permanent berthing ports** between the Lunar or Mars base habitats. Virtually all designs of Lunar/planetary bases and rovers assume an International Space Station type port with the standard 1.25 m square hatch. While this hatch is an excellent design for permanent berthing in zero gravity, it is much less appropriate for the partial gravity environments of the Moon or Mars, and for the different duty cycle of daily connecting and disconnecting the pressure seal. Therefore, it will be important to develop a specific planetary docking port.

The **planetary EVA airlock design** is by now an old story. Despite many efforts to reinvent the wheel in the form of the "big dumb airlock" or in personal airlocks that break up the buddy protocol, there is really only one solution: the airlockless airlock. Whether this airlock takes the form to the Suitport, or the "Ready to Wear" Mars Suit, or some other more clever implementation, the solution clearly lies in this direction. The airlockless airlock is the only system that -- in routine operations -- allows rapid donning and doffing, egress and ingress, de minimus loss of atmosphere without expending huge amounts of pump power and pump cooling. The Suitport also saves crew time and offers a measure of protection against external contamination and dust intrusion.

Perhaps it is not too much to hope, that for the next round of lunar and planetary exploration exercises, NASA learns these lessons. Then the space program can move ahead to building a prototype pressurized rover as a highly capable exploration vehicle.

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REFERENCES

- Allton, Judith H. & Lauer, Howard V. Jr (1991) "Effects of Dust on Teflon Face Seals: Implications for Martian Soil Containers," in *IDEEA ONE, The First International Design for Extreme Environments Assembly*, University of Houston, November 12-15, 1991, Houston TX: Sasakawa International Center for Space Architecture. Pp. 313-317.
- American Glovebox Society (1994) Guideline for Gloveboxes, AGS-1994-G001, Santa Rosa, CA.
- Arno, Roger, (1999) "Planetary Surface Vehicles," in Larson, Wiley J. & Pranke, Linda K., Eds, *Human Spaceflight: Mission Analysis and Design*, New York: McGraw-Hill & Co., pp. 447-476.
- Bufkin, Ann L. & Jones, William R., II (1986) (1986) "Manned Mars Mission Surface Transportation Elements," *Manned Mars Missions*, Vol. 1, NASA-M002, A Workshop at Marshall Space flight Center, Huntsville AL, June 10-14, 1985, Los Alamos, NM: Los Alamos National Laboratories pp. 386-396.
- Capps, S., & Case, C., (1993, Feb 16-19) A New Approach for a Lunar Airlock Structure, AIAA 93-0994, Aerospace Design Conference, Irvine, CA
- Cintala, M. J., Spudis, P. D., and Hawke, B. R. (1985) "Advanced Geologic Exploration Supported by a Lunar Base: a Traverse Across the Imbrium-Procellarum Region of the Moon," in Mendell, Ed., (1985) Lunar Bases and Space Activities of the 21st Century, Houston: TX: Lunar and Planetary Institute.
- Clark, Benton C. (1996) "Mars Rovers," in Stoker & Emmart, Eds, *Strategies for Mars: A Guide to Human Exploration*, Vol. 86, Science and Technology Series, American Astronautical Society, San Diego: Univelt, Inc., pp. 445-463.
- Cohen, Marc M. (1985) "Overview: Human Factors in Space Station Architecture," in Cohen & Rosenberg, Eds., *Proceedings of the Seminar on Space Station Human Productivity*, NASA-TM-86673, Moffett Field, CA: NASA- Ames Research Center pp4-1 to 4-27.
- Cohen, Marc M. (1987) "Introduction: Ames Space Station Architectural Research," in Cohen, Eichold & Heers, Eds., *Space Station Human Factors Research Review, Vol. 3 - Space Station Habitability and Function: Architectural Research*, NASA CP-2426, Washington DC: NASA Scientific and Technical Information Division, pp. 1-116.

- Cohen, Marc M., & Bussolari, Steven, (1987, April) HUMAN FACTORS IN SPACE STATION ARCHITECTURE II: EVA Access Facility, A Comparative Analysis of Four Concepts for On-Orbit Space Suit Servicing, NASA TM-86856, Washington DC: National Aeronautics and Space Administration.
- Cohen, Marc M. (1995) The Suitport's Progress, AIAA-95-1062, AIAA Life Sciences and Space Medicine Conference, Houston, TX, April 3-5, 1995, Reston VA: American Institute of Aeronautics and Astronautics.
- Cohen, Marc M. (July, 1999) Mars Surface Science Laboratory Accommodations and Operations SAE 1999-01-2142, 29th International Conference on Environmental Systems, Denver, CO, July 12-15, 1999, Warrendale, PA: Society of Automotive Engineers.
- Cohen, Marc M. (2000, July) Design Development Strategy for the Mars Surface Astrobiology Laboratory, SAE 00-ICES-398, 30th International Conference on Environmental Systems, Toulouse, FRANCE, July 10-13, 2000, Warrendale, PA: Society of Automotive Engineers.
- Compostizo, C. & Ariza C. (1990) "Columbus Scientific Airlock," *Proceedings of the Fourth European Symposium on Space Mechanisms and Tribology*, ESA SP-299, Cannes, France, September 20-22, 1989, pp. 281-288.
- Compostizo, C. & de Olazabal, I. (1993) "An Opening Mechanism for the Scientific Airlock Outer Hatch," *Proceedings of the Fifth European Space Mechanisms and Tribology Symposium*, ESA SP-334, Noordwijk, The Netherlands, October 28-30, 1992, pp. 277-282.
- den Haak, W. A. (1983) "Spacelab Scientific Airlock," *Proceedings of the First European Symposium on Space Mechanisms and Tribology*, ESA SP-196, Neuchatel, Switzerland, October 12-14, 1983, pp. 47-50.
- ESA Space Studies Division (2000, February) Statement of Work: European Mission Architectures and Technologies in the Mars Exploration Scenario, Noordwijk, The Netherlands: ESTEC.
- Fisher, Mike (1992, February) "Roving the Moon - The Boeing Company's 'Daylight Rover'" *Final Frontier*, P. 11.
- Henize, K. G., & Weinberg, J. L. (1973, May) "Astronomy through the Skylab Scientific Airlocks," *Sky and Telescope*, Vol. 45, p. 272-276.
- Hodgeson, Edward W. Jr. & Guyer, Tracy L. (1998) An Advanced EVA System for Planetary Exploration, SAE 981630, 28th International Conference on Environmental Systems, Danvers MA, July 13-16, 1998, Warrendale PA: Society of Automotive Engineers.
- Hodgeson, Edward & Guyer, Tracy (2000, February) "Ready to Wear: Hamilton Sundstrand's Mars Suit," *Launchspace*.
- Hoffman, Stephen J., and Kaplan, David I., ed., (1997, July) Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team, NASA SP-6107, Houston, TX: NASA- Johnson Space Center.
- Hirata, Ryozo; Kusunose, Yuichi; Takenaka, Yasuhiro; Asami, Kaiichi; Ninomiya, Takashi; Wakida, Kunihiro; Matsuda, Kouji; Yonezawa, Toyosaku (1997, July) "Development of the JEM Airlock Cylinder Structure for the International Space Station," *Kawasaki Technical Review*, Vol. 134.
- Mendell, Wendell W. (1985) Lunar Bases and Space Activities of the 21st Century, Houston: TX: Lunar and Planetary Institute.
- Morrison, Donald A. & Hoffman, Stephen J. (1993) "Lunar Science Strategy: Exploring the Moon with Humans and Machines," in CNES (1993) Missions, Technologies and Design of Planetary Mobile Vehicles, Toulouse, France: Cépaduès-Éditions.
- Nash, Douglas B.; Plescia, Jeffrey; Cintala, Mark; Levine, Joel; Lowman, Paul; Mancinelli, Rocco; Mendell, Wendell; Stoker, Carol; Suess, Steven; (1989, June 30) Science Exploration Opportunities for Manned Missions to the Moon, Mars, Phobos, and an Asteroid, NASA Office of Exploration Doc. No. Z-1.3-001, JPL Publication 89-29, Washington DC: NASA Office of Exploration.
- Price, Larry R., (1975) Skylab Trash Airlock, 9th *Aerospace Mechanisms Symposium*, NASA TM X-3274, Washington DC: NASA Scientific and Technical Information Office, pp. 149-160.
- Rouen, Michael (1997) EVA Advanced Research and Development Road Map, SAE 972460, 27th International Conference on Environmental Systems, Lake Tahoe, NV, July 14-17, 1997, Warrendale, PA: Society of Automotive Engineers.
- Stoker, C.R.; McKay, C.P.; Haberle, R.M.; Anderson, D.T. (1992) "Science Strategy for Human

Exploration of Mars," *Advanced Space Research*, Vol. 12. No. 4, pp. (4)79-(4)90.

Stump, W. R., et. al. (1988) "Lunar Surface Transportation Systems Conceptual Design," *Lunar Base Systems Study Task 5.2.*, EEI Report 88-188, NASA Contract Number NAS9-17878, Houston TX: Eagle Engineering, Inc. pp. 78-83.

ter Haar, Ir. G. R. (1979) "Hatch Latch Mechanism for Spacelab Scientific Airlock," *12th Aerospace Mechanisms Symposium*, NASA CP-2080, Washington DC: NASA Scientific and Technical Information Office, pp. 89-100.

Trevino, Robert C. (1997) Antarctica Mars Analog Field Report EVA Engineer's Experience and Lessons Learned, SAE 972459, 27th International Conference on Environmental Systems, Lake Tahoe, NV, July 14-17, 1997, Warrendale, PA: Society of Automotive Engineers.

University of Maryland (1998?) MERLIN: Martian Exploratory Rover for Long-range Investigation, LPI Contribution No. 955, Houston TX: Lunar & Planetary Institute, pp. 201-222.

Van den Abeelen, Luc (1999, April) "The Persistent Dream - Soviet Plans for Manned Lunar Missions," *Journal of the British Interplanetary Society*, Vol. 52, No. 4, pp. 123-126.

Weaver, David B. & Duke Michael B. (1993) Mars Exploration Strategies: A Reference Program and Comparison of Alternative Architectures, AIAA 93-4212, AIAA Space Programs and Technologies Conference and Exhibit, Huntsville, AL, September 21-23, 1993, Reston VA: American Institute of Aeronautics and Astronautics.

Williams, M. D., De Young, R. J., Schuster, G. L., Choi, S. H., Dagle, J. E., Coomes, E. P., Antoniak, Z. I., Bamberger, J. A., Bates, J. M., Chiu, M. A., Dodge, R. E., and Wise, J. A., (1993, Nov.) Power Transmission by Laser Beam from Lunar-Synchronous Satellite, NASA TM 4496, pp. 19-20, Washington DC: National Aeronautics and Space Administration.

Woodcock, Gordon R.; Sherwood, Brent; Buddington, Patricia A.; Folsom, Rolfe; Koch, Robert; Wittaker, William "Red;" Bares, Lee Campeny; Akin, David L.; Carr, Gerald; Lousma, Jack; Schmitt, Harrison H. "Jack" (1990, January 2) Robotic Lunar Surface Operations, Boeing Report D 615-11901, NASA Contract No. NAS 2-12108, Huntsville AL: Boeing Aerospace & Electronics Company.

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ADDITIONAL SOURCES

Boeing Company (1964, March 1) LESA: Lunar Exploration Systems for Apollo, NASA CR-39.

Boeing Company (1964, December 16) LESA: Lunar Exploration Systems for Apollo -- Human Factors and Environmental Life Control Systems Study, NASA CR-60909.

Burkhalter, Bettye B., and Sharpe, Mitchell R. (1995) "Lunar Roving Vehicle: Historical Origins, Development and Deployment," Vol. 48, *Journal of the British Interplanetary Society*, pp.199-212.

Burnham, D. L. (1995) "Mobile Explorers and Beasts of Burden: A History of NASA's Prospector and Lunar Logistics Vehicle Projects," Vol. 48, *Journal of the British Interplanetary Society*, pp. 213-228.

Case, C., Capps, S., Ruff, T., McGhee, J., Roberson, R., (1992, August) "'Doorlock' Single-Crew Conformal Airlock for First Lunar Outpost Application," presentation by Boeing Advanced Civil Space Systems Group, Huntsville, AL.

Centre National D'Etudes Spatiales, CNES (1993) Missions, Technologies and Design of Planetary Mobile Vehicles, Toulouse, France: Cépaduès-Éditions.

Cohen, Marc M. (1987) Suitport Extravehicular Access Facility, U. S. Patent No. 4,842,224, June 27, 1989.

Covington, Clark (1985, October 15) "EVA/Airlock Medical Requirements," in JSC 31000, Houston TX: NASA-Johnson Space Center Systems Engineering Office.

Centre National D'Etudes Spatiales, CNES (1993) Missions, Technologies and Design of Planetary Mobile Vehicles, Toulouse, France: Cépaduès-Éditions.

Eagle Engineering (1987, December 1) Lunar Surface Operations Study, EEI Report #87-172, NASA

Contract Number NAS 9-17878, Houston TX: Eagle Engineering, Inc..

Fullerton, Richard K.; Tsygankov, Oleg S.; Yurzov, Nikolai; & Ibramov, Isaac P. (1997) U.S./Russian EVA Status, SAE 972455, 27th International Conference on Environmental Systems, Lake Tahoe, NV, July 14-17, 1997, Warrendale, PA: Society of Automotive Engineers.

Kohout, Lisa; Banyai, Mark; & Amick, Robert (1986) "Long Range Inhabited Surface Transportation system Power Source for the Exploration of Mars (Manned Mars Mission), *Manned Mars Missions*, Vol. 1, NASA M002, A Workshop at Marshall Space flight Center, Huntsville AL, June 10-14, 1985, Los Alamos, NM: Los Alamos National Laboratories. pp. 397-405.

Kozlov, I. A. & Shevchenko, V. V. (1995) "Mobile Lunar Base Project," *Journal of the British Interplanetary Society*, Vol. 48, pp. 49-54.

Lockheed Missiles and Space Company (1966, December) "Manned Roving Vehicle," MIMOSA Study, Doc. No. 2423, pp. 4-22.

Lockheed Missiles and Space Company (1967, April 30) MIMOSA: Mission Modes and System Analyses for Lunar Exploration, NASA CR-123832-1238335.

Marmolejo, Jose A. & Landis, Philip A. (1996) Servicing and Performance Checkout Equipment for the International Space Station Joint Airlock to Support Extravehicular Activity, SAE 961422, 26th International Conference on Environmental Systems, Monterey, CA, July 8-11, 1996, Warrendale, PA: Society of Automotive Engineers.

McDaniel, S. Gregg & Mulqueen, Jack (1986) "Manned Mars Mission Surface Transportation Elements," *Manned Mars Missions*, Vol. 1, NASA M002, A Workshop at Marshall Space flight Center, Huntsville AL, June 10-14, 1985, Los Alamos, NM: Los Alamos National Laboratories. pp. 437-444.

"NASA tests new suit design at equivalent of lunar gravity," (1994, April 25) Aviation Week & Space Technology, Vol. 140, No. 17, p 61.

Pieniasek, L. A. (1988, October) Planetary Surface Systems Elements Catalog, Houston TX: Lockheed Engineering & Sciences Company.

Shapland, David & Rycroft, Michael (1984) Spacelab: Research in Earth Orbit, New York NY: Cambridge University Press.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

ACM: Apollo Command Module

AL: Airlock on Skylab

AX-5: Ames Experimental Suit 5, an all-hard, high pressure suit.

BTV: Bulldozer Traverse Vehicle

DOE: U. S. Department of Energy

DRM: Design Reference Mission, or The Reference Mission of the NASA Mars Exploration Study Team, edited by Hoffman and Kaplan.

EMU: EVA Mobility Unit, the space suit developed for the Space Shuttle Program and being used on the ISS.

ESA: European Space Agency

EVA: Extravehicular Activity, to venture outside the pressurized crew cabin in a space suit.

GTV: Geological Traverse Vehicle

HEDS-UP: Human Exploration and Development of Space – University Projects

ISS: International Space Station

JEM: Japanese Experiment Module, laboratory on the International Space Station.

Kibo: Japanese name for JEM.

LESA: Lunar Exploration Systems for Apollo, study by Boeing in 1964-66.

LSTR: Lunar Surface Transportation Rover, Eagle Engineering, 1988.

MDA: Multiple docking adapter on Skylab, to which the ACM docked.

MIMOSA: Mission Modes and System Analyses for Lunar Exploration, study by Lockheed, 1966-67.

NASA: National Aeronautics and Space Administration

NASDA: National Space Development Agency of Japan

PLSS: Portable Life Support System, typically a back pack for a space suit

SPE: Solar Proton Event, radiation burst that occurs during a solar storm.