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Global Overview: Returned Astrobiology Sample Mission Architectures

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ABSTRACT

This paper presents a global overview of current, planned and proposed sample missions. At present, missions are in progress to return samples from asteroids, comets and the interstellar medium. More missions are planned to Mars and the asteroids. Future sample return missions include more targets including Europa, Mercury and Venus. This review identifies the need for developing a coordinated international system for the handling and safety certification of returned samples. Such a system will provide added assurance to the public that all the participants in this new exploration arena have thought through the technical challenges and reached agreement on how to proceed.

All these future returned sample missions hold relevance to the NASA Astrobiology program because of the potential to shed light on the origins of life, or even to return samples of biological interest. The possibility that samples returned from other bodies to the Earth may contain biotic material or living organisms raises many considerations for preventing forward contamination of the samples and back contamination of the Earth and its biosphere. Multiple space-faring nations propose to conduct sample return missions, and the issue is whether they will adhere to comparable standards for sample handling and biocontainment. The restrictions on such a sample return are quite stringent and require further research and development to make possible the safe receiving and handling of extraterrestrial samples

INTRODUCTION

During the 21st century, NASA and other space agencies will plan many extraterrestrial sample return missions. The goals will be to return samples from planets, moons, asteroids, comets and other bodies throughout the solar system and possibly beyond it. Most or all these sample return missions support the NASA Astrobiology Roadmap.

This paper starts from the recognition that the planetary protection considerations, procedures, reviews and approval processes for current and near term sample return missions -- while based upon some internationally agreed standards – are occurring mainly on a case-by-case basis. This basis includes two fundamental choices: unrestricted return or restricted return.

Unrestricted return refers to missions in which the space agencies deem the probability of finding biotic material to be negligible. The constraints upon an unrestricted return are relatively lenient, and concern mainly the ordinary safe and secure recovery of the spacecraft without any special biohazard protection.

Restricted return refers to missions in which the space agencies deem the probability of finding biotic material to be non-negligible, although perhaps still extremely small. In contrast, any mission that may return biotic material by definition shall be a restricted return. A restricted return would require extraordinary measures above and beyond those of an unrestricted return, including stringent protections against the possible release of any extraterrestrial biotic material and against the contamination of the spacecraft and the returned sample by earth biota. These restricted return protections must operate from the time the spacecraft lands through the transfer to a biosafety laboratory, and the safe handling of the returned samples in strict bioisolation until scientists determine that they are non-hazardous or sterilize them to ensure that they are non-hazardous.

However, this determination is shaped to a significant extent by the availability of appropriate sample receiving, quarantine and analysis facilities on Earth – known collectively as “Sample Handling Facilities.” NASA and perhaps all the space agencies need to develop and adopt a comprehensive, consistent and unified approach to receiving and handling these returned samples. Most particularly, NASA needs to develop an advanced Sample Receiving Facility in which to open Earth entry spacecraft, extract their payloads, and analyze them scientifically under the most rigorous quarantine conditions.

This top-down, analytical view of the Mission Architecture addresses challenges for NASA to receive, handle, process and evaluate Astrobiology samples on the Earth. NASA must hold Astrobiology samples returned from other planets and moons of biological potential in quarantine until an appropriately constituted Sample Science Team determines their biological character and safety. The safe analysis of these samples is a critical step in the development and progress of Astrobiology. This challenge, unique to NASA's needs, is how to contain the samples (to protect the biosphere) while simultaneously protecting their pristine nature for scientific studies. This analysis covers several mission architecture considerations for receiving, handling and analyzing these samples. The criteria in this design analysis include: location and types of facilities, transportation of samples or the Earth return vehicle, modes of manipulation; capability for destructive as well as non-destructive testing; avoidance of cross-contamination; sample storage and retrieval within a closed system.

THE RETURNED SAMPLE HANDLING CHALLENGE

This paper attempts a broad methodological approach to the general issues of handling and processing extraterrestrial samples once they are returned to the Earth. In this respect, it constitutes an expansion upon an earlier paper, Mission Architecture Considerations for Mars Returned Sample Handling (Cohen, 2002), in which the author went directly to some findings and observations that he considered self-evident. This paper presents more completely the chain of evidence and reasoning that laid the foundation for those conclusions.

THE IMPORTANCE OF SAMPLE RETURN

The analysis of extraterrestrial samples is well understood because of extensive work on meteorites (including ALH 84001). This work depends upon the ability to employ all the latest and most sensitive instruments in the analysis of samples – age dating, mineralogical analysis, isotopic analysis of noble gases, rare chemical species, organics analysis and, potentially, molecular biology. Presently, it is not yet feasible to miniaturize these instruments without compromising their analytical capabilities. Also, sample preparation requires direct human expertise, skill and manipulation and so is not a candidate to occur remotely on a robotic planetary mission in the foreseeable future. Furthermore, the necessary instruments may not yet exist to investigate certain specimens or prospective life forms. Sample preservation would allow pristine samples to be stored for analysis by instrumentation yet to be developed.

Because of these limitations, the only way to determine scientifically whether samples from extraterrestrial sources contain pre-biotic, biotic or "post-biotic" (e.g. fossil) signatures is to return them to the Earth for analysis by expert science teams in state of the art biological laboratories. The determination of the existence or non-existence of biota on other planets, such as Mars, is a vital precursor to preparing a safe human mission to explore them, and to returning that crew safely to the Earth.

BACKGROUND – THE APOLLO AND LUNA EXPERIENCE

Both NASA and the Soviet lunar programs returned samples from the Moon. The six Apollo landings spanned the period July 20, 1969 to 1972. The Apollo missions proved the scientific value of sample return – leading to exquisite scientific analyses. The Soviet Experience was also rich and productive, although the implications of their results are somewhat less clear.

<u>Apollo</u>—FIGURES 1 to 4 illustrate the sample collection and return aspects of the Apollo missions. The six Apollo missions returned 2196 individual samples of rock and soil weighing a total of 381.7 kg. (Allton, 1989). FIGURE 1 shows Apollo 11 astronaut Buzz Aldrin digging for lunar geological cores. The Principal Investigator was Eugene Shoemaker. FIGURE 2 shows the Apollo 11 Lunar Module "Eagle" which served as the first ascent stage for an extraterrestrial sample return. FIGURE 3 shows two men carrying one of the two Apollo 12 rock boxes from a transport plane. The official NASA caption states: "Peterson is with the Recovery Operations Branch, Landing and Recovery Divison, and Graves is with the Project Support Office, Preventive Medicine Division." The irony of this photograph is that these two were charged with medical precautions, but took none to protect themselves from potential contamination from the rock box. FIGURE 4 shows an Apollo 14 Sample Container (rock box), characterized by a gasket seal around the perimeter. In use, the seal proved vulnerable to fouling by lunar dust (Allton, IDEEA1, 1991), and also by the plastic bags used to sort samples, such as those to the right of the large dark rock. Different standards for planetary protection existed at the time of the Apollo missions than apply today. For an evaluation of how the Apollo sample returns would compare to current standards, please see the discussion under *Astronaut Protection*, below.

<u>Luna</u>—Luna 20 returned 30 grams and Luna 24 returned 170 grams of lunar material. However, it is not known what happened to the Soviet Luna samples or what back-contamination measures the Soviets took with their three Luna sample return missions from 1970 to 1976 (Luna 16, Luna 20, Luna 24). It is known that in the case of the Luna 20 mission, the Earth-return vehicle landed in Kazakhstan, where it took the Soviet team about 24 hours to locate it. FIGURE 5 shows a photograph of the Luna 20 reentry vehicle as the Soviet search team found it. This experience raises the question of means and methods of recovering the return sample after landing on Earth.

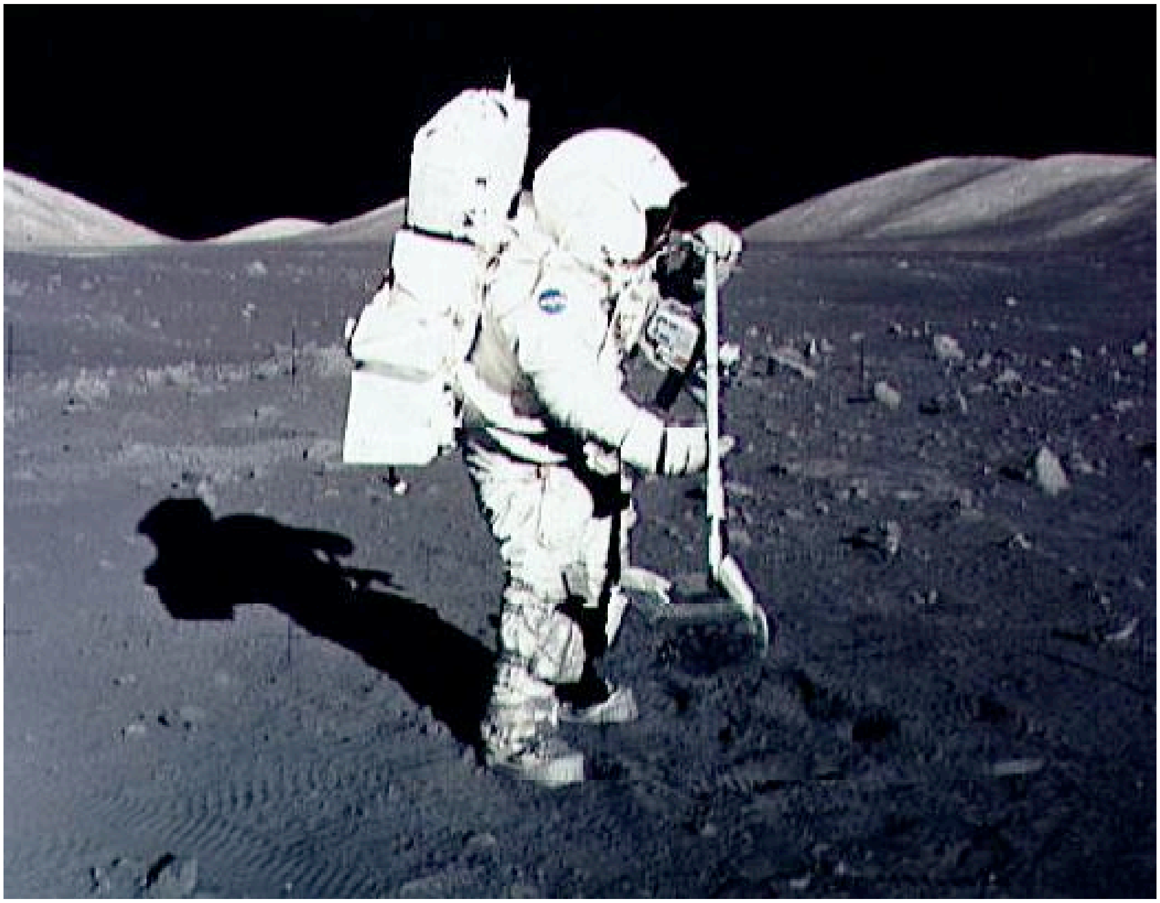

FIGURE 1. July 21, 1969. Buzz Aldrin digs for lunar geology cores. The Apollo 11 crew collected 21.6 kg of lunar surface materials, which they returned in two sample "rock boxes." NASA photo taken by Neil Armstrong.

FIGURE 6 shows a view of the Luna 24 spacecraft, the culmination of several cycles of sample return vehicle development. In this artist's rendering, the design of the Luna system becomes clear as a construction of low cost, conventional bolted-head pressure vessels that house each of the stages.

THE PLANETARY PROTECTION DOCUMENTS

Over the past decade NASA, the National Academy of Science, and other interested parties produced an impressive (and sometimes bewildering) array of reports, recommendations, workshop proceedings and proposed guidelines or standards. This section attempts to present a clear and, hopefully, not oversimplified summary of these documents insofar as they apply to returned sample handling mission architecture.

This analysis of the literature indicates that there are four loci of concern for planetary protection:

1. ***Forward Contamination from the Earth to another planet.***

2. ***Contamination of Extraterrestrial Samples by Terrestrial Organisms ("Round Trip Contamination" of Earth organisms on the spacecraft to the target body and back to Earth).***

3. ***Backward Contamination from another planet to the Earth, or to astronauts.***

4. ***Forward Contamination from the Earth to a returned sample after return of the mission to the Earth.***

FIGURE 2. Apollo 11 Lunar Module "Eagle" at Tranquility Base. The Eagle's ascent stage served as the first Lunar or planetary sample return ascent vehicle.

FIGURE 4. Apollo 14 Sample Return Container (rock box) with bagged and non-bagged samples.

FIGURE 3. November 25, 1969. David E. Peterson and Richard C. Graves carry one of two Apollo 12 rock boxes off a C-141 in Houston, on its way to the LSL. NASA PhotoS69-60229.

FIGURE 5. Luna 20 Sample Return Capsule, as it landed in the snow, February 27, 1972. It was found and recovered February 28. Soviet photo courtesy of NASA-GSFC, NSSDC ID:1972-007A.

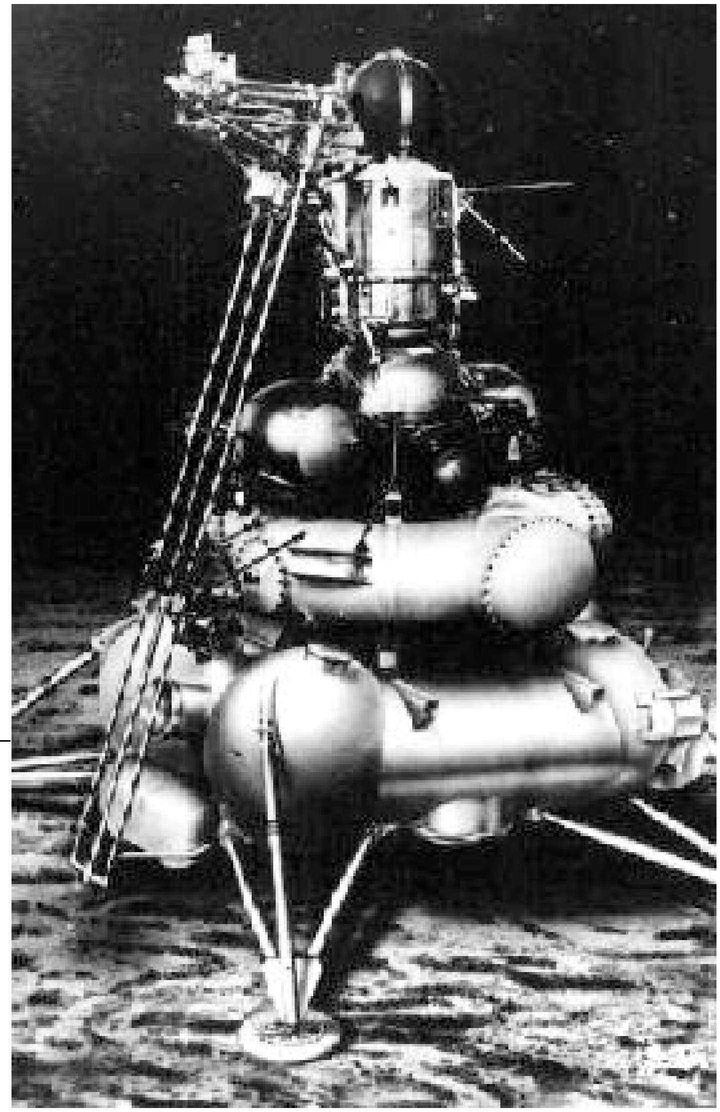

FIGURE 6. Luna 24 Lander on the surface at Mare Crisium, August 1976, Soviet Artist's rendering. The long diagonal linear object from the lower left to the top of the return capsule appears to be a screw-driven drill sample extraction and retrieval system. Courtesy of NASA-GSFC, NSSDC ID:1976-081A

FIGURE 7. Russian Mars '96 probe at NPO Lavochkin, Moscow. Courtesy of CNES. http://www.cnes.fr/qualite-espace/numero39/pages39/article8.htm, p. 7, accessed Sept. 19, 2002.

TABLE 1. COSPAR and NASA "Categories and Associated Restrictions That Apply to Solar System Exploration Missions" & NASA NPG 8020.12B (NASA, 1999, p. 4)

	CATEGORY I	CATEGORY II	CATEGORY III	CATEGORY IV	CATEGORY V
Type of Mission	Any but Earth return	Any but Earth return	No direct contact (flyby, orbiters)	Direct contact (landers, probes)	Earth return
Target Planet	Sun, Mercury, Pluto	Any except Mars, Sun, Mercury, Pluto	Mars	Mars	TBD
Degree of Concern	None	Documentation only	Passive bioload control	Active bioload control (more stringent for life detection mission)	Inbound Restricted Earth return: –No impact on Earth or the Moon –Sterilization of returned hardware –Containment of any sample
Represent-ative range of procedures	None	Documentation only	Documentation (more involved than category II)	Detailed documentation (substantially more involved than category III)	Outbound –Per category of target planet/ outbound mission *Inbound* Restricted Earth return: –All category IV –Continual monitoring of project activities –Preproject advanced studies/research –Possible sample containment ***Unrestricted Earth return***: None
NASA Planet Priorities from NPG 8020.12B	A. Not of direct interest for understanding the process of chemical evolution. No protection of such planets is warranted & no requirements are imposed.	B. Of significant interest relative to the process of chemical evolution but only a remote chance that contamination by spacecraft could jeopardize future exploration.	C. Of significant interest relative to the process of chemical evolution and/or the origin of life or for which scientific opinion provides a significant chance of contamination which could jeopardize a future biological experiment.		All. Any Solar System Body

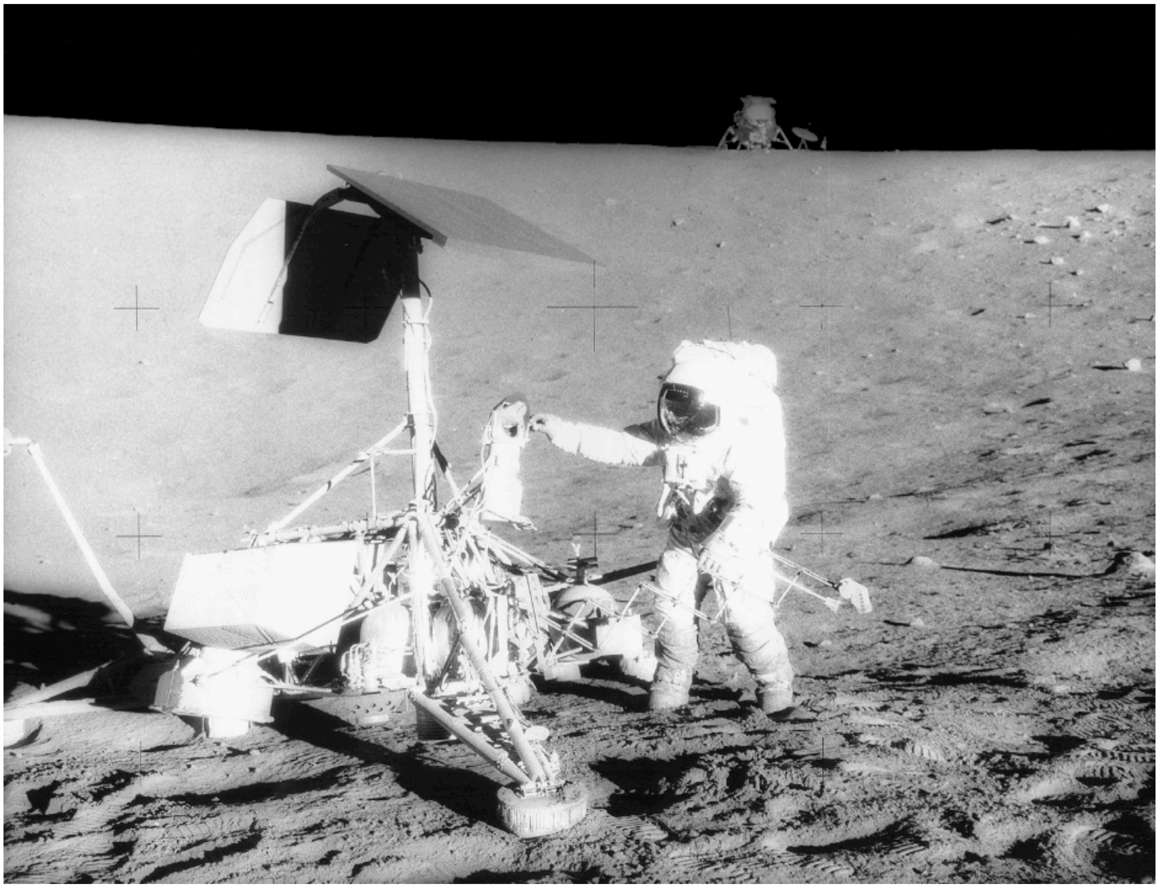

FIGURE 8. Pete Conrad reaches out to the Surveyor III camera that Alan Bean and he will remove and return with them to Earth via the Intrepid Lunar Module (LM) and the Yankee Clipper Command Module (CM). Intrepid appears in the background. NASA Photo AS-12-48-7133.

Note: Astronaut protection does not bear directly on planned sample return, but is notable within this discussion.

This section will correlate the applicable documents to each of these potential contamination points. For NASA, the controlling document is a NASA Policy Directive, "Biological Contamination for Outbound and Inbound Planetary Spacecraft," (Office of Space Science, Feb. 19, 1999) NPD 8020.7E, for both Forward Contamination to other planets and Backward Contamination to the Earth.

1. Forward Contamination—The controlling standards for preventing forward contamination are well in place. They are defined clearly under the NASA Procedures and Guidelines document "Planetary Protection Provisions for Robotic Extraterrestrial Missions." The Forward Contamination aspects of this NPG do not bear directly upon sample return missions, except insofar as the NPG refers to a standard for microbiological assay techniques to determine that a spacecraft carries no more than a specified bioburden upon departure from the Earth (Office of Space Science, NHB 5340.1B). FIGURE 7 shows the Russian Mars '96 probe in a clean room at NPO Lavochkin where it was subjected to strict measures against forward contamination by reducing the bioburden on the spacecraft.

The current "working goal" for the prevention of forward contamination of Mars is a reliability of 10^{-2} against release of earth organisms on Mars (MSR SSG, 2002, p. 13). This goal includes limits on the spacecraft bioload before launch, orbital lifetime requirements and probability of impact constraints (See NASA NPG 8020.12B).

2. "Round Trip Contamination"—Round trip contamination would occur when Earth organisms hitch a ride on the outbound spacecraft, and survive the entire mission, returning to Earth with the sample return payload. NASA experienced a unique and remarkable case of round trip contamination on the Surveyor III and Apollo 12 missions. The Surveyor III landed on the Moon in a location now named Surveyor crater.

The Apollo 12 mission in November 1969 performed the remarkable navigation feat of landing 156m from the robotic precursor, within easy EVA walking distance. One of the objectives for the Apollo mission was to retrieve the camera on Surveyor. FIGURE 8 shows Pete Conrad reaching out to the camera on Surveyor 3, with the Apollo 12 LM *Intrepid* in the background. Some years later, a culture of a 1cc polyurethane foam sample from the inside of the Surveyor III camera yielded bacterial growth, which the Centers for Disease Control in Atlanta identified as Streptococcus miti, a common harmless bacteria from the nose, mouth and throat in humans. FIGURE 9 shows the streptococcus miti culture from the Surveyor III camera foam, which now poses the classic example of round trip contamination. Such a possibility could invalidate any finding about the presence or absence of extraterrestrial biota in a returned sample. It also tends to confirm the early finding of the Scher-Packer-Sagan team that Earth microbes could survive in a hostile extraterrestrial environment. The Space Studies Board placed particular emphasis on preventing round trip contamination, discussing it first among the Technology Issues for Mars Sample Return (Space Studies Board, 1997, p. 9-1).

To prevent round trip contamination, the same standards apply as for preventing forward contamination. In addition, it is essential for the facility preparing the outward bound spacecraft to keep a careful and complete archive of microbiological assay samples from the spacecraft and witness plates from the clean-room in which the preparations occurred. If earth-like organisms are found in the returned vehicle or payload, one of the first steps to rule out false positives would be to compare those findings to the records of bioburdens on the witness plates and assays from the bioburden reduction process before the spacecraft was launched from Earth.

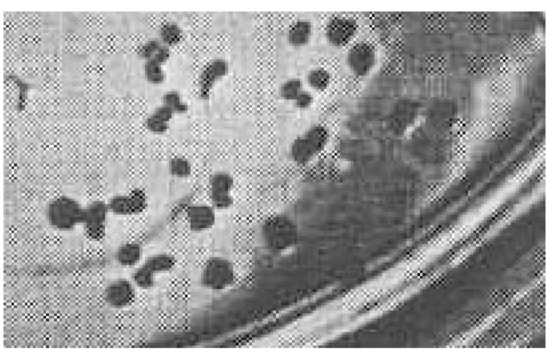

FIGURE 9. Culture plate from Surveyor 3 camera foam sample confirmed by the CDC as Streptococcus miti. http://science.nasa.gov/newhome/headlines/ast01sep98_1.htm accessed Sept. 10, 2002.

3. Backward Contamination—The NASA NPD and NPG both apply to preventing back contamination of the Earth. The NPG designates "Planet Priorities" that appear at the bottom of TABLE 1. Under this joint NASA/COSPAR construct, Earth-return missions (presumably regardless of whether the spacecraft is intentionally bearing scientific samples) from all "Solar System Bodies" are Category V missions; subject to strict review for biological potential. Under Category V, there are two degrees of "certification." Certification for "Unrestricted Earth Return" is possible only when there are no credible concerns for biological contamination, and there are "no further planetary protection requirements beyond those levied on the outboard phase of the mission" (Office of Space Science, April 16, 1999, p. 8). However, if an Earth-return mission does not qualify for the unrestricted certification, then it must comply with an extremely rigorous set of requirements to protect the Earth from back contamination, which the NPG specifies. The current working goal to prevent the backward contamination of the Earth is 10-6 reliability against release of extraterrestrial materials from biosafety containment (MSR SSG, 2000, p. 13).

As the following discussion of Unrestricted and Restricted Earth Return illustrates, any sample return to the Earth adds a significant degree of complexity and difficulty to the prospective planetary protection indicated in the NPD and NPG. What sample return to the Earth involves, at a minimum, are the following essentials:

1. Placing specimens into sealed containers on or near the planet or Solar System Body of origin;
2. Breaking the chain of contact with the planetary body
3. Maintaining the sample in pristine or near-pristine condition while returning it to the Earth,
4. Recovering the Earth Return Spacecraft;
5. Transporting the sample container with or without the Earth Return Spacecraft to a Sample Receiving Facility (SRF);
6. Opening the sample container in the SRF under the appropriate level of biocontainment.

Strict bioisolation of the samples would be mandatory, as the Space Studies Board argues:

> The requirements for strict containment should apply to all relevant mission activities starting with collection of materials and separation from the target body, through en route transport of the samples, and ultimately to continued quarantine

> on Earth at an appropriate receiving facility until comprehensive testing is completed. (Space Studies Board, 1998, p. 7-6).

Each of these six steps under stringent biocontainment or quarantine is worthy of many dissertations by themselves. This paper and its sequels address essentially the activity from Step 3 onward, with particular focus upon developing the Sample Receiving Facility and its quarantine capabilities.

4. Forward Contamination after Return to Earth

There are significant issues that continue for years after sample return. The Lunar Sample Laboratory at NASA-Johnson Space Center is designed largely to protect the existing lunar samples from potential contamination by Earth materials or microbes. It employs an air pressure gradient, with higher pressure inside the sample handling gloveboxes that tends to keep particulates and other contaminants from entering the glovebox.

An example of this concern manifested in the controversy over the ALH8401 Mars meteorite in the criticisms that any incidence of life could have occurred after the meteorite landed in Antarctica. In fact, an independent team found living organisms in an ALH8401 specimen. In their presentation to the First Astrobiology Science Conference at NASA-Ames Research Center in April 2000, A. Steele et. al, reported finding "the presence of a wealth of heterotrophic microbial species;" all of terrestrial origin (Steele, et. al., April 2000, p. 23). In their article in *Meteoritics and Planetary Science,* this same team stated:

> The detection of terrestrial organisms and their products in this meteorite do not necessarily negate the possibility that it contains evidence for early life on Mars. However, it becomes more challenging to separate such evidence from the terrestrial contamination (Steele, et al, 2000, p. 240).

From this example, it becomes evident that protection of samples throughout the return cycle is essential for preserving their scientific integrity and credibility. In some respects Forward Contamination after return to Earth may resemble "Round Trip Contamination" insofar as its discovery is likely only after return to Earth and because both pose the threat to validity of potential false positives for non-terrestrial life. However, the protection or returned samples against terrestrial contamination will require an on-going vigilance for years, encompassing all forms and modes of handling, transport and storage.

EARTH RETURN

The COSPAR category that attracts the most attention and concern is Category V, Earth Return. The two aspects of Earth Return – Unrestricted and Restricted – both merit extensive discussion as they have profound implications for all aspects of sample return.

CATEGORY V UNRESTRICTED EARTH RETURN

The first sample mission scheduled to return to the Earth is the NASA-JPL and Los Alamos National Lab Genesis Mission that will collect solar wind particles. The second mission to return -- even though it was launched more than 2 years before Genesis -- is the NASA-JPL STARDUST mission that will collect cometary and interstellar dust particles in an aero gel medium.

The international missions are of special interest for planetary protection because they comprise novel approaches that differ significantly from the NASA model. The Japanese MUSES-C spacecraft will fire projectiles at an asteroid and collect the ejecta. FIGURE 10 shows the MUSES-C spacecraft. The Russians announced a Phobos Sample Return (PSR) to land on Phobos to collect regolith and rock by as yet unannounced means. FIGURE 11 shows an artist's rendering of the proposed SCIM spacecraft, passing through the Mars upper atmosphere, collecting samples of Mars dust and atmosphere. It will use an aero gel collector similar to the one currently deployed on STARDUST. FIGURE 12 shows the aero gel collector in a clean room before integration onto the STARDUST spacecraft, which is similar to that proposed for SCIM.

Category V Unrestricted with a Proviso—The certification of an "Unrestricted Category V" Sample Return was precisely how the NASA Planetary Protection Advisory Committee (PPAC) evaluated the Japanese MUSES-C asteroid sample return to Woomera Prohibited Area in Australia (Noonan, 2002). The evaluation, based on the recommendations of the U.S. National Academy of Science's Space Studies Board (SSB) in its Report Evaluating the Biological Potential in Samples Returned from Planetary and Small Solar System Bodies: Framework for Decision Making (National Research Council, 1998), included the proviso that should new information warrant a change in the presumed nature of the target asteroid, the issue would be revisited. COSPAR, and the Australian government adopted the recommendations. The Australian Government Agency responsible for quarantine, mindful of the recommended proviso, included the following in its own recommendations [Many thanks to Perry Stabekis for patiently explaining these nuances]:

> ***Manner in which the proposed action is to be taken*** [original emphasis]

> ISAS will, prior to commitment to earth re-entry and in consultation with relevant internationally recognized experts, conduct a review of any new scientific data or opinion available (including data obtained during the MUSES-C mission to that point) in order to determine whether the mission should be reclassified to 'restricted Earth return' status. The Sample canister will not be returned to Australian territory if the weight of new scientific evidence or opinion is that 'restricted' status is warranted (Banks, Biosecurity Australia, June 2002, p. 13).

Presumably ISAS has an abort plan that avoids Earth entry, but it is not clear that there is an alternate plan in the highly unlikely event that the "the weight of new scientific evidence or opinion is that 'restricted' status is warranted." It is equally unlikely that the Russian Space Agency and Lavochkin have plans to receive or handle a potential biological sample from Phobos, and that they are, in effect, betting on an unrestricted Category V Earth Return mission. Such a bet is reasonable given present scientific understanding about the fundamental nature of biology, ***but it is still a bet.***

RESTRICTED CATEGORY V EARTH RETURN

Restricted Category V sample return represents the frontier of planetary protection and biocontainment. Each step in this sample return process demands extensive study, scrutiny and testing. The Returned Sample Mission Architecture begins, in a practical sense, when the sample returns to the Earth, at Step 3 i.e. the recovery of the Earth Return Spacecraft. The challenging part is to ensure, to a very high degree of reliability, the "near absolute containment" of the sample from the time it reaches the Earth until specific units of processed sample are certified for safe release from the SRF. The 2002 Draft Test Protocol (Rummel, Race, et al, 2002, October) outlines stringent constraints to prevent the unintended release of extraterrestrial sample material. Quantitative draft guidelines were proposed for the now-cancelled 2011 Mars Sample Return mission (cancelled in late 2001). The central requirement in these guidelines was the reliability of 1/1,000,000 (.999999) against the unintended release of extraterrestrial samples:

> The sample return canisters (here, the OS and any additional sealing materials provided within the Earth Entry Vehicle [EEV]) shall be sealed to an integrity, which for planning purposes should be such that the probability of releasing a ≥ 0.2 μm particle into the Earth's biosphere is $<10^{-6}$. The OS/EEV system should be able to maintain the required seal integrity under all nominal environmental conditions and under non-nominal operational conditions to the degree that the combined probability of inadvertent release into the Earth's biosphere is maintained at $<10^{-6}$. (John Rummel, June 14, 1999, letter to William O'Neil, Mars Sample Return Program, e-mail from John Rummel, NASA Planetary Protection Officer, April 13, 2003).

The Draft Test Protocol develops the NASA Planetary Protection Levels paradigm. The most demanding of these levels, Planetary Protection Level Alpha (PPL-□) incorporates several guidelines: bioisolation equivalent to the Centers for Disease Control's Biosafety Level 4 (BSL-4); two-way protection against forward contamination of the sample or back contamination from the returned sample to the earth; and uniquely, maintaining the sample in a pristine Mars-like atmosphere.

Astronaut Protection—A special case of protection against back contamination, and indeed of a potential Category V Restricted Return concerns astronauts on a Human Exploration Mission to Mars. Since the premise of any human space mission is to return the crew safely to the Earth, any human exploration mission to a Solar System body involves "sample return" because, as in the case of Apollo, the crew will bring quantities of Martian rocks with them and the ubiquitous Martian dust will pervade their spacecraft, spacesuits and persons.

During the first three Apollo missions that landed on the Moon, NASA took quarantine measures to isolate the crew from the general population in case they carried any infectious pathogens. At the completion of the Apollo 11 mission, the crewmembers donned bioisolation suits before exiting the CM to board a life raft. FIGURE 13 shows Buzz Aldrin, Neil Armstrong and Michael Collins and a Navy frogman in their bioisolation suits, awaiting helicopter pickup and transport to the U.S.S. Hornet. FIGURE 14 shows the Apollo 11 crew Buzz Aldrin, Neil Armstrong and Michael Collins being greeted by their wives on the tarmac upon arrival in Houston. It should be noted, however, that before and during the Apollo Program, the prevailing scientific opinion – and NASA's position – were that the Moon did not harbor any extant life. Indeed, under today's planetary protection standards, the Apollo missions would be certified as *Category V, Unrestricted Earth Return* (Pericles Stabekis, NASA HQ, phone conversation, April 23, 2003).

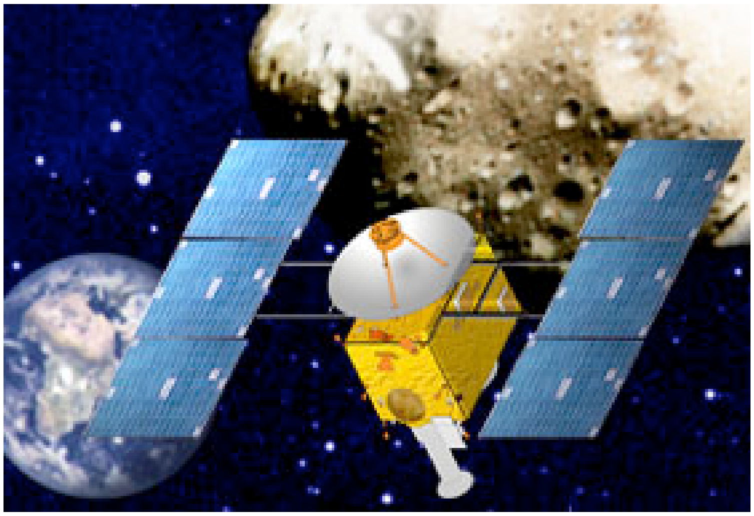

FIGURE 10. Japan's MUSES-C sample return spacecraft will fire a projectile at asteroid 1998 SF36 and collect the impact ejecta particles. It will return to Earth at Woomera, Australia. Image courtesy ISAS.
http://www.isas.ac.jp/e/enterp/missions/muses-c/index.html

FIGURE 11. Artist's rendering of the SCIM spacecraft passing through the Mars atmosphere, collecting atmospheric samples and dust particles. Courtesy of JPL.

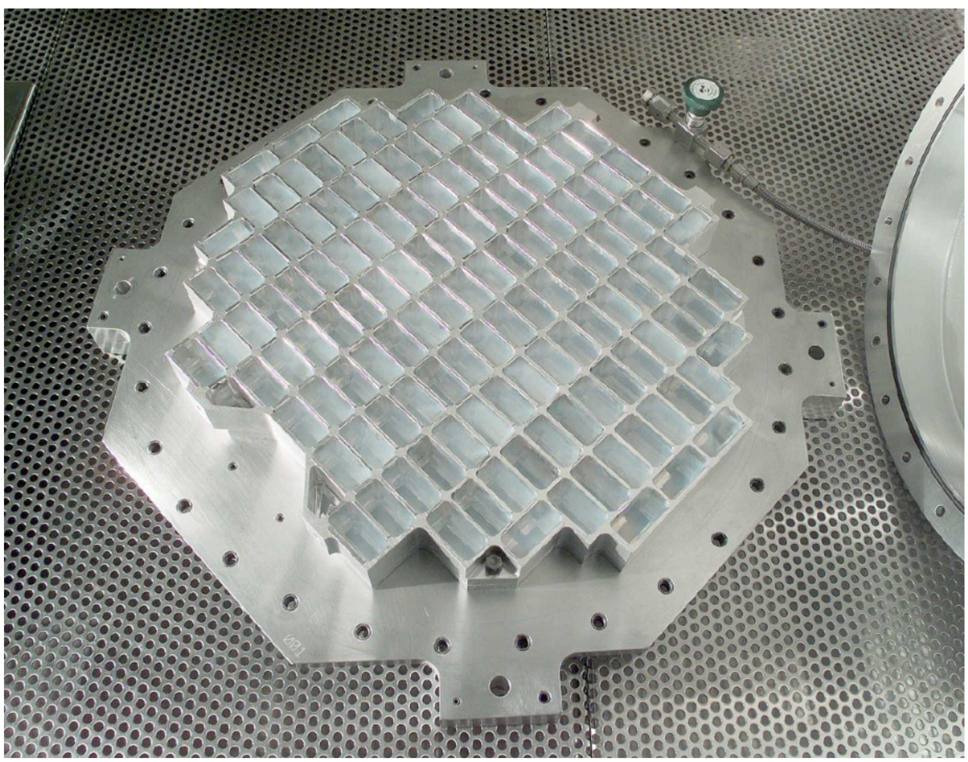

FIGURE 12. STARDUST Aero gel collector in the clean room. The rectangular cells contain the aero gel that will absorb the impact of dust particles and hold them in place. Courtesy of JPL.

FIGURE 13. July 24, 1969, Apollo 11, Columbia Splashdown, about 640 km SSW of Wake Island, about 1,300 km SW of Hawaii, and 24 km from the recovery ship USS Hornet, returning the 3 astronauts safely to Earth. (NASA photo ID S69-21698).

FIGURE14. July 27, 1969. Apollo 11 Astronauts in Mobile Quarantine Facility, greeted by their wives upon arrival at Ellington Air Force Base, Houston, TX. NASA Photo ID: S69-40147.

TABLE 2a. Non-Mars Surface Sample Return Missions.

Mission Name	Org.	Date of Launch	Target Body	Sample Sought	Nation	Landing Site	Return Date	Return Restriction	Status
STAR DUST	NASA -JPL	Feb. 6, 1999	Comet Wild-2	Cometary & Interstel-lar Particles	USA	UTAH UTTR	Jan. 2006	None	In Flight
Genesis	NASA -JPL-LANL	Aug. 8, 2001	Sun, from L1 Point	Solar Wind Particles	USA	UTTR	Aug. 2003	None	In Flight
MUSES-C	ISAS	Dec. 2002	Asteroid 1998 SF36	Impact ejecta particles	Japan	Woomera South Australia	June, 2007	None	In Launch Prep.
SCIM	NASA JPL-ASU	Aug. 2007	Mars	Atmos. Dust	USA	UTTR	2011	None	Scout Study
Phobos Sample Return	Lavo-chkin	2007	Phobos	Regolith, Rock	RUS	Russia, Range TBD	2010?	TBD	Plan & Testing
Comet Nucleus Sample Return	NASA LARC	TBD	Comet Brooks 2 Wirtem, Kopff or Tritton	Comet Frozen Core	USA	TBD	TBD	TBD	Study Phase

TABLE 2b. Proposed NASA ***Mars Surface*** Sample Return Missions.

Mission Name	Org.	Date of Launch	Target Body	Sample Sought	Nation	Landing Site	Landing Date	Planet Protection Restriction
Mars Sample Return	Ball / NASA	2011 or later	Mars	Regolith, Rocks, Cores	USA	HEEO Quaran-tine, then STS or ISS Rendezvous or Stardust Type EEV to UTTR	2014 or later	Required
Mars Sample Return	Boeing / NASA	2011 or later	Mars	Regolith, Rocks, Cores	USA	STS Rendezvous	2014 or later	Required
Mars Sample Return	Lock-heed Martin / NASA	2011 or later	Mars	Regolith, Rocks, Cores	USA	UTTR, mid-air capture of parachute entry vehicle	2014 or later	Required
Mars Sample Return	TRW/ NASA	2011 or later	Mars	Regolith, Rocks, Cores	USA	UTTR preferred, Alternate water landing at Kwajalain	2014 or later	Required

Samples returned from Mars trigger the rigorous protections of a restricted Earth return. However, except for the short-lived quarantine precedent of the Apollo program, there is no specific standard for protecting astronauts from the Mars environment. Evidently, the assumption is that we will have been able to conclude on the basis of robotic missions that Mars is free of life or that any such life is benign. The SSB recommended that piloted missions to Mars should wait until such a determination can be made. Given the difficulty of proving a negative, this assumption gives cause for reflection as to whether this approach is satisfactory or reasonable. Recently, NASA has initiated a long-term effort to develop the Planetary Protection requirements for human missions to Mars.

MISSION ARCHITECTURE

For the purpose of this discussion, the Mission Architecture approach to design 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 (Cohen, 2000, p. 3). The Returned Astrobiology Sample Handling Mission Architecture (Architecture with a "Big A") encompasses everything that happens to the returned sample from the time that it enters the Earth's atmosphere in a return entry vehicle. It includes landing, retrieval, transport to sample receiving facility, cleaning of the vehicle, opening the sample canister, inspection, analysis, testing, assaying, possible sterilization and release of the sample to the scientific community. The facility architecture (architecture with a "small a") addresses the design of specific ground-based facilities: the Sample Handling Testbed, Sample Receiving Facility, Mars Curation Facility, and Science Support System associated with those facilities. At this time there are no less than nine sample return missions in progress or concepts in preparation. Almost all of these missions and the many more that will follow support the goals and objectives of the original NASA Astrobiology Road Map (see http://astrobiology.arc.nasa.gov/roadmap/). Each returned sample may contain a small or large piece of the puzzle that these three questions comprise:

How does life begin and develop?

Does life exist elsewhere in the universe?

What is life's future on Earth and beyond?

The *original* Astrobiology Roadmap incorporates 17 specific objectives, a number of which sample return can help to address. ***Planetary Protection***, Objective 17 applies to all sample return missions. TABLE 2a presents a brief summary of the currently operating or planned non-Martian sample return. TABLE 2b presents four Mars Sample Return missions listed representing proposals from four different offerors. NASA will select one mission concept when the time (and funding) comes.

The current thinking about planetary protection against the "back contamination" of the Earth is that Mars Sample Return will need to work to goals on the order of 10^{-6} reliability against the release of extraterrestrial materials from biosafety containment (MSR SSG, 2002, p. 13). While this goal has yet to be formalized as a programmatic "requirement," it is the baseline for many of the mission studies cited in this essay, and a major driver of mission cost, complexity and difficulty. ***A challenge, unique to the needs of sample return mission managers, is how to contain the samples (to protect the biosphere) while simultaneously protecting their pristine nature for scientific studies.***

A "tall pole" in any schedule to return potential biotic samples is the lack of capable Sample Receiving and Quarantine Facility in the United States or elsewhere in the world. There are a number of Biosafety Laboratories built and operated on the Centers for Disease Control Biosafety Level paradigm. However, these labs constitute a technology designed to meet different requirements from those of receiving and handling extraterrestrial samples of unknown biologic potential.

GLOBAL GEOGRAPHIC CONSIDERATIONS

It is essential to understand the geographic considerations of sample return missions, current and future, in order to grasp the challenge of an integrated or unified Returned Astrobiology Sample Mission Architecture. Since Sample Return promises to be the next great step in space exploration, there are already multiple countries and space organizations that wish to participate. In an era of constrained budgets for human spaceflight, sample return may prove to be "the next best thing to being there."

However, the prospect of rapidly proliferating unique or "one of a kind" sample return missions bringing back specimens from an array of objects through out the Solar System raises serious issues for effective planetary protection. How are the space agencies of the space-faring nations to assure a sufficient degree of compliance with the more stringent protocols? TABLE 2a describes the menu of currently active missions, and those under active consideration or study. Table 2b describes the four proposals to NASA for a Mars surface sample return mission.

The first sample mission scheduled to return to the Earth, GENESIS, will land at the Utah Test and Training

Range, about 200 miles SW of Salt Lake City. The second mission to return, even though it was launched more than 2 years before Genesis, is STARDUST, also landing at UTTR.

The international missions are of special interest for planetary protection because they comprise novel approaches that differ significantly from the NASA model. The two well-known international sample return missions at this time are Japan's MUSES-C and Russia's Phobos mission.

Western Hemisphere—FIGURE 15a provides a view of the Western Hemisphere showing the key research and project center, launch, sample return and potential handling locations for missions planned by NASA and its French partner, CNES. NASA launched the Stardust and Genesis missions from Kennedy Space Center and their sample-containing re-entry capsules will return to the Utah Test and Training Range (UTTR) as the designated landing area. NASA has determined that quarantine is not required for either Stardust or Genesis as both are collecting only free particles in deep space. The French Centre National d'Etudes Spatiales (CNES) has signed a partnership agreement with NASA for planetary protection studies for Mars Sample Return. While much remains to be decided about this mission, NASA may wish to use the UTTR as it plans to do for Stardust and Genesis. Fasanello, et al argue the case in favor of impact landing an MSR Earth Entry Vehicle on the soft clay of UTTR (Fasanello, et. al, 2002, p. 242), but alternative landing locations are possible. The one notable alternative location is the TRW alternate water-landing site at Kwajalein Missile Range in the Pacific Ocean.

Eastern Hemisphere—FIGURE 15b shows the sample return mission geography in the Eastern Hemisphere. ISAS will launch asteroid sample return mission MUSES-C from Kagoshima and, in its nominal plan, the sample containing capsule will return to Australia's Woomera Prohibited Area, where it will be subject to quarantine controlled by the Australian government (Banks, 2002, Biosecurity Australia) The Biosecurity Australia plan is to place the MUSES-C sample container and associated spacecraft equipment in a larger bioisolation container, and then export it immediately back to Japan, where the ISAS will open it in its curation laboratory at Sagamihara near Tokyo. There, the responsibility will belong to ISAS to analyze the samples and not release them until the samples are certified as free from potentially harmful organisms or other materials.

Landing Site Location—The proposed landing sites for sample return missions encompass a wide range of opportunities. Like the Luna missions and unlike the Apollo missions, almost all the proposed return landing sites are on land, in relatively isolated and desolate areas. The selection of landing sites for sample return encompasses important criteria. Generally, it is in a restricted area, on the property of a national or federal government agency, to which it is possible to limit physical access to the search and retrieval team. The landscape should lend itself to searching for the return vehicle and finding it easily, which means availability of an airfield and terrain that is dry and, ideally, not covered by forests or deep snow. It is vital that the longitudinal vector of the landing ellipse not align with any populated area for a considerable distance (measured in at least hundreds of kilometers) on either end of the entry and landing trajectory. It is not a given that the landing site should be proximate to the Sample Receiving Facility, although such proximity may confer convenience and other benefits.

The Russian Space Agency's (RSA) has been studying a Phobos sample return mission (Eismont, Sukhanov, 1997). Their contractor, NPO Lavochkin, announced plans to launch a Phobos Sample Return Mission, presumably from Baikonur in Kazakhstan (Byelo, 2002). Lavochkin has stated that it will land the returned the returned sample "on the territory of Russia" (Kulikov, et al, 2001, abstract). Although NPO Lavochkin has clean rooms and procedures in place to prevent forward contamination, so far, apparently there has been no information available from RSA or NPO Lavochkin about backward planetary protection, quarantine requirements or other sample return biosafety considerations.

Sample Receiving Facility Location—The sites for the Sample Receiving facility are equally important. The Space Studies Board's COMPLEX team recommends affiliating the Sample Receiving Facility and Quarantine capability with an existing Biosafety Level 4 facility (BSL-4). COMPLEX specifically mentions BSL-4 sites at the Centers for Disease Control (CDC), in Atlanta, GA, the US Army Biomedical Lab in Ft. Detrick, MD, or the University of Texas Medical Branch (UTMB) in Galveston, TX (COMPLEX, 2002, pp. 3, 56).

NASA-JSC commissioned a study by the architecture firm B2HK-Smith Carter and engineering firm CCRD Partners (2000, p. 2.1) for the design of a new Mars Sample Receiving Facility (SRF) at the NASA White Sands Test Facility (WSTF) in White Sands, NM. The White Sands concept would be "stand-alone" in the sense that it would not be connected to a BSL-4 institution.

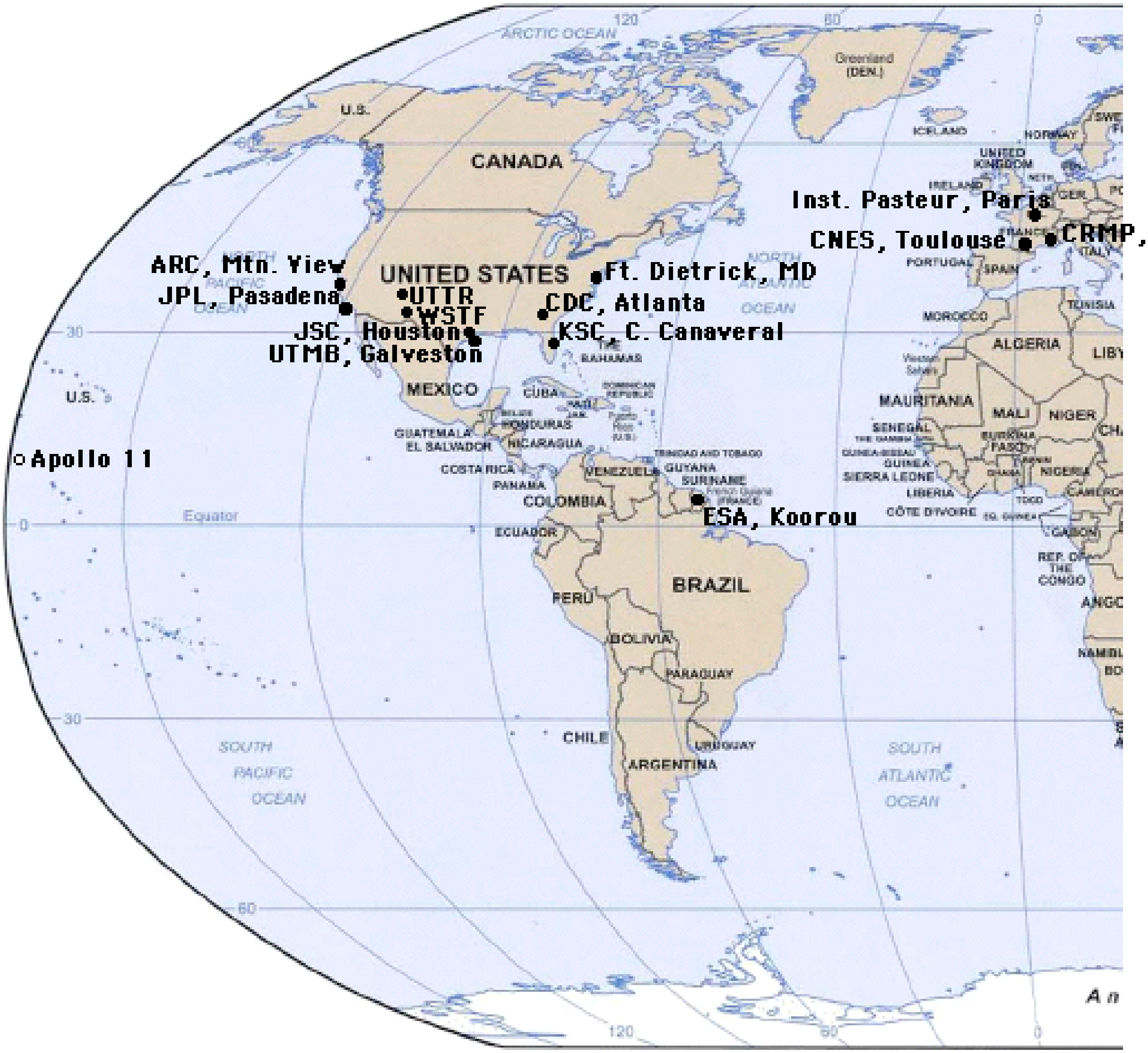

FIGURE 15a. View of the Western Hemisphere showing the key research and project center, launch, sample return and potential handling locations for NASA sample return missions.

FIGURE 15b. This view of the Eastern Hemisphere shows the geography of two sample return missions: the Japanese Institute for Space and Astronautical Science's MUSES-C Asteroid Sample Return Mission and the Russian NPO Lavochkin's Phobos Sample Return Mission. It also shows the TRW water landing back-up option at Kwajalein.

FOUR MARS SAMPLE RETURN MISSION ARCHITECTURES

Mars may not be the only extraterrestrial site from which returned samples should give us pause (the deep Europa ocean and the clouds of Venus are extreme environments where the case has been made that micro-organisms might flourish). Nevertheless, as regards planetary protection concerns, our principal attention in the near term surely must be paid to our outer neighbor. In 2001, NASA let four contracts with aerospace contractors to develop conceptual mission architectures for Mars Sample Return: Ball Aerospace, Boeing, Lockheed Martin, and TRW (Ball, 2001; Boeing, 2001; Lockheed Martin, 2001; TRW, 2001). FIGURE 16 presents a generic NASA concept for a Mars Sample Return vehicle ensemble on the Mars Surface. The basic parameters of these four proposals are summarized in TABLE 2b, based on an earliest launch date in 2011. Together they add a considerable expansion of the Returned Sample geography. For example, the Boeing proposal calls for a Space Shuttle rendezvous with the MSR Earth-return vehicle, and the Shuttle to reenter the Earth's atmosphere carrying this interplanetary spacecraft. As the most frequent and preferred landing facility for the Shuttle, NASA's Kennedy Space Center (KSC) appears both as a launch site and a landing site in FIGURE 15a. An additional option arises where TRW prefers a landing at the UTTR, but proposes an alternate concept for a water landing at the Kwajalein Missile Range in the U.S. Marshall Islands, FIGURE 15b.

All four of the contractor studies mention recovering the returned sample payload and transporting it safely to a bioisolation laboratory, but they offer little detail about this aspect of the mission. The one intriguing departure appears in the Ball Aerospace report that calls for placing the Earth Entry Return Vehicle into a High Earth Elliptical Orbit, parking it there safely for twenty to thirty years if necessary, until all planetary protection issues can be resolved on Earth. The reason for this HEEO precaution is Ball's explicit skepticism that NASA will prepare a properly certified Sample Receiving Facility that meets either the 10^{-6} reliability requirement in time for the sample return.

REVIEW SUMMARY

This review indicates that the world's Space Science community is on the verge of a "Golden Era of Sample Return." Many countries and agencies are now planning to send spacecraft to other bodies and returning samples that could contain biota. Robotic spacecraft are becoming increasingly affordable to more countries. In twenty years, a dozen or more nations may join in the great Solar System exploration of the 21st century. Many of these missions will seek to return samples from small bodies and planets as a point of national pride and prestige. European, Japanese, Russian, and US aerospace companies will likely be happy to sell their flight-tested hardware at increasingly affordable prices.

This review indicates that few countries appear to be preparing seriously for all the potential contingencies of sample return, especially for the possibility of returning biotic material. The Japanese-Australian arrangement seems to be that if there is any reason to believe the MUSES-C sample may have biotic content, then they will simply abort the mission and not return the vehicle to Earth, a profoundly unsatisfactory scenario for astrobiologists. Such a self-defeating approach is caused by the lack of a safe biocontainment landing system, and of needed quarantine and sample receiving facilities.

In the meanwhile, other organizations have taken the lead on planetary protection for sample return in significant ways. The National Academy of Science has undertaken three important studies at the behest of NASA concerning sample return. These studies provide recommendations to NASA that the Agency generally adopts and uses as guidelines in developing planetary protection specifications for flight projects. Two other countries, Japan and Russia, plan to return solid samples from solar system bodies before NASA undertakes the long-awaited Mars Sample Return mission.

This review identifies the need for developing a coordinated international system for the handling and safety certification of returned samples. Such a system will provide added assurance to the public that all the participants in this new exploration arena have thought through the technical challenges and reached agreement on how to proceed.

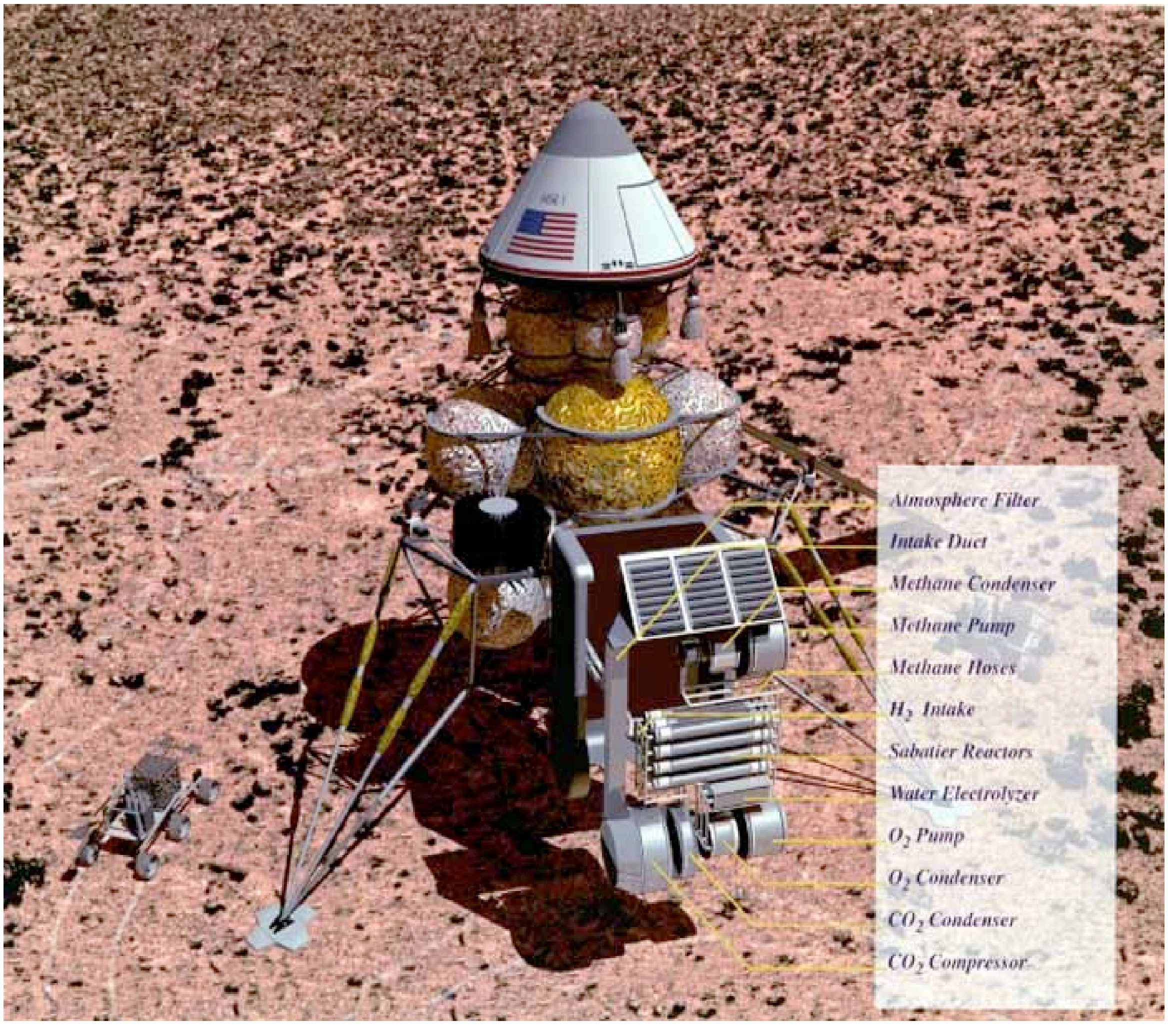

FIGURE 16. Generic conceptual model of a Mars Sample Return Ascent Vehicle, that would generate its own ISRU fuel and carry the payload of .5 kg of Mars samples in the conical capsule on top. Courtesy of NASA.

CONCLUSION

This Returned Astrobiology Sample Handling Mission Architecture will begin with systems for returning samples to the Earth by internationally agreed means to internationally agreed locations. Once landed, Returned Sample Handling Architecture would include recovering the sample entry vehicle, transporting the sample payload to a sample receiving and quarantine facility, and once it arrives, opening it and extracting the samples under strict PPL-alpha conditions. Developing this coordinated international Returned Astrobiology Sample Handling Mission Architecture will offer a challenge and an opportunity for international cooperation among the space-faring nations, and will help to ensure the safe and accountable handling of all samples returned to the Earth. To achieve this goal, NASA and its international partners will need to marshal a comprehensive program of technology development, testing and integration to prepare responsibly for potential biologic sample return.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ARC: NASA Ames Research Center, Moffett Field, CA

Back contamination: biological contamination of Earth as a result of samples returned from solar system bodies

BSL: Biosafety Level (Centers for Disease Control, 1993)

BSL-4 — is used for the diagnosis of exotic agents that pose a high risk of life-threatening disease, which may be transmitted by the aerosol route and for which there is no vaccine or therapy.

BSL-3 — Applies to agents that may be transmitted by the respiratory route, which can cause serious infection.

BSL-2 — is appropriate for agents that can cause human disease, but whose potential for transmission is limited.

BSL-1 — applies to agents that do not ordinarily cause human disease.

CDC: Centers for Disease Control and Prevention, Atlanta, GA

CMEX: Center for Mars Exploration at NASA-Ames Research Center

CNES: Centre National d'Etudes Spatiales, France, the principal French space agency.

Containment: physical and biological isolation and handling of returned samples as specified for samples returned from particular Solar System bodies.

COSPAR: Committee on Space Research of the International Council of Scientific Unions

NASA CP: NASA Conference Proceeding

CRMP: Centre de Recherche Mérieux-Pasteur (CRMP) in Lyon, France, operated by the Institut Pasteur.

ΔP: "Delta P" — pressure differential between to atmospheres.

DFRC: NASA Dryden Flight Research Center (DFRC) at Edwards Air Force Base, Lancaster, CA.

Forward contamination: biological contamination of a solar system body from a sample return mission or other "contact" mission.

HEEO: High Earth Elliptical Orbit, proposed by Ball Aerospace as an interim quarantine orbit

IAF: International Astronautical Federation

ICES: International Conference on Environmental Systems

ISAS: Institute of Space and Astronautical Science, Japan, lead on the MUSES-C asteroid sample return mission.

ISS: International Space Station

IVS: Institut de Veille Sanitaire: French Public Health organization, with nine regional epidemiological centers.

JPL: NASA Jet Propulsion Laboratory, Pasadena, CA

JSC: NASA Johnson Space Center, Houston, TX

LRS: Landing Retrieval System

LSL: Lunar Sample Lab at NASA Johnson Space Center

MCF: Mars Curation Facility

MQF: Mobile Quarantine Facility, used during the first three Apollo missions that landed on the Moon to provide isolation for the three returned crew members.

MRSH: Mars Returned Sample Handling

MSR: Mars Sample Return Program

MSR SSG: Mars Sample Return Science Steering Group, commissioned by the NASA Office of Space Science.

MUSES-C: Mu Space Engineering Spacecraft, for asteroid sample return mission lead by ISAS, Japan.

NPO Lavochkin: Russian Aeronautical and Space Company, headquartered in Moscow.

PI: Principal Investigator

PPL: Planetary Protection Level, [Office of Planetary Protection.(DRAFT,2001, May 31). A Draft Test Protocol for Detecting Possible Biohazards in Martian Samples Returned to Earth, Washington DC: NASA.]

PPL-□ — for incoming samples and archived samples; maximum biocontainment and cleanliness; maintains an inert gas environment.

PPL-□ — maintains maximum biocontainment and protection for workers and the environment; maximum cleanliness, but allows exposure to ambient terrestrial conditions.

PPL-□— maintains maximum biocontainment with moderate cleanliness and ambient terrestrial conditions (i.e.., for animal testing scenarios).

PPL-□—maintains “BSL-3-Agriculture” containment conditions, with less emphasis on cleanliness, and ambient terrestrial conditions.

PPO: Planetary Protection Office at NASA HQ.

Regolith: Lunar, planetary or asteroid surface material. Regolith is the term preferred to “soil” because soil implies that a biological or organic process was involved in creating it.

PSR: Phobos Sample Return Mission, proposed by NPO Lavochkin

RSA: Russian Space Agency

SAE: Society of Automotive Engineers, Warrendale, PA

SETI: Search for Extraterrestrial Intelligence Institute, Mountain View, CA

SSB: Space Studies Board

SScS: Sample Science System

SRF: Sample Receiving Facility

STS: Space Transportation System, the NASA Space Shuttle

TBD: To be determined.

UN: United Nations

UTMB: University of Texas Medical Branch, Galveston, TX

WSTF: NASA White Sands Test Facility, White Sands, NM