The Evolution of an Orbiting Sample Container for Potential Mars Sample Return

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Abstract— **Although NASA has no specific plans at this time to return samples from Mars, the Program Formulation Office of the Mars Exploration Program sponsors ongoing mission concept studies, systems analyses, and technology investments which explore different strategies for the potential return of samples from Mars, consistent with the charter of the program and stated priorities of the science community. A critical component of such a campaign would be an Orbiting Sample container (OS), which would contain the Mars samples to be returned to Earth.**

This paper discusses the most recent efforts by the JPL's Mars Formulation Office to mature an OS design planned for use on a potential Mars Sample Return (MSR) mission. Similar to the "Decadal Study Architecture" [1], the current MSR architecture envisions as a three-mission campaign with each mission serving a critical role towards returning Martian rock and atmospheric samples back to Earth.

An OS would be a central piece of hardware in the proposed MSR architecture due to its interfaces to all the three missions of the potential campaign. Additionally, numerous stakeholders and subsystems such as science and planetary protection impose challenging requirements on the OS's functions and capabilities. As a result, designing an OS that meets all the requirements is challenging and quite complex.

The story of the OS's evolution from black box concept thru to the current-and-still-maturing baseline design is the focus of this paper. From the OS's launch off Earth aboard a Sample Retrieval Lander (SRL) through to return to Earth, the design and functional requirements generated by and for each stage of the OS's mission are discussed. Then, with an understanding of what the OS would be required to do, a mapping of the main requirements to the design features of the current OS concept is explained. Many tests and analyses have been conducted to support and validate the current OS design. Results from test and analysis in the areas of aerothermal, impact dynamics, optical tracking, and radio electromagnetics are presented.

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1. INTRODUCTION

The scientific community has advocated for the return of Mars samples for several decades. The 2011 planetary science "Decadal Survey" [1] by the National Academy of Sciences emphasized the high priority of making progress on this task in the subsequent decade. Due to a series of successful Mars exploratory missions, the space exploration community, including NASA, ESA, and other agencies, have become increasingly interested in returning geological and atmospheric samples from Mars. Additionally, the successful demonstration of several technically difficult planetary exploration missions such as Mars Science Laboratory (MSL), Rosetta, and others have raised the confidence within the space community that such a complex effort is feasible. The currently notional MSR campaign is bringing the space science and exploration communities closer to the MSR goals articulated by the "Decadal Survey." Now with the Mars 2020 mission currently approaching CDR, it appears the first step in this process—collecting well-selected samples for possible return—is approaching reality.

2. MSR CAMPAIGN OVERVIEW

The scope of the scientific investigation of Mars has thus far been limited by what instruments can be brought into orbit around Mars or delivered to the Martian surface. Due to the practical engineering constraints of planetary missions, these in situ instruments have been by necessity compact, low mass, and low power. The great value of returning samples from the surface of Mars to Earth is that the full capacity of a global network of science laboratories could be utilized in conducting investigations on the returned samples, allowing for discoveries that are simply not practical under the limitations of in situ instruments. Furthermore, many previous sample return missions such as Genesis, Stardust, and Japanese Hayabusa missions have firmly demonstrated the scientific advantage of bringing samples back to Earth,

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where they can be examined with advanced scientific equipment and preserved for future study.

Returning samples from the surface of Mars is a complex undertaking. The current notional MSR architecture follows closely the recommendations of the “Decadal Survey” [1] and distributes the complexity and functions of the potential MSR campaign over three individual mission concepts and a ground facility, as shown in Fig. 1:

(1) The first mission in the series is Mars 2020, which is a NASA rover under development and planned for a launch in 2020. Mars 2020 will extract rock core samples from the surface of Mars, store them in hermetically sealed tubes, and then deposit the sealed tubes on the Mars surface for possible later collection and return to Earth.

(2) The potential second mission, called a Sample Return Lander (SRL), would collect the Mars 2020 tubes or those from a subsequent mission, secure the tubes in the OS, collect atmospheric in-situ samples into the OS, and then launch the OS into Mars orbit on an attached launch vehicle called the Mars Ascent Vehicle (MAV).

(3) In the “Decadal Survey” architecture, a potential third mission called Sample Return Orbiter (SRO) would capture the OS on orbit around Mars and deliver it to Earth for entry, decent, and a parachute-less soft soil impact landing. Ongoing studies may split the SRO functions into more than one orbiter. One possible scenario is to launch a first orbiter as early as in 2022 or 2024 to perform the OS rendezvous and capture. Potential subsequent mission(s) would then bring the OS to the Earth-Moon system and deliver it to Earth for scientific analysis.

(4) The fourth element of MSR would be a Mars Returned Sample Handling (MRSH) Facility on Earth, which would store and quarantine the landed samples, insure their safety and preservation, and provide the infrastructure for sample distribution and scientific analysis.

Of these four MSR elements, only the Mars 2020 mission has been approved and funded at this time. Although the SRL, SRO, and MRSH mission concepts and facilities have not yet been approved or funded, the Mars 2020 hardware must be basically compatible with SRL, SRO, and MRSH missions if the Mars 2020 mission is to serve as the start of the MSR campaign.

The most obvious example of how SRL and SRO impose requirements on Mars 2020 hardware is the impact accelerations anticipated during Earth return. It is currently assumed that a SRO would place the OS into an Earth Entry Vehicle (EEV) that would be subsequently ejected from SRO into Earth’s atmosphere. Due to statistical concerns with reliability, the EEV would not have a parachute, and the EEV would hit the playa of the landing site—notionally the Utah Test and Targeting Range (UTTR)—at a terminal velocity of approximately 50 m/s or less. The compliance of the playa and the energy absorbing materials inside the EEV would limit the acceleration on the OS to approximately 1300 g or less. Because the Mars 2020 sample tubes and rock cores would be inside the OS during this event, those items would also be exposed to this acceleration environment and must preserve the scientific integrity of the Martian samples. In addition, the mechanical interface between the Mars 2020 tubes and a SRL OS must be capable of withstanding the loads associated with these accelerations. The details of the mechanical interface between the Mars 2020 tubes and a SRL OS must also be fully defined in the present in order for the Mars 2020 tubes to incorporate the required features. These

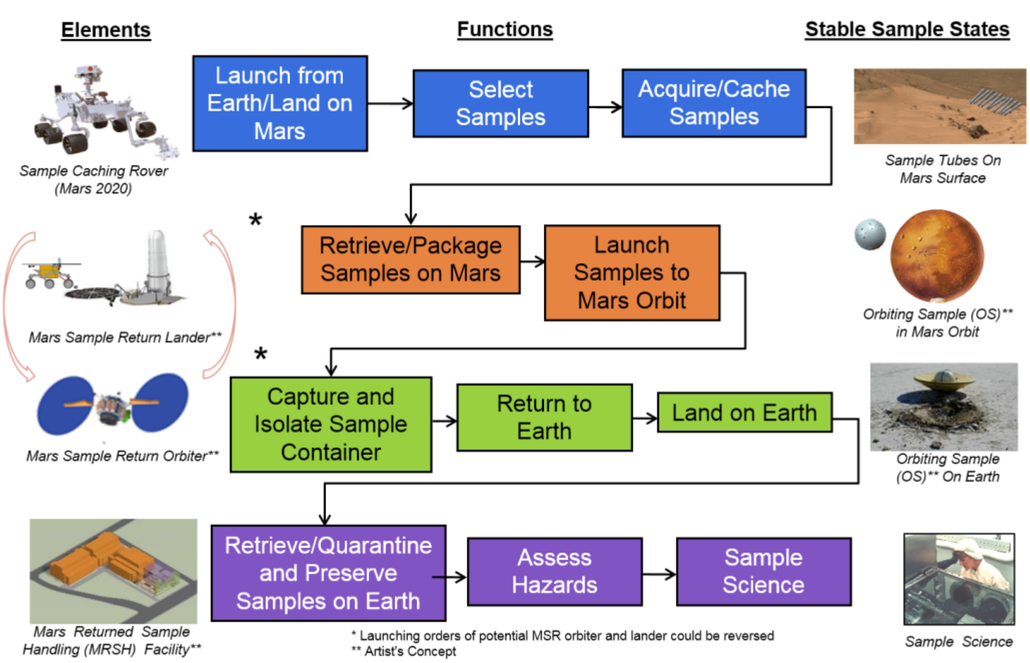

Figure 1. Potential Mars Sample Return (MSR) Elements, Functions, and Sample States

interfaces must also be defined so that accurate loads analysis and test cases can be defined: once these cases are defined, the Mars 2020 tubes can be shown to satisfy them.

The OS would have additional functions beyond holding the Mars 2020 rock cores: it captures and stores samples of the Martian atmosphere, it interfaces to a Mars Ascent Vehicle (MAV) on SRL that would launch the OS into orbit around Mars, it interfaces to the capture and planetary protection hardware on SRO, and it interfaces with the EEV on the SRO. Every functional requirement imposed on the OS affects the size and mass of the OS. Because the OS may be the first payload launched into orbit around another planet, mass and size are critical factors in determining the size of hardware elements integral to the SRO and SRL mission concepts (for example, the MAV and EEV).

3. OS Engineering Challenges

As just mentioned, the OS is tasked with numerous functions. Any viable OS design must handle all of those functions in order for MSR to be a success. As a result, designing an OS becomes a fine balancing act between an unusually multifarious set of sometimes opposing engineering challenges. The key engineering challenges for the OS are depicted by mission phase in Fig. 2 and discussed in this section.

SRL Launch

The SRL launch would chronologically occur last in the sequence of launches for MSR. The OS would launch as two separate parts, the first attached to the top of the MAV, and the second attached to the either a fetch rover body or to a compartment near the MAV launch tube in the case of a mobile MAV architecture. In either case the key issues for the OS would be to have a secure launch lock configuration and viable forward contamination control procedure. To protect Earth from uncontained Martian materials and to ensure the scientific integrity of the samples within, special forward contamination control measures must be followed in compliance with NASA NPR 8020.07 [2]. These procedures result in the need for careful material selection for the OS such that the components can withstand vacuum bake-out, chemical sterilization, and/or other procedures before launch from Earth.

Mars Surface Operations

After EDL at Mars, the SRL rover would move to secure the sample tubes left by the Mars 2020 mission. Surface operations would need to be conducted in accordance with NASA NPR 8020.12D [3] to minimize planetary contamination of Mars. During the rover surface operations, the cold, dry, and dusty surface environment can cause issues with mechanical hardware. Dusty tubes would be grabbed robotically from the surface and must be reliably retained in the OS canister. The OS would have to be compatible with the Mars 2020 tubes such that they could be retained reliably inside the OS even in cases of extreme surface dust or issues. Additionally, developing a simple, reliable, and ultra-low leak method for collecting atmospheric samples that has the ability to select the time and duration of sample collection could be challenging.

MAV Launch

After filling the OS canister with tubes and atmospheric gas,

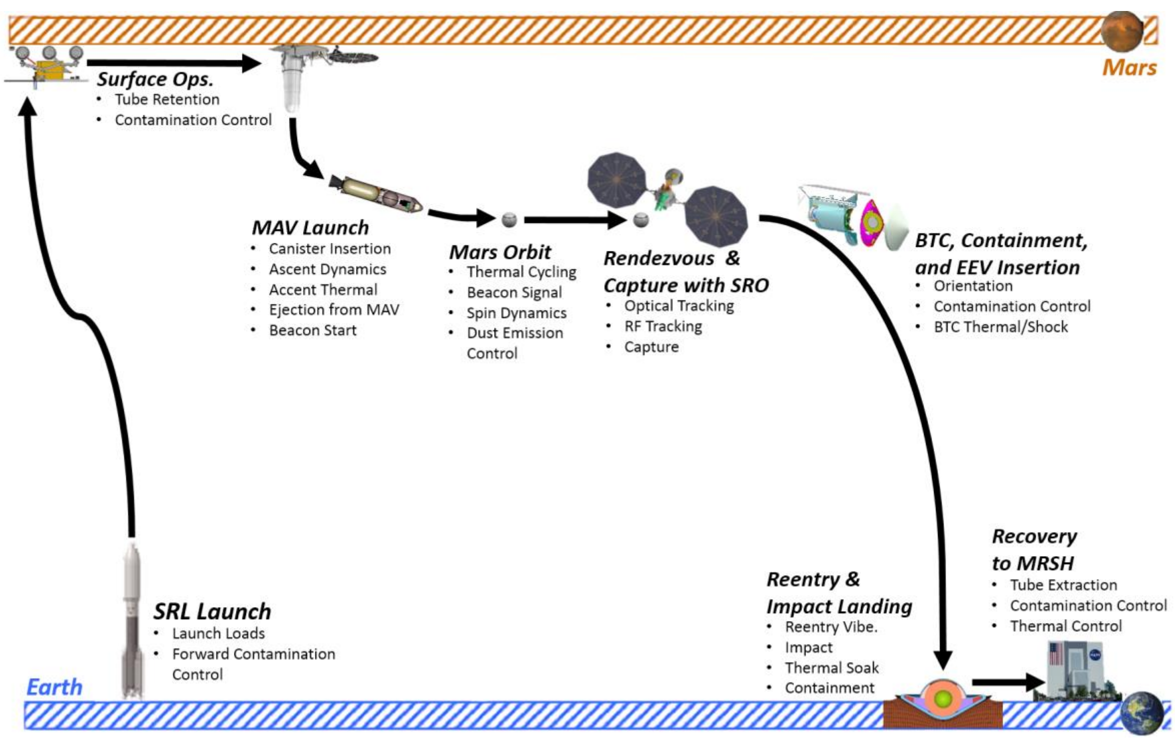

Figure 2. Key OS design considerations by notional mission phase

the canister needs to be inserted into the MAV and secured with enough preload to ensure safe and deterministic impact landing loads. The challenge for canister insertion is to simplify and minimize the number of actuators required whilst not offending any MAV requirements. Additionally, during MAV assent there are significant thermal, structural, and acoustic loads on the OS which the OS must be able to withstand as well as shield the samples from. As the MAV approaches the OS's intended orbital trajectory, smooth and reliable ejection with a predetermined translational velocity and spin rate is needed. Lastly, during assent or at ejection there needs to be a way to initiate the beacon electronics after a long period of dormancy so that RF tracking of the OS is possible by the SRO.

Mars Orbit

After ejection from the MAV the OS would be spinning about its CG and its beacon should have started transmitting. To keep the samples and beacon electronics within a defined temperature range, solar radiation absorption is need and must be managed through the cycles of light and dark as the OS passes in and out of sunlight. Maintaining a beacon signal for at least 90 days could be challenging with primary batteries at low temperatures and installed many years before. Spin is used so that the radiative heat absorbed from the Sun is distributed evenly around the OS. Depending on how well the OS is sealed before launch, even after MAV ejection, the OS may still be slowly depressurizing; releasing Marian atmosphere and ejecting Mars dust in orbit. Since forward and backward contamination control is such a big issue for this mission, dust emissions in any orbit near the SRO would likely need to be minimized.

Rendezvous and Capture with SRO

For the SRO to find the OS from thousands of kilometers away in space, optical tracking is baselined as the primary mechanism and the main challenge is to ensure that the OS is reflective enough and in the expected orbit such that the SRO can detect it even near the horizon. For RF tracking, which is planned as a backup to Optical tracking, the key challenges are to have an antenna that can generate a strong enough omnidirectional RF field to be detected by the SRO and to have enough battery power to broadcast long enough to be tracked. As the SRO approaches the OS, a significant difference in translational velocity and rotational velocity would likely still be present and the OS would need to have the right surface features and shape to enable easy capture by SRO.

BTC, Containment, and EEV Insertion

"Breaking the chain" (BTC) is the tricky task of definitively and cleanly separating contact by a spacecraft with any dust or other particles derived another planet. The goal in the case of MSR is to ensure without a doubt that no uncontained Martian dust or potential microbes arrive at Earth. Towards that goal, the OS must be well contained before returning to Earth. Many technologies and novel approaches are currently being developed to perform the BTC task. The three most promising so far are explosive welding, brazing, and bagging. Each pose different challenges on an OS. With explosive welding, shock and damage to the samples are the biggest concern. For brazing, the heat load and duration could threaten the OS structurally and the samples thermally. The main challenge with bagging is being able to reliably orient the OS through the bag and to ensure that the bag doesn't snag or rip on other containment or EEV structure. Each of the containment approaches also needs to be redundant, thus at least two layers are required. Lastly, after being redundantly contained, the two containers and the OS would need to be reliably inserted into the EEV in a prescribed orientation for impact landing on Earth, which may be challenging for the robotics team.

Reentry and Impact Landing

The OS would experience significant vibroacoustic and aerodynamic deceleration loads during reentry. Even so, the loads and stresses on the OS would be dominated by the impact landing event. The impact landing is one of the largest challenges for the structural design of the OS. Additionally, after landing, it could take hours or even longer to find and recover the EEV and OS. During this delay, a very hot TPS on the EEV would be slowly heating the samples inside. Lastly, in accordance with NPR 8020.7G [2], extraordinary efforts are being made to ensure no Martian material is accidentally released from the OS even in the low probability event of a hard off-nominal impact. The OS structure must be very tough to minimize the possibility of tertiary damage or breach of the redundant containment systems in the EEV.

Recovery to MRSH

After a successful landing on Earth, the EEV is intended to be rapidly recovered and delivered to the MRSH for extraction and initial analysis. During this last phase, it would be necessary to carefully open up the OS without damaging the tubes, without Earth contamination to the samples, and without uncontrolled Mars contamination to the Earth.

4. KEY REQUIREMENTS

The multitude of requirements on the OS are driven by the confluence of interfaces with each of the potential MSR campaign missions. This includes Mars 2020 (tube geometry, sample volume, mass, tube environments, and number of tubes), a SRL (OS mass, OS surface geometry, aerothermal loads on the OS) and a SRO (BTC containment and 1300 g Earth landing). The key requirements for each mission or mission concept are:

Mars 2020

Each tube collected by the Mars 2020 rover is hermetically sealed by the rover to preserve the scientific integrity of the geological sample and any entrained atmosphere for its flight to Earth. This seal must not only keep any contaminants from reaching the samples during the return to Earth, it must also minimize the escape of dust particles and gas from inside the tube as well. The sealed sample tube diameter and length combined with the tube mass and total number of tubes to be returned, dictate the minimum possible OS diameter and mass. OS mass would be critical to the SRL & MAV as outlined in the SRL section below. Additionally, for science preservation the samples are required to never exceed a temperature of +60^{o} C and never be subjected to a magnetic field larger than ½ mT.

Sample Return Lander/Mars Assent Vehicle

It has been determined that for every kilogram increase of OS mass, the MAV mass must also increase by 5 kg to lift it into Mars orbit. In turn, the Mars entry mass of a SRL must increase by 20 kg to support every additional kilogram of MAV. Mass is thus a key consideration of SRL/MAV mission design. The OS cannot grow above its notional allocation of 12 kg without significant impact on the MAV/SRL system. In addition to holding the sample tubes, the OS must contain a dedicated tank to collect one or more 50 cc or larger samples of uncompressed Mars atmosphere. The tank(s) and valves would be tasked with ensuring an extremely low leak rate during the return to Earth. There would be significant thermal challenges for the SRL, MAV, and OS while on Mars. The sample tubes must be loaded into the OS through a thermal insulation system surrounding the MAV that is needed to keep the MAV oxidizer from freezing. Additionally, during the ascent from the Mars surface, the MAV may experience a peak stagnation heating on the order of 10-20 W/cm$_{2}$ at the nose. This heating must be isolated from the tubes (via a thermal protection system (TPS) or other means) such that the samples do not exceed the +60^{o} C limit. Once released on orbit the sample tubes must remain within the temperature ranges of -128^{o} C to +60^{o} C.

Sample Return Orbiter/Earth Entry Vehicle

The three major tasks of SRO are 1) rendezvous with and secure the OS while in Mars orbit, 2) ensure that no uncontained Mars particles are returned to Earth, and 3) facilitate safe return of the OS to Earth's surface. The first task is the responsibility of the Rendezvous and Orbital Capture Subsystem (ROCS). The baseline method for the SRO to find the OS on orbit is optical tracking. The OS must have sufficient albedo to be seen by the SRO during the initial approach while the OS is many kilometers away and in a different orbit than the SRO. As a supplemental tracking mechanism, the OS must contain a RF beacon that has as least a 1% duty cycle that transmits a 100 mW pulse every 90 seconds for 90 days. At the moment of capture, any remaining translational and rotational momentum must be removed by the SRO during the transition from free flight to 6DOF control of the OS. The second task of SRL is the responsibility of the BTC sub-system. Many sterilization and containment approaches are actively being tested at JPL to determine the most promising one. Depending on the BTC approach used, insulation, specialized materials and/or physical features may be levied by the BTC system on the OS. As mentioned in the MSR overview section, after containment is assured by the BTC system, the OS is inserted into an EEV. Once confirmed secure in the EEV, the OS and EEV are ready for release into EDL at Earth. The EEV protects the OS during its entry, decent, and parachutes-less impact landing. The OS and the core sample tubes must withstand the expected 1300 g nominal Earth-landing loads imposed during the parachute-less landing. To prevent damage to the samples and tube seals, the OS must not exacerbate loads internally on the sample tubes above the 1300 g peak load applied to it. Any heat sterilization or other BTC isolation steps requiring high temperatures must be isolated from the core sample tubes such that the samples do not exceed the +60 ^{o}C limit. In order for the core sample tube seals to survive the 1300 g landing, the OS must have mechanical features to enable reorientation and at least 5 DOF controlled positioning of the OS within the EEV to ensure favorable tube seal and sample orientation during impact landing.

5. Early OS Concepts

Prior to the OS concept work currently being performed by the Mars Formulation Office at JPL, past MSR concept efforts included the analysis and test of EEVs containing an OS. Some of the earliest work was by NASA and CNES teams that aimed at the 2003/2005 MSR launch opportunity in a joint NASA/CNES MSR project [4]. That joint project was cancelled and until recently work on MSR and especially the OS has been sporadic. Despite the cancelation, the early work by Mitcheltree et al.[5] laid the foundation for the current MSR campaign architecture including the EEV and defining key OS constraints.

Until recently the prior work considered the OS as a 'black box' or simply as a 'spherical payload' with little if any hardware features defined internally. In 2013, in what is perhaps the first attempt at a hardware prototype OS, ESA revealed a proof-of-concept spherical sample container as shown in Fig. 3. The design was relatively small, stored 11 geological samples, stored an atmospheric sample, was 23 cm in diameter, and weighted less than 5kg [6]. Very few

Figure 3. ESA proof-of-concept sample container [6]

additional details however appear available publicly on this concept.

Recent NASA funded efforts have resulted in notional OS concepts as well. One such concept funded under an SBIR contract to Honeybee Robotics proposed a spherical canister with samples stored in the rock core drill bits rather than in tubes [7]. The bits were, for that design, intended as single use and each bit was sealed in its entirety and inserted into the OS for return to Earth. Architectural changes to the Mars 2020 mission lead to tubes being used for sample containment rather than the bits. The shift in the Mars 2020 mission architecture as well as mass and size issues associated with returning 31+ bits prohibited further development of the Honeybee concept.

Previous to our team's efforts, others at JPL have provided valuable insight for the most current OS hardware concepts. The earlier efforts were supporting pre-mission work for Mars 2020 and developed concepts for the canister and caching system alone [8]. At that time, the tubes were anticipated to be much smaller and had a diameter of 13 mm. One important aspect of that work was investigating tube-packing arrangements as shown in Fig. 4. A number of arrangements were looked at: circular, hexagon, triangular, quadrilateral, and pentagonal. Then and now, hexagonal pattern tube arrays were selected for concept designs. The hexagon array has been determined to have better volumetrically tube packing and be more efficient than other patterns, particularly for higher tube counts.

Work on developing OS concepts that aimed in earnest to meet all of the design requirements begun at JPL in 2014. Immaturity of the SRL/MAV surface operation architecture initially drove preliminary designs of the OS and the methods for securing the sample tubes. Our team's more recent efforts are designed to be 'architecture agnostic', that is to say feasible in most explored sample collection architectures.

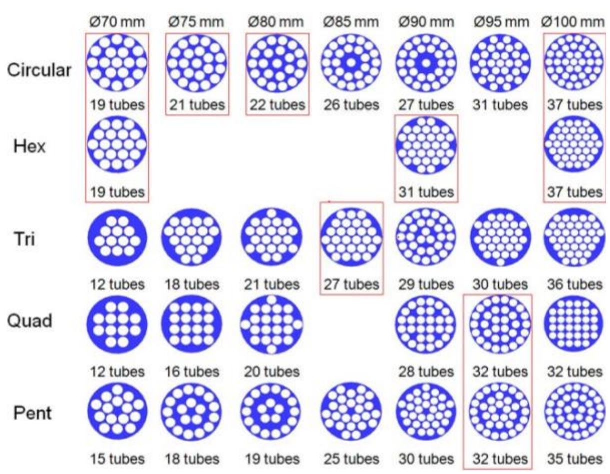

Figure 4. Early JPL study showing a variety of potential tube storage configurations [8]

Design iterations during this architecture shift produced three preliminary OS concepts:

Flexure Latching Plate OS

Initially the OS was envisioned to be onboard a fetch-rover during the sample tube retrieval process. A concept CAD image is presented in Fig. 5. This belief led the initial design. At each location, the sample tube would be loaded into the OS via a robotic end-effector. Once all samples had been placed into the OS, two flexure-latching plates on opposite ends of the sample would be actuated by a camshaft and then secured in place by spring plungers via the same robotic end-effector. The then secured OS would be loaded into the MAV and subsequently prepared for launch. This concept was eventually abandoned due to the high camshaft torque required to preload and secure all sample tubes simultaneously.

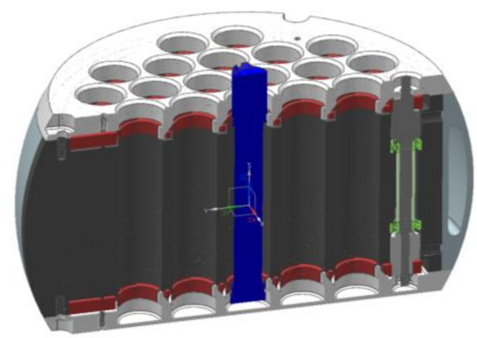

Figure 5. Early flexure latching OS concept

Collet OS

A collet design was also investigated which allowed for individual securing of each sample tube. Concept CAD images of the collet OS design concept are found in Fig. 6. Similar to the flexure concept discussed above, the collet OS was envisioned to travel onboard a fetch-rover. A robotic end-effector would insert the sample tube into a collet located on the retention plate within the OS; using torque reaction features on the retention plate, the-end effector would then thread in the collet, producing a large radial preload used to secure the sample tube. Small flexures provided a ratcheting feature to ensure the collect could not back out during return environments. This concept was eventually abandoned due to packaging issues, higher mass, and architectural changes.

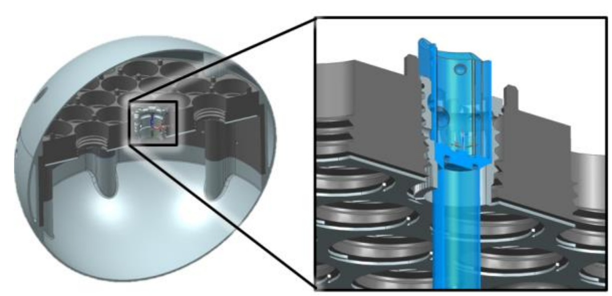

Figure 6. Early collet OS concept

Axial-Preloaded Canister OS

In early 2015 a consensus was reached within NASA to use an 'adaptive caching' approach wherein tubes would be left of the ground individually or in piles rather than in a consolidated cache container. With this change, the tubes would be consolidated by a SRL rather than Mars 2020, into a cache or even directly into a MAV-mounted OS. The adaptive cache approach pushed the need for precise tube level manipulation onto the future SRL mission. The canister OS concept presented in Fig. 7 is one concept that considers the adaptive cache collection approach in its design.

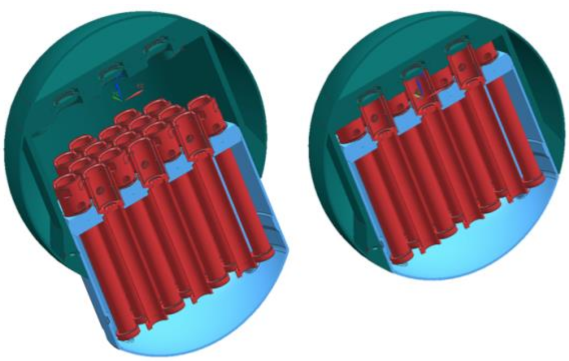

Figure 7. Early axial-preload canister OS concept

The canister OS would be a two-part system comprised of a canister and a shell (pre-installed on MAV during Earth ATLO). Similar to the previous OS concepts, a robotic end effector would be used to retrieve and insert the sample tubes into the canister. Once the retrieval phase was completed, the canister would be inserted into the OS shell onboard the MAV. In the concept, the sample tubes are secured via a large axial preload between the canister's retention plate and flexures located within the shell. This OS design was down selected due to difficulties in applying the large preloads required for securing the tubes for impact landing. This design is considered the foundational concept for the current OS configuration.

5. CURRENT OS DESIGN

Design Overview

The current OS baseline design introduces new concepts and refines upon previous concepts. It consists of two main sub-assemblies: the OS Shell and the OS Canister as shown in Fig. 8). It can accommodate up to 36 soil sample tubes, and two atmospheric sample tanks. It also has accommodations for a UHF tracking beacon, which is isolated from the samples but integrated into the OS Shell structure. The design functions via a Flexure Claw Secure Mechanism, which applies preload between the OS Shell and the OS Canister through an axial rod in the OS Shell. At the same time, preload would be applied to each of the soil sample tubes to secure them in place for Mars ascent, cruise to Earth, Earth entry, and impact landing. The current best estimate (CBE) of the total mass of an OS with beacon hardware and 31 sample tubes (per the requirement) is 12.0 kg, and the overall diameter is 27 cm. A more detailed mass breakdown can be found in Table 1.

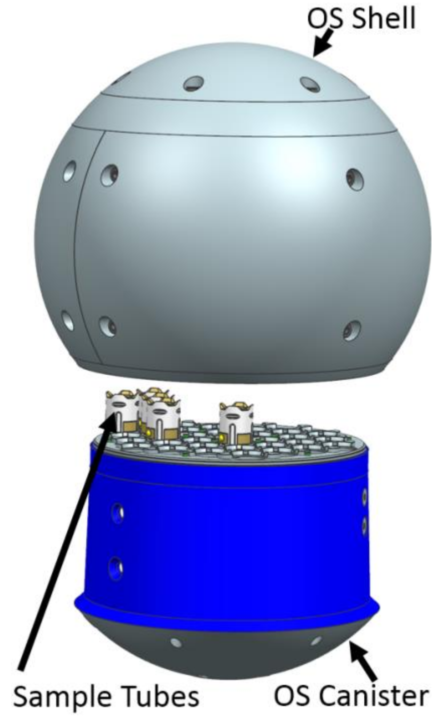

Figure 8. Current OS Baseline Design: exploded view

OS Shell

The OS Shell, shown in Fig. 9, serves several functions. It consists of a shell top, a shell core, two shell sides, an axially positioned shell rod, and a crushable aluminum foam sheet. The shell assembly forms one-half of the structure needed to contain and protect the air and soil samples from the mission environments and the large impact landing loads. The shell rod is the main load-bearing member that preloads the OS flexure claw secure mechanism, which is discussed in detail later. Additionally, the crushable aluminum foam sheet is part

Table 1 - Current OS Mass Breakdown (CBE)

Sub Assembly	Material(s)	Mass (kg)
OS Shell	Aluminum, Titanium, Torlon	5.7
OS Canister	Aluminum, Titanium, CRES	3.1
Beacon Electronics and Batteries	Silicon, Aluminum, Other	0.3
Atmospheric Sample Tanks	Aluminum, Other	0.3
Soil Sample Tubes	Titainum, Other	2.6
Total OS Mass		12.0

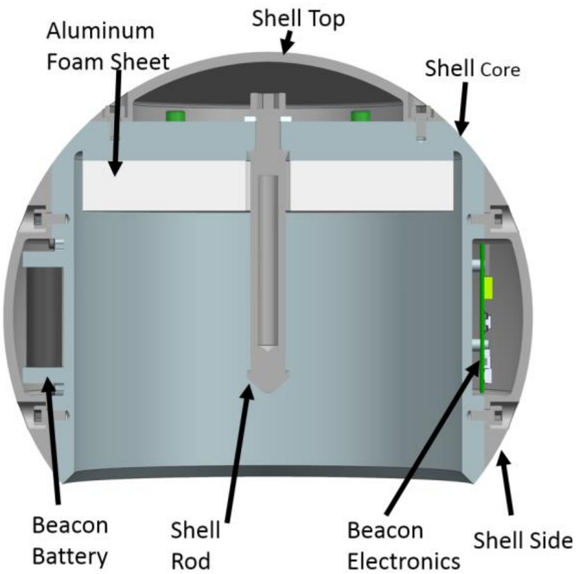

Figure 9. OS Shell: section view

of the sample tube secure interface. When the flexure claw secure mechanism preloads the two pieces of the OS shell and OS canister together, the sample tubes forced into contact with the aluminum foam. The foam deforms locally to conform to the crown of each sample tube, and secures the tubes in place against the OS canister as shown in Fig. 10. The OS shell also features an annular cavity around its equator. This space is used to accommodate the beacon electronics and the beacon batteries which are used to locate and track the OS while on orbit around mars awaiting rendezvous. The beacon works in conjunction with the shell side panels, which are made from a high performance polymer called Torlon. The Torlon material is plated in such a way that the shell side panels can serve the dual function as shell and the OS canister together. It interfaces with the structure for the OS shell, and as an antenna for the beacon.

The OS shell also contains the OS launch interface to the MAV which is currently still in design. While still on Earth, the OS shell would be installed on top of the MAV and would travel with the MAV to the surface of Mars as part of the SRL. The OS shell would then be ready for the OS canister to be inserted and secured for the journey back to Earth.

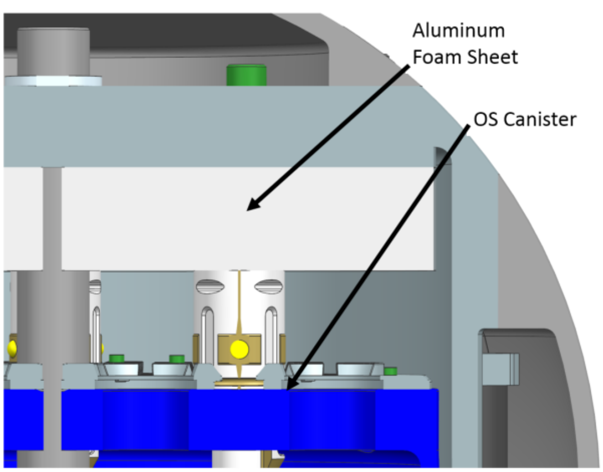

Figure 10. Aluminum foam sheet showing interference with sample tube crowns

OS Canister

The OS Canister, shown in Fig. 11 is the second major piece of the OS, and also serves several functions. It is made up of a canister body, a canister bottom, a sample tube retain plate, a flexure claw secure mechanism, and a sample tube bottom restraint plate. The canister bottom also accommodates two atmospheric sample tanks which can be filled on the surface of Mars. The OS canister forms the other half of the structure needed to protect the atmospheric and soil samples from the mission environments and the large impact landing loads. The flexure claw secure mechanism interfaces to the shell rod in the OS shell and allows the OS canister and the OS shell to be connected and preloaded together. This preloading also secures the soil sample tubes in place by forcing them against the top of the OS canister body and the aluminum foam sheet in the OS shell, as shown above in Fig. 10. The sample tubes are loaded into the OS Canister and retained in place during Mars surface operations by the sample tube retain plate. When the sample tubes are seated and retained in the OS canister, the bottoms of the tubes form a clearance fit with the sample tube bottom restraint plate as shown in Fig. 12. This serves to limit the deflection and the cantilever induced stresses on the tubes during impact.

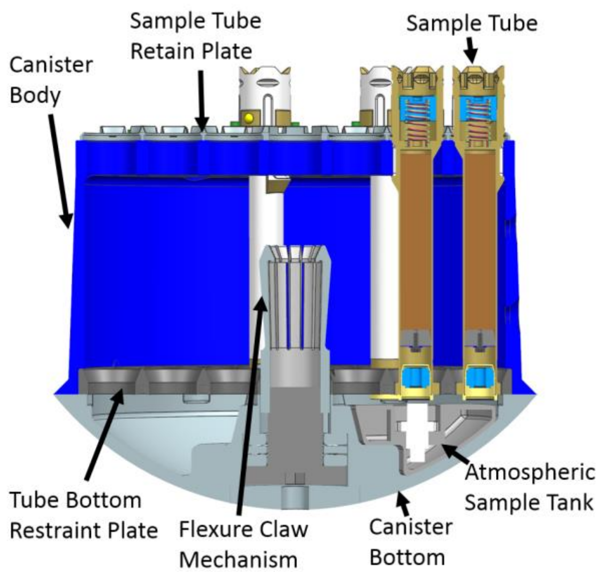

Figure 11. OS Canister: section view

The OS canister serves as the collection container for the soil sample tubes while on Mars. The sample tubes are loaded into the OS canister by the SRL where they would be retained

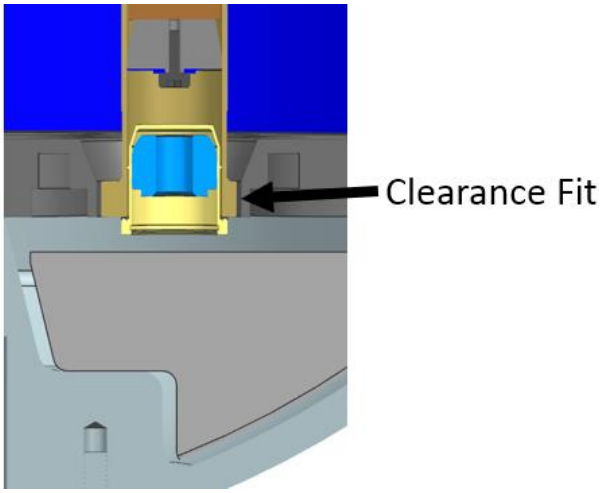

Figure 12. Tube bottom restraint plate: detailed view

until the OS canister is inserted into the OS shell on top of the MAV and the two pieces of the OS are tightly secured for flight via the flexure claw secure mechanism.

Retain Mechanism

When the sample tubes are inserted into the OS canister, they must be retained in place to prevent them from falling out during Mars surface operations and OS canister handling and insertion. This retain feature must be strong enough to prevent the tubes from dislodging or falling out, but must be reversible in case the tubes need to be removed or replaced prior to final canister insertion into the OS shell. The sample tubes have an annular groove around them specially designated for the retain feature interface. The OS retain mechanism is still a work in progress, but in the current iteration, the sample tube retain plate installed on top of the OS canister uses flexible tabs that interface with the retain feature on the sample tubes and hold them in place. As shown in Fig. 13, the tabs flex out of the way as the tubes are inserted and then seat themselves into the annular groove on the sample tube. The tabs are also flexible enough that the tubes can be removed if needed.

Flexure Claw Secure Mechanism

In addition to the retain mechanism, the OS requires a secure mechanism which creates a stronger and more permanent restraint on the tubes capable of withstanding the substantial entry and impact loads. In the current OS, this mechanism is called flexure claw secure mechanism. The mechanism consists of a flexure claw, a retractor screw, and a thrust bearing that allows the retractor screw to rotate freely. When the OS canister is inserted into the OS shell, the fingers of the flexure claw flex outward and slip around the shell rod. They then snap into place in the circumferential notch on the shell rod. At this point, a robotic end effector still in design, turns the retractor screw which pulls the flexure claw downward and applies tension through the shell rod, thus creating preload between the OS canister and the OS shell. An illustration of this can be found in Figs 14 and 15. As the retractor screw tightens, the OS shell and the OS canister are

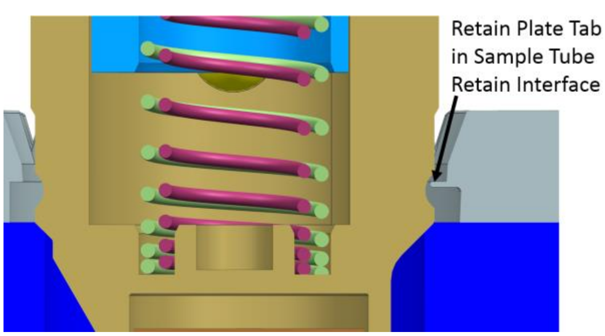

Figure 13. Sample Tube Retain Plate: detailed view

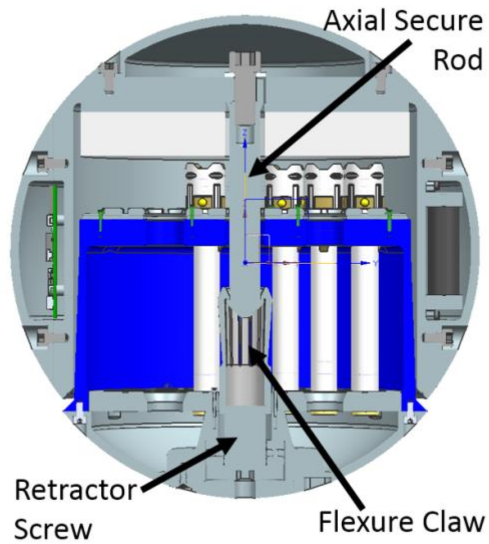

Figure 14. Flexure Claw engaged with shell rod

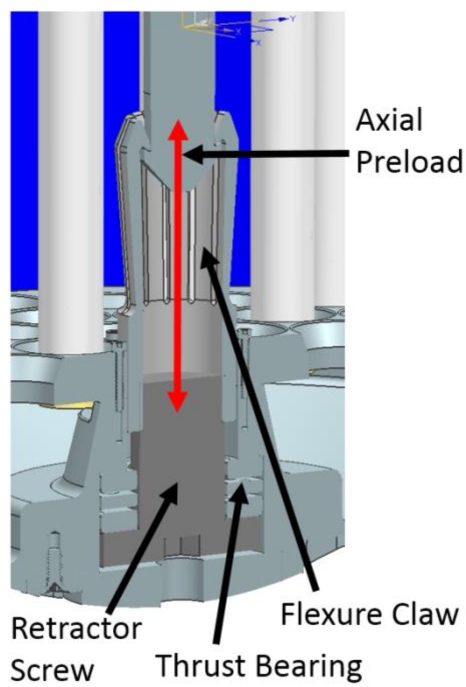

Figure 15. Flexure Claw: detailed view

forced tightly together, generating preload on the tubes as well as a dust seal on the lip of the OS shell. As mentioned earlier and shown in Fig. 3 the preload causes the tops of the sample tubes to locally deform the aluminum foam, creating form-fitting seats for themselves in the foam. This secures the sample tubes for the loads they would experience during Mars ascent, through Earth entry, and impact landing. The flexure claw and shell rod are designed so that the claw can engage the rod with a relatively minimal force (currently less than 100 N but with plans for improvement), and the system can support up to 60 kN of tensile load when fully preloaded.

Atmospheric Sample Tanks

The atmospheric sample tanks, shown previously in Fig. 11, would be housed within the bottom of the OS canister. There are currently two 70 cc sample tanks, capable of storing 140 cc of Martian atmosphere in total. Each sample tank is filled and sealed through two solenoid-operated valves connected in series to provide redundancy and reduce the leak rate when the valves are closed. The valve technology requires additional development, but the current concept calls for the solenoids to be removed by a robotic end effector prior to MAV launch, leaving only the compact, lightweight valve bodies behind. This reduces mass and allows for all 36 sample tube locations in the OS Canister to potentially be populated, if mass constraints permit.

RF Beacon and Antenna

Although optical detection is the primary mode of locating and tracking the OS on orbit at Mars at about 500 km altitude, the RF beacon in the OS could aid these navigation functions introducing angular and Doppler of the Beacon radio frequency transmissions. The UHF band was selected for the initial prototype. The signals would be processed by a cooperating Mars orbiter equipped with an Electra UHF radio. The beacon electronics are housed within the annular cavity in the OS Shell. They are powered by a pair of 18650 sized primary batteries, also housed within the circumferential cavity in the OS Shell.

The OS houses a low-power radiation-tolerant UHF beacon PWA in a small 1.5" x 3" form factor. When activated, the beacon transmits a UHF signal for approximately 700 ms at 70 second intervals, translating to a 1% RF duty cycle. The average DC power dissipation during operation is less than 20 mW, allowing for an estimated lifetime greater than 90 days on the target application Li-ion batteries. The design incorporates an LDO voltage regulator, a comparator with related circuitry for timing and control, a SAW oscillator for UHF tone generation, and an SMT RF amplifier. Two bi-directional signals, used in conjunction with a reference ground, are used to control the beacon and provide telemetry. The beacon can be activated or de-activated by shorting different combinations of the two signals and ground together. Telemetry can be gathered by measuring the DC voltages of the two signals relative to ground. One signal presents the input battery voltage and the other indicates whether the beacon is active or not. This allows for simple but effective in-situ control and monitoring of the UHF beacon within the OS. Figure 16 shows the circuit logic diagram for the prototype UHF beacon.

The OS antenna under development is a conformal patch-type low-gain antenna designed for a narrow band of frequency centered around 433.5 MHz (Wavelength: 69.156 mm or 27.227 in). It would perform as a quasi-omni-directional antenna with a gain of better than -5 dB for a substantial range of angles, and a VSWR of better than 2:1 across the frequency band of interest. The field polarization is linear. HFSS software from ANSYS was used to analyze this antenna.

The current preliminary outer radius of OS shell is about 135 mm (5.315 in) with a circumference of about 848 mm (33.4 in). Thus circumference is slightly larger than a wavelength. This allows for a patch-type antenna on the surface on a dielectric shell of approximately 5 mm in thickness, which can be fed by a coaxial line from inside the spherical shell, having a ground plane on the back of the dielectric shell. Presently the candidate dielectric material is Torlon 5530 (30% Glass Reinforced PolyAmide-Imide) with a dielectric constant of 6.3. One candidate design is of the form shown in Fig. 17, which is a bow-tie configuration.

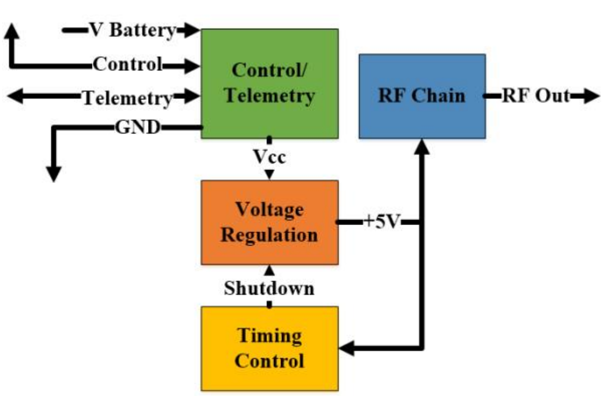

Figure 16. Simplified circuit diagram for prototype UHF beacon

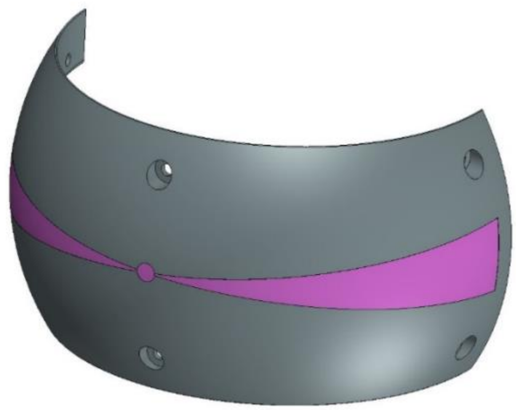

Figure 17. Proposed "Bow-tie" patch antenna

Thermal & Albedo Control Coatings

The surface coatings on the OS serve to satisfy two separate requirements. First, the OS must have an average solar reflectance (albedo) greater than 0.37 to enable optical track on orbit. Second, the OS surface properties must allow for on orbit thermal control. The albedo requirement of 0.37 was determined via analysis with selection of conservative values for a broad array of hardware and physical parameters. More details regarding the albedo analysis are found in the Testing and Analysis section.

Thermal control of the OS during MAV ascent and orbit was previously discussed in Ref. [9], but additional work has been completed since then. One key realization from the effort is that OS on orbit thermal control is strongly affected by two ongoing design architecture trades. First, it is affected by the option to incorporate a RF beacon or to simply rely on Optical detection. Second, it is affected by the decision to apply TPS directly to the OS, or to apply TPS on a secondary structure or fairing around the OS. Thus at this time the coating plan is still very much in flux. Preliminary surface coating designs for each scenario are discussed next.

Since optical detection and navigation is the primary mode of locating and tracking the OS, there is a possibility that a battery, beacon, and electronics may not be necessary on the OS. In this case, the allowable flight temperature (AFT) of the OS would be limited only by the capability of the OS and tube hardware and the samples themselves. The sealed sample tubes have an AFT range of -128° to +60° C. The collected samples would also need to be kept below +60 C, with a goal of keeping them below +40° C. Without a battery, beacon, and electronics, the OS can be biased colder and can achieve a high optical reflectance through the use of bare gold and white paint surface coatings. TPS could be placed directly on the OS, or on a secondary structure. Keeping the OS within the range of -128° to +40° C would then be straightforward. However, with a beacon, the temperature limits of the OS become much more restricted due to the presence of a battery and electronics. The battery is the primary concern, with an AFT ranging from as narrow as -20° C to +30° C to as wide as -40° C to +50° C. If TPS is placed on a secondary structure and not directly on the OS, then OS surface properties should be a mix of ~87% bare gold and ~13% black paint in a zebra stripe or polka dot pattern. This would enable both the temperature and optical requirements to be met. The minimum estimated reflectivity for this coating configuration is 0.61, which is safely above the requirement of 0.37.

If TPS is placed directly on the OS, it becomes extremely challenging to maintain such tight OS temperatures due to the high thermal emissivity of the TPS, which biases the OS toward cold. In this case, some type of thermal isolation between the OS and TPS would likely be necessary. One example of a thermal isolation system would be titanium bipods as shown in Fig. 18. The OS would also need to spin around the z-axis (see Fig. 18) in order to eliminate the temperature dependence on OS orientation. If the TPS was thermally isolated from the OS in such a manner, the OS temperature would depend primarily on the non-TPS side of the OS, which could then be a mix of ~87% bare gold and ~13% black paint in a zebra stripe or polka dot pattern. In addition, the selected TPS would need to be white, not black, since with black TPS on an entire hemisphere, the minimum reflectivity is reduced to just 0.3. These concepts are just one of many ongoing design trades for OS on orbit thermal control.

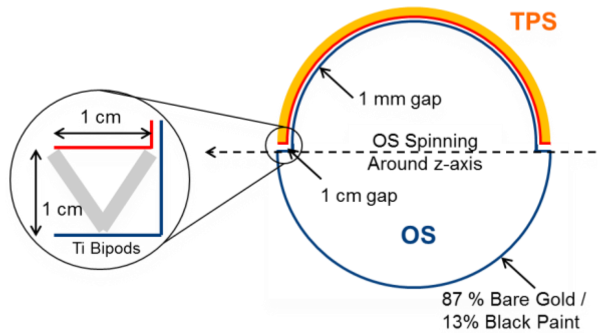

Figure 18. Thermal isolation concept showing Ti Bipods between the OS and TPS. Thermal isolation between the TPS and OS may be needed for certain OS configurations.

6. Testing and Analysis

Aerothermal

Analysis - During the ascent from the Mars surface, the MAV accelerates rapidly in the lower Martian atmosphere. While the atmospheric density is low compared with Earth, the high velocities do lead to potentially significant convective heat fluxes at the MAV nose. Figure 19 shows examples of the altitude and velocity for preliminary "nominal" and 99% high heat flux (HF) trajectories coming out of a Monte Carlo trajectory analysis, along with the corresponding cold-wall convective heat flux and heat load for each (predicted using the engineering-level analysis tool CBAERO [10]). While these results are preliminary, they indicate that unmargined peak heat fluxes can be in the 10-20 W/cm^2 range, which would likely require some form of TPS to maintain integrity of the OS structure and help minimize temperature rise in the OS interior where the samples reside.

Using these results and some preliminary assumptions on aeroheating and thermal response margins, a transient one-dimensional thermal analysis was conducted (using the FIAT code [11]) at the nose to determine the suitability of several TPS material options. The peak heating is low enough that there are many possible material candidates, and it was recognized that other requirements such as on-orbit capture and manipulation and also the impact landing on Earth, may play a larger role in deciding the most appropriate option. Therefore, analysis was conducted on both high strain-to-failure ablative materials such as SIRCA [12], as well as more hard but brittle materials such as the family of Shuttle tile materials (e.g. FRCI-12, AETB-8, and LI-2200, along with a

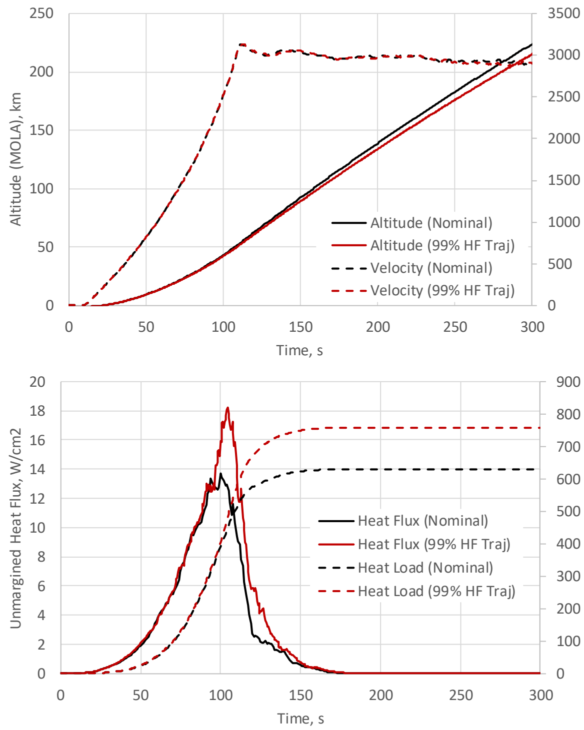

Figure 19. Example "Nominal" and "99% High Heat Flux (HF)" trajectories used in MAV ascent aerothermal preliminary analysis

TUFI coating) [13]. For each TPS stackup analyzed, the primary TPS material thickness was optimized to meet the bondline temperature requirement.

The results indicated that the maximum outer surface temperature peaks in the 1350 – 1500 K range, depending on the specific stackup. While this considerably exceeds the maximum use temperature of Aluminum (for example), it does stay well-within the limits of the TPS materials discussed above. Overall, these TPS materials are successful in insulating the interior substructure and meeting the bondline temperature requirements. While these preliminary results highlight some of the aerothermal challenges faced in the OS design, they also display that there are engineering design solutions available to meet the requirements. Further work is underway in several areas, including generating higher-fidelity aeroheating predictions using Computational Fluid Dynamics (CFD), two- and/or three-dimensional thermal response analysis to better quantify lateral conduction effects, and more investigation into the most appropriate TPS materials that meet both the aerothermal and mechanical/handling requirements for the OS. Transient thermal analysis of the current design, for predicting sample temperature rise due to the MAV assent heating is also in the works.

Impact Dynamics

Testing – In support of future Mars mission hardware development and requirements validation, the Mars Formulation Office at JPL has supported the construction of a 26-m tall truss-frame tower with a pneumatically actuated penetrometer acceleration system for full scale impact testing into UTTR surrogate soil. A picture of the tower is presented in Fig. 20. At the tower, controlled and well instrumented 'EEV like' penetrometer impacts with up to 140 kJ of kinetic energy are able to be conducted. A total of 16 'EEV like' penetrometer impact tests have been conducted to date with a variety of penetrometers ranging from 40 kg to 140 kg. The goal of initial testing was to validate numerical soil models

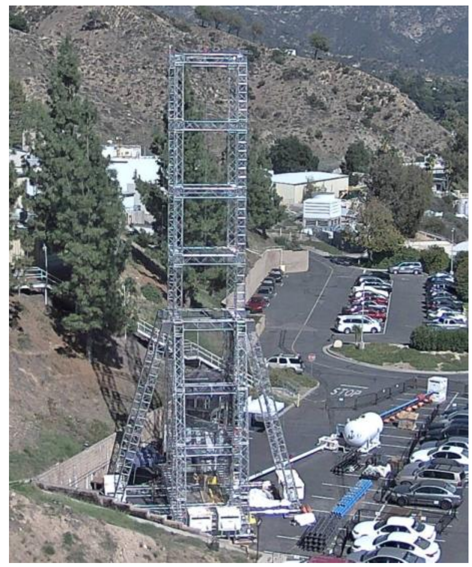

Figure 20. Impact tower constructed at JPL

across a large range of impact velocities, soil saturation levels, and penetrometer masses. The models generated have been validated to an accuracy of ±15% of peak acceleration across the parameter ranges of interest. High-speed images of one impact test of a 140 kg penetrometer impacting at 44.6 m/s is shown in Fig. 21 with a qualitative comparison to a corresponding FEM.

As a result of this effort, a suite of broadly validated and high fidelity soil models representing the playa at UTTR are now available for structural impact analysis of EEV and OS concepts using the FEA code LS-DYNA. More about the impact tower and soil model validation is available in Ref. [14]. Based off impact testing and LS-DYNA models, the 1300 G Earth impact load requirement at the OS was

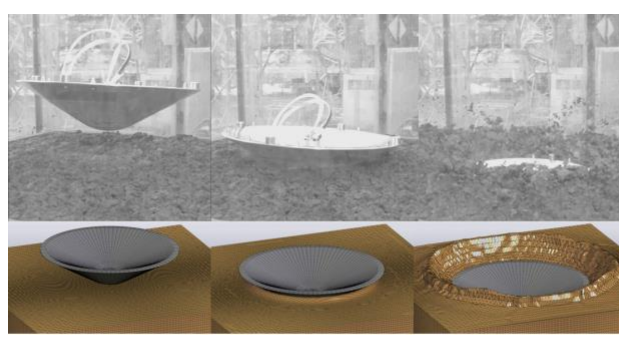

Figure 21. High-speed video frames and corresponding FEA model of soft soil penetrometer impact

developed. Future planned penetrometer impact testing will include full OS hardware including tubes instrumented with miniaturized shock accelerometers.

Analysis – Numerous OS concepts and penetrometer hardware have been vetted structurally with the use of the explicit FEA code LS-DYNA. Early designs were down selected in many cases due to design issues discovered or confirmed through simulation. In the case of the current OS design, five official revisions have occurred, each undergoing dynamic impact analysis to determine stress margins, areas for improvement, impact orientation effects, secure force requirements, tube and tube seal loads, and overall dynamic response. The most current FEM of the OS shown in Fig. 22 simulates three important mission phases: 1) MAV insertion and engagement with the claw mechanism, 2) Secure preload actuation with aluminum foam crush, and 3) 1300 g half-sine impact loading. Future planned simulations include OS ejection from MAV, OS FEM validation against planned full scale OS impact testing, and robust OS design studies to identify failure modes in the extreme off nominal scenarios.

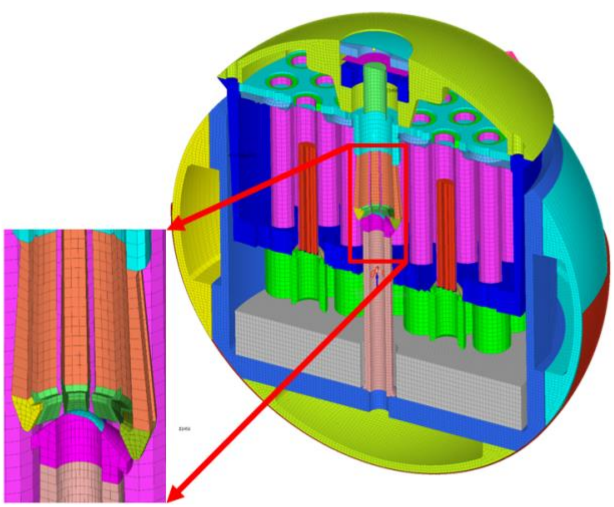

Figure 22. Current OS FEM with close up image of flexure claw structure

Optical Tracking

Analysis – Simulations to determine the required OS albedo were conducted. The results of the effort are currently quite preliminary due to the lack of definition of the SRO optical tracking system. This analysis should be revisited once the hardware and mission parameters become more stable.

The detectability of the OS via the optical camera on board the SRO may be assessed from the signal-to-noise ratio (SNR) of the OS optical signature on the camera detector. A mathematical expression was developed for SNR, based upon the photon energy from the illuminated OS captured within the camera aperture during an exposure, the energy-to-data number conversion factor for the detector, and the system noise expressed as a data number. This expression is dependent upon the solar energy flux at Mars, the camera characteristics, the range from SRO to the OS, the phase angle of the OS as viewed by SRO (i.e., the Sun-OS-SRO angle), the diameter of the OS, and the albedo of the OS.

In order to develop a requirement for the OS albedo, conservative values were chosen for each of the parameters in the SNR equation, allowing the equation to be rearranged and solved for OS albedo. An SNR limit of 5 was selected for detectability, and the maximum line-of-sight range between SRO and the OS was utilized. For example, with a phase angle of 90°, maximum line-of-sight range, and conservative assumptions for all other parameters, the SNR equation shows that the OS albedo must be 0.37 or greater to ensure detectability. The OS albedo requirement may be met through selection of OS material and surface coatings.

Radio Electromagnetics.

Beacon Testing - A prototype of the beacon was built, assembled, tested, and is currently undergoing an extended test using the target application Li-ion batteries to demonstrate RF and DC performance over the battery lifetime. Preliminary results suggest six cells of the target battery type should be sufficient to broadcast at a 1% duty cycle, with an average of 20 mW power consumption, for over 90 days. An image of the prototype UHF beacon electronics board is found in Fig. 23.

Figure 23. Prototype UHF beacon electronics board

Antenna Simulation – One candidate design is of the form shown in Fig. 17. A bow-tie configuration was utilized. Preliminary numerical analysis of the beacon indicate that the signal is very narrowly banded around 433.5 MHz as intended. The next image in Fig 24 shows a view of the RF emission pattern generated by the antenna. Although the bow-tie design is at the preliminary stage, it is promising to meet the key OS detection and tracking requirements

Future Plans

Continued progress and maturation of the OS design is required to support studies of interface requirements between the current and possible future projects of the MSR campaign. A representative OS is needed for a near term study and possible demonstration of the baseline MAV design, as well as for a study of the rendezvous and capture system for a possible next Mars orbiter

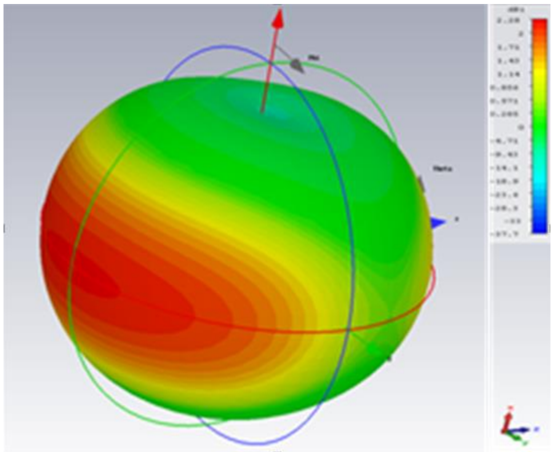

Figure 24. Preliminary antenna emission pattern derived from analysis

Metallic OS test hardware is currently in fabrication and soon a functioning OS test article will be complete. The test article will accept a suite of sensors that then can be used to recover data from full-scale impact testing of the OS in realistic Earth impact environments. The test article is also planned to be used for thermal, vibration, tube manipulation and other testing efforts. Continuous design improvements are in the works, and the next generation of the OS design is also anticipated to see hardware testing. The upcoming OS revisions are anticipated to be better performing and with lower mass. Lastly, the preliminary proof-of-concept beacon design is in fabrication and soon will begin testing to determine its viability for path-to-flight.

Numerous future analyses are also planned. Ongoing aerothermal and thermal analysis aim to determine if the Mars assent and on-orbit phases of the mission pose a significant threat to the sample temperature requirement. Other planned thermal analyses would determine if the under-development BTC brazing technology poses a problem for the samples or OS structure. A new MAV to OS support structure in design has critical interfaces to the OS, new features on the OS will have to be added, which then will need to be vetted through dynamic analysis. Continuous analysis of emerging OS design concepts will ensure that future OS features are capable of withstanding the intense Earth impact event. Lastly, topological optimization is planned for use in several structural areas to see what, if any, mass savings can be made that were previously overlooked.

7. Summary

This paper has addressed the recent development of an OS concept for potential MSR by the Mars Program Formulation Office at NASA/JPL. We have discussed the OS functional, environmental, and interface requirements and evolution of its baseline design to meet these requirements. The OS would serve as a common link between the existing Mars 2020 sample caching mission and possible future MSR projects. As such, the OS design would have to meet all of its functional requirements during its transit from Earth to Mars, Mars surface operations, Mars launch, Mars orbit, transit from Mars to Earth, and Earth landing. Adding to the design challenges is the dual nature of the OS interfaces: on one hand, the OS must securely interface with the existing sample tube hardware being developed by Mars 2020, while interfacing with possible future projects that are yet to be defined.

Thus the OS designer must assume reasonable future systems that do not overly constrain the design, cost, and operational flexibility of these potential future systems. To verify and validate the designs, the OS design team has been performing extensive finite element numerical modeling as well as a thorough test program to simulate the environments associated with the potential downstream missions. The current preliminary OS design strikes a good balance between the existing Mars 2020 tube interface and the needs of the potential future projects. As the team's development efforts continue and as knowledge of the future mission interfaces improves, it is expected that the OS design also will mature from where it is today.

Acknowledgements

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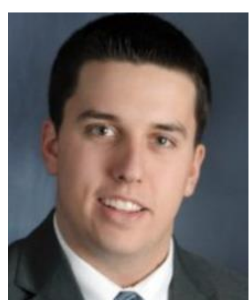
BIOGRAPHY

Scott Perino *is the mechanical lead for the Mars Advanced Development Team (ADT) at JPL, He directs the development, analysis, and testing of preliminary hardware for the post Mars 2020 sample return missions. Other assignments include dynamic analysis support for the Mars 2020 percussion drill, OS containment technology development, and the Asteroid Redirect Robotic Mission (ARRM). Scott has a BSME from the University of Washington in 2009, and a PhD ME from Virginia Tech in 2014. At VT with support from NASA Langley, his research focused on created rapid analysis techniques and new impact absorber technologies for the MSR EEV concept.*

Darren Cooper *received his B.S. in Mechanical Engineering from the University of Texas at Austin in 2007 and his M.S. in Mechanical Engineering from University of Southern California in 2012. He is currently a design engineer for Mars ADT, supporting future mission hardware development including the Orbiting Sample subsystem. Prior to working on Mars ADT, he worked as the Mechanical Integration and Test Lead for the Low Density Supersonic Decelerators (LDSD) project. He also has worked as a System Integration and Test Engineer for the Soil Moisture Active Passive (SMAP) mission.*

David Rosing *is the System Engineer for the Advanced Development Team (ADT) in the Mars Program Formulation Office of the NASA/Jet Propulsion Laboratory (JPL) in Pasadena, CA. The ADT develops require-ments and interfaces between the existing Mars projects and possible future Mars Sample Return projects. His past assignments included system engineering on Space Shuttle experiment, the Galileo Jupiter Orbiter, and other Earth Orbiting Instruments as well as serving as the group supervisor for the opto-mechanical engineering group in the JPL mechanical system division. David has a BSAE degree from the University of Colorado and MSAE degree from Stanford.*

Louis Giersch *received his PhD in Aeronautical and Astronautical Engineering from the University of Washington in 2005. He has been at JPL for more than 9 years. He was the lead engineer for the successful development and dem-onstration of the Supersonic Inflat-able Aerodynamic Decelerator Robotic-class (SIAD-R), a part of the Low Density Supersonic Decelerator (LDSD) project. He has also worked on a number of planetary mission formulation efforts, including Mars Sample Return.*



Zachary Ousnamer *was a mechanical design engineer for JPL’s Mars ADT and helped to develop preliminary OS concepts and the define the Mars 2020 sample tube retention interfaces. Zach is currently the Cognizant Engineer for the Mars 2020 Rover’s Remote Sensing Mast (RSM) at JPL. Zach received his BS in Aerospace Engineering from the University of Michigan in 2010 and his MS in Engineering from UCLA in 2013.*

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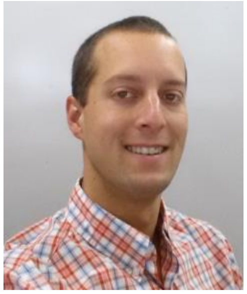
***Carl Spurgers** received his B.S. and M.S. in Electrical Engineering from the University of Texas at Dallas with a focus in RF and microwave design. Prior to JPL, he supported digital and RF hardware design efforts for several military applications while at Rockwell Collins and L-3 Communications, including conformal composite UHF phased array antennas. He arrived at JPL in 2013 and has since supported a variety of programs including NISAR, SWOT, DSOC, FINDER, Mars ADT, Mars 2020 Rover, and Mars Helicopter Scout. Assignments include design of digital electronics for the NISAR UST – KaM radio, capable of downlinking data to Earth over Ka-Band at 1 Gsps OQPSK, and piezoelectric transducer amplifier and receiver electronics for use in an acoustic modem to support down-hole wireless communications.*



***Matthew Redmond** is a part of the Instrument and Payload Thermal Engineering group at JPL, and is currently the OS thermal lead. He is also supporting the Mars 2020 rover surface thermal design. In the past, he has worked on MAV technology development, as well as the Low Density Supersonic Decelerator (LDSD) project. Prior to working at JPL, Matthew received a B.S. and M.S in Mechanical Engineering from Georgia Tech, and performed microchannel research in Turkey as a Fulbright student grantee for one academic year.*

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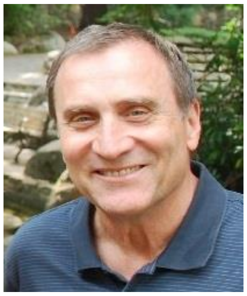

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