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Synchronous Separation, Seaming, Sealing and Sterilization (S4) using Brazing for Sample Containerization and Planetary Protection

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Abstract

The return of samples back to Earth in future missions would require protection of our planet from the risk of bringing uncontrolled biological materials back with the samples. This protection would require "breaking the chain of contact (BTC)", where any returned material reaching Earth for further analysis would have to be sealed inside a container with extremely high confidence. Therefore, the acquired samples would need to be contained while destroying any potential biological materials that may contaminate the external surface of the container. A novel process that could be used to contain returning samples has been developed and demonstrated in a quarter scale size. The process consists of brazing using non-contact induction heating that synchronously separates, seams, seals and sterilizes (S4) the container. The use of brazing involves melting at temperatures higher than 500°C and this level of heating assures sterilization of the exposed areas since all carbon bonds (namely, organic materials) are broken at this temperature. The mechanism consists of a double wall container with inner and outer shells having Earth-clean interior surfaces. The process consists of two-steps, Step-1: the double wall container halves are fabricated and brazed (equivalent to production on Earth); and Step-2 is the S4 process and it is the equivalent to the execution on-orbit around Mars. In a potential future mission, the double wall container would be split into two halves and prepared on Earth. The potential on-orbit execution would consist of inserting the orbiting sample (OS) container into one of the halves and then mated to the other half and brazed. The latest results of this effort will be described and discussed in this manuscript.

Keywords: Sample return, planetary exploration, brazing, synchronous Separation, Seaming, Sealing and Sterilization (S4), break the chain (BTC), containerization, and planetary protection.

1.0 Introduction

Humans have always been curious about if we are alone in the Universe and addressing this question is one of the key goals of the ongoing NASA exploration mission. Initially, the missions were focused on observing the various Solar bodies by orbiting or flying by them. As the capability has advanced in landing on planetary bodies, major reports such as the Planetary Science Decadal Survey have prioritized returning samples from such bodies back to Earth for study [1]. Testing returned samples would provide critical information about the composition of these bodies surface, and help us learn as much as possible about the evolution of the surface and atmosphere. The return of samples back to Earth would require protection of our planet from backward contamination from the returned samples. A key requirement of such a mission is that if the probability of failure is estimated higher than 10^{-6}, the mission would be aborted and the sample container would not be returned to Earth [2]. An effective and extremely reliable mechanism is required to assure a high level of planetary protection of Earth in support of potential sample return missions from potentially habitable environments. The protection mechanism would have to hermetically seal the returned sample container, sterilizing the sealing/seaming section, and preventing contaminated surfaces from exposing the external surfaces of the returning container. To ensure success at the required probability, it will be necessary to "break the chain of contact (BTC)", where any material reaching Earth would have to be inside a sealed container with extremely high level of confidence. Therefore, it would be necessary to contain the acquired samples and destroy any potential biological materials that may contaminate the outside of the container while protecting the sample for further analysis.

The focus of the current study is on potentially returning samples from Mars. For this purpose, a novel synchronous seaming, sealing, separation, and sterilization (S4) process has been developed and demonstrated to provide containerization and planetary protection [3 - 6]. Using brazing [7], a double wall container prototype with inner and outer shells and an equivalent of "Earth clean" inner surfaces were designed, produced, and used to demonstrate the process. In a potential future mission, the double wall container would consist of two halves produced on Earth, while on-orbit the S4

process would be executed by inserting the sample into the inner halves and then putting them in contact and melting the braze material. The brazing material that melts at temperatures higher than 500ºC is being used to assure sterilization of the exposed surfaces since, at this temperature, carbon bonds break via pyrolysis. The complete process consists of two-steps, Step-1: the double wall container halves are fabricated and brazed on Earth; and Step-2: Assembling and brazing on-orbit the samples in a sealed and externally sterilized container. The progress in this ongoing study is described and discussed in this manuscript.

2.0 Analytical modeling of the induction heated BTC brazing process

Predicting the performance of the brazing process using analytical modeling is critical to allow an effective and reliable design of the BTC mechanism. For this purpose, finite element (FE) methods were used to perform numerical analyses and simulations of various configurations and container materials with focus on stainless steel and titanium containers. The models were used to evaluate the characteristics of potential designs, predict the temperature rise of the samples during the induction brazing process, conduct parametric studies, and optimize the design for better temperature control and lower power consumption.

A concept configuration of applying the brazing break-chain technique in orbit around Mars is shown in **Figure 1 right**. It consists of a hemispherical BTC lower shell, which is a part of the wall of the spacecraft, and it is pre-brazed to the base structure on Earth. The Cap and the BTC top section of the shell are pre-brazed together on Earth forming a double wall assembly. The inside space of the double wall assembly is Earth-clean (has only been exposed to Earth's environment) and it is the lower section in the Figure. The samples that are inside tube assemblies would be fixed and covered by a spherical OS shell and would potentially be contaminated with Mars dust on its external surface. A closeup view is shown in **Figure 1 left** with details of the area where the brazing of the BTC shell and separation of the shell from the Cap and Base would be performed. The two vertical interfaces are the pre-brazed joints that would be separated. The oblique interfaces are those that are would become jointed. A multi-physics FE analysis including induction heating and thermal models was performed to simulate the S4 process in support of the concept design. The shell of the OS is made of aluminum with diameter of 27 cm (i.e., full scale size). The BTC container and double wall are made of stainless steel 304 or titanium alloy Ti-6AL-4V. The measured temperature dependent electric and thermal properties used in the simulation were taken from the open literature. A simplified model is applied to the sample tube assemblies represented by three cylindrical tubes with homogenous material having equivalent thermal properties. A high temperature insulation material made of ceramic foam (MIN-K) is selected for the insulation layer between the BTC shell and the OS. The melting point of the brazing material is set at 750°C. The material properties applied to the FE analysis are listed in **Table 1**. In addition to the heat conduction in the solid elements, the thermal model includes the heat radiation within the enclosure of the Cap-BTC top shell and from the outer surfaces to ambient.

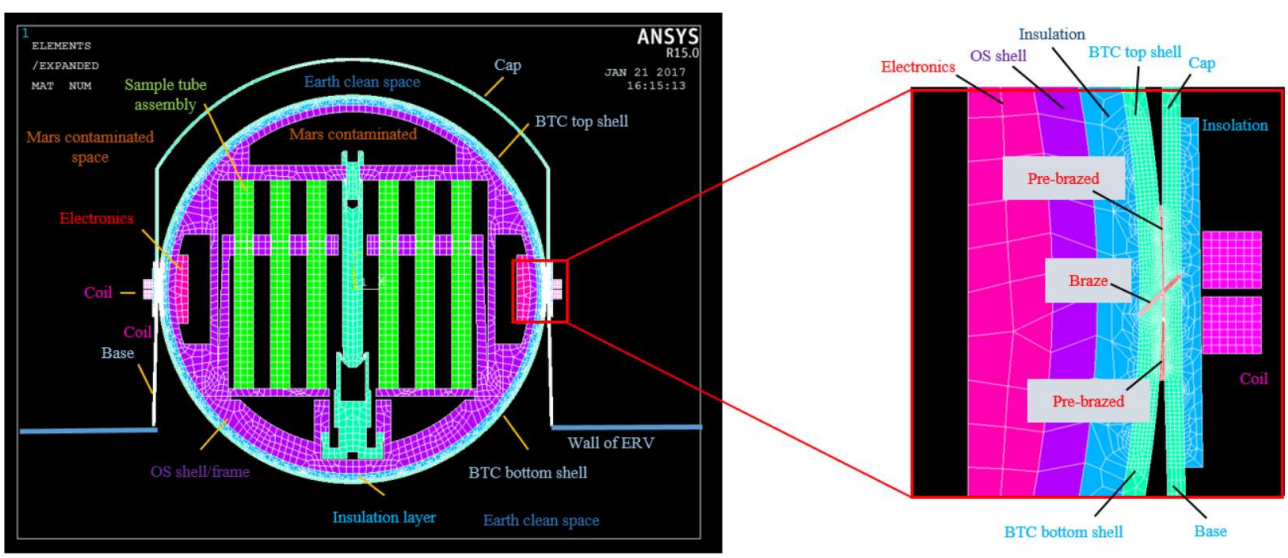

Figure 1: FE thermal model of a concept design for the BTC using inductive heating. The OS shell, cap and base made of Ti-6Al-4V or SS304. The insulation layer is assumed to be made of ceramic foam MIN-K.

Table 1: Data of the material properties that is being used in the simulations

Material	Density (kg/m^2)	Thermal conductivity (W/m-C)	Specific heat (J/kg-C)	Resistivity (Ohm-m)
Ti-6AL-4V	4430	7.04*	525*	164e-8*
SS304	7969	12.9*	475*	70e-8*
Al6061	2700	155	1015	4.11e-8
Copper	8940	388*	380*	1.54e-8*
MIN-K	320	0.03*	740	
Sample Ass.	1570	2	500	
Braze	9170	110	343	11e-8*

*: Temperature dependent data were applied. The listed numbers are the values at 0°C.

An electromagnetic FE model was established to simulate the induction heating and it is shown in **Figure 2** and it is similar to the thermal model described above. For simplicity, the detailed structures inside the aluminum shell of the OS were omitted because the EM field is expected to be very weak inside due to the shielding effect of the metallic shells in the frequency range of interest (20 – 60 kHz). This simplification was validated by preliminary simulations for SS304 BTC shell at 0°C. The material properties that were using in the simulation are listed in **Table 1** and magnetic relative permeabilities of all the materials are assumed to be 1. A 2-turn copper coil with a cross section of 6.5x6.5 mm^2 is placed close to the brazing region and the gap between the coil and the BTC wall surface is 5 mm and the spacing of the two turns is 1 mm.

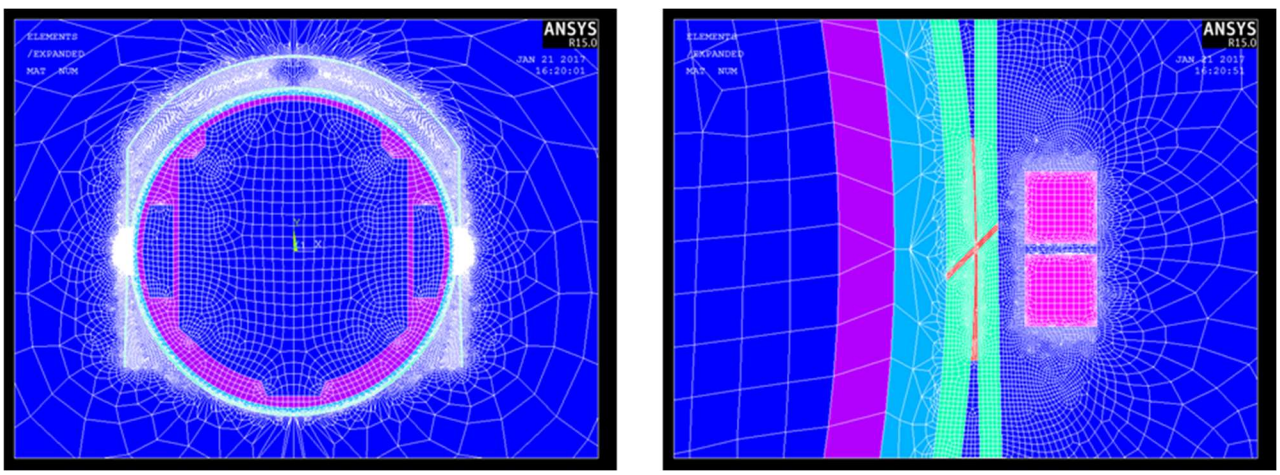

Figure 2: The magnetic model for induction heating. The structures inside the conceptual OS shell were omitted because the electromagnetic field inside is shielded by the metallic shells in the frequency range being used.

A multi-frame FE model including both the thermal and electromagnetic models described above were used to simulate induction heating brazing BTC process. The two models run alternatively to mimic the mechanism and material properties are updated to account for the highly temperature dependent properties. This model was applied to both SS304 and Ti-6Al-4V BTC shells. Temperature dependent thermal and electrical material properties were applied to the stainless steel, copper, and insulation ceramic. The assumed ambient temperature and the temperatures of all components at the beginning of the simulation is 0°C. The temperature of the coil is assumed to be well controlled by liquid flow cooling, i.e. the temperature rise is neglected in the coils and the brazing temperature is 750°C. Using the model it was determined that, for the SS304 shells, 420 seconds (7 minutes) are required for all the braze material to reach or exceed the brazing temperature of 750°C when 480A current at 50kHz was applied to the coil. The major heat energy is still limited to the zone surrounding the heating area and very small temperature rise takes place inside the OS and the total energy consumption is 200 kJ. The input electric power (Total), heating power on shell and coil loss with 480A coil current at 50

kHz are shown in **Figure 3**. The input electric power is from 4.26 kW at the beginning and rises to 5.30 kW at 420 second. The total energy consumed after 420 s are 2108kJ, 1729kJ and 379 kJ for the electrical input, heating and coil loss, respectively. The average coil efficiency is 82%.

According to the temperature rise curve predicted in the simulation, the heating step of the simulated process is set to last for 420 seconds. Then, the BTC container would be separated from the Cap-Base, and moved into Earth Return Vehicle (ERV) and cooled down there. In the simulation, the container is assumed to be moved to a position far away from the heated Cap-Base area and cools down by the radiation loss in the 0°C ambient environment. The maximum temperatures in the sample assemblies are shown in **Figure 3:** Input electric power (Total), heating power on shell and coil loss with 480A 50 kHz Induction heating. as a function of the cooling time. The temperatures first rises and then falls after reaching a maximum. The maximum temperature in the sample assemblies is found to be 28.7°C, which is an acceptable temperature rise for sample stability.

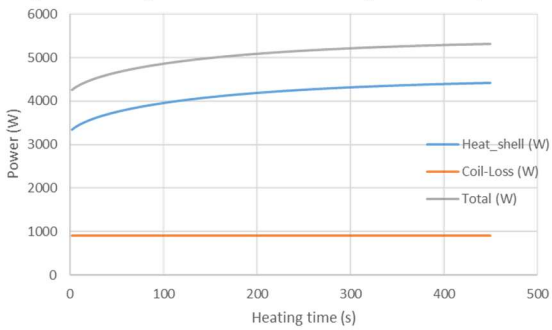

Figure 3: Input electric power (Total), heating power on shell and coil loss with 480A 50 kHz Induction heating.

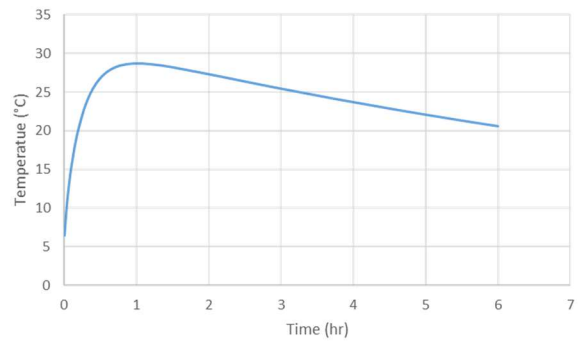

Figure 4: Maximum temperature at sample tube in cooling process after the brazing is 28.7 °C.

The simulation was also performed for Ti-6Al-4V BTC shell under the same assumptions except a smaller electric current of 370A was applied. The comparison of the two cases are summarize in the **Table 2**. The analysis suggests the use of the titanium alloy instead of stainless steel signifigant decreases the required power, energy and sample temperature rise.**Table 2: Comparison of the stainless steel and titanium alloy base materials**

Material	Input current	Input power	Average power	Coil efficiency	Heating time	Energy	Sample temperature
	A	kW	kW	%	s	kJ	°C
SS	480	4.26-5.30	5.20	82.01	420	2108	28.74
Ti	370	2.68-3.66	3.39	84.37	326	1105	16.66

3.0 The container configuration concept

The development of the BTC brazing process started in 2004 and initially the focus was on cylindrical configurations that had the size of a coffee cup in which returned samples could be contained. The task objective has been to demonstrate the feasibility of using brazing as a process of synchronous sterilization, seaming, sealing, and separation. The details of the process were covered in two NASA New Technology reports [3 - 4]. The original design and details were developed for execution on the surface of Mars. As indicated earlier, the method is based on using a double wall container having internal gap simulating "Earth clean" volume. A brazing material seams the two containers/walls where the inner one is used for the returned sample and (upon separation of the inner container) the external one becomes integral part of a lander. The double wall container is prepared on earth in two separate components: a lid and a base, both having double wall or shells. The orbiting sample is captured and inserted into the lid inner shell and the lid component is aligned and brought in contact with the base component. The outer shell of the base component is attached to the spacecraft structure. The inner shells are lined on the inside with a thermally insulating layer for protecting the samples. By heating with an inductive heater, the brazing material joining the inner shells to the outer shells and the brazing materials between the two components are melted separating the inner shells and sterilizing the joints area. The inner shells are then separated from the outer shells while being held in contact, the heating is stopped and the joints are allowed to cool down. In this way the lid outer shell is brazed to the base outer shell creating a separation wall between the contaminated area and the earth clean

area of the spacecraft. The inner shells are brazed together forming an outside clean container that encloses the sample. The newly formed container located inside the clean area of the spacecraft can now be transferred to the earth return vehicle for futher processing.

The process was demonstrated in a vacuum chamber and the induction heating was done by inserting the container assembly inside the coil and connected via a feed-through to the drive electronics. To minimize oxidation, once the vacuum reaches a level of milli-Torrs, research grade Argon with 99.99% purity back-fills the chamber and the vacuum pumping is resumed. A successful sealing and separation process was demonstrated and the verification of the sealing was done using a spectrometer based He leak detector by creating a vacuum inside the container connected to the spectrometer and spraying helium on the outside next to the separated and seamed area [6].

During the process of heating the container, it was mounted on a support fixture using a bottom screw for aligning the brazing rings with the center plane of the coil. In addition, a retaining bar was placed above the container to keep the inner container from an uncontrolled ejection during the melting of the braze material. The assembly was heated until the brazing rings melted and created flow of the brazing material as needed to accomplish the S4 process. The process was stopped when the formed container (seamed lid and the inner container) were ejected by the force of the spring located between the inner and outer lid shells.

The details of the proposed S4 process were enhanced to address the lessons learned from the various brazing tests and it has been designed for execution in two steps as follows:

Step-1: This Step is the hardware fabrication on Earth prior to the mission. It involves a double-wall container with brazing rings and a separation joint.

Step-2: This process is designed for execution on-orbit.

- Synchronously, the container that contains the OS is sterilized, seamed, sealed, and separated.
- The sealing is technically a welding process since it brazes the pre-brazed metal surface of the base and cap together.

As pointed out previously, the BTC-brazing sterilization is the result of heating above 500ºC for several minutes (depending on the structure and materials). Further, the sealing, seaming and separation takes place synchronously:

- Unless the braze melts, the OS is not transferred to the Earth-clean area in the sealed and seamed container that is externally Earth-clean.
- Synchronously with the separation of the sealed container, the outside shell of the double-wall hemisphere "closes the door" to Mars contaminants.

The key challenge that was identified when using the cylindrical container configuration has been the possibility of jamming when inserting the double wall lid into the base. This risk has been addressed by extremely careful insertion when the process was done manually. However, this autonomous insertion is expected to be a great challenge for a robotic mechanism on-orbit. To address this jamming concern, a cone-within-cone design was conceived [6]. Here, the open edge of the double wall container has an interface with a cone configuration. Similarly, the base lid has a cone configuration at its open edge. The two cone angles match each other and they are used to guide the double wall lid when it is brought in contact with the base for precision alignment. In addition, it eases the heat transfer in the process of melting the braze material. After the induction coil is activated and the brazing materials have melted, a spring between the outer and inner shells of the double wall lid keeps the lid inner shell preloaded against the base inner shell. The base inner shell position is controlled by an active element such as an actuator or a passive element with a timer. The newly formed container encloses the OS vessel but continues to be held in place until the joint, which is formed along the conical surface, solidifies. The separation of the container is done along a second conical shaped surface oriented opposite to the initial conical surface such that it allows for the movement of the container axially away from the coil. This increases the radial gap between the moving parts and, therefore, preventing the possibility of parts jamming. The mechanism steps consist of the following: approach, contact, coil activation, separation, coil deactivation and cooling (**Figure 3**). The angles of the two cones and the number of the brazing rings can be chosen based on space availability and the need to use a smaller or larger volume of braze material.

The process is summarized graphically in **Figure 4** with the Step-1 prepared components are shown in **Figure 4a**. The Step-2 process takes place after the capture and enclosing the OS and the activation of the induction heater to make the braze seal/seam and the separation braze rings melt. Successful demonstration of the cone-within-cone configuration has been done where a set of parts have been brazed and tested leak-free using spectrometer, vacuum and helium spray as described earlier. Even though the seal was successful, during the S4 process of brazing the prototype container that is

shown in **Figure 4**, the lid inner shell shifted from the axis of the container. To address this issue, a registration feature was added to the conical interfaces of the lid and the container and the process was repeated. Again, the container that was subjected to the two steps process was found leak free, in addition, the registration features produced a successful alignment during testing.

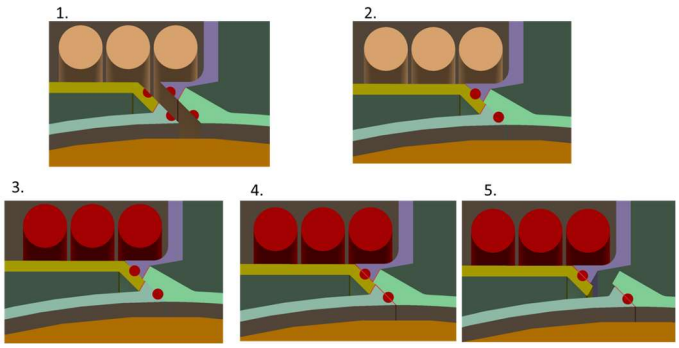

Figure 3: The S4 process steps and the double cone-within-cone representation.

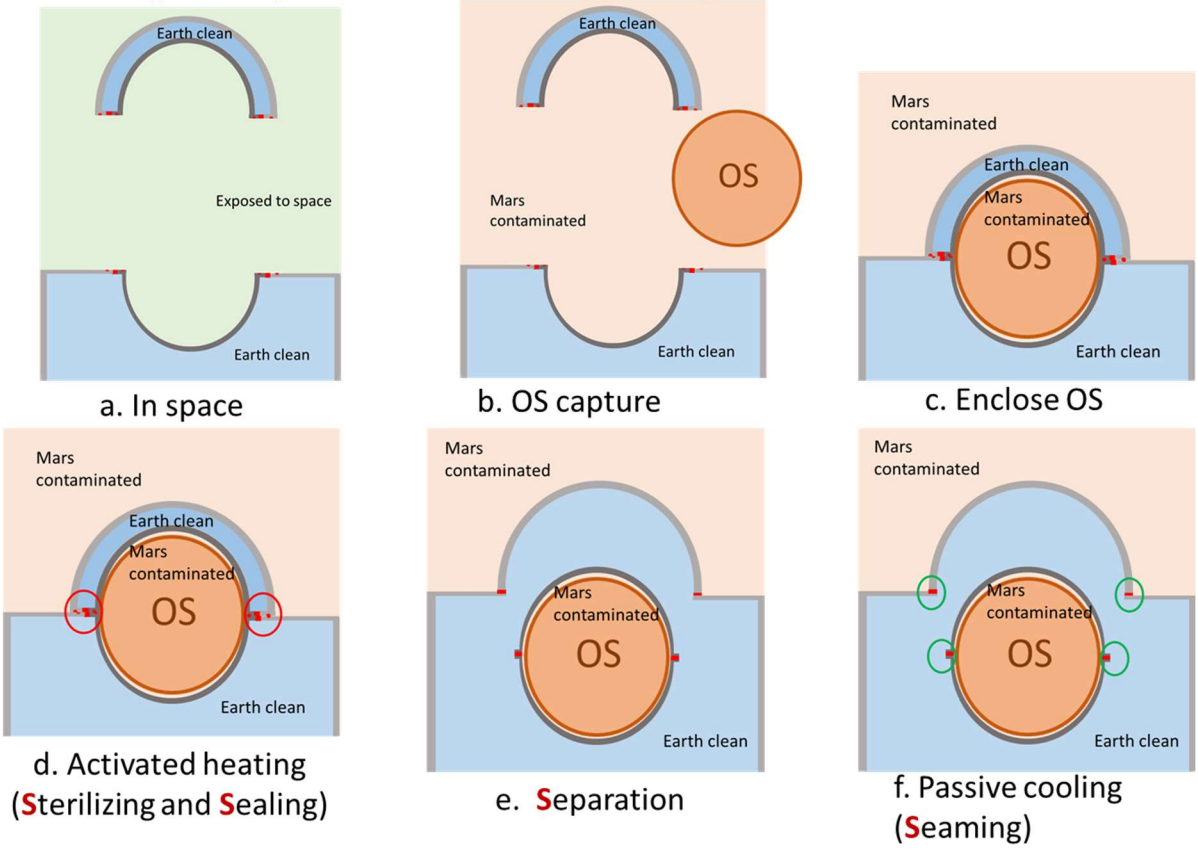

Figure 4: The Step-2 process of synchronous Sterilization, Sealing, Separation, and Seaming on-orbit

4.0 The full scale testing

As the concepts for potential Mars Sample Return have evolved, the shape of the notional container has been modified to be 27 cm diameter. This container is designed to be filled with the sample tubes inside the OS for return and to be launched to orbit via a conceptual Mars Ascent Vehicle (MAV). The location for the execution of the BTC process would potentially be on-orbit about at an altitude of 500 km. The OS would need to be contained and subjected to the BTC brazing S4 process and then inserted into an Earth Entry Vehicle (EEV) in an orbiting spacecraft. Towards the goal of testing these size full scale containers, efforts are currently underway to establish the test chamber that will perform the BTC brazing

autonomously . For this purpose, a vacuum chamber with specially designed feedthrus has been purchased and the control of the separation process via actuators, springs and load cells are being designed and produced for mounting inside the chamber. A design rendering view of the chamber and its photo are show in **Figure 5.** Given that the highest vacuum level that can be reached is about 2x10-6 torr, the use of argon for back-filling and avoiding oxidation is not expected to be necessary.

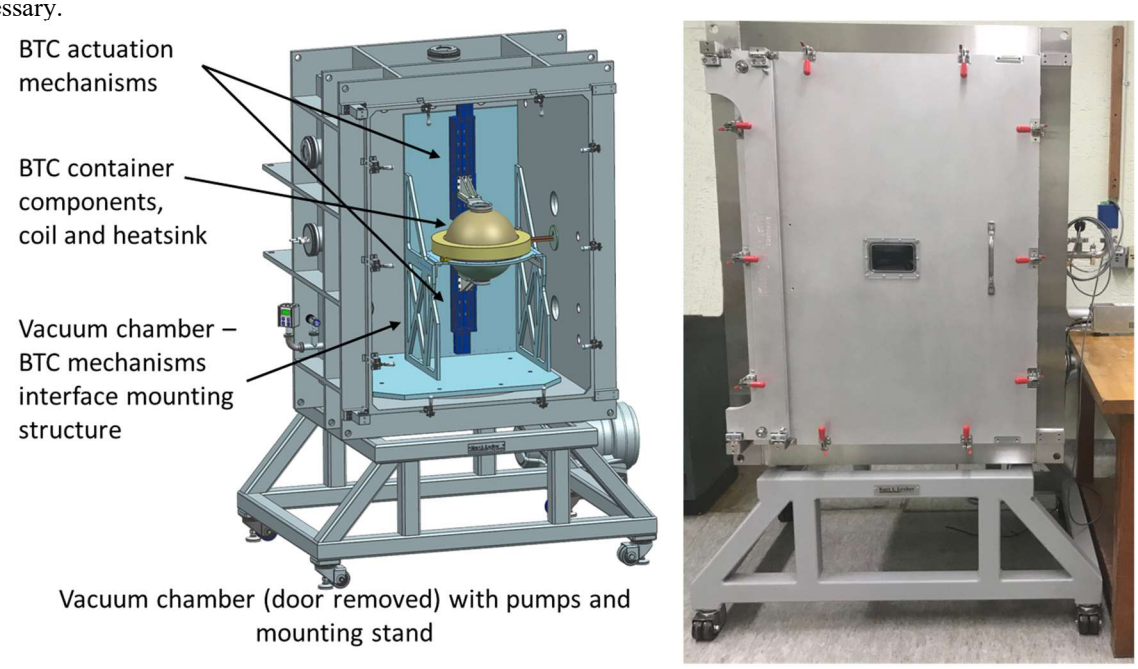

Figure 5: The vacuum chamber.

5.0 Summary and conclusions

Potential Sample Return from Mars and other planetary bodies would require protection of our planet from backward contamination. For this purpose, it would be necessary to enclose the acquired samples inside a sealed container and destroy any contaminants on the external surface before returning the container to Earth. A brazing method has been developed and described in this manuscript that meets the containerization and protection requirements and its feasibility has been demonstrated [3 - 6]. The initial method of sterilization and sealing has been developed using a cylindrical configuration. However, the related design did not effectively address potential issues that are involved with putting in contact and aligning the container components and separating the container from the launch vehicle after it was seamed and sealed. A modification of the proposed mechanism using a double-wall container design has been demonstrated that allows for seaming, sealing and sterilization. This separation of the container from the launch vehicle either on the surface of the explored planet, on-orbit, or on Earth can be accommodated by the technology. A double wall configuration is used with clean inner-spaces allowing brazing the inner container with the returned sample. For sealing the container, the use of brazing material that melts at temperatures that are higher than 500 ^{o}C assures the destruction of biological materials via pyrolysis. A cone-within-cone design has been conceived and demonstrated to allow a robotic mechanism to reliably handle and manipulate the components of the process. The developed BTC process based on brazing has been chosen as the primary containerization method for potential Mars Sample Return.

6.0 Acknowledgment

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7.0 References

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