Heating and thermal control of brazing technique to break contamination path for potential Mars sample return

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ABSTRACT

The potential return of Mars sample material is of great interest to the planetary science community, as it would enable extensive analysis of samples with highly sensitive laboratory instruments. It is important to make sure such a mission concept would not bring any living microbes, which may possibly exist on Mars, back to Earth's environment. In order to ensure the isolation of Mars microbes from Earth's Atmosphere, a brazing sealing and sterilizing technique was proposed to break the Mars-to-Earth contamination path. Effectively, heating the brazing zone in high vacuum space and controlling the sample temperature for integrity are key challenges to the implementation of this technique. The break-the-chain procedures for container configurations, which are being considered, were simulated by multi-physics finite element models. Different heating methods including induction and resistive/radiation were evaluated. The temperature profiles of Martian samples in a proposed container structure were predicted. The results show that the sealing and sterilizing process can be controlled such that the samples temperature is maintained below the level that may cause damage, and that the brazing technique is a feasible approach to breaking the contamination path.

KEYWORD: seal, sterilizing, Mars sample return, contamination.

1. INTRODUCTION

Potential future NASA missions are expected to increasingly seek the return of samples to Earth for further processing and analysis. These sample return missions may have the objectives of searching for evidence of life in the universe, using the most capable analytical techniques that are available on Earth. In addition, this data would be useful in planning for the landing of humans on Mars and beyond. In preparation of such mission concepts, there are considerations to acquire Martian samples, seal them in a container, and store them on Mars for future missions to potentially carry back. Various approaches have been investigated to develop sample acquisition, handling and sealing techniques [Younse et al. 2012, 2014, Backes, el al. 2013, Bao et al. 2013]. The issue of planetary protection of Earth is a challenge to potential Mars sample return. Techniques that would reliably seal the "Mars-dirty" in an "Earth-clean" container, and have assured clean, uncontaminated outer surfaces are critical for "Breaking The Chain" (BTC) of contamination from Mars to Earth. Several methods have been proposed and investigated [Dolgin et al. 2000; Bao et al, 2015; Bar-Cohen et al, 2004, 2017]. The most critical issue of planetary protection of Earth is living biological contamination. The method of Simultaneous Separation, Seaming and Sealing using Brazing (S^4B) has shown to have the potential to assure the containment of the acquired samples in a hermetically sealed container with its exterior free of unsterilized Mars material.

The sterilization method involves heating selected sections of the container to high temperature over 500°C while the temperature of the samples that may be returned is controlled to an acceptable level to assure the integrity of the samples. The power required to conduct the brazing process in orbit or on the Mars surface is another concern related to the application of the S^4B technique. The break-the-chain procedures for proposed container configurations were simulated by multi-physics finite element models. Two heating methods including induction and resistance-radiation were evaluated. The required power and energy consumption and the temperature profiles of Martian samples in the proposed container were predicted. The results will be used to help advancing the developed capability.

2. INDUCTION HEATING CONCEPT FOR APPLYING S^4B IN MARS ORBIT

Finite element (FE) approaches were used in the concept development. FE models were constructed to perform numerical analyses and simulations for various concept designs for the applications of the BTC technique to the stages of sealing the ground cache and in-orbit sealing of a conceptual Orbit Sample (OS) container. The models were used to evaluate the characteristics of different potential designs, predict the temperature rise of the samples during the sealing

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process, perform design parametric studies, and optimize the design for better temperature control and lower power consumption. Examples of FE model analysis results for preliminarily optimized concept designs for OS sealing are presented in the following sections.

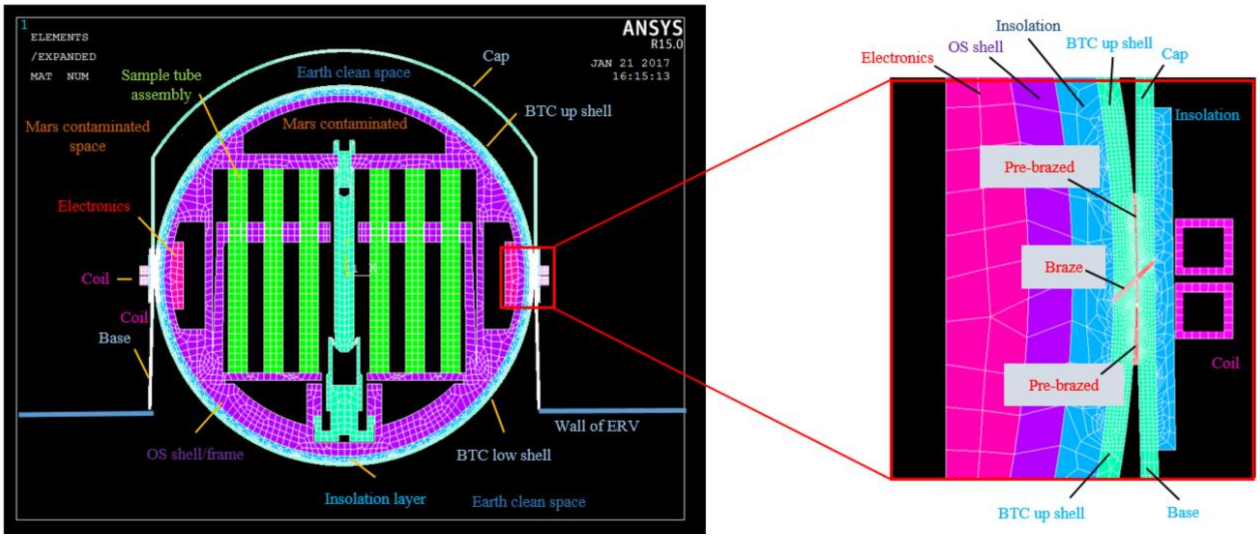


Figure 1: Concept design for application of the brazing break-chain technique in orbit around Mars using inductive heating. Configuration and FE thermal model showing a conceptual OS shell, cap and base made of Ti-6Al-4V or SS304. The insulation layer is assumed to be made of ceramic foam MIN-K.

Figure 1 shows a concept design to apply the brazing break-chain technique in orbit around Mars. In this concept, a hemispherical BTC lower shell is pre-brazed to the base structure on Earth, which is a part of the wall of the spacecraft. The lower space in the figure is inside of the Earth clean spacecraft structure. The Cap and the BTC top section of the shell are pre-brazed together on Earth to form a double wall assembly. The inside space of the double wall assembly is also Earth-clean (only exposed to Earth's environment). The samples that are inside the sample tube assemblies would be fixed and covered by a spherical OS shell on the surface of Mars and are launched to orbit by a conceptual Mars Ascent Vehicle (MAV). The OS would potentially be contaminated with Mars dust on its outer surface. A spacecraft mechanism would capture the OS, open the Cap-BTC top shell assembly from the Base-OS, place the OS between them and press the Cap-BTC top shell assembly to the Base- BTC bottom shell. In this operation, the OS may contaminate the exposed surfaces of the surrounding areas. Figure 1 shows the components in position after these operations and ready to perform the S^4B brazing Break-The-Chain procedure.

The zoomed figure on the right of the Figure 1 shows the 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 are going to be separated. The oblique interfaces are those that are going to be jointed. When the area is heated to a temperature over the melting point of the braze material a mechanism (not illustrated in the Figure) would hold the two halves of the BTC shell together and move them to the inside of the Earth Return Vehicle (ERV) while the Cap is continuously being pressed onto the Base. After cooling down, the two halves of the BTC shell would be brazed together and form a BTC container that seals the OS inside. The outer surfaces of the BTC container would be Earth-clean and the interface joint would be sterilized by the high brazing temperature which is nominally over 500°C. At the same time, the Cap would be brazed to the Base with high temperature sterilized joint to prevent the contamination of Mars to the Earth-clean environment inside the ERV.

FE thermal analysis was performed to simulate the S^4B procedure for the concept design. The main dimensions are noted in Figure 1. The shell of the OS is made of aluminum with diameter of 27 cm. The BTC container and double wall are made of stainless steel 304 or titanium alloy Ti-6AL-4V. Measured temperature dependent thermal properties taken from open literature are used in the simulation. A simplified model is applied to the sample tube assemblies. It is modeled as 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.

Table 1: Thermal properties of materials

Material	Density (kg/m^2)	Thermal conductivity (W/m-C)	Specific heat (J/kg-C)
Ti-6AL-4V	4430	7.04 (0°C)	525 (0°V)
SS304	7969	12.9 (0°C)	475 (0°C)
MIN-K	380	0.03 (0°C)	740 (0°C)
Sample Ass.	1737	3.05	620
Braze	8440	40	343

An electromagnetic FE model was established to simulate the induction heating as illustrated in Error! Reference source not found.. The modeled configurations are the same as the thermal model described in previous section. The detailed structures inside the aluminum shell of the OS were omitted for simplification because the EM field there are expected to be very weak due to the shielding effect of the metallic shells in the frequency range of interest (20 – 60 kHz). The simplification was validated by preliminary simulations for SS304 BTC shell at 0°C. A 2-turn copper coil with a cross section of 6.5x6.5 mm^2 is placed close to the brazing zone. The gap between the coil and the surface of the BTC double wall is 5 mm and the spacing of the two turns is 6.5 mm.

Figure shows the flux patterns of the magnetic field. The magnetic field inside the OS shell is very weak for frequency higher than 20 kHz. Figure shows the induced Joule heat density (J/m^3) in the brazing zone and coil. The skin effect can be clearly seen in the coil and the heated zone. The Joule heat inside the double wall BTC assemblies is insignificant. It also shows that the Joule heating in the braze material is significantly higher than the heating in the immediate vicinity. The high conductivity of the braze alloy helps to transfer the heat energy to the desired region.

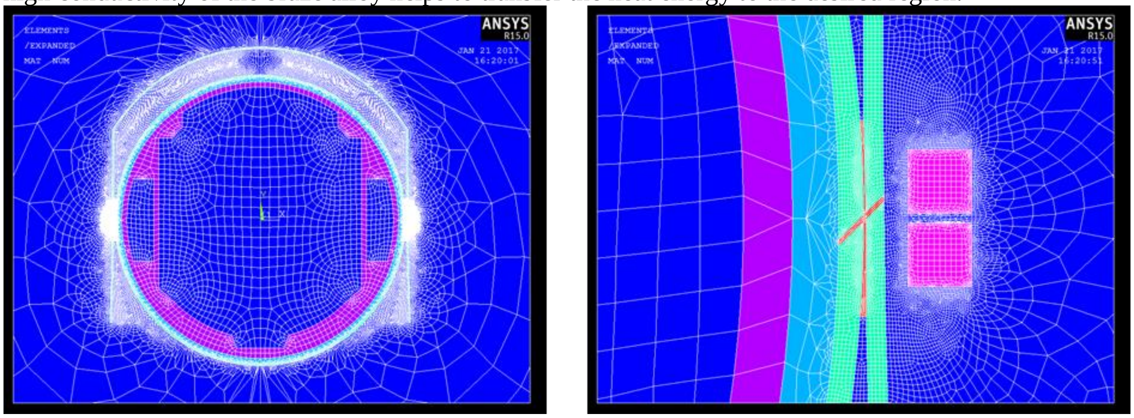
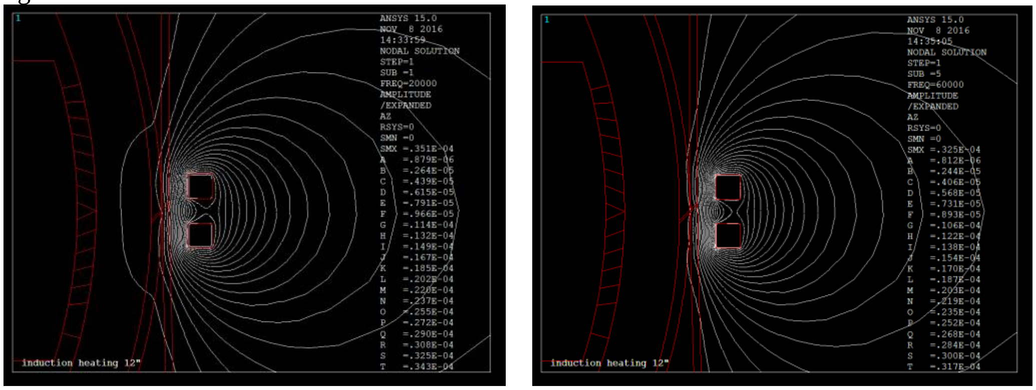
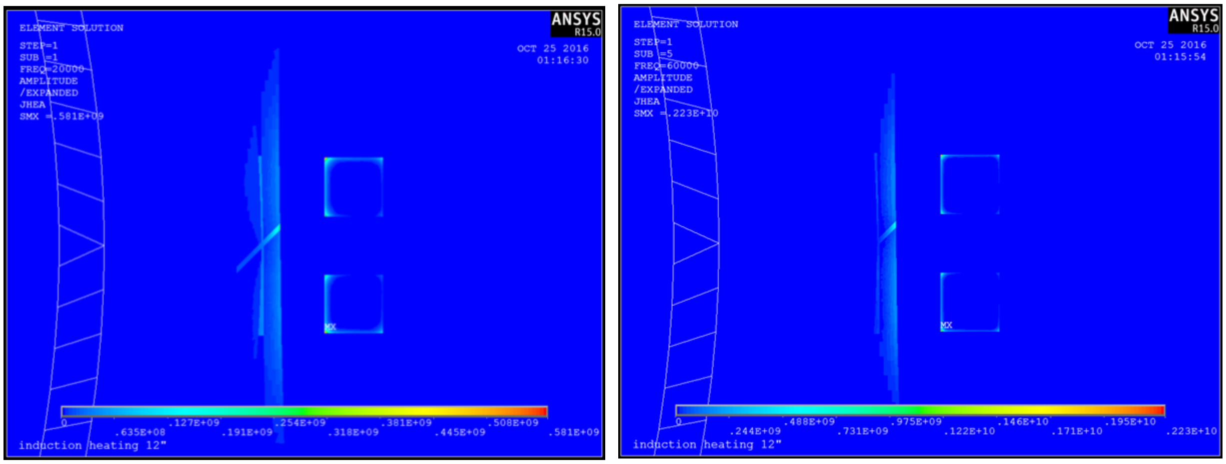


Figure 2: The magnetic model for induction heating. The structures inside the conceptual OS shell were omitted because the electromagnetic field inside is shielded by the metallic BTC double walls and the aluminum OS shell in the frequency range we used.



20 kHz 60 kHz

Figure 1: Contour line plots of magnetic equipotential (Az*radius) induced by an electric current of 500 A in amplitude through the copper coil that generate the flux patterns.



20 kHz

60 kHz

Figure 4: Contour plots of Joule heat density (J/m^3) induced by an electric current of 500 A in amplitude through the coil.

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 being well controlled by liquid flow cooling, i.e. the temperature rise is neglected in the coils. The brazing temperature is 750°C. The results for the SS304 shell are presented in Figure 5 to Figure 8. With an electric current of 480A in amplitude at 50 kHz the temperatures at four endpoints of the X-shaped braze material are ploted in Figure 5. The results show the required 420 seconds (7 minutes) for all the braze material to reach or exceed the brazing temperature of 750°C. Figure 6 shows the temperature distribution at the time. The major heat energy is still limited in the zone surrounding the heating area and very small temperature rise takes place in the OS. The total energy consumption is 200 kJ, which is an amount the ERV could provide.

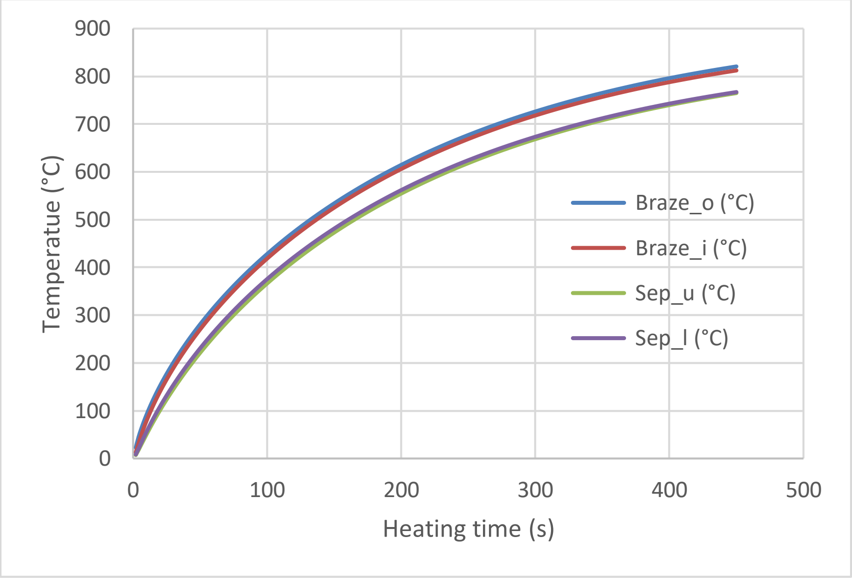


Figure 52 Model predictions of the temperature rise at multiple positions in the braze area. with a current amplitude of 480A at 50kHz induction heating starting from 0°C ambient for SS304 shell. It takes 420 sec and 2108 kJ for the temperature to rise above the brazing temperature of 750°C.

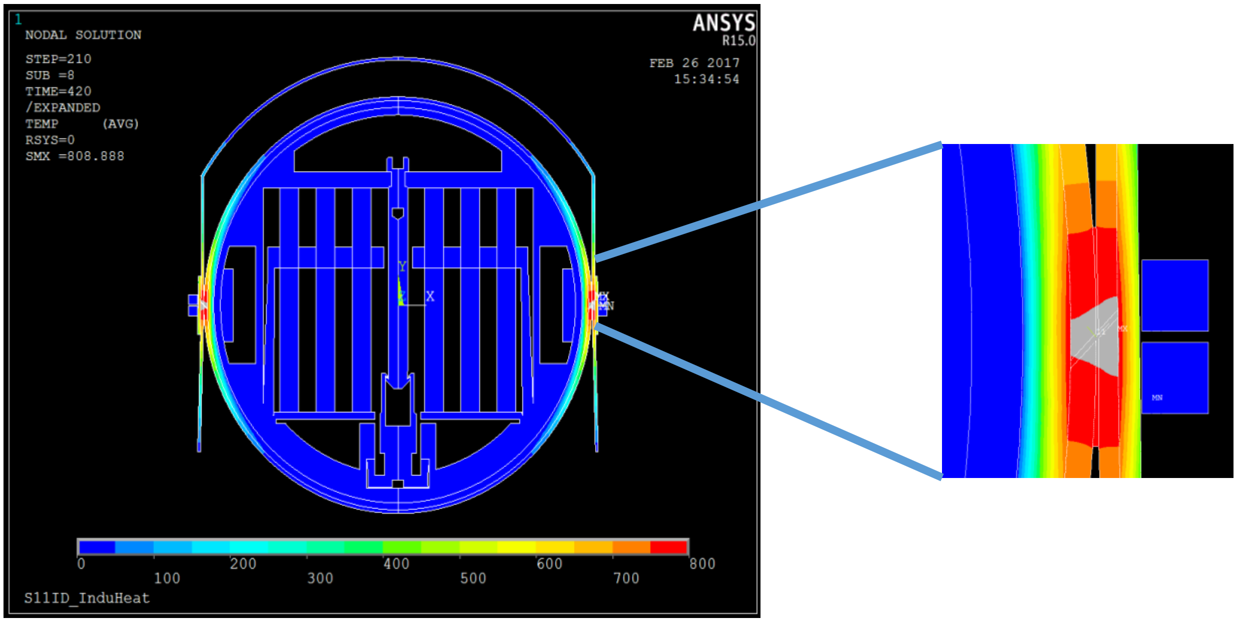


Figure 6: Model predictions of the temperature distribution at 420 seconds by 480A 50kHz induction heating in 0°C ambient.

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 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 presented in Figure 7 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 for sample temperature control.

The input electric power (Total), heating power on shell and coil loss with 480A coil current at 50 kHz are shown in Figure 8. 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%.

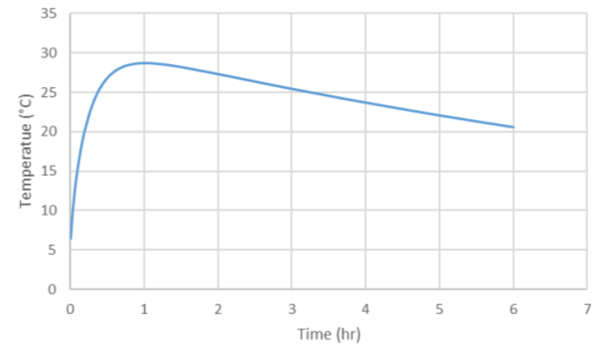


Figure 7: Model predictions for maximum temperature at sample tube in cooling process after the brazing is 28.7 °C.

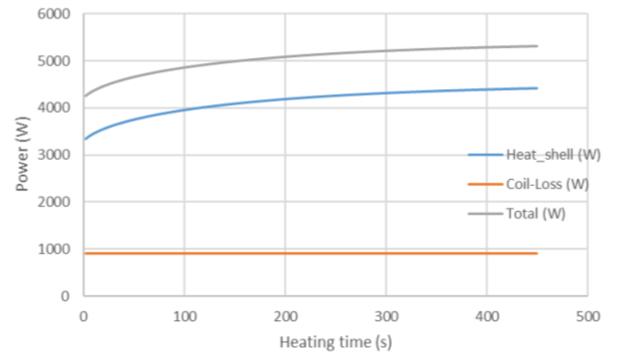


Figure 8: Model predictions for Input electric power (Total), heating power on shell and coil loss with 480A 50 kHz Induction heating.

The simulation was 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**. By using titanium alloy instead of stainless steel the analysis suggests that the required power, energy and sample temperature rising are reduced significantly.

Table 2: Comparison of stainless steel and titanium alloy material

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. RESISTIVE RADIATION FURNACE CONCEPT FOR APPLYING S^{4}B BTC

The main challenge to the resistive heating approach for our application is the lack of efficient delivery of high heating power to the braze surface over the limited area. Preliminary analysis showed that the use of a radiation furnace with ceramic heating element shows promise with respect to transferring the required heat energy. FE modeling analysis was conducted to investigate the feasibility of the oven configuration. The modeled configuration of the furnace is shown in Figure 9. A ring-shaped furnace with molybdenum disilicide (MoSi2) ceramic heat elements covers the heating area of the BTC shell. The heating area is blackened in order to have a high emissivity of 0.9. Three turns of a ceramic heating coil with a diameter of 6 mm is covered by a high temperature firebrick and thermal insulation MIN-K. The emissivity's of these materials are marked in the figure. The BTC shell is the 12" (304.8 mm) OD stainless steel shell.

An electric power of 5 kW is applied to the heating elements in the furnace. Figure 10 is the contour plot of temperature at 406.89 seconds and shows the temperature of the brazing/separating zone is over 750°C. The temperatures at five positions in the furnace as a function of the heating time are presented on the left part of Figure 11. It takes 407 seconds (6 minutes and 47 seconds) and 2035 kJ total energy to reach the brazing temperature of 750°C while the temperature at the heater element is 1350°C.

The previous thermal modeling showed that the 12" BTC SS shell reaches the brazing temperature in 7 min with 4kW heat power. Comparing these two results, ones see the heating efficiency of the resistive radiation furnace as a little over 80% (4kW/5kW).

A more detailed design of the furnace may allow the use of a resistive heating element which allows for the use of the DC voltage of the electric supply directly and only requires a high power switch to control the heating power. This could result in a very simple electronic driver with very high (near 100%) efficiency.

The modeling results for the furnace show a potential to get a higher efficiency than the induction heating and this approach is very promising.

The commercially available molybdenum disilicide ($MoSi_2$) elements are suitable for use in air or low vacuum environment. The performances, especially the temperature limit and lifetime in high vacuum, are not clear. Tungsten heating element which can reach temperatures up to 3000°C in high vacuum could also be used as an alternative heater option.

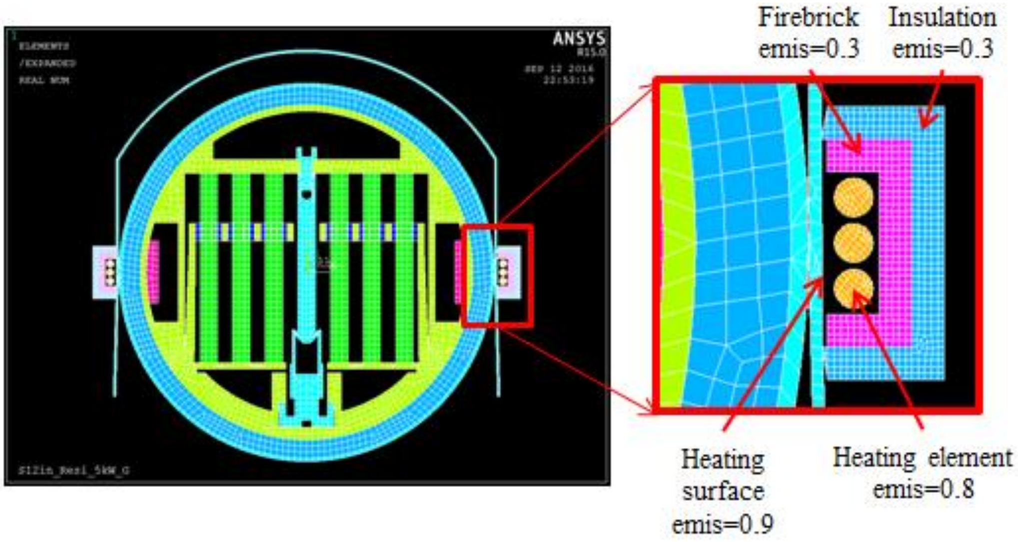


Figure 9: Configuration and FE thermal model of the resistive radiation heating.

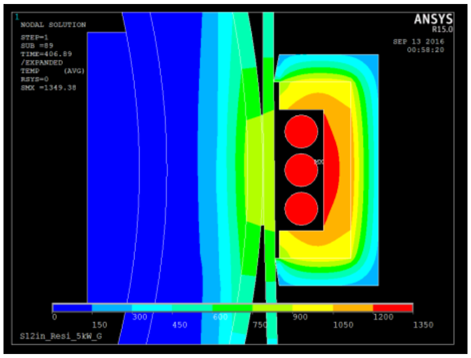


Figure 10: Simulated contour plot of temperature at 406.89 seconds with 5 kW electric power. The temperature of the brazing/separating zone is over 750°C.

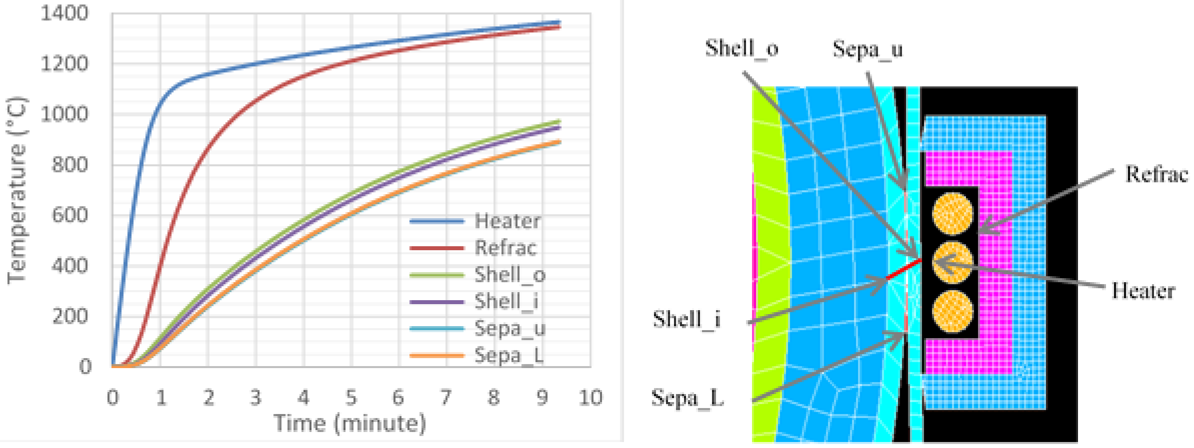


Figure 11: Model predictions: Temperatures rise curves at five positions with **5 kW** electric input power into resistive heaters(left). The right figure shows the positions of the temperature control points that are presented in the left figure. It takes **407 seconds (6 minutes 47 seconds)** and 2035 kJ for the temperature of brazing/separating zone to rise above 750°C.

4. SUMMARY

This paper reports study efforts related to the application of the method of Simultaneous Separation, Seaming and Sealing using Brazing technology (S^4B) that is potentially applicable to sample return from Mars or other bodies in the solar system. The break-the-chain procedures for proposed container configurations were simulated by multi-physics finite element models. The models were used to evaluate the thermal behaviors of initial designs, predict the sample temperature rise during the process, perform design parametric study, and optimization of the design for better temperature control and low power consumption. Different heating methods including induction and resistive radiation were evaluated. The temperature profiles of Martian samples in the proposed container were predicted using thermal modeling. The results show that the sealing and sterilizing process can be controlled such that the samples temperature is maintained below the required level and the brazing technique is a feasible approach to break the contamination path. The application of S^4B technology to potential future sample return to assure planetary protection of Earth looks promising.

5. ACKNOWLEDGMENT

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