FE simulation of SMA seal for Mars sample return

Xiaoqi Bao[1], Paulo Younse and Pradeep Bhandari
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

ABSTRACT

Several NASA rovers and landers have been on Mars and performed successful in-situ exploration. Returning Martian samples to Earth for extensive analysis is of great interest to the planetary science community. Current Mars sample return architecture would require leaving the acquired samples on Mars for years before being retrieved by subsequent mission. Each sample would be sealed securely to keep its integrity. A reliable seal technique that does not affect the integrity of the samples and uses a simple low-mass tool is required. The shape memory alloy (SMA) seal technique is a promising candidate. A study of the thermal performances of several primary designs of a SMA seal for sample tubes by finite element (FE) simulation are presented in this paper. The results show sealing the sample tube by SMA plugs and controlling the sample temperature below the allowed temperature level are feasible.

KEYWORD: SMA, Shape memory alloy, seal, FE simulation, Mars sample return.

1. INTRODUCTION

After NASA rovers and landers have been on Mars and performed successful in-situ exploration, returning Martian samples to Earth for extensive analysis is of great interest to the planetary science community. Current Mars sample return architecture would require leaving the acquired samples on Mars for a couple of years before being retrieved by a subsequent mission. Each sample should be sealed securely to keep its integrity. A reliable seal technique that does not affect the integrity of the samples and uses a simple low-mass tool is required.

The primary function of the tube seal is to prevent material loss including the loss of gases and volatiles from the sample, structural damages, chemical degradation and contamination. Figure 1 provides an overview of the mechanisms that could affect sample integrity. The sealing assembly and the sample tube should be made of chemically stable and easy-to-clean materials. The temperature in the sealing process should be controlled to be lower than allowed.

The sealing mechanism using a shape memory alloy is attractive. The pre-deformed SMA material like nickel titanium alloy (Nitinol) can recover its original shape by raising its temperature above the phase transition point. The recoverable strain could be 5% or more. The materials are stable and can be activated at relatively low temperature with a simple tool using a heater.

[1] Correspondence: xbao@jpl.nasa.gov

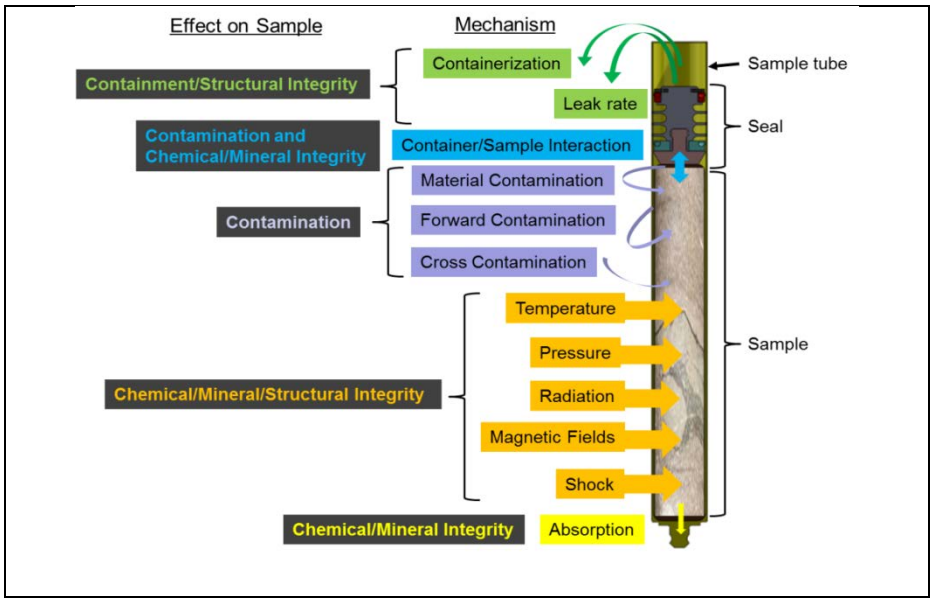

Figure 1: Various mechanisms dealing with sample integrity.

2. SEALING BY SMA PLUGS

A prototype for a potential hermetic sample sealing technique for encapsulating samples in ~1 cm diameter thin-walled sample tubes using a heat-activated finned shape memory alloy plug was developed. The plug consists of a series of preformed Nitinol shape memory alloy fins that deploy when heated, pressing into the inner wall of the tube and forming a hermetic seal [1, 2]. A heater is used to directly apply the heat needed to actuate the plug inside the tube. The sealing mechanism with the finned plug and a sealing operation using a heater is illustrated in Figure 2.

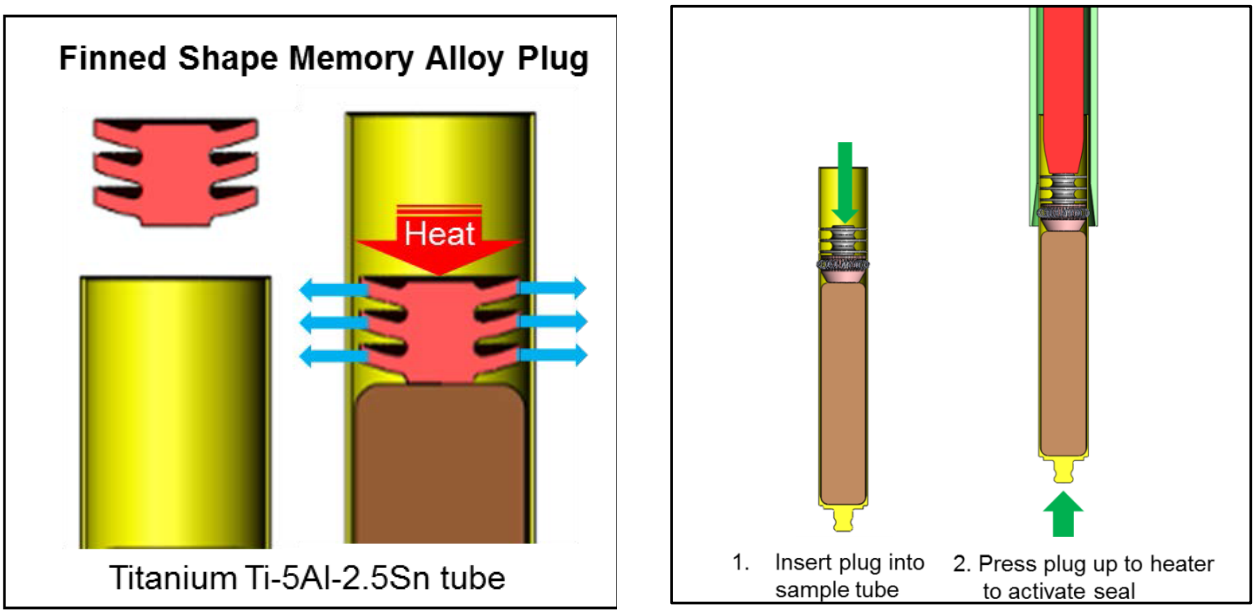

Figure 2: A schematic view of SMA plug sealing concept

3. ALLOWED MAXIMUM TEMPERATURE FOR SAMPLE

During the process of sealing the sample in its container tubing, several metrics are used to ensure that the integrity of the sample has not been compromised. One of the key metrics is the maximum temperature that the sample would be subjected to during the sealing. Excessively high temperatures could degrade or damage the sample. While on the surface of Mars, before the sealing, the sample undergoes diurnal as well as seasonal temperature cycles, and it would have gone through these cycles for millions of years. Hence the process for coming up with the maximum temperature requirements during sealing should take this realization into account. In other words, to ensure that the process of sealing does not lead to the sample getting hotter than what it would have been subjected to for millennia on Mars, a requirement to not exceed these values is derived and employed for sealing.

The temperatures experienced by the sample (soil/rock) on the Martian surface (prior to its excavation and sealing) depend on many factors: latitude, season, time of day, Mars local albedo & thermal inertia, and the atmospheric extinction coefficient. Obviously, for a given location (primarily latitude), the sample should have already experienced the entire diurnal cycles and peaks for millennia. Comparison of ground temperature data for a range of latitudes on Mars (30 S to 30 N) shows that the highest temperature for any location is about 38°C, which occurs during summer at 30 S. The range of the maximum diurnal ground temperatures during summer is 38°C to 17°C in the southern latitudes, and 0°C to 17°C in the northern latitudes.

Since the landing latitudes would not be known until very late in the mission development cycle (possibly as late as one year or less before launch), and this is a generically applicable sample sealing technology for future missions, a general guideline or goal of approximately a 20°C maximum temperature at the end of the sealing process (assuming a 0°C temperature at the start of the sealing process) was used for designing the sealing system. However, it was also recognized that sealing may occur early in the morning on Mars when the sample would be quite cold, hence roughly a 20°C temperature rise would probably still lead to the sample not getting hotter than 0°C after the sealing is complete. During acquisition, orbit around Mars, and transit back to Earth the samples could exposure to temperatures around 20-30°C. Hence even though strictly speaking a sample from northern latitudes could be warmer during these phases than what it experienced on Mars prior to excavation, a reasonable practical goal of 20°C was used as the maximum temperature requirement during sealing.

4. FINITE ELEMENT SIMULATION OF HEATING PROCESS

To seal the sample tube, the trained plug is put in the tube and heated up to a temperature above the phase transition temperature. When the Nitinol transfers from martensite phase to austenite, the plug tends to recover its original shape with a diameter larger than the inner diameter of the tube and seals the sample in the tube. A major concern for this process is the temperature rise of the sample. The maximum sample temperature experienced in the process should be controlled below the allowed value to maintain its integrity. FE simulations are performed to evaluate various designs of sealing assemblies and heating procedures to assess this.

The sealing assembly includes the Nitinol plug, a thermal barrier to reduce heat flow to the sample, and surrounding rings to avoid initial contact of the plug with the tube and help to clear

possible dust on the tube's inner surface for a reliable sealing. Based on the mechanical and thermal properties and chemical stabilities, Teflon or fused silica is considered as the preferred material for this barrier. Spring-energized Teflon seal or stainless circular helical spring is chosen for the surrounding spring. Stainless steel or titanium alloy is selected for the sample tube.

The constructed axisymmetric thermal transient FE model based on ANSYS includes the sealing assembly, tube, sample and a heat sink. To heat up the plug, a constant high temperature heater is placed in contact with the upper surface of the plug. Major heat flows in the heating process are through heat conduction paths. Prior analysis showed that heat convection and conduction in thin CO_2 gas gaps in a Martian atmosphere is negligible except for very narrow gaps. Gas conduction between the fin tips of the plug and the tube is accounted for in the model. The radiation heat loss from the heated parts to their surroundings is also accounted for.

The material properties employed are listed in **Table 1** and **2**. The data were collected from datasheets, books on materials and published literature. Only properties at 20°C are presented in the Table. When temperature dependent data are available for any materials, e.g., Ti and 316 SS, they are used in the FE model. Basalt rock is considered as a typical sample. The properties of basalt rocks vary in a broad range. The data near the middle of the range are picked. In the **Table 1**, the A_s is the starting temperature of the phase transition of the Nitinol from martensite to austenite in heating, and the A_f is the finishing temperature. M_s and M_f are that of phase transition temperatures from austenite to martensite. The M_s and M_f are generally lower than the A_s and A_f. These temperatures are dependent on compounds of the alloys, training and stress conditions. The values employed in the models correspond to those for Type H Nitinol [3].

Table 1: Properties of Nitinol applied in the simulation

Nitinol	Density	Thermal conductivity	Specific heat	Emissivity	Heat of trans.	A_s	A_f	M_s	M_f
	kg/m^3	W/m-C	J/kg-C		J/kg	°C	°C	°C	°C
Martensite	6450	9	837	0.68	28420	90	100		
Austenite	6450	18	837	0.68				-90	-100

Table 2: Material properties applied in the simulation (Data at 20°C)

Material		Titanium	Stainless steel	Copper	Silica	Teflon	Basalt	Basalt dust	CO2	Nitinol	Nitinol
		Ti-6Al-4V	SS316		fused		rock	with Martian CO2	Martian	Martensite	Austenite
Density	kg/m^3	4430	7969	8940	2200	2130	2670	1545	20	6450	6450
Thermal conductivity	W/m-C	7.08	13.24	391	1.38	0.3	2.30	0.15	0.016	9	18
Specific heat	J/kg-C	536	485	385	740	1083	814	900	850	837	837
Emissivity		0.68	0.68	0.77						0.68	0.68

The Nitinol plug is initially in martensite phase and transforms to austenite in the heating process. While it recovers its original shape in phase transition from martensite to austenite, extra latent heat is required. The properties of the material, especially the thermal conductivity, changes with the phase transition [4]. The phase transition of Nitinol is hysteretic as illustrated in **Figure 3**. To simulate these hysteretic property changes two materials were defined for Nitinol, one (Niti_m-a) for the Nitinol initially in martensite phase that changes properties corresponding to temperature A_s and A_f, and the other (Niti_a-m) for initially in austenite phase that changes properties corresponding to temperature M_s and M_f. The latent heat of phase transformation is simulated by increasing its specific heat in the temperature range of phase transition. At the beginning of the simulation all the

elements of plug are associated with material Niti_m-a. The material Niti_a-m is assigned to the elements where the temperatures are over A_f in the heating process.

In the heating process, the expansion of the plug fins makes the fins contact the tube and changes the heat transfer paths. The changes are simulated by modifying the material of the elements in the gaps between the fin tips and the tube from CO_2 gas to Nitinol (NitiA) when temperature at the corresponding tip reaches the A_f.

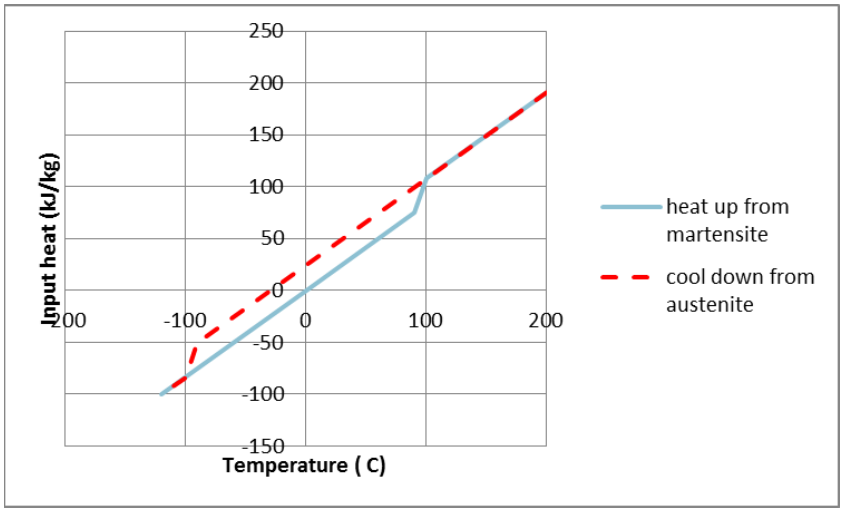

Figure 3: The heat energy change of Nitinol referring to martensite phase at 0°C shows hysteretic characteristics.

The FE model was applied to evaluate the thermal performances of various designs for optimization. Some examples are shown in the followings. **Figure 4** (left) presents a meshed model of a seal assembly design with a fused silica thermal barrier and stainless circular helical spring. It is an all-inorganic parts design to minimize the risk of contamination to the sample. A copper ring functioning as a heat sink is coupled to the outside of the tube to control the temperature of the Ti tube in the place near the sample through a thermal pad. The thermal conductance of the pad is set at 1000 W/m^2-C, which is feasible with special kinds of interface materials. The sample is a core of basalt rock surrounded by a thin layer (0.25 mm) of dust. The circular helical spring is not exactly axisymmetric in geometry. It is represented by an annual solid ring having equivalent thermal conductance from the barrier to the tube in the axisymmetric model. The heat is provided by a heater. The temperature of the heater is controlled at 200°C. It contacts the upper surface of the plug. The ambient temperature is 0°C. The positions of the control points are illustrated in **Figure 4** (left), and the calculated temperatures at the points are shown in **Figure 4** (right). The upper fin tip (Tip1) hardly reaches the required temperature for shape recovery (100°C) after heated for a long time of 243 seconds. Further calculations show when the temperature distribution reaches a quasi-static state, the other tips still do not reach 100°C. **Figure 5** (left) shows the temperature distribution and **Figure 5** (right) displays the heat flow in the quasi-static state. A large heat flow and temperature drop was found in the neck of the plug that prevented the lower tips from reaching the temperature target 100°C.

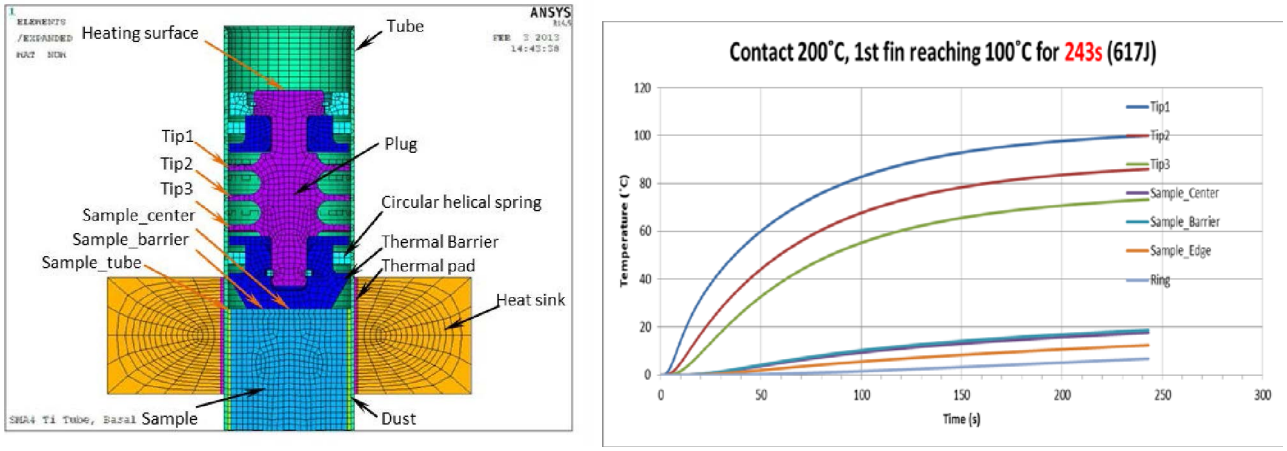

Figure 4: Left: FE thermal model of a design with a long plug, fused silica barriers, stainless circular helical spring and copper heat sink coupled to the outside of the tube. The sample is a solid basalt core. Right: Simulation results of the temperatures at various spots of the long plug and basalt rock sample.

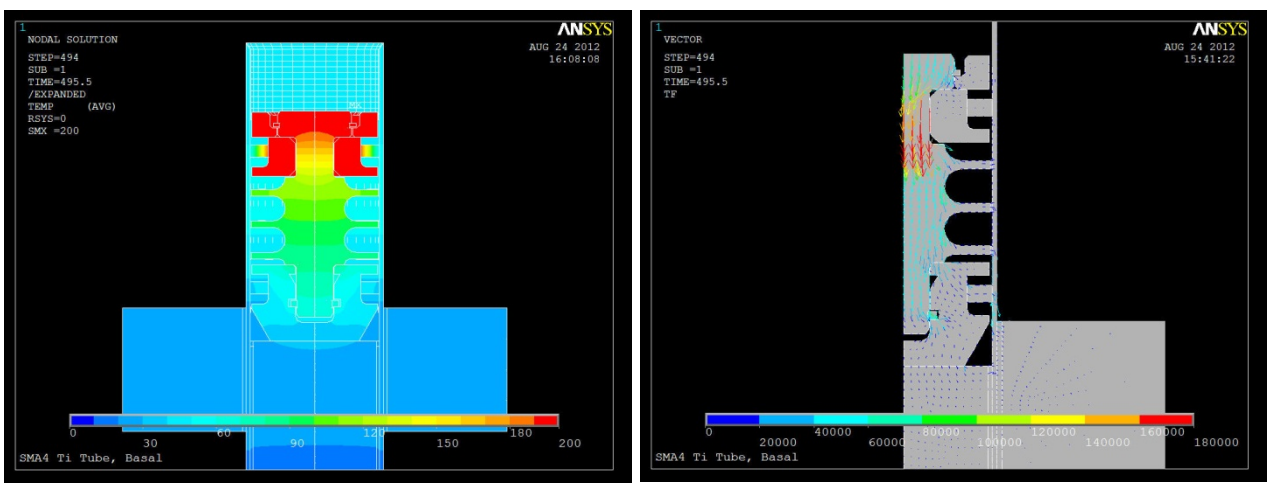

Figure 5: Temperature distribution (left) and heat flow (right) at heating time of 495 seconds. A quasi static temperature distribution is reached.

To improve the performance, the part of the neck was omitted. A new seal assembly design with a short finned plug is presented in **Figure 6**. With the same heating condition, the FE model predicted all tips could reach 100°C in 24 seconds. The results are shown in **Figure 7**. The heater was removed at the time the temperature of the low tip (Tip3) reached 100°C. The maximum temperature of the basalt sample was predicted to be 17°C. The FE simulation was also performed for the case that the sample is basalt dust. The basalt dust has much lower specific heat and conductance than the solid basalt rock. The surfaces of the dust are much easier to be heated than the solid basalt. Results in **Figure 8** show the maximum temperature on the up surface of the dust

sample may rise to 49°C, which is much higher than that of solid basalt rock and misses the temperature control target.

Two approaches for thermal performance improvements were evaluated by FE simulation. One is replacing the barrier material of the fused silica by Teflon, which has lower thermal conductivity than the silica. As shown in **Figure 9**, the FE simulation predicted the maximum temperature of the dust sample was reduced to 18°C. It meets the temperature control goal with the dust sample that is considered as the worst sample type for the temperature control although the design includes an organic material of Teflon. Another approach is to insert a heat shunt between the thermal barrier and the sample (see **Figure 10**). The shunt is 0.875 mm thick stainless disk. It contacts the tube through its ring edge. The ring edge is 0.25 mm thick and 3 mm high. The thermal conductance of the contact interface is assumed to be 500 W/m^2-C. As presented in **Figure 10** this new all-inorganic design can control the maximum temperature of the dust sample to 18°C and meet the temperature control goal of 20°C. The required heating energy is 327 Joules which is close to the 310 Joules that required by assembly with Teflon barrier.

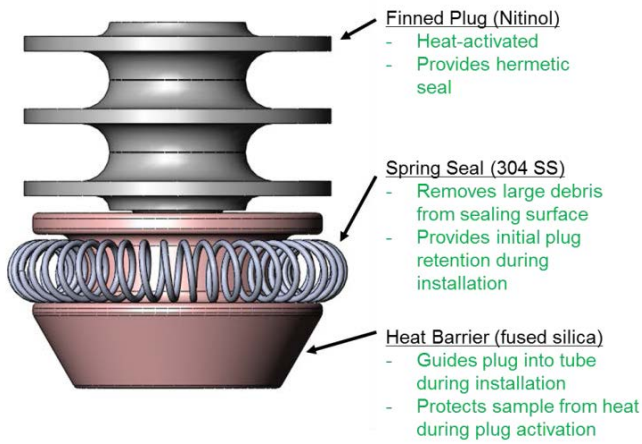

Figure 6: Improved seal assembly design with a short finned plug.

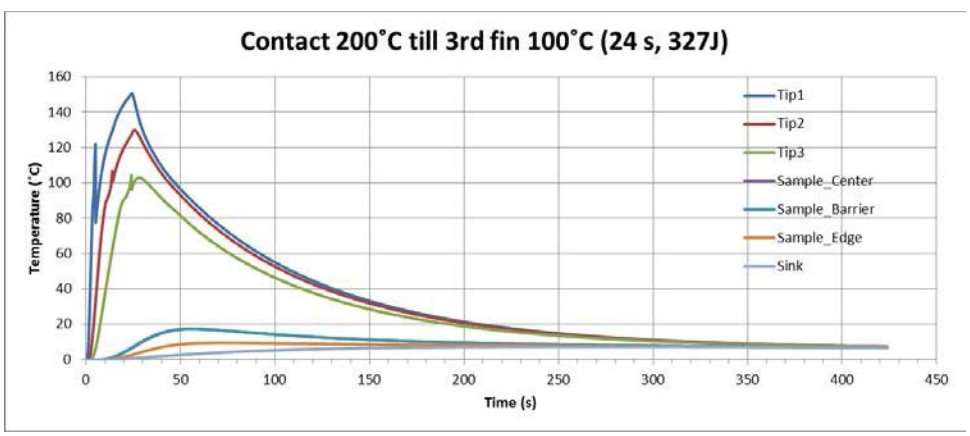

Figure 7: Simulation results of the temperatures at various spots of the short plug and basalt rock sample. Heating time 24s, Energy 327J, Max sample temperature 17°C.

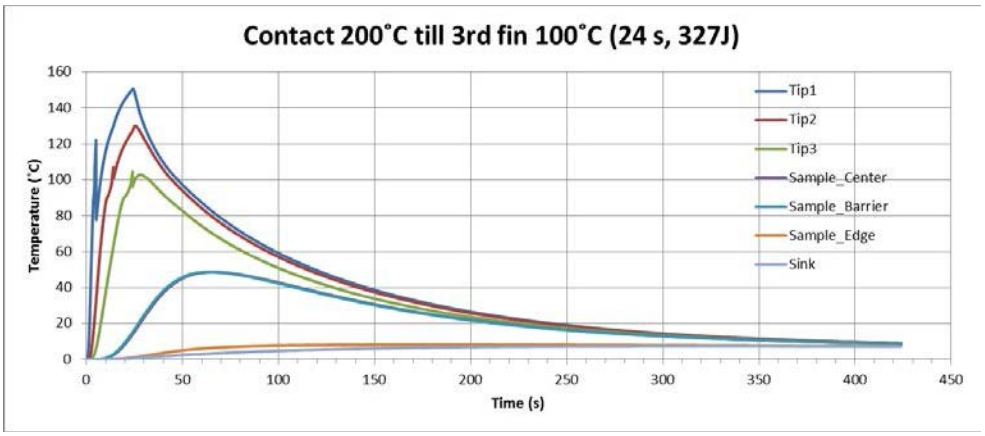

Figure 8: Simulation results of the temperatures at various spots of the short plug and basalt dust sample. Heating time 24s, Energy 327J, Max sample temperature 49°C.

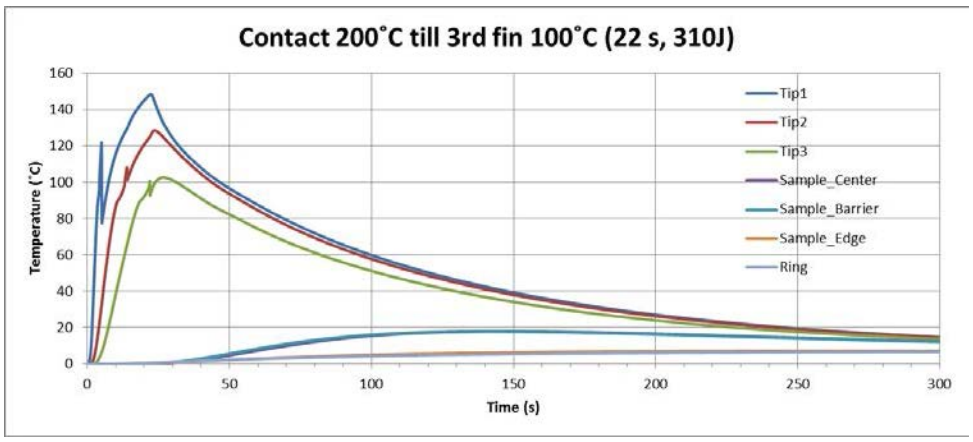

Figure 9: Simulation results of the temperatures at various spots of the short plug and dust sample with Teflon barrier. Heating time 22s, Energy 310J, Max sample temperature 18°C.

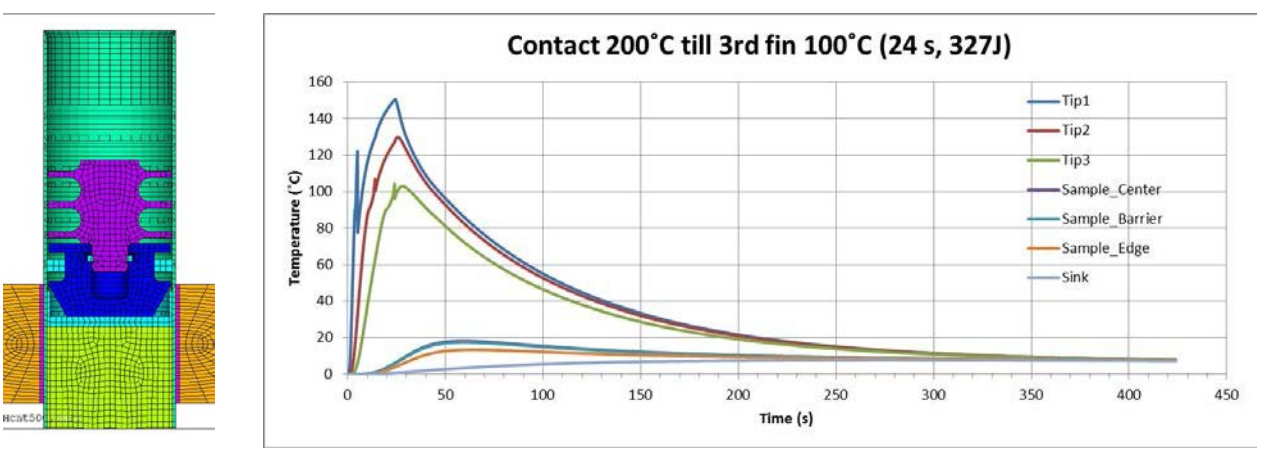

Figure 10: Simulation results of the temperatures at various spots of the short plug with a heat shunt between the barrier and the dust sample. Heating time 24s, Energy 327J, Max sample temperature 18°C.

5. SUMMARY

In the research and development of potential SMA plug sealing technology for sample return from Mars or other bodies in the solar system, a thermal finite element model was employed to simulate the heating process of Nitinol plugs for sealing sample tubes. A method to deal with hysteretic thermal behavior of the shape memory alloy was developed and an alternative approach was used to simulate the thermal contact change during the shape recovery of the Nitinol plug. The FE model was used to evaluate various designs of SMA sealing assemblies and this helped in arriving at optimized performance designs. The simulation results show that during the sealing of the sample tube by SMA plugs, control of the sample temperature below the allowed temperature level is feasible by using these optimized designs even for the all-inorganic seal assemblies. The techniques developed in this effort to accurately assess various designs, as well as the optimized designs arrived at, should be useful for future work in developing and improving upon these technologies for sample sealing and preservation.

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