

Heating Methods for Deployment of CHEM Foam Structures

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ABSTRACT

In this paper, the advantages and disadvantages of many methods for deployment of CHEM foam structures are discussed. The best heating method is determined to be the use passive solar heating via a thermal blanket due to its simplicity, minimal payload and spacecraft requirements, and cost. An initial theoretical model of this heating method is presented and explored for a thermal blanket with an absorptance to emittance ratio of 15. The model found this heating method to be feasible for deploying up to 10 cm thick structures on the Mars surface and up to 15 cm thick structures in a solar orbit at a solar distance of 1 AU.

INTRODUCTION

Experiments and analyses have confirmed the feasibility of an innovative, new class of very simple, reliable, low mass, low packaging volume, and low-cost self-deployable structures for space and commercial applications. The material technology called "cold hibernated elastic memory" (CHEM) utilizes shape memory polymers in open cellular (foam) structures.^{1,2} It represents the next generation self-deployable structure and intends to be supplemental to space inflatable structure technology.

CHEM foam technology takes the advantage of polymer's shape memory in addition to the foam's elastic recovery to deploy a compacted structure and tailors the glass transition temperature T_g to rigidize the structure in the fully deployed configuration.^{3,4,5} The stages in utilization of a CHEM foam structure are illustrated in Figure 1 and are as follows:

- **Original Structure:** The original structure is fabricated/assembled in a room held below T_g .
- **Folding or Rolling:** The structure is warmed above T_g to make it flexible and then compacted, rolled and/or folded up for stowing.
- **Hibernation (storage):** The rolled/folded structure is cooled below T_g so that it becomes

firm in the compressed state. As long as the temperature is maintained below T_g , no external forces are needed to keep the structure compressed.

- **Deployment:** The rolled/folded structure is warmed above T_g . Memory forces and foam's elastic recovery cause the structure to naturally deploy back to its original shape without external actuation.
- **Rigidization:** The deployed structure is cooled below T_g to rigidize it, whereupon it is put into service.

Once deployed and rigidized, a part could be heated and recompact. In principle, there should be no limit to the achievable number of compaction-deployment-rigidization cycles.

Another attractive aspect is the wide range of T_g that can be selected for deployment and rigidization. The T_g of shape-memory polymers ranges from -75°C to $+100^{\circ}\text{C}$, thus allowing a wide variety of potential space and commercial applications in different environments. In these applications, the T_g of CHEM structure should be slightly higher than the maximum ambient temperature; this will keep the structure in the glassy state without requiring special measures to provide additional heat. Heat would only be applied for deployment, followed by radiative cooling to effect rigidization.

The advantage of CHEM structures over conventional polymer foams is that high total compressive strain, both elastic and plastic, is recovered without any compression set. Thus, a higher full/stowed volume ratio is accomplished in rubbery state and the original shapes are recovered with higher accuracy after cold hibernation stage. In addition, very high ratios of elastic modulus E below T_g to E above T_g (up to 500 for solid SMP) allow the component to keep the original shape in the stowed, hibernated condition without external compacting forces for an unlimited time below T_g .

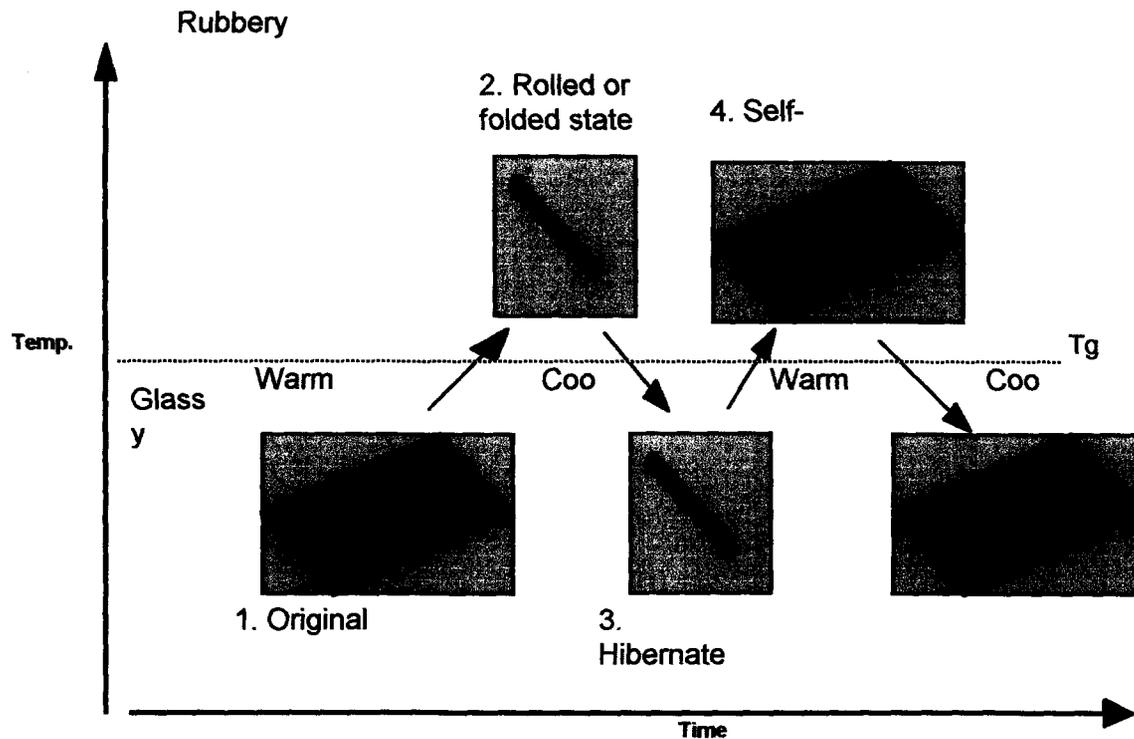


Figure 1 Cold hibernated elastic memory (CHEM) processing cycle.

The overall simplicity of the CHEM process is one of its greatest assets. The CHEM technology provides a simple end-to-end process for stowing, deployment and rigidization that has the benefits of low mass, low cost, high reliability. It avoids the complexities associated with other methods for deploying and rigidizing structures by eliminating deployable booms, deployment mechanisms, inflation and control systems that required majority of the mass budget.

Based on these attractive features, a myriad of potential CHEM applications are anticipated for space and commercial users.^{5,6} Various preliminary investigations under different programs at JPL and elsewhere confirmed the feasibility of some potential CHEM space and commercial applications. However, the disadvantage of CHEM structure is that heat energy is needed for deployment. The space environment makes heating difficult due to the low temperature of space and the lack of available power. Recently conducted preliminary studies indicated that natural space heat sources could be utilized for deployment.⁷

MAIN SECTION

EVALUATED HEATING METHODS

A variety of heating methods in order to deploy CHEM foam structures were explored including: use of microwave radiation, storing and using the electronic heat generated on the spacecraft, pre-cooling the CHEM

foam below T_g and letting it naturally heat up during transit, stowing the material in its compacted state above its glass transition temperature (T_g), and the use of passive solar heating. Each method was evaluated for simplicity, mass (the lower the better), amount of spacecraft volume used, and amount of spacecraft power needed. Table 1 summarizes the advantages and disadvantages of each heating method described below.

Using microwave radiation

The main advantage of using microwave radiation over all the other heating mechanisms proposed here is that the low conductivity of the SMP (0.025 W/m K) would not be relevant since activation of chemical bonds throughout the material would be responsible for the heating process. Since the material would be stored below its T_g no external compressive force would be needed in order to keep the components stowed. Finally, once the microwave radiation was turned off the material would naturally cool in the space environment to be below its T_g , leaving the material in its rigid state. Unfortunately, in order to generate the microwave radiation significant spacecraft power would be necessary. The device that produced the microwaves would need to be designed, built and tested to make sure the microwaves resonated with the bonds in the SMP. In addition, this device would require payload mass and volume. These disadvantages far outweigh the advantages making this option unfeasible.

Using electronic heat storage (EHS)

This heating method was considered since it did not require any additional spacecraft power, but instead used the "waste" heat of the spacecraft electronics in order to deploy the CHEM structure. However, a heat storage device as well as heat delivery system from the electronics to the storage device and from the storage device to the polymer would be necessary. The increase in payload volume and mass due to this system as well as the complexity of the heating mechanism removed electronic heat storage from further consideration.

Using pre-cooled CHEM structures

The idea behind this heating method is to choose the CHEM foam with the lowest T_g possible, pre-cool the CHEM structure below its T_g before loading it onto the spacecraft, and then letting the CHEM foam naturally heat up during flight. This heating method would: 1) require less heat in order to deploy because of the low transition temperature of the material, and 2) be much simpler than the other two methods proposed so far. However, deployment during flight would be detrimental making this method unfeasible.

Using CHEM structures stowed with compressive force

This method for deployment is really an extension of the pre-cooled CHEM structures already presented. It has the same advantages as the previous method, but the addition of a compressive force would ensure that the material would stay compacted in transit thus making the method feasible. Deployment and rigidization would be performed by just removing the compressive force and letting the ambient space temperature do the rest.

This method while being both simple and feasible has some key disadvantages. Currently, studies have not been done on the long term effect of keeping the CHEM foam compacted in its soft or rubbery state. In addition, issues such as what will provide this necessary compressive force and would the material stay warm enough long enough in order to fully deploy would need to be resolved.

Using passive solar heating

This method would use a solar/thermal blanket that would be a good absorber in the visible light region of the electromagnetic spectrum, but a poor emitter in the IR region of the electromagnetic spectrum. This method uses a readily available source (the sun, as long as the component is not in the shadow of another object) in order to deploy the structure. This method is simple, does not require the addition of a compressive force during transit, is lightweight and low volume, and uses no spacecraft power making it ideal for a more detailed feasibility study as described in this paper.

Method	Power	Payload	Complexity	Other
Microwave	YES	HIGH	HIGH	
EHS	NO	HIGH	HIGH	
Pre-cooled	NO	LOW	LOW	Deploy during transit?
Compact	NO	MEDIUM	LOW	Stowage effect?
Solar	NO	LOW	LOW	Chosen for study

Table 1: This is a heating method feasibility chart. Note the Power column refers to whether or not the method requires spacecraft power, and the Payload column refers to the amount of extra space or mass the method would need.

DETAILED SOLAR HEATING ANALYSIS

Passive solar heating via a thermal blanket which encases the CHEM foam structure is chosen as the best heating method due to its simplicity, low volume, and low cost. In order to utilize thermal blankets effectively as a deployment method for the CHEM structure, the in-flight parameters must be known. The standard spacecraft flight temperature range is 239K to 344K.⁸ Using these in-flight parameters, a SMP whose glass transition temperature was 364K is necessary to ensure no deployment during the flight. Current SMP have glass transition temperatures between 173K and 373K, so the shape memory polymers used for deployment of space structures will need to be on the high end of this range.

The chosen value of the glass transition temperature in this study (364K) sets the upper temperature limit for the material once deployed. The material will need to stay in its rigid state after deployment, so an ambient environment or heating that produces temperatures above 344 K are undesirable. The scenarios for deployment looked at in this study are: 1) in space orbiting earth, 2) on the surface of Mars, and 3) in space orbiting the sun at distance of 1 AU. The extreme temperatures for each of these scenarios are given in Table 2.

Currently, there is no SMP with a glass transition temperature high enough to remain rigid in earth orbit without an addition of a phase change material or other temperature regulating device. This scenario was therefore not studied in greater detail. The aim here for the rest of the scenarios is to do only the initial modeling to determine whether or not the thermal blanket would

be a feasible method of deploying the CHEM foam

Scenario	Low Temp (K)	Hi Temp (K)
Earth orbit ⁹	230 K	375 K
Mars surface	130 K	180 K
Sun orbit	1.7 K	

structure.

Table 2: Relevant temperatures for thermal modeling. Please note that only a low temperature is given for the Sun orbits since no appreciable temperature change is necessarily expected. The temperature values given for the Mars surface are approximate radiant sky temperatures.

The initial modeling was based on the fact that the heat flux from the sun (Equation 1) and the radiated heat flux (Equation 3) are the two main factors governing the temperature of the structure:

$$q_s = \alpha A I_s, \quad \text{Eqn. 1}$$

where q_s is the heat flux from the sun, α is the absorptivity of the thermal blanket, A is the surface area of the blanket facing the sun, and I_s is the solar load. The solar load will vary depending on how far the component is from the sun according to the equation:

$$I_s = \frac{1385 \text{ W/m}^2}{x^2}, \quad \text{Eqn. 2}$$

where x is the distance from the sun to the component in astronomical units. The radiated heat flux (q_r) equation is given by:

$$q_r = \sigma A \varepsilon ((T_f^4 - T_s^4) + (T_b^4 - T_s^4)), \quad \text{Eqn. 3}$$

where σ is the Stefan-Boltzmann constant, A is the surface area of the thermal blanket, ε is the emissivity of the thermal blanket, T_f is the temperature at the front face of the material, T_s is the space temperature or the temperature to which the material is radiating heat, and T_b is the temperature at the back face of the material.

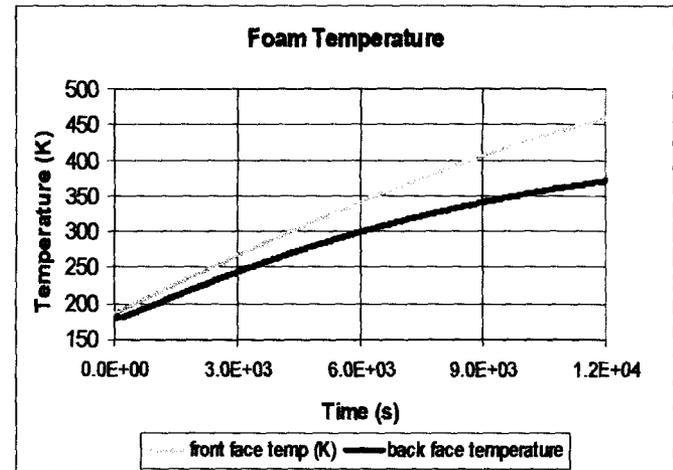
The initial modeling takes the component to be in thermal contact with the thermal blanket. In order to determine the temperature of the back face of the material, the net heat flux into the material the conducted heat flux (q_c) is used:

$$q_c = k A \Delta T / l, \quad \text{Eqn. 4}$$

where k is the conductivity of the material, A is the cross-sectional area of the material, ΔT is the temperature difference between the front face and the back face and l is the thickness or length of the material. It is important to note that the conductivity of the CHEM foam is approximately 0.025 W/m^2 and so keeping the thickness relatively small will be important for reaching the glass transition temperature in a reasonable amount of time.

For all models the thermal blanket is a one side gold-deposited Kapton thermal control material whose typical a/e is 15.0, and whose front surface area is 1.00 m^2 . For the Mars surface, the thermal blanket will only rise in temperature during the day, and during this time the solar loading on the surface is taken to be 550 W/m^2 (assuming a high transmissivity factor). In order to achieve deployment in a few hours the thickness of the CHEM structure was varied. Using the time constraint of a few hours, a thickness of about 10 cm was found to be the limit. A plot of the front and back face temperatures of the 10 cm thick CHEM structure on the Mars surface is shown in Figure 2. Both the front and back surfaces of the structure are above the glass transition temperature of the CHEM foam after a few hours.

Figure 2: Front and back face temperatures of the CHEM structure as a function of time for Mars surface scenario with a structure that is 10 cm



thick.

The solar orbit at a distance of 1AU model, only changes the solar loading to be 1385 W/m^2 , and also changes the space temperature to be 1.7 K. For the purpose of using the worst case the model the CHEM structure is also taken to be at 1.7 K before deployment, however it would also be reasonable to assign the CHEM structure the minimum spacecraft temperature, which would be significantly higher than the space temperature. Using these modifications and the same time limit of only a few hours the maximum thickness is approximately 15 cm. A plot of the front and back face

temperatures of the 15 cm thick CHEM structure in solar orbit is shown in Figure 3.

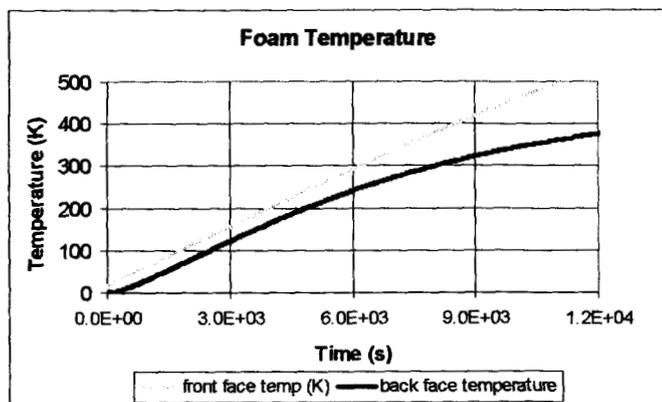


Figure 3: Front and back face temperatures of the CHEM structure as a function of time for a solar orbit scenario with a structure that is 15 cm thick.

The current times and thicknesses are not ideal, but do show that deployment of a CHEM foam structure using a thermal blanket is feasible. One of the important factors currently limiting the thickness of the material is the conductivity of the material itself. One possible solution to this problem is to increase the conductivity by using carbon fiber reinforced shape memory polymers that are described elsewhere.¹⁰

CONCLUSION

Various heating methods to deploy CHEM foam structures are explored. Passive solar heating is chosen as the best method due to its simplicity, minimal payload requirements, and because it uses no additional spacecraft power. This method is found to be feasible for deploying up to 10 cm thick structures on the Mars surface and up to 15 cm thick structures in a solar orbit at a solar distance of 1 AU. The next steps in the process will be to test the model experimentally in a vacuum chamber and to improve the thermal conductivity of the foam.

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