Applications of cold hibernated elastic memory (CHEM) structures

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ABSTRACT

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. The CHEM foams are self-deployable and are using the foam’s elastic recovery plus their shape memory to erect structures. These structures are under development by the NASA’s Jet Propulsion Laboratory (JPL) and Mitsubishi Heavy Industries (MHI). Currently, the CHEM structure concept is well formulated with clear space and commercial applications.

The CHEM structures are described here and their major advantages are identified over other expandable/deployable structures. Previous experimental results were very encouraging and indicated that the CHEM foam technology can perform robustly in the Earth environment as well as in space. Some potential space applications were studied under various programs at JPL with promising results. Although the space community will be the major beneficiary, a lot of potential commercial and biomedical applications are also foreseen for the earth environment and are described in this paper as well.

Keywords: expandable structures, shape memory polymers, open cellular structures, glass transition temperature Tg, glassy and rubbery states

1. INTRODUCTION

Currently, existing approaches for producing large, ultra-lightweight, deployable structures in space typically rely upon electro-mechanical mechanisms and mechanically expandable booms to deploy structures and maintain them in the fully deployed, operational configuration. These support structures, with associated deployment mechanisms, launch restraints and controls, comprise sometimes more than 90% of the total mass budget. In addition, they significantly increase the stowage volume, cost, and complexity. Therefore, one of the major efforts at NASA and DoD has been to develop expandable structures characterized by low mass and small launch volume to be used in small, low-cost missions. As a result, space inflatable structures have emerged several years ago. A cold hibernated elastic memory (CHEM) structure is the most recent result of the quest for simple, reliable and low-cost expandable structures. It represents the next generation self-deployable structure and intends to be supplemental to space inflatable structure technology.

CHEM foam structures are under development by the Jet Propulsion Laboratory (JPL) and Mitsubishi Heavy Industries (MHI). Currently, the CHEM technology is well formulated, with clear space and commercial applications. Previous experimental results were very encouraging; the accumulated data indicate that the CHEM technology performs robustly in the Earth environment as well as in space. In addition, the test/evaluation results and preliminary analyses show that the CHEM is a viable way to provide a lightweight, compressible structure that can recover its original shape after long-term compressed storage. Some of potential CHEM space applications were studied under various programs at JPL and are described in this paper. Although the space community will be the major beneficiary, a lot of potential commercial and biomedical applications are also foreseen for the “earth environment” and described in following sections as well.

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2. CHEM STRUCTURE DESCRIPTION

2.1 Shape memory polymers (SMP)

The CHEM technology utilizes shape memory polymers (SMP) in open cellular (foam) structures. The solid SMP materials have been developed by Mitsubishi Heavy Industries, Nagoya R & D Center, Japan in the last 12 years. They offer unique properties for a variety of applications. These materials are polyurethane-based thermoplastic polymers with wide glass transition temperature Tg range. They are unique because of exhibiting large changes in elastic modulus E above and below the Tg. A large amount of inelastic strain (up to 400%) may be recovered by heating. The reversible change in the elastic modulus between the glassy and rubbery states of the polymers can be as high as 500 times. In addition, these materials also have high damping properties in transition temperature range and large temperature-dependence on gas permeability. Mechanical and chemical properties, durability and moldability are the same as in conventional polyurethanes. The material's shape memory function allows repeated shape changes and shape retention. This phenomenon is explained on the basis of molecular structure and molecular movements. The molecular chains can undergo micro-Brownian movement above the Tg (rubbery state) when the elastic modulus of the polymer material is low. In the rubbery state, the material can be easily deformed by application of external force, and the molecular chains can be oriented in the direction of the tension. When the temperature is lowered below the Tg and the deformation remains constant, the micro-Brownian motion will be frozen and the chain orientation and deformation will be fixed. When the material is heated above the Tg, the micro-Brownian movement starts again, the molecular chains lose their orientation and the material will recover its original shape. In this case, the shape-recovery function of the material requires crosslinking or partial crystallization.

2.2 CHEM foam structures

Figure 1: Cold hibernated elastic memory (CHEM) processing cycle
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 $^6$.$^7$. The stages in utilization of a CHEM foam structure are illustrated in Figure 1 and are as follows.

- **Original Structure:** The original structure is assembled in a room held below $T_g$. The structure is then fine-tuned to a desired shape. $T_g$ may be warm or cold depending on the application.

- **Folding or Rolling:** The structure is warmed above $T_g$ to make it flexible and then rolled and/or folded up for stowing. External forces are applied to keep it compressed.

- **Hibernation (storage):** The rolled/folded structure is cooled below $T_g$ so that it becomes firm in the compressed state. The structure can then be stowed for transportation to a deployment site. 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 in space above $T_g$ in an unconstrained configuration. 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 recompressed. In principle, there should be no limit to the achievable number of compaction/deployment/rigidization cycles. The stowed and deployed CHEM structures are shown in Figure 2.

![Figure 2: Stowed and deployed CHEM structures](image)
The overall simplicity of the CHEM process is one of its greatest assets. In other approaches to space structures, stowing and deployment are difficult and challenging, introducing significant risk, heavy mass, and high cost. The simple procedures for stowing and self-deployment provided by this technology greatly simplify the overall end-to-end process.

Another attractive aspect is the wide range of Tg that can be selected for deployment and rigidization. The Tg of shape-memory polymers ranges from -75°C to +100°C, thus allowing a wide variety of potential space and commercial applications in different environments. In these applications, the Tg 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 briefly for deployment, followed by radiative cooling to effect rigidization. For example, for a Mars surface mission, the Tg of a structure might be approximately 0°C; for terrestrial commercial use the Tg might be 50°C or higher.

The main 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 Tg to E above Tg (up to 50 for solid SMP) allow to keep the original shape in stowed, hibernated condition without external compacting forces for an unlimited time below Tg. Furthermore, a narrow transition temperature range for full transformation from glassy to rubbery state reduces the heat consumption during deployment (shape restoration).

3. BASIC PROPERTIES

Basic properties of a baseline CHEM foam, designated MF5520 are shown in Table 1 below. This shape memory polymer foam with the glass transition temperature Tg of 63°C, was developed for convenience and simplicity of the demonstration and testing in earth environment. Therefore, our CHEM structural test sample and models were fabricated and machined at ambient temperature in rigid state, compacted and/or folded above 63°C in flexible state, stowed in a cold hibernated state in ambient environment, deployed by heating above 63°C and rigidized by cooling again to room temperature.

<table>
<thead>
<tr>
<th>Properties</th>
<th>MF 5520</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>0.032</td>
</tr>
<tr>
<td>Tg (°C)</td>
<td>63</td>
</tr>
<tr>
<td>Compressive Strength (MPa)</td>
<td>0.09 - 0.102</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>0.2</td>
</tr>
<tr>
<td>E (compression) below Tg (MPa)</td>
<td>2.57 - 2.69</td>
</tr>
<tr>
<td>E (tension) below Tg (MPa)</td>
<td>11.4</td>
</tr>
<tr>
<td>E (compression) above Tg (MPa)</td>
<td>0.042 - 0.064</td>
</tr>
<tr>
<td>CTE (glassy state) (ppm/°C)</td>
<td>27.5</td>
</tr>
</tbody>
</table>
During CHEM technology development, evaluation and test results were very encouraging. All structural models including rods, tubes, wheels, chassis, boards, tanks demonstrated the basics of CHEM concept. In addition, a shape memory polymer foam designated M-18G with the Tg of \(-4^\circ\text{C}\) was developed specifically for Mars applications. Its elastic modulus was increased 3 times by chopped fiberglass reinforcement.

4. ADVANTAGES

The CHEM technology provides a simple end-to-end process for stowing, deployment and rigidization that has benefits of low mass, low cost, high reliability and great simplicity. 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. A long line of CHEM structure’s major advantages are listed below:

- **Low mass and stowage volume**
  Polymer foam structure assures lightweight: almost 2 orders of magnitude lighter than aluminum. Incorporation of shape memory polymers in open cellular structure affirms high compressibility and full/stowed volume ratios.

- **High reliability and low cost.**
  No deployment mechanisms, controls nor inflation systems etc. Already developed solid shape memory polymers are inexpensive. Short time for technology development is anticipated.

- **Self-deployable and simplicity.**
  Precision deployment by elastic recovery and shape memory of SMP foam. Simple deployment and rigidization. A structural & thermal isotropy behavior results in predictable thermal & temporal dimensional stability.

- **High dynamic damping and clean deployment & rigidization.**
  Foam acts like a structure composed of thousands of interconnected springs. Deployment by elastic recovery & shape memory effects and rigidization by transition from rubbery to glassy state assure clean, contamination-free environment.

- **None long-term stowage effects and ease of fabrication**
  CHEM structures can be stowed in glassy state for an unlimited time without any compression set. They offer indefinite storage/shelf life in rubbery state compared with restricted storage or refrigeration of other polymers. Good machinability in glassy and rubbery states. Cutting and shaping possible by conventional & computer numerically controlled (CNC) machining.

- **Impact & radiation resistant and thermal & electrical insulators.**
  Polyurethane-based CHEM foams belong to preferred class of space radiation resistance materials. They can effectively absorb the energy of impact or of forces generated by deceleration without creating high damaging stresses. Very low thermal and electrical conductivity.

The disadvantage of CHEM structure is that heat energy is needed for deployment. However, the solar heating deployment appears to be feasible. Recently conducted studies and analyses indicated that solar radiation could be utilized as the heat energy for deployment in Mars and Earth environments.
5. SPACE APPLICATIONS

CHEM structure technology provides NASA a robust, innovative self-deployable structure with significantly higher reliability, lower cost and simplicity over other expandable/deployable structures to be used on many future space missions in Earth and Space Science Programs. A myriad of CHEM applications are anticipated for space robotics and other support structures for telecommunication, power, sensing, thermal control, impact and radiation protection subsystems as well as for space habitats. Therefore, various feasibility studies and preliminary investigations have been conducted on potential CHEM space applications under various programs at JPL. Some of these studies are described in the following subsections.

5.1 Advanced self-deployable wheels for mobility systems

Ultra-lightweight self-deployable and rigidizable wheels were developed and demonstrated at JPL utilizing CHEM structure process technology. During this investigation, several different wheel designs were developed and evaluated for a prototype nano-rover. The structural models of different designs were fabricated from the CHEM foam and assessed using a CHEM thermo-mechanical processing cycle. All wheels recovered completely after several cycles and a wheel design with the fastest recovery (deployment) was selected for a nano-rover. Full-scale structural wheels were fabricated and assembled on a two-wheeled prototype nano-rover, shown in Figure xx. Finally, the compacted wheels were successfully deployed at ~80°C and subsequently rigidized at room temperature in a simulated low pressure (6 millibars) Mars environment. Demonstrated complete wheel recovery after a CHEM processing showed that this structural concept is a viable way to provide ultra-lightweight, compressible, self-deployable wheels that can recover (deploy) their original size after cold hibernation storage. The recovery forces were able to fully deploy compacted CHEM wheels without any mechanical or inflatable systems. A high ratio of elastic modulus E below Tg/E above Tg in CHEM foams indicated very effective rigidization and eliminated support structures to maintain CHEM wheels in fully deployed, operational configuration.

Figure 3 CHEM nano-rover wheels
The present mechanically deployed rover wheels are heavy, complex, not reliable and not autonomous with small full/stowed volume ratios. In addition, the MEMS and microelectronics embedded in CHEM foam structures will be self-protected from harmful effects of debris/micrometeoroid impact or thermal environment. Autonomous, lightweight, self-deployable wheels technology for future space vehicles is critical and enabling further robotics and future human exploration of space.

5.2 CHEM Horn Antenna

Development of ultra-light deployable systems is one of the critical needs for many missions including recent proposed JASSI (Juniper Deep Atmospheric Sounder and Synchrotron Imager) deployable horn antenna. Preliminary investigation and analysis results indicated that CHEM self-deployable and rigidizable foam structure technology is one of the promising methods for this application. During these studies, several different designs of baseline 3.5 m long conical corrugated horn antenna were developed and structural/dynamic analyses were performed for each design configurations. A small CHEM structural antenna model was fabricated and a thin conductive Al layer was successfully deposited on inside surface of the model. This structural model went through the CHEM processing cycles demonstrating the basics of CHEM concept such as: high full/stowed volume ration, cold hibernated stowage, deployment when heating above Tg, original shape restoration and rigidization when cooling below Tg. This studies indicated the feasibility of using CHEM foam structure technology for self-deployable horn antennas.

Present mechanically deployable antennas are heavy, complex, not reliable and packaging volume inefficient. CHEM foam antennas will provide a novel, self-deployable antenna structure technology with significant higher reliability, low mass, low cost and simplicity.

![Figure 4 CHEM Horn Antenna](image_url)
5.3 Precision Soft Lander

There is a demand and need for precise, reliable, safe, low cost landing systems for small, single landers as well as for large multi-probe missions for planetary and small body exploration. Current spacecraft use complex systems such as aeroshells coupled to parachutes, solid rockets, and ultimately airbags to minimize the impact of landing or use all propulsive soft landing approaches. Airbags are being used for intermediate-sized landers but they are too complicated and expensive for small (1 to 50kg-class) landers. As lander mass increases airbag systems become too heavy. Airbags have problems as well. On first impact, they produce lander bounce making it difficult to land within a small, scientifically interesting target area. Also, past mission experience indicates that the lander platform is not sufficiently stable to perform some precision operations even after airbags deflation. In addition, airbags do not provide sufficient thermal insulation against heat loss from the lander body to the cold ground.

Preliminary investigation indicated that problems of achieving a soft, stable, precision landing can be solved with the Precision Soft Lander (PSL) concept. This concept employs a cold hibernated elastic memory (CHEM) foam technology as the main thermal and energy absorbing element of the system. The PSL concept is described as followed. A CHEM foam pad has a glass-transition temperature $T_g$ well above ambient temperature. It will be compacted, at the temperature above $T_g$ to about a tenth or less of its original volume, then cooled below $T_g$ and later installed on a spacecraft without compacting restraints. Upon entry of the spacecraft into a planetary atmosphere, the temperature will rise above $T_g$ causing the pad to expand to its original volume and shape. As the spacecraft decelerated and cooled, the temperature will fall below $T_g$ rigidizing the foam structure. The structure will absorb kinetic energy during ground impact by inelastic crushing thus protecting the payload from damaging shocks and providing a safe stick-at-the-impact-site landing. Thereafter, this pad will serve as a mechanically stable, thermally insulating platform for the landed spacecraft. When developed, the PSL system will offer a near-term technical solution for access to scientifically interesting site including difficult and hard-to-reach areas. In addition, it has the potential to be highly reliable: no moving part, no actuators, no sub-systems that have to be deployed by other mechanical mechanisms.

5.4 Radar Antenna

Preliminary studies indicated the CHEM foam structure could be used for self-deployable, lightweight radar antennas. A novel CHEM structure-based radar antenna is described in Reference 13. The radar antenna is a flat array consist of microstrip patches with microstrip transmission lines as power dividers. To achieve the required dual polarizations with 80 MHz of bandwidth, the antenna is a three-layer membrane design. The top layer has 18 x 6 radiating square patches, the middle layer is the ground plane, and the bottom layer has the power dividing transmission lines. Each layer is a 2-mil thick polyimide material with 5-micron copper deposited on it. The top layer has a spacing from the middle layer, while the bottom layer is spaced from the middle ground plane. The CHEM foam structure, which is to be made into flat sheets, is placed between the three membrane layers to not only serve as spacers but also used as antenna deployment mechanism. In other words, the three membranes and the two sheets of CHEM foam material are pressed together to form a very thin structure and then is rolled up for stowage. During deployment, the CHEM foam returns to its original shape & size and un-rolls the structure to form a flat antenna. The CHEM structure-based radar antenna is shown in Figure 5 below.
Currently, existing approaches for producing large deployable antenna structures in space typically rely upon mechanical mechanisms or inflatable booms to deploy structures and maintain them in the fully deployed, operational configuration. These support structures are heavy, expensive and not reliable. The CHEM structure-based radar antenna when successfully developed, will have application for Earth mapping L-band Synthetic Aperture Radars (SAR) to provide measurement of changes in ice-water, soil moisture, global ecosystem, as well as Earth surface deformation. In addition, this structure technology could be used for other applications such as space deployable solar arrays.

5.5 Sensor Delivery System

Future planetary exploration missions to Mars and other planets/small bodies are aimed at understanding the global geology and climate history. While orbital platforms provide a detailed understanding of a surface at the order of 10 meters resolution, detailed in-situ exploration at the sub-meter level has been limited to landed mission such as Mars Pathfinder in 1997. The in-situ exploration of science sites has been envisioned using mobile robots or rovers, however, due to the assumed rugged terrain, rovers may have difficulties accessing these sites due to mobility and power availability limitations.

Recently, another approach for widespread planetary exploration is the deployment of a network of sensors located in diverse and hard-to-reach locations on the planet surface. However, the major technological challenge to overcome is how in effective, reliable, simple way to deploy and scattered them across a planetary surface.

Our proposed development of CHEM-based SDS (sensor delivery system) is the answer to that technical challenge. Recently conducted preliminary studies confirmed a feasibility of low mass, low packing volume, self-deployable sensor delivery system (SDS) technology to future planetary missions specifically to planet Mars. Integrated SDS system utilizes a cold hibernated elastic memory (CHEM) open cellular structure as the main structural element. The CHEM-based integrated sensors are in hibernated, compacted condition during the launch & flight stages and then are dropped in different locations from a planetary lander or aerial vehicles. They are deployed and if necessary, rigidized during the falling or on planetary surface. The CHEM foam packaging structure absorbs a large amounts of impact energy without generating high damaging stresses and SDS system will be able to robustly survive the surface impact. Once deployed, the CHEM structure will expand to deploy the elements of the sensor system. These sensors would be scattered across a scientifically interesting but hard-to-reach surface sites to form a network of sensors for in-situ detection of life.

The development of a simple, low cost CHEM-based sensor system that leads to the deployment of a large number of sensors to a planet surface will benefit NASA by providing a means for robust planetary exploration over a wide surface area. In-situ exploration of scientifically interesting sites by such a system will certainly improve NASA’s ability to reach difficult terrain settings without the need for mobility as is required for rovers.

6. COMMERCIAL APPLICATIONS

Although space community will be the major beneficiary, a lot of potential CHEM commercial applications are also foreseen for the earth environment. However, the commercial applications were not the main objectives of this paper and are reviewed briefly.

The CHEM technology could be applied to deployable shelters, hangars, camping tents or outdoor furniture to mention just a few in recreation area. Such articles could be made of CHEM foam with a Tg slightly above the highest outdoor summer temperature. The CHEM parts can be transported and stored in small packages then expanded by heating at the outdoor site. After expansion, CHEM parts will be allowed to cool to ambient temperature below their Tg, so that they would become rigid as needed for use.

Other potential commercial application are seen in: self-deployable tanks, coolers/thermoses, construction, toys, automotives, thermal insulation, packaging, impact energy absorption product, filters, high damping sound and electromagnetic shielding, and more. The researchers have been already contacted regarding potential CHEM applications in recreation, toy, automotive and construction areas.
7. BIOMEDICAL APPLICATIONS

A number of medical applications are being considered for shape memory polyurethane-based CHEM foams. Two of their properties are of particular interest to the medical world. One is that the dramatic softening of shape memory polyurethanes can be tailored to occur at 30°C and resulting CHEM material is rigid and compacted at the room temperature but becomes soft and deployed when placed inside the body. The other property is that polyurethane are generally recognized as having excellent biocompatibility. Several independent standard cytotoxicity and mutagenicity test have been conducted on shape memory polyurethanes of CHEM foams in vitro to ensure biocompatibility, all with excellent results.

Biomedical and dental applications are foreseen for vascular and coronary grafts, catheters, orthopedic braces and splints, dental implants and prosthetics, just to name a few. One of these potential applications, endovascular treatment of aneurysm was experimentally investigated at Ecole Polytechnique, Montreal 15. Lateral wall venous pouch aneurysms were constructed on both caroid arteries of 8 dogs. The aneurysms were occluded per-operatively with CHEM blocks. Internal maxillary arteries were occluded via a 6F transcatheter technique using compressed CHEM blocks. Angiography and pathology were used to study the evolution of the occlusion and neointimal formation at the neck of experimental aneurysms after 3 and 12 weeks. The CHEM extract demonstrated no evidence of cell lysis or cytoxicity and no mutagenicity. The efficient vascular embolization was confirmed in the aneurysms and good neointimal formation over the neck of treated aneurysms was demonstrated at the CHEM interface. Maxillary arteries embolized with CHEM foam remained occluded during this experiment. The major conclusion of the investigation was that the foamy nature of this new embolic agent favors the ingrowth of cells involved in neointima formation and new embolic devices for endovascular interventions could be designed using CHEM’s unique physical properties.

8. CONCLUSIONS

Attractive CHEM structure technology provides NASA a robust, innovative self-deployable structure with significant higher reliability, lower cost and simplicity over other expandable/deployable structures to be used on many future space missions in Earth and Space Science Programs. A myriad of CHEM applications are anticipated for space robotics and other support structures for telecommunication, power, sensing, thermal control, impact and radiation protection subsystems as well as for space habitats. Various preliminary investigations under different programs at JPL confirmed the feasibility of some potential CHEM space applications.

One early demonstration example of CHEM wheels was developed for a nano-rover. Other potential applications, such as a horn antenna, radar antenna, and a sensor delivery system, were studied under various programs at JPL. Besides space structural use, the impact energy absorption applications such as self-deployable soft landing systems and micrometeoroid protection shielding were considered and investigated recently with promising preliminary results. Although the space community is the major beneficiary, a lot of potential commercial applications are foreseen for the “earth environment”. Potential commercial application are seen in recreation, toys, construction, automotives, thermal insulation, packaging, impact energy absorption products, filters, high damping sound and electromagnetic shielding, and more. Also a number of medical applications are being anticipated for polyurethane-based CHEM foams for self-deployable vascular and coronary grafts, catheters, orthopedic braces and splints, dental implants and prosthetics

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