ABSTRACT

Currently, existing approaches for producing large, ultra-lightweight, deployable structures in space typically rely upon electro-mechanical mechanisms and mechanically expandable that are heavy, not stowage volume efficient, expensive and complex. Therefore, one of the major efforts at NASA and DoD has been to develop expandable structures characterized by low mass and small launch volume. As a result, space inflatable structures have emerged 9-10 years ago.

A cold hibernated elastic memory (CHEM) structure technology is the most recent result of the quest for simple, reliable and low-cost expandable structures. The CHEM technology utilizes shape memory polymers in open cellular (foam) structures or sandwich structures made of shape memory polymer foam cores and polymeric composite skins. It takes the advantage of polymer's heat activated 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. The CHEM foam 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.

The CHEM foam structures are under development by the NASA’s Jet Propulsion Laboratory (JPL) and industry. Presently, the CHEM structure concept is well formulated with clear space and commercial applications. These structures are described here and their major advantages are identified over other expandable/deployable structures. Previous experimental and analysis results were very encouraging, confirmed the feasibility of this innovative, new class deployable structure 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. Present further improvements in CHEM technology widen potential space applications including gossamer structures. Although space community is the major beneficiary, a lot of potential commercial applications are also foreseen for the earth environment and are described briefly in this paper as well.

1. INTRODUCTION

Presently, a modern spacecraft is undergoing revolutionary change towards higher capability at low-cost and small size. It is envisioned that eventually the spacecraft avionics will shrink to the size of a single microchip. However, there are some spacecraft subsystems that resist miniaturization. Space antennas require large sizes to deliver high data rates or in case of mobile communication satellites provide simultaneous multiple user access increasing profits, large size sensors are often dictated by the physics of the specific application, etc. All these science, commercial and National Aeronautics and
Space Administration (NASA) or Department of Defense (DoD) applications call for large expandable, deployable space structures. 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 9-10 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 industry. 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. The majority of investigated applications were not high-load carrying structures. However, present further improvements in design, manufacturing and processing of CHEM materials broaden potential space applications including some gossamer structures. Although the space community is 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.

2. DESCRIPTION OF CHEM TECHNOLOGY

The CHEM technology utilizes shape memory polymers (SMP) in open cellular (foam) structures or sandwich structures made of shape memory polymer foam cores and polymeric composite skins. 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 and is described elsewhere.
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.

![Diagram](image)

**Figure 1**: Cold hibernated elastic memory (CHEM) processing cycle $^7$

1. **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.

2. **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.

3. **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.
4. **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.

5. **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 recompacted. 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 $T_g$ that can be selected for deployment and rigidization. The $T_g$ of shape-memory polymers ranges from $-75^\circ C$ to $+100^\circ C$, 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 briefly for deployment, followed by radiative cooling to effect rigidization. For example, for a Mars surface mission, the $T_g$ of a structure might be approximately $0^\circ C$; for terrestrial commercial use the $T_g$ might be $50^\circ C$ 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 500 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. PROPERTIES OF BASELINE CHEM STRUCTURE

Basic properties of a baseline CHEM foam, designated MF5520 are shown in Table 1 below. A baseline 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. It was foamed by the conventional blowing method. Our CHEM structural test samples 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>
<tr>
<td>Th. conductivity (W/mK)</td>
<td>0.027</td>
</tr>
<tr>
<td>Th. conductivity (95% compressed) (W/mK)</td>
<td>0.12</td>
</tr>
<tr>
<td>Specific heat (30°C) (J/kg K)</td>
<td>1320</td>
</tr>
<tr>
<td>Outgassing (Wt. Loss – WVR) %</td>
<td>1.17</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°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. The major advantages of CHEM structures are listed below:

- **Low mass and stowage volume**
  2 orders of magnitude lighter than aluminum. Full/stowed volume ratios > 40
- **High reliability and low cost.**
  No deployment mechanisms, controls nor inflation systems etc. CHEM materials are inexpensive.
- **Self-deployable and simplicity.**
  Deployment by elastic recovery and shape memory of CHEM foams.
- **High dynamic damping and clean deployment & rigidization.**
  Foam acts like a structure composed of thousands of interconnected springs. Deployment by elastic recovery & shape memory assures clean, contamination-free environment.
- **None long-term stowage effects and ease of fabrication**
  They can be stowed in hibernated state for an unlimited time. Good machinability, cutting and shaping.
- **Impact & radiation resistant and thermal & electrical insulators.**
  CHEM foams belong to preferred class of space materials. They absorb the energy of impact. Very low thermal and electrical conductivity.

The disadvantage of CHEM structure is the 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. Also the CHEM foams produced by the conventional blowing method have relatively low strength and structural rigidity. However, CHEM foam cores can be used in high-load carrying-on applications as a strength/stiffness augmentation and deployment mechanisms when combined with composite laminate skins in the sandwich CHEM structures.
5. INVESTIGATED SPACE APPLICATIONS

CHEM technology provides NASA an innovative self-deployable structure with significantly higher reliability, lower cost and simplicity over other space expandable/deployable structures. A number 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. Consequently, various feasibility studies and preliminary investigations have been conducted on potential CHEM space applications under different programs at JPL and industry partners\textsuperscript{10-14}. Some of these applications with their present TRL (Technology Readiness Level) are shown in Table 3 below.

Table 2 Investigated space CHEM applications

<table>
<thead>
<tr>
<th>TRL</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nano-rover wheels</td>
</tr>
<tr>
<td>2-3</td>
<td>Sensors Delivery Systems</td>
</tr>
<tr>
<td>2-3</td>
<td>Horn Antenna</td>
</tr>
<tr>
<td>2-3</td>
<td>Radar Antenna</td>
</tr>
<tr>
<td>2</td>
<td>Thermal-Meteoroid Shield</td>
</tr>
<tr>
<td>2-3</td>
<td>Habitats Structures</td>
</tr>
<tr>
<td>2-3</td>
<td>In-Situ Propellant Production Tanks</td>
</tr>
<tr>
<td>3</td>
<td>CCSL Deployable Boom</td>
</tr>
</tbody>
</table>
Notes: TRL: From 1 - Basic Principles Observed & Reported to
to 9 - Actual proven flight system
CCSL: CFRF/CHEM Spring Lock
CFRF: carbon fiber reinforced polymer

More information about these investigations can be found in relevant references\textsuperscript{7,10-14}. In general, most of investigated potential applications were developed up to the TRL 3 that is: analytical and experimental proof of concepts were demonstrated in the laboratory. In these experiments, small structural models were utilized in earth ambient condition. One exception was the CHEM wheels for nano-rover that have been developed to the TRL 4. Full-scale structural wheels were fabricated and assembled on two-wheeled prototype nano-rover, shown in Figure 3. Finally, the compacted wheels were successfully deployed at 80\textdegree C and subsequently rigidized at room temperature in a atmospheric as well as in a simulated low pressure (6 millibars) Mars environment.

![Figure 3 CHEM nano-rover wheels. Outside diameter of 6 cm\textsuperscript{7}](image)

The majority of investigated applications were not high-load carrying-on structures. In these cases, we tried to take advantages of some other unique properties of CHEM foams such as impact & radiation resistance, thermal and electrical insulation, self-deployment, simplicity, low mass and stowage volume etc.

In other applications such as radars or solar arrays, the analyses indicated the sandwich CHEM structure designs of high strength composite skins and CHEM foam cores are needed for larger structures to increase the structural rigidity.

The CCSL (CFRF/CHEM Spring Lock) truss element concept for boom structure that involved a unique hybrid design of CHEM foams and polymer composites was applicable
to high-load carrying-on support structures. The CCSL structure is described in the section of potential gossamer applications later in this paper.

6. PRESENT CHEM ACTIVITIES

One of the major efforts in CHEM technology in the last few years has been to improve and optimize the quality and physical properties of the CHEM foams. Wright Material Research Co (WMR) working with JPL under the SBIR (Small Business Innovation Research) Program, is developing new CHEM micro-foam materials. WMR utilizes its proprietary foam processing to create the micro-foams from the MHI's (Mitsubishi Heavy Industry) shape memory polymer raw materials. These CHEM micro-foams have similar cells in micron sizes uniformly and evenly distributed within the cellular structure. The sizes of cell can be controlled during the foaming process. WMR successfully completed the SBIR Phase I in 2003 confirming the feasibility and demonstrating the proof-of-CHEM micro-foam concept. Presently, in the Phase II WMR has been working on scaling-up the processing of the CHEM micro-foams, further reducing their density and optimizing their mechanical properties as well as processing conditions. When compared with conventionally made foams, the CHEM micro-foams when developed successfully, will enhance physical and mechanical properties, raise isotropy, increase compressive/tensile strength, enlarge tear strength and fracture toughness.

Other activities have been directed to develop the sandwich CHEM structures intended for high-load support structure applications. WMR Co under SBIR Phase I Program is working on sandwich CHEM structures that involve fiber reinforced shape memory polymer composite skins and CHEM foam cores. The same shape memory polymer is used in composite skins and foam cores. This allows to achieve high packaging ratios and reduce the stowage volume of the sandwich structure. In addition, it is planned to develop new CHEM micro-foams reinforced with the carbon nano-tubes. This will increase the mechanical strength as well as thermal conductivity. The improvement in thermal conductivity specifically is very critical because of saving heat energy and time during CHEM structure deployment in space.

7. POTENTIAL GOSSAMER APPLICATIONS

Preliminary investigations and analyses indicated that CHEM foams themselves cannot be used in high-load carrying-on gossamer structures. However, it appears the sandwich CHEM structures or hybrid design of CHEM foams and polymer composites could be applicable to support structures for large deployable antennas, telescopes, sunshields or solar arrays. In these applications, the CHEM foams will be used as the strength/stiffness augmentation and/or deployment mechanisms when combined with composite laminate skins.

For instance, Composite Optics Inc (COI) working with JPL, developed the CCSL (CFRF/CHEM Spring Lock) truss element concept for large (50-100 m) boom structures that involved a unique hybrid design of CHEM foams and polymer composites.
The CCSL truss element is essentially two Carbon Fiber Reinforced Polymers (CFRP) tape springs separated by the Cold-Hybernated Elastic-Memory (CHEM) foams (Figure 4).

![CCSL truss element](image)

**Figure 4** CCSL truss element

The two material systems are used in a strategic manner that allowed the truss element to be stowed and deployed from small volumes without the use of complex mechanisms. CCSL uses the CHEM foam to lock the truss element in the stowed and deployed state, control the deployment and add the buckling resistance. The CFRP tape is used to provide high axial stiffness to the truss members, reduce weight, offers the elastic spring energy for deployment and increases overall stability to the boom. The baseline truss boom design was a tri-legged CCSL longeron truss element configuration supported with diagonals and horizontals all connected at joints. All other truss elements were considered to be made from CFRP material to maintain ultra-low mass, high stability and durability. The results of preliminary investigation on the CCSL truss element were encouraging and COI has successfully demonstrated a proof-of-CCSL structure concept.

In addition, COI has conducted some studies on other lightweight deployable structures utilizing sandwich CHEM structures. One of investigated applications was a furlable mirror with CHEM foam cores as a deployment mechanism and piezo-actuators to tune the face composite sheets to the desired shape.

As mentioned before, WMR Co is working on improved sandwich CHEM structures that combine fiber reinforced shape memory polymer composite skins and CHEM foam cores. When successfully developed, they will exhibit very high packaging-strain capabilities while guaranteeing more predictable, precision deployment when compared to traditional composite skin sandwich CHEM structures. That improved CHEM structure technology could be applicable to support structures for large deployable gossamer applications such as antennas, telescopes, sunshields, radars or solar arrays. Potential usage of future-developed CHEM micro-foams reinforced with the carbon nano-tubes is considered in thin membrane applications specifically in solar sails. What we envision is an potential boomless CHEM membrane deployed by the shape memory and elastic recovery. Certainly, more research, experiments and analyses must be done in this area. However, the pay off could be high. Currently, existing approaches for producing large, ultra-lightweight, deployable gossamer structures in space typically rely
upon electro-mechanical mechanisms or inflatable booms to deploy structures and maintain them in the fully deployed, operational configuration. These support structures, with associated deployment mechanisms, launch restraints, inflation systems, and controls, comprise more than 90% of the total mass budget. In addition, they significantly increase the stowage volume, cost, and complexity.

Our advanced CHEM membrane concept represents the next generation self-deployable structure and creates simple, lightweight, and low cost deployable membranes reducing the areal density and stowage volume. This new concept may launch a new paradigm in structure configurations and future mission architecture. This innovative concept would be one of the precursors and fundamental technologies for future next generation, thin-film, self-deployable structures in general and for solar sails specifically, without booms and other support structures.

8. 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 products, filters, high damping sound and electromagnetic shielding, and more.

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 with very promising results.

9. CONCLUSIONS

Attractive CHEM technology provides NASA an innovative self-deployable structure with significant higher reliability, lower cost and simplicity over other space expandable/deployable structures. 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. Preliminary investigations and analyses indicated that CHEM foams themselves cannot be used in high-load carrying-on gossamer structures. However, it appears the sandwich CHEM structures or hybrid
design of CHEM foams and polymer composites could be applicable to support structures for large deployable antennas, telescopes, sunshields or solar arrays. In these applications, the CHEM foams are used as the strength/stiffness augmentation and/or deployment mechanisms when combined with composite laminate skins. Present further improvements in CHEM structures such as development of the CHEM micro-foams as well as improved sandwich CHEM structures that combine shape memory composite skins and CHEM foam cores broaden potential space applications. When successfully developed, they will exhibit high-load carrying-on capabilities and very high packaging-strain ability while guaranteeing more predictable, precision deployment. That improved CHEM structure technology will be applicable to support structures for large deployable gossamer applications. The pay off of future development of the boomless CHEM membrane deployable by the shape memory and elastic recovery could be high. If successfully developed, this new concept may launch a new paradigm in structure configurations and future mission architecture. This innovative concept would be one of the precursors and fundamental technologies for future solar sails with self-deployable membranes without booms and other support structures. Although the space community is the major beneficiary, a lot of potential commercial and medical applications are foreseen for the earth environment.

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