

Potential bio-medical and commercial applications of cold hibernated elastic memory (CHEM) self-deployable foam structures

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ABSTRACT

A cold hibernated elastic memory (CHEM) foam structure is one of the most recent results of the quest for simple, reliable and low-cost expandable space structures. The CHEM technology utilizes shape memory polymers in open cellular (foam) structure or sandwich structures made of shape memory polymer foam cores and polymeric composite skins. It takes advantage of the polymer's heat activated shape memory in addition to the foam's elastic recovery to deploy a compacted structure. The glass transition temperature T_g is tailored to rigidize the structure in the fully deployed configuration.

Previous experimental and analytical results were very encouraging and indicated that the CHEM foam technology can perform robustly in space as well as in the Earth environment. CHEM structures are described here and their major advantages are identified over other expandable/deployable structures. Although the space community is the original major beneficiary, a number of potential applications are also anticipated for the "earth environment". CHEM developers strongly believe that this technology has great promise for a host of commercial and bio-medical applications. Some of these potential and already investigated CHEM applications are described in this paper.

Keywords: expandable structures, shape memory polymers, open cellular structures, glass transition temperature T_g ,

1. INTRODUCTION

Currently, some spacecraft technologies are targeted toward higher capability at low-cost and small size. However, there are some spacecraft subsystems that still require large sizes and working areas. Space antennas require large sizes to deliver high data rates and mobile communication satellites provide simultaneous multiple user access increasing profits. Large size sensors are often dictated by the physics of the specific application. Therefore, the space community is getting ready for new spacecraft architectures: for example, a spacecraft that is Lilliputian at launch but deploys huge apertures and appendages when in space.

Unfortunately, presently used electro-mechanically deployable structures are heavy, complex, with some notable in flight failure, expensive, and not stowed volume efficient. Consequently, 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 in the last approximately ten years. A cold hibernated elastic memory (CHEM) structure is one of the most recent results 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), Mitsubishi Heavy Industries (MHI) and other industry partners. Presently, the CHEM technology is well formulated, with clear space and commercial applications. Previous experimental results were very encouraging and are described briefly later in this paper. The accumulated data indicate that the CHEM technology performs robustly in the Earth environment as well as in simulated space environment. 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. Although the space community is the major beneficiary, a number of potential applications are

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also foreseen for the "earth environment". CHEM developers believe that this structure technology when fully developed, will enable various companies to design and build new, innovative structures for commercial and biomedical applications. Some of these potential and already investigated CHEM applications are described in this paper.

2. DESCRIPTION OF CHEM STRUCTURE

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 skins¹. The solid SMP materials have been developed by Mitsubishi Heavy Industries, Nagoya R & D Center, Japan in the last 14 years^{2,3}. They offer unique properties for a variety of applications. These materials are polyurethane-based thermoplastic polymers with a wide glass transition temperature T_g range. They are unique because of exhibiting large changes in elastic modulus E above and below the T_g . A large amount of inelastic strain (up to 400%) may be recovered by heating. The reversible change in the elastic modulus in tension 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 the transition temperature range and large temperature-dependence on gas permeability. Mechanical and chemical properties, durability and moldability are similar 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^{4,5}.

The CHEM foam technology takes advantage of the polymer's heat activated shape memory in addition to the foam's elastic recovery to deploy a compacted structure. The glass transition temperature T_g depending on the application is tailored 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.

1. Original Structure: The original structure is produced/assembled in a room held below T_g .

2. Compaction or Rolling: The structure is warmed above T_g to make it flexible and then compacted and/or rolled up for stowing.

3. Hibernation (storage): The compacted/rolled structure is cooled to ambient temperature to achieve the hibernated stowage. As long as the temperature is maintained below T_g , no external forces are needed to keep the structure compressed.

4. Deployment: The compacted/rolled structure is warmed above T_g in an unconstrained configuration. Memory forces and the foam's elastic recovery cause the structure to naturally deploy back to its original shape and size without external actuation.

If needed:

5. Rigidization: The deployed structure is cooled by ambient temperature 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. Examples of stowed and deployed CHEM structures are shown in Figure 2.

The overall simplicity of the CHEM process is one of its greatest assets. 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°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 a CHEM structure should be slightly higher than the maximum ambient temperature; this will keep the structure in the hard 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°C ; for terrestrial commercial use the T_g might be 50°C or higher.

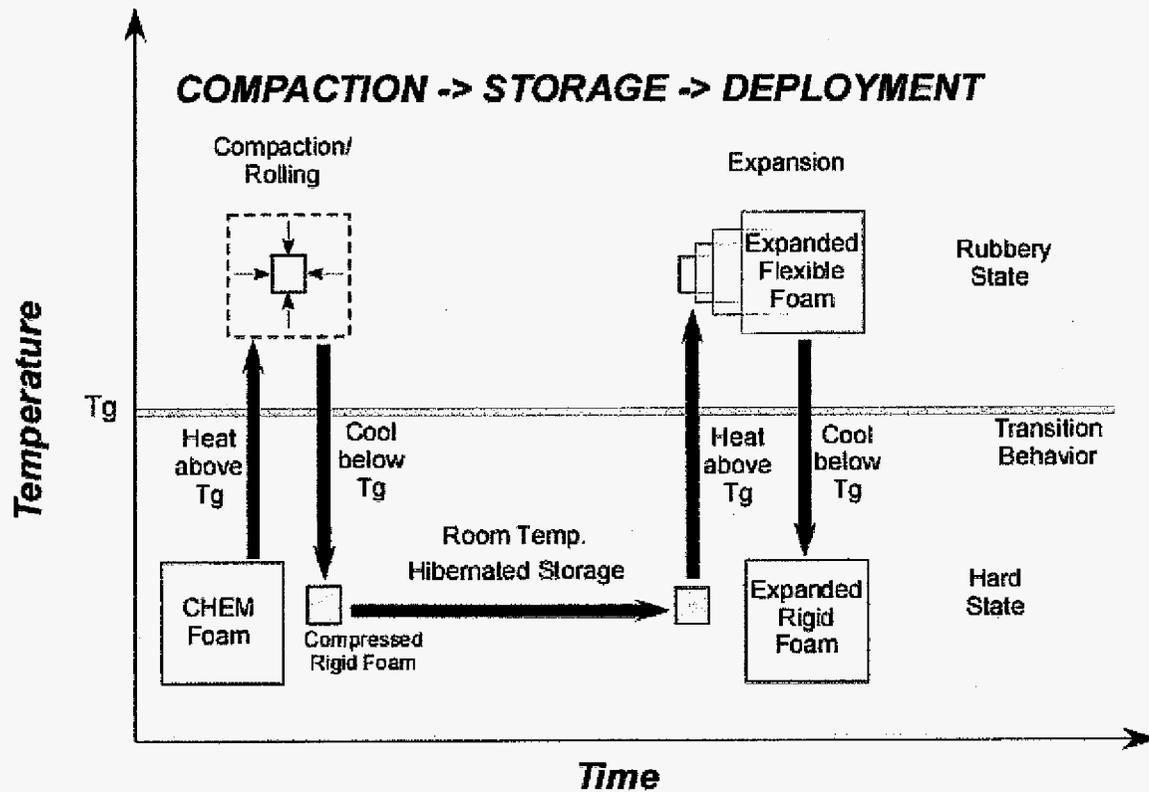


Figure 1: Cold hibernated elastic memory (CHEM) processing cycle

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 in tension E below T_g to E above T_g (up to 500 for solid shape memory polymer) allow to keep the original shape in stowed, hibernated condition without external compacting forces for an unlimited time below T_g . Furthermore, a narrow transition temperature range for full transformation from hard to rubbery state reduces the heat consumption during deployment (shape restoration).

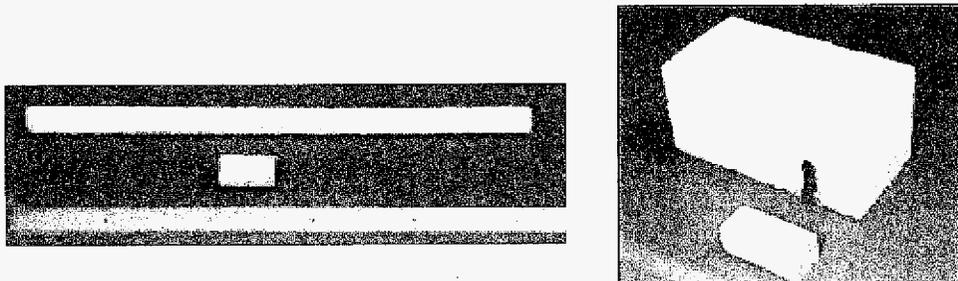


Figure 2: Stowed and deployed CHEM structures⁹

3. PROPERTIES OF BASELINE CHEM STRUCTURE

Basic properties of a baseline CHEM foam, designated MF5520 are shown in Table 1 below ⁸.

Table 1: Properties of baseline MF5520 foam

Properties	MF 5520
Density (g/cm ³)	0.032
Tg (°C)	63
Compressive Strength (MPa)	0.09 - 0.102
Tensile Strength (MPa)	0.2
E (compression) below Tg (MPa)	2.57 - 2.69
E (tension) below Tg (Mpa)	11.4
E (compression) above Tg (MPa)	0.042 - 0.064
CTE (glassy state) (ppm/°C)	27.5
Th. conductivity (W/mK)	0.027
Th. conductivity (95% compressed) (W/mK)	0.12
Specific heat (30°C) (J/kg K)	1320
Outgassing (Wt. Loss – WVR) %	1.17

A baseline shape memory polymer foam with the glass transition temperature Tg of 63°C, was developed for demonstration and testing in earth environment. It was manufactured by the conventional foaming method. Our CHEM structural test samples and models were fabricated and machined at ambient temperature in a 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.

4. CHARACTERISTICS OF CHEM STRUCTURES

CHEM technology provides 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 potentially eliminating deployable booms, deployment mechanisms, inflation and control systems that require large fractions of the mass budget ⁹. The following list is offered as an incomplete list of many advantages of CHEM structures ^{9,10}:

- Clean and quiet deployment by shape memory and elastic recovery (no mechanisms nor inflation systems)

- Low mass: 2 orders of magnitude lighter than Aluminum
- High full/compaction volume ratio: 20/1 in one dimension has been attained.
- Simple end-to-end process for stowing, deployment and rigidization
- Allows long unconstrained stowage at room temperature
- Can be transported in small pieces and deployed at required locations
- Air droppable and safe, stick-at-the-impact site landing at a variety of local terrain
- Impact/shock absorbent and blast wave energy absorption
- Dynamic, sound & electromagnetic wave attenuation
- Self-healing/repairable structures
- Excellent biocompatibility
- High thermal and electrical resistance
- Easily integrated to act as multifunctional structures
- Low cost: shape memory polymer foam materials are inexpensive.
- Highly reliable, no maintenance, and no deflation problems.
- Easily fabricated: good machinability, cutting and moldability
- Autonomous deployment

One potential drawback of a CHEM structure is the heat energy 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^{11,12}. The other option of deployment is the foam's elastic recovery by the release of a mechanically compressed structure. Also the CHEM foams themselves have relatively low strength and structural rigidity. However, CHEM foam cores can be used in high-load carrying applications when combined with composite laminate skins or face sheets in a sandwich CHEM structure.

5. INVESTIGATED SPACE APPLICATIONS

CHEM technology offers NASA an innovative self-deployable structure with potentially higher reliability, lower cost and simplicity over other space expandable/deployable structures. A number of CHEM applications have been 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. More information about these investigations can be found in relevant references¹³⁻¹⁷.

The majority of investigated applications were not high-load carrying structures but utilized other unique properties of CHEM foams such as impact & radiation resistance, thermal and electrical insulation, self-deployment, simplicity, low mass or stowage volume. One of these space applications were CHEM wheels for a nano-rover. Full-scale structural wheels were developed, fabricated and assembled on a two-wheeled prototype nano-rover, shown in Fig. 3. Finally, the compacted wheels were successfully deployed at 80°C and subsequently rigidized at room temperature in a atmospheric earth pressure as well as in a simulated low pressure (6 millibars) Mars environment.

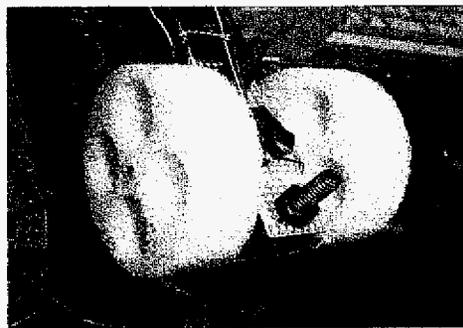


Figure 3: CHEM nano-rover wheels⁷

6. POTENTIAL COMMERCIAL APPLICATIONS

Although the space community is the major beneficiary, a lot of potential CHEM commercial applications are also foreseen for the earth environment. Such applications could be made of CHEM foam with a T_g slightly above the highest ambient temperature. The CHEM products will be compacted, stowed unconstrained in small volumes at room temperature, transported if needed and deployed at required locations. They also can be dropped from aerial vehicles and deployed in hard-to-reach locations. Sensors, circuitry and automated components will be easily integrated to enable CHEM-based systems to act as smart structures which operate autonomously. In addition, CHEM structures are potentially self-repairable by temporary heating and re-cooling.

Depending upon the application, CHEM technology may utilize just a CHEM foam or a sandwich structure in case of high-load carrying applications. The sandwich CHEM structures involve fiber reinforced polymer composite skins and CHEM foam cores.

CHEM structures can be compacted and packaged in different ways. Some of these techniques are shown in Fig. 4. The structures can be compacted by compression, rolling or combination of these two or other methods. Also, the packaging could be in forms such as accordion folding, roll up, combination of these two or other appropriate packaging for selected CHEM applications.

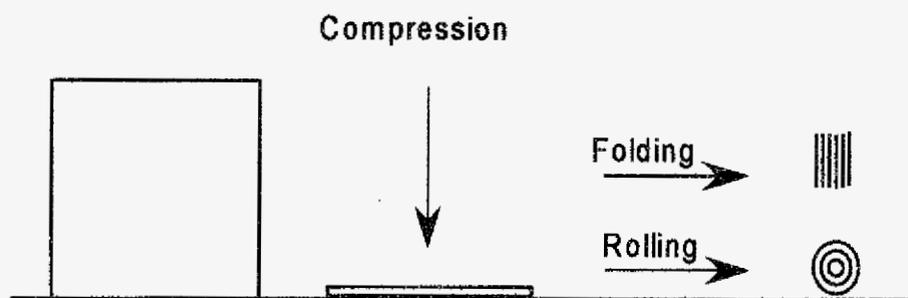


Figure 4: Compaction/packaging of CHEM products

The CHEM products can be deployed by using different heat sources. They can be heated for instance in ovens, or by portable heaters such as a hair dryer. In some applications, conductive embedded fibers can provide the resisting heating for deployment as well as reinforcement for higher load carrying products. Recently conducted studies and analyses indicate that solar radiation could be utilized as the heat energy for deployment in Mars and Earth environments^{11, 12}. The CHEM product in a compacted, hibernated state can be covered by a thermal control blanket that has a high ratio of solar absorptivity-to-infrared emissivity. When exposed to solar radiation, heat is radiated inside the package and the original structure is deployed. After full deployment, the thermal blanket is removed and the structure is rigidized by ambient temperature.

Intrinsic properties of CHEM foams such as impact/shock resistance, thermal and electrical insulation, structural or sound/electromagnetic wave attenuation, make them a potential technology for numerous self-deployable commercial products. Here is a long list of interesting potential CHEM applications:

- Deployable thermal insulation
 - Insulation for building and transport systems such as refrigerated trucks, railway cars, ships designed to carry liquid natural gas.
 - Coolers, thermoses, liquefied gas tanks.
 - Hot/cold-refrigerated storage.
 - Thermal insulation shields/barriers.
- Deployable packaging/impact absorption
 - Packaging of impact and thermal sensitive products.
 - Sensors/drug/food air delivery/landing systems.
- Deployable structures
 - Thermally insulated deployable shelters, storage places, hubs.
 - Temperature-controlled rooms.
 - Prefabricated walls/slabs.
 - Access denial barriers/walls.
- Deployable recreation/sport products
 - Tents and camping equipment.
 - Boats, kayaks, rafts.
 - Life jacket, floating wheels.
 - Water and snow skis.
 - Surf and snow boards.
- Deployable automotive applications
 - Car safety and security subsystems.
 - Human protection products.
- Deployable food equipment
 - Dishes & meal containers.
 - Plates and coffee cups.
 - Hot/cold storage for food.
- Deployable toys
 - toys that take the advantage of simple reversible compaction, deployment and rigidization CHEM cycle.
 - decoys with high fidelity features
- Sound/electromagnetic attenuation
 - High damping sound and electromagnetic wave shielding.
 - Sound and electromagnetic wave-controlled rooms.

However, this long list is by no means meant to be exhaustive. CHEM developers strongly believe that this technology has great promise for a host of commercial applications when fully developed. They have been already contacted regarding potential CHEM applications in recreation, automotive, packaging construction and bio-medical sectors. Some development work is under way in automotive and packaging 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 these materials were found to have excellent biocompatibility. Several independent standard cytotoxicity and mutagenicity test have been conducted on CHEM foams with excellent results¹⁸. Another attractive aspect is the glass transition temperature T_g of these materials can be tailored for shape restoration/self-deployment of different clinical devices when inserted in the human body.

In addition, CHEM technology provides a simple end-to-end process for stowing and deployment, and avoids the complexities associated with other methods for deployment of medical devices. Consequently, a lot of CHEM medical applications are foreseen for vascular and coronary grafts, catheters, orthopedic braces and splints, medical prosthetics and implants, just to name a few.

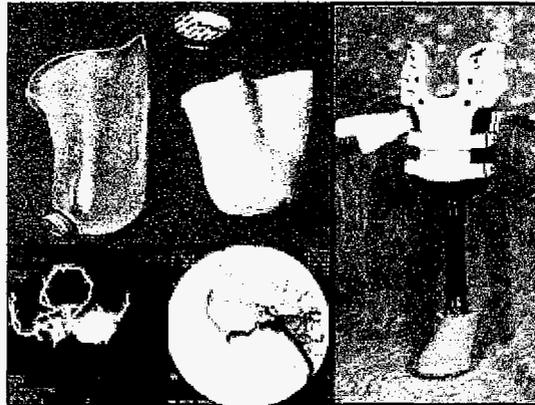


Figure 5: Potential CHEM bio-medical applications

Presently, several important CHEM applications are being considered for self-deployable vascular and coronary devices. One of these potential applications is the removal of a blood clot (thrombus) from the arterial network. The formation or lodging of thrombus in the arterial network supplying the brain, typically causes strokes. The stroke is the third leading cause of death and the principal cause of long-term disability in the United States.

Another CHEM application, endovascular treatment of aneurysm was experimentally investigated at Ecole Polytechnique¹⁸, Montreal. 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 weeks⁹. The CHEM extract demonstrated no evidence of cell lysis or cytotoxicity 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

Although the space community is the major beneficiary, a lot of potential commercial and biomedical CHEM applications are foreseen for the "earth environment". The unique attributes of shape memory effect and intrinsic properties of CHEM foams such as impact/shock resistance, thermal and electrical insulation, structural or sound/electromagnetic wave attenuation, make them a perfect technology for numerous potential self-deployable commercial products. A long list of potential CHEM applications are provided here. However, this list is by no means meant to be exhaustive. The CHEM developers strongly believe that this technology has great promise for a host of commercial and biomedical applications when fully developed. If the development is successful, it's application will

enable a revolution in low-cost deployable structures which can be used in ways never before conceived. The CHEM technology will gain widespread attention for new product innovation. It will open a door to design and build novel and exciting commercial products. The developers already have been contacted regarding potential CHEM applications in recreation, automotive, packaging and construction sectors. Some development work is under way in automotive and packaging areas.

A number of medical applications are being considered for shape memory polyurethane-based CHEM foams because their properties are of particular interest to the medical world. Currently, several important CHEM applications are being considered for self-deployable vascular and coronary devices. One of these applications, endovascular treatment of aneurysms was experimentally investigated with encouraging results. The major conclusion of this investigation was that new embolic devices for endovascular interventions could be designed and built using CHEM's unique physical properties.

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