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Advanced Self-Deployable Structures for Space Applications

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Cold-hibernated elastic memory structures technology is one of the most recent results of the quest for simple, reliable, and low-cost self-deployable structures. The cold-hibernated elastic memory technology uses shape-memory polymers in open-cell foam structures or sandwich structures made of shape-memory-polymer foam cores and polymeric laminated-composite skins. It takes advantage of a polymer's shape memory and the corresponding internal elastic recovery forces to self-deploy a compacted structure. This paper describes these structures and their major advantages over other expandable and deployable structures presently used. Previous experimental and analytical results indicate that the cold-hibernated elastic memory foam technology can perform robustly in the Earth's environment as well as in space. Further improvements in cold-hibernated elastic memory technology that can widen potential space applications, including advanced solar-sail structural concepts, are revealed and described.

Introduction

CURRENTLY existing approaches for deployment of large structures in space such as solar arrays, solar sails, sunshields, or radar antennas typically rely upon electromechanical mechanisms and mechanically expandable booms for deployment, and to maintain them in the fully deployed, operational configuration. These support structures and their associated deployment mechanisms, launch restraints and controls, comprise sometimes more than 90% of the total mass budget for a deployed assembly [1]. In addition, they significantly increase the stowage volume, cost, complexity, and modes of failure. Therefore, one of the efforts at the National Aeronautic and Space Administration (NASA) and the Department of Defense (DoD) has been to develop expandable structures with relatively low mass and small launch volume to be used in low-cost missions. As a result, space inflatable structures have emerged in the last 10 years [2,3].

Inflatable technology is very attractive for space applications because inflatable structures are lightweight and have a small packing volume. However, some complete space inflatable systems are not simple because, besides an inflatable structure, they must include an inflation system [a gas container(s), the plumbing, a launch restrainer, a controlled deployment device, etc.] that increases the total weight, stowage volume, and complexity [4,5]. In addition, inflatables are vulnerable in space due to potential debris and micrometeorite strikes that may damage these structures [6].

The development of structures made of cold-hibernated elastic memory (CHEM) technology is one of the most recent results of the quest for simple, reliable, and low-cost self-deployable structures [7]. These lightweight foam structures are deployed via shape memory and the foam's elastic recovery. The key to this technology is the use of shape-memory-polymer-material systems. These materials behave very differently, depending upon whether they are above or below the glass transition temperature (Tg). Above Tg these materials are flexible and rubbery; below Tg, they are glassy and rigid. Most important of all, structures formed initially below Tg "remember" their shapes and sizes through successive warm/cold cycles and, if unconstrained, return to their original shapes when warm. Thus, a structure can be formed below Tg, warmed above Tg to make it flexible, folded or rolled for stowage, cooled below Tg so it can be stored in the compressed state without external forces, transported to space, warmed above Tg to allow it to self-deploy back to its original shape, and cooled below Tg to rigidize it for use. This approach provides a simple end-to-end process for stowing, deployment, and rigidization that has benefits of low mass, low stowage volume, low cost, and great simplicity. In addition to other appealing properties, shape-memory foam structures have debris impact energy absorption and dynamic damping capabilities [8].

There are other shape-memory polymer systems being developed in industry. The elastic memory composites (EMC) have been developed recently by Composite Technology Development Company, Lafayette, Colorado [9]. EMC materials are similar to traditional fiber-reinforced composites except for the use of a thermoset shape-memory resin that enables EMC materials to achieve higher failure strains and provide higher packing capability than traditional composites through a specific thermomechanical load cycle [10]. Cornerstone Research Group, Inc., Dayton, Ohio has been developing dynamic polymer composite (DPC) systems. DPC materials are like other high-performance composites except they use polystyrene-based shape-memory polymers in the matrix. Fabrication with these resins allows flexibility above its Tg and high strength and stiffness at lower temperatures [11].

The objectives of this paper are to describe the CHEM technology, provide some basic property data, discuss advantages over other deployable structures, and identify potential space applications. Some of these applications have been experimentally and analytically investigated with encouraging results. Present and future improvements in design, manufacturing, and processing of CHEM materials that will broaden potential space applications are revealed here as well. One section, dedicated to potential solar-sail structure applications, describes some advanced concepts including an ultralightweight self-deployable porous CHEM membrane.

CHEM Structure Technology

Description

The CHEM technology uses shape-memory polymers (SMP) in open-cell foam structures or sandwich structures with a core made of

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a shape-memory polymer foam and polymeric laminated-composite skins [12]. These materials are polyurethane-based thermoplastic polymers with wide Tg ranges. 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 [13,14]. 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 their transition temperature range and large temperature dependence on gas permeability. Mechanical and chemical properties, durability and moldability, are practically the same as in conventional polyurethanes. The material's shape-memory function allows repeated shape changes and shape retention without material degradation. This phenomenon is explained on the basis of molecular structure and molecular movements and is described elsewhere [15,16].

In CHEM foam technology the Tg can be tailored to rigidize the structure in the fully deployed configuration. The stages involved in the utilization of a CHEM structure are illustrated in Fig. 1 and are as follows [17].

The original structure is fabricated and assembled in a room held below Tg. Later, the structure is warmed above Tg to make it flexible and is rolled or folded up for stowing. Then, the packaged structure is cooled below Tg so that it becomes firm in the compressed state. As long as the temperature is maintained below Tg, no external forces are needed to keep the structure compressed. Next, the packaged structure is warmed in space above Tg 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. Finally, the deployed structure is cooled below Tg to rigidize it, whereupon it is put into service.

An attractive aspect is the wide range of Tg that can be selected for deployment and rigidization. The Tg of polyurethane-based shape-memory polymers ranges from −75°C to +100°C, thus allowing a wide variety of potential space and commercial applications for different environments. In these applications, the Tg of a CHEM structure should be slightly higher than the maximum ambient temperature. Heat would only be applied briefly for deployment, followed by radiative cooling to initiate rigidization.

Very high ratios of the elastic modulus E below the Tg to the modulus above Tg (up to 500 for solid SMP) enable users to keep its original shape in a stowed, hibernated condition without external compaction forces for an unlimited time below Tg. Furthermore, a narrow transition temperature range for full transformation from a glassy to a rubbery state reduces the heat consumption during deployment (shape restoration).

CHEM structures are under development by the Jet Propulsion Laboratory (JPL) and the industry. They are based on polyurethane SMP that have been developed by Mitsubishi Heavy Industries in the last 15 years. Experimental results that have been obtained so far are very encouraging; the accumulated data indicate that the CHEM technology performs robustly in the Earth and space environments. Furthermore, the test and evaluation results and preliminary analyses show that the CHEM technology is a viable way to provide a lightweight, compressible structure that can recover its original shape after long-term compressed storage [18].

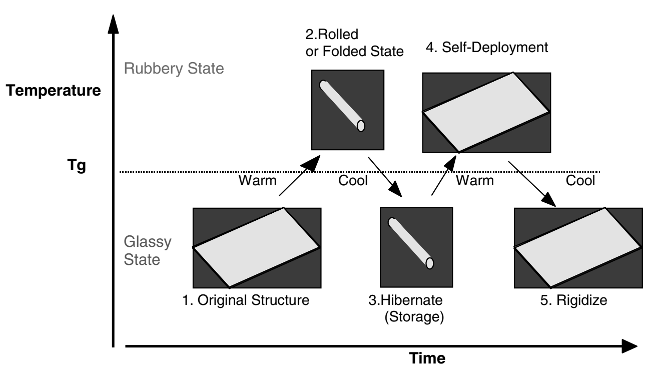

Fig. 1 Cold-hibernated elastic memory (CHEM) cycle.

Table 1 Properties of CHEM 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
Coefficient of thermal expansion (glassy state), ppm/°C	27.5
Thermal conductivity, W/mK	0.027
Thermal conductivity (95% compressed), W/mK	0.12
Specific heat (30°C), J/kg · K	1320
Outgassing (wt. loss—water vapor recovered) %	1.17

Properties of Baseline Foam Material

A baseline shape-memory-polymer foam, with a glass transition temperature Tg = 63°C, was developed for convenience and simplicity of demonstration and testing in the Earth's environment. The basic properties of the foam, designated as MF5520 herein, are given in Table 1. An additional shape-memory-polymer foam, designated as M-18G with a Tg = 4°C was developed specifically for Mars applications [17,18]. The elastic modulus of M-18G was increased 3 times by adding chopped fiberglass reinforcement. Typically, conventionally made CHEM foams have relatively low strength and structural rigidity. However, CHEM foam cores can be used in high-load carrying applications when combined with laminated-composite skins to form sandwich structures.

Advantages

The overall simplicity of the CHEM process is one of its greatest assets. In other approaches to space-deployable structures, stowage and deployment are difficult and challenging and introduce a significant risk, heavy mass, and high cost. Simple procedures provided by CHEM technology greatly simplify the overall end-to-end process for designing, fabricating, deploying, and rigidizing gossamer structures. The CHEM technology avoids the complexities associated with other methods for deploying and rigidizing structures by eliminating deployable booms, deployment mechanisms, and inflation and control systems that can use up the majority of the mass budget.

In addition, shape-memory foams act like the structures composed of thousands of interconnected springs and have high dynamic damping capabilities. Also, they can absorb the impact energy of space debris and micrometeorites. Their deployment by the elastic recovery and shape memory assures a clean, contamination-free environment. Furthermore, the CHEM structures exhibit no long-term stowage effect and can be stowed in a hibernated state for an unlimited time. These structures are easy to fabricate and possess good machinability, cutting, and shaping characteristics.

The disadvantage of a CHEM structure is the heat energy needed for deployment. However, the solar heating deployment approach appears to be feasible. Previously conducted studies and analyses indicate that solar radiation could be used as the heat energy for deployment in Mars and Earth environments [19,20]. Briefly, in this concept a shape-memory structure is compacted and in the hibernated state can be covered by a thermal control blanket that has a high ratio of solar absorptivity-to-infrared emissivity. Before heating, the assembly must be kept out of direct solar radiation environment. When exposed to solar radiation, heat is generated inside the package and the original structure is deployed. After full deployment, the thermal blanket is removed and the structure is rigidized by the ambient (space) environment.

Space Applications

Investigated Applications

A number of CHEM technology applications are anticipated for space robotics and other support structures involving tele-

Table 2 Investigated space CHEM applications

Applications	TRL	Comments
Nanorover wheels	4	Integrated with a nanorover and demonstrated in a laboratory experiment.
Precision soft lander	2–3	Safe and stick-at-the-impact-site landing. Small model proof of concept.
Sensors delivery systems	2–3	CHEM-based integrated sensors are dropped and deployed in different planetary locations.
Horn antenna	2–3	Deployable conical corrugated horn antenna. Small model proof of concept.
Radar antenna	2–3	Three-layer membrane design. Small model proof of concept.
Thermal-meteoroid shield	2	Lightweight deployable thermal and meteoroid protecting system.
Habitat structures	2–3	Shelters, hangars, crew cabins, trans. habs. Small model proof of concept.
In situ propellant production tanks	2–3	Small model proof of concept.

communication, power, sensing, thermal control, impact, and radiation protection subsystems as well as for space habitats. Various feasibility studies and preliminary investigations have been conducted on potential CHEM technology space applications under different programs at JPL and by the industry partners [21–27]. Some of these applications and their present technology readiness level (TRL) are shown in Table 2. TRLs range from TRL-1, for which basic principles have been observed and reported, to TRL-9, in which an actual flight system has been proven.

In one investigation, CHEM-material wheels for a nanorover were developed, fabricated, and assembled on a two-wheeled prototype nanorover, shown in Fig. 2 [21]. For the nanorover wheel application, compacted wheels with an outside diameter of 6 cm were successfully deployed at 80°C and subsequently rigidized at room temperature in an atmospheric environment. Rigidization was also successfully conducted in a simulated low pressure (6 mbars) Mars environment.

The majority of applications investigated were not high-load-carrying support structures. For large-structure applications such as solar sails, radars, and solar arrays, analyses have indicated that sandwich structures with high-strength laminated-composite skins and CHEM foam cores are needed for support structures to increase the overall structural rigidity.

Although the space community is the major beneficiary, a lot of potential CHEM technology commercial and medical applications are also foreseen for the Earth environment and are described elsewhere [28].

Improvements for Large Structures

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 Company (WMR), working with JPL under the Small Business Innovation Research (SBIR) Program, has developed new CHEM microfoam materials [29]. WMR used its proprietary foam processing to develop the microfoams from the shape-memory polymer raw materials. These CHEM microfoams exhibit micron-sized cells that are uniformly and evenly distributed within the cellular structure. The cell sizes can be controlled during the foam forming process. When compared with conventionally made CHEM foams, the CHEM microfoams have enhanced physical and mechanical properties, improved isotropy of properties, increased compressive and tensile strength, tear strength, and fracture toughness. Also, because of the very small size of the cells, the material is well suited for ultralightweight porous membrane or thin-film space applications.

Other activities have been started to develop CHEM sandwich structures intended for high-load support-structure applications. WMR under the SBIR contract has worked on CHEM sandwich structures that involve fiber-reinforced shape-memory-polymer composite face sheets and CHEM foam cores [30]. The same memory polymer was used for the face sheets and for the foam cores. This approach maximized the packaging ratio and reduced stowage volume of the sandwich structure.

In the future, it is planned to develop new CHEM microfoams that are reinforced with carbon nanotubes. This material system will increase the mechanical strength as well as the thermal conductivity. The improvement in thermal conductivity is important because it will cut down the time required to deploy a CHEM structure in space.

Preliminary investigations and analyses have indicated that CHEM foams by themselves cannot be used for high-load-carrying support structures. However, it appears that the sandwich CHEM structures or a hybrid design of CHEM foams and polymer composites could be used to develop support structures for large deployable solar sails, antennas, telescopes, sunshields, and solar arrays. For these applications, the CHEM foams are combined with laminated-composite skins to augment strength or stiffness or to serve as a deployment mechanism.

In one of these applications, Composite Optics, Inc. (COI), working with JPL, developed a spring-lock truss-element concept for large (>50 m) boom structures that involved a unique hybrid design of CHEM foams and polymer composites [31]. This truss element, referred to herein as the CCSL truss element, is essentially two carbon-fiber-reinforced polymers (CFRP) that are separated by blocks of CHEM foams, as shown in Fig. 3.

The two material systems are used in a manner that allows the truss element to be stowed in a small volume and then deployed without the use of complex mechanisms. The CCSL concept uses the CHEM foam to lock the truss element in the stowed and deployed states to control the deployment and to enhance the buckling resistance. The CFRP tapelike skins are used to provide high axial stiffness to the truss members, to reduce weight, to provide elastic spring energy for deployment, and to increase the overall stability of the boom. The

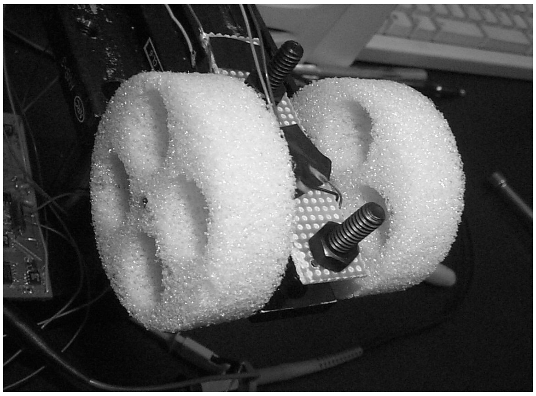

Fig. 2 CHEM nanorover wheels.

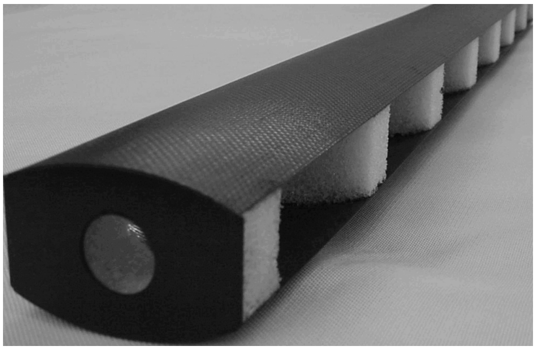

Fig. 3 CCSL truss element.

Table 3 Comparison of mechanical, inflatable, and elastic memory-deployable structures

Characteristics	Mechanical deployment	Inflatable	Shape-memory deployment
Mass	Heavy	Up to 3× lighter	>10× lighter
Stowage volume	Bulky	2–30× smaller	50× smaller
Reliability	Good	Good	Potentially highest
Cost	High	Lower	Lowest
Simplicity	No	Better	Best
Deployment/inflation subsystem	Yes	Yes	No
Impact resistance	Not good	Not good	Good
Dynamic damping	Good	Very good	Very good
Clean deploy/rigidization	Clean	Potential gas leak	Clean[a]
Stowage effects	Yes	Yes	No
Fabrication	Difficult	Easier	Easiest

[a]Meets NASA outgassing requirements.

baseline truss-boom design was a three-legged CCSL-longeron truss-element configuration supported with diagonals and horizontals, all connected at joints. All other trust elements were made from CFRP material to maintain ultralow mass, high buckling resistance, and high durability. The results of a preliminary investigation on the CCSL truss element were encouraging and, as a result, COI has successfully demonstrated a proof of concept for the CCSL structure.

Potential Solar-Sail Applications

The potential use of CHEM microfoams reinforced with carbon nanotubes that may be developed in the future are being considered for thin-membrane applications, specifically for solar sails [32]. In particular, a CHEM membrane without support booms that is deployed by using shape memory and elastic recovery, is envisioned. In this advanced structural concept, the CHEM membrane structure is warmed up to allow packaging and stowing before launch, and then cooled to induce hibernation of the internal restoring forces. In space, the membrane remembers its original shape and size when warmed up. After the internal restoring forces deploy the structure, it is then cooled to achieve rigidization. For this type of structure, the solar radiation could be used as the heat energy used for deployment. This solar-sail concept, that uses an ultralightweight microporous membrane that is deployed by shape memory, could advance solar-sail technology and enable the development of sail materials with areal densities less than $2\ \mathrm{g/m^2}$. In addition, highly integrated multifunctional CHEM membranes with embedded thin-film electronics, sensors, actuators, and power sources could be used to perform other spacecraft functions such as a communication, navigation, science gathering, and power generation.

Certainly, more research, experiments, and analyses must be done to fully realize the potential of the self-deployable CHEM membranes. Future research is needed to determine if the shape-memory elastic recovery forces in thin CHEM membrane will be substantial enough to provide a viable structural concept. Likewise, research is needed to determine if the stiffness of the rigidized membrane that is reinforced with carbon nanotubes is high enough to support deployed structure in space. Structural models need to be developed to demonstrate, characterize, and improve the understanding of self-deployment and rigidization mechanisms. All these activities will help to assess the applicability of future structural concepts.

The payoff of this research could be high. This advanced membrane concept represents the introduction of a new generation of self-deployable structures. If developed, this innovative technology will introduce a new paradigm for defining configurations for space-based structures and for defining future mission architectures. It will provide new standards for fabricating, stowing, deploying, and rigidizing large deployable structures in a simple, straightforward process. This new technology could 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.

Comparison of Deployable Structures

Currently existing approaches for deployment of large, ultralightweight gossamer structures in space typically rely upon electromechanical mechanisms and mechanically expandable or inflatable booms for deployment and to maintain them in a fully deployed, operational configuration. These support structures with the associated deployment mechanisms, launch restraints, inflation systems, and controls can comprise more than 90% of the total mass budget. In addition, they significantly increase the stowage volume, cost, and complexity.

In a preliminary investigation, a generic elastic memory, self-deployable structure was compared with other deployable structures. The results of this comparison are summarized in Table 3 [33]. Similarly, the mass budgets for the inflatable sunshield used for the inflatable sunshield in space (ISIS) experiment and for a corresponding hypothetical elastic memory-deployable sunshield are presented in Table 4. ISIS was a one-third-scale next generation space telescope (NGST) sunshield flight demonstration experiment. The total weight of the ISIS four-membrane sunshield design was 104.35 kg. The dominant items contributing to the mass budget were the support tubes (7.87 kg), the inflation system (16.43 kg), a launch restrainer (30.22 kg), a controlled deployment device (11.87 kg), and a container (34.02 kg). These items created an areal density greater than $3\ \mathrm{kg/m^2}$. Most of these items are eliminated by using CHEM technology, thus drastically reducing the areal density, stowage volume, and cost. Also, the CHEM processing cycle of stowing, deployment, and rigidization results in significant reductions in complexity and improvements in reliability, compared to existing alternative deployment methods.

Conclusions

CHEM technology has the potential to provide innovative self-deployable space structures with significantly higher reliability,

Table 4 Mass budgets for ISIS inflatable sunshield and elastic memory concept

ISIS		
Sunshield subsystem[a]	Inflatable mass, kg	Shape-memory deployment mass, kg
Membrane	2.58	7.1[b]
Support structures	7.87	~1.0[c]
Inflation system	15.43	0
Launch restraint	30.22	0
Container	34.02	0
Controlled deploymen	11.87	0
Thermal insulation	1.38	1.4[d]
High absorptivity blanket	0	0.7[e]
Subtotal	104.35	~10.2

[a]Sunshield area = $28.19\ \mathrm{m^2}$.
[b]$0.25\ \mathrm{kg/m^2}$ areal density or lower.
[c]Attachment to the spacecraft.
[d]Uses the same insulation as ISIS.
[e]Absorbs solar heat for deployment.

lower cost, and simplicity than other space expandable and deployable structures. A myriad of potential CHEM applications are also 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 have confirmed the feasibility of some space CHEM applications. Further improvements in CHEM structures, such as the development of the CHEM microfoams reinforced with carbon nanofiber and improved CHEM sandwich structures, broaden the potential applications, including large space structures. When successfully developed, CHEM sandwich structures will possess high-load carrying capabilities, high packaging-strain ability, and will guarantee more predictable and precision deployment.

The development and usage of ultralightweight porous membranes made of CHEM materials and deployed by the elastic recovery forces associated with shape memory appears to have great potential for improving solar-sail technology. This advanced membrane concept provides a simple end-to-end process for stowing, deployment, and rigidization and avoids the complexities by eliminating booms, deployable mechanisms, launch restraints, inflation, and control systems. This new technology could revolutionize the design and manufacturing of space structures and future solar sails mission architecture. Although the space community is the major beneficiary, a lot of potential CHEM technology commercial and medical applications are also foreseen for the Earth's environment and are described elsewhere.

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