Recent Advances in the Rigidization of Gossamer Structures

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1 Introduction

The interest of using inflatable and rigidizable structures for space equipment (such as solar arrays, antenna reflectors $\cdots$) has been identified for many years, but this has not yet been implemented on operational space equipment in Europe, due to the lack of adapted materials and technologies. Recent improvements in these fields allow today the development of such projects and solar arrays have been identified as one of the most promising application. This paper focuses on inflatable and rigidizable lightly loaded structures. Typical driving requirements are high packaging efficiency, very low specific mass and large size. As with other flexible-wall structures, they exploit gas pressure for their deployment ("inflatable structures"). But, inflated structures unavoidably loose the gas that pressures them, and therefore require a pressure control apparatus and a gas supply to replenish the losses. This disadvantage is acceptable only for items that have to last for very short periods of time or for items where pressurization is a basic function (as in the case of habitats). It is commonly admitted that all inflated structures shall be rigidized in space as soon as their life time exceeds one week. As a result, the use of rigidizable materials that enable an inflated structure to become permanently rigid without relying on inflation is obviously a key technology in the field of Gossamer structures. For a given architecture, various kinds of rigidization techniques can be proposed: chemical rigidization [use of UV radiation (solar or with integrated light sources), thermal curing (using solar radiation and/or active heating)], physical rigidization [removal of volatile components in vacuum (solvent boil-off)], or mechanical rigidization [metal

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layer stretch/aluminum laminates]. One of the most promising rigidization techniques envisioned by EADS-ST is in-orbit UV curing of a composite structure. After a brief overview of Gossamer structures, exemplifying applications and potentialities of the technique by showing impressive realizations, we will detail a technology trade off related to the many rigidization processes that may apply to inflatable structures. Finally, we will focus on radiation initiated polymerization as a versatile tool to rigidize backbone structures.

2 An Overview of Gossamer Structures

2.1 Definition

Since the beginning of space flight, researchers and experimenters have been confronted with the problem of packaging into the restricted volumes available on the carrier vehicles items that they actually wanted to become much greater; and since those beginnings "inflatable" elements were among those proposed to master this challenge [1]. In recent years, NASA has introduced the "gossamer" expression to label those forms of spacecraft exceptionally low in mass and suitable for packaging into very small volumes, compared to conventional spacecraft: in general, it applies to inflatable and membrane structures for space use.

A more descriptive term, especially as it relates to the theme of the present book, is that of flexible-wall, expandable structures. The (initial) compliance of the walls allows the compact packaging and also enables the geometric efficiency of the materials that leads to the low mass, reinforced by the fact that one can design such structures for the space environment properly – not mainly to survive the launch phase. And, we refer to all those structures that are completely assembled at their manufacture site, then folded, stowed, packaged, or otherwise compacted for transport to their operational location, where they are deployed and installed for functional use. The installation sequence may include a rigidization procedure (mechanical, physical, or chemical – as discussed in the next Section), spinning the spacecraft (for a rotationally-stabilized object), pressurization (for continuously-inflated objects), etc. Expandable structures with flexible walls have been flown but only in a small number of cases. To date, the greatest majority of " large" structures deployed in space belong to the rigid-component, variable-geometry (RCVG) kind, that rely on actuation mechanisms to perform the transition from packaged to deployed state.

The range of technological approaches to the implementation of flexible-wall expandable structures is just as vast as that of the applications for which such structures can be used. One can organize the field using different discrimination criteria, deriving them from application-oriented considerations (e.g., the type of loads or geometrical requirements that drive a design), from characteristics of the structural elements' build-up (e.g., whether thin-walled

membranes or thicker, more plate-like layouts), or from the methods used to stabilize shape of the object at installation. A first attempt classifies the structures according to four use and requirements criteria as follows:

- "Lightly-loaded", flexible-wall, expandable space structures - sized for the orbital environment (generally against buckling loads); typical requirements are: high packaging efficiency, very low specific mass, large size; the tension within an element's wall is of the order of 0.1 kN/m; a further subdivision distinguishes between:
  - support structures in general ("backbones"), in which a small-to-moderate integration between structure and system function occurs, and
  - precision structures, where the structural element and its shape have a direct system function impact
- "Heavy-duty" flexible-wall, expandable structures - sized to carry (internal) loads (generally, pressurization forces); typical requirements are: large enclosed volumes, compatibility with crew presence, moderate packaging efficiency and/or specific mass; the tension within an element's wall is of the order of 100 kN/m.
- "High-temperature" flexible-wall, expandable structures - sized to sustain significant temperature levels, as generated during planetary entry (although reduced thanks to the lower area loading such structures enable).

This article focuses mainly on lightly-loaded and heavy duty flexible-walls and not on high temperature elements which differ from the two first classes in technological terms even if some synergies exist and are used.Wilde and colleagues [2] give a summary of recent work in Western Europe on high temperature flexible walls.

2.2 Applications & Historical Background

Early Work: Inflatable Satellites

After the pioneering suggestions by Gatland and co-workers [1], the idea of inflatable spacecraft –in particular, to create optically observable orbital bodies– was developed by John O'Sullivan and his colleagues at Langley Research Center [3]. Soon, they prepared 12-ft (3.66-m), mechanically rigidized spheres, launched as Explorer IX and Explorer XIX for contributing to the measurement of the high atmosphere's density [4]. The Explorer spheres were sturdy enough to support themselves unpressurized under 1-g acceleration (Fig. 1). From this work evolved the concept and the technology for the passive communications satellites (Echo I & II, [5]), that eventually enabled the 40- m diameter PAGEOS (PAssive GEOdetic Satellite) [6]. Advanced concepts studied to achieve better mass efficiency than using spherical reflectors involved inflated lens/torus configurations and the wire grid sphere satellites, using photolyzable wall materials for the deployment and leaving eventually only a

structure of stretched metal wires, making a radio reflector less sensitive to the solar pressure. Several such wire-grid spheres actually flew, e.g. the USAF OV1-8 satellite.

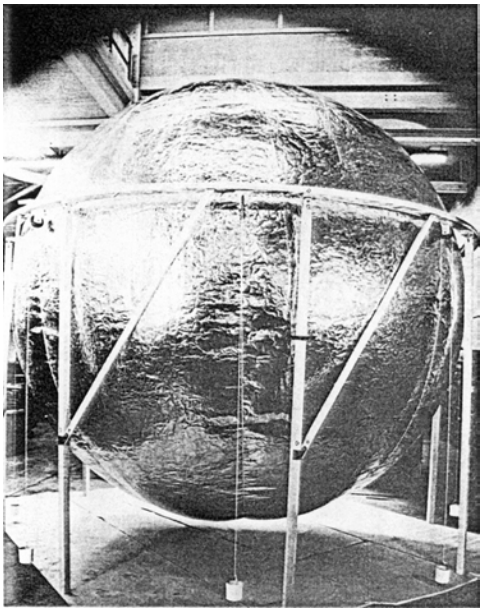

Fig. 1. An example of a balloon satellite: a mechanically-rigidized, 12-ft Explorer IX inflatable sphere under full-gravity testing. (NASA picture)

Precision Structures

Solar concentrators (for thermodynamic power generation) represent a further application that received extensive treatment using different gossamer technology approaches (with inflated membranes, with various foam-in-place techniques, with chemically-rigidized composites – both in form of membranes and of expandable-honeycomb structures), and with most designs adopting the lens-torus layout. Throughout the 1960s, they were studied in the US [7], but also in Germany where, around 1965, Bölkow investigated an inflatable foam-rigidized solar-thermal power collector [8]. Eventually, early in the 1970s, MBB built a 1-m inflatable and rigidized antenna reflector using glass- fibre-reinforced gelatin for the torus and the reflector shells, and a polymer-film radome [9].

In 1979, ESA began sponsoring a series of development contracts at Contraves (Zurich, Switzerland) that one of the authors (MCB) had the privilege

to execute, lead, and participate in. For historical reasons, those development activities concentrated on microwave antenna reflectors, exemplified by the realization of the first rigidized offset reflector, but work was done in all classes of objects but for the "high-temperature" one.

Work on this technology –identified as Inflatable Space-Rigidized Structures (ISRS)– included a series of experimental activities using objects in the size range from 1- to 10-m aperture. First came three small models of a symmetric (center-fed) reflector to gauge issues such as folding and deployment, manufacture processes, and initially achievable accuracy. In successive phases, three 2.8-m reflectors (called LOAD-3 and designed for operation at 3.6 GHz) allowed the execution of following tests [10]:

- accuracy - improved manufacturing procedures adopted during that development phase allowed a reduction of the RMS error from 0.9 to 0.7 mm, while identifying the main sources of the remaining inaccuracies;
- packaging efficiency - were verified using the object that was successively subjected to electrical measurements; without degradation of surface quality as consequence of the folding and deployment exercises;
- controlled deployment in vacuum - a test within ESTEC's Dynamic Test Chamber demonstrated the quality of the residual air control procedures, the correctness of the deployment sequence, and the controlled deployment of the structure;
- electrical performance – measures were performed on the first complete object, after a full cycle of pressurization tests, folding, packaging, deployment, and cure;
- cure under (simulated) space conditions - a thermal-vacuum chamber solar simulation test demonstrated the correctness of the reflector's thermal design.

Further reflectors were manufactured and tested (under clean-room conditions):

- a 5.7-m diameter Test Article for the QUASAT radio telescope reflector, a center-fed layout [11], and
- a 10-m aperture offset-fed reflector (LOAD-10, Fig. 2), designed for operation at 1.6 GHz; after the folding and deployment cycle, the surface error had grown from 2.15 mm to 2.66 mm RMS, still yielding a gain of 42.6 dB and a sidelobe level of -33.8 dB [12].

The ISRS developments in Europe apparently found a resonance in Japan. Around the mid 1980s, a team formed around ISAS and began work on a modular, hybrid antenna reflector concept [13] – a variable-geometry truss backbone carrying ISRS reflector facets – as an unsuccessful candidate for the VSOP mission (the Japanese equivalent of QUASAT that eventually flew as HALCA).

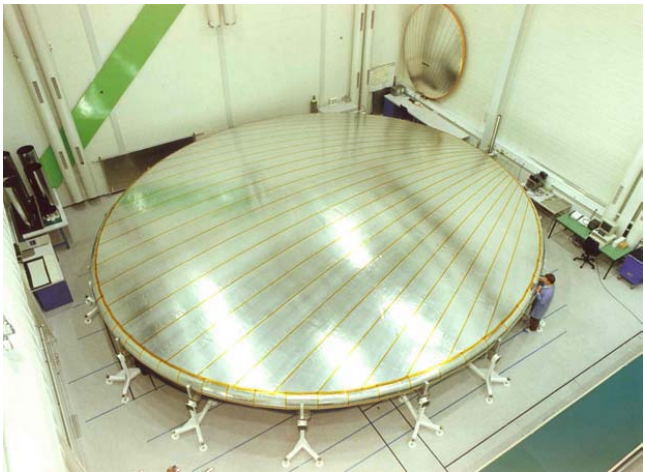

Fig. 2. The LOAD-10 offset reflector

While the ESA initiative originally had but vague relations to previous US work, it contributed to the renewed interest there, when ESTEC personnel introduced the work done at Contraves to several JPL science projects teams. On the other hand, in 1980, L'Garde had proposed new approaches to continuously inflated antenna reflectors [14] and, after a number of development activities, in 1996 they finally achieved a test flight for a 15-m object, deployed from the Shuttle Orbiter [15]. Work on those inflatable reflectors continues [16].

Finally, under the USAF leadership, the inflatable solar concentrator was born again, this time to support the development of solar-thermal propulsion [17], a concept originally introduced by Ehricke [18]. While most designs foresee two offset parabolic reflectors, alternative configurations have investigated the use of flexible Fresnel lenses, also supported by gossamer elements. ESA has also sponsored studies for applying solar-thermal propulsion to upper stages for geocentric transportation [19] (Fig. 3).

Backbones

Concepts, type of applications, and study and development activities have been too numerous to attempt even a brief summary as done for the precision structures above. Many backbone structures (but not all by any means) involve skeletons, assembled from tubular components. Indeed, such a "one-dimensional" element forms the simplest backbone morphology. Following evolutionary considerations, one may discuss morphology and applications of backbones in the following order:

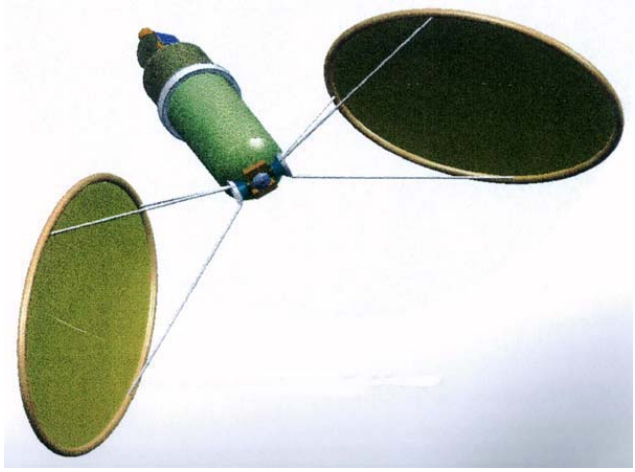

Fig. 3. European solar-thermal upper stage concept, with inflatable offset concentrators (EADS-ST image)

- *Planar Frames*: two-dimensional support for items such as, e.g., flat shields, solar sails [20], solar reflectors, and photovoltaic arrays [21] (Fig. 4), RF devices (reflectarrays, rectennae, lens,... [22]), or arrays of sensors.
- *Single-Tier Structures*: prismatic backbones (tripod, tetrapod, etc) for other functions, e.g. for light aerobraking [23], lens positioning, etc.
- *Two-Tier Structures*: Three-dimensional elements for telescopes tubes, cryogenic shield, hangars, and other unpressurized enclosures. The Contraves FIRST ISRS thermal shield concept belongs to this category: a complete 3.5-m skeleton [24] (Fig. 5), was manufactured and used for packaging, deployment, cure, and geometric tests.
- *Special Configurations*: Mast and booms, other (mostly) planar structures – for low-gain aerial structures (helix, Yagi), radiators.
- *Trussworks*: generic support structures, e.g. backbone structures both for Michelson [25] and Fizeau interferometers [26];
- *Polyhedral Skeletons & other, more complex forms*: Modified two-tier designs (e.g. for greenhouses), more complex lattice structures, spheres and spherical approximations.

Heavy-Duty Elements for Manned Flight

Gossamer structures hold the promise to provide significant capabilities in support of manned missions: throughout the 1960s, NASA and USAF studied and developed relatively small crew transfer tunnels and airlocks, orbital and surface shelters in support of exploration missions, full space stations,

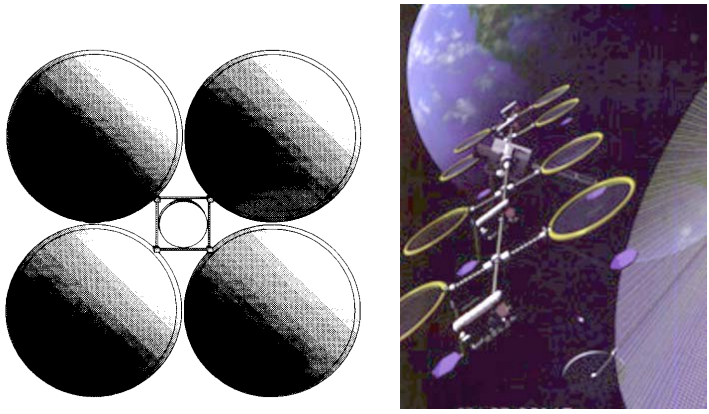

Fig. 4. Concept for a solar sailing spacecraft with four 2,500-m^2 saillets.(left); the "Sun Tower" solar power station builds on gossamer structures: supporting tori and flexible Fresnel-lens concentrators (right) (NASA picture)

Fig. 5. The 1/3-scale model of the ISRS skeleton for the FIRST's thermal shield (right) deployed out of an annular stowage volume around a simulated spacecraft central cylinder (left)

and pressurized hangar enclosures capable of holding entire spacecraft during scheduled maintenance/repair activities. The latest US entry in this class in the TransHab concept for a multi-storied habitat [27,28]. Activities along this direction have also been started in Europe [29,30].

3 Review of Rigidization Techniques

The use of rigidizable materials that enable an inflated structure to become rigid is a key technology in the field of Gossamer structures. The term "rigid" needs however to be clarified when discussing lightweight structures. For example, the 155 microns thick chemically rigidized material used for ISRS [31] is 39 times less rigid than a 100 microns thick steal foil in term of membrane stiffness and 280 000 times less rigid than a 10 cm thick foam plate in term of beam stiffness. Those ratio drop to 6.4 and 10500 respectively, once one considers the stiffness to surfacic weight ratio. This illustrates the fact that the weight and packed volume are the concepts that drive the development of thin flexible rigidizable walls.

Many technologies are identified for in orbit rigidization of Gossamer structures [32]. We firstly present a discussion of rigidization technologies, beginning with the identification and review of the different techniques and finally up to an evaluation of the existing technology. A set of evaluation criteria is defined and used to select the best candidates for a tubular solar array structure, to be suitable for Gossamer structures. The selection criteria include the material's ability to be folded, rigidization conditions (including power needs), thermal and mechanical properties, outgassing, durability in space environment, costs, rigidization reversibility... Discussions of specific materials for the different technologies are covered incidentally, to exemplify options and to assist the designer in his evaluation activity.

3.1 Rigidization Techniques and Associated Materials

Rigidization technologies can be classified depending on the nature of the phenomena that induces rigidization:

- Mechanical rigidization is obtained by stretching a polymer/aluminum laminate above its yield strain,
- Physical rigidization is obtained by phase transition (cooling a material below its glass transition temperature), using shape memory materials or by plasticizer or solvent evaporation,
- Chemically based rigidization is obtained either by thermally or UV induced polymerization. In orbit curing can be triggered or accelerated by gaseous catalysts carried by the inflation gas.

The different rigidization techniques are described below.

Mechanical Rigidization

This is class of structures deployed by inflation and rigidized by inducing through the pressure forces a stress higher than yield stress in a wall's metallic layer. Once the pressure is removed, the stressed aluminum maintains the

structure's rigidity and shape. This concept is very attractive, and was used in flight on the Echo-2 satellites in the sixties [33], as well as on the Optical Calibration Sphere in 2000. The main advantages of this rigidization process are its reversibility, simplicity, predictability and rapidity. Furthermore it does not require additional power, has good space durability and no specific storage constraints. However, the anisotropy of the stresses and the need for an accurate control of the pressurization levels are issues that affect this technique for its application to cylindrical or toroidal objects. L'Garde proposes a solution to that problem which is based on fibers winding around a tubular structure [34]. Two main issues remain with regard to this technology: the first one is the different thermally induced dilatation of the constituting materials (polymer and aluminum) and the second is the compatibility of this technology with rolled-up storage.

Physically induced rigidization: cold rigidization, shape memory and solvent evaporation

The cold rigidization process relies on the exposure of originally flexible plastic layers – typically elastomers [35] – to the deep space thermal sink to cool them below their glass-transition temperature, rigidizing the structure essentially by freezing the matrix. This concept appears particularly indicated for shielding applications outside Earth's orbit, and was studied for shadowing shields of cryogenic stages for Mars flights. More recently, ILC Dover and L'Garde presented structures rigidized using this technique, respectively a hexapod structure [36] and the Space Solar Power Truss [37]. This technique is attractive mostly because of its reversibility, simplicity and low energy requirements compare to thermal curing. However, the need for temperature control and the coefficient of thermal expansion of the resins are serious drawbacks.

Recently, a number of studies have been conducted on shape memory composites, materials that mimic the behaviour of metallic shape-memory alloys [38,39,40]. The structure is completed on ground and consolidated at an elevated temperature, to set the material's geometric shape. The material will return to its original shape when heated above its glass transition temperature. For packaging, the structure is softened by heating it above Tg , taking care to keep it below its set temperature. After cooling, it is kept stowed. Prior to deployment, the stowed structure is again heated above Tg to make it flexible enough to be deployed by inflation. This is quite a complex process that limits the overall size of an object. The deployment in space requires a fair amount of power and control functions, as the heating must be rather uniform overall; also, presumably, the temperature should not drop below Tg.

Rigidization of a structure can also be obtained using evaporation of a solvent or a plasticizer in the material. The major issue of this solution is the large amount of solvent or plasticizer involved (e.g. between 13-50% for the Ciba polyimide tested during the Contraves ISRS program [41]). During the 1960s, a fairly large effort was dedicated to the study of rigidizable structures

of this type utilizing fiber-reinforced gelatin prepregs. This approach has been improved more recently [42]. This solution presents the advantage to be a reversible process even if this is quite difficult on large structures. However it has many drawbacks related to packaging, outgassing, temperature variation sensitivity, weight...

Chemically induced rigidization : UV, thermal polymerization, gaseous catalyst and foaming in space

Thermal curing is a very classical path for aerospace composites. Various materials are available on shelf that can become rigid upon subsequent heating [43]. However, this technique has the major drawbacks to require a lot of power and energy to heat the structure. Numerous epoxy laminating resin formulation have been investigated in this class. The Contraves/ Ciba evaluation field alone included: conventional epoxy-based resin cured with an aromatic amine, epoxy resin cured with an amide, epoxy resin cured with an anhydride catalytically-cured cycloaliphatic epoxy and acryl-terminated epoxy resin [41]. The major drawbacks of this solution are the energy need and the additional weight due to the necessary thermal heaters [44], and/or the need for special coatings/MLI (Mulit Layer Insulation) that would increase the temperature of the structure [45].

Thermal curing can be triggered or accelerated using catalyst carried by the inflation gas. Pure catalytic cure systems offer the potential for "cure-on-demand". External catalysis involves the release of a gaseous catalyst within the inflated volume to activate and/or accelerate the reaction: such is the case of boron trifluoride with resin H developped by Contraves [31]. This solution has however the drawbacks that a secondary gas delivery system needs to be implemented on the Gossamer structure.

The use of solar UV for curing space-rigidized objects is extremely popular, in and beyond the literature. The first use of solar radiation to rigidify a structure was considered in the sixties for the Echo II balloon, and in the eighties by Contraves. An "on-command" cure capability is an aim for this class as well as Adherent Technologies proposes such a solution [46,47].

Thin walls based on foaming in space were also studied early in the sixties [48] and later in the nineties [49,50]. However this process faced non-uniformity and uncontrolled rigidization problems.

3.2 Technology Evaluation

Rigidization Techniques Selection Criteria

The elements to be taken into account for the evaluation of the rigidization methods and materials can be classified depending on the life phases of a Gossamer structure: non-rigidized, during rigidization and in the final rigid state. The main items are listed below.

- During manufacturing, and in the non rigid phase:
  - Cost and availability of the material
  - Shelf life, storage duration and constraint (raw materials and manufactured structure),
  - Weight,
  - Compaction ability,
  - Manufacture complexity (criteria linked to costs): foldability (ease to fold, damage risk), specific constraints related to the rigidization technique that directly impacts the design and manufacture of the structure (Multi Layer Insulation, specific coatings, heaters integration, specific deployment control system...), dimensional stability.
- During rigidization:
  - Rigidization reversibility and/or testability,
  - Process quality: reliability, rigidification on command, sensitivity, risk of uncontrolled rigidization, rigidization time, energy needs, in orbit specific constraints (rotation of the structure), outgassing.
- After rigidization:
  - Dimensional stability of the structure (Coefficient of Thermal Expansion),
  - Thermo-mechanical properties of the rigid material,
  - Specific properties regarding the application, - Aging in space environment (vacuum, UV, atomic oxygen, electrons, protons...),
  - Outgassing.
- Miscellaneous:
  - Adaptability to different design and architectural concepts,
  - Technology maturity (state of the art and user experience).

The accuracy and the relative importance of the selection criteria were discussed within this review. This analysis raises questions and considerations that need further discussion. Our technology evaluation was based on results presented in various up to date publications. However those deal in most cases with one specific material and as a result make it obviously difficult to evaluate technologies as a whole. Furthermore, the interest for inflatable structures was very strong in the sixties and is coming back on the scene nowadays; the age of some references should not hide the huge progress of polymer and materials related technologies since the seventies. Also, an important aspect relative to Gossamer technologies is the weight of the structure; but the rigidizable part in a Gossamer structure is in general 10 to 20 % of the total and, in the frame of rigidization technologies selection, one should not overrate this aspect. The rigidization reversibility is also often considered as a very important aspect. However, even if a specific technology is reversible, the applicability of such a concept is most of the time difficult on large structure. Finally it comes out that the most important criteria is the reliability of the rigidization technique and the required energy for rigidization.

Technology Evaluation

The evaluation criteria have been listed and weighed as a function of our preceding remarks. The criteria where we wished to put more weight are the reliability of the technology and the required energy for rigidization, the cost expressed in terms of material cost, but also in terms of manufacturing cost and the mechanical properties of the rigidized structures. As a result, the rigidization process itself accounted for 50% of the total. The materials properties after rigidization was evaluated as 14% of the total, taking into account that the structure (i.e. the weight) were dimensioned to fulfill mechanical specifications. Our evaluation led to the following results: 7 technologies – solvent evaporation, foam rigidization, thermal curing with the addition of a gaseous catalyst, solar UV curing, solar thermal curing and shape memory composites were ranked below 700 out of 1000. Four rigidization technologies were significantly better ranked than the others, according to our selection criteria and sensitivity: sub Tg rigidization, thermal curing with embedded heaters, UV curing with lamps and aluminum laminates.

3.3 Conclusion

This literature review allowed us to evaluate the performances, maturity, advantages and drawbacks of the different rigidization techniques, on the bases of an extended literature survey. The results highlight the diversity of the potential techniques and their very variable maturity. Selection criteria have been assessed in order to evaluate the different technologies. The reliability and maturity are especially important criteria. All the other selective criteria have been discussed.

As a result of the technology evaluation, Four technologies appear as especially interesting: stretching of aluminum/polymer laminates, thermal and UV curing with lamps of composite based material as well as sub Tg based composite rigidization. Among those four technologies, UV curing with internal light source comes out as the best solution.

As a result, the following part of this document is focused on UV based technologies for rigidization of Gossamer structure. The mature technology that is UV initiated polymerization will be detailed in the frame of its application to in space polymerization of lightly loaded composite structures.

4 Rigidization by UV-Visible Curing

UV-curing is now a well established technology finding a large number of industrial applications because of its distinct commercial, technical and environmental advantages. Initially developed for the fast drying of solvent-free formulations as printing inks, functional or protective coatings, adhesives and

resins for microelectronics, polymerization induced by UV-visible light recently proved to be also an efficient method for curing various composite materials and gel coats [51].

In general, a formulated liquid or a molten powder is transformed almost instantly into a solid polymer simply by a short exposure to actinic light. A typical formulation for a clear coat consists of a mixture of functionalized oligomers mixed with low molecular weight monomers as thinners and with a photosensitive molecule or system, which is able to generate on demand the initiating species for the polymerization reaction. When powdery or fibrous fillers are added to the reactive blend, the penetration of light in the deeper layers of the material to be cured is a critical issue. Absorption, scattering and reflection phenomena decrease dramatically the amount of UV light that does penetrate into the material beyond a few tens micrometers of a coating with standard filler content (25–75 vol.-%).

The UV curing of composites and related filled materials is thus achieved by using a diffuse light source which has most of its emission in the long wavelength UV-visible light range. These diffuse lamps have the additional benefit of operating from a regular electricity supply. Stopping the exposure before completion of the polymerization process interrupts the cure and allows further working of the composite or gel coat if required, yielding extended processing flexibility.

There are essentially two types of UV-visible curable systems. They are based on free radical or on cationic mechanism. Both types of polymerization can be photochemically triggered by adequate initiators.

The majority of commercial light cure products are of the free radical type and use primarily acrylic (acrylate) components. Free radical systems are the most versatile in regard to product properties because many different types of monomers and oligomers are available for use to obtain the desired features. With a free radical system, polymerization stops almost as soon as the light is turned off. Free radical systems are also subject to oxygen inhibition, which means that oxygen in the air prevents the molecules at the surface from polymerizing, leaving an incompletely cured network.

Cationic systems contain epoxy and/or vinyl ether materials rather than acrylic components. Because only a restricted variety of monomers and oligomers are available for use in these systems, versatility in tailoring properties is limited. Unlike free radical systems, some cure does continue after the light source is removed, but it is sometimes minimal and often requires a thermal bump, or prolonged heating, to be effective. Cationic systems are not very sensitive to oxygen inhibition, but are easily poisoned by high humidity and nucleophilic contaminants.

4.1 Photo-Initiation

To obtain by this curing method rigid networks exhibiting a glass transition temperature T_g significantly above the operating temperature, monomers de-

rived from bis-phenol A can be selected and adequately formulated [52]. The epoxy monomer DGEBA and its acrylated derivative EPDA (Chart 1) polymerize upon appropriate photo-initiation by a cationic or a free radical mechanism, respectively.

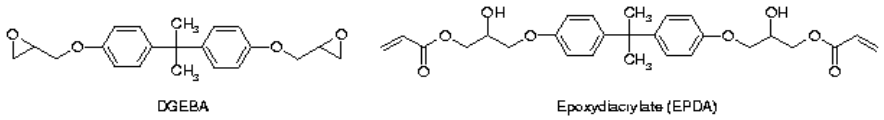

Chart 1. Examples of monomers derived from bis-phenol A

For an efficient exploitation of the incident UV-visible light, the absorption spectrum of the photo- initiating package has to be adjusted to the spectral characteristics of both the curable material and the light source [53]. In the case of a representative structure where the radiation curable material is sandwiched between protecting thermoplastic films, the light-filtering effect of the latter shall be overcome by minimizing the screen thickness, or alleviated by selecting an initiator exhibiting a long wavelength absorption, above the cut-off line of the enveloping film.

The transmission spectra of Fig. 6 clearly show the cut-off line at 320 nm by a 10 μm-thick PET film, whereas polyimide films do not allow the penetration of light for wavelengths shorter than 400 nm. Additionally, the dramatic reduction of transmitted light can be calculated at various operating wavelengths as a function of film thickness.

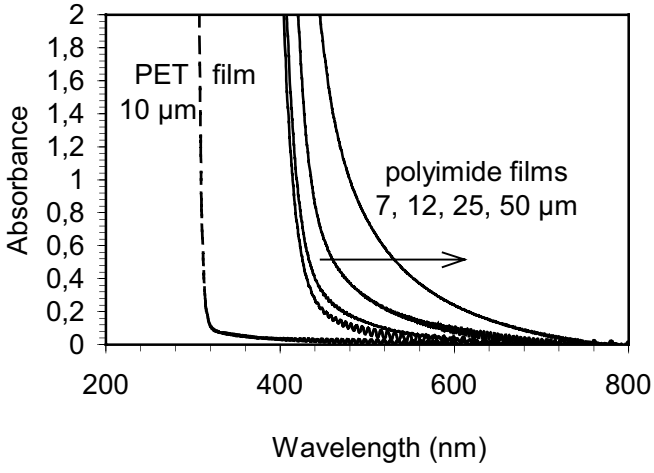

Fig. 6. UV-visible absorption spectra of protective thermoplastic films

Obviously, if PET absorption spectrum makes it possible to use a photoinitiator to cure the inner composite material with UV-A light, initiators sensitive to visible light are requested when using polyimide films.

Commercial phosphine oxide initiators, as mono-acylphosphine oxide (MAPO) and bis-acylphosphine oxide (BAPO) [54] exhibit long-wavelength absorptions that are not filtered by PET and that enable the curing of composites including transparent or white powdery fillers as well as glass fibres. Indeed the UV-curing of white-pigmented coatings is already state-of-the-art [55]. The bleaching of MAPO upon UV-visible irradiation filtered with PET (Fig. 7) allows the light to penetrate in the deeper layers of the material.

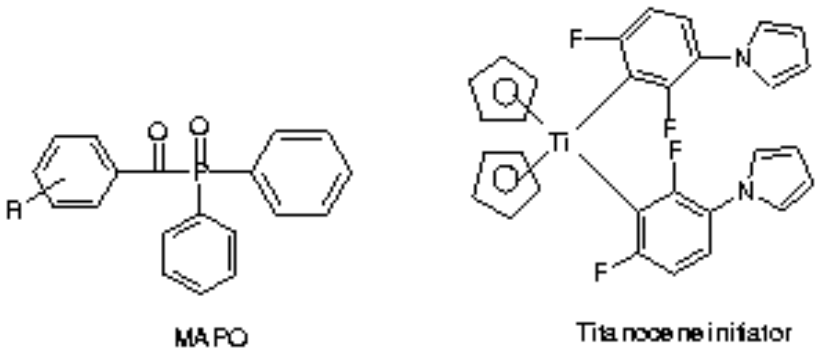

Chart 2. Acylphosphine oxide and titanocene photoinitiators

The progress of type I initiator photolysis can be modeled by simple absorption and decomposition laws owing to the monomolecular nature of the reaction. For a low initial absorbance at operating wavelengths, no significant gradient of energy absorption is expected and a first order description fits satisfactorily the observed rate of disappearance of the photosensitive compound.

The visible absorption spectrum of the titanocene initiator is convenient for initiating efficiently acrylate photopolymerization with 500 nm light, that is to say above the cut-off wavelength of the polyimide films mentioned above (Fig. 9). In the case of strong initial absorbance at operating wavelength, a gradient of light absorption in the curable material shall be taken into account, but as a consequence of gradual bleaching, in depth curing is achieved after predictable times of exposure. In the experiment corresponding to the spectrum of Fig. 9, zero-order kinetics is indeed observed over the main part of the photolytic process. This type of quantitative approach is particularly helpful to design and to control the rigidization process by radiation curing.

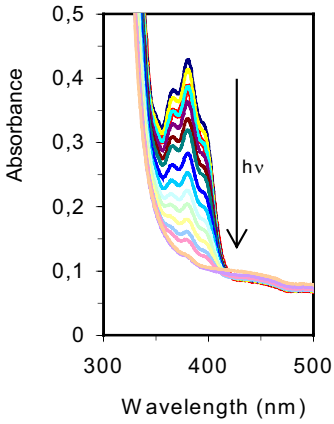

Fig. 7. (left) – Bleaching of a clear blend containing MAPO upon exposure to UV-visible light (PET filter)

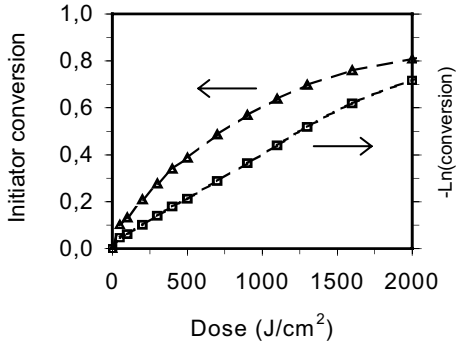

Fig. 8. (right) – Progress of MAPO photolysis (same conditions as for Fig. 7)

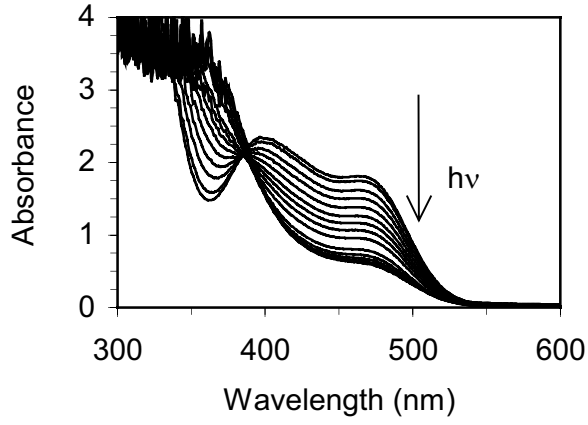

Fig. 9. Bleaching of a clear blend containing the titanocene initiator upon exposure to visible Xenon light filtered with a polyimide film

4.2 Optimizing Material Properties

The curing kinetics of acrylates as well as of other types of monomers can be monitored accurately by infrared spectroscopy [56]. Lab experiments for testing initiating system efficiency and for adjusting irradiation conditions can be conducted on samples of various thickness (from a few micrometers to some millimeters) using adapted sampling methods (transmission or ATR-IR)

[57,58]. The kinetic profile of EPDA photopolymerization at constant temperature can be varied by changing the nature of the photo-initiator and of the irradiation source. At 25°C, using various Type I initiators and appropriate filtered light, we have observed the curing within various timescales but with the same limiting conversion $\pi_{\max} = 0.37 \pm 0.02$ (Fig. 10). This demonstrates that vitrification exerts its control over the progress of polymerization in the different situations, provided that thermal control is effective.

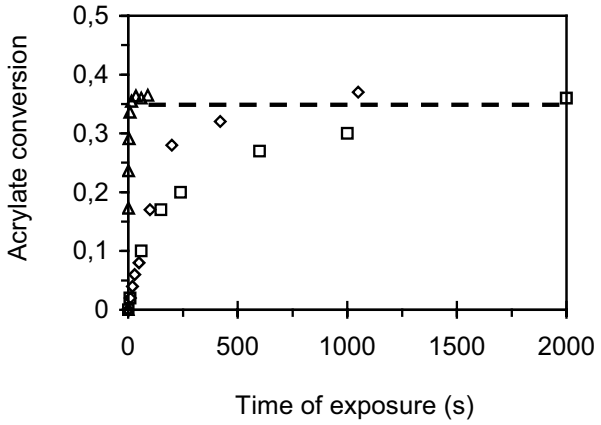

Fig. 10. Kinetic profile of EPDA photopolymerization under various conditions (initiator type and content, light source) at 25°C

The profiles recorded at various temperatures ranging between 10°C and 90°C are shown in Fig. 11, giving another evidence of the effect of mobility restrictions that are shifted to higher conversion levels as the curing temperature is raised.

The continuous progress of polymerization can be described by a phenomenological equation as shown below, with adjustable parameters c_{1-3}, which appeared more convenient than so-called autocatalytic models [59,60]

$$\pi(t) = c_1 t + c_2 - \frac{1}{c_3 t + c_2^{-1}}$$

After parameter adjustment by standard least square procedure, the model allows to predict satisfactorily the conversion degree of a sample submitted to given curing conditions (full lines in Fig. 11). The influence of initiator concentration, light intensity and temperature on the kinetic profiles can also be taken into account [61].

For slow photocuring reactions conducted under isothermal conditions, the curing temperature controls the final degree of conversion. A typical conversion-temperature relation for EPDA monomer is shown on Fig. 12.

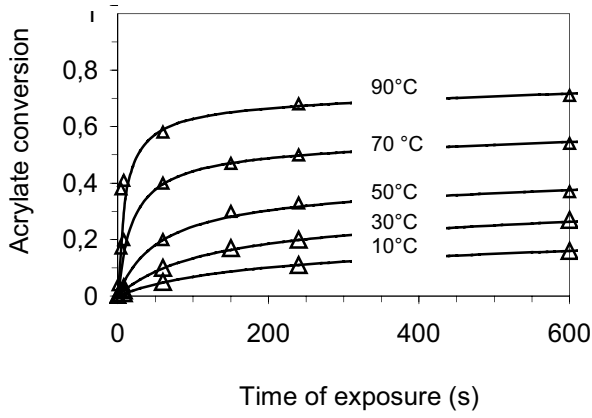

Fig. 11. Time-dependence of acrylate conversion as a function of curing temperature for EPDA photopolymerization with 1 wt-% type I photo-initiator under filtered light

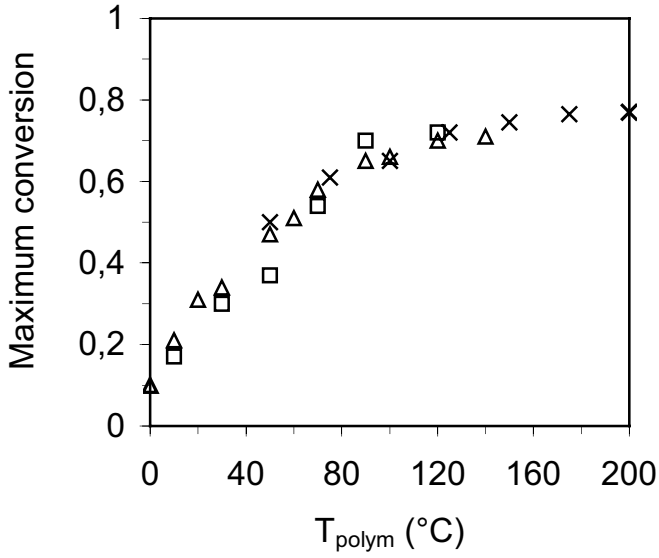

Fig. 12. Dependence of ultimate conversion as a function of curing temperature during isothermal EPDA photopolymerization

The determining influence of vitrification on the curing process is evidenced in Fig. 13, where the Tg of the network in the photocured samples is expressed as a function the curing temperature.

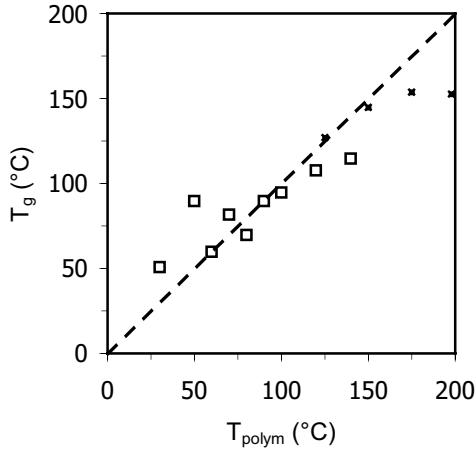

Fig. 13. Relation between the Tg of the cured EPDA network and the photocuring temperature

The adequate combination of thermal and irradiation effects on the cure kinetics of clear or filled resins therefore allows achieving the desired properties for the composite material of the rigidizable structure.

Alternative monomer chemistries and visible initiation packages have been assessed, exhibiting distinct advantages and limitations. A determining factor is the flexibility of the process in terms of light source spectrum and power as well as in terms of thermal conditions. Photosensitization of free radical and cationic initiators by visible light is a key issue. Several mechanisms including energy or electron transfer as well as redox reactions involving photolytic free radicals offer a broad range of combinations to be tested. Mechanical performance is rather easily achieved, but minimizing power and energy consumption of the light sources still appears as one of the most demanding features for the desired photocurable system.

4.3 Feasability Demonstration on Composite Structures

Large-scale UV rigidified tubes were recently manufactured based on light curable formulations at EADS-ST in collaboration with the LCOM.

The manufacturing process of the large scale demonstration boom consisted of the following steps: an inner polyimide bladder is assembled over a mandrel. Light curable prepreg fabric is then laid-up on the inner bladder, resulting in a 300 micron thick, structural composite layer. An aluminized, space qualified outer restrain is then placed over the composite layer and the whole tube is slid-off the mandrel. After boom end caps integration, the structure is compacted in order to occupy the least space possible. Finally, the boom is deployed by gas inflation and cured using internal lamps. The final boom

is shown on Fig. 14. The typical sizes of the boom are respectively 2 meter long and 160 mm in diameter. The composite material was made of a light curable formulation for the matrix and of glass fibers. The rigidization of the boom was obtained after 8 hours of illumination. Further development shall include improvement of the resin formulation, compatibility of the process with carbon or organic fibers, and manufacturing processes development for larger structures.

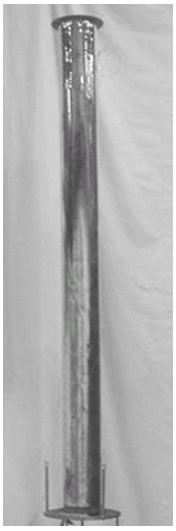

Fig. 14. 2 meter-long UV rigidized demonstrator manufactured, deployed and cured at EADS-ST

5 Conclusion

Despite the long-known potentialities of inflatable structure for space applications, this technology has not yet been implemented on operational space equipment in Europe, due to the lack of adapted materials and technologies. However, recent improvements in these fields now allows the development of such projects; and solar array has been identified as one of the most promising applications.

In-orbit rigidization of Gossamer structure is one of the key technology that shall be mastered. Radiation initiated polymerization is a validated on-ground technology in the field of thick and moderately filled composite materials. Due to its versatility and potentialities, it shall be able to fulfill the industrial need for a versatile, low power, low energy, controllable and predictable in-orbit rigidization technique. EADS-ST and the LCOM have a strong background in radiation curing of composite materials and in the formulation of radiation

curable systems for specific high-requirement applications based on 10 years of close collaboration.

In the recent years, EADS-ST has heavily invested for developing Gossamer technology and is actively working in the frame of ESA funded activities on inflatable structures. EADS-ST aims at validating the technology in the course of a flight demonstration in the year 2007 (TRL 6) [62,63].

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