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Scheel

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[54] **SPACE-SAVING STORAGE OF FLEXIBLE SHEETS**

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Nov. 17, 1972 Germany 2144034

[52] **U.S. Cl.** .... **242/55,** 135/1 R

[51] **Int. Cl.** **B65h 45/02**

[58] **Field of Search** .... 242/55, 54 R, 67.1; 135/1 R, 1 A, 1 B, 1 C, 1 D, 5 R, 8

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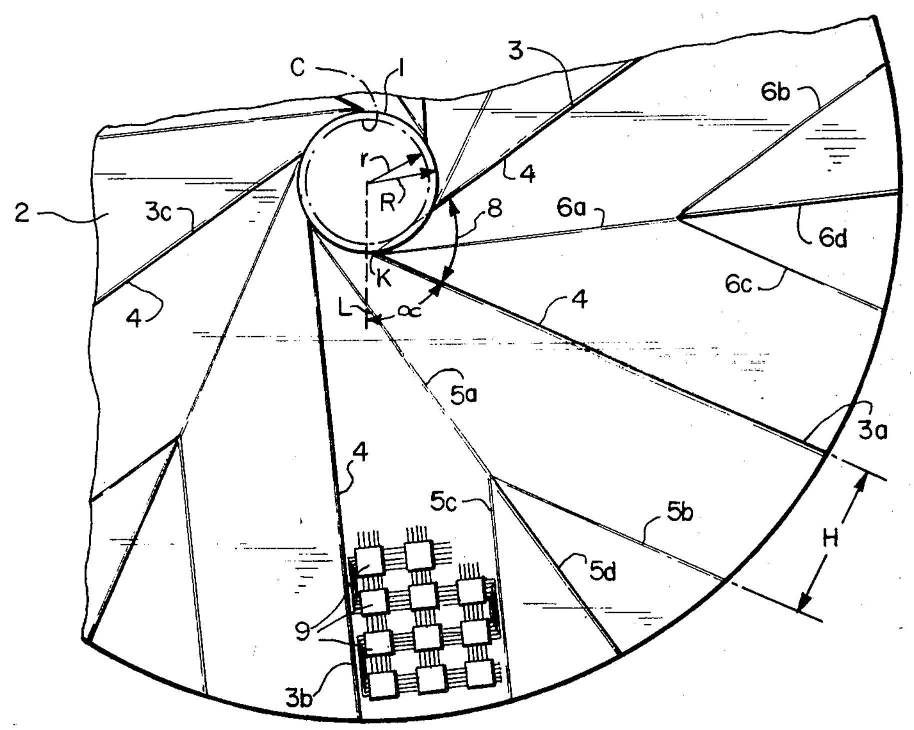
Attorney, Agent, or Firm—Arthur E. Dowell, III

[57] **ABSTRACT**

A hub and deployable annular sheet folded and wrapped thereon, the folds including major fold lines lying in straight lines which are tangent to an imaginary cylinder located just inside of the hub, and the sheet material being additionally folded or pleated between the major fold lines in such a way that at each fold line only one thickness of the material is folded upon itself, and the sheet being deployable to extended position, and in some modifications held therein, by rib means lying along the major fold lines.

10 Claims, 12 Drawing Figures



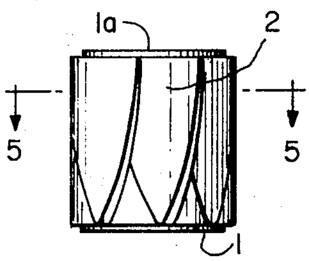


FIG. 1

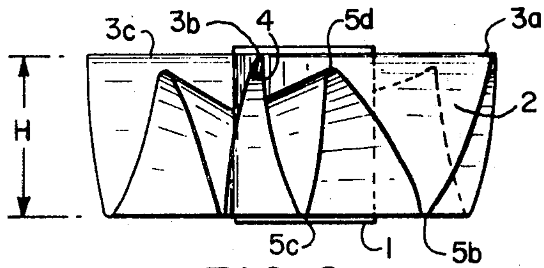


FIG. 2

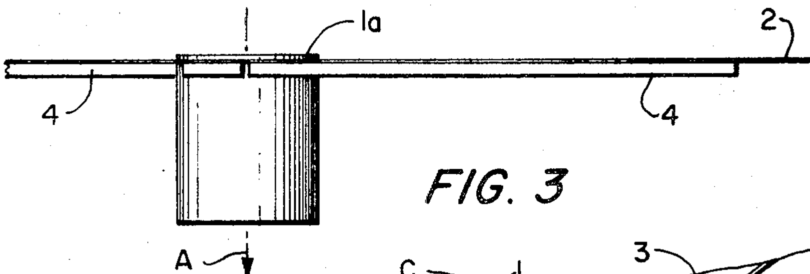


FIG. 3

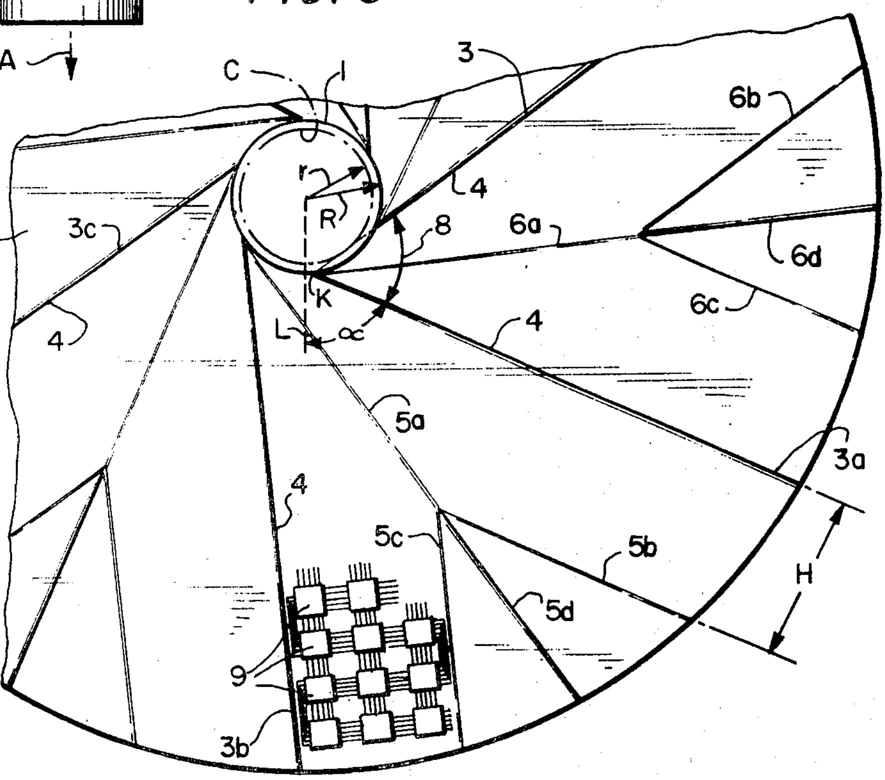


FIG. 4

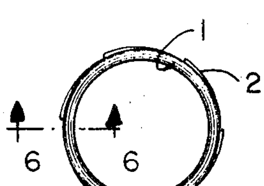


FIG. 5

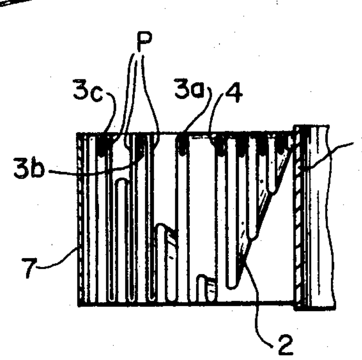


FIG. 6

FIG. 7

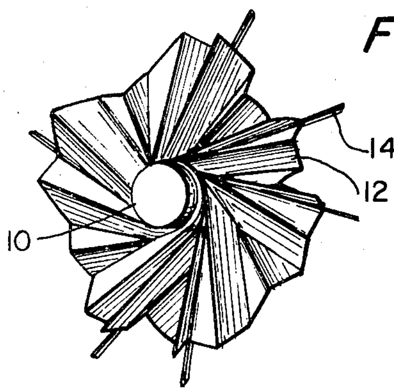


FIG. 8

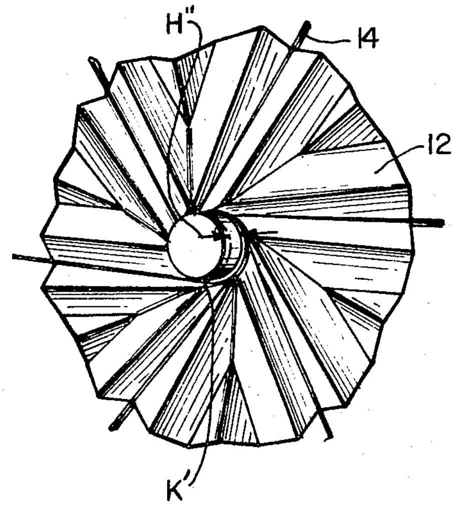


FIG. 9

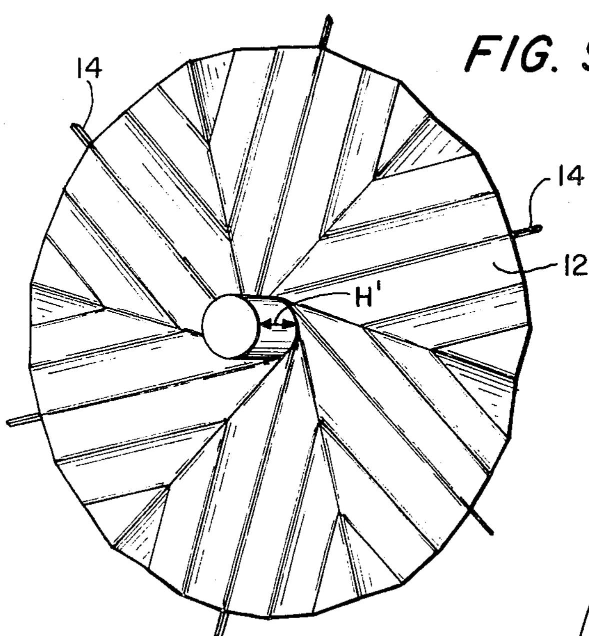


FIG. 10

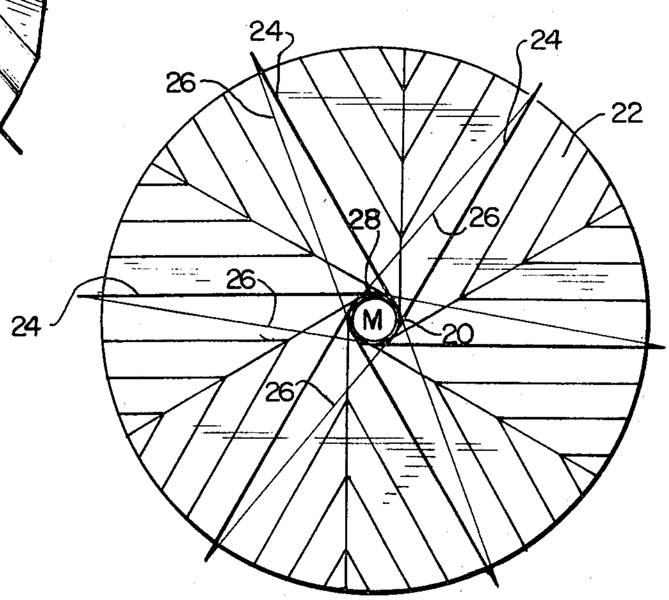


FIG. 11

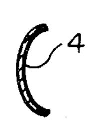
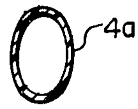


FIG. 12



SPACE-SAVING STORAGE OF FLEXIBLE SHEETS

This invention relates to apparatus for storing and deploying a thin flexible sheet, particularly an annular or circular sheet of plastic or fabric material, by folding the sheet in a way resembling pleating while wrapping it against the outer surface of a cylinder or prism to which the sheet is fixed in the vicinity of its center. Storage according to the present invention is useful for many purposes, for instance, to wrap and store tents, umbrellas, sails, sheet filter materials, reflecting radiators, etc., and this apparatus is especially useful for storing and deploying large arrays comprising solar cells mounted on a supporting sheet for use in connection with spacecraft power generation. Another use is to fold and store, and to automatically deploy heat shields, micrometeorite shields, or the like.

It is a principal object of the invention to provide structural means for folding and wrapping circular sheets and for easily unwrapping and deploying, preferably automatically, these same sheets without damage thereto or tangling, and preferably to provide means by which such sheets can easily be stored again by folding and wrapping in the original configuration. An essential characteristic of this type of storage is that the finally stored sheets must occupy only a very small spatial volume, and that when folded and wrapped, they must be protected from damage, especially environmental damage such as pressure, shock, vibration, or exposure to humidity or to other detrimental contact.

It is well known in the prior art to fold circular sheets together or to roll them up on a drum. Folding them together in multiple layers tends to result in rather disorderly storage in which damage to the sheets is likely especially where multiple thicknesses are first piled up and then folded at a bend line. On the other hand, rolling unfolded sheets on a drum results in a final stored configuration which is excessively lengthy axially of the drum.

The present invention seeks to teach an optimum way to fold and wrap a sheet of material having a memory for its bend lines against the surface of a cylindrical hub which is fixed concentrically to the center of the sheet and has its axis normal to the surface of the sheet when deployed, regardless of which of the above practical applications the present invention is applied to. This is quite difficult to accomplish because plane sheets are only foldable along straight lines. As a result, the spiral type of wrapping as shown, for example, in FIG. 3 of U.S. Pat. No. 3,109,608, starting precisely at the center of the sheet is out of the question.

The problem sought to be solved in the above U.S. patent using radially extending fold lines, can however be solved using major fold lines which extend in a direction which is almost tangent to the hub. The present invention uses such major fold lines, which extend from the cylinder or hub and are disposed at a certain angle alpha with respect to radial lines extending from the center of the hub. The words "almost tangent" are used because the major fold lines are actually tangent to an imaginary cylinder which is somewhat smaller in diameter than the cylindrical sheet-wrapping hub itself, the imaginary cylinder being located concentrically therewithin. Between these major fold lines there are intermediate fold lines which bisect the angle between two adjacent major fold lines and extend out to the perimeter of the circular sheet, folding the sheet material in alternate directions so as to produce a pleating effect. According to the present invention there may be multiple additional minor fold lines about which the sheet is pleated; the more such fold lines, the shorter the wrap of the sheet on the outer surface of the cylinder as measured axially of the cylinder. When pleated in this manner, the sheet material is then wrapped tightly around the surface of the cylindrical hub and the pleated surfaces are thereby laid on top of each other for support adjacent to the surface of the cylinder.

In order to reduce the axial length of the cylinder required to receive and support the circular sheet when folded into pleats, the number of times that the sheet material is pleated along minor fold lines can be increased, so long as folded sectors are all essentially the same width as measured parallel to the axis of the cylinder when the pleats are wound upon it. In the several illustrated embodiments, it will be noticed that there are different numbers of pleats appearing between adjacent major fold lines.

Another object of the present invention is to provide a system for folding and wrapping a circular sheet about a cylinder while at the same time placing padding spacers between the adjacent pleat segments of the circular sheet when it is initially folded and as it is being wrapped upon the cylinder. This is especially useful, for instance, where the present teaching is employed to provide a solar cell array so as to pad the individual solar cells and prevent breakage thereof during wrapping of the supporting circular sheet material onto the cylinder. When once wrapped thereon, it is also useful to securely hold the array close to the cylindrical hub using releasable bindings and/or plastic band covers, so that the stored array cannot be prematurely displaced as a result of shocks, vibrations or accelerations.

Still another important object of the invention is to provide stiffening means to supplement the memory of the pleated sheet, such as spring-type ribs or even inflatable rib tubes which can be pressurized from within to cause them to extend outwardly of the array, these stiffening means being preferably attached to the sheet material at the major folds and being wrapped together with the sheet material around the storage cylinder. Deployment of the sheet material can be easily permitted or effected, by releasing the bindings and/or plastic covers and using the spring tendency or inflation of the stiffening ribs to cause them to assume straight-line configurations so as to unwrap the sheet and deploy it in an approximately radial plane, thus resulting in deployment to a stable configuration which can then be used as a tent, umbrella, sail, filter, radiator, etc. This same type of circular planar configuration is also especially useful as a solar array in which solar cells are attached in a pattern to the sheet material, or in which the sheet material is deployed for use as a radiation or micrometeorite shield.

It is another object of this invention to provide a structure of the character set forth wherein deployment of the sheet can be retarded and damped at a controlled rate using string-like filamentary means attached between the cylinder and the sheet or the stiffening ribs to prevent excessively rapid deployment, especially where the ribs have high spring-like qualities.

Active control of the rate of deployment can be achieved for example, by using strings which are fastened to the outer tips of the ribs and which can be spooled on or off of the reel means located at or inside of the hub, using brakes or motors. Refolding and wrapping of the sheet material, once deployed, can be achieved remotely by using the same motor to pull the strings back in towards the center of the hub and thereby wrap the sheet back into the stored position.

In other possible configurations of the present invention, a force field acting radially from the center of the structure can be used to accomplish deployment. For instance, in a spin stabilized vehicle the centrifugal force created by rotation of the hub and sheet may be used to deploy the sheet and maintain it in an extended condition with or without stiffener ribs, or in alternative configurations it may be possible to use electrostatic repulsion from an electrostatically charged hub to accomplish deployment of the sheet.

It is also satisfactory to use inflatable stiffener means built into the sheet or attached to it in such a way as to automatically stiffen it and urge it into deployment, for instance, using elongated flexible tubes which can be pressurized from within, perhaps using internally generated gas or foam material so that once deployed it will remain deployed.

Moreover, the present structure and technique need not be limited to the storing and deployment of essentially planar sheets because, for example, parabolic sheet material structures can be stowed in a similar manner if the over-all sheet material is provided with small elastic intermediate segments of suitable area which would be attached to the major and to the intermediate or secondary fold lines. If this were done, the deployment processes and structures described above can be used to accomplish non-planar resulting structures, such as parabolic dish structures capable of use as high gain RF antenna reflectors.

The present technique and structures have certain advantages which exist whether the structure is used as a tent, umbrella, sail, filter, reflector, etc. One very important advantage is that all sheet material folds are accomplished using only single folds where only single thicknesses of the material on opposite sides of the fold lines and contiguous thereto will lie against each other, as distinguished from several layers of material being first stacked together and then all folded about a common bend, which latter type of folding tends to unduly stress and stretch the outer layers of the stacked material. Since all of the pleats are single pleats, tangling during deployment is avoided, and in fact almost impossible. Another advantage of this type of structure is that whatever stiffening ribs are used, whether spring metal or pressurized tubes, etc., these can also be wrapped around the hub. When released, the stiffeners materially aid in the deployment of the structure into extended position with exceptional ease and rapidity.

Unlike some of the other storage and deployment means, especially those used in solar arrays, the present sheet, being supported at its center, can be stiffened by ribs which are relatively short in length so that when deployed, the sheet becomes exceptionally stable. Moreover, the stiffening means can be selected and shaped in cross-section so as to provide stiffening of the deployed sheet in any predetermined direction whereby the sheet is held substantially planar when deployed. The sheet has a slight fish-bone pleating pattern when deployed, the pattern being attributable to the lines about which it was folded, and these lines give the sheet when deployed an attractive and interesting appearance.

The present invention has special advantages when applied to lightweight solar generator arrays for space vehicles, these advantages being especially apparent when compared with the usual "roll-up" array where single solar cells are mounted on large rectangular flexible sheets of plastic, usually called "blankets." In order to achieve a certain over-all area for the array, the roll-up blanket can generally extend from the drum on which it is rolled only to a distance which is about five times its width, because beyond that length the blanket would have too low a degree of torsional stiffness. When the present novel structure is used to provide a solar array of circular shape, such an array has the following advantages over the conventional roll-up strip blanket array.

The outer dimensions of the circular array according to the present invention can be designed quite freely and without serious concern over the axial length of the cylindrical hub on which it is to be stored after folding, whereas a non-folded roll-up blanket array would require a long hub whose length would be determined by the diameter of the unrolled blanket. Where space is important, as in a space vehicle, the axial length of the drum on which the array is stored can be very important.

The present storage structure provides much less friction during deployment between the various solar cell components and/or the sheet on which they are mounted, since the pleats open about the bend lines which act as hinges and do not tend to scrape across the adjacent pleat. The successful deployment of a circular array is more reliable, and once deployed in the array can be maintained deployed very reliably simply by centrifugal force in a spin stabilized unit.

In order to achieve a certain cell area of the solar array, much shorter stiffening means can be used in the present structure than in the case of the rolled-up blanket array, thus, the bending stresses on the stiffening means can be less and they can be designed from lighter-weight materials. The power-to-weight ratio of the solar cell can accordingly be increased, and for the same reason the vibrational bending frequency of the present circular solar array will be much higher as compared to that of a roll-up array. Hence, the array will provide less interference with the attitude control system of a spacecraft upon which it is mounted.

Displacements of the center of gravity of a circular array according to the present invention from its geometric center, such as might occur as a result of incomplete deployment, thermal dilatations, etc., are minimized because the array is symmetrical about its center, and it therefore results that torques caused by solar pressures are non-existent.

The deployed array is subject to balanced forces which extend, not in only a few directions, but in all directions from the center, whereby it is maintained exceptionally planar.

For power transfer, no slip rings or long braided wires are necessary.

The pleats of the supporting sheet material between the folds are all strips of the same width, and thus all of the solar cell arrays can be mounted thereto using the same jigs. Such constant-width strips can be fabricated at high production rates using individual seriesconnected thin film solar cells, which would provide for economic production of an array.

Finally, the cylindrical shape of the stowed array makes its incorporation as a part of a spacecraft especially easy since the stowed array will lie neatly beneath a cylindrical shroud or fairing of the launch rocket. Moreover, where it is necessary to deploy a number of similar solar arrays in orbit from a single spacecraft, a number of storage hubs, each carrying its own solar array wrapped according to the present disclosure, can be folded outwardly on lightweight structural arms from the spacecraft, and then each of the individual arrays deployed from this extended position.

Other objects and advantages of the present invention will become apparent during the following discussion of the drawings, wherein:

FIG. 1 is a side view of a storage cylinder or hub upon which a circular sheet has been folded and wrapped;

FIG. 2 is a view similar to FIG. 1 but showing the sheet partially unwrapped from the cylinder;

FIG. 3 is an elevation view similar to FIGS. 1 and 2 but showing the circular sheet fully unwrapped and deployed in a plane normal to the axis A of the cylinder;

FIG. 4 is a partial view looking up along the axis of the storage cylinder and showing the circular sheet fully deployed;

FIG. 5 is a cross-sectional view taken along line 5—5 of FIG. 1;

FIG. 6 is a schematic partial sectional view taken along line 6—6 of FIG. 5 but showing the sheet somewhat expanded from its normal tightly wound stored position so as to make its folds visible;

FIGS. 7, 8, and 9 are related perspective views showing a somewhat modified embodiment of the invention in three different degrees of deployment, FIG. 7 showing the sheet in an early stage of deployment, FIG. 8 showing the sheet in an advanced state of deployment and FIG. 9 showing sheet fully deployed;

FIG. 10 shows a still further modified version of the invention including means for controlling the rate of deployment and for rewrapping the sheet around the cylinder.

FIG. 11 shows an enlarged cross-sectional view through a spring metal rib; and

FIG. 12 shows an enlarged cross-sectional view through an inflatable plastic rib.

Referring now to the drawings, FIGS. 1, 2 and 3 show a cylindrical hub 1 having an outer surface against which the sheet material 2 is stowed by folding and then wrapping it in the manner described. FIG. 5 illustrates the fact that when the sheet is fully stowed, the outer diameter of the cylinder is only slightly enlarged because the sheet material lies flat against it. Thus, in stowed condition the sheet requires only a very little space. The structure also includes a plurality of flexible rib members or stiffeners 4 each of which is attached to the storage cylinder 1 at its inner end and extends therefrom outwardly along a major fold *3a*, *3b*, *3c*, . . . of the sheet material 2. The sheet material is attached all along the length of its contact with each of the ribs 4. FIG. 6 is a view of the wrapped-up sheet material which has been radially expanded to show how the sheet 2 is draped over the respective ribs 4 at major folds *3a*, *3b*, *3c*, . . . Between the major folds 3, there are located a number of intermediate and minor folds *5a*, *5b*, *5c*, and *5d*, and these four folds repeat between each of the major folds all the way around the pattern. Note that the folds *5a*, *5b*, and *5c* fold (down in FIGS. 2 and 3) toward the viewer in FIG. 4, whereas the folds 3 and *5d* fold away from the viewer (up in FIGS. 2 and 3). There are intermediate folds 5a, and 5d and there are minor folds *5b* and *5c* which are located so that they intersect the intermediate folds. Where solar cells or other fragile components are used the individual folds of the sheet may be interspersed with padding spacers P as shown in FIG. 6. Around the outer periphery of the assembly there may be located a plastic retaining band 7, FIG. 6, which can be held together at its ends in a suitable manner designated to tightly confine the folded and wrapped circular sheet to prevent damage thereto, and in the case of a space vehicle to hold the wrapped sheet and ribs tightly against all possible displacements.

FIG. 2 shows the circular sheet partially deployed. Note that the axial height of the wrapping on the hub cylinder 1 is labelled H and that this height is the same as the widths H of the strips between the fold lines as shown in FIG. 4. As shown in FIG. 11, the cross-sectional shape of each rib 4 is arcuate so that it can be bent for wrapping around the cylinder, but so that when it is extended in a straight line it will have stiffness as required to hold the circular sheet material firmly deployed in a planar manner.

FIG. 3 shows the circular sheet 2 in elevation view completely deployed and supported by the arcuate stiffener ribs 4 which are mounted in the cylindrical hub 1.

FIG. 4 shows a view of the deployed circular sheet 2 as seen from above along the axis A of the cylinder 1, FIG. 3, thereby illustrating the extended ribs 4 as straight lines and attached to the circular sheet 2 at the major folds *3a*, *3b*, *3c*, . . . When the circular sheet is deployed, it lies substantially transversely at the upper end *1a* of the circular hub just above the ribs 4.

The sub-folds *6a*, *6b*, *6c*, and *6d* correspond with the folds *5a*, *5b*, *5c*, and *5d* but are located between another pair of ribs 4. The intermediate folds *5a* and *6a* bisect the angles 8 formed between each pair of adjacent major folds 3 and are pleated in alternating directions with respect thereto. A group of solar cells 9 are shown on the fabric between the ribs 4 and the minor fold *5c* to show typical placement thereof.

Although at first glance it may appear that the major folds *3a*, *3b*, *3c*, . . . and the ribs 4 attached thereat extend in directions which are tangent to the outer surface of the hub cylinder 1, this is not true. Actually, they are tangent to an imaginary circle C which is of slightly smaller radius r than the radius R of the outer surface of the hub 1, FIG. 4. The radius r of the imaginary circle C is selected with respect to the radius R of the hub 1 such that extensions of any two adjacent major bend lines 3 will intersect at a common point K which lies slightly outside the surface of the hub 1. Moreover, the ribs 4 and the major folds *3a*, *3b*, *3c*, . . . lie at a certain angle alpha with respect to a radial line L passing through the center axis A of the cylinder 1 and the point of intersection of the ribs 4 and major fold lines 3 with the surface of the cylinder 1. This angle varies, depending on how many major folds and ribs are employed around the periphery of the cylinder 1. The angle alpha must be carefully selected in order to provide proper geometry to achieve correct storage and deployment of the assembly. For example, if four major folds are employed, the angle alpha should be about 52° (R/r equals 1.28). If six major folds are used, as shown in FIG. 4, then the angle is about **66** degrees, (R/r equals 1.10). For eight major folds, an angle of about 71° is proper (R/r equals **1.05**).

FIGS. **7, 8** and **9** show a modification of the structure illustrated in FIG. **4,** in which the number of pleats is increased between each pair of ribs **14** for the purpose of shortening the height H of the sheet **12** when it is wrapped upon the cylindrical hub **10.** Initially when the sheet **12** and ribs **14** are fully wrapped upon the hub **10** the length of the hub is substantially covered in the same way as the hub **1** is covered by the sheet **2** in FIG. **1.** Then, as the sheet material unwraps and becomes deployed, the diameter of the sheet **12** becomes larger and larger while the covered height H'' of the cylinder, FIG. **8,** remains constant until all subfolds **5***b*, **5***c*, and **5***d* are deployed, i.e. the deployment reaches the point K'. Then H'' rapidly increases as can be seen by comparing the dimension H'' in FIG. **8** with the dimension H' in FIG. **9** in which the sheet material is fully deployed. Since the number of pleats has been increased as shown in FIG. **9,** as compared with the number of pleats shown in FIG. **4,** the dimension H' is accordingly smaller than the dimension H in FIG. **4** assuming the same outside diameter of the deployed sheet material.

Finally, FIG. **10** illustrates a still further modification of the structure in which two things are changed. In the first place, the number of pleats has been still further increased to illustrate a different embodiment which would wrap on an even shorter length H of storage hub. The second difference is that in FIG. **10** means has been added by which a controlled rate of deployment of the sheet material can be achieved, and by which the sheet material can be mechanically rewrapped into folded condition. In this illustration, the hub is generally referred to by the reference character **20,** and the sheet is referred to by the reference character **22.** The ribs are referred to by the character **24,** and at the end of each of these ribs **24** there is attached a string **26** which extends from the tip of the rib in toward the central hub. Within the cylindrical hub **20** there is a drive means, in the illustrated case a motor M capable of rotating a wind-up reel **28** attached to it and lying concentric with the cylinder **20** on which the fabric wraps. Each of the strings **26** is wrapped onto the reel **28** and secured thereto, and it will therefore be seen that starting with the strings wound tightly on the reel and the sheet **22** folded and wrapped tightly on the storage cylinder **20,** as the motor M is rotated clockwise the strings will be paid out from the reel, thereby allowing the ribs **24** to extend to their fully deployed positions at a controlled rate. On the other hand, if it is desired to return the sheet **22** to the stowed condition, the motor can be reversed to drive the reel **28** counterclockwise, thereby pulling the strings tightly in toward the cylinder and returning the sheet material to wrapped condition. Since the sheet material is permanently creased at each of the major and minor folds and bends, it rolls up to its stored condition again quite readily. In the working embodiment of the present invention, the sheet material is a plastic fabric having sufficient memory to regain its folded position about the original creases when the ribs **24** to which it is attached are wound again onto the hub **20.**

Other modifications of the present invention are of course possible, for instance, including a modification in which the ribs, instead of being C-shaped as shown in FIG. **11,** are hollow plastic tubes **4***a* as shown in FIG. **12,** which are inflated from within by gas pressure or by a foam substance to a sufficient pressure that the ribs **4***a* assume and retain linear deployment. In addition, it is also possible to deploy the sheet by a force field operating substantially radially from the axis A of the cylinder, for instance, an electrostatic force or the centrifugal force caused by rotation of the entire assembly.

The invention is not to be limited to the exact illustrative embodiments, for obviously changes may be made therein within the scope of the following claims.

I claim:

1. Apparatus for storing on a hub an annular sheet in folded condition and for deploying it into extended position, comprising:

a. a hub of diameter which is small as compared with the diameter of the sheet when extended and the hub having an axis;

b. a sheet made of thin flexible material fixed in the vicinity of its center to the hub such that when the sheet is in extended position it lies substantially normal to said axis of the hub;

c. the sheet having multiple predetermined sharply-defined bend lines about which the sheet is pleated by folding the sheet in one axial direction at multiple major bend lines uniformly spaced about the sheet and then folding the sheet oppositely at intermediate bend lines bisecting the angle between adjacent major bend lines, the folds being made in such a way that at each bend line only the sheet material contiguous thereto is folded upon itself, said major bend lines each extending from the hub as a substantially straight line which is tangent to an imaginary coaxial cylinder located within the hub and of slightly smaller diameter and selected such that extensions of adjacent major bend lines would intersect at common points lying near the surface of the hub; and

d. the pleated sheet having sufficient memory of said sharply defined bend lines to assume said folded condition when rolled onto said hub.

2. Apparatus as set forth in claim **1,** wherein the sheet is further pleated to form said segments by folding it in alternating axial directions about minor bend lines which are also substantially straight lines so located on the sheet when in extended position that each minor bend line is parallel to an adjacent major bend line and that the spacings between each minor bend line and an adjacent parallel major or minor bend line is substantially a constant distance measured anywhere on the sheet.

3. Apparatus as set forth in claim **1,** wherein padding spacer means are placed between the pleated segments of the sheet when folded for storage.

4. In apparatus as set forth in claim **1,** including releasable retaining means surrounding the pleated and rolled sheet when in folded condition.

5. In apparatus as set forth in claim **1,** said sheet being deployable by a radially outwardly acting force field.

6. In apparatus as set forth in claim **1,** flexible tube means comprising stiffening rib means fixed to the sheet along each major bend line and each rib means being attached to the hub where the bend line intersects it, the tube means being inflatable to stiffen them and deploy the sheet into extended position.

7. Apparatus as set forth in claim **1,** including spring-like stiffening rib means fixed to the sheet along each major bend line and each rib means being attached to the hub in a position such that when the sheet is in extended position, the rib means lies tangent to said imaginary cylinder, the spring-like qualities of the rib means serving to deploy said sheet into extended position.

8. Apparatus as set forth in claim **7,** including control means attached to the hub and including string means extending to the rib means, and said control means being operative to control the rate of deployment of said sheet.

9. Apparatus as set forth in claim **7,** said control means including motor driven reel means at said hub, string means attached to the reel means and to the rib means, and said sheet being deployed toward extended position when the reel means is driven to unwind the strings therefrom and being wrapped on the hub toward folded condition when the reel means is driven to wind the strings onto the reel.

10. Apparatus as set forth in claim **1,** wherein said sheet is non-planar when in extended position.

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