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3 PRESSURIZED STRUCTURES OF HIGH MOBILITY 6

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PRESSURIZED STRUCTURES OF HIGH MOBILITY

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ABSTRACT

A method is presented for constructing a cylinder having low bending stiffness and zero restoring moment from the bent condition throughout a wide range of bending deformations. The behavior of the structural mechanism which carries the pressure load and accommodates the bending is described and possible applications to space suit components are shown.

I. INTRODUCTION

A requirement exists for pressure-resistant structures that can be made to undergo large geometrical changes, while inflated, with a minimum of associated resistance to deformation. Tubular members'having this property could be used to advantage, for example, in rocket-motor fuel lines (to reduce the flange moments, as discussed in Reference 1). Other potential applications may be found in pneumatic conveyors, temporary pipelines, etc. More complex shapes and mobility requirements exist for the pressure constraint layers of high altitude protection garments and space suits (Ref. 3).

A theoretical basis for pressurized structures of zero stiffness can be approached from two points of view:

- Since the stiffness due to pressurization is of primary concern, it can be postulated that this stiffness will vanish if the membrane forming the structure can be deformed in such a fashion that the enclosed volume remains constant during the deformation. This postulate arises from the fact that the work of deformation which is associated with pressure stiffness must reappear in the form of potential energy in the contained gas and therefore must be represented by a volumetric change; alternatively,

- the equilibrium conditions of a filamentary membrane with internal pressure and externally applied loads can be formulated and'the force-deformation characteristics can be derived from consideration of statics. From these considerations, the kinetic and elastic properties of the membrane can be inferred which will tend towards minimizing the resistance against deformation.

This second approach has been pursued in the work subject of the present report.

II. GENERAL DISCUSSION OF SLIP-NET PRINCIPLE

In the conventional types of flexible, pressure-resistant tubing, such as convoluted tubing or braid-reinforced rubber tubing, the structural material is arranged in a way such that the longitudinal loads are carried along curved load paths. The local normal curvature of these load paths is established (ideally) by the internal pressure and the tension stresses in the structural material. When a bending moment is applied to bend the tubing, a gradient in the tension loading develops across the cross section of the tube,' and the local load-path curvature changes, producing the bending deformation. The elastic properties of this general type of structure characteristically include a bending stiffness which is proportional to pressure and which increases with deformation, a distinct equilibrium shape (except for minor hysterisis) for each value of applied bending moment, and a tendency to fold (becoming creased on the inside and flattened on the outside) at a bend radius of several tube diameters.

The structural concept presented here, which has been given the name of "slip-net" tubing, differs from the conventional approach in that the structural material is permitted to slip locally with respect to the surface so as to redistribute itself to reduce (or, ideally, eliminate) the longitudinal'tension gradients which give rise to the restoring moment in the deformed tube. This sliding action, with its associated friction, completely changes the characteristics of the structure, with the result that the behavior of the tube under bending approximates that of a distributed plastic hinge.

The construction of the slip-net tubing is shown in Figure 1. The structural wall is made of three separate, independent layers of (essentially) unidirectional filamentary material, of which two are wrapped as opposing, mirror-image sets of helical load-paths, while the third is circumferential. The helical layers are free to slide, independently, over the surface and to stretch in the "cross-grain: direction in order to accommodate the bending deformation of the tube. This sliding freedom gives the desired bending compliance. The circumferential layer is required to stabilize the cross section of the tube, as described later. Both the circumferential layer and the impermeable inner liner (which is required to confine the pressurized fluid) must have enough compliance in the longitudinal direction to remain unstressed as the tube is bent.

During the bending deformation, the surface deforms in a way such that the original helical paths become steeper at the outside of the bend and less steep at the inside. This general type of helix-angle distribution can be observed by bending a helically-wound cylinder on which the intersections of the opposing helices have been pinned to prevent sliding. Here the unit structural-element is a rhomboidal cell with a fixed perimeter. As indicated in Figure 2, the cells at the outside of the bend become longer and narrower, while those on the inside become shorter and wider. The resulting fiber pattern has geodesic curvature which is concave toward the inside of the bend and therefore produces a tension gradient that increases the load in the outer fibers and unloads the inner fibers. The net result is that the deformed tube develops a restoring moment: the longitudinal stress resultant, $T \cos\gamma/a$, increases across the cross section from inside to outside, since $T_o > T_i$, $\cos\gamma_o > \cos\gamma_i$, and $a_o > a_i$.

The effect of the sliding of the two helical wraps relative to each other is to reduce the geodesic curvature and, therefore, to redistribute the longitudinal structure in a way such that the gradient of the longitudinal stress resultant is reduced through changes in all three components: the tension, the helix angle, and the spacing. It is instructive to compare the bent portion of the tube with a section of a helically-wound isotensoid toroid. Figure 3 is a photograph of a toroid which was designed according to Reference 2 to have a geodesic winding pattern and (therefore) uniform fiber tension. It can be seen in this photograph that the fiber spacing (dimension a of Figure 2) is greatest at the outside of the bend, while the helix angle γ is greatest at the inside. These relations are basically different from those discussed for the bent helically-wound tube with pinned intersections.

Because both the fiber-packing density and the longitudinal (i.e., equatorial) component of fiber tension on the toroid are greater at the inside of the bend, the center of effort of the longitudinal components of fiber tension at any meridian lies toward the inside from the center of area of the cross section. For the toroid in the photograph the center of effort is displaced from the center of area by 41 percent of the mean radius of the cross section. It must be concluded that if the bent tube had the same curvature and fiber distribution as the toroid shown, the internal structural forces would act to increase the bending deformation, rather than decrease it, which is to say it would exhibit a negative restoring moment. Such a tendency has been observed in varying degrees in the models which have been built. It has been found that the negative restoring moment can be counteracted by incorporating sufficient cross-grain stiffness in the sliding layers.

III. STABILITY CONSIDERATIONS

In applying the slip-net principle, it is necessary to take precautions to avoid certain instabilities which arise as a result of the sliding freedom. One potential instability involves the tendency of the helical fibers to bunch together to form a helical crease in the surface of the tube. Such a crease can grow with progressively more fibers sliding into it, until the tube is grossly distorted. A similar tendency which can appear when the tube is sharply bent involves the spreading of fibers on both layers to form a rhomboidal area over which the surface is unsupported. Eventually the gap becomes great enough to allow the circumferentially-wrapped bladder to push its way completely through the helical structure. Both of these instabilities can be eliminated by incorporating in each of the layers sufficient cross-grain stiffness to prevent large local variations in fiber spacing.

Another instability which has been observed in this type of device occurs when there is insufficient stiffness associated with the circumferential dimension of the tube, as is the case with a cylinder which has only helical fibers. Such a tube will grow in diameter in one section and shrink in an adjacent section, as the filamentary layers slide from the region of high curvature and low tension to the region of low curvature and high tension (See Fig. **12**). This tendency is readily controlled with a layer of circumferential fibers to constrain the cross section to a given perimeter.

Since a circumferential layer is required for stability reasons, the helix angle γ is a free parameter which can, in principle, have any value less than the "hose angle", 54.7° (above which the circumferential wrap would be loaded in compression). No attempt has been made to find an "optimum" value for this angle or to explore the likely range. It can be seen, however, that there are counteracting effects which indicate that a best value might be found. Thus the steep helix (small γ) requires more sliding and more lateral stretch to accommodate a given bend. It can, however, slide more easily because of the smaller tension and normal curvature, which produce the normal pressure that gives rise to the sliding resistance. The shallow helix, on the other hand, requires less sliding but has higher resistance to sliding.

IV. EXPERIMENTAL

In order to gain experience with the slip-net concept, several prototype tubes were fabricated. Figures 5 - 7 show tubes made from Dacron fiber; figures 8 - 10 show tubes made from Teflon fiber in various positions of bending, These tubes were constructed with three individual layers of knitted fabric, using a helix angle of 45 degrees.

Knitted construction was chosen for these prototypes because of two properties which are of special importance in this application. Knitted sheeting is readily fabricated, and, particularly with a knit-and-purl pattern, makes an especially smooth and slippery "unidirectional" layer. More important, however, its bidirectional elastic properties are such that the "fibers" (i.e., the "whales" of the fabric) show a strong tendency to remain uniformly spaced. This tendency arises from the fact that the unidirectional sheet is shortened where the spacing is large and relaxes where the fibers are bunched. Such a "Poisson's-ratio" effect results in a strong stabilizing reaction to the tendency to form creases and waists.

Each layer of the tubes was knit in a long strip which was wound in place on a cylindrical form. The strip was stretched so as to behave essentially like a unidirectional fabric, and then sewn together along the seam. The liner is a "cigarette roll" tube of surgical rubber sheeting, as shown in the photographs. These models can be bent easily by hand, with an internal pressure of 30 psi, around its own diameter (4.5 inches) and then straightened.

Bending-stiffness measurements were made on the prototype slip-net tube models by supporting one end on a fixed clamp, and applying to the other end a pure bending moment through a dead-weight-pulley arrangement as shown in Figure 11. The most important factor in the behavior of this tube appears to be the frictional resistance to sliding between the layers. In all the models which were made, the restoring moment was zero for essentially the entire range of bending deformation (see Figs. 5, 6, 8 and 9), whether the deformed condition was reached by increasing or decreasing the bending deformation. When a pure bending moment was applied, the tube would not respond until the bending moment reached a threshold value, at which point the interlaminar shear loads would overcome the static friction and the tube would start to bend. The bending deformation would then proceed through approximately a radian on a tube that was about eight diameters in length until the limits of the apparatus were reached. The threshold bending moment was such that $M/p\pi r^3 \cong 0.2$ throughout the entire range of deformation, for the tube made of Dacron roving. This tube showed a slight tendency to bend more easily than to straighten; the threshold moments were lower and the subsequent travel was greater when the bend radius was being decreased.

A tube made without the third "circumferential layer" is shown in Figure 12. It exhibits the "pinch" instability discussed in Section 111.

In addition to the tube models, several prototypes of more complex structures were constructed.

Figure 1B shows a structure involving a bifurcation, such ,as would be required for a fingered glove or hip-leg portion of a space suit. Figure 14 shows the same structure in an unconstrained, deformed mode under a 7 psi internal pressure.

Finally, a full-sized shoulder-arm joint was fabricated and patched into the constraint layer of a regulation space suit, obtained for this purpose from Houston Manned Spacecraft Center. Figure 15 shows the limits of upward arm mobility at 5 psi internal pressure obtained with conventional (link-net) and the slip-net design. The conventional portions of the suit have been retouched to obscure details for reasons of classification.

It was observed, that the side made from slip-net fabric exhibited markedly better mobility. Overhead "reach" was improved by approximately 3" without compromise on other position limits. Further, a much better conformance to the human shape was achieved in all positions examined, effectively reducing the bulk of the suit.

V. CONCLUSIONS

The slip-net principle appears to offer a practical approach to the problem of reducing the bending stiffness of pressurized tubular members. Experiments with using this principle in the restraint layer of a space suit have shown the concept to be very promising in improving the mobility of critical joints, since it offers the attractive combination of low bulk (in contrast to that associated with convolutions and bearings), low bending stiffness, and zero restoring moment in the deformed condition.

Further work is required, both theoretical and experimental, to establish quantitatively the performance characteristics obtainable with this concept. Particularly, more work is required to realize the full potential mobility characteristics of complex shapes typical in space suit applications.

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2. Burggraf, O. R. and Schuerch, H.: Analysis of Axisymmetric, Rotating Pressurized Filamentary Structures. NASA TN D-1920, May 1963.

3. Johnston, R. S., Correale, J, V., and Radnofsky, M. I.: Space'Suit Development Status. NASA Manned Spacecraft Center Report S-102, December 1965.

FIGURE CAPTIONS

1. Construction of Slip-Net Tubing
2. Geometry of Unit Structural Cells on Helically-Wound Tube with Pinned Intersections
3. Geodesically Wound Toroid
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6. Pressurized Three-Layer Slip-Net Tube Made From "Dacron" - Bent
7. Pressurized Three-Layer Slip-Net Tube Made From "Dacron" - Curled
8. Pressurized Three-Layer Slip-Net Tube Made From "Teflon" - Straight
9. Pressurized Three-Layer Slip-Net Tube Made From "Teflon" - Bent
10. Pressurized Three-Layer Slip-Net Tube Made From "Teflon" - Curled
11. Bending Test Setup with "Dacron" Tube
12. Pressurized Two-Layer Tube with "Pinch" Instability
13. Bifurcated Slip-Net Structure - 7 PSI Internal Pressure
14. Deformation of Bifurcated Slip-Net Structure - 7 PSI Internal Pressure
15. Operational Space Suit with Slip-Net Shoulder Joint - Relative Mobility Demonstration at 5 PSI Internal Pressure

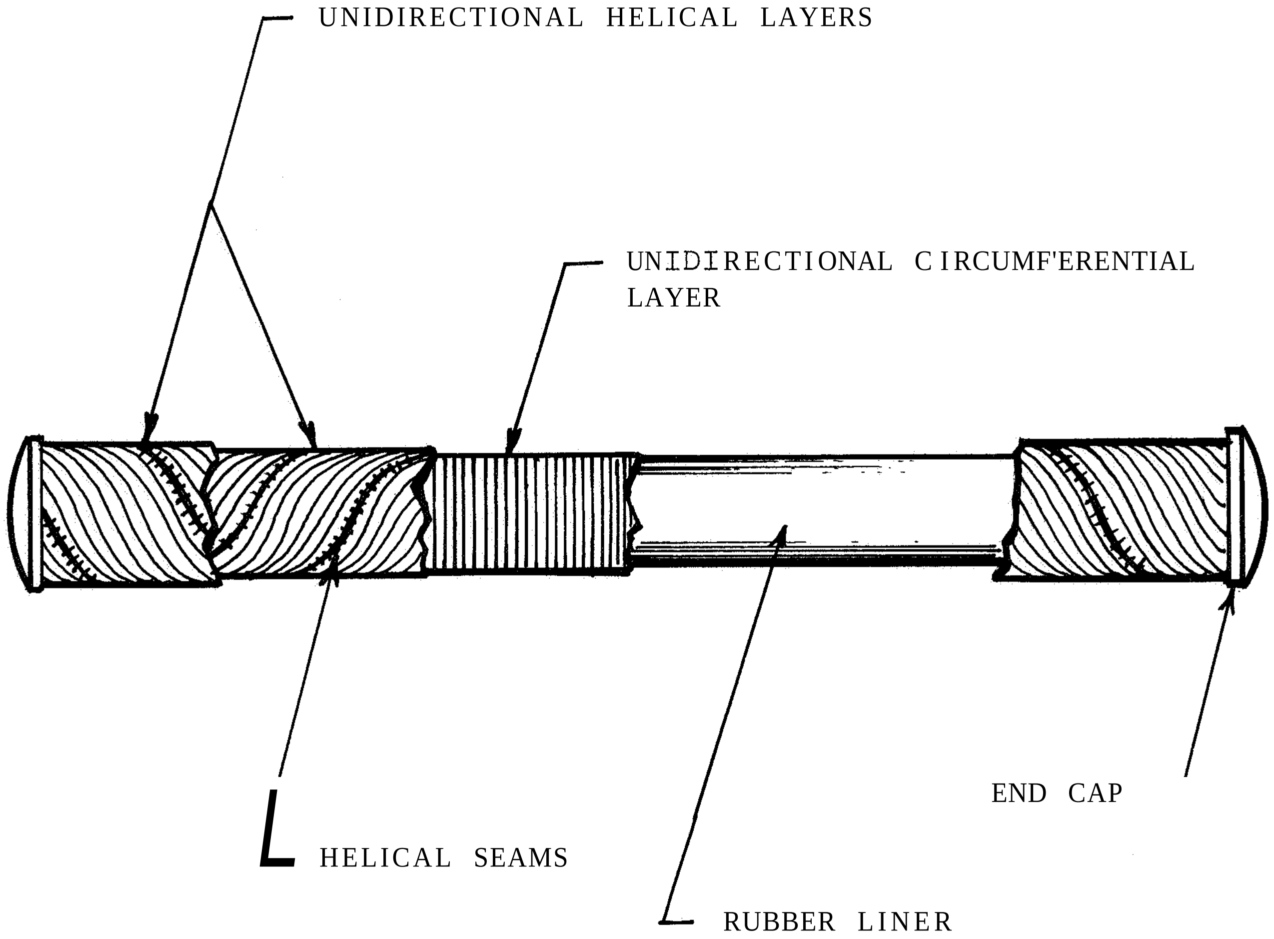

FIGURE 1. CONSTRUCTION OF SLIP-NET TUBING

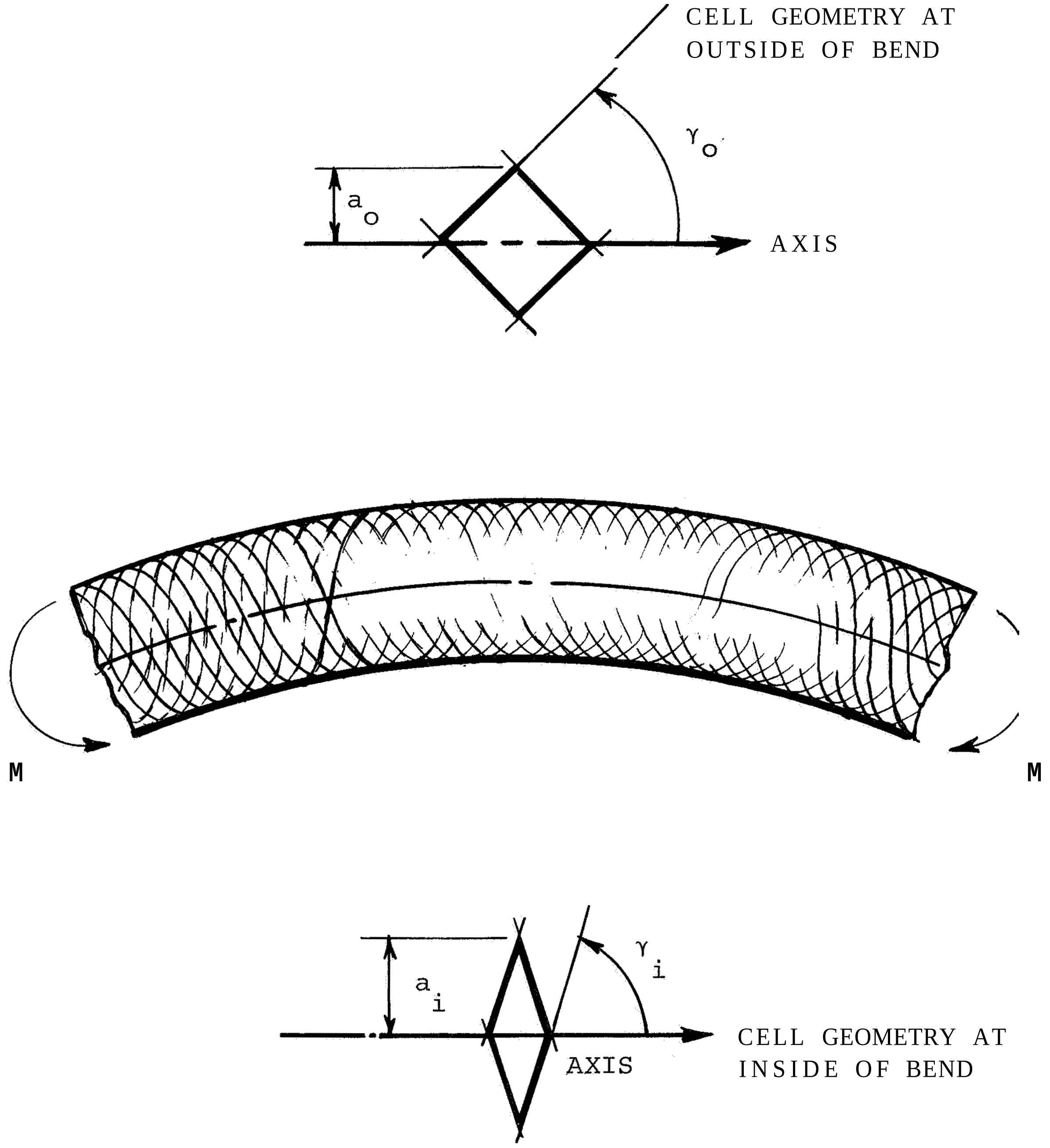

FIGURE 2. GEOMETRY OF UNIT STRUCTURAL CELLS ON HELICALLY-WOUND TUBE WITH PINNED INTERSECTIONS

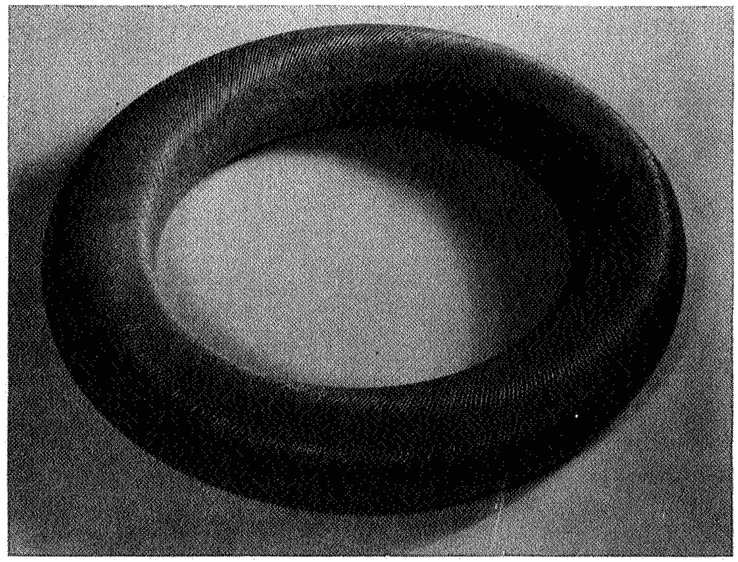

FIGURE 3. GEODESICALLY WOUND TOROID

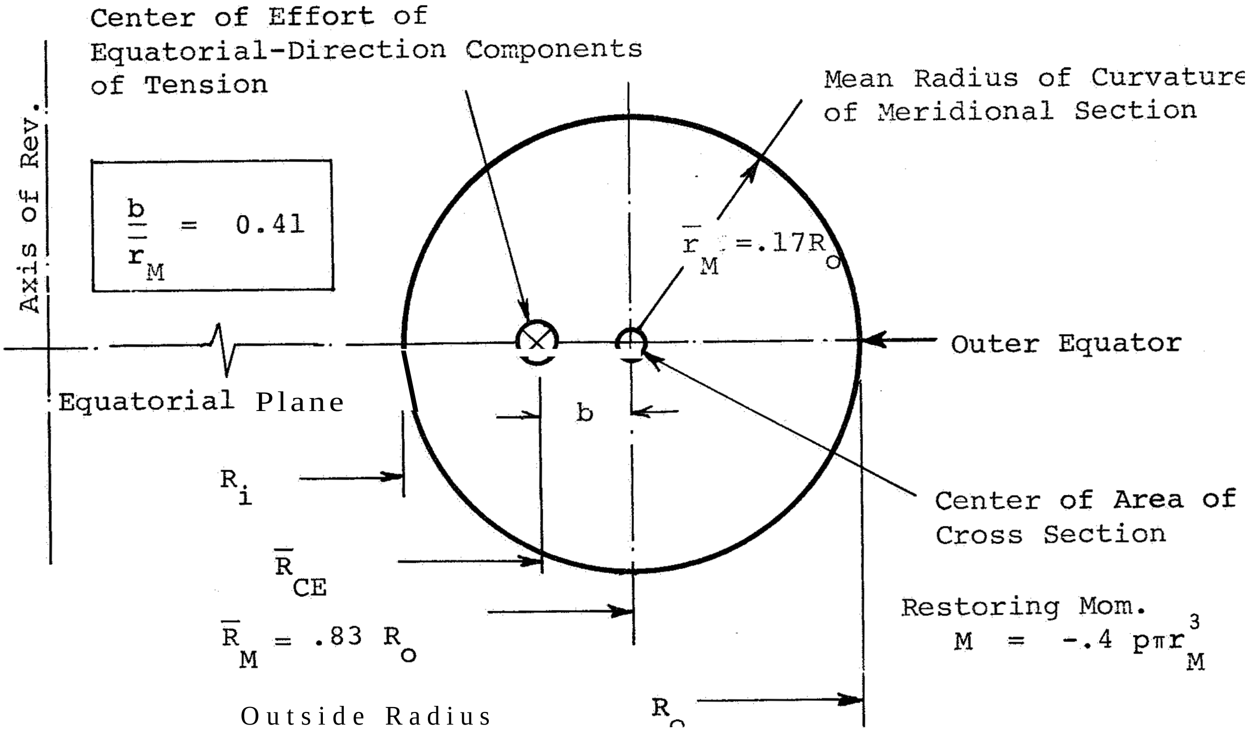

FIGURE 4. DISPLACEMENT OF CENTER OF EFFORT OF FIBER FORCES FROM CENTER OF AREA OF CROSS SECTION

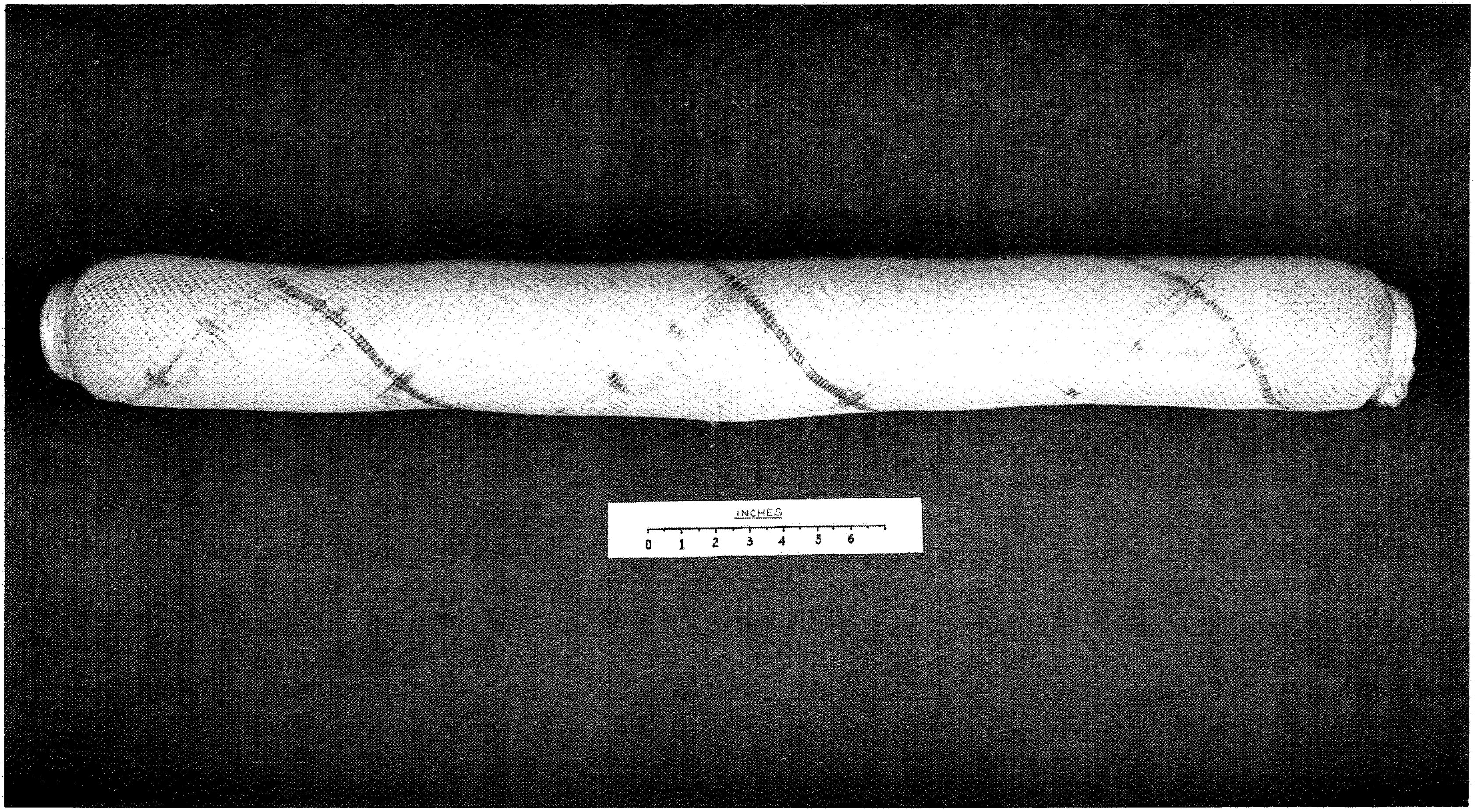

FIGURE 5. PRESSURIZED THREE-LAYER SLIP-NET TUBE MADE FROM "DACRON" - STRAIGHT

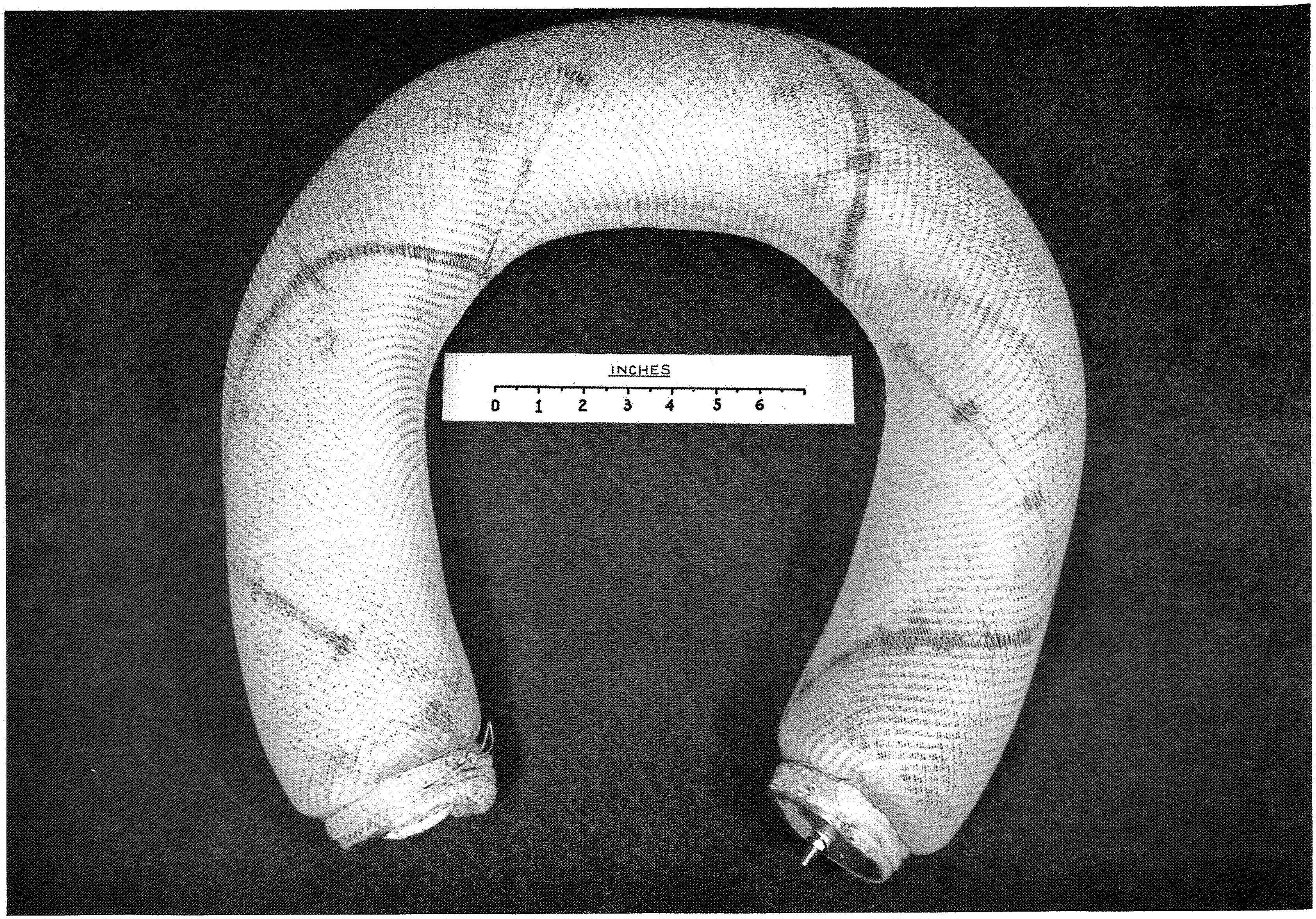

FIGURE 3 PRESSURIZED THREE-LAYER SLIP-NET TUBE MADE FROM "DACRON" - BENT

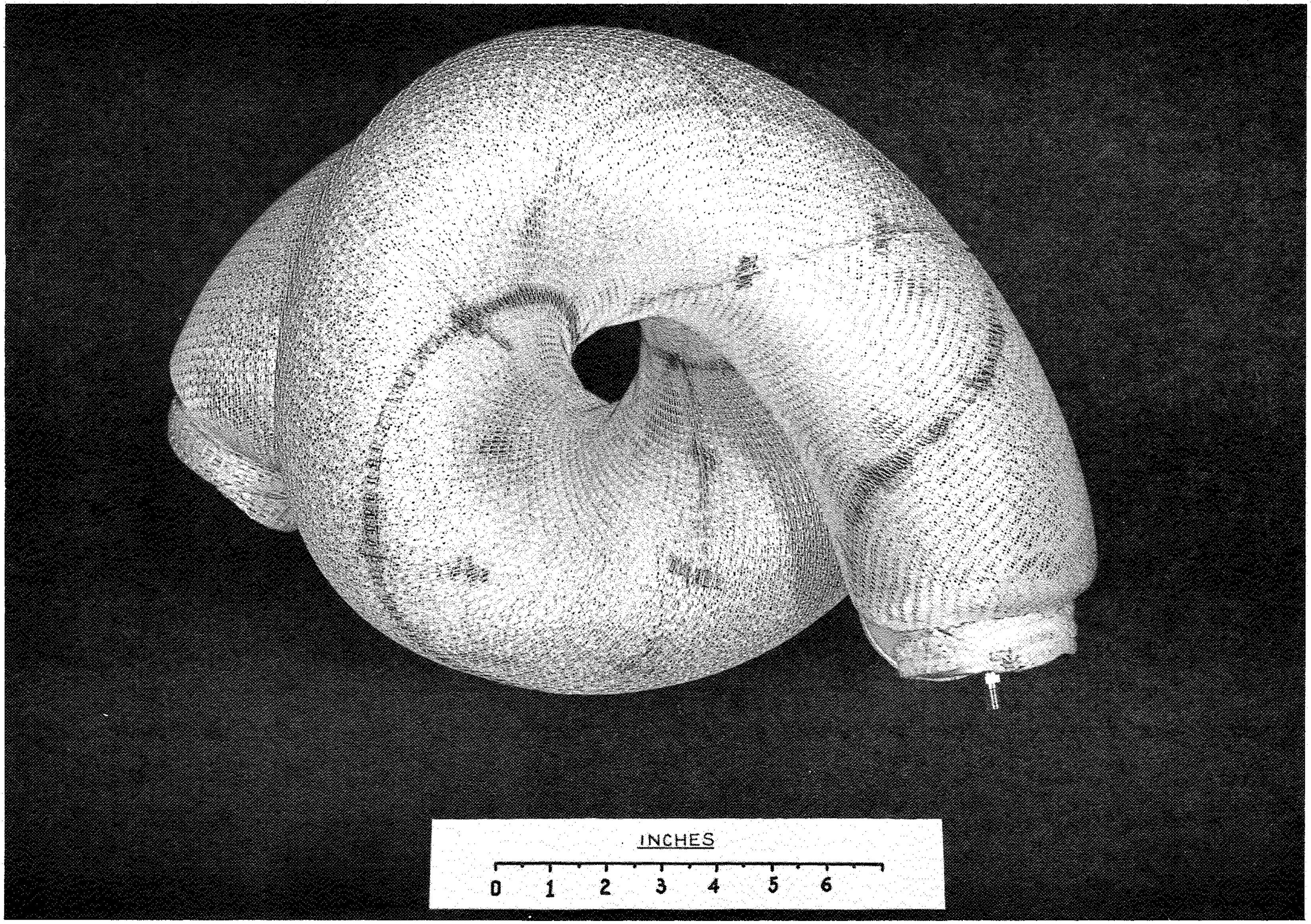

FIGURE 7. PRESSURIZED THREE-LAYER SLIP-NET TUBE MADE FROM "DACRON" - CURLED

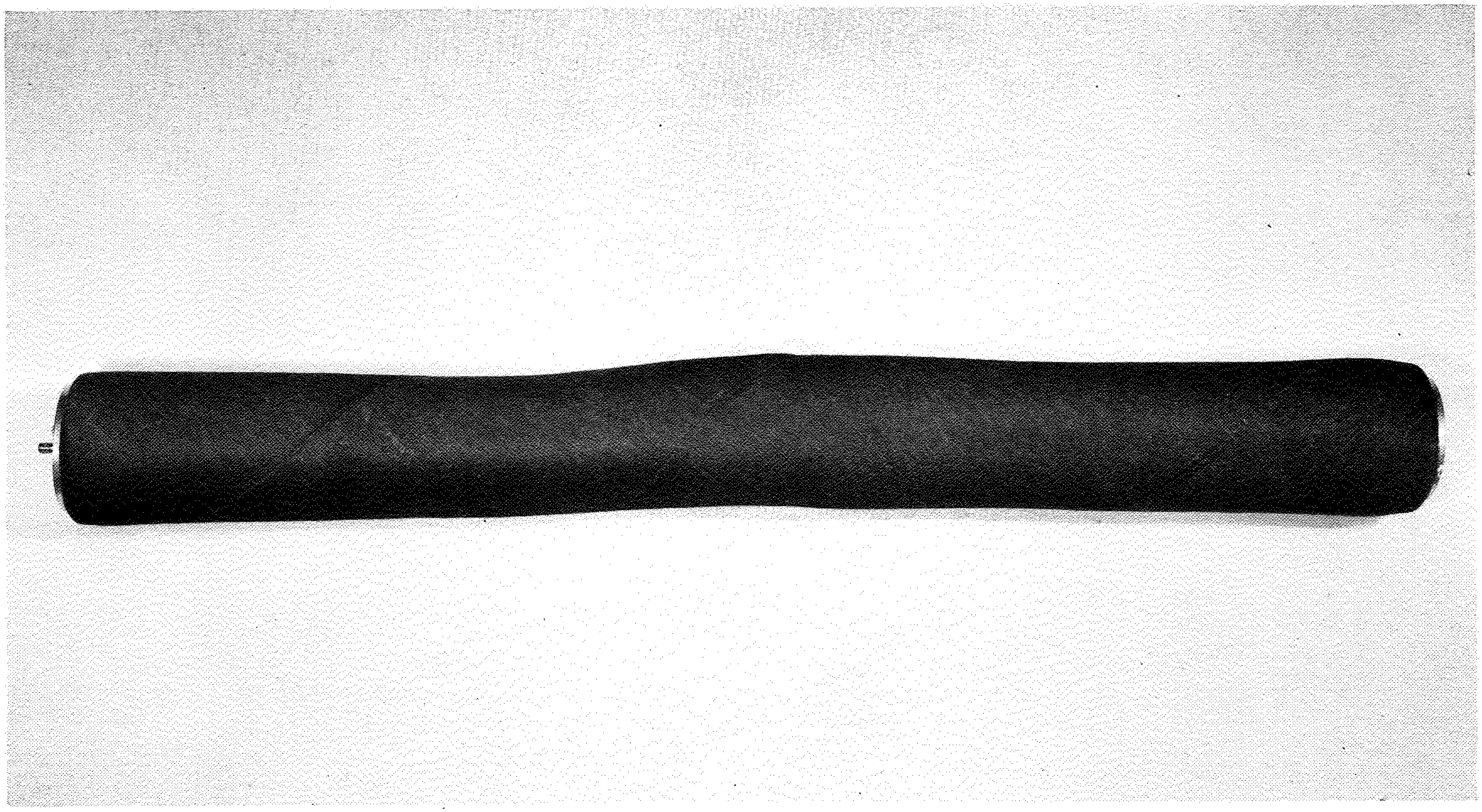

FIGURE 8. PRESSURIZED THREE-LAYER SLIP-NET TUBE MADE FROM "TEFLON" - STRAIGHT

FIGURE 9.   PRESSURIZED THREE-LAYER SLIP-NET TUBE MADE
FROM "TEFLON" - BENT

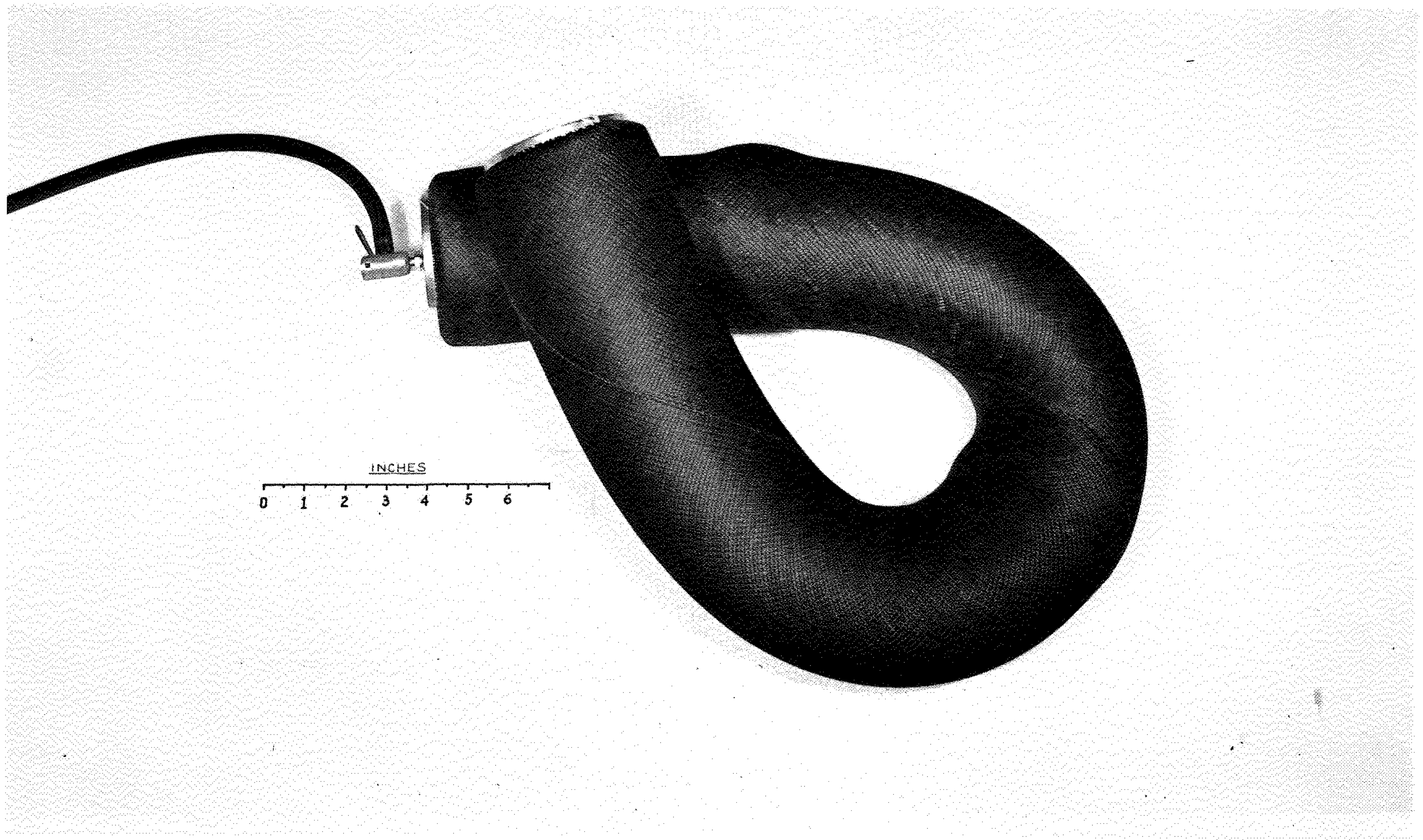

FIGURE 10. PRESSURIZED THREE-LAYER SLIP-NET TUBE MADE FROM "TEFLON" - CURLED

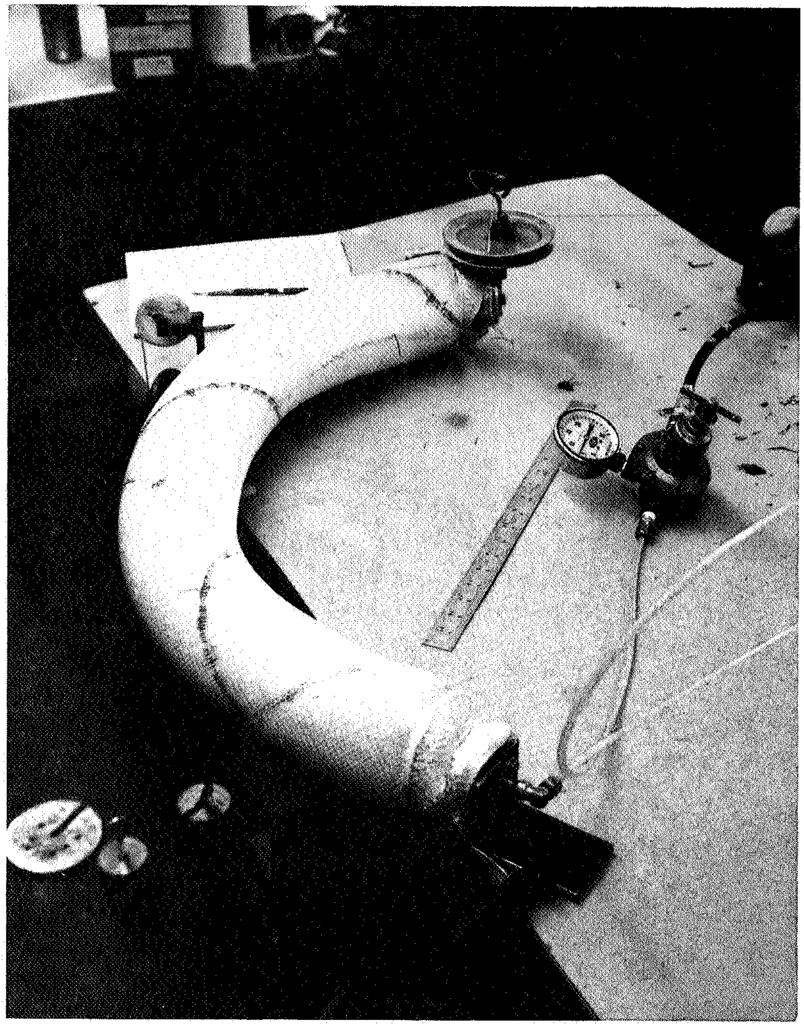

FIGURE 11. BENDING TEST SETUP WITH "DACRON" TUBE

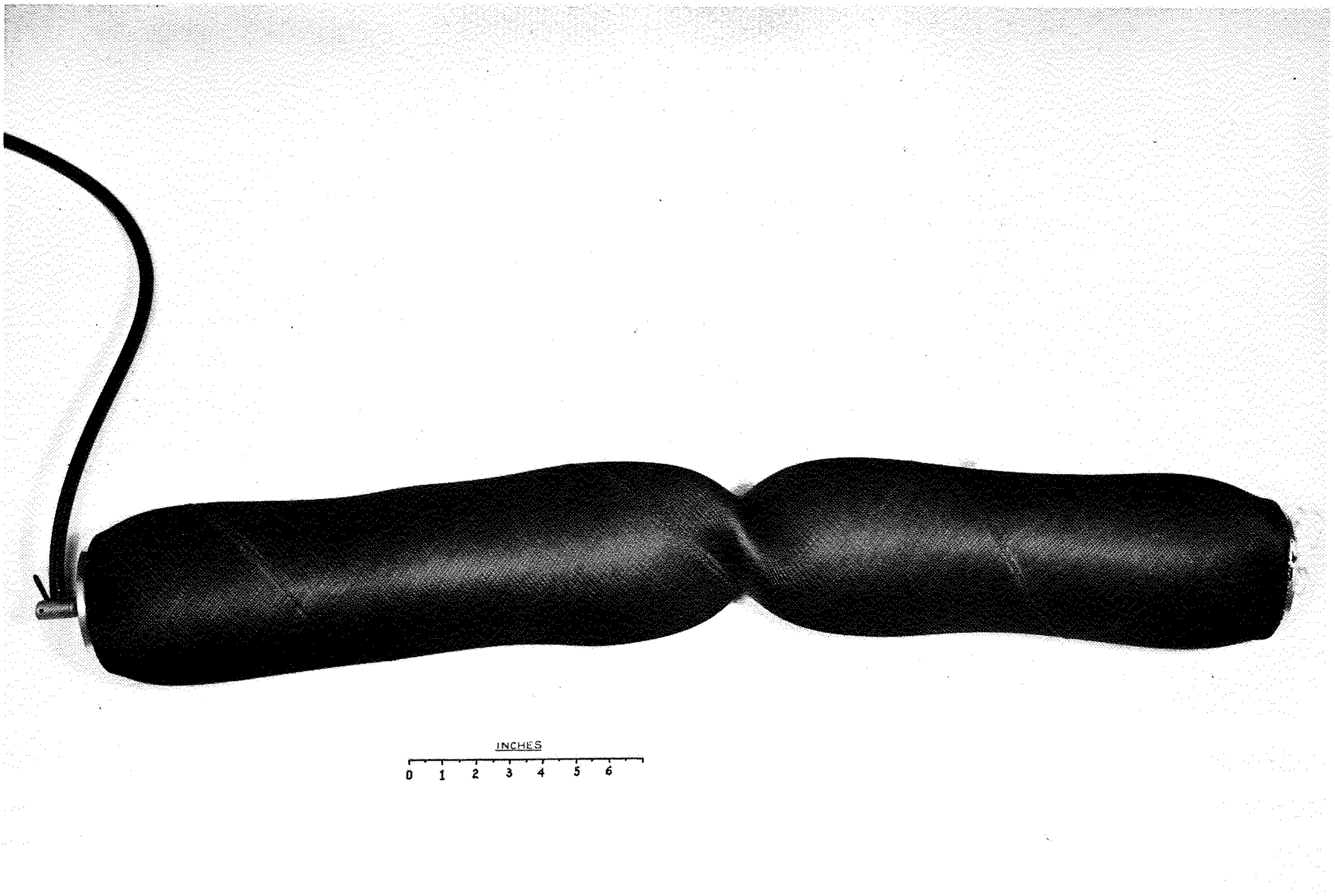

FIGURE 12. PRESSURIZED TWO-LAYER TUBE WITH "PINCH" INSTABILITY

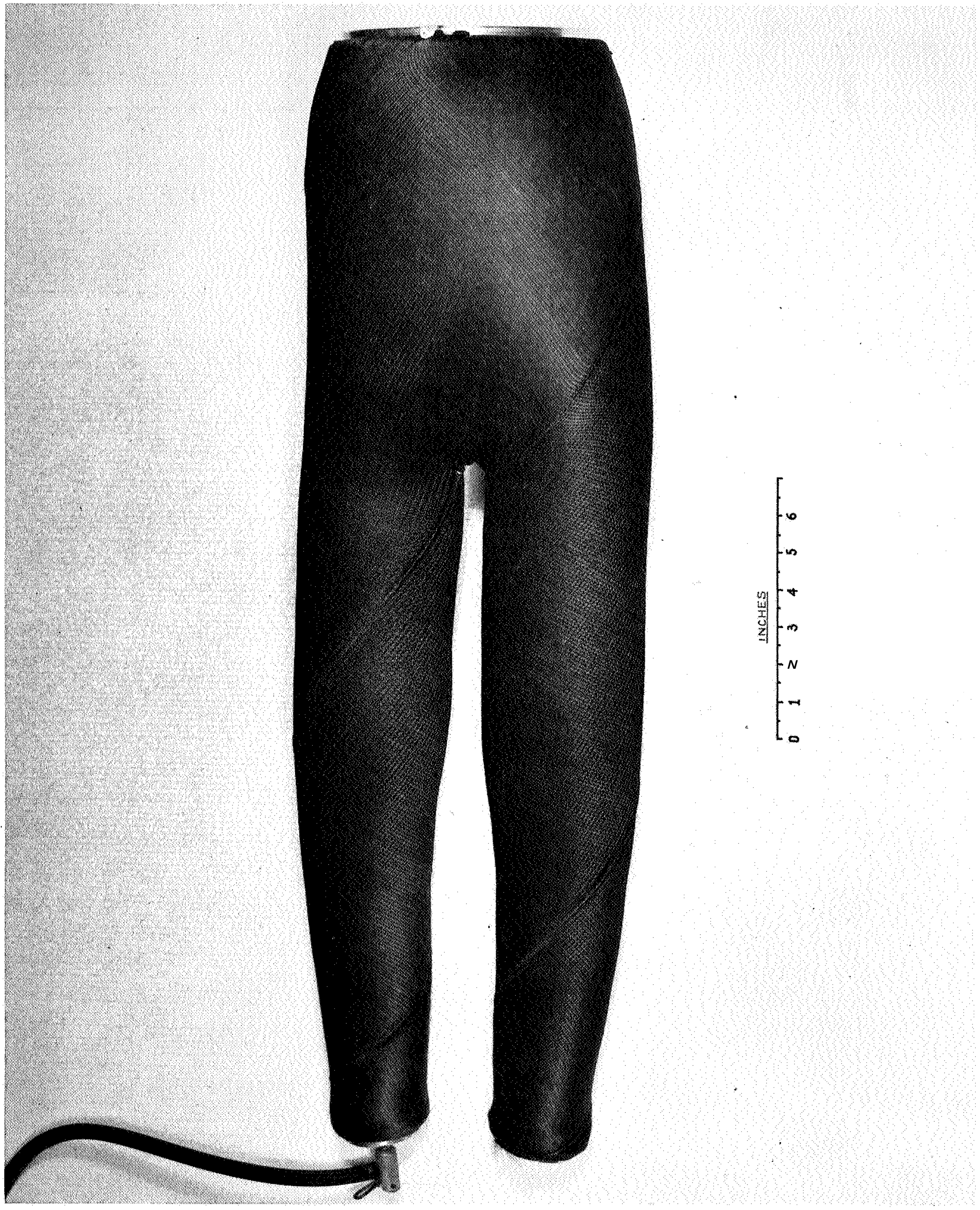

FIGURE 13. BIFURCATED SLIP-NET STRUCTURE - 7 PSI INTERNAL PRESSURE

FIGURE 14. DEFORMATION OF BIFURCATED SLIP-NET STRUCTURE – 7 PSI INTERNAL PRESSURE

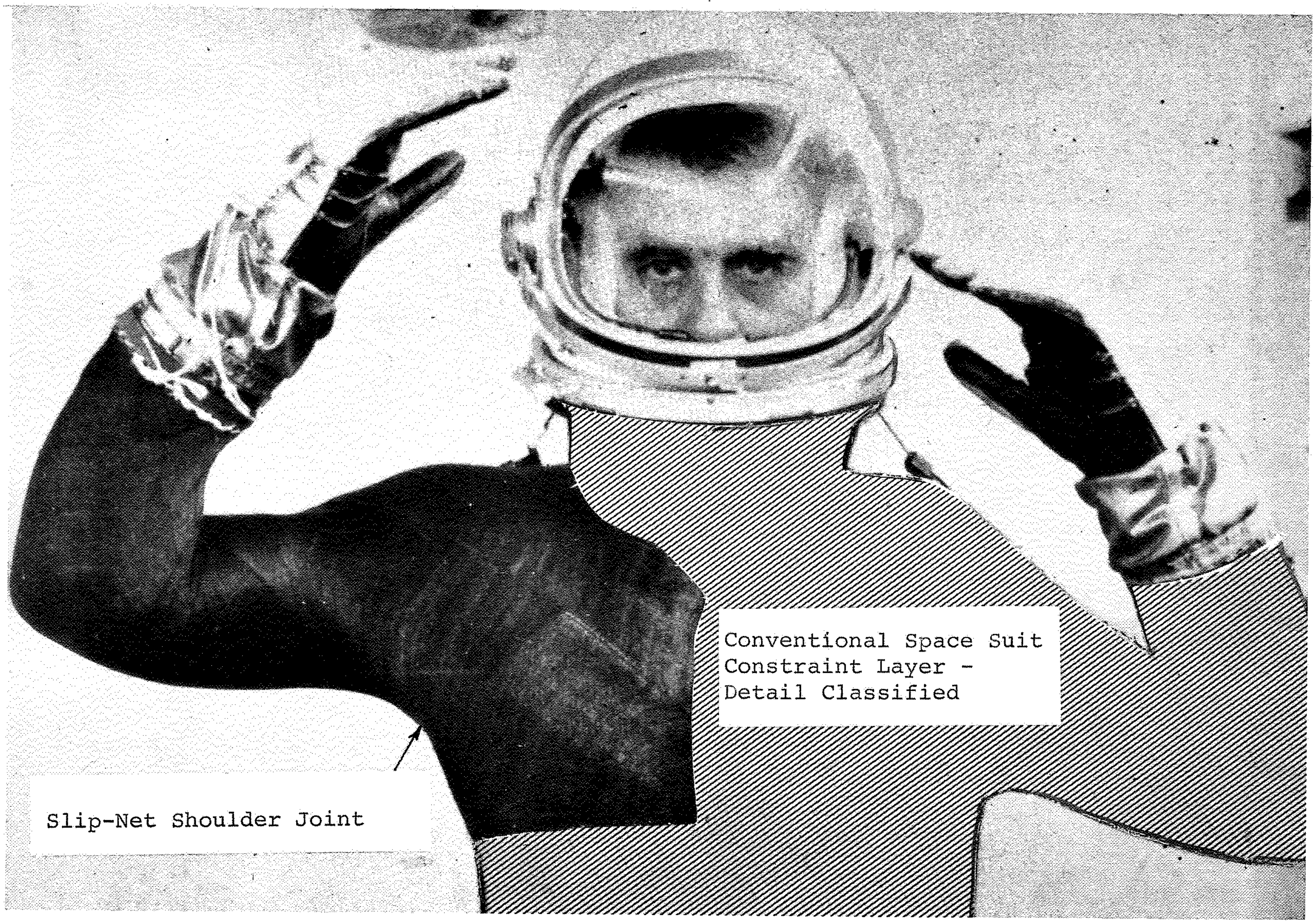

FIGURE 15. OPERATIONAL SPACE SUIT WITH SLIP-NET SHOULDER JOINT - RELATIVE MOBILITY DEMONSTRATION AT 5 PSI INTERNAL PRESSURE