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Principal Investigator: Robert B. Leighton

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ABSTRACT

Problems and opportunities are discussed for adapting certain design features and construction techniques, developed for producing high-accuracy ground-based radio dishes, to producing millimeter-wave dishes for space use. Specifically considered is a foldable telescope of 24 m aperture and 9.6 m focal length, composed of 37 rigid hexagonal panels, which will fit within the 4.5 m diameter x 18 m long payload limits of space shuttle. As here conceived, the telescope would be a free-flyer with its own power- and pointing-systems. This preliminary report considers some of the structural design features and construction procedures by which the target surface accuracy of approximately 50 μm rms might be achievable.

INTRODUCTION

The advent of space shuttle in the coming few years will bring with it new capabilities for deploying payloads of considerable bulk and weight into earth orbit relatively economically. The further capability of periodic revisitation also offers the possibility of assembling larger structures out of smaller elements or modules carried aloft in successive flights.

Large radio antennas stand out as prime examples of space structures for which a need can be clearly foreseen and for which the space environment offers unique advantages such as the complete absence of the blanketing effects of the earth's atmosphere and of the deformation effects of gravity and wind.

Several alternative methods can be visualized for erecting large antennas in space; for example: by unfurling, in the manner of an umbrella; by inflation, in the manner of a life raft; by unfolding of a number of rigid "petals" or panels, possibly braced by a number of hinged or telescoping struts; by assembly, piece by piece, out of separate component parts.

Each of these methods could be appropriate for antennas of some particular range of size and surface accuracy. In general, the first two methods would appear to be best adapted to the largest sizes, but limited to relatively long wavelengths where poorer surface accuracies are tolerable, while the last two methods would be more useful for smaller antennas of higher surface accuracy, needed for operation at shorter wavelengths. As a rough guess, the relative surface accuracy as a fraction of the diameter of the antenna probably would be limited to 10^{-3} or more for the former methods, but might attain 10^{-5} or less for the latter.

The present discussion assumes that coherent (diffraction-limited) operation is the goal for a given case. The possible use of relatively inaccurate reflectors as concentrators or "light buckets" is not considered.

In recent years a program of research and development of high-accuracy antennas ("dishes") for use in the 0.3 - 10 millimeter wavelength range has been pursued at the California Institute of Technology under NASA and NSF support. Under this program, dishes of 10.4 meter diameter have been produced whose departure from an ideal parabolic surface is approximately 25 μm (0.001 in.) rms; a surface rms of 10 μm appears within reach by straightforward extensions of present techniques. In addition to having a relatively good surface accuracy, these dishes also may be disassembled into their component panels and struts and later reassembled, without jigs or other aids, so as to regain their initial surface shapes.

As a basis for further discussion, the construction of these dishes will be briefly described.

The 10.4 meter dishes, intended for millimeter-wave interferometry, consist essentially of a large number of aluminum honeycomb panels, supported on stiff steel support frames. The support frame is a steel tubular framework with a high degree of redundancy, based upon a lattice of equilateral triangles in plan view (Figure 1). The tubes have wall thicknesses chosen to optimize the stiffness for given weight. All members are fabricated to precise, computer-calculated lengths and are assembled using close-fitting ground pins in reamed holes. This permits occasional partial disassembly and reassembly with negligible dimensional variation. At each node, all strut forces pass through a single point to avoid bending deformations which would reduce the stiffness (Figure 2).

A lattice of 84 hexagonal-shaped aluminum honeycomb panels, each about 1.15 m in size and 7 cm thick, is supported at the triangle vertices by thin, laterally flexible steel studs having differential screw-jack adjustment capability (for fine-figuring of the surface), (Figure 3). The open-celled upper honeycomb surface is machined to shape using a radially movable, template-guided high-speed cutter, and slow rotation of the mirror. During assembly and machining, the dish is supported on a large air bearing. The time required to complete a single cut over the whole dish is about 4-8 hours.

The reflecting surface is 1.0 mm thick sheet aluminum, elastically deformed by about 1 psi of external pressure to mate with the machined honeycomb surface and held in place by epoxy. The machining of the honeycomb is sufficiently accurate that no further finishing of the aluminum skin is needed; however, experience with a prototype dish suggests that a finer figure may be obtained by etching or grinding the skin after panel assembly, and this will be done on at least one of four planned dishes.

Some of the features of the construction described above are depicted in Figures 4-9.

The principal purpose of the present preliminary study is to examine possible application of the above techniques to the production of shuttle-deployable dishes of various sizes, from 10 m to 30 m or more in diameter.

Thus in the present discussion we examine the feasibility and the possible merits of one particular approach to the design, construction, and deployment of a diffraction-limited space antenna for the wavelength range from 0.5 - 5.0 millimeters. The more ambitious goal of diffraction limited operation to much shorter wavelengths such as 0.2 mm may prove feasible as experience with sequented reflectors is developed. According to that approach, the entire antenna structure would be built to the necessary precision on the ground, and would then be partially disassembled, suitably packed, launched into earth orbit, and there unfolded or reassembled.

Specific aspects of the adaptation of the present dish design that are to be considered include:

- Evaluation of automatic deployment <u>vs.</u> assembly with astronaut participation.
- Opportunities for weight reduction
- Thermal characteristics of the present dish and expected thermal characteristics of a space dish.
- Nature of the ground assembly, deployment, and test procedures to help establish and verify the procedures to be followed in zero-g.

BASIC CHOICES

Many factors and tradeoffs enter into the design of a mechanical structure for the space environment. If the structure is relatively large and yet must attain and hold a high degree of dimensional accuracy, certain of these factors are enhanced in importance. In the present case, we are concerned with the geometrical relationships of a whole large area - the antenna reflecting surface - with a single point - the focus or receiver horn. On the one hand, the stability of the optical parts must be maintained to within a small fraction of the shortest operating wavelength, while on the other hand the structure must be as open as possible toward the incoming or outgoing radiation.

Factors to be considered in attaining, regaining, and holding the necessary surface accuracy are, the basic mechanical stability and reproducibility of the proposed design concept and fabrication methods, the thermal stability, - insulation, or - compensation of the critical structural parts, the manner of packaging and method of reconstruction in orbit. Although obviously important, the choice of materials is discussed here only where a specific functional need is involved.

The essential problem is the same for all wavelengths, from about 0.1 µm near Lyman α in the far ultraviolet to at least several centimeters, namely, to provide a reflecting surface of the largest feasible size having the necessary surface accuracy of about 1/20 wavelength. However, the solution may look vastly different at the two extremes of this range, from a 2.4-meter aperture optical Space Telescope to a "parasol" radio antenna several hundred meters in diameter.

At the one limit, one clearly produces the final optical figure on the ground, probably as a single optical element, and launches the "mirror" and its supporting "tube" into orbit; at the other limit size alone, under gravity, even if air currents were unimportant, would preclude any full-scale tests of a working model on earth - one can only build the final structure in space. A millimeter-wave telescope is just at the borderline. At 0.5 mm (.020 in.) wavelength, rms surface accuracies of 25 µm (.001 in.) are needed, and one immediately thinks of mirrors prepared as integral units* on the ground; at 5 mm, with tolerances ten times looser, segmented, replicated reflectors or multi-mirror telescopes show promise.

We choose as our objective the design of the largest feasible integrated reflector having an rms surface accuracy as small as 25 µm that can be carried into orbit within the size and weight constraints of space shuttle. (Outer envelope 4.5 m x 18 m, maximum landing-weight 14,500 kg.)

Because of the relatively long, narrow shape of the shuttle cargo

*We distinguish between integral mirror telescopes, whose one or more mirror panels or segments are finished together as a single unit and need not be further adjusted relative to one another, and multi-mirror telescopes whose mirror segments are prepared individually and are later brought into alignment by suitable adjustment procedures.

space as compared to the short, broad outline typical of radio telescope reflectors; one is immediately attracted toward an array of contiguous tile-like panels of nearly the same size and shape, packed like a stack of wafers for transport, and reassembled in orbit. A foldable array of seven regular* hexagons is an obvious possibility that would yield a dish of 10 m diameter. Larger hexagonal arrays of $3n(n+1)+1$ panels, where n is the number of "layers" surrounding the central member, are also of interest (Fig. 10), as are foldable systems of radial gores.

We select for specific consideration two designs wherein the paraboloidal** surface of an f/0.4 dish is composed of 7 or 37 approximately regular hexagons, the largest of which will fit within the shuttle payload envelope diameter of 4.57 m. The assembled dishes have major diameters of approximately 10.28 m or 24.00 m, and approximate focal lengths of 4.11 m or 9.60 m, respectively.

The final design feature to be chosen arbitrarily for this discussion is the operational mode - prime focus vs. compound (cassegrain or Gregorian). We choose a cassegrain mode with an overall focal ratio of f/4.

DEPLOYMENT VS. ASSEMBLY BY ASTRONAUT

The present 10-m dish design could almost be taken over directly for shuttle launch, simply by disassembling the steel support structure into manageable sized pieces, packing the panels in foam-lined "pie racks", substituting snap fasteners for screws and washers, and providing a compressed-gas operated pin-driver to aid in reassembly of the support frame. However, several days of intensive astronaut activity would be required, and this is simply not feasible. Furthermore, the resulting dish would be far heavier than necessary.

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*Strictly speaking, hexagons that tile a paraboloid cannot be regular, but for actual cases are approximately so. In the limit of a very large number of very small hexagons tiling a spherical cap, a stereographic projection of a regular-hexagonally tiled tangent plane onto the sphere yields equiangular hexagons whose scale varies slowly with distance from the tangent point.

**To attain greater aperture efficiency, non-conic - section surfaces are sometimes used. This presents no difficulty in principle and therefore, for simplicity, a paraboloidal primary surface will be assumed.

Thus one immediately looks for ways to reduce the necessary EVA rather drastically. Fortunately, the zero-g environment will have the very beneficial effect of reducing the need for an elaborate support frame and, indeed, it should be possible to eliminate it altogether. We assume that this is done, but will re-examine the question again later.

Even so, we still face the question of automatic deployment vs. astronaut assembly for the remaining structure, which now consists of a number of panels, a pointing/control/receiver module, and the subreflector (cassegrain secondary mirror) support. With the elimination of the most complicated part of the assembly - the primary mirror support frame - and assuming a relatively small number of relatively large panels, it then seems not only feasible but desirable to avoid any need for the astronauts to handle separate pieces at all, i.e., we should seek a completely foldable structure. This is certainly possible for a 7-panel dish, and may well be possible also for a 37-panel one.

In the remaining discussion, we shall place great weight upon the desirability of a completely foldable structure. However, the possibility of astronaut participation in the unfolding process is kept open, for it seems clear that a limited amount of astronaut EVA may avoid the need for a very costly, highly sophisticated, fully automatic operation. Astronaut participation would be especially valuable in the areas of:

1) Verification of satisfactory completion of each successive step of a sequence of semi-automatic steps.

2) Initiation of the successive steps, possibly by manual actuation of release latches.

3) Observing an operation at close range, and manually facilitating it where necessary.

4) Close-range inspection and evaluation of the whole structure at any given stage of the operation.

5) Performance of operations that are undesirable or impractical to automate, or which require judgement based on existing conditions.

The tentative conclusion, to be adopted for the purposes of the remaining discussion, is that even a rather complex folded dish structure may be unfoldable essentially automatically, but that limited astronaut participation is probably desirable and may be necessary.

WEIGHT CONSIDERATIONS

In the preceding discussion it was noted that the need for a support frame like that of the 10.4 dish should be greatly reduced in a zero-g environment and that it might be completely eliminated. The dish would then consist essentially of a number of contiguous hexagonal panels joined at their vertices or along their common edges, plus some sort of multi-pod support for the secondary reflector. The conventional support frame behind the dish could certainly be eliminated if the secondary support in front were appropriately augmented so as to perform some of the stiffening function normally provided by the rear structure, without also introducing undue loss of aperture efficiency. We shall pursue this line of approach.

One can now consider the weight question in two more-or-less separate parts. First, since the size of a hexagonal panel and its points of support are essentially known, one can investigate what factors in the fabrication process, the subsequent handling and delivery into orbit, and the operational use of the dish, determine the optimum panel structure as to overall thickness or depth, skin thickness, etc. Second, having approximately defined the panel characteristics, the corresponding characteristics of the secondary support truss needed to further stabilize the multi-panel dish and provide secondary support can be treated.

As to overall thickness of a panel, it is essential to avoid wrinkling effects due to bending or plane shear in the panel during fabrication, launch, or use, and of course the panel skin should not buckle during normal handling of a panel. These requirements will normally be at least marginally met if the panel skin is thicker than about 2% of the typical maximum unsupported dimension and the panel thickness is greater than about 2% of its major diameter. Thus if the cell size of a honeycomb core supporting the panel skins is 1 cm, the skin should be thicker than about 0.2 mm, and the thickness of a 4-meter diameter panel should be greater than $0.02 \times 400 = 8$ cm. As preliminary values we double both of these figures to allow a reasonable safety factor.

With these values we find the frontal area density of a panel to be $3 \times 0.04 \times 2.7 + 16 \times .064 = 1.76$ g/cm^2 (3.62 lb/sq ft) or 220 kg/panel 484 lb) assuming aluminum honeycomb core of average density .064 g cm^{-3}

and aluminum skins. With graphite-epoxy skins a small weight saving will result; aluminum honeycomb is the core material of choice for maximizing the face-to-face thermal conductivity. Graphite-epoxy skins are preferred for light weight, high Young's modulus, and low thermal expansion coefficient.

The frontal area densities given are about one-third that of the existing 10.4 m dish, but several times that of single-dish space antennas of 3-4 m diameter, so that there is clearly room for further weight reduction through a more careful consideration of panel design. However, even with these values the approximate total weight of a seven-panel dish would be 1540 kg, and of a 37 panel dish, 8140 kg. Since the latter value is well within the 14,500 kg landing-weight limit of shuttle, and allows more than 6,000 kg for the remaining components, which seems adequate, we shall not pursue the matter of weight reduction further at this time. Our main present concern is simply with the feasibility of the general approach rather than with the ultimate possibilities of weight reduction.

THERMAL CHARACTERISTICS

The 10.4 m ground-based dish, composed of aluminum panels supported by a steel support frame, might appear to be highly susceptible to thermal distortions due to the different expansion coefficients of these two materials. Indeed, over the approximately $\pm 30^{\circ}$ C temperature range between the extremes of winter and summer, a total differential expansion of about $\pm$ 1.8 mm exists from center-to-edge of the dish due to this effect. However, none of this appears as a distortion of the dish surface away from a parabolic shape, because of the lateral compliance of the thin panel support rods. (Since these rods are perpendicular to the paraboloid surface, their bending leads to no first-order component perpendicular to the paraboloid.) Of course, the expansion of each panel, and of the whole steel support frame, does lead to two new paraboloids having focal lengths which are changed by the same fractional amounts as are the dimensions of the corresponding members themselves. Thus, the aluminum panel focal lengths change by approximately $\pm$ 1.5 mm and the steel support frame equivalent "focal length" changes by about $\pm$ 0.8 mm. The net effect is equivalent to each panel acquiring a small "scallop" curvature whose sagitta is about $\pm$ .01 mm or $\pm$ .0004 in.

As discussed previously, a space dish would probably need no support structure similar to the steel frame used on the 10.4 m dishes, but any other such structure, such as a modified secondary-reflector support, should be designed with some care so as to avoid differential thermal effects which would lead to distortion of the dish surface.

Of far greater significance in terms of thermal distortions, for the 10.4 m dish, are temperature differences between various support frame members due to oblique solar illumination. If the temperature rise (above ambient air) of a member due to normally incident sunlight is ΔT_o, then the temperature rise of a member which is obliquely illuminated at an angle α away from a plane normal to the member is very nearly $\Delta T(\alpha) = \Delta T_o \cos \alpha$. Thus the side-illuminated dish tends to expand into an elliptical paraboloid whose major diameter is perpendicular to the direction to the sun.

If some of the struts are in sunlight and others are in shadow, more complicated changes in dish shape will occur, but generally these will not be greater than the anisotropic expansion just discussed.

As to the magnitude of the effect, careful attention to the thermal reflecting and emitting properties of the paint used to coat the members leads to values of ΔT_o of approximately 3^o C. The extreme difference in radius (for fully broadside illumination) is thus about 0.4 mm (major axis-minor axis), corresponding to a whole-dish rms surface distortion of about 0.12 mm.

In space, solar illumination effects are potentially much more serious unless they are carefully controlled by using low-expansion-coefficient materials, sun shields, restricted allowable pointing directions, or active temperature control.

Specific measures which should reduce the magnitude of the problem include:

1) The use of graphite-epoxy for at least the most sensitive elements such as panel skins and support frame struts. Graphite-epoxy laminates can be fabricated so as to have either positive or negative temperature coefficients, and coefficients smaller than 1/10 that of aluminum are easily attained.

2) The use of aluminum honeycomb as a core for the panels, to attain high thermal conductivity and rapid thermal equalization between the two outer faces of a panel. By this means, thermal distortion

of a panel heated on one side can probably be held within tolerable limits even if only part of a panel is in sunlight and part in shadow.

3) The use of a cylindrical sun shield of thin aluminized plastic film supported on light, longitudinal ribs. This could help stabilize the thermal environment and would permit the antenna to operate over a larger range of pointing directions.

4) Judicious use of reject heat from power generation (solar cells or RTG), perhaps via circulation of warm gas through a vascular network, might provide a practical means of temperature control of the antenna system.

5) Combined with some of the above, the use of insulating blankets and radiation shields can greatly reduce heat loss and promote temperature uniformity.

To summarize, the worst effects of the thermal environment on a space antenna can be minimized by a) using low-thermal-expansivity materials, b) avoiding differential-expansion (thermal bending) effects by minimizing thermal gradients and using materials all having the same expansivity.

SPECIAL DESIGN FEATURES

The general features of a satisfactory high-accuracy space antenna as discussed above can probably be realized in many ways. The purpose of this report is to present the principal features of one possible way. This particular design is based closely upon experience with the 10.4 m dishes described earlier, and can probably be regarded as practically achievable by existing techniques or straightforward extensions thereof. Because of the close relationship of the design to the manufacturing methods for realizing it, both the characteristics of the dish structure *per se* and the construction and measurement techniques for producing it will be discussed together.

The present report constitutes simply an initial sketch or outline of the subject, and is thus quite incomplete and preliminary. However a number of the most critical factors are discussed, even though briefly, and it should be possible to proceed directly toward a specific design suitable for detailed analysis and thence prototype fabrication. Because of the brevity and incompleteness of the presentation, the topics that are covered in this section are outlined below.

I. General dish design features

   A. Hexagonal array of hexagonal panels

   B. Foldable; offset hinges; corner fasteners

   C. Panels

      1. Dimensions and geometry

      2. Graphite-epoxy skins on aluminum honeycomb core

         a. Bottom and center skins

         b. Top skin

      3. Hinges and folding

         a. Geometry of folding

         b. Rigid or flexible hinges

      4. Fasteners

         a. Neutral-surface location

         b. Coplanar ball-and-sockets or edge-mating fasteners

         c. Mechanical <u>vs.</u> magnetic latching

         d. Stress-free attachment

II. Tooling and construction techniques

   A. Air-or-oil bearing

   B. Cutter guide-track girder

   C. Machining-support frame

      1. Provision for panel flotation

      2. Provision for rigid panel support during cutting operations

      3. Need for 3 fixed reference points

   D. Machining operations

      1. Initial setup

      2. Rough cuts

      3. Final cuts

III. Measurements; adjustments; accuracy

   A. Cutter track adjustment

   B. Air-bearing adjustment

      1. Planeness

      2. Levelling

      3. Lateral positioning

C. Panel top-skins

1. Material
2. Fabrication
3. Attachment

D. Final surface figure measurement and correction

IV. Attachment to feed-support superstructure

V. Packaging for transport and launching

VI. Tests of panel deployment

A. Ground

B. Space

I. Dish Design

As previously discussed, the dish design is based upon the concept of an integral unit composed of 7 or 37 separable hexagonal panels fastened together at their corners, machined while fastened together and later disassembled and packaged for delivery into orbit where they would be unfolded, reattached together, and attached to suitable other component structures to form a complete free-flying radio telescope. The case of 37 panels will be specifically discussed. A 7-panel dish will be recognized as a simpler case which would be easier to produce, and which might constitute an appropriate and useful initial instrument.

For simplicity, the panels are assumed to be quasi-regular hexagons of roughly equal size and of uniform thickness. The panel array is to be unfoldable in orbit, and re-foldable for possible return to earth. Foldability into a tall stack of wafer-like panels is accomplished by sets of offset hinges which sequentially pivot four to six of the panels ("petal" panels) surrounding each of a number of "core" panels into a sequence of equally-spaced positions behind the core panel, in a manner indicated in Fig. 11, and by special virtual-axis hinges which arrange the sub-stacks into the final, total stack, as shown schematically in Fig. 12. A possible overall hinging arrangement is shown in Fig. 12: In the final packing arrangement the center panel is at one end of the stack, in its original, "forward"-facing orientation; each of the other "core" panels also faces forward. The majority of the panels face "backward", in sequences of four or five, behind each "core" panel.

The center panel is a regular hexagon approximately 3.80 m in minor diameter and 4.39 m major diameter, allowing a radial clearance of 9-39 cm to the 4.57 m limiting payload diameter. The remaining panels are of five different shapes, one of which occurs in both a right- and left-handed version; these are all approximately regular hexagons and diminish in size with increasing distance from the center: The outermost panel is about 92% as large as the center one.

The concave reflecting surface has a focal length of 9.60 m and a central radius of curvature of 19.20 m, which corresponds to a sagitta (curve depth) of 13 cm for the center panel.

The choice of a flat <u>vs</u>. convex rear face (to give a constant panel thickness) rests upon considerations of weight, volume (i.e., nestability for stacking) and cost of manufacture. Matching curves on rear and front faces would save about 25 kg of weight per panel and reduce the stack length by almost 4 meters. On the other hand, curved graphite-epoxy skins and honeycomb cores might be considerably more expensive to fabricate than flat ones. The choice may also depend upon the method used to produce and apply the reflecting sheet material (the "top-skin"), which will be discussed below and again later under outline topic III-C.

According to present practice, the panels are constructed using <u>three</u> thin sheets or skins rather than the two that are used for ordinary honeycomb sandwich panels. This is so that a panel will be sufficiently rigid as to be self-supporting during machining, since the top skin is not yet present at that time. The bottom skin and the "center skin" are merely structural members and need not be made to very strict tolerances as to thickness. The top skin, on the other hand - again, according to present practice - serves partly as a structural member but, more importantly, it provides the actual reflecting surface of the dish. As such, its outer concave surface is the one whose actual shape is of interest. The rms surface fluctuations will include terms both for the machined honeycomb surface and for the thickness variations of the top skin sheet. The top skin must therefore either be fabricated initially so as to have suitably small thickness fluctuations, or must be itself readily machinable (or otherwise correctable) after application. This is a very important matter which will need considerable attention, particularly at the laboratory and shop level, before the actual panel construction can be fully defined.

The total panel thickness at its center will probably be in the range 10-20 cm, with 2/3 or more of this falling between the bottom and center skins, and the relatively small remainder between the center and the top skins.

The panels should be relieved around their perimeters at the rear so as to leave a relatively thin rim around the front edge, to provide working space for hinges and corner fasteners, and clearance for unfolding. (See Fig. 13)

Each "core" panel has four to six sets of hinges, of progressively greater axial offset as one proceeds around or across the panel. These hinges are built into the panels so as to provide the necessary kinematic guidance during unfolding, and to carry the stresses generated in the process. For the case of a single "petal" panel unfolding about its core, those stresses will be minimal. However, for those cases where a panel is hinged to <u>two</u> core panels, the stresses may become quite appreciable, particularly if a significant impact occurs as this "bridge" panel comes to its final position. This is because such a panel is attached to two quite large and massive structures - the part of the dish so far unfolded, and the part yet to be unfolded, plus the remaining components.

This raises the question whether the hinges, particularly those attached to a "bridge" panel, should be rigid or flexible. If the hinges are rigid, they might also function to preserve the local alignment of the panels in the fully deployed dish. But in this case, very high stresses could occur as panels seat together unless unfolding speeds are held very low and energy-absorbing bumpers are provided. Thus one thinks of using relatively flexible hinges, and providing other means for defining the local alignment of panels. In the remaining discussion it will be assumed that the hinges, whatever their degree of rigidity or flexibility, <u>do not</u> perform a primary panel-alignment function as well, but that this is provided by fasteners at each corner or along the edges of a panel. We next discuss these fasteners.

The complete dish will have a considerable total depth, and if it were a single, unjointed dish having the 10-20 cm thick honeycomb construction discussed above for panels, would possess considerable rigidity just because of its compound curvature: It would be a shell rather than simply a flat plate. Ordinary egg shells and incandescent lamp bulbs provide impressive examples of the strength and rigidity of thin-walled shells. Evidently, such a shell derives much of its effectiveness by converting local normally-applied loads into <u>plane</u> stresses at a distance from the load, rather than <u>bending</u> stresses. The elastic properties of a thin-walled, open-ended cylinder as compared to a sphere of the same radius and wall thickness, with respect to point-loads applied across a diameter, are spectacularly different because the cylinder is substantially in bending at all points, while the sphere is substantially in bending only near the application points of the load. Thus we try to preserve this important property of a compound-curved shell in attaching the panels to one another.

For highly curved shells the conversion from local bending to plane stress takes place within a few shell-thicknesses of a load point, so that a paneled dish can evidently attain much of the rigidity of a seamless shell if the corner fasteners are very stiff in the plane of the panels, i.e., the fasteners must be able to communicate plane stress between panels with minimal deflection. By properly choosing the plane in which the attachment point lies with respect to the thickness direction of a panel, one can avoid the reintroduction of unwanted local bending deflections.

Thus we arrive at the following concept: At each of the mating edges or corners of a panel there is built into it a relatively thin, flat plate. All plates of a given panel are coplanar, and this plane is chosen so that forces in the plane, applied along an edge or at the corner points, introduce a minimum of bending into the panel. In terms of the neutral surface of the panel cross section (analogous to the neutral axis of a beam in bending), the attachment plane will intersect the neutral surface about 1/3 to 1/2 way from the center to the edge of the panel. The precise location must be determined so as to optimize the overall dish rigidity including the effects of the front support frame. Assume the plane is suitably determined.

As a specific example that might provide a sufficiently rigid joint, a ball-and-socket system of corner fasteners will be described. Model tests should be made to determine whether corner - or edge - fasteners are more satisfactory.

The three plates at a given vertex where three panels meet will all intersect at this vertex. Let a solid sphere be attached to one plate such that the sphere is centered at the common point, and let hemispherical cups be attached to the other two plates. By suitably cutting away the plates and shaping the spherical cups, a joint will result that is very rigid for forces in the plane of the plates, and very compliant with respect to torques about the common point, i.e., the relative positions of the vertex point of three panels will be rigidly defined spatially, but not rotationally, just as is in fact desirable. A schematic sketch of such a ball-and-socket joint is shown in Fig. 14.

Thus this design includes such joints at each panel corner intersection, with the ball and the two sockets attached to the panels in a way that is dictated by the panel unfolding order: The first panel to "arrive" at a given vertex generally carries a socket, the second a ball, and the last a socket. In some cases the first panel might carry a ball (if the second and third panels arrive from opposite directions).

An alternative system in which the adjacent <u>edges</u> of <u>pairs</u> of panels are fastened together can be developed along analogous lines. In that case only two mating elements, a "top" and a "bottom", would be required. Each panel would be provided with appropriate "top" and "bottom" elements, fully joined, at the time of manufacture, as described below for the example of ball-and-socket fasteners. The edge-mating joints would probably provide greater rigidity to the overall structure, but might be more difficult to provide for proper clearances during deployment. The edge-joint would have to be rigid and kinematically defined in all directions in order to fulfill its functions. It could consist of a single, long toothed strip extending along the entire edge, a series of shorter strips interrupted as required for clearance, or even a series of ball-and-socket joints like those described here.

The joint, whatever its nature, requires some method of latching or tying it together. Whatever method is used must be neutral, or at least uniform, in its elastic effects perpendicular to the plates that comprise the joint (compression of ball or sockets, bending of plates) since that is the direction in which the dish surface deformations are to be minimized.

Two latching methods have been considered. In the first, one socket would have a threaded hole and the other a loosely captive screw and a self-aligning washer. The ball would have an oversized hole through it.

When the three parts were mated, a 1/4-turn of the screw would lock them together. In the second method, each socket would contain a strong magnet and the ball would be of iron or steel. A magnetic force of only a few kilograms perpendicular to the plates would maintain the joint against many tens or even some hundreds of kilograms in the plane of a plate. A release cam or screw would permit breaking the magnetic circuit for refolding when necessary, and could be built so as to serve as a backup mechanical latch for the joint. A lineas edge-joint could have a series of such self-aligning latches along its length.

The fasteners obviously play a central role in defining the large-scale surface shape of the completed dish, and therefore must carry the same stresses in space as they did while the dish was being fabricated on the ground. It is clearly desirable that this stress be very small in both cases. Thus it is important that the panels be individually supported, each independently of the others, up to the time when the final machining is done. Just prior to that time the joints should be "rigidified" in a stress-free condition, probably by the use of a low-distortion potting compound or adhesive system, perhaps augmented by screws or pins applied after the adhesive has set and before the final machining has begun.

II. Tooling and construction

In this section are described some of the more important features of the tooling needed to produce a large integral dish, and techniques used in the fabrication of the dish itself.

Fundamental to the method is a plane air- or oil-lubricated bearing of sufficient size as to carry the load and enable the dish and its supporting structure to be rotated smoothly and accurately about a fixed vertical axis. For the 10.4 m dishes, an air bearing 10 ft. O.D., 8 ft. I.D., composed of two similar hollow rings 10 in. high, is used. The lower ring carries air at 10 psi and delivers this air to the plane flotation air gap through approximately 200 small orifices in the lower ring's top surface. The air film is approximately 0.001 in. thick. The top ring is held in place against lateral forces by four cam-follower ball bearings mounted on brackets attached to the lower ring and rolling on the machined cylindrical outer edge of the lower face of the upper ring. These bearings can be adjusted to fix the axis of rotation at the desired lateral position.

The lower air bearing ring is solidly supported at three points by simple levers of 10:1 ratio, with fine-thread screws at their "handle" ends. By means of these screws the bearing can be leveled so as to render the rotation axis vertical to within about 1 arc second. (See Fig. 9)

Because of the finite stiffness of the air bearing rings, the lower ring sags somewhat between the three support points. Similarly, the dish frame, supported at three points on the upper ring, bends the ring and causes an azimuthally non-uniform load distribution around the rings. This in turn gives rise to small fluctuations in both the vertical height and the axial tilt of the dish. To minimize these effects (which are in any case mappable and correctable in the 10.4 m dish) the lower bearing ring is supported on pre-loaded springs at several intermediate points. This matter is mentioned so that it may be avoided in designing the flotation bearing for a space dish.

The air bearing is rotated by a small variable-speed gear motor through a rubber-wheel drive. The drive seems somewhat sluggish but is easily overridden by hand, which provides a certain safety factor during cutting and measurement operations.

Permanently mounted over the air bearing is a large, stiff, built-up girder beam which extends from the central axis to the dish outer edge and somewhat beyond and which carries two accurately ground guide tracks of cross section 0.500 in. thick by 8.000 in. wide. (See Figs. 4-9) The top of the girder is straight and carries the so called "top track" which is adjustable by pairs of push-pull screws to be straight and level within a few micro-meters along its entire length. The bottom of the girder is curved and carries the "bottom track" which is similarly adjustable to render it into the curve needed to generate the desired surface shape, in this case a paraboloid. The bottom track also is adjusted to within a few micro-meters of the desired curve. The means of measurement will be described later.

A massive carriage called the "cutter cart" rides on the bottom track, supported vertically by three low-friction plastic, ball-jointed "feet", and laterally by four of the same, so that any particular point of the cart follows a definite, accurately repeatable path as the cart slides along the bottom track (Fig. 6).

Locomotion of the cutter cart is by a variable-speed gearmotor cog-wheel drive, engaging a toothed rack attached to the bottom track. Means are provided for the cutter cart to move radially along the track in incremental steps between fixed "stations" a few inches apart, when triggered by a switch closure.

The cutter motor and cutter are shown in Fig. 6. The 8-inch diameter high-speed tool steel cutter blade is flat on its bottom side, hollow ground to a knife-edge, serrated, and hard chrome plated. The motor is an ordinary 1/2 KW 3450 rpm motor, checked for minimal end-play. A dove tail slide with micrometer screw adjustment defines the cutter height and a number of lockable screws permit tilt adjustment of the cutter plane.

In the case of the 10.4 m dishes, the support frame is assembled on the air bearing and the panels are attached to it, for machining, in precisely the same way as they are attached later when the dish is mounted on a telescope mounting. For any large space dish, the dish support structure to be used <u>in space</u> would fall far short of being able to support the dish panels <u>on the ground</u> during machining. A separate, rigid, stable, relatively massive support frame like that of a ground-based dish is needed to hold the dish parts in the precise relative positions they will later have when free of gravity loading. This frame must be sufficiently stable as not to change its shape during the final machining operation, and must include suitable means for "floating" each dish member, i.e., to remove the distortional effects of gravity.

Possible flotation systems include:

1) Plastic air bags, one under each panel, carrying accurately controlled air pressure. The flotation force in this case would be perpendicular to the panel back rather than vertical; the horizontal components could probably be removed with sufficient accuracy by simple gravity-operated lever systems at the panel corners (Fig. 16).

2) By resting each panel on a uniform layer of resilient foam plastic. In this case the support frame would have to have a conformable shape to assure uniform support over the panel area. Horizontal forces would have to be balanced out as above.

3) By using a large number of very-low-friction air-actuated cylinders to apply precisely-defined, precisely-vertical loads at selected points on the rear faces of the panels. The force to be applied at each point would have to be calculated on the basis of the actual weight distribution in each panel, but might be defined with sufficient accuracy by using a symmetrical arrangement of support points and assuming a uniform weight per unit area. This would be a particularly attractive scheme if each

Having "floated" the dish panels by some method, one must still provide two important further functions. First, there must be three immovable reference points sufficiently widely spaced, to define the precise spatial orientation of the dish on the air bearing. The flotation system air pressure might be controlled by valves actuated by sensors attached to these points. Second, the dish must be sufficiently rigid to withstand the machining forces without distortion. This may require artificial "rigidification", e.g. by providing low-friction, lockable clamps which permit the dish freely to assume its desired shape under flotation, and then firmly fix the clamp-point locations while the flotation forces are held constant (Fig. 17).

The machining operations are visualized to proceed as follows:

1) The panels are mounted on the support frame, individually "floated", and the necessary horizontal forces applied at at least three points of each panel so as to hold them in positions that are compatible with the hinges and the geometry. The hinges and fasteners themselves are not attached or, if present, are loose.

2) An array of sensitive dial indicators or electronic linear transducers is provided to indicate the position of each panel (in a direction perpendicular to the panel back surface) throughout the machining and skin attachment phases.

3) The clamp system is activated and rough machining cuts are made so as to bring the panel surfaces to within a few millimeters of the desired shape.

4) The clamps are de-activated, the flotation system readjusted to again bring the panels to their desired locations, and the hinges and corner fasteners "potted" in their correct locations.

5) The clamp system is again activated and finishing machining cuts are made so as to bring the panel surfaces to the desired shape.

6) The clamps are de-activated, and the "jump" in reading of each dial indicator is noted. If these jumps are sufficiently small, one proceeds to the next step. Otherwise, one returns to step 5.

7) The panel top-skins are attached, preferably with the panels removed from the support frame.

The procedure by which the dish surface will be further measured, mapped, and corrected will be discussed below. (See III D)

III. Measurements; adjustments; accuracy

The overall accuracy of the final dish surface is determined by numerous factors, many of whose effects combine quadratically in the manner of independent statistical errors. Among the more critical of these are errors due to:

1) Setting of the cutter track
2) Air bearing adjustment (planeness, levelling, centering)
3) Thickness variations of the top skins
4) Panel deformations due to elastic deformation of top skin
5) Variations in ambient conditions (thermal, vibrational, compensation of "g" forces, ageing of materials).

In this section are described the measurement and adjustment techniques that have been successfully used to reduce some of the terms in the error budget.

The cutter track for the 10.4 m dishes has been adjusted to within 7 μm rms of the desired curve by a null method utilizing a laser interferometer. The method makes use of the path-length invariant property of a focusing system: The optical path length along a ray from one focal point to another is constant. For a parabola, one focal point is at infinity, so the condition takes the familiar form that the sum of the distances from a point on the parabola to the focus and to a given straight line is constant. In the present case, shown in Fig. 18, the focus is at a mechanically and optically well-defined point which is the vertex of a retro-reflecting corner cube, and the straight line is the well-adjusted top track. The "point on the parabola" is the cutting edge of the cutter, which, for setting the bottom track, is replaced by a plane mirror situated at precisely the desired level of the cutter edge at the final cut. On the top track a motorized wheeled cart runs. The beam of the laser interferometer is directed horizontally parallel to the top track so as to pass through the interferometer beam-splitter on the cart and strike a pentaprism, which renders it precisely vertical, independent of small angular deviations of the pentaprism. The beam then strikes the plane mirror, is redirected so as to strike the corner cube, and returns to the laser by the same path,* rejoining the comparison beam at the beam splitter. The lateral position of the return beam is sensed by two photo

*For technical reasons, the outgoing and returning beams are laterally separated by 0.5 in., but this is not important for the present application.

diodes on the top cart, and the top cart position is servo-controlled so as to keep the beam centered as the cutter cart is driven slowly along its track. The interferometer is thus caused to measure just the desired quantity, namely, variations in the optical path as a function of cutter cart position along the lower track.

Numerous effects which influence the results must be sought out, eliminated or measured, and included in the track-setting procedures, and these cannot all be discussed here. It suffices to say that the path of the cutter edge is reproducible and can be <u>measured</u> to within about 1 µm relatively easily, and with care the path can be <u>set</u> to within about 2 µm rms, given sufficiently closely-spaced adjustment screws. Once set, the track remains stable to within 2 µm or less over a several months' period

Setting the cutter track includes determination of the focal point: rather than to fix the focus and adjust the track alone, a least-squares fit of the actual curve to a parabolic curve is made, using the vertical and horizontal coordinates of the focal point as parameters.

The focal point (corner-cube apex) is then physically moved to this best-fit position and the track readjusted to remove or reduce the resulting residuals.

The vertical position of the focus is not of interest, but the horizontal position <u>is</u>, for the rotation axis of the dish must be precisely vertical and must pass through the focus. This is accomplished by adjustment of the air bearing.

The air bearing must be adjusted for <u>planeness</u>, for <u>level</u>, and for <u>lateral position</u>.

Planeness is best assured by proper bearing design for adequate stiffness and by careful manufacture. In any case, it must be measurable and adjustable under load. Direct measurement of the air gap thickness as a function of rotation angle θ, using position sensors on both the fixed and moving bearing rings, is effective in diagnosing and correcting planeness errors. Actually, only one bearing surface is required to be plane, given adequate stiffness for that surface. In practice, the lower (fixed) surface is the one whose planeness is most readily and effectively set and maintained.

If, as in the case of the 10.4 m dishes, the air bearing cannot be rendered perfectly plane, it is still possible to map the effects of non-planeness, both in vertical height and angular tilt, as a function of rotation angle and remove these effects from the final dish surface by adjustment screws built into the dish.

The air-bearing level can be determined and set, and the angular wandering of the rotation axis mapped, using a water manometer system attached to the dish structure. Two reference reservoirs (Erlenmeyer flasks) and a moderate-sized riser tube (about 6 mm bore) separated by about a dish radius, together with a microscopic readout of the water level in the tube, provide an extremely convenient, sensitive (and inexpensive) system. One-tenth arc second sensitivity is achievable, and, with chart recorder readout and a programmable pocket calculator, the phases and amplitudes of the two principal fourier-series terms of the level readout can be rapidly calculated, and the fundamental one corrected out by adjustment of the air bearing level. (The two principal terms for the 10.4 m dish bearing are the $\sin(\theta + \delta_1)$ and $\sin(3\theta + \delta_3)$ terms. The first is removed by levelling, and the second is minimized by the planeness adjustment.)

With the air bearing now level, the lateral position of the rotation axis is finally set. This is done by viewing a small aluminized sphere whose center is on the desired axis, through a high-power telescope mounted on the dish support frame. A small pen-light mounted beside the telescope objective is directed toward the sphere, and the tiny virtual image of this light in the sphere is viewed in the telescope. The horizontal position of this image is read on a reticle, and departure from a fixed location due to misalignment of the axis is readily detected and corrected.

With the cutter track adjusted, the air bearing levelled and the rotation axis set, the machining operations are done as outlined previously. Experience indicates that the honeycomb "surface" is an exceedingly accurate reproduction of the cutter path, as modified by the non-planeness, etc. of the air bearing, and by the following effect, called "scalloping".

The cutter is held fixed for nearly a full rotation of the dish and, triggered by a switch actuated by the air bearing, moves a distance d (1 in. $\leq$ d $\leq$ 3 in.) to a new fixed position, cutting as it moves. Two effects prevent the dish surface, generated in this way, from having precisely the shape defined by the cutter track. The effects follow from the finite radial step size, and are similar in their appearance.

A circular cutter whose rotation axis intersects the dish rotation axis will generate a spherical annulus whose center of curvature is at the intersection of the axes. This is also the sagittal radius of curvature of the desired paraboloid. However, a paraboloid has a quite different meridional radius of curvature, which would of course result if the cutter were moved radially with the dish held fixed. The actual surface is thus a series of spherical segments of gradually (but stepwise) increasing radius from center to edge. Relative to the desired curve, the actual one exhibits a series of "scallops" whose amplitude depends only upon the radial step length. These scallops are readily visible on the finished surface of the 10.4 m prototype dish, where the radial step length of 7.6 cm was selected so as to give a peak-to-valley amplitude of less than 25 μm for the effect. (Fig. 8).

The second, related effect arises from the need to tilt the cutter so as to provide a small but definite clearance between the following edge of the cutter and the machined surface. If R is the cutter radius, S the step length, and C the rear-edge clearance, the additional scallop amplitude α produced by the cutter tilt, with $C << S << R$ is $\alpha = C\ S^2/8R^2$. For $C = .075$ mm, $R = 10$ cm, and $S = 5$ cm, $\alpha = 2.3$ μm.

Omitted from consideration here is an effect that can be important if the honeycomb skins possess an appreciable coefficient of expansion and aluminum honeycomb is used. This is the transcient surface distortion caused by differential expansion of the center and bottom panel skins, due to the heat generated in the honeycomb by the machining. It is assumed to be negligible for graphite-epoxy skins.

Next to be considered is the effect of thickness variations of the top skin. As was previously indicated, these variations combine directly with the surface as machined, since one side of the skin sits firmly on the honeycomb. If a curved graphite-epoxy skin is to be produced by laying up crossed layers of filamentary graphite on a convex mandrel, serious consideration should be given to curing the skin while it is held between the base mandrel and a hard concave mating surface, preferably one cast from the mandrel itself.

If sufficiently uniform curved graphite-epoxy skin material cannot be produced, alternative means of eliminating or controlling the effects of thickness variations must be found.

Whatever the material, and the degree of uniformity and smoothness of the top skin, it will most likely be applied to the machined honeycomb using room-temperature-curing epoxy and vacuum-bag techniques to attain close, solid-contact mating of the parts. Given a reasonably close match between the curvatures of the skin and the honeycomb, this will be straightforward. We consider it accomplished, and the panels restored to their positions during machining.

The dish surface shape can now be measured and compared with the desired shape as defined by the guide-track, simply by removing the cutter blade and mounting a suitable surface-sensing transducer in the proper corresponding place. For the 10.4 m dishes, a Hewlett-Packard DC-to-DC linear motion transducer was found useful. Surface deviations of but a few μm are easily and reproducibly detectable, and are recorded both on a chart recorder and on magnetic tape. Large-scale deviations, such as the bulge of a panel due to the stresses involved in deforming a flat sheet aluminum skin into the hollowed-out panel shape, are readily measured.

A sequence of color-coded height values can be automatically marked directly on the dish surface using felt-tipped marking pens actuated by magnetic reed switches mounted on a chart recorder, a small magnet being mounted on the pen carrier. This color sequence is easily converted into a conventional countour map by hand.

Several methods have been considered for further improving the dish surface accuracy from this point, should this be necessary: by etching, grinding or machining away material from the high spots, by spraying additional material onto the low spots, or by gross warping of the panel by a light, flexible frame attached to the back side of each panel. Of these, all but the spraying idea have been tested on a 10.4 m dish.

For aluminum skins, the heat produced in grinding or machining (which is many times greater than that produced in machining the honeycomb per unit depth of cut) is so great as to produce an immediate, large warping of the panel, rendering the method useless for this case. The method might well be useful for low-expansion graphite-epoxy skins, however.

On the other hand, etching away successive small layers of aluminum skin over selected areas defined by the contours proved to be quite easy. A 4 percent NaOH solution removes material at a rate of a few mils per hour and can be calibrated with temperature sufficiently accurately that one can predict the proper etch time including effects of solution heating with use.

Gross warping of a panel is a possible way to correct for relatively simple, uniform bending or bulging of the panel. A cross-shaped frame attached at five points permits the introduction of arbitrary curvatures along any two principal directions. The cross-frame can be attached to any panel if it is needed, provided that the necessary attachment points are provided on the panel. Such points, in the form of 1-inch square nuts cemented to the panel rear skin, were provided on all panels of a prototype 10.4 m dish, but were not actually used.

Perhaps the most intriguing idea for correcting the panel surface is through the automatic application of a thin layer of "paint" by modulated air spray controlled by the transducer reading. If the top skin is non-conducting, the paint might be the conducting paint that would be needed in any case; a uniform layer could be applied over the whole surface either before or after the correction coats.

Whatever means are used for the correction of surface deviations, some residual deviations on a local scale will inevitably remain. If it is deemed desirable to remove these, some type of lapping operation using a simi-rigid lapping tool may be feasible. Preliminary experiments with an orbital sanding system based upon a doubly-curved aluminum plate surfaced with cemented-on abrasive paper show some promise. Commercially available lapping stones, mounted on a segmented plate, may also be tried.

It should be emphasized that the dish surface, as produced, should possess quite sufficient accuracy and smoothness. The above discussion is intended mainly to indicate the possibilities for further improvement if, for example, light-bucket type operation at even shorter wavelengths than 0.35 mm were contemplated.

IV. Feed support and superstructure

Up to this point the space dish has been fabricated and it still rests on the rigid support frame on the air bearing, in precisely the shape it is to have when in space. The next step is to attach to it the superstructure that is to carry the cassegrain secondary reflector and that will also improve the rigidity with respect to large-scale patterns of deformation. This attachment must of course be done so as to leave the whole structure unstressed both on the ground and in space.

Stress-free attachment will be assured if the superstructure itself is essentially free of gravity-produced stress and if attachment is accomplished by "potting" the several mounting joints with the superstructure suspended - essentially floated - above the dish. One can visualize a number of tiers of load-sharing harnesses suspended from an overhead crane hook, each of the ultimate cords being attached to an appropriate point of a strut or leg so as to support its small share of the total load (Fig. 19).

The main body of the telescope, which houses the pointing, control, power, and receiver systems would be attached in a similar manner, except that in this case the compactness and rigidity of the unit would permit a simpler suspension system to be used for flotation during potting of its three or more mounting "feet".

Any other subsystems such as solar panels, attitude/pointing/control wiring and plumbing, etc. should of course also be attached in such a way as to avoid introducing unwanted stresses into the system. The guiding principle is to simulate by quasi-flotation, to the degree necessary, the zero-g space environment during the attachment process, and to be sure that no unwanted stresses are inadvertently introduced in the process, such as by the creation of differential-expansion-sensitive elements.

V. Packaging for transport and launch

Although it is much too early to specify in detail the configuration of the telescope elements in the folded or stowed condition, certain desirable or necessary features of the packaging and deployment concepts can already be seen.

First, some kind of a stiff crate-like container is needed to provide the necessary support for the individual parts during transport and launch. For deployment of the telescope, the crate might be pivoted upward so as to point parallel to the yaw axis, and the contents slid bodily upward on six parallel rails, dish-end-first. (Fig. 20) As each panel clears the end of the crate, it could be unfolded, mated with other previously deployed panels, and latched in place.

Magnetically coupled joints augmented by mechanical latches would be advantageous in holding partially deployed panel sets together until the full complement of sockets and ball had been assembled at a given vertex.

When the full complement of panels had been unfolded and latched together, the dish assembly with the pointing/control/receiver module would be held firmly by the crate rails while the front structure support legs were unfolded and attached to the dish. The assembled telescope would now look like a mushroom or a parasol with a rather broad "stalk", protruding from the shuttle bay.

After suitable systems checkout, the telescope would be cast loose and operated by ground command, with periodic revisitation for maintenance, repair, and replenishment of consumables.

The telescope or some of its components could be returned to earth by repacking it into the same crate as was used to carry it into orbit.

Particularly desirable would be the ability to detach the relatively small but complex electronic pointing/control/receiver module from the large but relatively simple dish and subreflector, leaving the dish in orbit while refurbishing the electronic package on the ground. This capability should not be difficult to provide.

Still to be determined are the procedures by which the telescope would be packed into the transport crate while on the ground. Experiments with scale models will be helpful in this area. Rather than to attempt to fold the telescope on the ground, which would be at least very awkward and difficult, if not impossible, the parts would probably be removed from their places in the machining frame (by unlocking the ball-and-socket joints and removing the hinge pins) and would be attached together again inside the crate. Each panel would be held firmly in its proper relative position not only by the hinges used in unfolding and refolding, but also by several (three to six) brackets attached to the crate rails and to the panel. These brackets might mate directly with the balls and sockets already provided on the panels, but could be independent of them if the launch environment were a threat to the dimensional stability of the ball-socket system.

VI. Panel deployment tests

Because of the relatively high inherent rigidity of the dish panels, and the one-step-at-a-time nature of the deployment process, it should be relatively easy to test hinge performance on an individual basis, at least in models, and the hinges on the actual telescope could conceivably be tested one-by-one as the panels are stowed in the crate.

Experience in zero-g deployment could be acquired relatively easily and inexpensively on scale models - say half or quarter scale - carried aloft on flights having some other main purpose. Such models could be built of relatively inexpensive materials since their absolute dimensional accuracy requirements would be minimal.

Figure 1: Schematic diagram of the 10.4 meter dish construction.

Figure 2: Schematic detail of support frame joints.

Figure 3: Schematic detail of honeycomb panel construction and support.

Figure 4: View of a 10.4 meter dish with panels mounted, ready for rough machining. Note the tooling girder which carries the cutting-tool motor.

Figure 5: A 10.4 meter dish with rough machining partially completed.

Figure 6: Close-up view of cutter, cutter motor, cutter cart, and lower track of the tooling girder. Note the thin layer of honeycomb being sliced away by the cutter.

Figure 7: A completed 10.4 meter dish with the panels remounted after "top-skins" are applied.

Figure 8: Close-up view of dish reflecting surface. Note the serrations along the edge of the sharp shadow-edge images in the dish. These are the spherical "scallops" described in the text.

Figure 9: View of partially disassembled support frame, being readied for shipment to the Owens Valley Radio Observatory. Note the large air bearing which supports the dish during machining of the honeycomb.

Figure 10: Schematic layouts of various arrays of hexagonal panels. The 7-panel and 37-panel configurations are considered as specific examples.

Figure 11: Schematic diagram of hinge action. By using a progression of increasing axis-offsets, the hinges carry the "petal" panels surrounding a central "core" panel into a uniform stack behind the "core" panel.

Figure 12: Schematic diagram showing (a) "Z-hinge" action of a doubly-hinged "bridge" panel (labeled 5); (b) one possible order of folding of the panels of a 37-panel dish. Arrows point to the "core" panels, and the small numbers indicate the stacking offset of the hinges; (c) the resulting panel stack, with core panels and bridge panels numbered.

Figure 13: Plan - and sectional views of a panel, showing the approximate relative dimensions, and the ball-and-socket positioning scheme.

Figure 14a: Schematic assembly detail of a joining vertex of three panels. The panels, shown in rear view, are labeled 1, 2, and 3.

Figure 14b: Schematic detail of a socket unit. The cut-outs are to provide clearance for the ball-support fin. (Two cut-outs are shown, but only one is needed for any given unit.)

Figure 15: Schematic sketch of possible a) mechanical and b) magnetic gripping mechanisms. A combination of the two would have some advantages. In b), two alternative arrangements of the magnet and "keeper" are shown.

Figure 16: Air-bag panel flotation scheme.

Figure 17: A possible panel-clamping mechanism. The lateral force F would be provided by springs. To de-activate the clamp, an electric solenoid would remove the spring force, freeing the loosely-fitting plates to slide between one another.

Figure 18: Schematic view of the laser-interferometer track-measuring system.

Figure 19: "Zero-g" support of the sub-reflector superstructure during attachment to the panels.

Figure 20: Two views of the 37-panel telescope structure: (a) folded, and (b) unfolded.

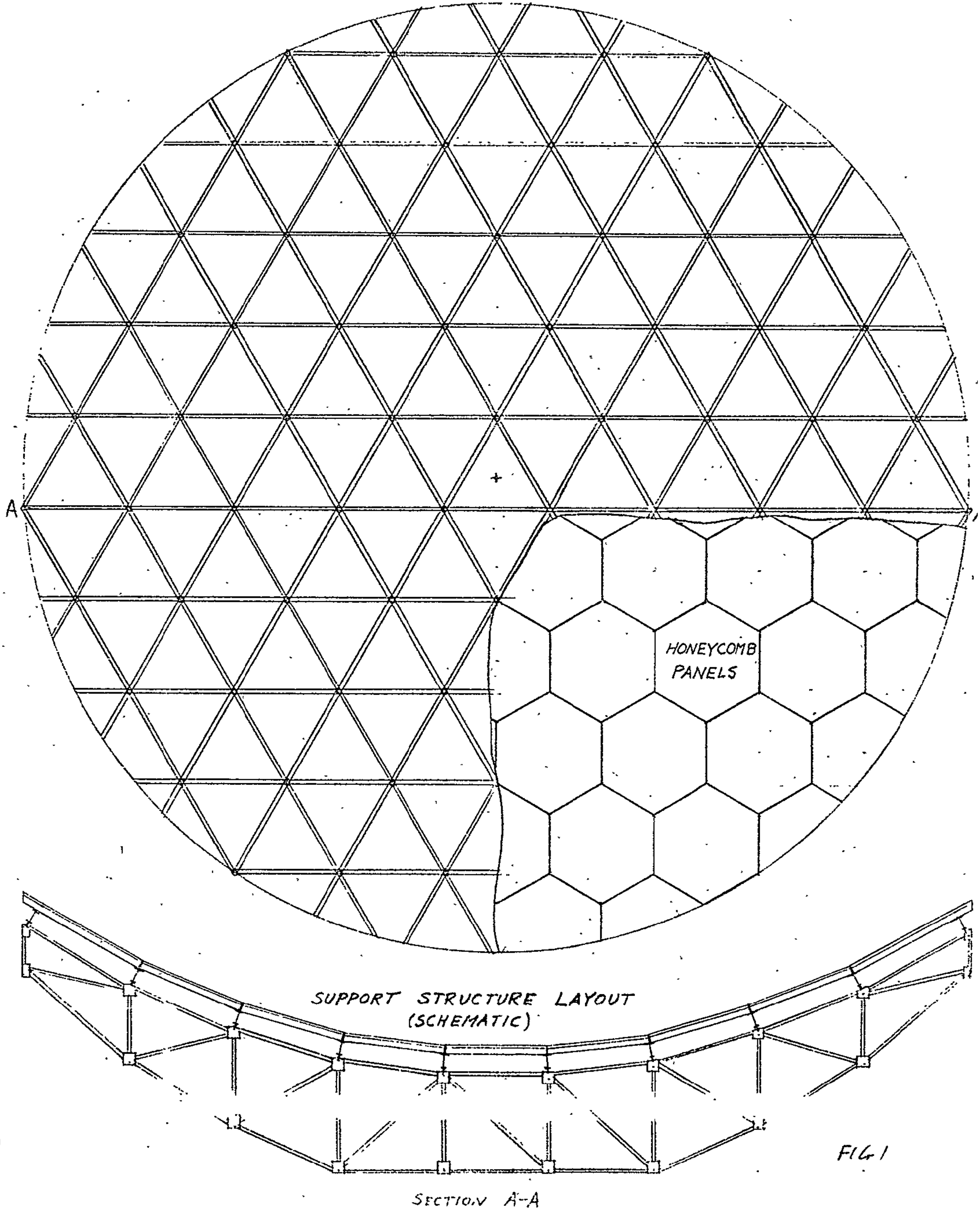

A
HONEYCOMB PANELS
SUPPORT STRUCTURE LAYOUT
(SCHEMATIC)
SECTION A-A

FIG 1

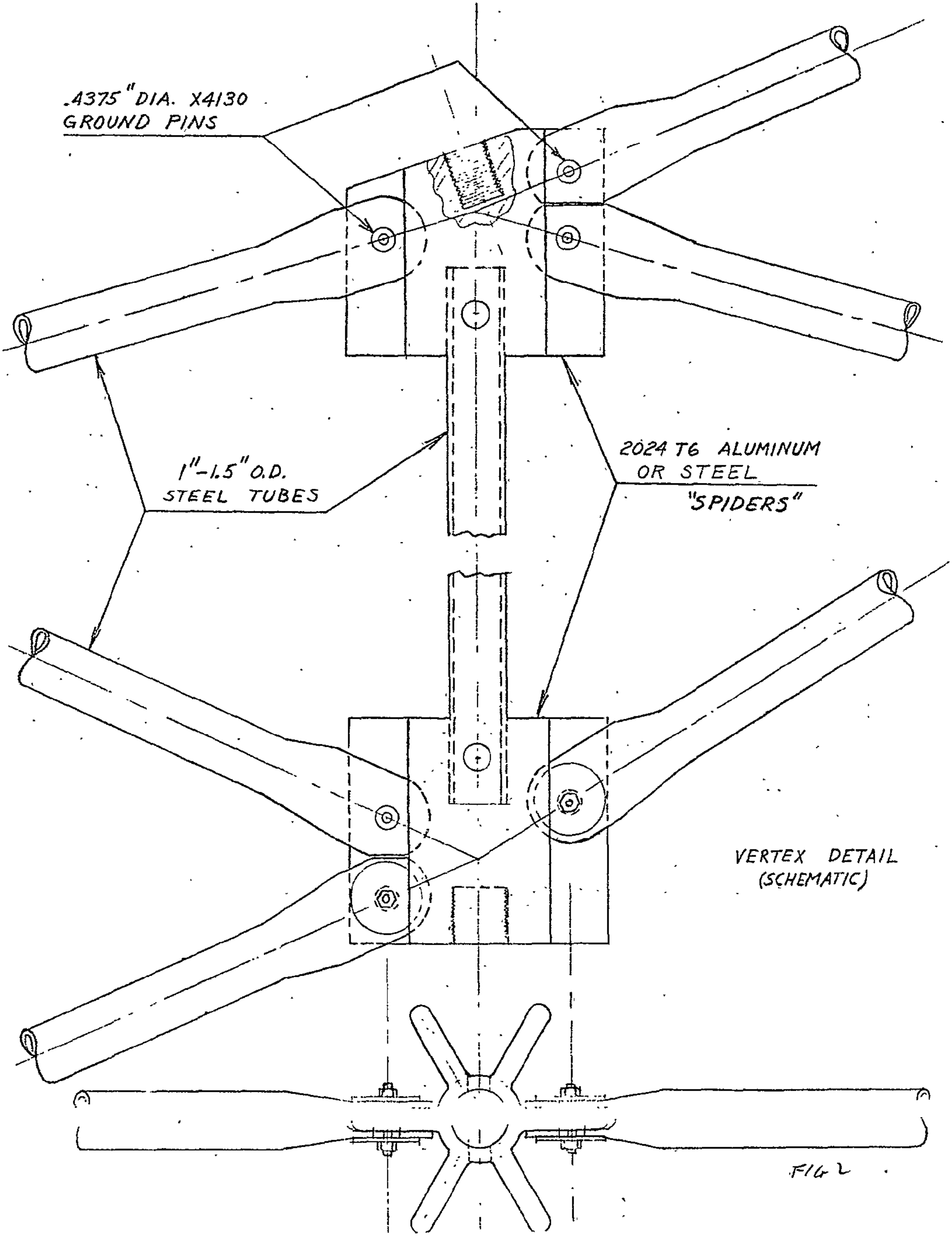
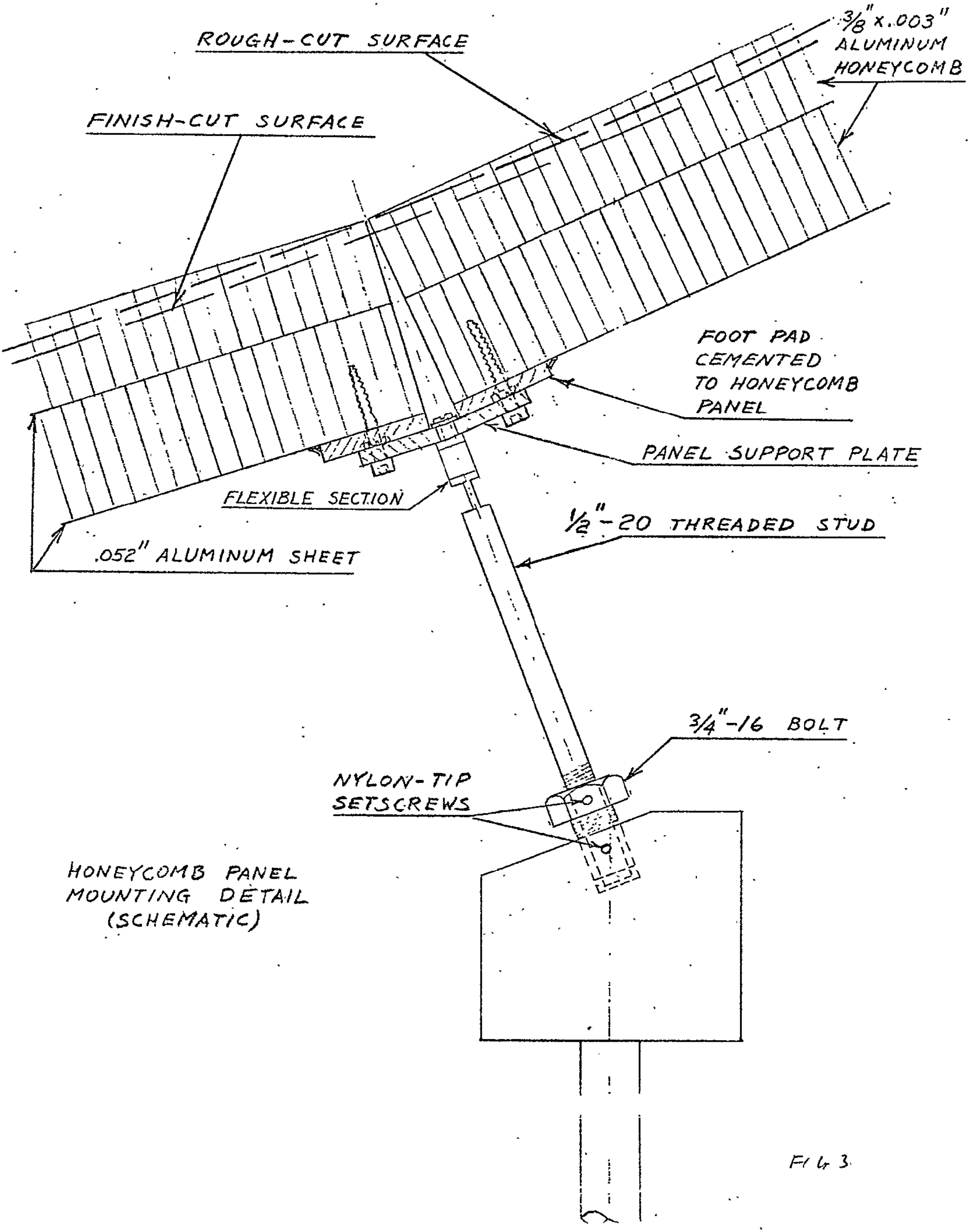

.4375" DIA. X4130
GROUND PINS
1"-1.5" O.D.
STEEL TUBES
2024 T6 ALUMINUM
OR STEEL
"SPIDERS"
VERTEX DETAIL
(SCHEMATIC)

FIG 2



HONEYCOMB PANEL MOUNTING DETAIL (SCHEMATIC)

FIG 3

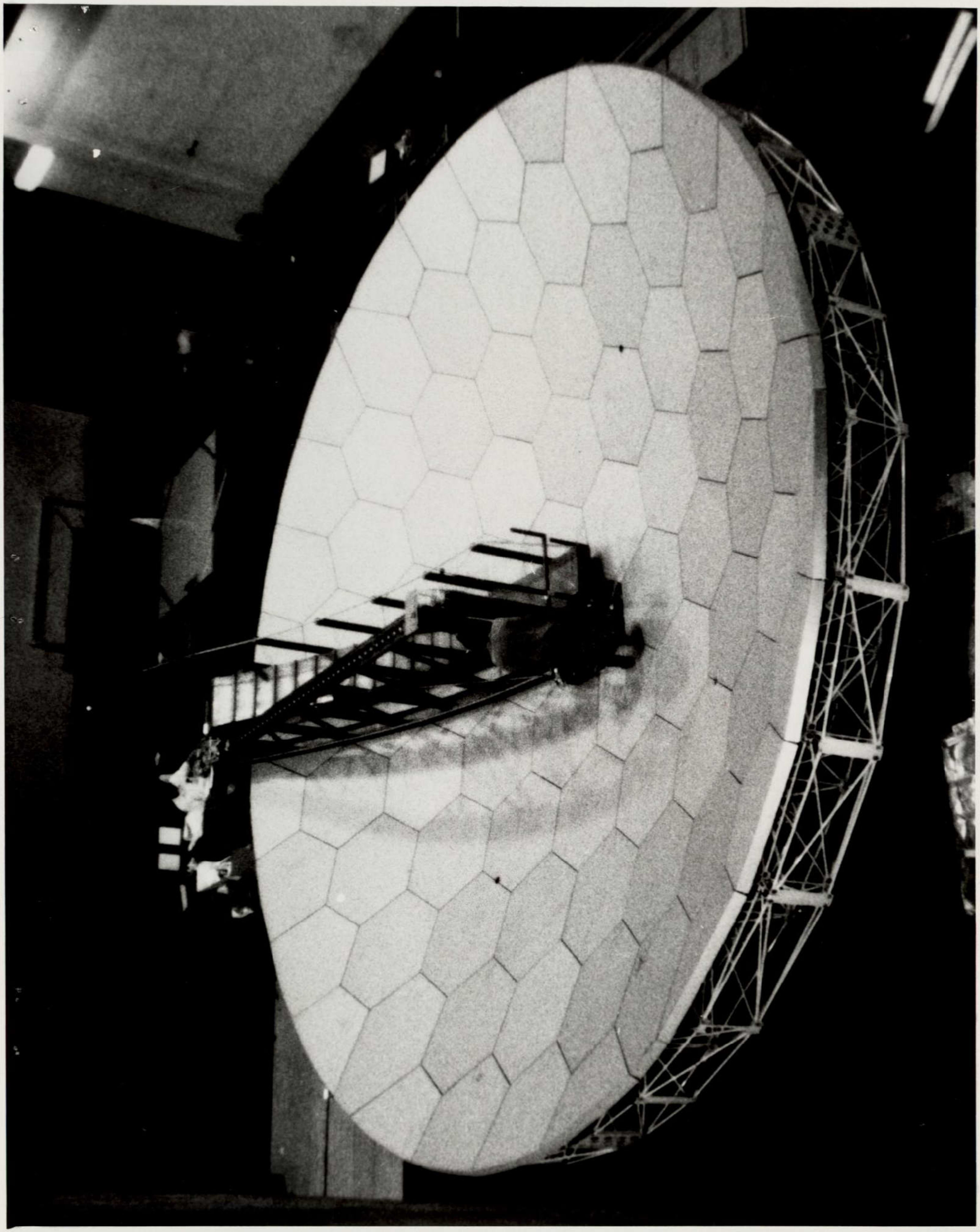


Fig. 4

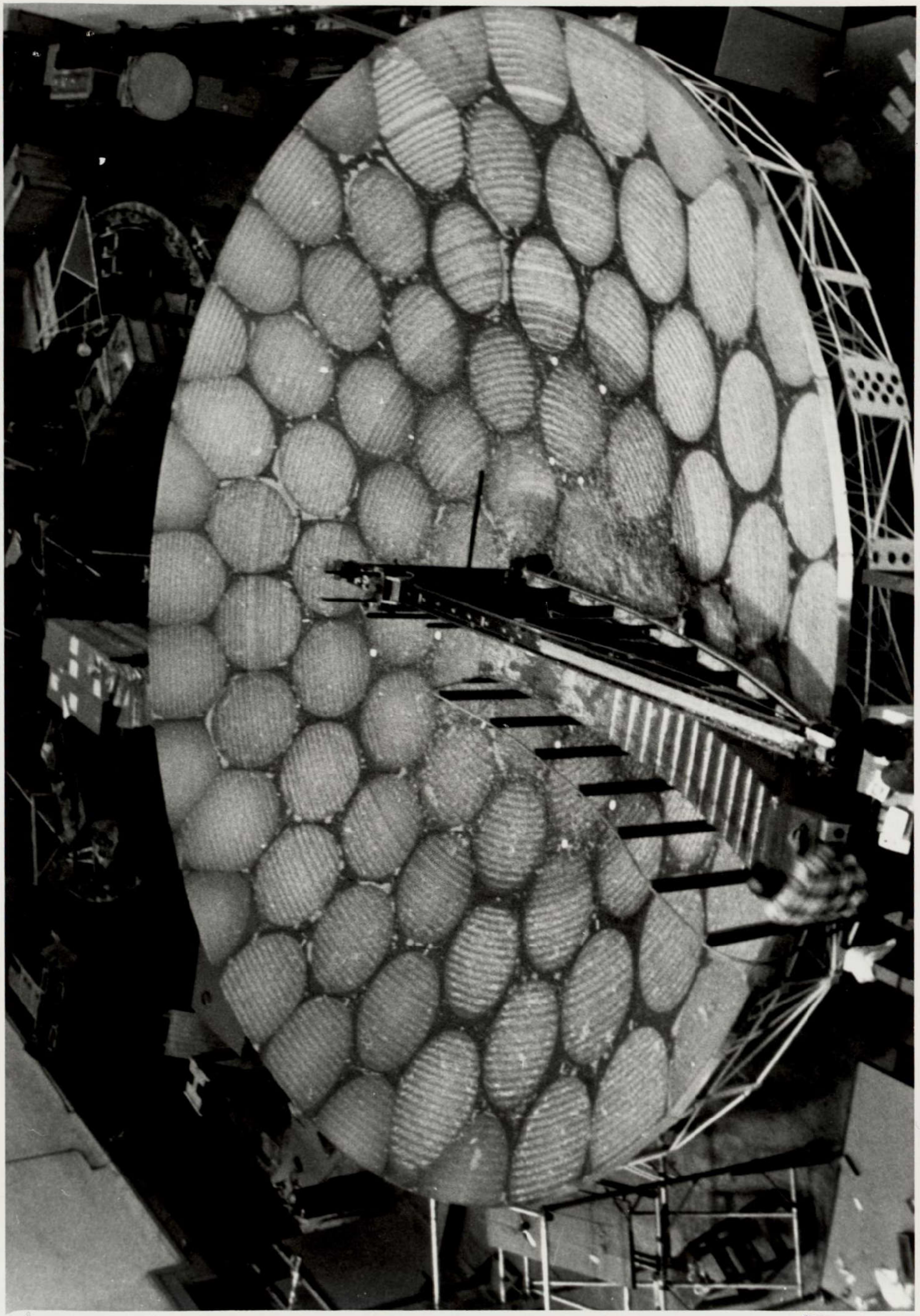


FIG 5

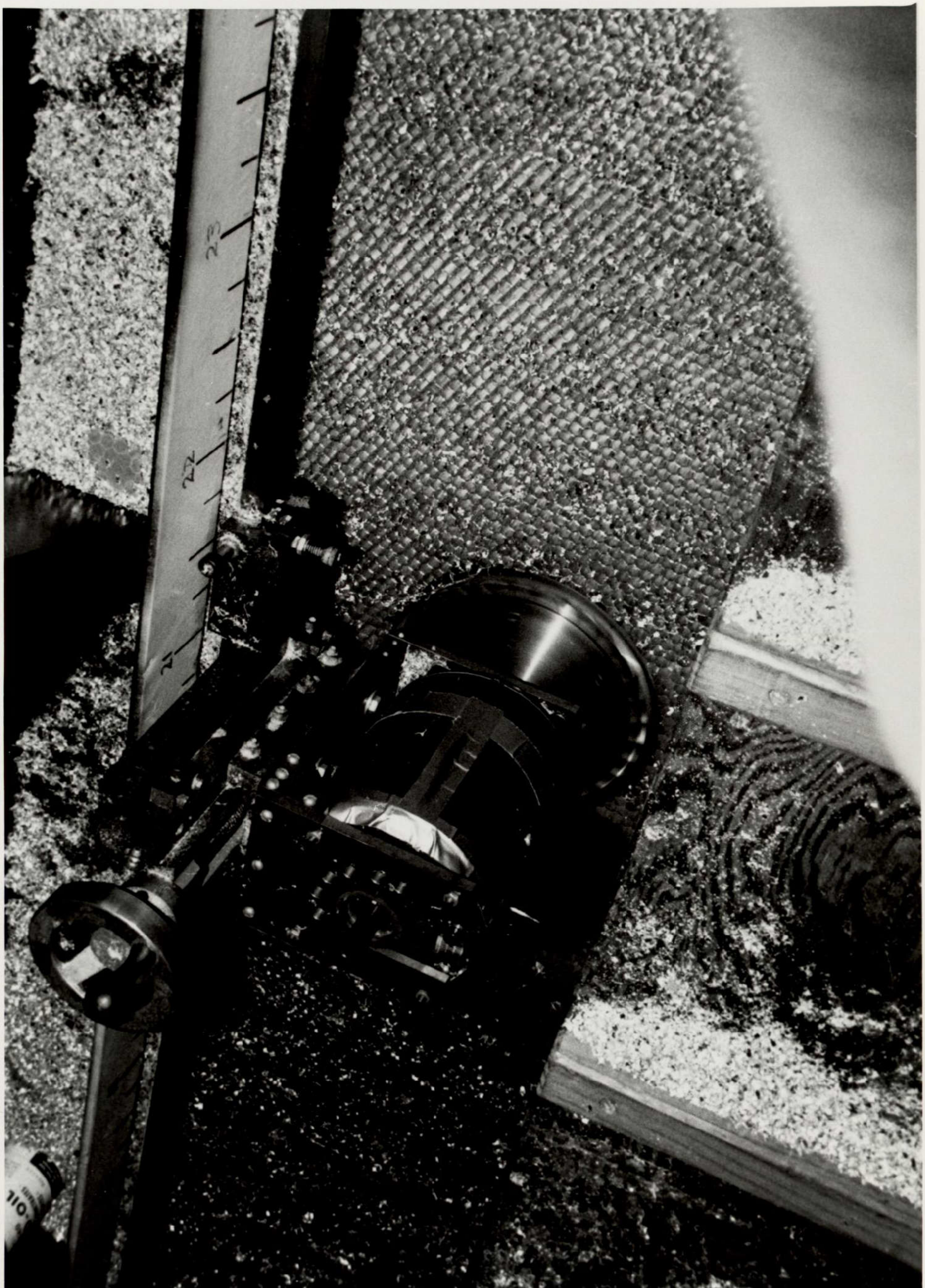


FIG 6

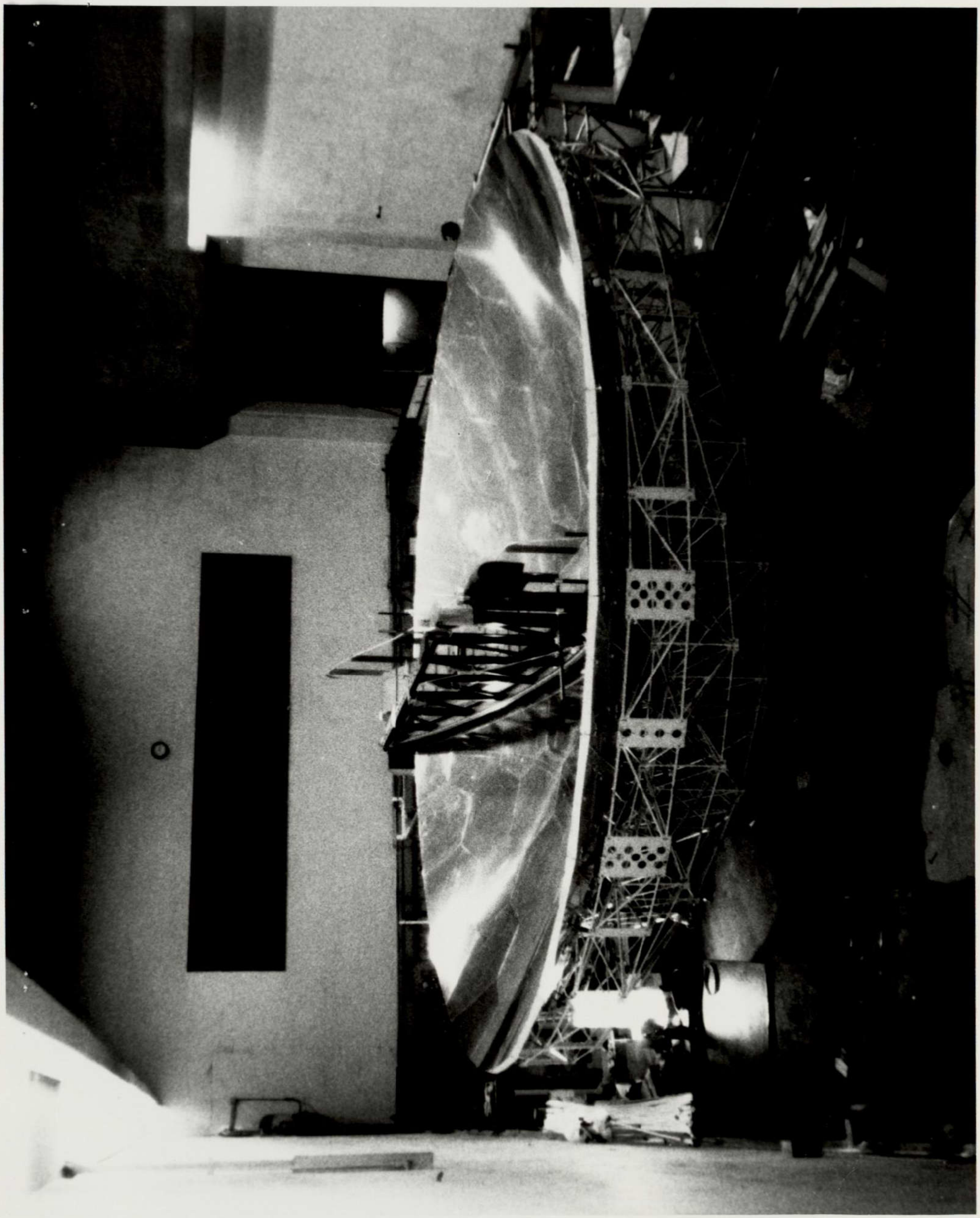


Fig. 7

Fig. 8

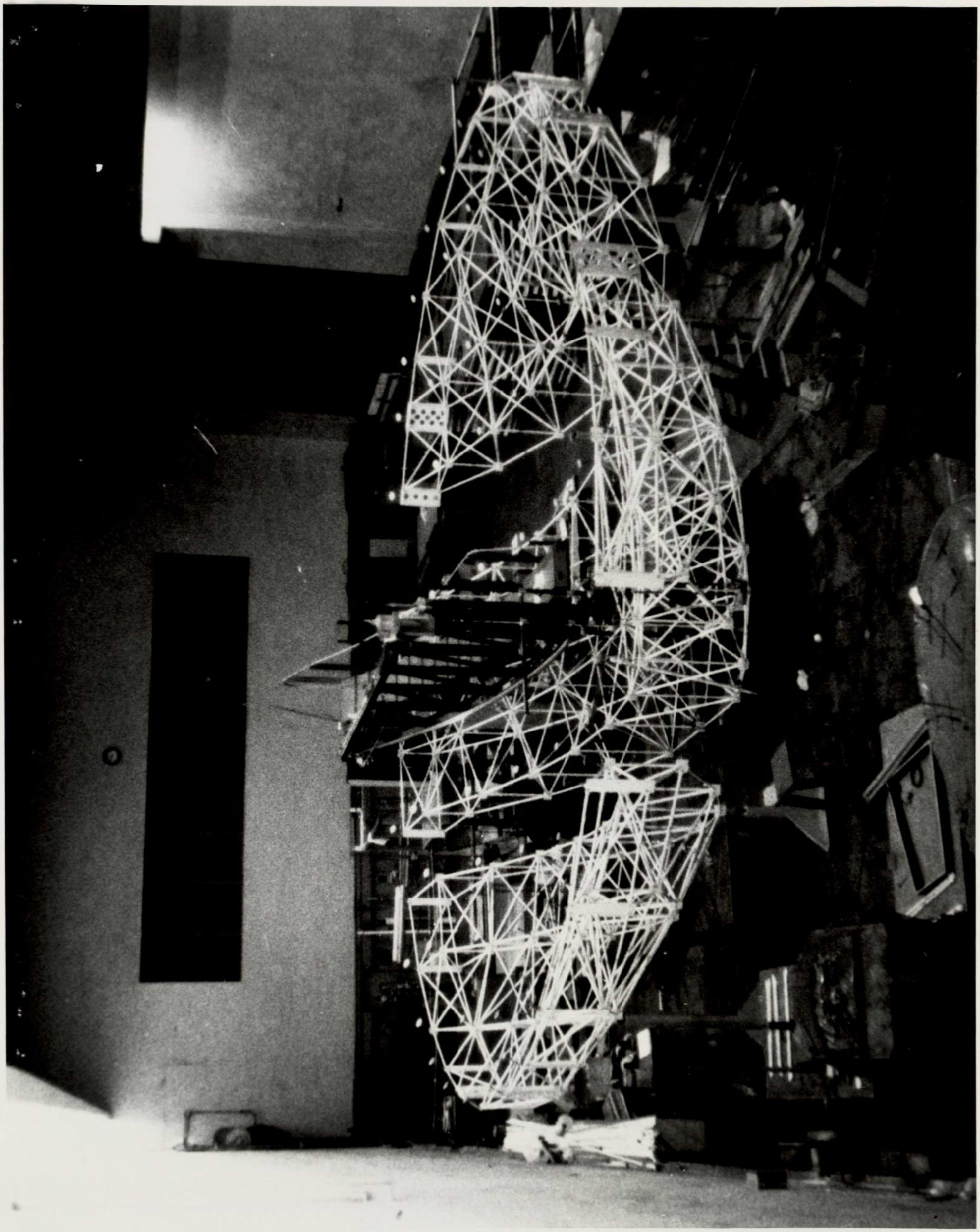


FIG. 9

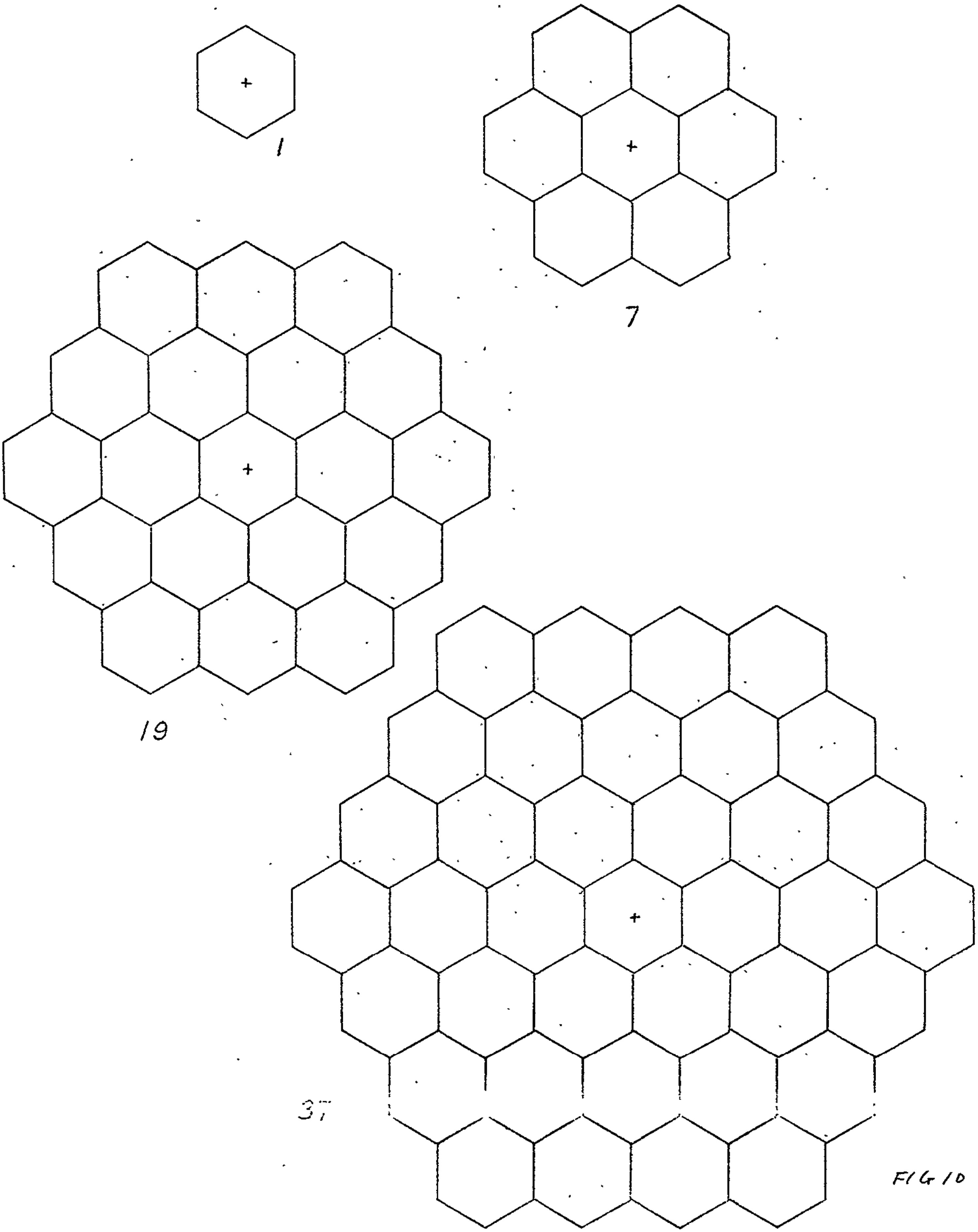


FIG 10

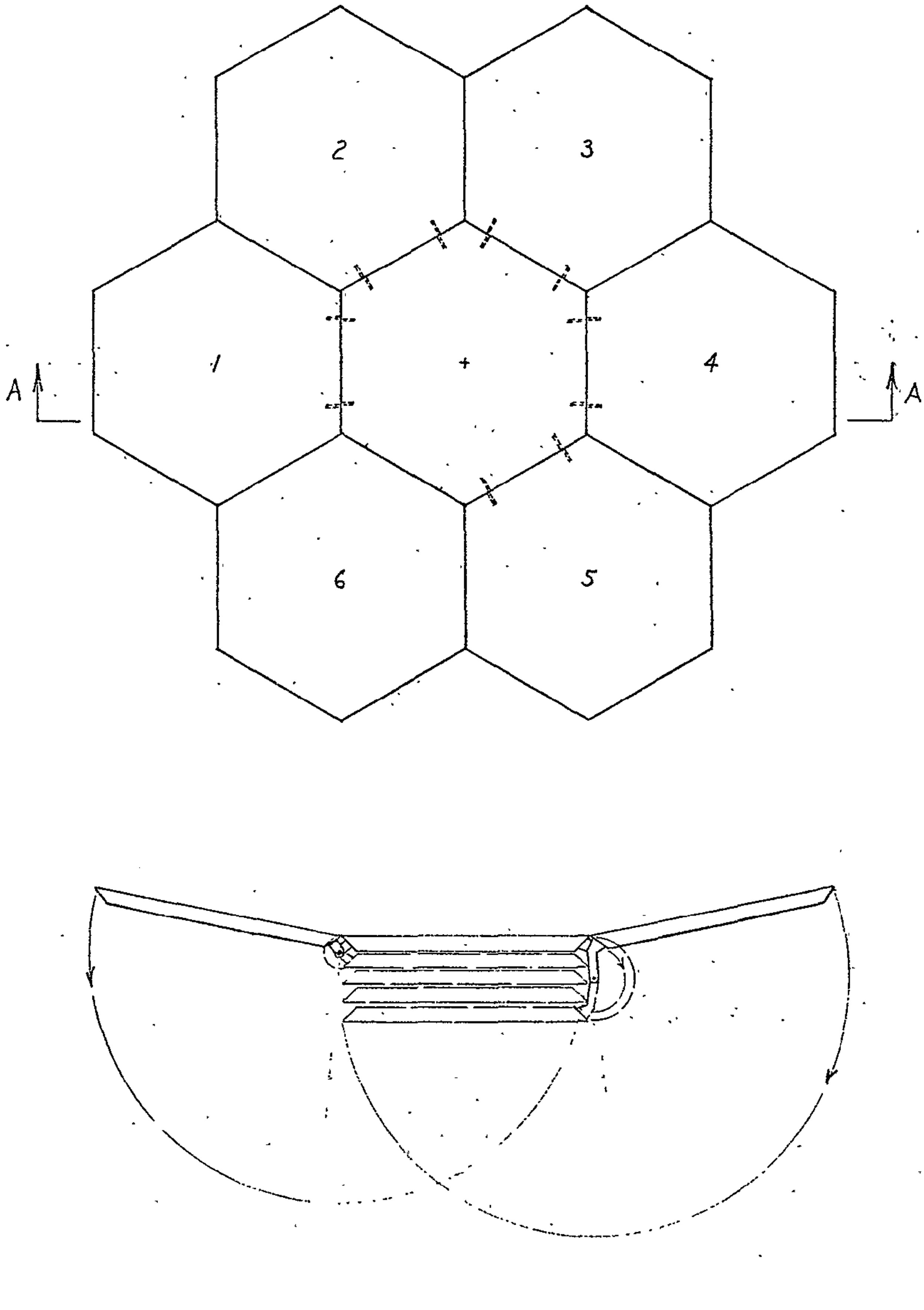
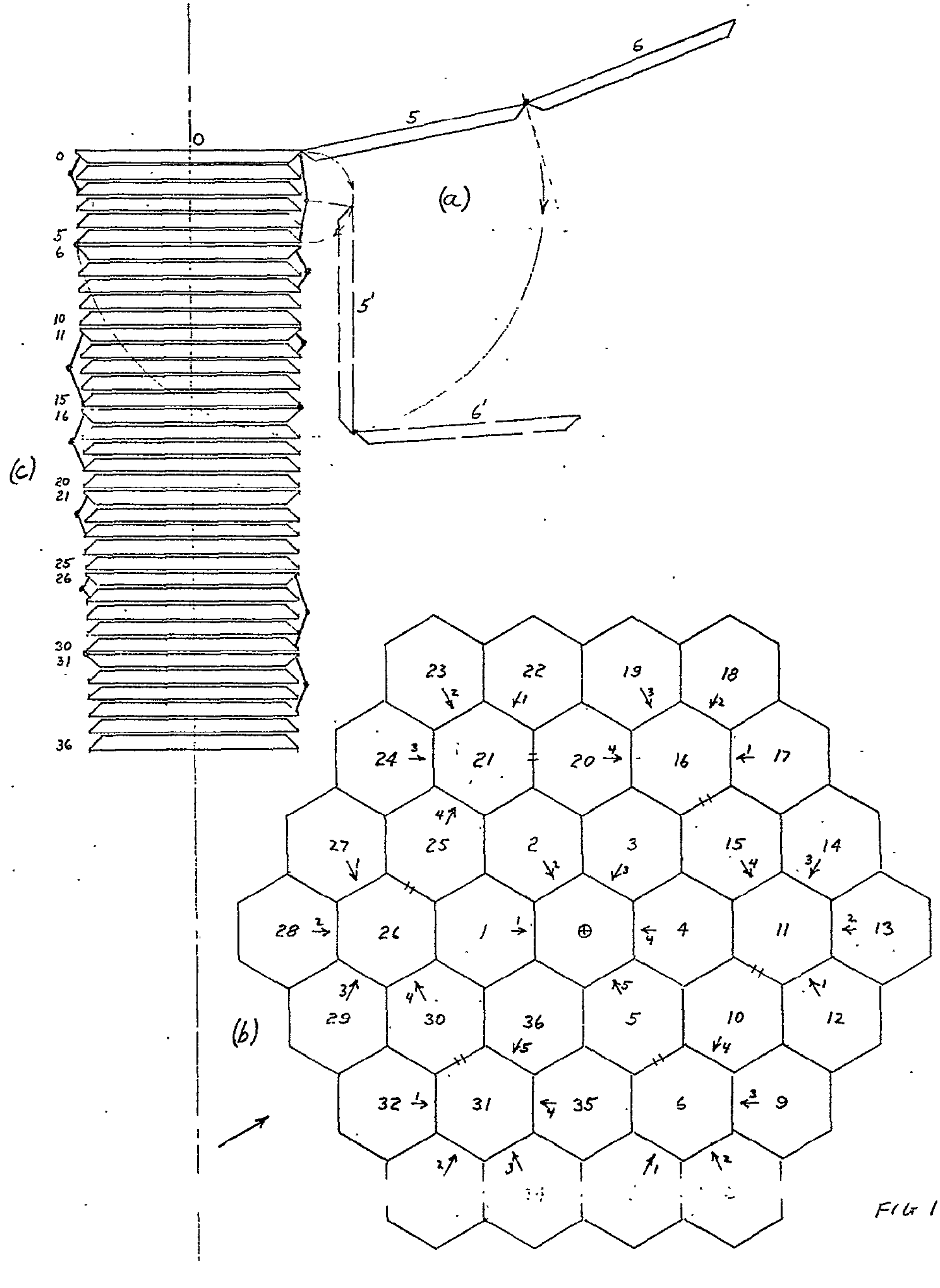


FIG 11



(a)
(b)
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9

FIG 12

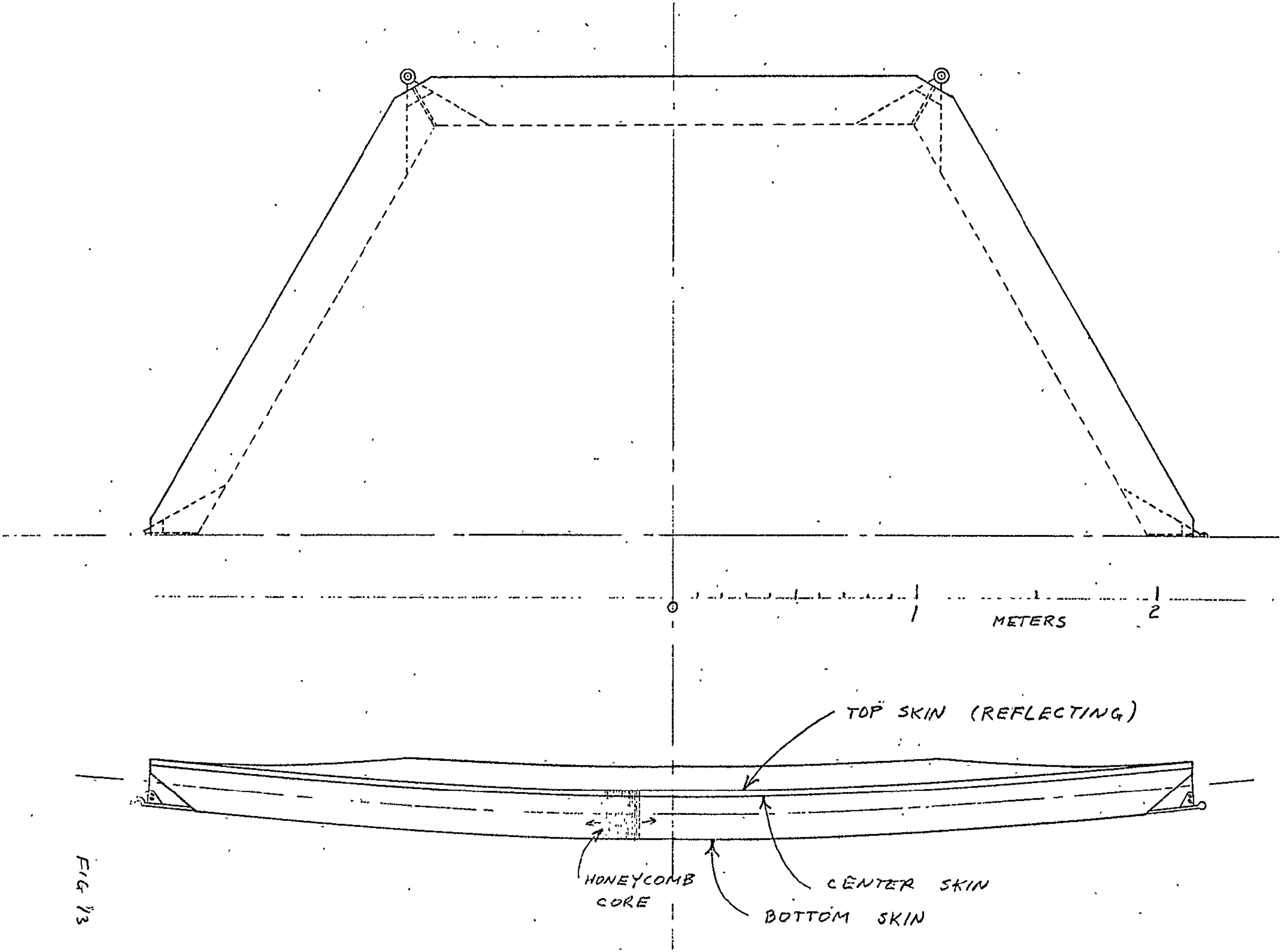
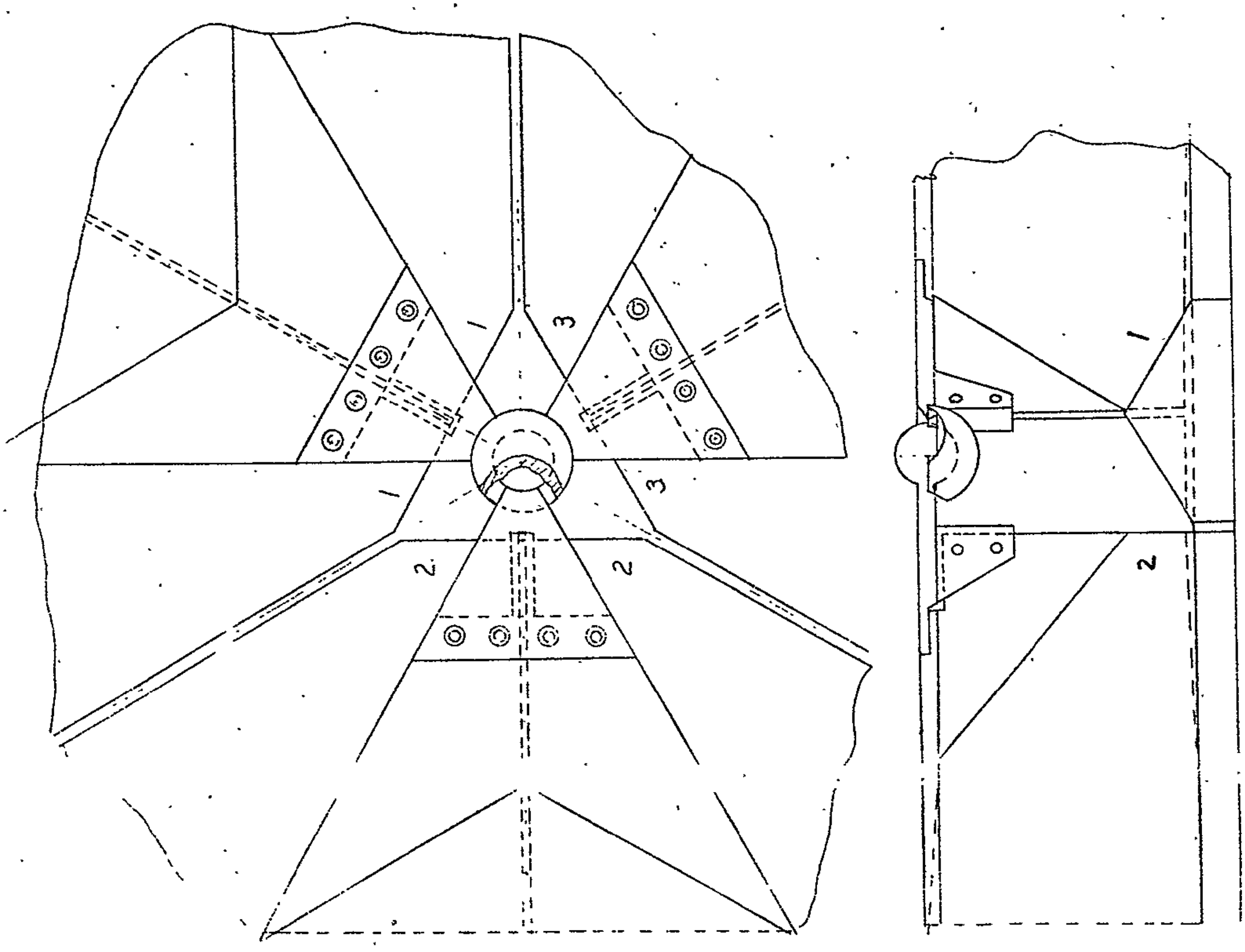

0
1
METERS
2
TOP SKIN (REFLECTING)
HONEYCOMB CORE
CENTER SKIN
BOTTOM SKIN

FIG 13

FIG 14a



SIDE VIEW (PANEL 3 REMOVED)

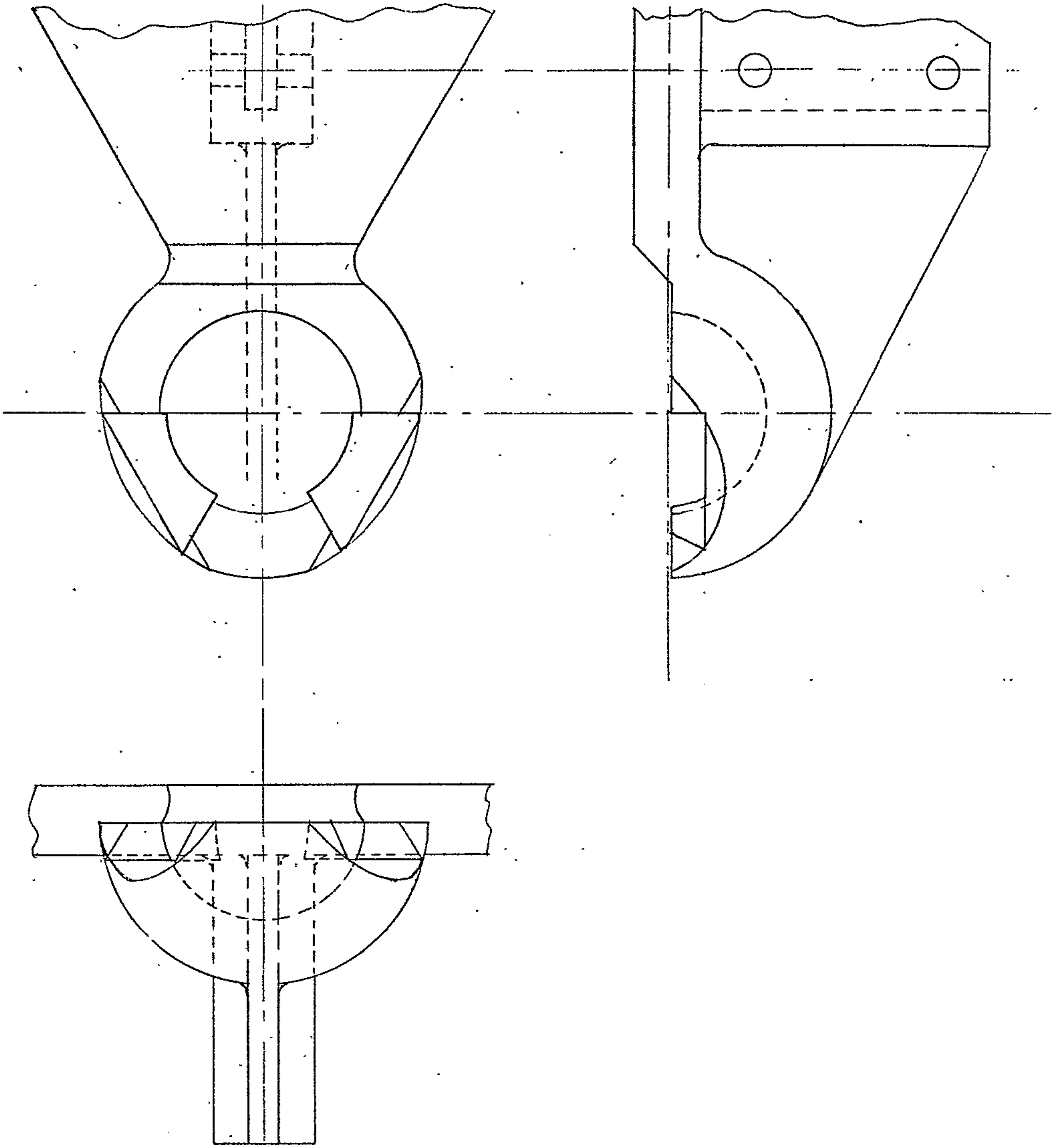


FIG 14 b

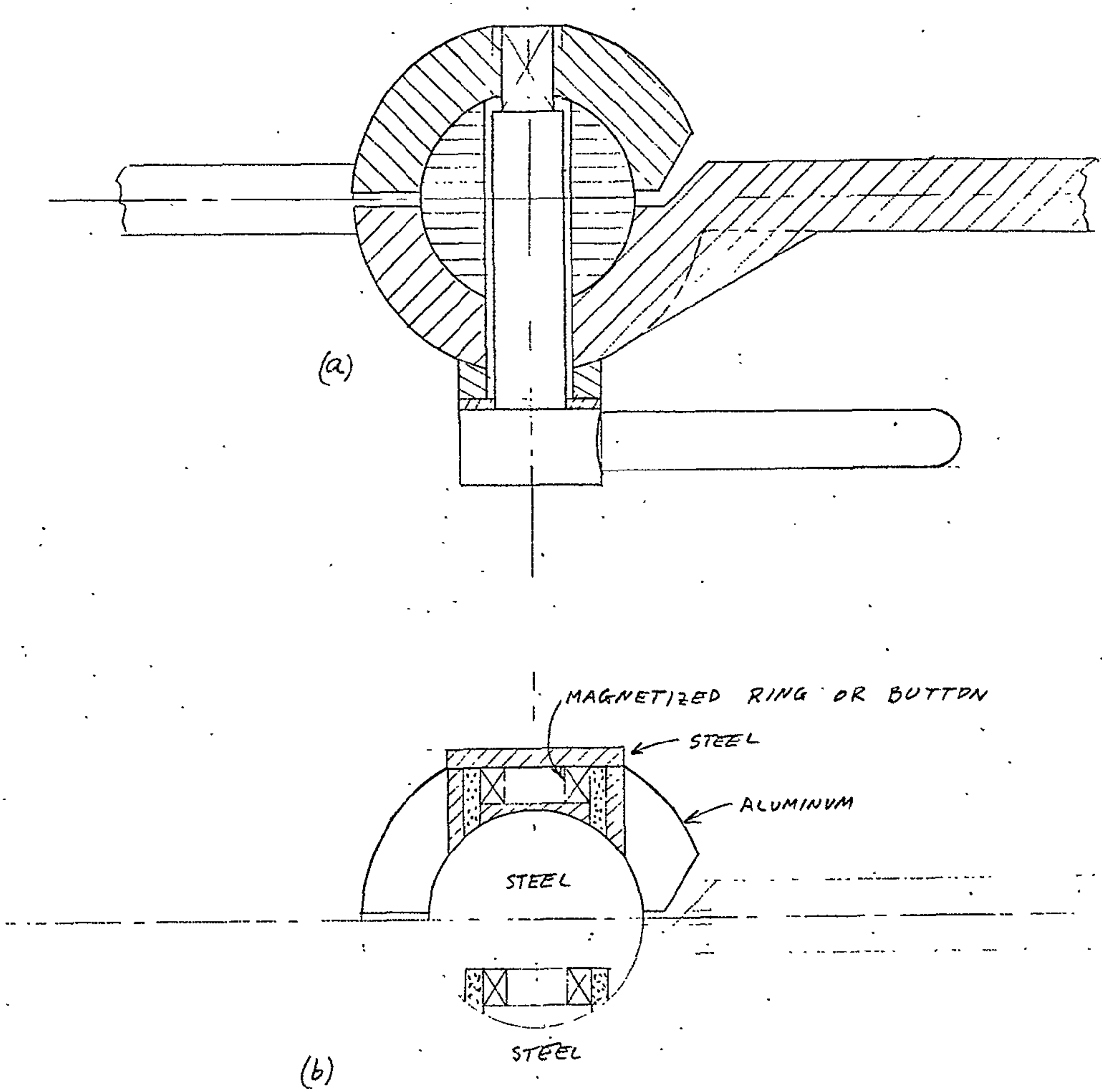
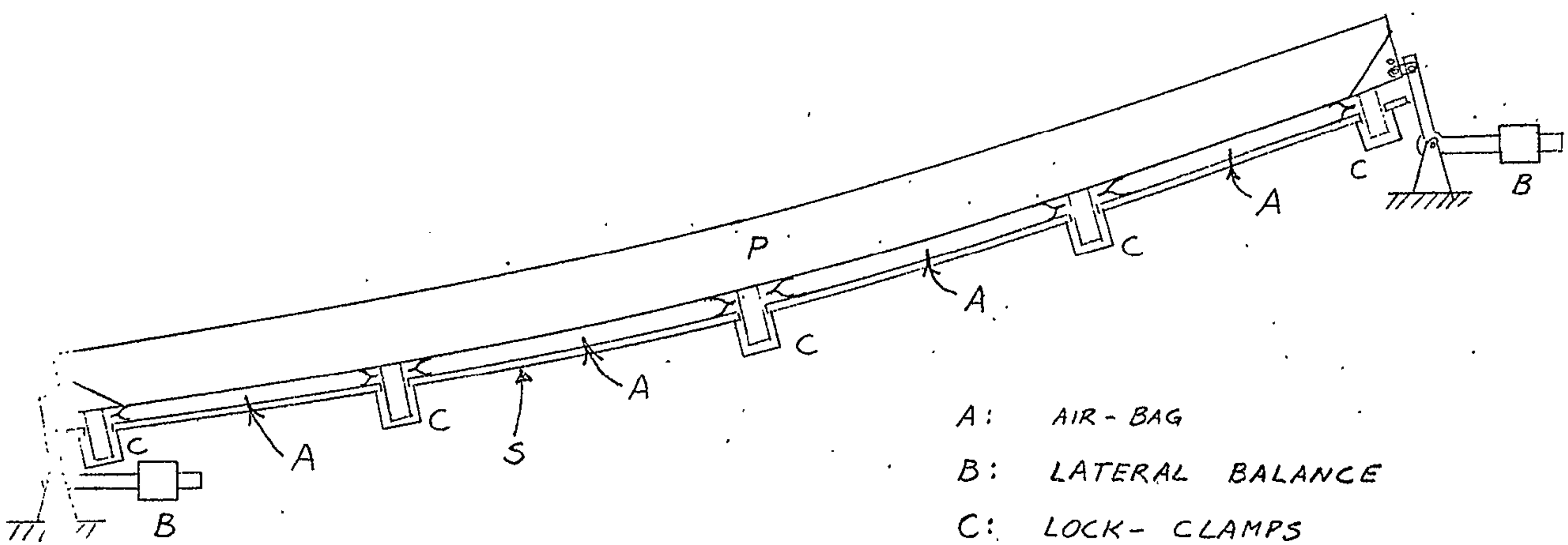


FIG 15



A: AIR-BAG

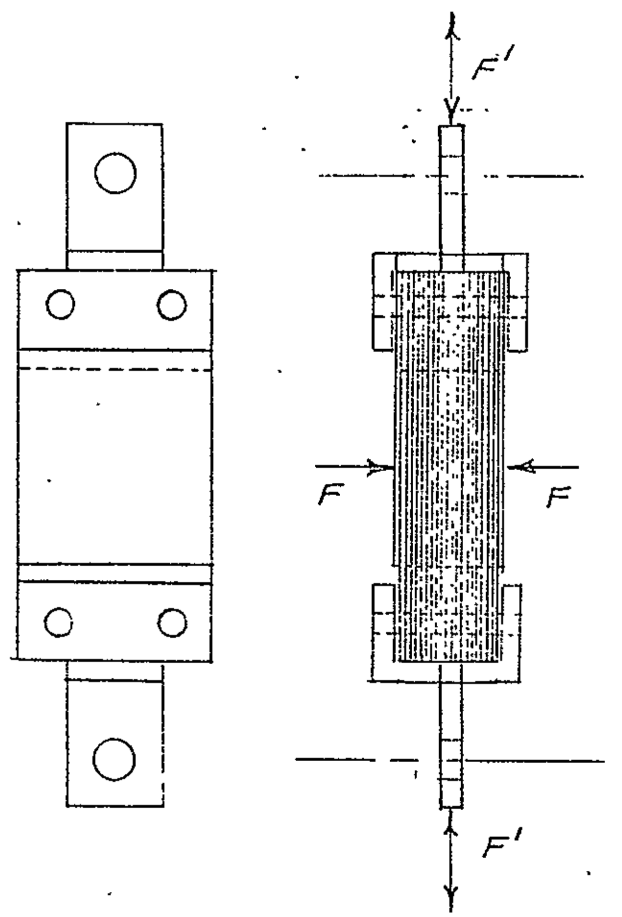
B: LATERAL BALANCE

C: LOCK-CLAMPS

P: PANEL

S: SUPPORT FRAME

FIG 16



$|F'| < n\mu F$

FIG 17

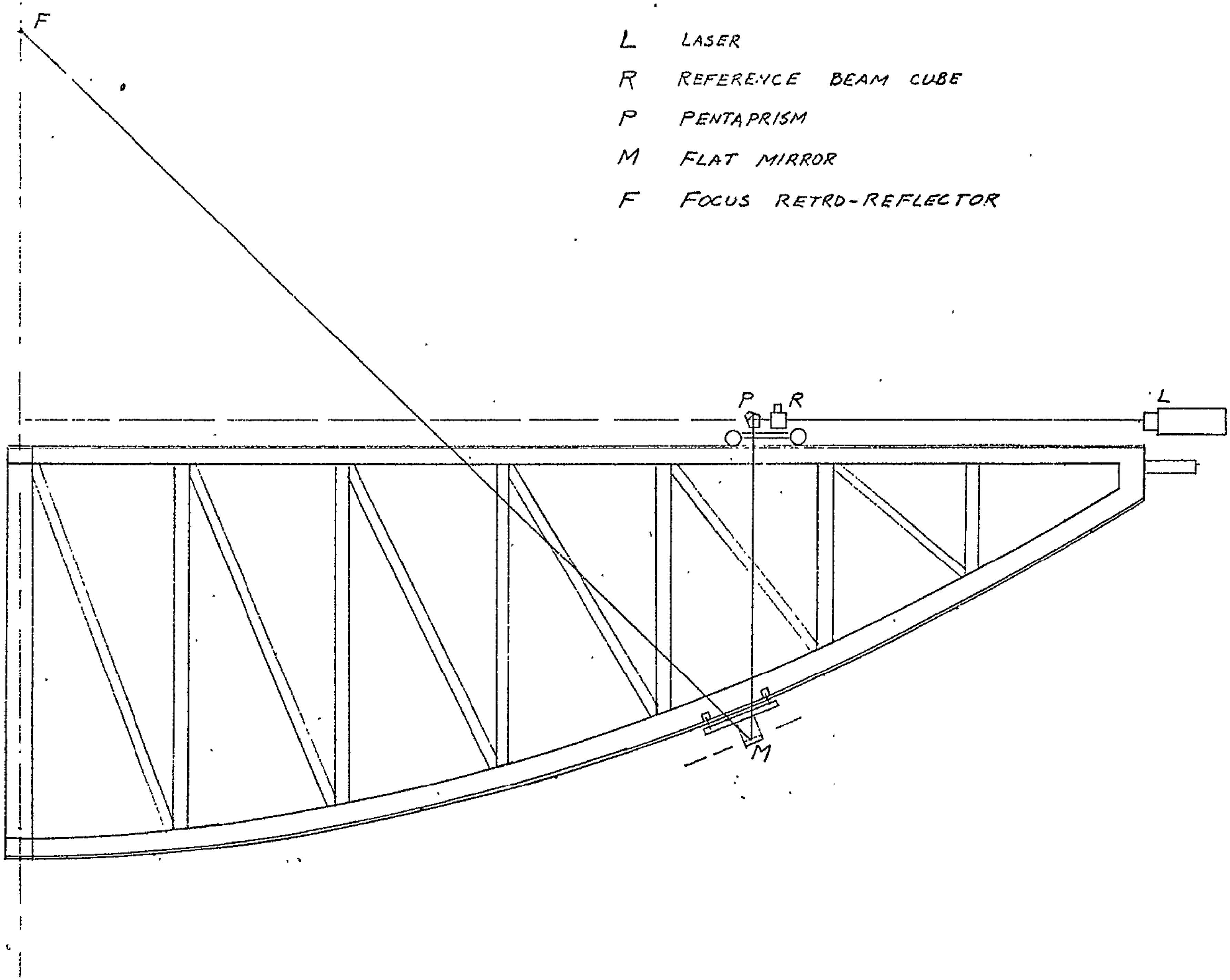

F
L LASER
R REFERENCE BEAM CUBE
P PENTAPRISM
M FLAT MIRROR
F FOCUS RETRO-REFLECTOR
P
R
L
M

FIG 18

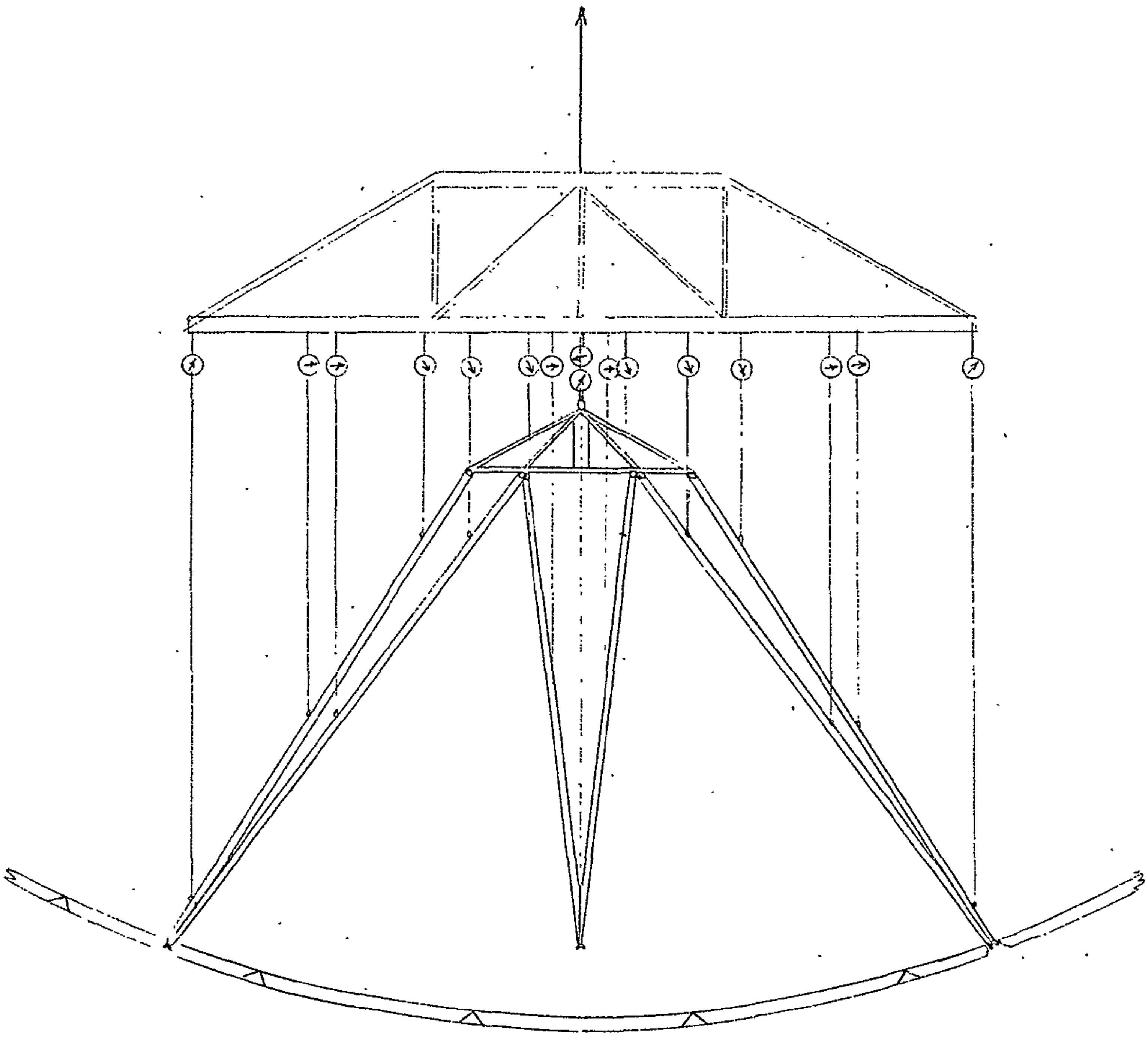
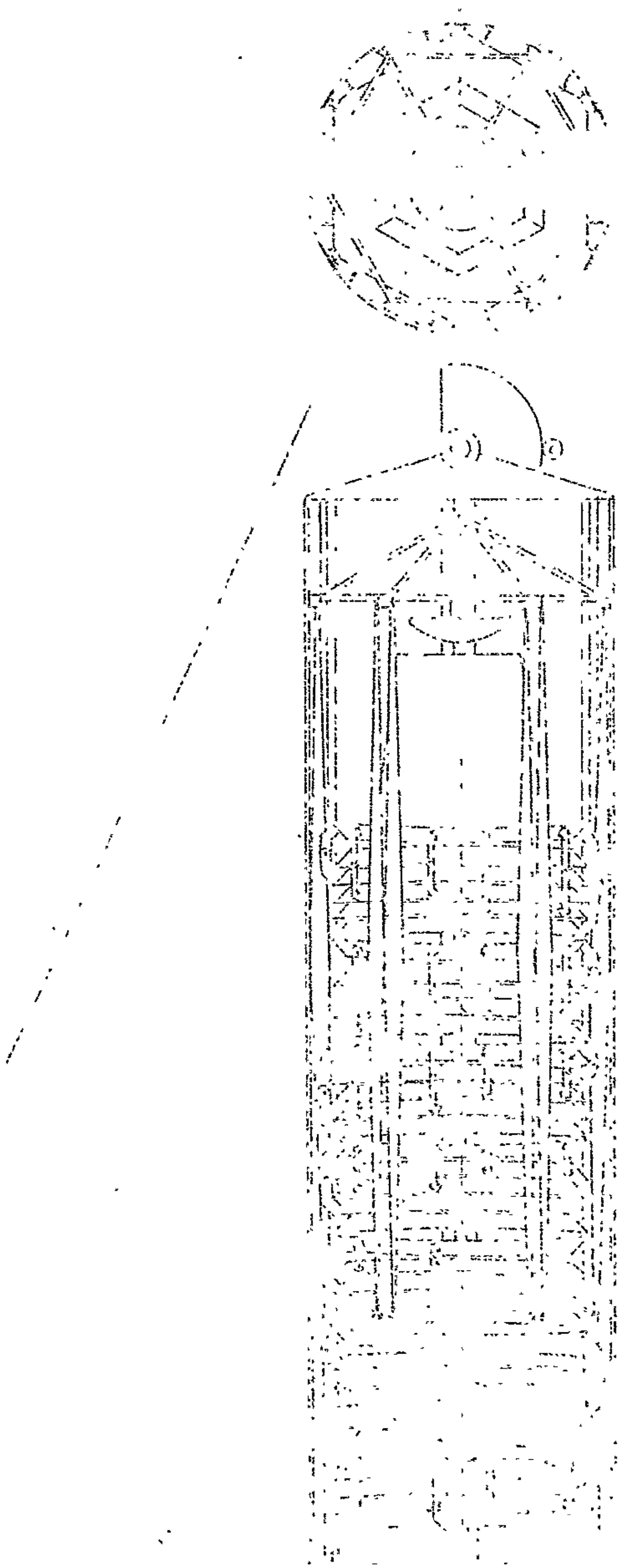


FIG 19



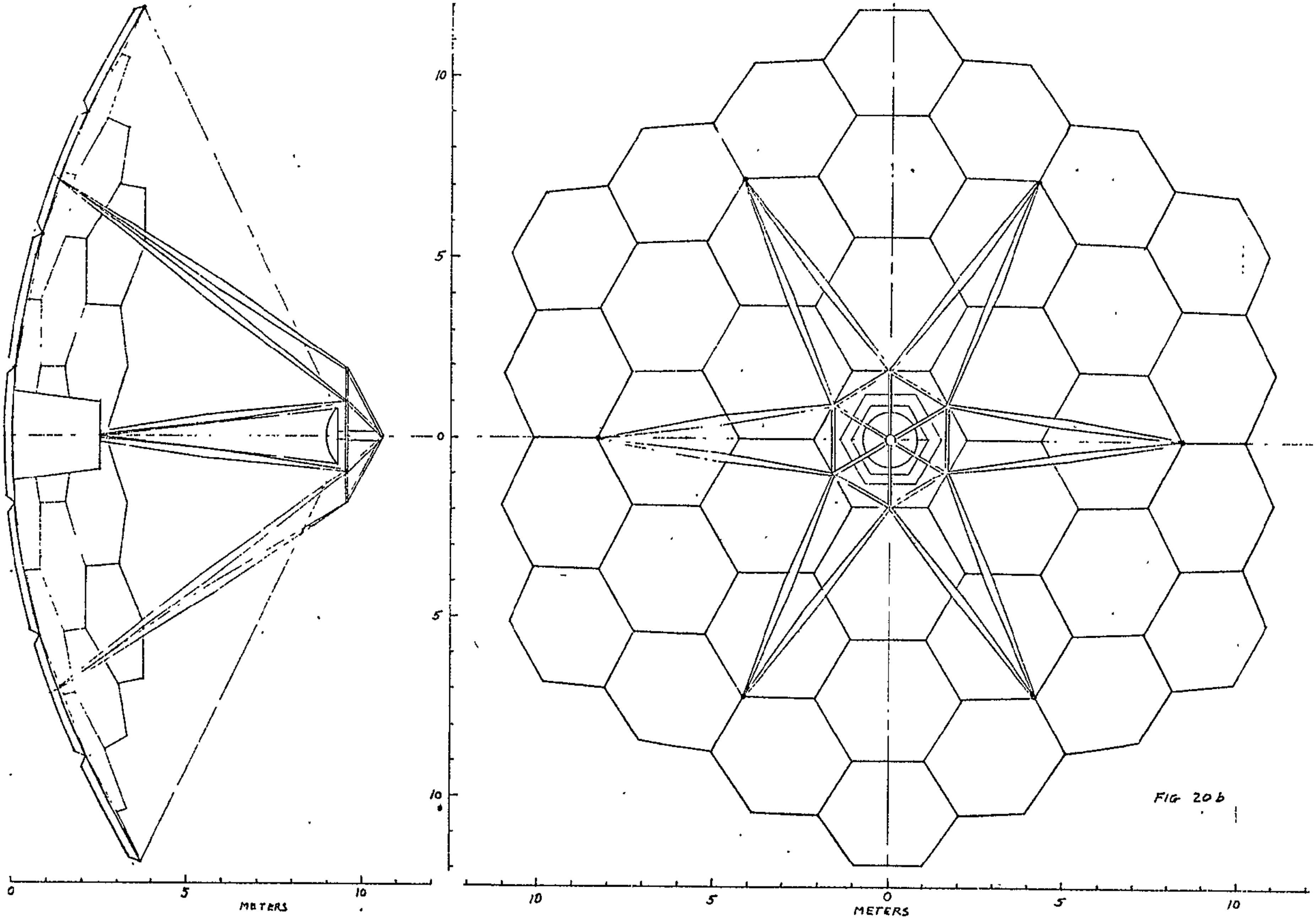


FIG 20b