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FINAL TECHNICAL REPORT

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(NASA-CR-146304) DESIGN AND CONSTRUCTION OF PROTOTYPE RADIO ANTENNA FOR SHORTEST RADIO WAVELENGTHS Final Technical Report (California Inst. of Tech.) 25 p HC $3.50 CSCL 03A G3/89

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The subject grant was initiated in 1963 as a broad, multidisciplinary research effort encompassing cosmic rays, solar physics, infrared astronomy, X-ray astronomy, theoretical astrophysics, and astronomical instrumental development. Gradually, over the ensuing years, the various activities that were begun under the "umbrella" of the original Grant split off and were funded directly through the appropriate NASA program offices.

In 1973, a major part of the residuum of the parent Grant was devoted to the design and construction of a prototype radio antenna or "dish", intended for use at the shortest radio wavelengths transmitted by the atmosphere. (Practically, this means 1.0 millimeter, or a frequency of 300 GHz). The present Final Technical Report deals mainly with the progress and present status of the millimeter-dish project.

Briefly, the present status is that a prototype antenna of 10.4 meter diameter, 0.41 meter focal length, has been successfully completed. The surface accuracy is at least four times better than that of any existing antenna in this size class: 50 µm rms. The design goal of 25 µm rms will be met or bettered in subsequent units. A prototype mount is being constructed under NSF sponsorship and will be ready by early 1976. The final remaining uncommitted funds in the present Grant, supplemented by $50,000 in additional NASA funds, have been applied to the continued development of an improved antenna of identical size but of heavier weight. This improved antenna is in mid-construction, and the remaining funds will suffice to nearly complete it.

Continuation of the effort to develop and build high-accuracy antennas for ground-based and space applications is the subject of a new proposal recently submitted to NASA.

For further information, a brief summary which describes the antenna design, and also the design of a prototype mounting being constructed for the antenna, is attached.

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APPENDIX A

1. General parameters. The 10-meter telescope described here is the result of a several-year effort at Caltech to design and built a highly accurate, yet relatively inexpensive telescope prototype of moderate size suitable for millimeter-wave interferometry and sub-millimeter infrared radiometry, over the full frequency range (up to approximately 860 GHz (λ = 0.3mm) for which the atmosphere transmits significantly under dry conditions at a favorable site. As a practical goal a 10-meter diameter paraboloid having a surface accuracy of 25 µm rms was adopted. This surface accuracy goal is nearly met by the prototype and will easily be met and probably bettered by subsequent dishes. The general features of the telescope are:

Antenna

Diameter	10.4 m	(34 ft.)
Focal Length	4.1 m	(13.5 ft.)
Weight	3600 kg	(8000 lb.)
Surface Accuracy (rms)	10-25 µm	(0.0004-0.001 in.)

Mount

Type	Altazimuth Fork, non-enclosed
Weight	35,000 kg (40 tons)
Pointing Accuracy	5" (absolute); 2" (short term)
Slew Speeds	40^{o}/min. (azimuth and elevation)
Wind Effects	operable to 50 km/hr; maneuverable to 80 km/hr; survive to 240 km/hr (peak)

Relocatability (for interferometric use)

Movable between reinforced concrete base pads by rail. Precision positioning to 0.2 mm by ball-and socket, cylinder and U-groove. Levelling by precision screw jacks.

Feeds

a) f/4.25 cassegrain focus 150 cm above paraboloid vertex.

b) f/12 cassegrain focus 40 cm below hollow elevation-axis torque tube.

2. Antenna. The antenna dish consists of a number of contiguous aluminum honeycomb panels attached to a steel support structure. The support structure is a tubular framework based upon a lattice of equilateral triangles in plan view. (Fig. 1) Four weights of tubing, ranging from 1 1/2 in. dia. x .280 in. wall to 1 in. dia. x .125 in. wall, are used, to approximately optimize the stiffness

for the given total weight. In all, 729 struts connect the tops, bottoms, and the shorter diagonal between adjacent pairs of the 99 parallel "posts". At each node, all forces pass through a single point to avoid bending deformations which would reduce stiffness. (Fig. 2) All members are fabricated to precise, computer-calculated lengths and are assembled using close-fitting ground pins in reamed holes. The structure, as assembled, is mechanically quite rigid, yet has very little internal stress and can be wholly or partially disassembled and reassembled with negligible dimensional change.

The vertex "spiders", to which the flattened steel strut-ends are pinned, are of three types: the central 24 (on the innermost 12 posts) are of steel (for maximum stiffness), the 3/8 in. thick fins being oven-brazed to a slotted 1 1/2 in. steel core; the others are of extruded 2024-T6 aluminum alloy, and are of two weights - one with 3/8 in. fins on a 1 1/2 in. circular core, and the other with 3/16 in. fins on a 1 1/4 in. core. All spiders are precision machined, jig drilled and reamed, and attached to their posts by epoxy adhesive reinforced by a 0.500 in. hardened steel cross-pin.

All posts and struts are zinc-phosphate plated, primed and coated with a high-durability, high-reflectivity white urethane enamel prior to assembly. At assembly, the pin holes are carefully re-reamed by hand to remove the urethane coating from the m. To further increase the stiffness, all struts, except those that must later be removed to disassemble the support structure for shipment, are coated on their inner faces at each end with a single-component epoxy adhesive, and each spider is baked (in place) when it has its full complement of struts attached to it.

The lattice of 84 hexagon-shaped aluminum honeycomb panels, each about 1.15 m in size, is supported by thin, laterally flexible steel rods, one threaded into the top spider of each post (Figs. 3,4) These rods, 0.500 in. in diameter and approximately 7 in. long, serve three purposes: the first, which determines their lateral stiffness, is to accommodate the differential expansion between the aluminum panels and the steel support frame over the temperature range of approximately - 10°C to +50°C to which the antenna will be exposed. (The lateral stiffness was chosen such that the bending deformation under the transverse weight of the panels when the antenna points at the horizon is equal to the thermally-produced transverse deformation of about 1 mm.) The steel rods are aligned perpendicular to the paraboloid surface so that their bending does not deform the reflecting surface.

A second function of these rods is to serve as sensitive, differential-screw adjustment points to apply small, precise corrections to the dish surface. One planned use of this capability is to correct for the non-homologous gravity deflections at a suitable intermediate zenith angle near 45°. Index marks are provided, to permit restoration of each rod to its exact setting at the time of manufacture, if desired.

A third function, to be implemented at a later time if necessary, is to serve as an active control element to correct for the remaining gravitational or other small, slowly-changing effects, by applying an appropriate heat source of a few watts to each rod. Suitable thermal insulation of the rod itself establishes a temperature profile whose integrated expansion effect is essentially independent of ambient wind and temperature.

During assembly and machining, the dish is supported on a large air bearing. The upper honeycomb surface (Fig. 3) is open-celled and is machined to shape using a high eed, knife-edged circular cutter. (Figs. 5,6) The cutter is carried on a motor-driven carriage which can move radially along an accurately adjusted curved rail or "track". The carriage is stationary as the dish slowly rotates, and, at the end of each dish revolution, moves outward a few inches to its next fixed setting. The time required to complete a single cut over the whole dish is 4 to 8 hours. The 8-in. diameter cutter blade is of high-speed tool steel, flat on its bottom side, hollow ground, shallowly serrated around its perimeter, and hard-chrome plated. A single cutter easily lasts through many full cuts. When the final cut has been made, the panels are removed from the support frame and the cutting chips removed by air-blast.

The reflecting surface is 0.040-inch sheet aluminum, selected for uniformity of thickness and freedom from short-period surface irregularities. The "skins" are pre-sheared to the correct outline, cleaned and etched, coated on one side with epoxy, and elastically deformed by about 1 psi of external ("vacuum bag") pressure to mate with the machined honeycomb surface until the epoxy cures. The machining of the honeycomb is sufficiently accurate that further finishing of the aluminum skin is not ordinarily required.

3. Mounting. The mounting, of the altazimuth fork type, emphasized stiffness, smoothness of operation, and ease and accuracy of re-positioning when it is moved from station to station. It is described here from the dish-mounting interface downward.

The dish rests on nine machined boss-plates which rigidly constrain these points. In attaching the dish, the dish is first lowered onto three 1/2 in. shimmed boss plates and the three corresponding "spiders" are firmly bolted to the same; these are the three points that were used to support the dish on the air bearing. This leaves the remaining six spiders unattached, with a gap of about 1/2 in. between each spider and its boss plate. Adjustable shims are inserted into these gaps and so adjusted that, as each remaining spider is bolted down, its vertex does not move.

The boss plates are part of a rigid weldment which is integral with the elevation axis torque-tube. This tube is 40 inches in diameter and 89 inches long, and is supported by crossed-roller bearings at its two ends. These bearings, in turn, rest on bearing supports on either side of a 7 x 9 foot rectangular azimuth platform. The platform provides working space at the f/12 cassegrain focus, and may be extended by several more feet toward the rear if desired.

The platform - fork assembly is bolted as a unit to the top of the azimuth axis cone, which carries the azimuth bearings and drive gear. The vertical thrust load is taken by a radial-thrust roller bearing at the lower end (apex) of the cone, while lateral loads are taken both there and by a roller-thrust assembly just below the azimuth platform. This latter assembly consists of a total of 64 cam-follower rollers, carried in 8 identical, articulated units spaced every 45° around the circumference of a heavy ring surrounding the top of the cone. The rollers press inward on a hardened, ground steel ring mounted on the top of the cone, and all 8 rollers share the load equally (in the manner of railroad car wheel trucks).

The mounting base weldment is an 11-foot square structure of 16-inch I-beams, to which a 7-foot tall octagonal, pyramidal frustum is attached. This structure carries the thrust-roller assemblies at its top and the radial-thrust bearing at the center of its base.

4. <u>Position readout and drives</u>. Position readout is by 21-bit (0.6") single-turn inductosyn encoders on each axis. The aximuth drive is a two-motor, anti-backlash arrangement with an approximately constant differential torque, so that the drive motors share the load for large external torques. The elevation drive utilizes a heavy-duty, pre-loaded ball screw and a single drive motor. Provision for attachment of a second ball screw and motor is included should this be needed. All three motors are identical and are driven through solid-state servo amplifiers having adjustable gain, velocity, feedback azimuthal

load-sharing, and inertia-simulating networks. The external inputs, supplied by the control computer and updated several times per second, are voltages proportional to the desired velocities.

5. Mounting adjustment, posit   e, and tie-down. Provision is made to set the elevation axis orthogonal   intersecting the azimuth axis, using shims and lock-screws. Vertical alig   c of the azimuth axis is accomplished in two steps; with the base levelled, the thrust-roller assemblies are adjusted in a suitable progressive pattern to both align the axis and to share the pre-load equally. This done, fine adjustment for true vertical is made using adjustment jack screws as two corners of the square base. A collimator   scope pointing vertically downward toward a shallow pan of oil is used to evaluate the degree of misalignment.

Each corner of the base is provided with a vertical (levelling) adjustment: two adjacent corners have plain acme-threaded jack screws and jam nuts, and two have precision screw jacks with gear-driven nuts for finer adjustment. The bottom of one plain screw is spherically cupped and rests on a hardened, stainless steel sphere embedded in a heavy steel fitting bolted to the concrete pad. This screw and ball, once set, are not subsequently readjusted either laterally or vertically. At the diagonally opposite corner is a fine-adjustment jack. Its screw is cylindrically cupped and mates with a protruding semi-cylinder on the pad. The axis of the cylinder points toward the sphere at the opposite corner. The jack can be positioned laterally on the mount base, and the cylindrical boss-plate can be positioned laterally on the pad as well as shimmed vertically. Once set, these adjustments too are not further changed save on special occasions. The two remaining corners comprise the remaining plain screw and fine jack, and each has a flat foot-pad which rests on a flat plate on the concrete pad. The plates can be adjusted laterally and shimmed vertically.

One of the latter two corners - that having the plain screw - also is equipped with a heavy coil spring which can be compressed so as to make up the desired portion of the total load, ideally, one-fourth. The plain jack screw at this corner is then set so as to rest on its steel plate but to carry essentially no load. Thus all four corners are caused to share the vertical load nearly equally.

Each of the steel plates at the four corners of the concrete pad is provided with male threads and each jack leg has a corresponding loose-fitting shoulder nut on it. When the mount has been emplaced and levelled, these nuts are tightened down to provide positive tie-down for the telescope — mandatory in high wind conditions.

Adjustment of the jack-screws on each telescope, and shimming and lateral positioning of the four tie-down plates in each concrete pad, is done so as to require a minimum of re-levelling when any particular telescope is relocated to a given pad: the tie-down plates in the assembly-pad are levelled and laterally positioned as the first telescope is assembled, and are not subsequently moved. As later telescopes are assembled on this pad, the plates serve as templates for setting the jack-screws on each telescope. Likewise, the first telescope, as it is moved to a newly constructed pad for the first time, is used as a template for setting the tie-down plates at that pad.

Telescopes are moved from pad to pad on a low-bed wheeled platform running on railroad rails, and are lowered hydraulically onto the kinematically defined tie-down plates. It is expected that careful attention to these features will permit relocating telescopes to within a fraction of a millimeter and will save much time in baseline calibration.

The concrete pads and track are on a T-shaped pattern, and all telescope pads are at the same absolute level within few millimeters.

Deformations and surface accuracy. The performance of a telescope on the earth's surface is limited by its intrinsic surface accuracy and by extrinsic deformations determined by the gravitational, thermal, wind, "seeing" and other ambient conditions. Through careful design, the variable effects can be minimized within a given cost budget; with skill and care in fabrication, the intrinsic surface accuracy can be as good as the design will permit; with careful scheduling and planning of observations, the most critical observations can be carried out under the most favorable ambient conditions; and with luck, good results may be obtained.

In the initial design of the prototype antenna, the total deformation of the support structure under symmetrical (vertical) loading, and the minimization of this deformation for a given structure weight and applied load, were the main considerations. Assuming that the structure started with a perfect figure under zero gravity, the departure of the panel-support vertices from a paraboloid of revolution under normal gravity was evaluated. Typically, the total deformation at the dish edge was about 200 μm, of which all but about 10 μm rms was homologous to a paraboloid. As the construction of the prototype dish proceeded, a more complete deformation analysis program was developed, which eventually included not only the effects of antisymmetrical (transverse) loading, but steady wind stresses and deformations, non-linear "looseness" in the pinned joints, thermal deformations for any sun angle, including shadowing of the structure by the dish surface, and deformations due to various mounting-plane constraints and feed support loads. This program is still used for improving the design and evaluating various effects of interest. The results quoted below represent typical expected properties of the "improved" dishes, subsequent to the prototype unit.

a. Lateral gravity deformations depend both upon the structure characteristics *per se* and upon the dish mounting constraints. Of several possible mounting schemes, the one chosen is the simplest to realize and is not markedly worse than the best one tested. The selected scheme is simply to fix the lower (rear) vertices of the nine posts next nearest the center, i.e. omitting the centermost three posts themselves. This yielded a deformation pattern with the top and bottom edges of the horizontally-pointed dish sagging generally downward, the support points dimpled inward or pushed outward. The total deformation range was +125 μm to -210 μm from the best fit paraboloid, with an rms deviation of 80 μm. The focal axis was shifted laterally by 1.0 mm and the focal length increased by 5 μm.

The effects of this important deformation source can be greatly reduced in two ways: first, by using the differential-screw panel support rods, the effect can be adjusted away at a suitable intermediate elevation angle - probably 40° -45°. This reduces the weighted rms deviation over the whole range from the horizon to zenith by a factor of between 3 and 4. Actually, much of the sky near the horizon is useless because of excessive atmospheric attenuation, so that a factor of 4, or 20 μm, is taken as realistically attainable by this means. Second, if the needed precision of a dish warrants it, active thermal control of the panel support rods (as earlier described) can be used to cancel the remaining deformation over a range of zenith angles.

b. Thermal distortions due to anisotropic solar illumination can be an important deformation source under some conditions. A worst-case calculation, based on a 3°C temperature differential between fully illuminated and fully shadowed struts gave an rms distortion of 13 μm. This effect is of course not present at night.

c. Wind deformations are of little concern at OVRO because of its very favorable wind-speed spectrum but considerable deformations may occur for prevalent wind speeds at some high-altitude sites. As an example, for a zenith angle of 45° with the antenna facing into the wind direction, a wind speed of 30 mph produces a pitch moment of 7000 lb-ft and a drag force of 1200 lb, according to available wind tunnel data. The resulting axis shift is 15" and the rms residuals from a paraboloid were 25 μm. As in the case of thermal deformations, the effects of wind can be avoided if critical observations are scheduled or reserved for periods of favorable ambient conditions, and if favorable conditions prevail sufficiently often.

d. Dish surface errors. In addition to the variable, extrinsic errors already discussed, an antenna also has an intrinsic error figure which remains even under the most favorable ambient conditions. A complete discussion of the sources of intrinsic errors is not appropriate here. However, to give some indication of the nature and magnitudes of such errors for the present dishes, some of them are listed in Table 1.

TABLE 1

CALTECH 10-METER DISH SURFACE ERRORS

Source	Approx. rms Magnitude, μm prototype	"improved"	Basis for Improvement
1. Cutter track shape	15	5	Interferometric, null method for track adjustment.
2. Panel elastic "rebound" and cutting-tool heating deformations	35	12	Heavier honeycomb panel skins.
3. Cutting tool "scalloping" effects.	7.5	2	Finer steps on finish cut.
4. Skin thickness variations.	7.5	7.5	
5. Air bearing "wobble" effects.	10	5	Adjust out using differential screws
6. Panel demount-remount errors.	5-15	5-10	Check dish shape on mount and adjust differential screws.
7. Support structure deassembly-reassembly.	5-15	5-10	
Total rms effect	41-46	17-22	

FIGURES

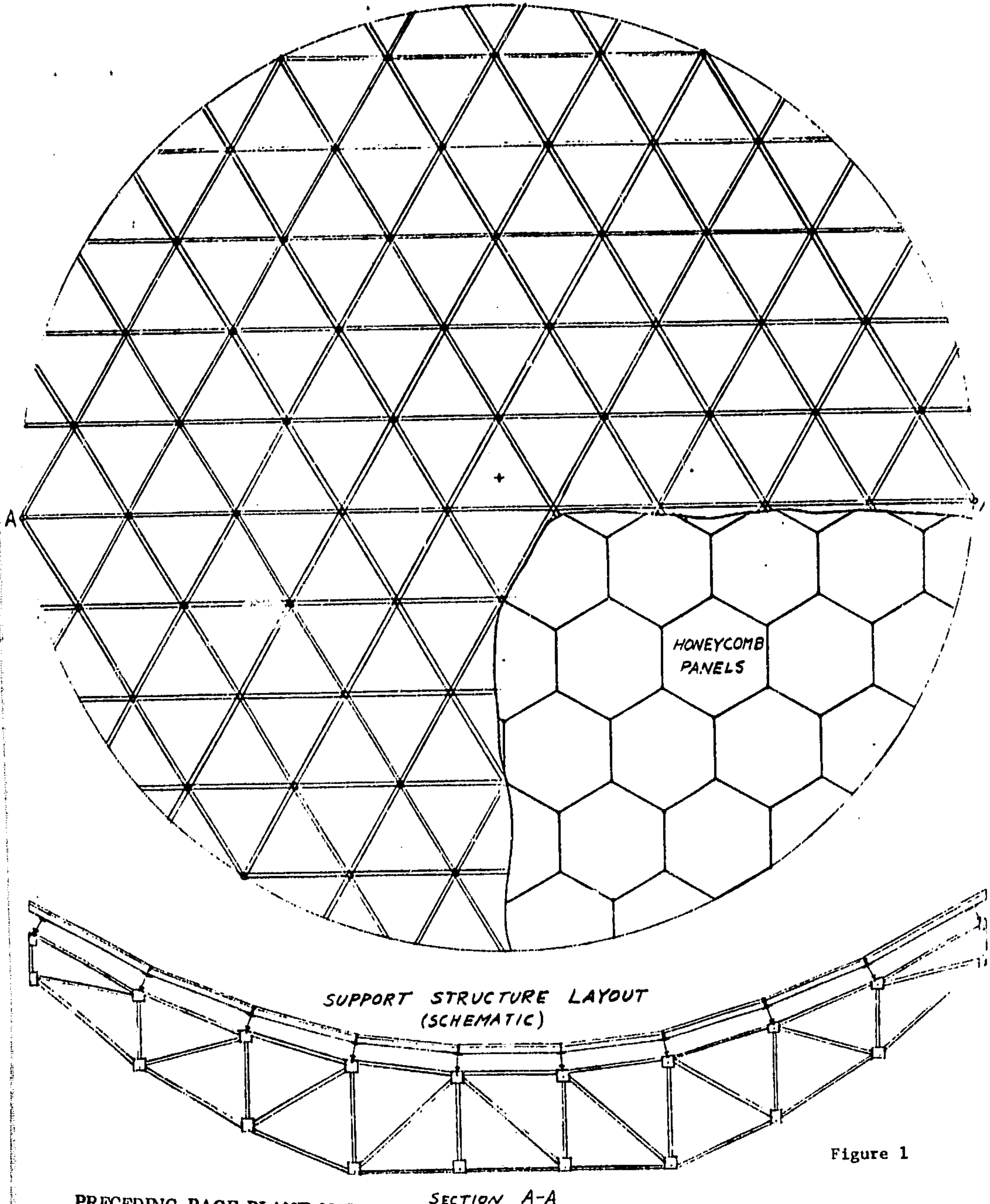
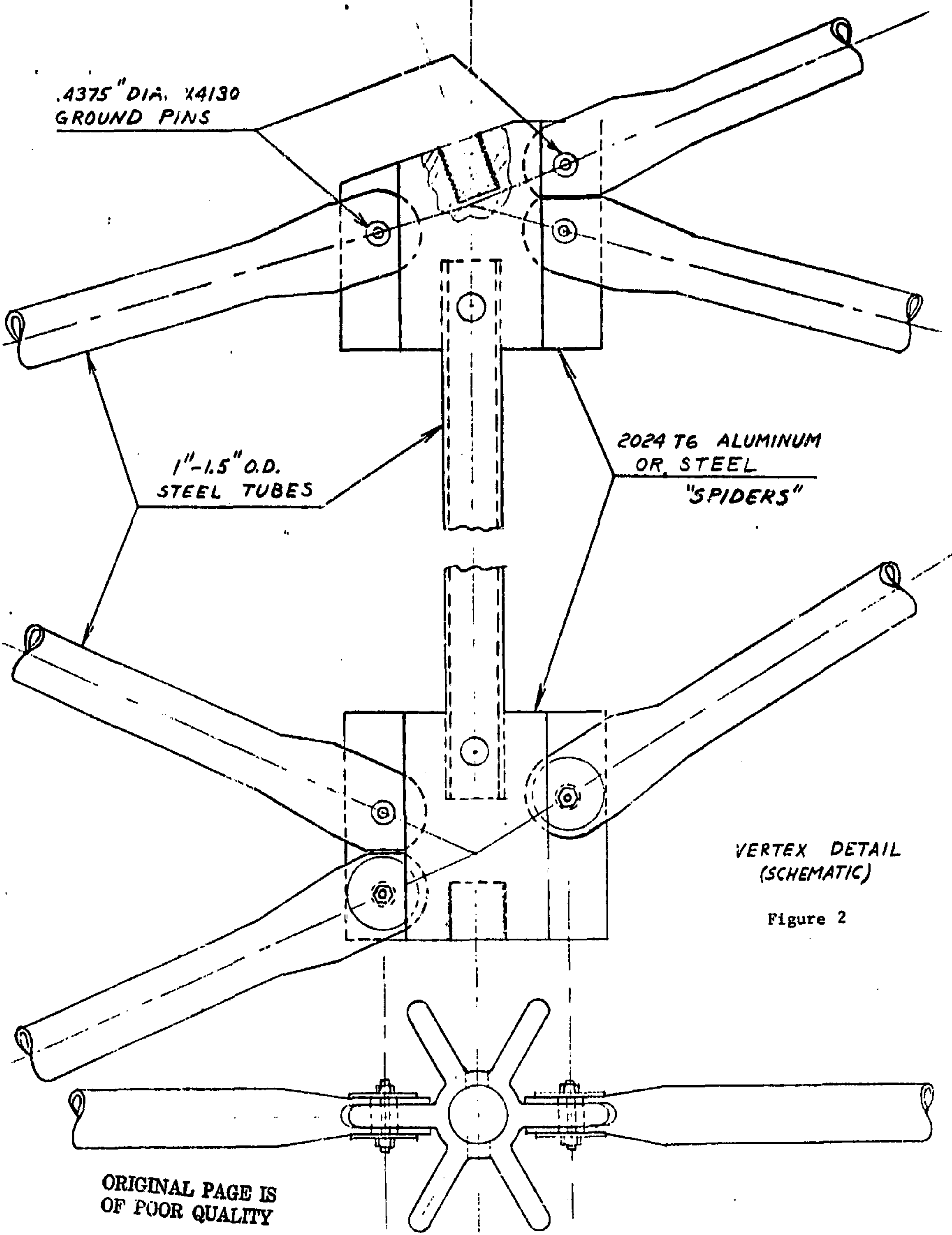
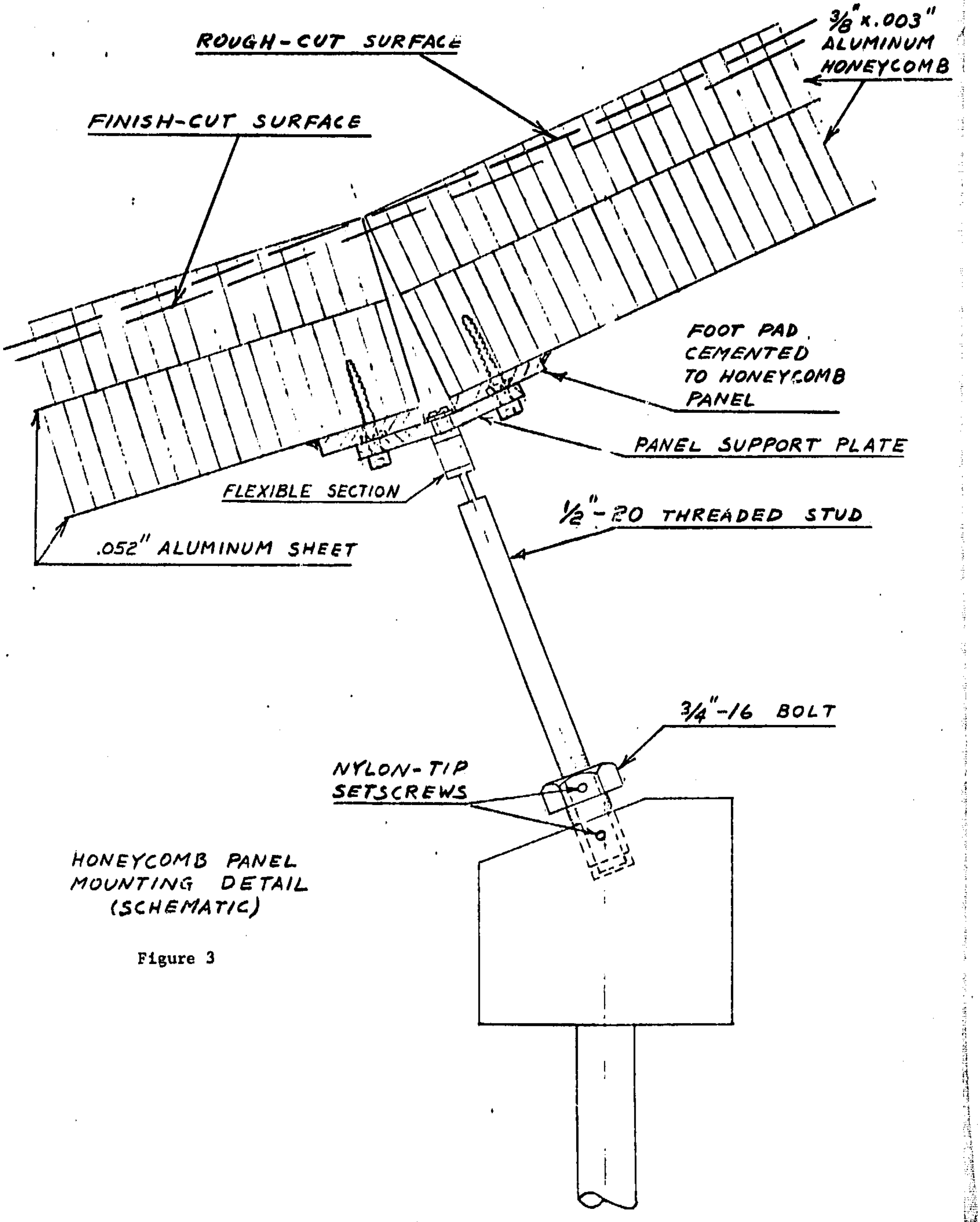

A
HONEYCOMB PANELS
SUPPORT STRUCTURE LAYOUT
(SCHEMATIC)
SECTION A-A

Figure 1



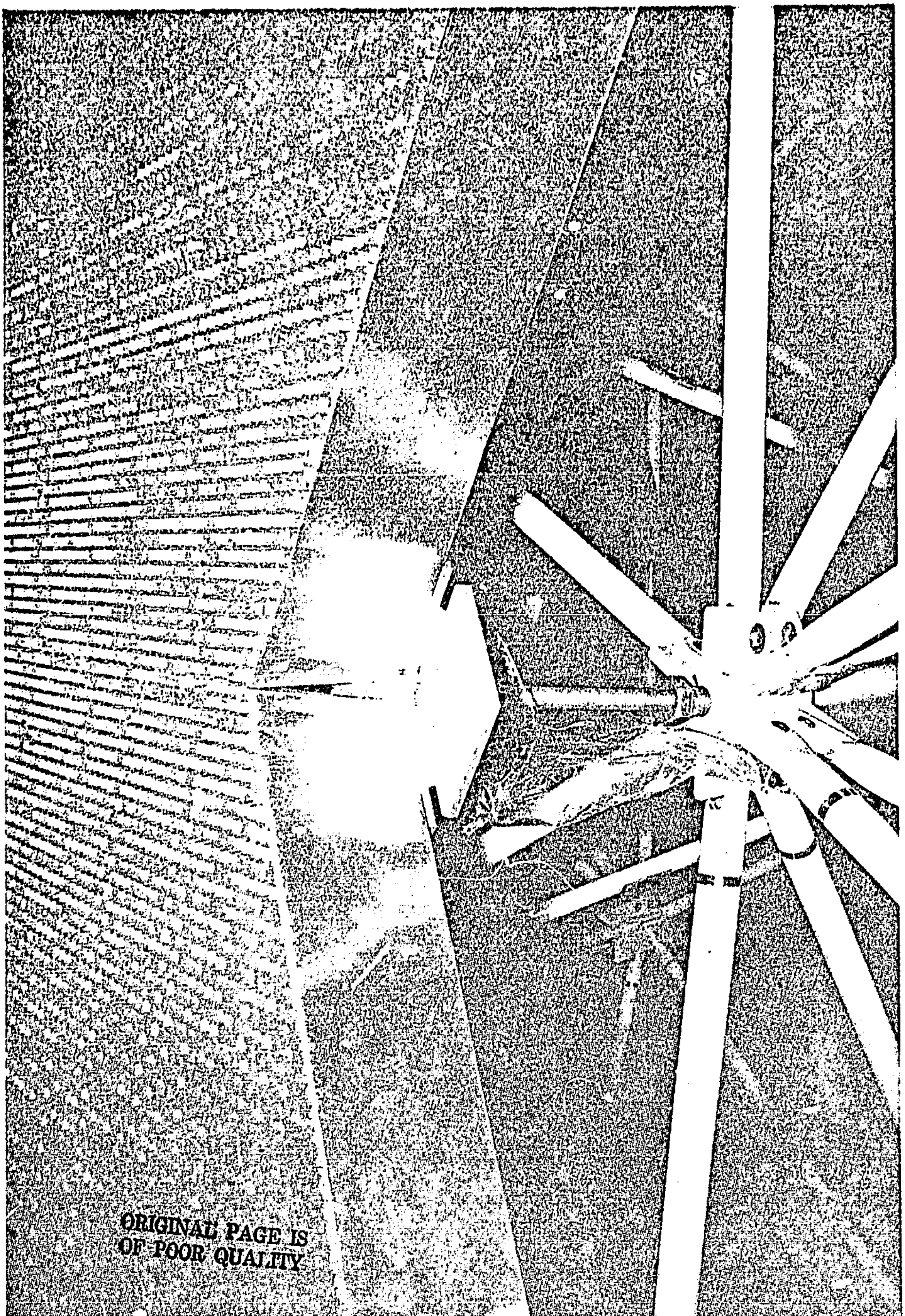
VERTEX DETAIL
(SCHEMATIC)

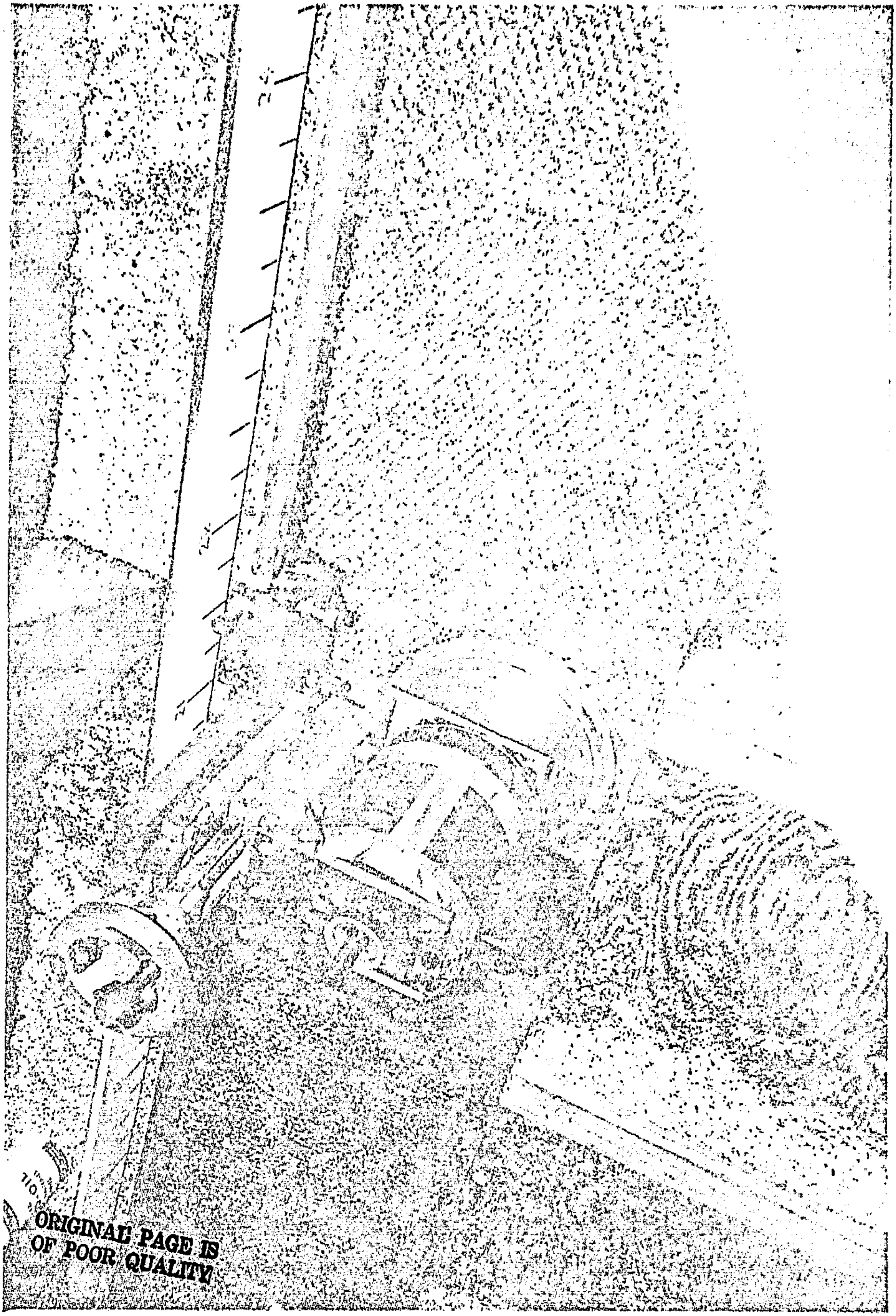
Figure 2

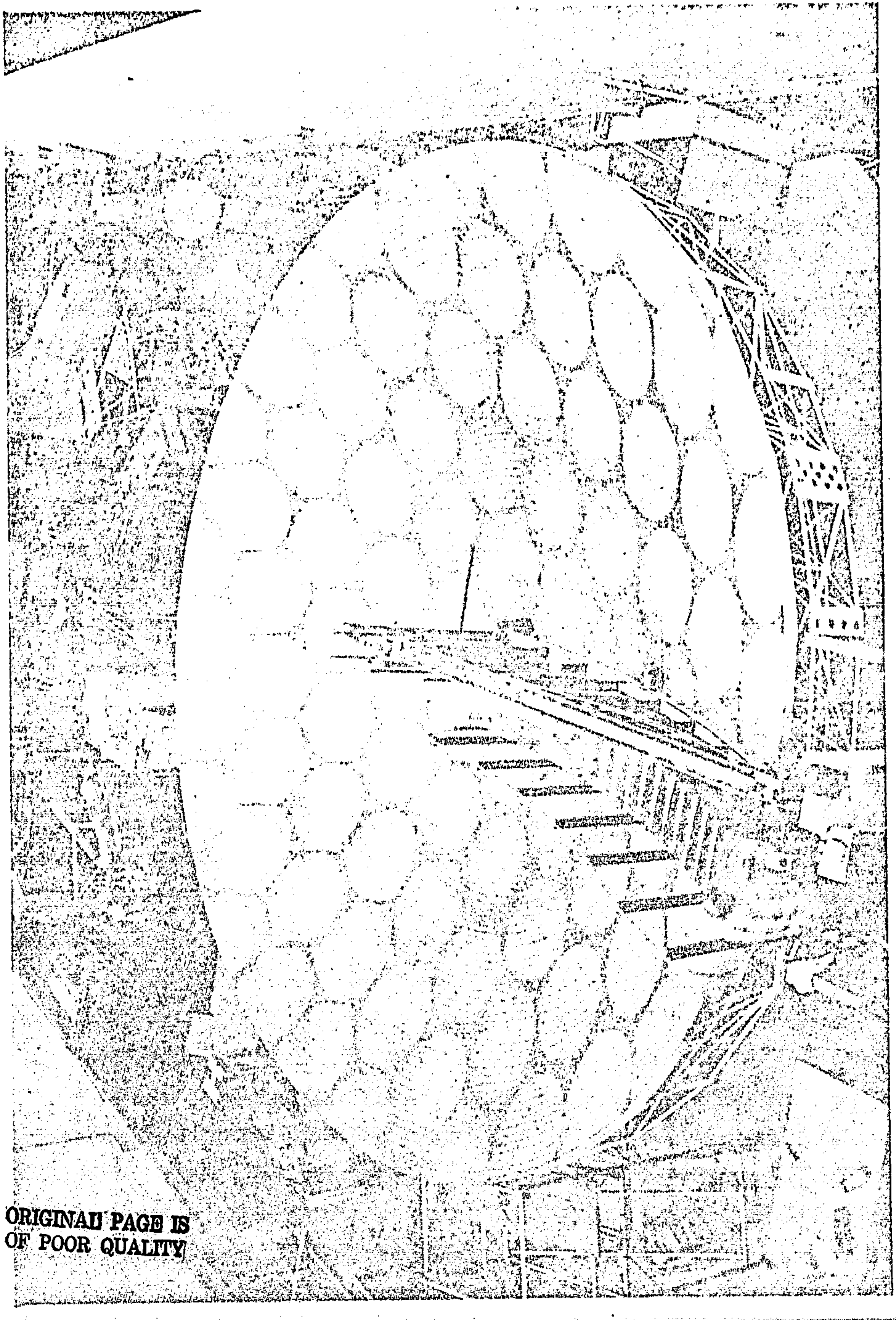


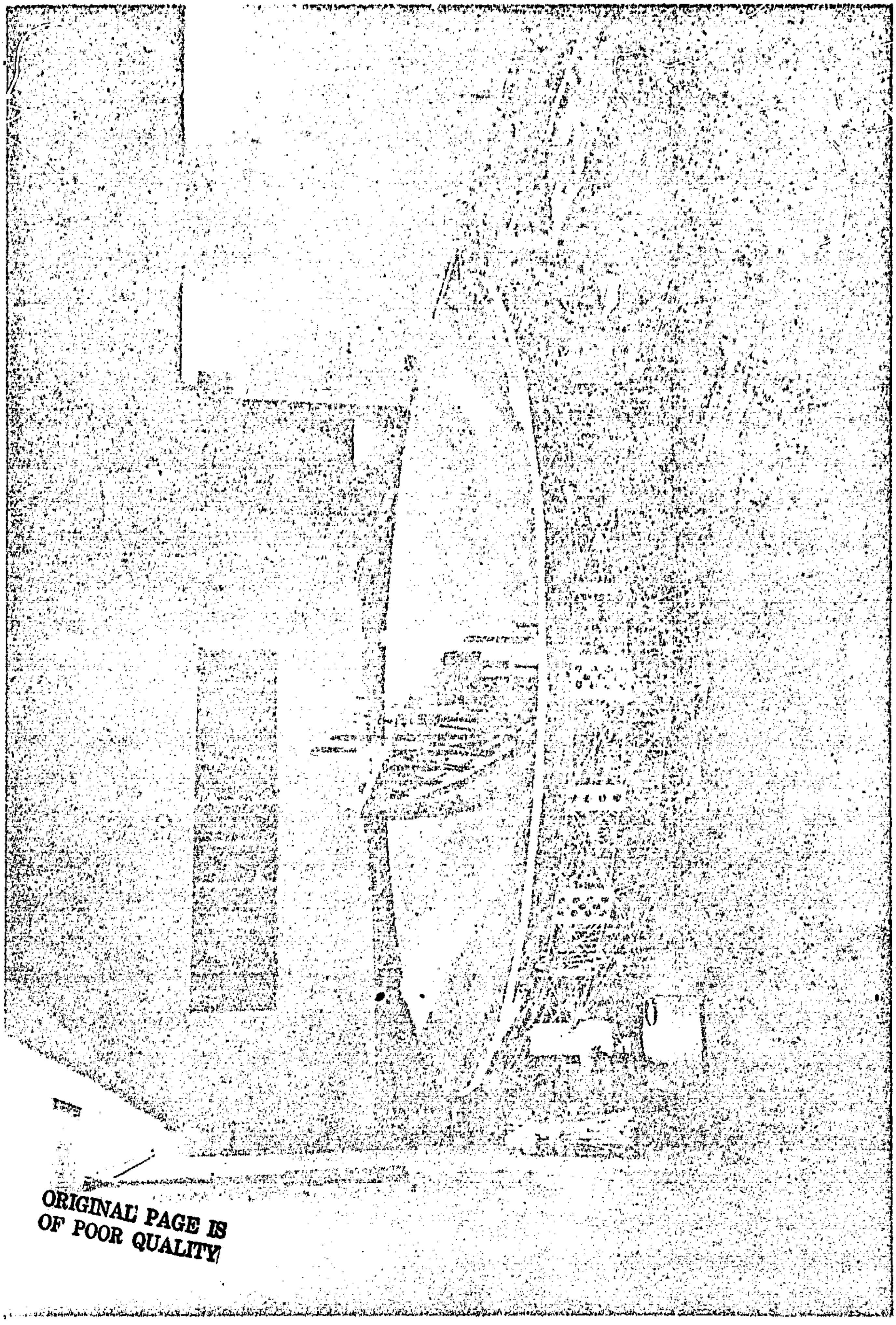
HONEYCOMB PANEL MOUNTING DETAIL (SCHEMATIC)

Figure 3









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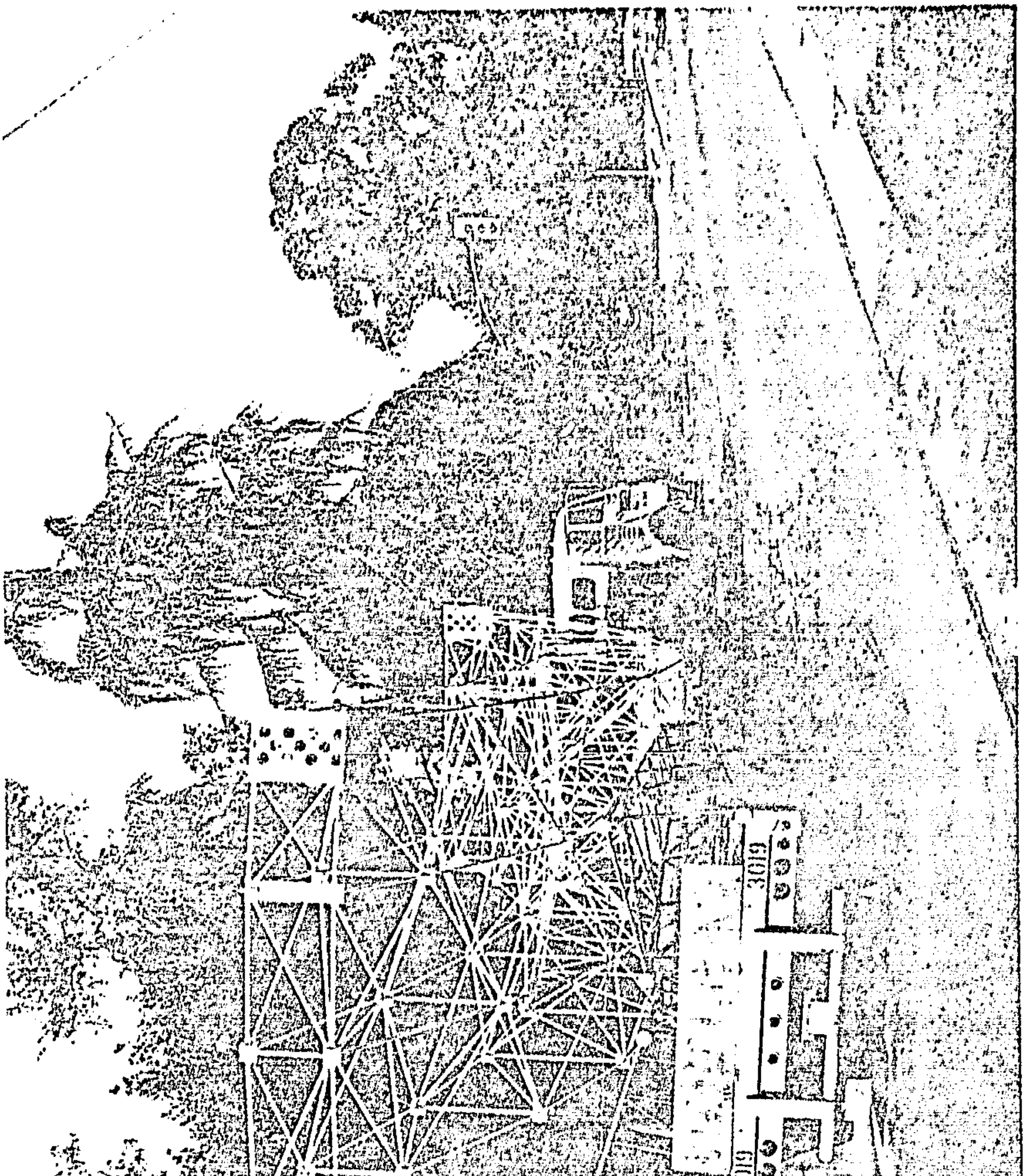
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