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Technical Report 32-952

Mariner Mars 1964 Antenna Structure Design and Development

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Contents

Figures

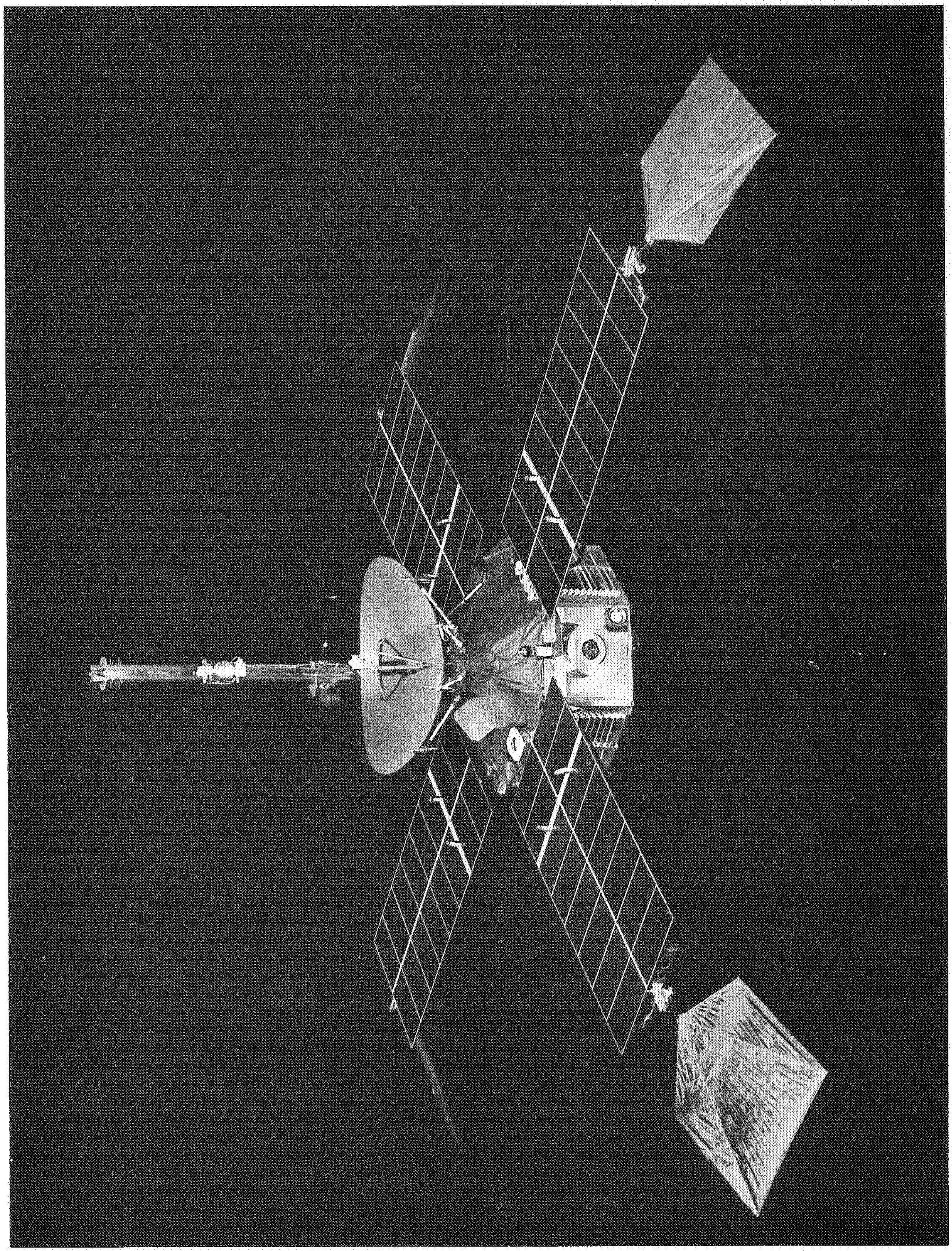
Contents (contd)

Figures (contd)

Abstract

Various approaches explored in the development of lightweight *Mariner* Mars 1964 *(Mariner IV)* high-gain and low-gain antennas are discussed and key problem areas highlighted. During the development of the *Mariner IV* high-gain antenna reflector, various design concepts and fabrication techniques were investigated and prototypes of the various designs were built. Special problems with their solutions are discussed and some suggestions are given for future lightweight antenna development. Also highlighted are special properties of foil gage aluminum honeycomb structures and of oriented fiberglass trusses. The background of the *Mariner IV* low-gain antenna structure, its design requirements, constraints, and fabrication problems are described.

The report emphasizes the importance of technical refinement in antenna development, the maintenance of balance between analysis and developmental testing of subassemblies, and the close coordination required between the mechanical and the electrical engineer to resolve special problems while meeting delivery schedule and performance criteria. Also discussed are procurement techniques that enhance the probability of delivering high quality hardware on schedule.



Mariner Mars 1964 spacecraft

Mariner Mars 1964 Antenna Structure Design and Development

I. Introduction

On July 14, 1965, after a flight of 229 days, the *Mariner IV* spacecraft flew by Mars to conduct scientific experiments, provide maximum information about the planet, and to obtain television pictures of the Martian surface. Mars atmospheric data was obtained from the behavior of the spacecraft radio signals during planetary occultation. After 307 days of flight (Oct. 1, 1965) communications capabilities were exceeded and spacecraft tracking was terminated. Regular tracking was resumed in May of 1967. Satisfactory spacecraft operation continued until Dec. 20, 1967, when tracking operations were suspended as a result of spacecraft attitude control gas depletion. Throughout the 1,117-day period (Nov. 28, 1964 through Dec. 20, 1967) the two antennas performed as designed.

During the early portion of its flight, while *Mariner IV* was near earth, the spacecraft transmitted scientific and engineering data through a low-gain, omnidirectional antenna. Because the antenna was omnidirectional, it could remain fixed, rather than pointing to earth, as earth moved across the spacecraft's "sky." After 97 days of flight, however, earth was so far from the spacecraft that only a weak signal was received from the low-gain antenna. Transmissions were then switched to a high-gain antenna to beam more of the transmitter's power in the direction of earth. At the time of the antenna switch, the pointing direction from spacecraft to earth had become nearly constant, and changed very little through the remainder of the mission to Mars.

Because the earth pointing angle remained nearly constant through the late portion of the mission, *Mariner IV*'s high-gain antenna was not required to track earth and was, therefore, rigidly fixed to the spacecraft. This rigid mounting of the antenna increased system reliability and reduced system weight. However, the decision to have a nonactuated high-gain antenna complicated the design of the antenna itself. The earth pointing direction *did* change slightly during the high-gain transmission. Therefore, it was necessary to make the antenna pattern elliptical along the direction of the earth's motion. The need for an elliptical antenna pattern led to a requirement for an elliptical parabolic antenna reflector, with the resulting problems of difficult mounting geometry and complicated structural analysis.

The *Mariner IV* spacecraft made use of new S-band (2.3 GHz) radio equipment rather than the more conventional L-band equipment (0.9 GHz) of the *Mariner* Venus 1962 project *(Mariner II)* and *Ranger* spacecraft.

This higher radio frequency presented some important size advantages to antenna design. Because the sizes of feeds, reflectors, and waveguides are inversely proportional to frequency, dimensions were reduced by a factor of 2½, compared with the old L-band systems. A serious disadvantage of utilizing this new frequency was that line losses in flexible coaxial cable were very high at S-band. Consequently, semi-rigid coaxial tubing had to be used for routing critical RF energy around the *Mariner IV*.

Due to the changes in radiated frequency, spacecraft configuration, and antenna pattern requirements, the *Mariner IV* mission required the design of entirely new low- and high-gain antennas. These antennas were required to be as light as possible because of spacecraft center of gravity restrictions, as well as the usual overall payload weight restrictions. In addition to weight restrictions, the antennas were required to have no severe resonances at low frequencies (a clearance restriction), to have accurate contours, to be reasonably priced, to have short production lead times, and to have high reliability as a design and from piece to piece. Beyond these design restrictions, the low-gain antenna was required to be placed high (7 ft) above the spacecraft. However, an oil-derrick type of support structure (as in *Ranger* Block 1 and *Mariner II*) could not be allowed because the science instruments and high-gain antenna look angles were such that it would disturb the antenna pattern and occlude portions of the instruments' views.

II. High-Gain Antenna Structure

A. Description

The *Mariner IV* high-gain antenna (Fig. 1) consisted of an elliptical sector of parabolic reflector and a double turnstile feed with strip line power splitter and matching network. A fiberglass feed support truss joined the feed and reflector, an antenna support truss joined the reflector to the spacecraft, and a section of rigid coaxial tubing, supported by the feed and antenna support trusses, passed from the feed through the reflector. The development of this high-gain antenna structure is best described

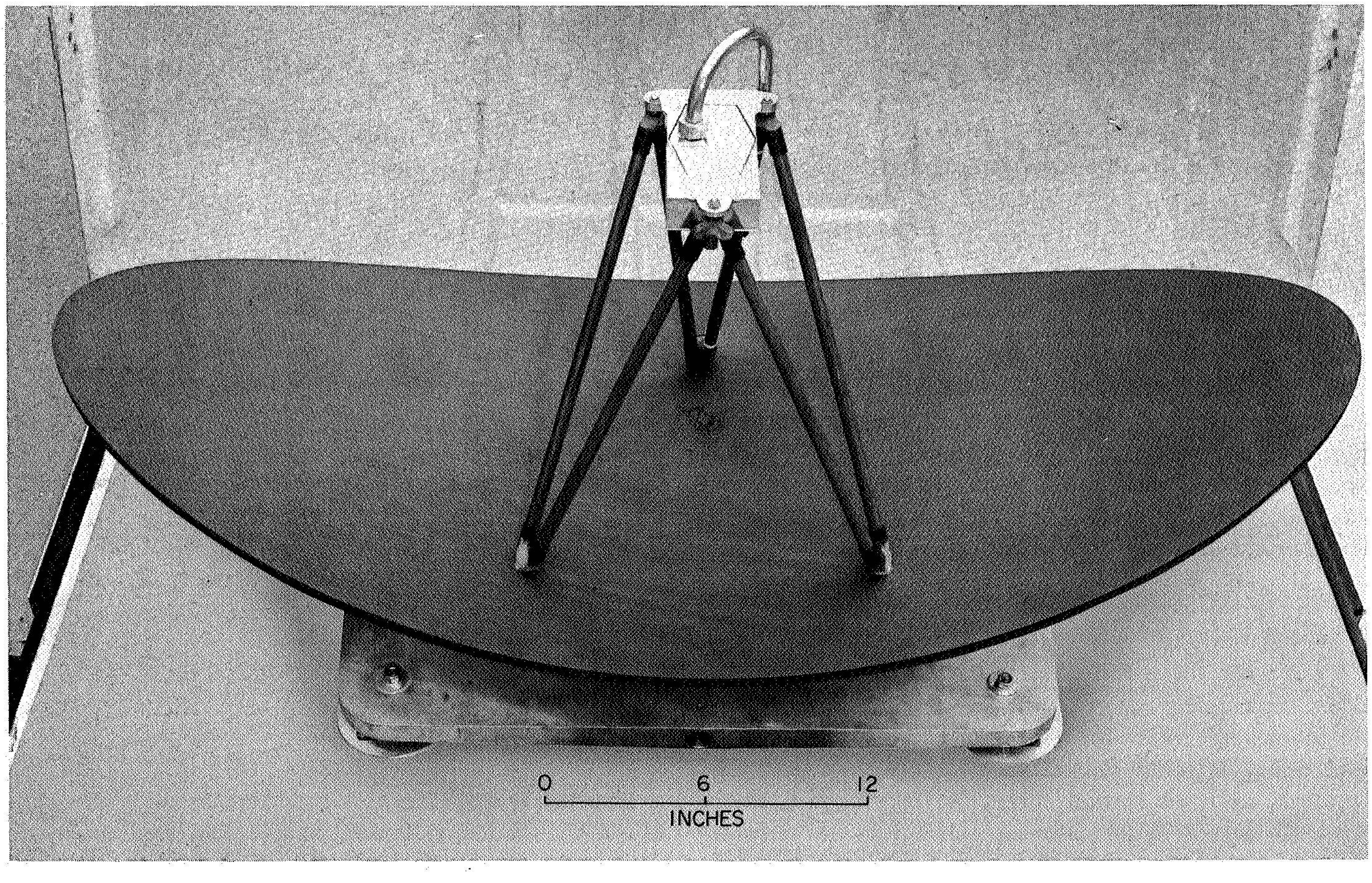


Fig. 1. *Mariner IV* high-gain antenna

by considering the development of each component separately, and then explaining the overall testing used to verify the structural integrity of the completed antenna.

B. High-Gain Antenna Reflector Development

*1. **Background.*** The *Mariner IV* high-gain antenna reflector, unlike those of *Mariner II* and *Ranger*, was required to be self-supporting during the vibration and acceleration of rocket launch. The auxiliary reflector support structure which reached up from the *Agena* adapter to the *Mariner II* and *Ranger* antennas could not be used for *Mariner IV*, because its antenna had to be located on top of, rather than underneath, the spacecraft. Without auxiliary supports, a *Mariner II–Ranger* type of reflector structure would have required considerable strengthening to survive the boost environment, and the resulting weight would have been prohibitive for the *Mariner IV* mission requirements. The unadaptability of the old space frame and wire screen *Mariner II–Ranger* reflector designs to *Mariner IV*'s requirements led to a search for new, lighter weight reflector, design concepts.

*2. **Reflector development programs.*** The development and fabrication of antenna reflectors based on new design concepts had been underway in the *Mariner/Centaur* project for approximately one year before the initiation of the *Mariner IV* project. Three approaches that showed promises of success were:

(1) Explosion form and chemically mill an aluminum parabolic reflector; then, fabricate a support structure to strengthen the basic shell and attach that structure to the shell's back side.

(2) Hot mold fiberglass honeycomb core to a parabolic shape, then lay up thin fiberglass face skins on that core.

(3) Machine aluminum honeycomb core to a parabolic shape, then vacuum draw aluminum foil face skins and bond them to the core.

All three approaches could be made to work. Each offered advantages and all introduced significant problems.

a. Explosion formed reflector. In its behavior and in the analytical techniques used to predict that behavior, the explosion formed reflector with a back stiffening structure was similar to previous *Mariner–Ranger* structures. The thick reflector skin (0.032 in.), though chemically milled in some areas, was heavy and required a heavy backing structure for proper stiffening. Through explosion forming an accurate parabolic contour could be achieved. An adequate structural analysis of this type reflector would have been easier to make than either of the honeycomb reflectors being studied. The main drawback of this otherwise attractive reflector was its low stiffness-to-weight ratio, hence high total weight for a given application. The *Mariner IV* weight limitations made this predictable and conservative approach seem an undesirable one to pursue.

b. Fiberglass honeycomb reflector. The fiberglass honeycomb reflector offered the high stiffness-to-weight ratio of a honeycomb sandwich construction combined with the ease of fabrication inherent in fiberglass laminate lay-ups. A minimum of tooling was required, yet accurate reflector dimensions could be maintained without problems. This approach looked so promising that a prototype (Fig. 2), similar to the *Mariner IV* flight reflector, was built and tested. This reflector revealed that difficult weight control problems were inherent in the fiberglass lay-up construction. The porous fabric used in forming curved face skins had to be heavily saturated with epoxy resin in order to assure reliable bonding of face skin to core and face skin to face skin. Furthermore, the honeycomb core, hot molded to a parabolic form, exhibited some fraying of the end grain to which the face skins were bonded. This fraying required a further increase in use of adhesive to ensure proper bonding. The result of using great quantities of adhesive in the manufacture of this reflector raised its weight considerably (25%) above the predicted value. It was felt that reducing this adhesive proportion would yield an unreliable structure with weak bonding in local areas.

A second difficulty with the fiberglass face skins of this reflector is their inability to reflect radio waves. Concurrent with the fiberglass reflector development, an investigation of radio reflective coatings was conducted. This study covered conductive paints, vapor deposited metals, and flame sprayed conductive layers. Each of these methods had a serious failing, either in reliable conductivity, adhesion to the fiberglass surface, weight of the surfacing agent, or in structural damage (from heat) during application of the coating. Even at the conclusion of the *Mariner IV* antenna development effort, no acceptable reflector coating had yet been developed.

Despite the difficulties, a prototype fiberglass reflector was completed and vibration tested to establish its fundamental resonant frequencies and mode shapes. A series of backing structure modifications was also conducted in an effort to understand interactions of the

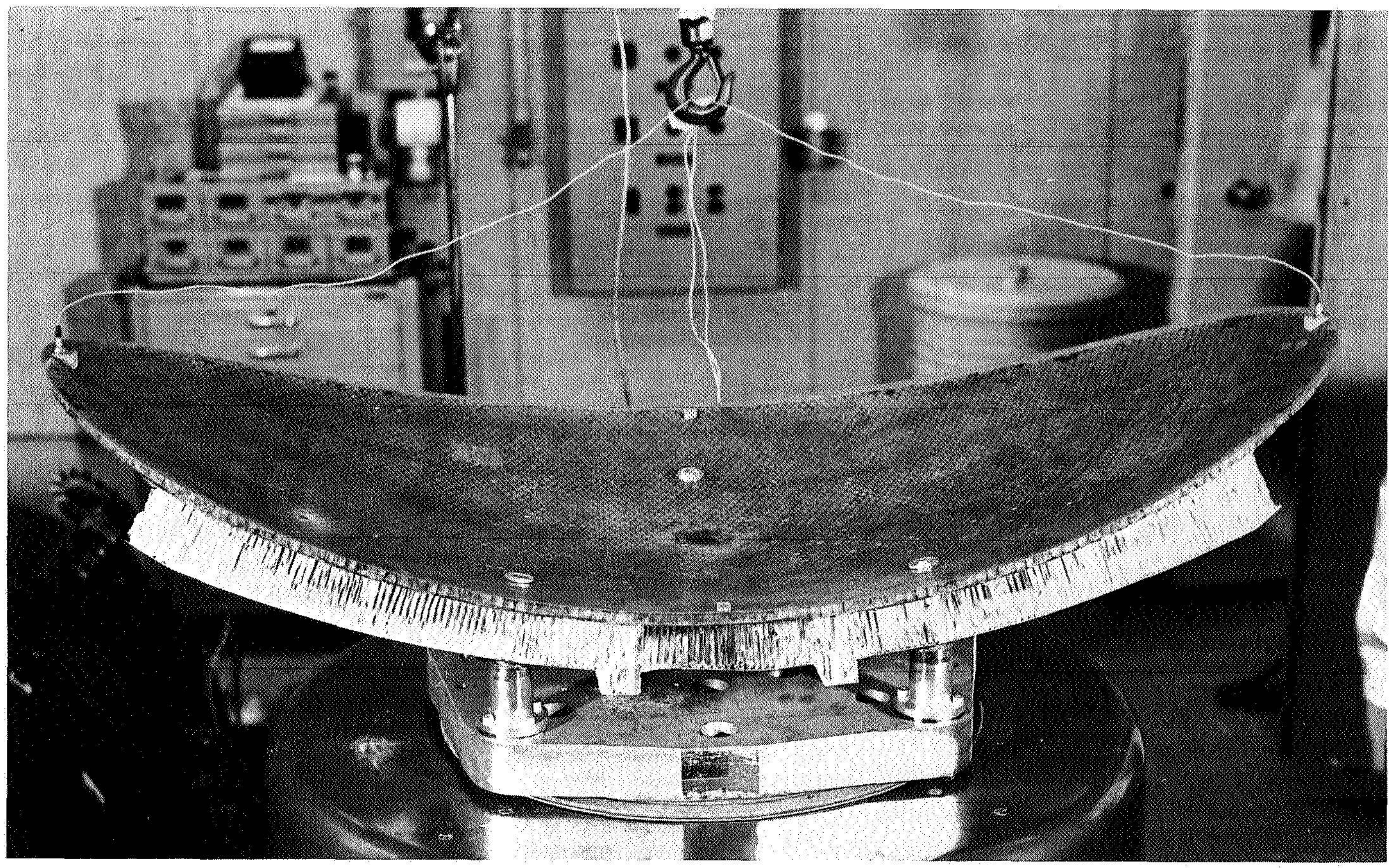


Fig. 2. Honeycomb antenna reflector, fiberglass prototype

reflector-to-backing structure. Briefly, the backing structure proved to be the primary structural contributor, whereas the fiberglass reflector shell was structurally soft. The reflector structure's (backing structure with reflector shell) lowest resonant frequencies were 48 Hz, 64 Hz, and 130 Hz when the backing structure's configuration approximated that of *Mariner IV*'s flight reflector. In contrast, the same resonances of an aluminum honeycomb prototype reflector structure were at 105 Hz, 122 Hz, and 193 Hz. The combination of conductive coating problems, weight control difficulties, and poor structural performance made the fiberglass honeycomb reflector an undesirable choice for the *Mariner IV* high-gain antenna design. Consequently, it was eliminated from further consideration.

c. Aluminum honeycomb reflector. The aluminum honeycomb reflector offered the potential of a higher stiffness-to-weight ratio (lighter structure) than any other usable material and fabrication process. Attainment of this full potential was hampered by the difficult fabrication problems associated with forming and bonding aluminum foils into a reliable structure. The *Mariner/Centaur (Mariner B)* reflector development program had produced an aluminum reflector whose core was machined from a massive block of aluminum honeycomb. With difficulty, the face skins had been vacuum-formed from aluminum foil and bonded to the core using a sheet of minimum-weight commercial honeycomb adhesive. This reflector was heavy in core and adhesive weights, but structurally much better than either the explosion formed or fiberglass reflectors. In designing the *Mariner IV* reflector, it was assumed that the problems encountered with this construction technique could be minimized and that the weight of unstressed material could be reduced resulting in a stiff, lightweight reflector. Under these assumptions, it was decided that the *Mariner IV* reflector design would utilize aluminum honeycomb construction.

3. ***Flight reflector fabrication problems.*** Three major fabrication problems were considered in formulation of the *Mariner IV* antenna reflector (Fig. 3):

(1) The difficulty of forming the foil face skins and core without damage.

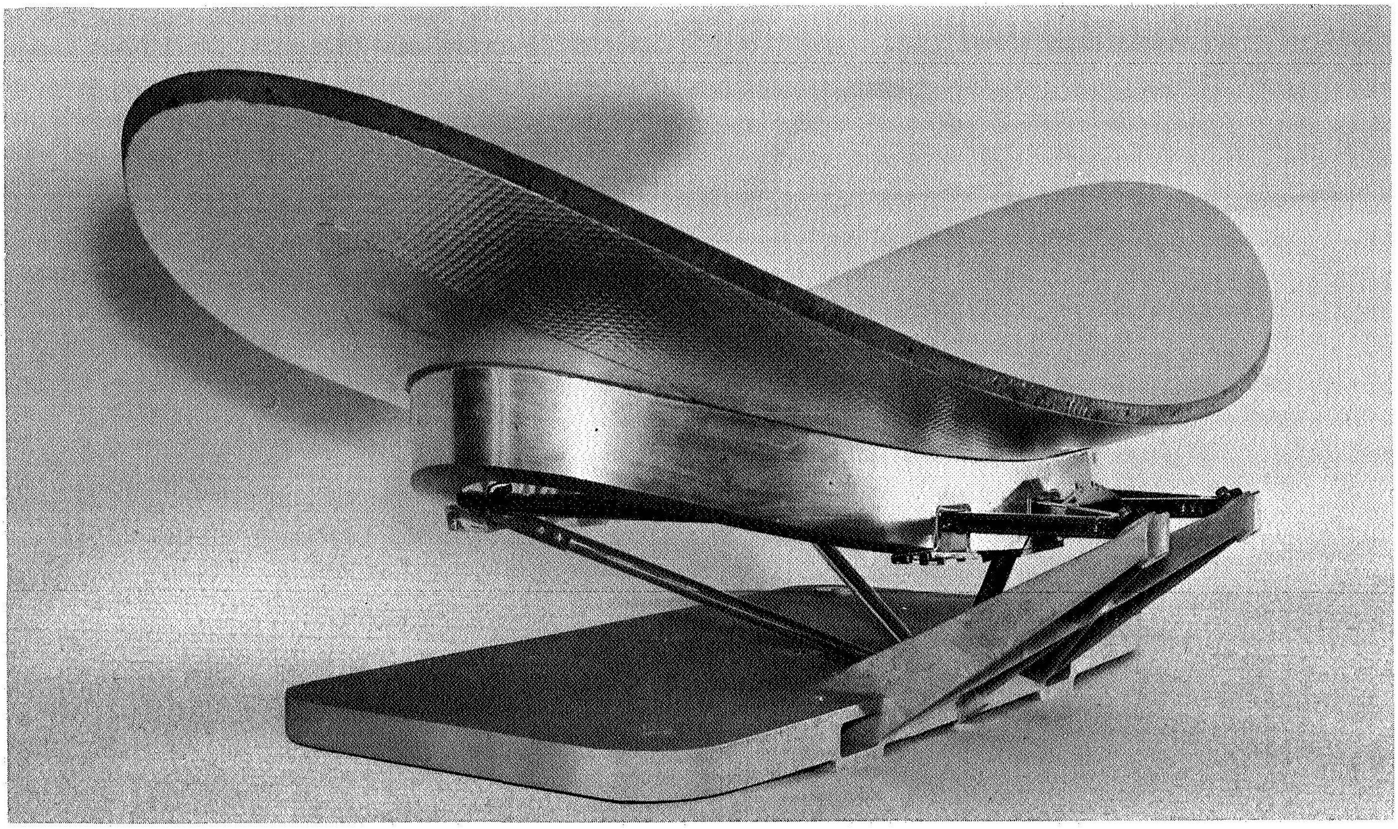


Fig. 3. High-gain antenna reflector, flight model

(2) The expense, production time, and accuracy involved in machining the reflector's honeycomb core from a massive block of aluminum honeycomb.

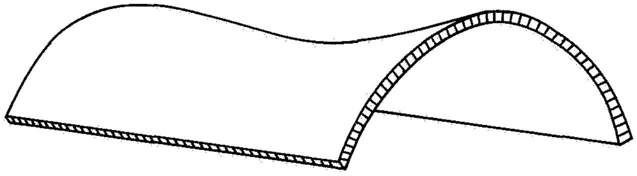
(3) The reduction of adhesive weight while ensuring structurally reliable bonds between face skins and core.

a. Skin and core forming problems. The problem of drawing the face skin was solved by using very soft (1145 series) aluminum and being exceptionally careful to select foil with no mill roller marks or imperfections. The use of low-yield strength aluminum face skins appeared to compromise the strength of the reflector. However, the failure mode of very lightweight honeycomb sandwich construction is a *buckling* of the face skins, a phenomenon dependent on the elastic modulus of the face skins and not on their yield strength. This phenomenon usually occurs in honeycomb sandwiches with cell diameter-to-skin-thickness ratios greater than 10.

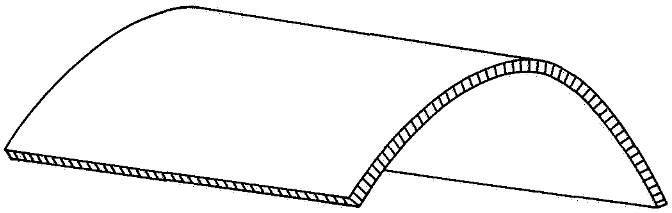
The contour molding of the aluminum honeycomb sheet to a double-curved surface was made difficult by both the fragility of the material (cell walls buckling, glue lines fracturing), and by its anticlastic properties (tendency to form a saddle when curved, as shown in Fig. 4a). The contouring was finally accomplished by forming the core sheet into a sharply curved half-cylinder (Fig. 4b) using sheet-metal roll forming techniques. The core sheet was then placed onto the parabolic antenna die and the prebent half-cylinder "opened up" (Fig. 4c) to match the die. This "opening up" caused the anticlastic half-cylinder to curve down at the ends, forming the desired parabolic dish, as shown in Fig. 4d.

b. Core machining problems. Core machining was minimized by designing the reflector as a thin shell supported by a honeycomb back beam. This design made it possible to form the thin parabolic shape from a 0.5-in.-thick sheet of honeycomb rather than machining it from a monolithic block. The back-beam structure might have been formed in the same manner, however, its ratio of thickness-to-bend radius was slightly larger than that of the reflector and this may have led to core damage during forming operations. The amount of machining required to produce a back-beam structure from a block of honeycomb core was small compared

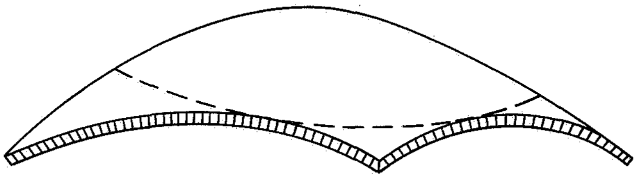
a. UNCONTROLLED ANTICLASTIC BENDING



b. CONTOURED RESULT OF ROLL FORMING



c. "OPENING UP" OF PRE-BENT HALF CYLINDER TO FORM COMPOUND CURVATURE



d. PARABOLIC REFLECTOR CORE; FINISHED BY TRIMMING CORNERS

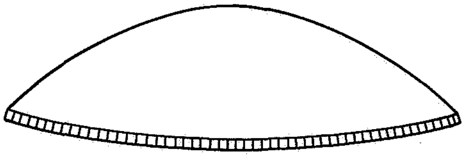


Fig. 4. Contouring of aluminum honeycomb sheet into a parabolic reflector core

with the amount required to produce a complete reflector shell. For safety it was decided to machine the back-beam structure, but to form the main reflector shell.

The thin-shell-plus-back-beam reflector design made it possible to produce a lighter weight structure than a deep section shell design would allow, because stiffness from the back beam could be strategically placed in areas of maximum stress with a minimum of deadweight being carried in the reflector structure.

An interesting fabrication sidelight was the development of "formable" core (flex core) which became available during the production of the *Mariner IV* reflectors. This core, developed by the Hexcel Corporation, can be hand-formed over bodies of revolution and other three-dimensional curves without using special techniques to overcome the anticlastic properties of conventional honeycomb core. Utilizing the Hexcel formable core (near the end of the *Mariner IV* project), an experimental reflector shell was made. This reflector was somewhat heavier than the flight reflectors because the lightest grade of flex core is heavier than the 1.6-lb/ft^3 core in the flight reflectors. However, when removed from the curing mold, this reflector shell was less stiff than the flight shells with less dimensional stability and larger "spring back." These undesirable properties may have been due to a lower shear stiffness in the new moldable core material, but no detailed testing was pursued.

c. Adhesive weight problems. The high adhesive weight, which was very serious in the fiberglass reflector fabrication, remained a problem in the fabrication of foil gage aluminum honeycomb structures. When enough adhesive is used to form large reliable fillets to bridge crevices between core and face skins, that adhesive layer becomes a significant part of the structure's weight.

Film adhesive. The obvious approach to reducing adhesive weight was the use of a very thin adhesive film in the face skin bonding operation. In the desired weight, no commercial structural adhesive was available. Some investigation revealed that a thin-film (1-mil) adhesive (FM 1044), originally designed for bonding copper foil to fiberglass circuit boards, was available from the Bloomingdale Rubber Company. This adhesive had not previously been used in honeycomb structural bonding, but had good wetting properties, fairly good peel strength, and was available on short notice. Laboratory testing on small samples of honeycomb indicated good sandwich strength (200 lb/in.^{2} flatwise tension) and acceptable peeling behavior. Ultimate bending strength tests on laboratory honeycomb sandwich samples revealed no bonding failures in buckled sections. Pressurization of single honeycomb cells (which might happen in vacuum if a cell's vent holes were plugged) revealed no propagation of local delamination. Instead, the 4-mil face skins would rupture (at very high pressures) and vent without general structural damage beyond the pressurized area. Examination of the bond joints revealed good filleting at the core-to-face-skin bond line despite the use of thin-film adhesive. The mechanism of this filleting appeared to be capillary attraction of the adhesive from the center of each cell's face skin to the edges, where the face skin contacted the honeycomb core walls. Thus, very little adhesive was left on the central area of each cell's face skin, whereas good fillets were formed at all joining lines.

Liquid adhesive. An alternate to the thin-film method of reducing adhesive weight was the use of liquid adhesive (rather than the partially pre-cured films discussed above) and roller coating it onto the honeycomb core cell edges just before applying the face skins. This approach put all the adhesive at the bonding joint lines and at first glance appeared to provide more efficient use of adhesive than the film approach. In actual practice, however, it became very difficult to roller-coat on as little adhesive as is contained in the 1-mil film, while ensuring a fair share for every cell. Quality control was nearly impossible with roller coating, since adhesive pot life and manufacturing down time would not permit "every-cell" adhesive inspection at this stage of fabrication. Also, it was nearly impossible to prevent random dry spots on the roller with the use of so little adhesive. These drawbacks of the roller coating technique led to the selection of thin-film bonding as the only acceptable lightweight bonding technique.

Crevices at joints. The direct extension of laboratory-bonded samples test data to large pieces fabricated in the open shop caused some worry about thin-film bonded structure's sensitivity to the tolerance variations encountered from piece to piece. Of special concern was the possibility of unevenly cut honeycomb failing to meet the face skins with a tight fitting joint line. If this occurred, crevices would exist at the joint, which the sparsely used adhesive could not fill, and the structural strength of the sandwich would be greatly reduced. To ensure that no such crevices would develop during bonding, the sandwich structure was bonded with a vacuum bag over the reflector's back skin and with a soft surface between the reflector's front skin and the parabolic mandrel. This arrangement pressed the 4-mil face skins against the honeycomb core hard enough to stretch the face skin material into dimples over each cell. This ensured that the perimeter of each cell was a tight joint line ready for bonding. The slight dimpling of the reflector face skins neither reduced the stiffness of the reflector, as measured by natural resonant frequency of the structure, nor degraded its radio reflector characteristics.

Dimpling technique. The dimpling technique worked very well in the production of thin skin reflector shells, resulting in successful production of ten reflectors without rejects. On the other hand, this technique was not applicable to bonding of the heavier (16-mil) skins used on the reflectors' back stiffening beam. A test back beam was bonded using the lightweight 1-mil-film adhesive and 16-mil skins, but significant areas of the face skins failed to bond properly to the core, because the skins were too stiff to follow slight variations in the core height. The total area of the beam skin bonds was only 154 in.^{2} compared to the reflector face skin's bond area of 1620 in.^{2}. Therefore, it seemed reasonable to switch to a heavier adhesive, rather than try to develop lightweight bonding techniques for thick face skins. The back beams were bonded with a 4-mil-film adhesive supported by a very light scrim cloth, and no further bond failures were experienced. The final result of reflector fabrication was a 46×21.2-in. elliptical sector of an 8-in. deep parabola with a weight of 1.73 lb, a fundamental resonant frequency of 120 Hz and a maximum variation from the desired parabolic surface of 0.040 in. or approximately 0.007 wavelength at S-band frequencies. We note that this accuracy is almost an order of magnitude greater than necessary for good reflector performance. Thus, frequencies of radio transmission an order of magnitude higher could be accommodated with no improvement in reflector accuracy.

C. Antenna Support Truss

The geometry of the transfer orbit from earth to Mars required the *Mariner IV*'s high-gain antenna to be mounted on top of the spacecraft and to be pointed 38 deg down from the vertical (sun direction). This pointing angle necessitated the use of a rather awkward support truss (Fig. 5) consisting of a conventional three-point to three-point trusswork skewed so that the top plane of the truss was at 38 deg to the bottom plane. With a little juggling of dimensions it was possible to place six of the nine truss members in a single plane. These six members and their associated joints were then simplified to a single magnesium plate "hogged-out" into a network of channel sections. The remaining three members were created by the conventional application of aluminum tubes with riveted-on magnesium end fittings. This truss could have been made stiffer and would have been easier to mate with the spacecraft superstructure, had it been a four-point to four-point mount rather than three-point to three-point. However, adjustability of the antenna pointing angle in the field by shimming the truss was considered an important design requisite. Had the truss been mounted at four points, it

Fig. 5. Antenna support truss

would have been very difficult to make adjustments and even more difficult to prevent development of residual stresses due to adjustments. Furthermore, the three-legged truss minimized the possibility of internal thermal stresses developing due to thermal gradients in the truss.

A major decision in the design of the antenna support truss was the choice between closing the top of the truss with three conventional truss members and closing the truss with the honeycomb reflector shell. The conventional truss member closure offered the advantages of easy analysis and member sizing, but had the distinct disadvantage of creating a redundant structure parallel to the reflector. Thus, if those three members parallel to the reflector were at a different temperature than the reflector itself, significant thermal stresses and reflector distortions could develop. The alternative of truss closure with the honeycomb reflector eliminated structural redundancy, but posed new problems associated with transfer of high truss loads through the honeycomb insert attach points, across the reflector itself, through an indeterminate path, and back out through the insert attach points.

Accurate analysis of the reflector was very difficult, and the combined solution of reflector loads and truss loads appeared nearly impossible in the time allowed. The uncertainties of this analysis would have led to a considerable overdesign of the reflector if it had been required to carry the truss loads. This overdesign would have led to considerably more total truss-antenna weight than the conventional truss closure approach. It was decided to use the conventional closure to avoid this weight penalty. The thermal stresses inherent in the redundant truss structure were minimized by thermally clamping the reflector and back truss. The truss tubes and joints were polished to minimize heat loss, whereas the attach points to the dish had attachments covering large areas to maximize heat transfer from reflector to truss.

Violent thermal testing of the reflector and back truss was conducted during spacecraft system tests with the reflector making transient thermal excursions from +200°F to −40°F in 15 min. No structural problems occurred during these tests. Further thermal tests of steady state conditions indicated that reflector tip deflections of less than 0.025 in. would occur as the reflector temperature ranged from 200°F (near-earth conditions) to 50°F (near-Mars conditions). These small excursions were entirely acceptable and the attempts at thermal clamping of truss and reflector were deemed successful.

D. Feed Support Truss Design

The feed support truss was required to hold the high-gain antenna's feed above the reflector and to be adjustable so that the feed could be translated both parallel to and perpendicular to the reflector plane. Also, it was desirable to allow rotation of the feed with respect to the support truss and enable accurate pointing of the feed toward the center of the reflector. These adjustments were accomplished by shimming between the reflector and truss for feed translations and shimming between the feed and the truss for feed rotations (rocking). In addition to providing support and allowing adjustment, the feed support truss was required to be transparent to S-band radiation and to maintain accurate feed alignment over a range of temperatures between earth and Mars. The radio transparency requirement led to the use of fiberglass tubing and plastic end fittings in the feed truss construction. However, to avoid truss buckling during boost vibration, the low elastic modulus of commercial fiberglass (less than three millon), combined with antenna pattern requirements of slender truss tubes, made it necessary to consider thick-walled fiberglass tubes. These tubes were so heavy that it seemed worthwhile to attempt development of a higher modulus fiberglass tubing (tube weight being inversely proportional to elastic modulus).

1. Unidirectional tubing. The approach which seemed most promising was special tubing fabricated with all the glass filaments running axially in the direction of the truss loads, raising the axial stiffness while sacrificing unneeded hoop strength. The fabrication of unidirectional fiberglass tubing was difficult, because it lacked hoop strength and was consequently susceptible to crushing and fraying. However, the result was a tube with approximately double the axial elastic modulus of commercial fiberglass tubing, and coincidentally, well over twice the axial ultimate strength of the commercial tubing. Use of unidirectional tubing reduced the feed truss weight by a factor of two and also provided some unexpected structural advantages. One of these advantages was due to the tremendously high strength-to-weight ratio of unidirectional fiberglass ($140{,}000\text{-lb/in.}^2$ tensile strength with the same 0.065-lb/in.^3 density as magnesium). This high ultimate strength allowed unidirectional tubing to buckle elastically under compressive overloads and then spring back with no structural damage. Midspan bowing of 1.25 in. was measured in tests of an 18-in.-long, ½-in.-diam pin-ended compression tube of unidirectional fiberglass (Fig. 6). Axial travel of the loaded tube end was nearly ⅜ in. with the resisting force exerted by the tube remaining constant and equal to the peak load sustained prior to initiation of buckling.

Such elastic buckling behavior absorbs a tremendous amount of energy (in this case, 14 times as much energy is absorbed during elastic buckling as is absorbed prior to initiation of elastic buckling) and this capability for energy absorption makes the truss almost indestructible during vibration and shock testing. During vibration testing if the truss resonances induce buckling loads in the truss tubes, the tubes begin absorbing energy and change their stiffness properties. This change in truss stiffness results in a shift of truss resonant frequency, which detunes it from the resonant driving force, and the combination of continuous detuning with large energy absorption capacity makes the truss difficult to damage in vibration.

Another unusual property of unidirectional tubing is that it will spring back after it has been broken and will then support better than 30% of its original ultimate load. The mechanism of this strength recovery is very interesting. When the tube is axially loaded in compression, it elastically buckles until the secondary hoop stresses become large enough to collapse (kink) the tube section and to form a flexible hinge at the tube's midspan. With this hinge formed in the tube, its two ends may be brought together without incurring further structural damage. Upon release of the load, the tube's flexing center section creates enough force to re-erect the tube and to pop the flattened section back into a round condition. When the re-erected tube is loaded again, it will support approximately 30% of the original ultimate load. The unidirectional fiberglass tube's unique property of re-erection after catastrophic failure is extremely desirable in spacecraft applications, because removal of boost loads will allow a damaged structure to re-erect itself without loss of structural alignments.

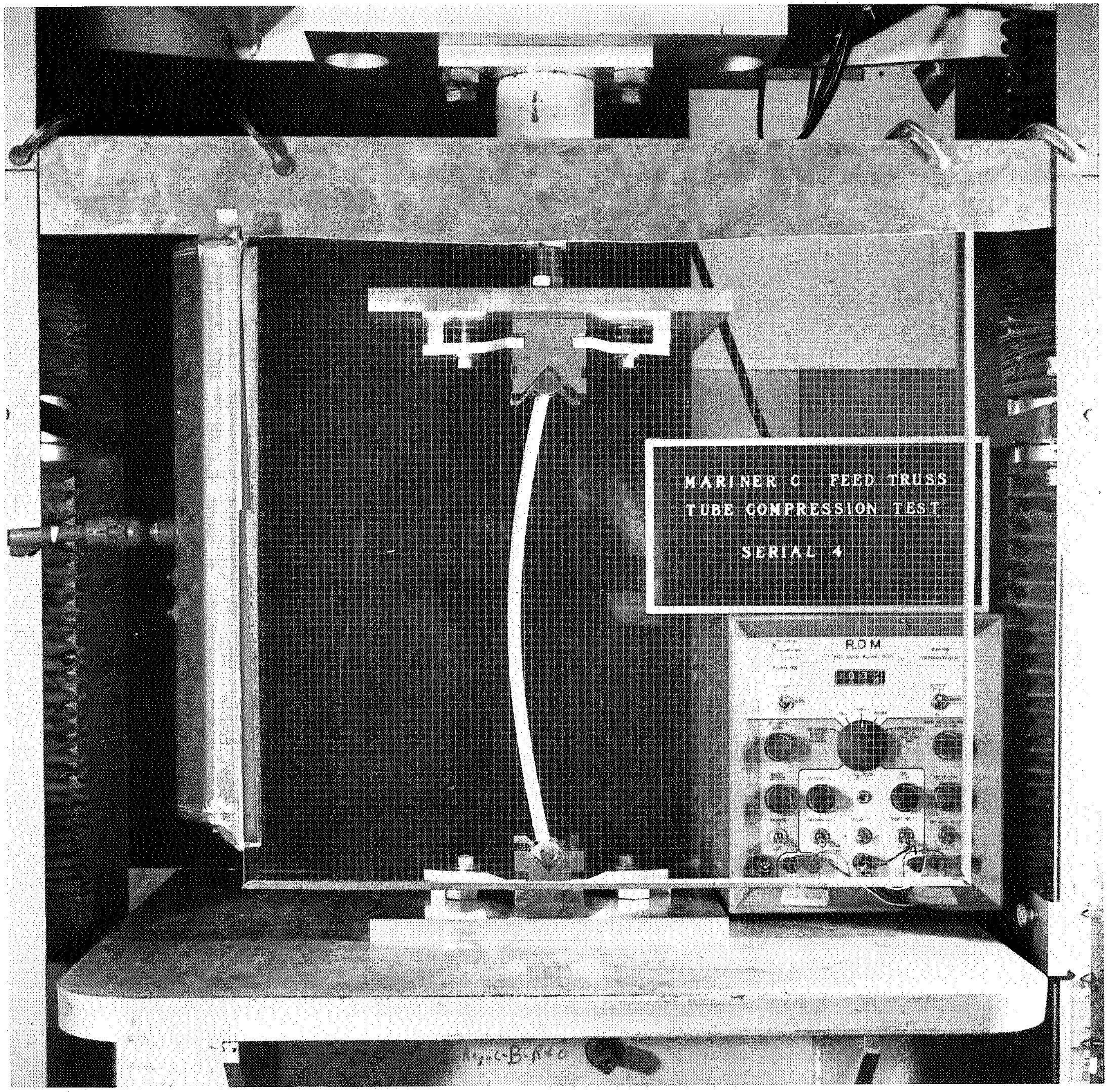


Fig. 6. Compression test of feed truss tube

2. *Attaching tubes.* Attaching unidirectional fiberglass tubes to truss end fittings posed a new problem in fabrication. The use of rivets was ruled out by the material's extremely low bearing strength in the direction of load (a rivet would just slide along between the fiber stringers under load). The only reasonable solution for end fitting attachment was to use bonded joints, which posed a problem of quality control. When a tube and mating joint were coated with adhesive then slid together, often less than 20% of the joint area was actually bonded. In order to achieve larger areas of bond, end fittings were drilled with a series of vent holes through which adhesive was injected with a syringe. This technique usually resulted in a bond of 80 to 95%. However, there were instances where less than 50% bond was achieved. Large bond areas could not be assured unless the bond joints were transparent, and the trusses could not be used unless large bond areas were assured. To enable inspection of the bond joints, the truss end fittings were machined from clear plastic and were designed to slip over the tubes rather than inside. The fittings were drilled with adhesive injection holes and adhesive was syringed in while its spread was observed through the clear tube fittings. This technique yielded consistently 85 to 90% bond areas and presented no significant problems.

The fittings themselves were machined from Lexan, a high-strength plastic (10,000-lb/in.^{2} ultimate) with good toughness, fairly good dimensional stability, and a density about half that of aluminum. Because truss fittings are sized primarily by joint geometry rather than strength requirements, the volume of material used remains constant regardless of the material's strength. Therefore, lightweight end fittings are best made from low density materials, even though such materials have a relatively low strength.

The use of Lexan end fittings, rather than aluminum, and the use of unidirectional fiberglass tubes, rather than commercial grade, led to the development of a feed support truss with half the weight of a more conventionally designed one. Furthermore, this lightweight truss resists vibrational and shock overloads much more than a conventional truss. This truss design concept was so successful that consideration of its application for future spacecraft designs is recommended.

E. High-Gain Antenna Feed Design

The high-gain antenna feed was composed of two turnstile antennas (feed tubes supporting crossed dipoles) mounted in a rectangular box which faced down toward the reflector vertex. The main support tube and crossed dipole tubes of each turnstile were machined as one piece from high temper aluminum alloy. Although these parts were difficult to machine, they were cheaper, lighter, stronger, and more accurately made than similar oven-brazed assemblies used on *Mariner II* and *Ranger*. A further advantage was the rapid delivery (three weeks) of these parts as compared to the *Mariner II* assemblies (three months). Brazed fabrication of the *Mariner II* turnstile assemblies led to thermal warpage of the parts to such an extent that each assembly had to be realigned by hand after brazing. In addition, the brazing temperatures caused complete annealing of the metal resulting in low yield strengths and sensitivity to misalignment by handling. In brief, the *Mariner IV* machined turnstile assemblies were superior in every way to the old brazed assemblies.

The feed box into which the turnstiles were fitted was also a single machining operation. With approximate dimensions of $3.75 \times 7.5 \times 1.25$ in. and a wall thickness of 0.025 in., the part was originally thought to require a rough machining followed by a final thinning down through chemical milling. The first test parts were made in this way. However, some experimentation with machining techniques produced finished parts with no chemical milling required. Because the all-machined parts had considerably smoother finish (for later polishing) and better delivery times, the flight parts were done by a straight machining operation. The final feed assembling was accomplished by simply bolting together into one assembly the turnstiles, feed box, electrical connector, and electrical distribution printed circuit. No shimming or adjusting was required.

The feed was designed with very close attention to minimizing weight. Even though it was not an inherently heavy assembly, it represented the top load to a fairly long trusswork and therefore played a major part in sizing that trusswork. A weight magnification factor of approximately 2 would have applied to any increase in feed weight by the time the supporting trusses had been adequately strengthened to support additional load. These sorts of weight magnification factors are typical of truss-mounted payloads and should be borne in mind when weight changes in such payloads are being considered.

F. Final Assembly

Upon completion of the various trusses, reflector, feed, and coaxial feed cable, each high-gain antenna was assembled. The reflector was installed onto the antenna support truss and shimmed into proper alignment; then, the feed, feed coax, and feed support truss were mated to the reflector and shimmed into alignment. After a final inspection verified reflector and feed alignment, the antenna was delivered to the antenna range for pattern checks.

G. Special Properties of Foil Gage Aluminum Honeycomb Structure

Because of the fragile nature of the high-gain reflector, considerable concern was expressed about its reparability and the likelihood of irreparable damage occurring during routine handling. To help prevent handling damage, the reflector was edged with a rigid foam filler that could withstand minor knocks and squeezes. This precaution was very effective, permitting normal handling of the antenna.

However, antenna reflectors were damaged twice, because of heavy blows to the edge of the reflector. Such blows caused the honeycomb core to collapse laterally and shear the face skin bonds. The unsupported face skins then lifted from the core surface and folded back with no severe wrinkling or tearing. Damage of this type looked worse than it was. Since no tearing or crumpling of the honeycomb cells or of the face skins occurred, it was easily repaired. To repair such damage the face skins were folded back from the core, which was pulled back into an expanded condition using right angled forceps. Then, the face skins were coated with adhesive, clamped into position against the core and allowed to cure. This repair sequence was done in less than an hour without removing the antenna from the spacecraft or significantly delaying other spacecraft operations.

Light weight combined with ease of repair makes aluminum honeycomb very satisfactory for spacecraft applications. Its advantages of structural efficiency, dimensional accuracy, and relative ease of fabrication are accompanied by no really serious drawbacks.

H. Special Testing of Foil Gage Aluminum Honeycomb Structure

The temperature sensitivity of bonded structure and the thin gage of the aluminum foils used in the structure led to two special tests unique to the antenna reflector. These tests were deemed necessary to the proper qualification of the reflector for spacecraft application.

One test was an acoustical environment test in which 145 dB of white noise were played upon the reflector face. There was concern that high amplitude flutter would be induced in the aluminum foils and that this flutter would either rupture the cells or weaken the bonds within the sandwich. In fact, no problems were encountered in this test.

The second, a low level vibration test, was conducted while the antenna was heated to 220°F. The shake level and temperature corresponded to the vibration and ascent heating encountered during the second stage firing of the boost vehicle. The test was conducted because it was assumed that boost heating might degrade the reflector's bond strength enough to make the mild second stage vibrations a dangerous condition. Although the results indicated no problems existed, similar tests should be conducted or considered on other boost vehicles or different trajectories.

III. Low-Gain Antenna Structure

A. Background

The *Mariner IV* low-gain antenna represents a radical departure from past antenna designs executed at the Jet Propulsion Laboratory. This unique combination of advanced structural and radio techniques was conceived, developed, flight qualified, and flown within the framework of a single project's cycle from inception to completion. The development of such a new concept inevitably led to unexpected structural and electrical problems. In addition, structural–electrical interactions had to be worked out on a short time scale. To emphasize, this "launch" of an entirely new design was only done of necessity. Serious problems were anticipated, but the *Mariner IV* mission constraints required antenna patterns, sizes, weights, and locations which could not be accomplished by extending previous designs.

B. Design Requirements and Conceptual Approach

The requirements which led to the existing design were:

(1) A low-gain antenna must be placed above the tips of the spacecraft's folded solar panels (for an unobstructed backward look over the solar panels during boost and cruise).

(2) The low-gain antenna must be placed near the spacecraft centerline to obtain antenna pattern roll axis symmetry.

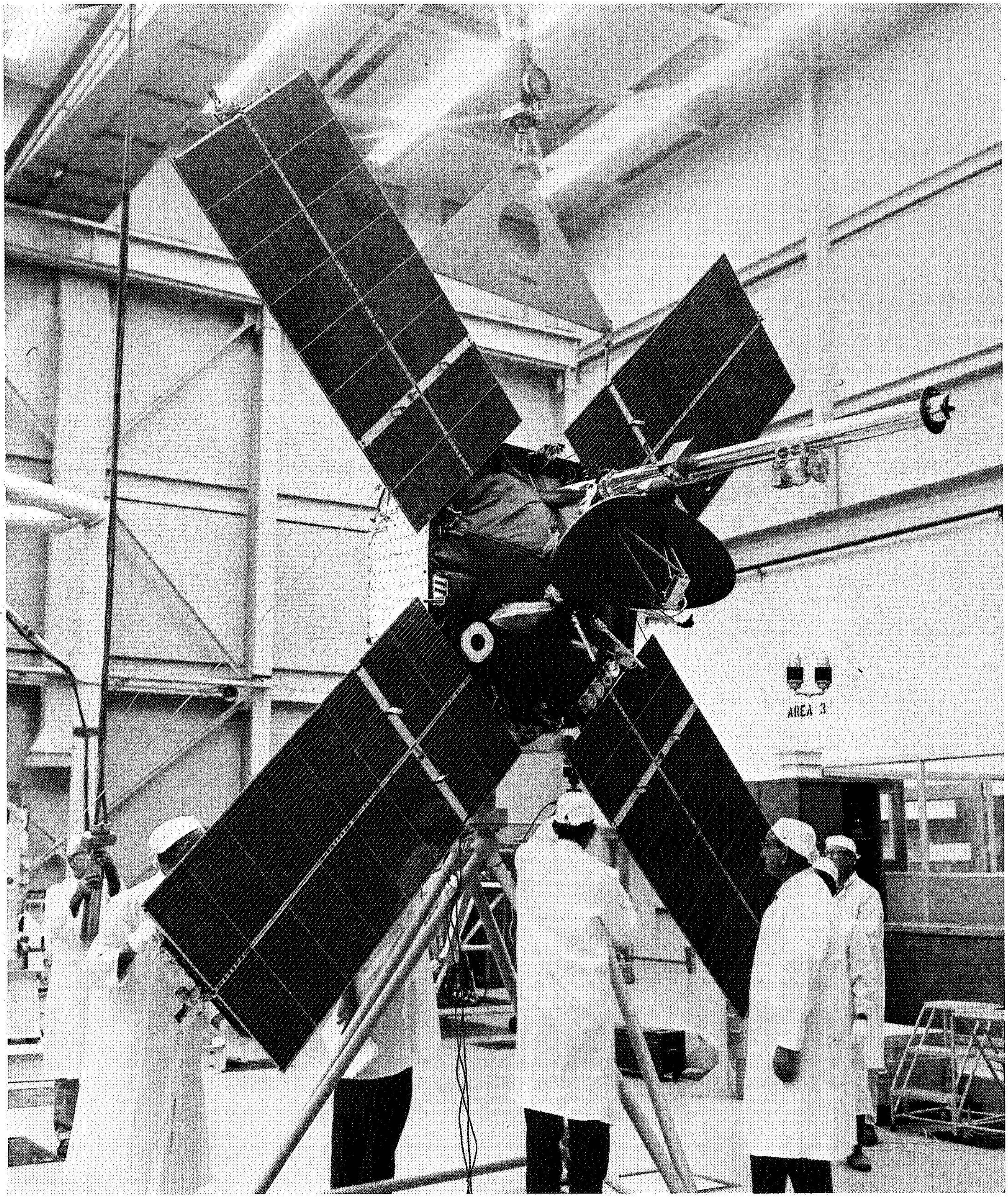


Fig. 7. Antennas installed on spacecraft

(3) The support structure for the low-gain antenna must not occlude the views of the high-gain antenna or the spacecraft's scientific instruments.

(4) The weights of antenna support structure and the antenna must be very light to avoid shifting the spacecraft center of gravity up and beyond the midcourse motor's pointing adjustment range.

The design concept satisfying these requirements was a low-gain antenna (shown installed on the spacecraft in Fig. 7) formed as the termination of a tall cylindrical tubular waveguide. The waveguide acts as both the mechanical support structure for and the electrical path to the low-gain antenna. The 7-ft-high, 4-in.-diam tubular waveguide was too weak a structure, when conventionally supported to withstand the vibration levels of the spacecraft boost environment, but it did fulfill the requirements of not occluding the high-gain antenna or scientific instruments' fields of view. Also it placed the low-gain antenna high above the spacecraft near its centerline. The waveguide was made of 0.025-in.-wall, 4-in.-diam tubing with the antenna aperture section being formed into the tube as a four-pointed crimp (see Fig. 8). The resulting total weight of 2.7 lb for antenna and support structure (contrasted with an estimated 12 lb for an unsatisfactory conventional design) met the requirement for lightweight construction. The remaining problem was how to make the structure survive during boost vibration.

The structural vibration problem was solved by supporting the waveguide tube with two damped struts (Fig. 9) whose damping coefficients were sized to couple heavily with the first few bending modes of the waveguide tube. The application of damped control to the waveguide structure was so successful that vibrational stresses in the tube's primary bending mode were reduced by a factor greater than 20. Secondary resonances

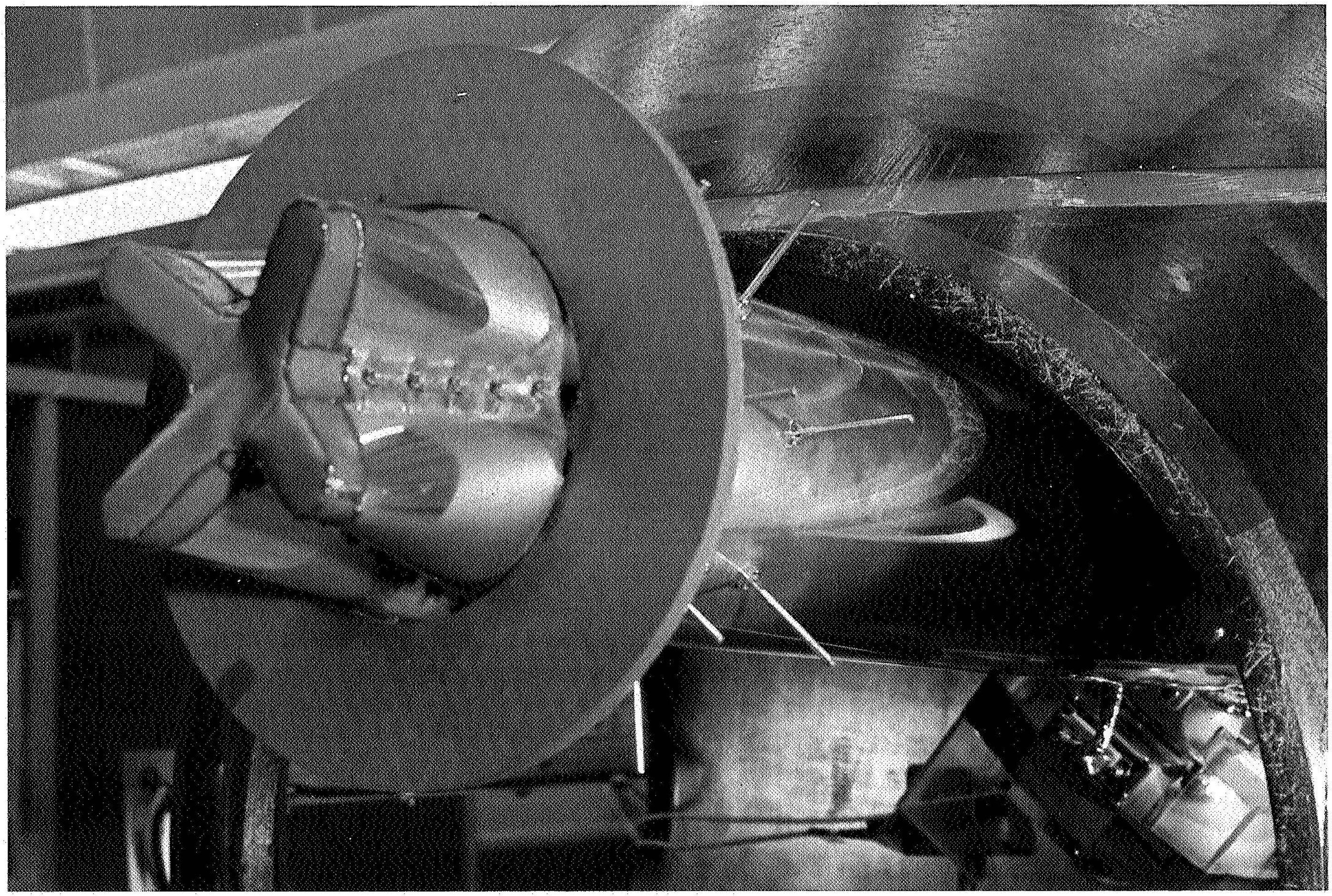


Fig. 8. Low-gain antenna aperture and ground plane

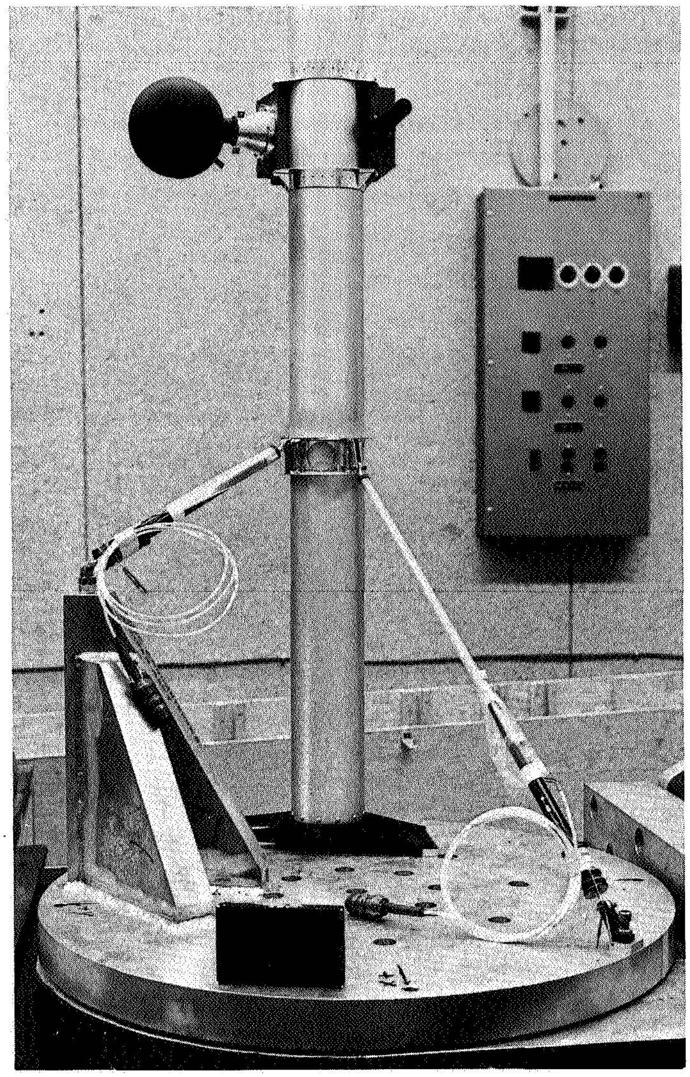


Fig. 9. Low-gain antenna support system

were similarly reduced below the level of structural significance.

C. Low-Gain Antenna Production Problems

Once it was established that the waveguide fed low-gain antenna was electrically and mechanically feasible, it became necessary to develop methods of manufacture which would produce, from large diameter thin-walled aluminum tubing, dimensionally accurate waveguides and terminations. Three waveguide tube dimensional requirements were:

(1) A tube roundness within 0.003 tube diam (an electrical constraint).

(2) A tube wall thickness equaling 0.006 tube diam (a weight consideration).

(3) Formation of a four-pointed crimp at the tube end, transitioning in 1.0 tube diam from the round waveguide section to an accurate, crossed slot aperture (an electrical constraint).

In addition to severe dimensional constraints, the waveguide was required to be made of highly tempered (6061-T6) aluminum in order to maintain tubing roundness during normal handling. The use of high yield strength aluminum in the tubing forming operations caused problems in manufacture. These were primarily springback, the possibility of brittle fracture during severe forming, and control of accurate dimensions. The tubing was specially drawn into 7.5-ft-long × 0.025-in.-wall sections from relatively thick-walled short sections of 6061-T4 tubing stock. In a multiple draw operation it was accurately sized to the required diameter and roundness tolerances. A secondary forming operation, utilizing an adjustable inside mandrel and an exterior clamping die, created the crossed slot (cruciform) aperture which forms the radiating element. The tube was then hung by one end in a heat treat oven and artificially aged to the T-6 condition. Each of the manufacturing steps significantly influenced the tube roundness, straightness, and cruciform dimensions to such an extent that only selected tubes could be used as flight antennas, the remainder being utilized for structural test models and antenna performance sensitivity tests.

Further complications in tube production developed when two additional specifications were generated. One of these required that the interior of the tubes be gold-plated to ensure the absence of skin corrosion that could restrict radio propagation within the waveguide. The second specification was that the tube's exterior must be polished to a mirror bright finish in order to control the temperature of the waveguide and scientific instruments attached to the waveguide. In a pilot feasibility study, gold-plating the interiors of two uncrimped tubes was accomplished through the use of long reach plating electrodes and careful handling. Nevertheless, one tube was dented in the process and rendered useless. Further development of the technique would have been necessary to achieve proper plating of a tube with crimp, because the crimp convolutions created serious variations in the plating geometry. It was felt, however, that a crimped tube could be successfully gold-plated after a reasonable process development time.

Concurrently with the tube plating study, an evaluation of tube surface corrosion rates and of surface corrosion effects on RF propagation was being conducted. The results of this corrosion evaluation were that no significant propagation effects would occur on a buffed 6061-T6 aluminum surface in an air-conditioned environment even over a period of several years. As a result of the corrosion testing program, the gold-plating program was dropped and after heat treat the tube interiors were given a corrosion inhibiting finish buff.

The temperature control requirement, that waveguide exterior surfaces be polished mirror bright, led to an unexpected production problem. Polishing the waveguide tube surface created high local temperatures and pressures where the buffing wheel contacted the aluminum. This buffing created unbalanced surface stresses which induced bowing in the tube. On test waveguides the finish buffing induced bends as large as ⅜ in. even though the tubes were water-cooled from the inside and the buffing was done by an experienced and competent workman. Tube warping during final polish proved to be such a problem that a serious look was taken at alternate techniques. The temperature control group was provided with samples of tubing finished to various degrees of brightness. It was concluded that a lightly buffed "hazy mirror" finish provided very nearly the same temperature effect as a heavily buffed "bright mirror" finish, but without the production problems of high surface stresses and bowed tubes. A "hazy mirror" finish was successfully used on the flight waveguides.

D. Detailed Design Problems

In the process of designing the low-gain antenna, its mounting hardware, and the attach bracketry for waveguide-mounted science experiments, problems encountered led to unusual design criteria. For instance, the process of choosing waveguide tube wall thickness was not based on the usual structural criterion of the strength required to withstand spacecraft boost environment. Preliminary structural analysis of the damped waveguide tube indicated that wall thicknesses as low as six mils would be adequate to withstand the spacecraft boost environment. A 4-in.-diam waveguide tube made of this six-mil aluminum foil would be so flimsy that handling it without incurring damage would be very difficult. The problems of producing such a tube within tightly held roundness and straightness tolerances would be insurmountable. Since the structural analysis indicated an unacceptable wall thickness, it became necessary to choose a wall thickness based on the nebulous criteria of minimum gage for:

(1) Achieving acceptable waveguide roundness.
(2) Successful tube production.
(3) Ease of handling.

At first glance it was not at all clear which criterion would be the limiting case on tubing gage: production, handling, or roundness. Therefore, it became necessary to establish the minimum gage for each of these situations. To produce quickly preliminary samples of tubing in thin gages, sections of commercial tubing were hand-selected for tolerances and then chemically milled to wall thicknesses of 15, 20, 25, and 35 mils. These samples were cut into short sections, inspected for dimensional accuracy before and after chemical milling, then distributed among design engineers, test engineers, and technicians for their opinion of how resistant the various tubing gages were to normal handling. The dimensional stability of the sample tube roundness was acceptable in wall thicknesses greater than 20 mils and marginal at 15 mils. The production by chemical milling proved feasible in gages down to 15 mils with 10- mil samples showing severe pitting and occasional "through etched" holes. The handling evaluation involved opinions of reasonable minimum gage ranging from 15 to 35 mils. As might have been anticipated, the most nebulous criterion, handling, was to size the waveguide. With opinions on desirable gage (and therefore antenna weight) ranging over a ratio of better than 2:1, it was finally decided to use a marginal gage of 25 mils and to resolve any handling or roundess problems by adding tube stiffening rings, if absolutely necessary. Special handling racks (Fig. 10) and techniques were developed to prevent operational damage.

During flight spacecraft assembly and operations, the assembly technicians were given some special instruction on antenna handling. Also, a special shipping and storing rack (Fig. 10) was utilized with the result that no flight waveguide tubes were damaged at any time in the *Mariner IV* program.

The dimensional variations of the waveguide termination cruciform ("antenna") and the variations in waveguide roundness from tube to tube caused serious difficulty in early phases of the low-gain antenna development program. At that time the use of stiffening rings to improve tube roundness was seriously considered, but never fully evaluated. Stiffening rings offered considerable improvement in waveguide roundness for a relatively

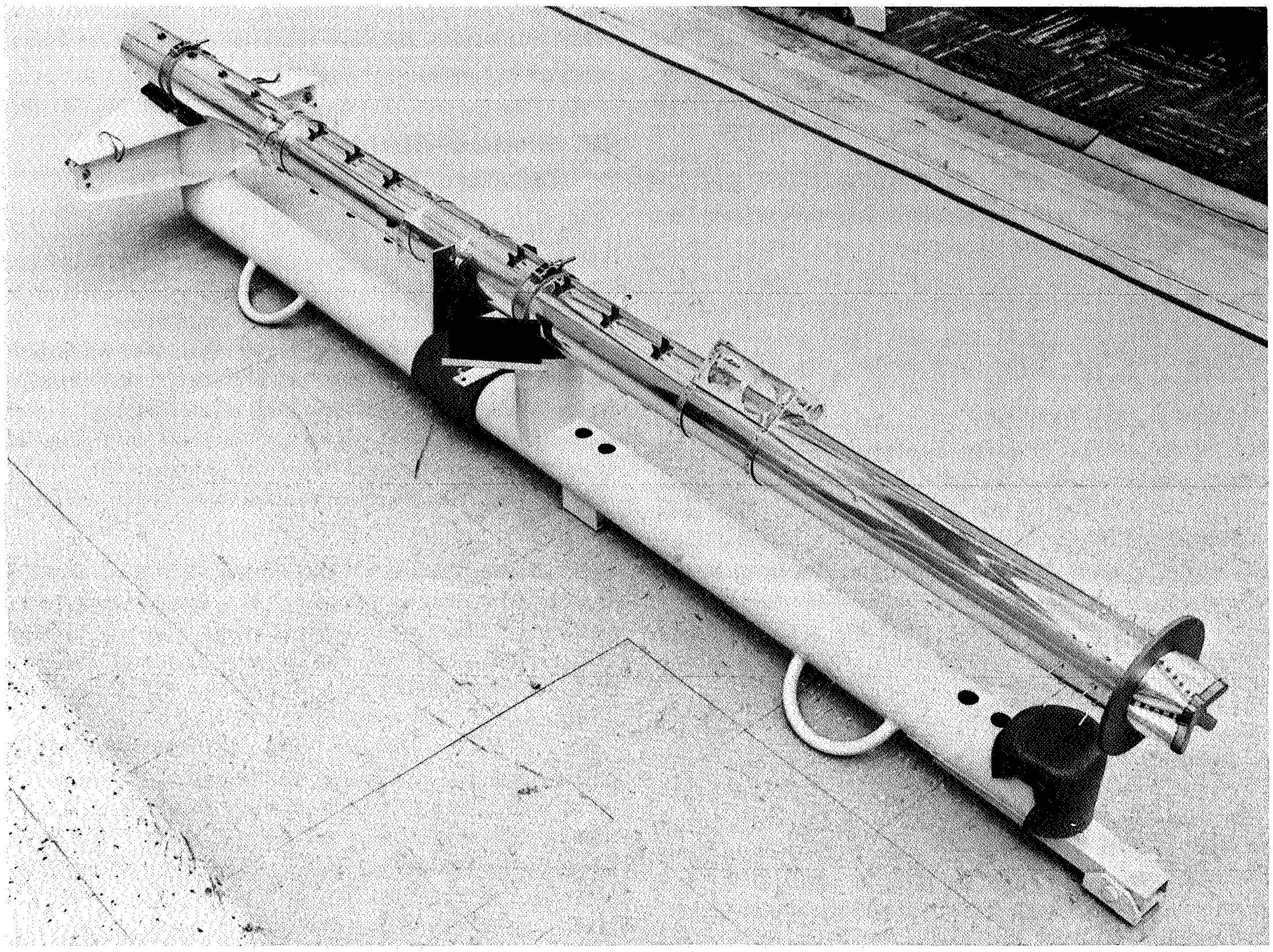


Fig. 10. Low-gain antenna installed in handling fixture

small weight penalty, however, they did not provide any improvement in cruciform tolerances. Antenna performance variations, due to waveguide out-of-roundness and cruciform tolerances, were minimized when the antenna group developed a technique of tuning with internally-mounted iris plates. This made the antenna performance less sensitive to the tolerances which we were able to achieve in waveguide and cruciform manufacture.

In addition to the problems associated with thin-gage waveguide tubing, another set of problems was presented by an electrical requirement. No rivets, screws, bolts, nuts, etc. could be allowed on the inner surface of the waveguide tube. This requirement eliminated most conventional techniques for attaching mounting bracketry and supporting structure to the waveguide, since welding and brazing were also unacceptable due to the thin gage of the tube wall and the severe tolerance requirements placed on its roundness. The result of disallowing riveting, welding, bolting, and brazing as fabrication techniques led to the extensive use of bonding in the attachment of bracketry to the waveguide tube. Some concern was displayed over the use of bonding for primary structural attachment of such things as the magnetometer experiment, the ion chamber experiment, and the low-gain antenna support bracket to the spacecraft. The bracketry was made in the form of close-fit hoops that slid over the waveguide tube and then were bonded in place. The bonding was accomplished by injecting adhesive through vent holes in the bracketry with a syringe. This injection technique proved to produce bonding over 50 to 80% of the joint area, as opposed to less than 20% when the parts were pre-coated with adhesive, then slid together. Even with 50% area bonding, it still seemed unwise to design the uninspectable bonded joints for high stress. Consequently, the bracket hoops were made quite wide, with typical joint safety factors running well over a factor of 10. Such conservative joint design alleviated all concern over bonded joint failure. Yet, because of the lack of load concentration, the flight bracketry designs came out lighter when designed for bonding than they would had they been designed for riveting.

No failures of bracket bond joints occurred during any phase of the *Mariner IV* test and flight programs. An ultimate load test of the most suspect bracket resulted in a bracket failure at five times the design load with still no failure in its bonded joint. An interesting advantage of the bonded bracketry was brought to light when magnetometer scientists asked that one bracket be electrically insulated from the waveguide tube. This was accomplished by simply bonding a thin layer of fiberglass inside the bracket hoop, then bonding the hoop to the waveguide tube. (It might be noted that the bonded bracketry without a fiberglass insulator made electrical contact with the waveguide tube, even though the adhesive was a dielectric.)

E. Bracketry Fabrication Techniques

In its original design form the bracketry used on the *Mariner IV* waveguide utilized several fabrication techniques. Two pieces, the ground plane and the ion chamber thermal shield, were bonded aluminum honeycomb plates 0.25 in. thick with 2-mil face skins and 0.7-mil × 0.25-in. cell core. The magnetometer bracket was bent up from 20-mil aluminum sheet metal and spotwelded together. One pair of rings, the ion chamber brackets, was "hogged out" of a solid aluminum block to typical flange dimensions of 35-mil thickness × 0.75-in. width. The base of the antenna was similarly "hogged out" to form a 4-in.-diam flat-bottomed cup, 2 in. deep, and with typical wall thicknesses of 25 mils. Finally, the waveguide support strut attachment ring was designed as an aluminum weldment with 40-mil minimum gages sized by the welding requirements at some fairly complicated joints. This last piece required long production times and had a high reject rate because of weld inclusions, cracks, and porosity which had to be thoroughly inspected by X-ray and magnaflux. The production difficulties and the overly heavy minimum gage of the welded part led to a redesign in which it was produced as a complicated machining "hogged out" of a solid block. This machined piece was lighter, stronger, dimensionally more accurate, cheaper, and quicker to produce than was the original weldment, even though the weldment was a fairly standard fabrication and the machining was quite a complicated part.

IV. Structural—Electrical Interactions of Low- and High-Gain Antenna Design

During the design phases of the low- and high-gain antennas, it was very important for the mechanical and electrical engineers responsible to understand each problem's constraints and alternative approaches. For instance, an electrical requirement that the waveguide interior be gold-plated resulted in a mechanical problem in holding tube tolerances and in developing plating techniques, but discussions and a short test program revealed that buffing the interior was easier than plating and satisfied the electrical conductivity requirements.

Close coordination of the electrical and mechanical trade-offs between weight, dimensional accuracy, antenna pattern variations, and antenna positioning was imperative to the successful development and production of high-performance lightweight antennas for the *Mariner IV* spacecraft. Too little time was available to proceed sequentially from antenna conceptual design to analytical performance evaluation, to "boiler plate" prototype construction, to prototype testing, to developmental optimization, to flight hardware design, to flight hardware "debugging," and finally to flight hardware delivery. This sort of series development could have nearly doubled the lead time required for delivery of a flight antenna. Instead of the series approach to antenna development, an analytical rough estimate of the antenna configuration was made. This was followed by parallel efforts of analytical configuration refinement and a gross test program, using a range of antenna geometries which would hopefully cover the optimum case. About midway through the analytical refinement and testing program, an educated guess was made at the exact configurations of the antennas, and detailed flight hardware design was begun on the assumption that this guess would be correct.

In the case of the low-gain antenna, the electrical predictions were enough in error that significant retrofits had to be made to the flight antennas in order to give them the proper radiation pattern. It was only because of the mechanical simplicity of these retrofits that very serious schedule slips were not incurred. In the case of the high-gain antenna, the configuration prediction involved choosing an optimum parabolic contour, an optimum feed position with respect to that contour, and an optimum feed size for the optimum contour. Approximately three man-months of design time elapsed after the configuration was chosen before the configuration could be verified as acceptable for flight. The possibility was always present that tests would prove the design unacceptable and the delivery schedule would abruptly slip three months as a new design was begun. A combination of good luck and sound engineering judgment on the part of the cognizant electrical engineer led to a test verification that the original flight antenna design satisfied all of the antenna efficiency and pattern requirements of the *Mariner IV* mission.

The final antenna design was begun on the basis of the electrical engineer's antenna performance predictions rather than prototype test data, because on-schedule delivery of the flight antennas could not have been accomplished if the antenna design had begun any later. It was risky to plan on the successful delivery of a flight quality high-gain antenna only 11 months after the mission requirements for antenna performance were established. This 11-month delivery time was achieved by what is very likely a non-repeatable process involving three-month forecasts of development test results, as well as development testing which proceeded smoothly to the predicted conclusions with very little backtracking or study of blind alley approaches. Had the antenna development testing turned up any serious technical problems, it might well have taken an additional two months to establish the proper antenna geometry. At the same time, the previous three months of design work would have been scrapped. It must be pointed out that future programs could well find themselves in trouble, if they based antenna development schedules upon the *Mariner IV* antenna development time.

V. Antenna Procurement Aspects

In general, both the high-gain and the low-gain antennas were made up of a main piece (the parabolic reflector, the waveguide tube), a series of detailed parts (truss members, end fittings, attachment brackets), and an electrical feed. These various parts were purchased from outside contractors. Inspection and final assembly of the detailed parts were done at the Jet Propulsion Laboratory, allowing close surveillance of piece part deliveries and the application of emergency procurement methods whenever a delay in part delivery threatened to hold up final assembly of an antenna.

The production of the antenna feeds was done by a subcontractor under the guidance of JPL's antenna group. All other parts were made under fixed price purchase orders to specialty machine and fabrication shops. The only complication was the fabrication of the high-gain antenna parabolic reflector, which required the installation of various parts supplied via JPL to the Advanced Structures Division of Whittaker Corporation, fabricators of the aluminum honeycomb reflector. The reflector was sufficiently expensive and complicated to receive special attention during its manufacture. At the fabricator's suggestion several reflector design changes were made, resulting in a stronger, lighter, and more reliable finished structure.

In the honeycomb reflector purchase order, multiple source purchase of prototype test hardware was followed by the placement of a supplemental order for additional flight pieces from the vendor judged best in delivery time, hardware quality, and purchase price. Such a purchasing approach works well for typical spacecraft production schedules, since a small purchase of prototype hardware, followed by testing and design modifications, usually precedes the main purchase of flight hardware. Despite the fact that parallel production of one part by two manufacturers doubles tooling costs, this cost is often recaptured when a request for quotes on the follow-up order reveals a significant rise in price from one vendor. The alternate vendor can then be chosen. Furthermore, when a part is intricate or difficult to manufacture, often one of the two vendors cannot produce it within the schedule necessary to meet project guidelines. The advantages of multiple source purchasing for complicated hardware were clearly manifested in various cases of the *Mariner IV* development. In general, the penalties of high tooling cost were made up for by the advantages of better quality hardware delivered more nearly on schedule.

VI. Conclusion

All of the detailed development problems – technical, schedule, procurement, and managerial – are not presented here, but those problems and solutions which have special interest and those special problems typifying general cases have been discussed. Technical refinement was very important in the development of the *Mariner IV* antennas, as is typical of spacecraft hardware. However, removing the last ounce of weight or obtaining the last bit of performance was avoided whenever a design became too sensitive to handling, too complex to assemble in the field, or too late in its delivery.

Probably, the most disconcerting constraint on the development of spacecraft hardware is that it must be done quickly. The designing engineers must use the most expedient rather than the most elegant or the most thorough approach to optimizing a design. The right balance of analysis and testing must be used to optimize rapidly the particular piece of hardware at hand, even though this approach may not result in the development of many elegant design tools for future use. The development of new analytical and test techniques must be left to advanced development projects or to the slower times between hardware developments, unless their development appears to offer the most rapid optimization of the hardware at hand.

It is hoped that some of the special materials, fabrication techniques, procurement practices and design approaches outlined in this report will help toward the successful development of more advanced hardware for future projects.