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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Memorandum 33-517

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PREFACE

The work described in this report was performed by the Engineering Mechanics Division of the Jet Propulsion Laboratory, under the cognizance of the Mariner Mars 1971 Project.

The English system of units was used for all calculations and measurements. Conversion to the metric system of units was accomplished for this report.

ACKNOWLEDGMENT

The information documented in this report was written by James H. Stevens and William E. Layman of the Engineering Mechanics Division of the Jet Propulsion Laboratory.

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ABSTRACT

In November 1971, the Mariner 9 spacecraft was injected into Martian orbit by a 574-kg (1265-lbm) propulsion system. Support for that system is provided by an 8.9-kg (19.5-lbm) truss assembly consisting of beryllium tubes adhesively bonded to magnesium end fittings. Beryllium was selected for the tubular struts in the truss because of its exceptionally high stiffness-to-weight ratio. Adhesive bonding, rather than riveting, was utilized to join the struts to the end fittings because of the low toughness (high notch sensitivity) of beryllium. Magnesium, used in the end fittings, resulted in a 50% weight saving over aluminum since geometric factors in the fitting design resulted in low stress areas where magnesium's lower density is a benefit.

This document describes the design, testing, fabrication procedures and problems associated with the development of the Mariner 9 propulsion support truss structure.

I. MISSION DESCRIPTION

In May 1971, the Mariner 9 spacecraft was launched by an Atlas/Centaur vehicle on a six-month flight to Mars. Upon arrival in November, a rocket motor was fired to decelerate the spacecraft and place it in orbit about the planet where it will remain for more than 17 years.

During its first 90 days in orbit, Mariner 9 will map 70% of the planet's surface. Scientists will obtain information on surface composition and temperature, as well as photos of surface features, cloud formations, dust-storm motion and seasonal darkening. In addition, data from ultraviolet and infrared instruments will be transmitted back to earth relating to the composition, density, pressure, and temperature of the Martian atmosphere. Instruments aboard Mariner 9 that provide information on these characteristics include wide- and narrow-angle TV cameras, ultraviolet and infrared spectrometers, and an infrared radiometer.

II. SPACECRAFT DESCRIPTION

The Mariner Mars 1971 (MM'71) Orbiter design (Fig. 1) varies little from that of the Mariner Mars 1969 (MM'69) flyby spacecraft. Some modifications have been necessary to accommodate the 1971 mission requirements. The most significant of these is replacement of the internally mounted 22-kg (48-lbm) MM'69 propulsion assembly with a 574-kg (1265-lbm) externally mounted propulsion module. The module, in addition to providing normal trajectory correction velocity changes in route to the planet, must decelerate the spacecraft approximately 1600 m/s at Mars to allow the planet's gravitational field to capture it.

The propulsion module is mounted on the top of a standard Mariner octagon structure, which houses and/or supports the various subsystems operating the spacecraft as a semiautomated vehicle. The five scientific instruments mentioned earlier are mounted on a scan platform located on the underside of the octagon structure. The platform rotates about two orthogonal axes to point the instruments at the desired location on the planet.

III. PROPULSION MODULE

The propulsion assembly (Fig. 2) utilizes a 1334-N (300-lbf) thrust rocket motor to accomplish in-transit trajectory corrections, an orbital insertion maneuver at Mars, and subsequent orbital trim maneuvers. The 476 kg (1050 lbm) of fuel and oxidizer required for the various maneuvers are stored in a pair of 76-cm (30-in.) diameter titanium tanks. Two 38-cm (15-in.) diameter nitrogen tanks supply the pressure that induces proper propellant flow to the engine.

The propulsion support structure (PSS) supports, aligns, and integrates the foregoing items along with the valving, filters, regulators, transducers, interconnect plumbing, and electrical cables that constitute the propulsion assembly. The propulsion module, consisting of the propulsion assembly and the support structure, was constructed to permit assembly, propellant loading, and subsystem testing independent of the spacecraft at a remote and safe location. Installation of the module on the spacecraft occurred at the conclusion of system testing, just prior to encapsulation in the launch vehicle nose fairing.

IV. PROPULSION SUPPORT STRUCTURE

The propulsion support structure consists of those structural elements that support the propulsion subsystem, its tanks, engine, valve packages, plumbing, and electrical cabling.

Primary support is provided by a 8.9-kg (19.5-lbm) truss assembly (Fig. 3). The truss consists of 16 beryllium tubes adhesively bonded to magnesium and steel end fittings. The truss bridges between the eight upper corners of the octagon and four tabs on each of the two propellant tanks. A figure-eight-shaped ring assembly (Fig. 4) encircles the tanks at their equator to react the horizontal component of loads generated in the canted truss members. The ring, upper truss fittings, and tank tabs bolt together in a series of eight common joints (Fig. 5). A pair of bipods attach to the outer surface of the ring to support the top of the pressurant tanks, while fittings at the base of the truss restrain the lower end of the tanks.

A. Alternative Designs

The structure was originally envisioned to be of the traditional swaged-end aluminum tube, riveted-to-aluminum end-fitting construction. However, as serious spacecraft weight problems developed, a weight-saving program was initiated. The high stiffness-to-weight ratio of beryllium (seven times that of aluminum, magnesium, titanium, or steel) permitted realization of a major weight saving in the truss structure. In the stiffness-critical truss design it was possible to replace approximately 5.7 kg (12.5 lbm) of aluminum tubing with 1.1 kg (2.5 lbm) of beryllium tubing. It should be noted that the strength-to-weight ratio of beryllium is only about 50% better than that of high strength aluminum extrusions such as 2024-T851. Beryllium's real weight-saving potential occurs in <u>stiffness</u>-critical not <u>strength</u>-critical designs.

Because of the notch sensitivity of extruded beryllium tubing, riveted, bolted, and threaded joints were not considered suitable fabrication techniques for the truss structure. Also, distortion and processing problems made welding essentially impossible and brazing very unattractive; it therefore followed that adhesive bonding, if it could be simply and reliably executed, was the most attractive joining technique.

B. Beryllium Tubing

All struts in the truss were the same diameter and wall thickness to simplify production and minimize procurement problems. This approach resulted in a calculated weight penalty of 0.23 kg (0.5 lbm) over a design in which all tube sizes were optimized for their individual requirements. The tubes used are 1.91 cm (0.750 in.) in diameter with a wall thickness of 1.02 mm (0.040 in.), and vary in length from 26.6 cm (10.47 in.) to 70.2 cm (27.63 in.).

1. Material Properties. Material was procured from the Nuclear Metals Division of the Whitaker Corporation with an extrusion billet quality equivalent to Berylco HP-20 Type II. Typical mechanical properties quoted for the extruded tubing are: compressive yield 40,769 N/cm^2 (59,000 psi), compressive ultimate 73,246 N/cm^2 (106,000 psi), and tensile ultimate 48,370 N/cm^2 (70,000 psi).

A serious problem associated with using beryllium in structural applications is its low toughness, i.e., low resistance to crack propagation. For reliable performance it is necessary that all surface cracks or scratches be eliminated from the material. In practice this is achieved by chemically milling 0.025 to 0.050 mm (1 to 2 mils) from all surfaces after machine work is completed. Tests were conducted to verify the criticality of this procedure using test specimens prepared from cross-rolled sheet stock. A portion of these specimens were chemically milled prior to testing, while the remainder were tested in the as-rolled condition. Typical properties obtained for chemically-milled specimens versus as-rolled specimens are as follows:

Property	As-rolled specimens	Chemically-milled specimens
Tensile yield	48,370 N/cm^2 (70,000 psi)	48,370 N/cm^2 (70,000 psi)
Tensile ultimate	49,752 N/cm^2 (72,000 psi)	69,100 N/cm^2 (100,000 psi)
Elongation	1%	20%

2. Test and Analysis. During the developmental program, 32 beryllium tubes from the production run were pull-tested to failure at tensile values ranging from 21,360 to 35,000 N (4,800 to 8,000 lbf). Of the

group, 16 for which measured cross-sectional area information was available, failed at values ranging from 21,850 to 33,375 N (4,910 to 7,500 lbf). Statistical examination of these specimens indicates a tension design allowable of 14,614 N (3,284 lbf) for 99% reliability at a confidence level of 95%. The highest load experienced in any member in the primary truss assembly (not including the upper pressurant tank support) during forced vibration testing of the spacecraft was 11,125 N (2,500 lbf). The accompanying histogram (Fig. 6) demonstrates graphically these load ranges.

In an auxiliary truss that supports the N_2 pressurant bottle, a beryllium-tube failure did occur. Subsequent analysis of the vibration test results revealed that the torsional response of the N_2 bottle at its natural frequency was significantly higher than anticipated. The resultant tube loading exceeded the statistically determined design allowable by 30 to 50% as shown in Fig. 6. Beryllium tubes in the pressurant tank supports were replaced with steel tubing and testing was concluded without further incident.

3. Handling and Safety. Two significant problems are associated with the use of beryllium as a structural material. The first is the toxicity of its dust, salts, and compounds. Berylliosis, a potentially fatal disease of the respiratory system, may be induced by inhalation of finely divided dust from beryllium, its compounds, or salts. The second problem is the low toughness or resistance of beryllium to crack propagation. Minute scratches and surface imperfections significantly reduce the material's load carrying capacity. To preclude the occurrence of either of these problems, a comprehensive handling procedure was established to reduce exposure of personnel and handling of the material to a minimum.

Nuclear Metals performed all operations that might result in the production of dust or fumes. The tubes were extruded, processed, cut to length, chemically milled, inspected, and sealed in non-chlorine-bearing plastic bags. (Beryllium is highly susceptible to corrosion when exposed to chlorine ions.) At JPL the material was stored in a restricted access area where it remained sealed and in its shipping container until needed for truss fabrication. Just prior to each truss fabrication cycle, thoroughly indoctrinated technicians removed the sealed plastic bags and prepared the tubes for the bonding operation.

4. Preparation for Bonding. All beryllium surface preparation techniques that dissolve metal into solution, creating toxic salts, were rejected for safety reasons. Rather, a treatment utilizing a conversion coating technique was chosen.

Just prior to performing the bonding operation, the beryllium tubes were removed from their protective covers and thoroughly cleaned in an oxalic acid bath to remove any residual oils or grease on the surface. They were then rinsed in distilled water and examined for "water break." The process was repeated until a uniformly wet surface was obtained. Once grease-free surfaces were obtained, the tubes were pickled in a solution of Berylcoat-D to generate a conversion coating, rinsed and placed on racks to dry. During processing, the tubes were handled only by technicians wearing either rubber or clean, lint free, white cotton gloves.

C. Magnesium Fittings

All truss fittings were machined from ZK60A-T5 magnesium extruded bar stock. Although the strength-to-weight ratio of magnesium is essentially equal to that of 2024-T4 aluminum, the use of magnesium does result in a weight saving. The complex geometry of the end fittings results in low stress areas where the lower density of magnesium is of significant benefit. Fittings were machined from the two materials to identical configurations; those machined from magnesium were 50% lighter than those machined from aluminum.

All magnesium fittings were treated with a 0.005- to 0.010-mm (0.2- to 0.4-mil) Dow 17 anodic coating for corrosion protection and sealed in desiccated plastic bags until time for bonding. Dimensional inspection was performed following machining and prior to Dow 17 treatment and bagging, thereby eliminating any need to expose the parts to atmospheric conditions or handling prior to the bonding operation.

Magnesium fittings were prepared for the bonding along with the beryllium parts, though no cleaning operation was involved. Four 0.127-mm (5-mil) aluminum wires were installed 90° apart in each fitting. The wires were inserted through holes in the fitting walls and bent parallel to the fitting centerline to lay along the wall of the fitting socket. The wires served to center the tube in the socket and produce a uniform bond thickness.

D. Steel Fittings and Tubes

As mentioned earlier (Subsection IV-B-2), steel tubes were used to replace beryllium in the upper pressurant tank support truss. Also, four of the eight upper fittings in the primary truss were changed from magnesium to steel (Subsection V-A). Figure 7 shows the location of those components that were changed to steel.

The tubing used in the pressurant tank support bipod was Mil-T-6736, seamless, 4130 steel, with a diameter of 1.91 cm (0.750 in.) to mate with existing fittings and the adhesive injection tooling. A wall thickness of 1.83 mm (0.072 in.) was chosen to duplicate the stiffness of the beryllium tubing, thereby maintaining the pressurant bottle response frequency.

The four upper truss fittings along the center-line between the propellant tanks, were machined from Mil-S-46850, type 250, class III, maraging steel bar stock. To preclude redesign of other parts of the structure, the geometry of their magnesium predecessors was essentially duplicated.

Steel fittings and tubes used in the truss were stored in the as-machined state and covered in a light coating of machine oil. In preparation for bonding, the parts were grit blasted and ultrasonically cleaned in methyl ethyl ketone. They were then dipped in EC2320 (3M Co., Minneapolis, Minn.), air dried, and cured at 66°C (150°F) for 30 min.

E. Adhesive Bonding

An investigation was initiated to find a high shear strength adhesive with moderately high peel strength and low temperature cure that would not outgas in the vacuum of space, and that was chemically compatible with the materials to be bonded. It was further decided to limit the investigation to paste adhesives that could be pressure injected into the joints and would not drain out during the cure cycle. Epon 913 was chosen as the adhesive with the best property compromise and room temperature curability. Adequate strength resulted when the adhesive was used to bond beryllium tubing to magnesium and steel end fittings, and steel tubes to magnesium end fittings.

Epon 913 (EA913, Hysol Co., L. A., Calif.) is a two-part, room-temperature cured paste adhesive that develops 2,280 N/cm^2 (3,300 psi) in shear and has a T-peel strength of 15.8 N/cm (9 lbf/in.). The adhesive was pressure injected into a 0.05 to 0.25 mm (2 to 10 mil) annular gap between the tube and fitting through molded RTV manifolds (Figs. 8 and 9). Injection was accomplished using a Semco gun pressurized to 89.8 N/cm^2 (130 psi) with dry nitrogen gas.

A complete truss consists of eight subassemblies in four essentially identical pairs. One-half of the truss was bonded in each of two consecutive operations. Following the cleaning and preparation for bonding, the components constituting half of the truss were installed in the bonding fixtures, aligned, and secured. Manifolds were then installed on each of the more than 25 joints and the adhesive pressure injected. Four witness holes near the bottom of the socket in each fitting enabled adhesive flow in the joint to be monitored. When adhesive began to flow from each of the holes, proper adhesive flow was verified and injection stopped. Figure 10 shows a completed bond joint. Also evident in the picture are a witness hole, centering-wire hole, and temporary-dowel-pin hole.

The entire bonding operation including preparation, assembly, bonding, and postbond cleanup was accomplished by two technicians in a single work shift. The bonded assemblies were allowed to cure for 72 h at room temperature before removal from the bonding fixtures. They were then placed in a 53°C (125°F) oven for 4 h to drive off any volatile materials that might remain, and to insure completion of the cure.

F. Joint Quality Verification

A bond test specimen was prepared each time a bonding operation was performed. Specimens duplicated the flight truss joints in that fittings and tubes were of materials and configuration identical to those in the truss. Specimen piece parts were fabricated, processed, cleaned, handled, and bonded in precisely the same manner and at the same time as the flight hardware. Thus each specimen served to verify the prebond, bond, and cure procedures.

In all, 43 pull-test specimens were prepared and pulled to destruction. Thirty-two contained beryllium tubes bonded to magnesium and/or steel end fittings. Eleven consisted of steel tubes bonded to magnesium end fittings. In the first group, beryllium tube failure predominated. In nine of the specimens the tubes fractured at tensile loads ranging from 21,360 to 35,600 N

(4,800 to 8,000 lbf) (Ref. Subsection IV-B-2). Magnesium-to-adhesive bond line failure occurred in the remaining three specimens at values ranging from 22,962 to 24,297 N (5160 to 5460 lbf).

Specimens containing steel tubes provided two data points. Since these tubes were sized to duplicate the stiffness of the replaced beryllium members, they were significantly overstrength, and failure always occurred in the bond. Once the initial bond failure in the specimen had occurred, the specimen was reinstalled and the second bond joint tested to failure. This procedure produced a range of minimum and a range of maximum values. Initial failure in the eleven specimens occurred between 34,977 N (7860 lbf) and 50,730 N (11,400 lbf). The second bond joint on each of the specimens failed between 40,050 N (9,000 lbf) and something greater than 53,400 N (12,000 lbf), which was the limit of the recording capability in the test setup. In all but one case, failure occurred predominately at the magnesium-to-adhesive bond line. In that one specimen, the failure occurred at the steel-to-adhesive bond line at 43,165 N (9700 lbf).

V. PROBLEM AREAS

During system-level forced vibration testing, several structural weaknesses were revealed. Four magnesium fittings cracked and one failed at a stress riser resulting from an insufficient fillet radius. Several more failed because of an overtest condition in which input levels were twice as great as planned. Still another magnesium fitting and a beryllium tube in the pressurant tank support fractured because of higher than anticipated response at the tank's natural frequency. A friction joint proved inadequate when a materials change in the joint resulted in a lower coefficient of friction.

Since the truss structure provides redundant load paths, the failures were localized and were not catastrophic. None of the failures resulted in damage to any other subsystem or component. In all cases, redesign and retrofit were accomplished on the existing truss assemblies with only minor schedule impact.

The following sections cover in more detail the problems mentioned above. In Fig. 11 the location of each is indicated along with a reference designator that refers to the appropriate section.

A. Upper Truss Fittings

During developmental test model (DTM) system-level vibration testing, the upper fitting on one of the end trusses fractured. The bipod containing the broken fitting was replaced and testing continued. After the test, all fittings were examined microscopically. Four upper fittings (1 in Fig. 11) (both center and both end bipods) exhibited hairline cracks in the fillet radius at the base of the vertical flange (Fig. 12). Analysis showed that an unsatisfactory root radius [less than 0.76 m (0.030 in.)] had produced a stress concentration factor greater than two. A shortcut in milling machine cutter grinding resulted in a 45° sloped fillet rather than the radius called for on the drawing. All center- and end-truss upper fittings were modified to increase the root radius to 2.28 mm (0.090 in.) (Fig. 13).

During propulsion subsystem testing at the Edwards Test Station, the four fittings supporting the oxidizer tank fractured in succession (2 in Fig. 11). As each fitting failed, its neighbor picked up a larger share of the load and in turn failed. The ring assembly was damaged locally at each of the failed fitting locations.

These failures that occurred during type-approval (TA) testing were caused by a test-level input twice as large as programmed. The overtest resulted from a shortcoming in the peak control system that allowed overshoot during control-channel switching.

Anomalies with the shaker control were investigated to achieve an understanding of the limitations of the system. Protective trip-limiting circuitry was applied to several of the more critically loaded members for backup protection. In addition, the upper fittings on the center- and end-truss members were changed to steel to preclude additional schedule impact in the event of a repeat of the overtest condition.

B. Pressurant Tank Supports

Difficulty was experienced with both upper and lower pressurant tank supports (3 and 4 in Fig. 11) during subsystem-level forced vibration testing. During the TA subsystem test, one of the four beryllium tubes in the upper support fractured (Fig. 14) (Ref. Subsection IV-B-2). Following the DTM subsystem test, both lower fittings were found to be cracked (Fig. 15). Both difficulties resulted from excessive stress induced by unexpectedly high response of the N_2 bottle at its fundamental resonant frequency. The subsystem-level test environment was found to be approximately 50% more severe than that experienced in previously performed system-level tests.

Another factor that may have contributed to the fitting failure was a probable reduction in the mechanical properties of the fitting material (ZK60-T5 extruded magnesium bar). Tests performed subsequent to the failure indicated that an approximate 25% reduction in low cycle fatigue life, could be expected in Dow 17-treated thin-section magnesium parts.

Fitting-material tests also indicated an approximate reduction of 45% could be expected in tensile yield when grain direction was oriented normal to the principal stress axis. Since grain direction was inadvertently omitted on the drawing, parts were machined in the orientation that required the least raw material. As shown in Fig. 15, the grain direction was approximately 35° off the axis of load application. The fitting was redesigned to optimize grain direction and reduce stress levels by increasing the cross section in the critical areas (Fig. 16).

C. Ring/Truss Joints

Four tabs equally spaced around the girth of each propellant tank are joined to the eight upper fittings of the truss assembly and the figure-eight ring in the ring/truss joint. Figure 5 depicts the joint in cross section. The vertical component of loads in the canted truss members is taken directly into the tank tabs through a pair of bolts. The horizontal component of the axial tube load is reacted by the figure-eight ring. Loads are delivered to the ring primarily through friction between the lower surface of the ring and the horizontal flange on the truss fitting.

When four of the upper truss fittings were changed from magnesium to steel, an approximate 40% reduction in coefficient of friction resulted. During system-level testing, one of the friction joints failed (5 in Fig. 11). Ring damage sustained was severe but localized, and the structure maintained its overall integrity (its ability to securely support the propulsion subsystem). The lower and inner webs of the ring were fractured in the area of interface with the end bipod upper fitting. Severe galling of the under surface of the ring was also evident. Figure 17 depicts the extent and location of the damage.

The joint was redesigned to increase its capacity to carry load in friction, and to carry the load in bearing if slippage did occur. A large doubler was riveted to the inner surface of the ring (Fig. 18) to distribute the load over a larger area. High strength bolts were used to improve the clamping force and thereby increase the friction force to a value 60% above that obtained with the original magnesium fittings. Close tolerance holes in the doubler provide a back-up capability for carrying the load in bearing. All truss assemblies were reworked to incorporate the change.

VI. CONCLUSIONS

The uncommonly high stiffness-to-weight ratio of beryllium (seven times that of aluminum, magnesium, titanium, or steel) made possible a 4.5-kg (10-lbm) weight savings in the truss assembly. The tubing performed its designed function faultlessly. (The one tube that fractured during test was stressed beyond its design allowable.)

Sufficient beryllium tubing for seven truss assemblies was purchased for under $30,000. The engineering and testing peculiar to the use of beryllium cost an estimated $30,000. An estimated $5,000 was deducted to allow for the substituted swaged aluminum tubes, yielding a figure of $5,500 per pound of launch weight saved on a single launch basis.

Careful planning, attention to detail, and thorough indoctrination of all personnel involved with the beryllium resulted in totally trouble-free fabrication and assembly operations. Personnel safety and protection of the delicate material were achieved with minimal impact on operations.

Adhesive bonding of the end fittings to the tubes by pressure injection, in addition to being necessary because of the notch sensitivity of beryllium, proved to be a simple, inexpensive, and effective procedure. Bonding of a test specimen during each bonding operation provided a high degree of confidence in the quality of the bond and the tubing.

In summary, several problems were encountered during testing of the structure that were unrelated to the use of either beryllium or adhesive bonding. Thorough evaluation, exploratory testing, and precautionary procedures provided for trouble-free use of these materials.

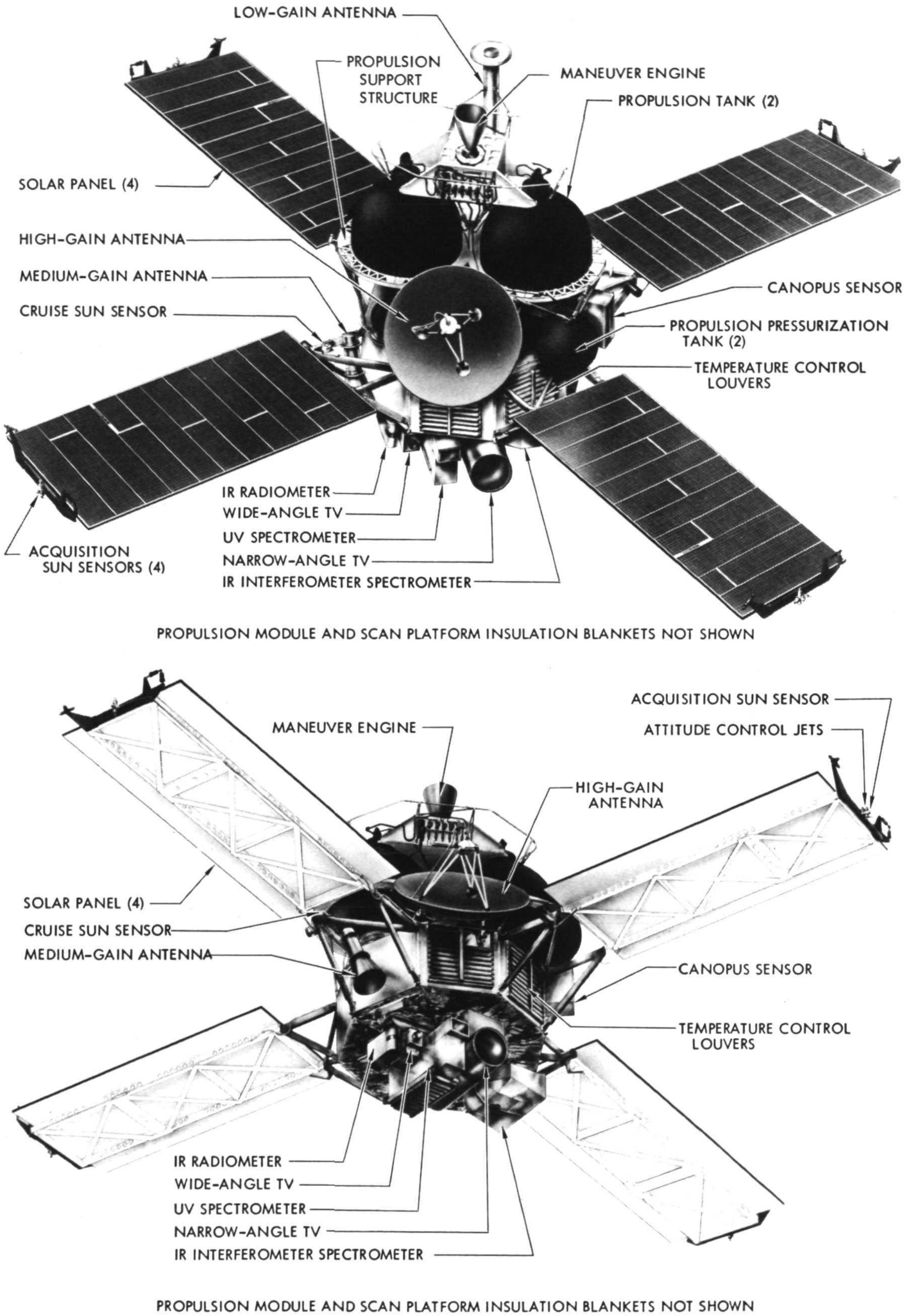


Fig. 1. Mariner Mars 1971 Spacecraft

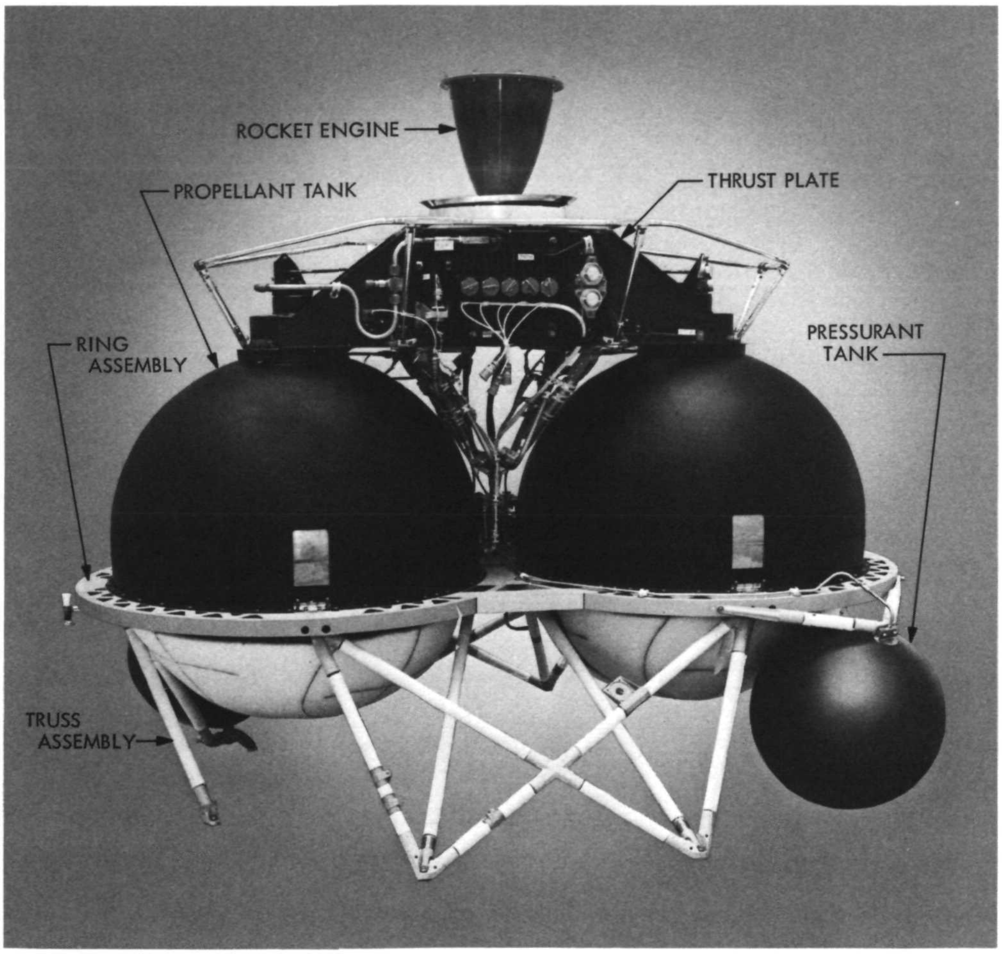


Fig. 2. Propulsion module

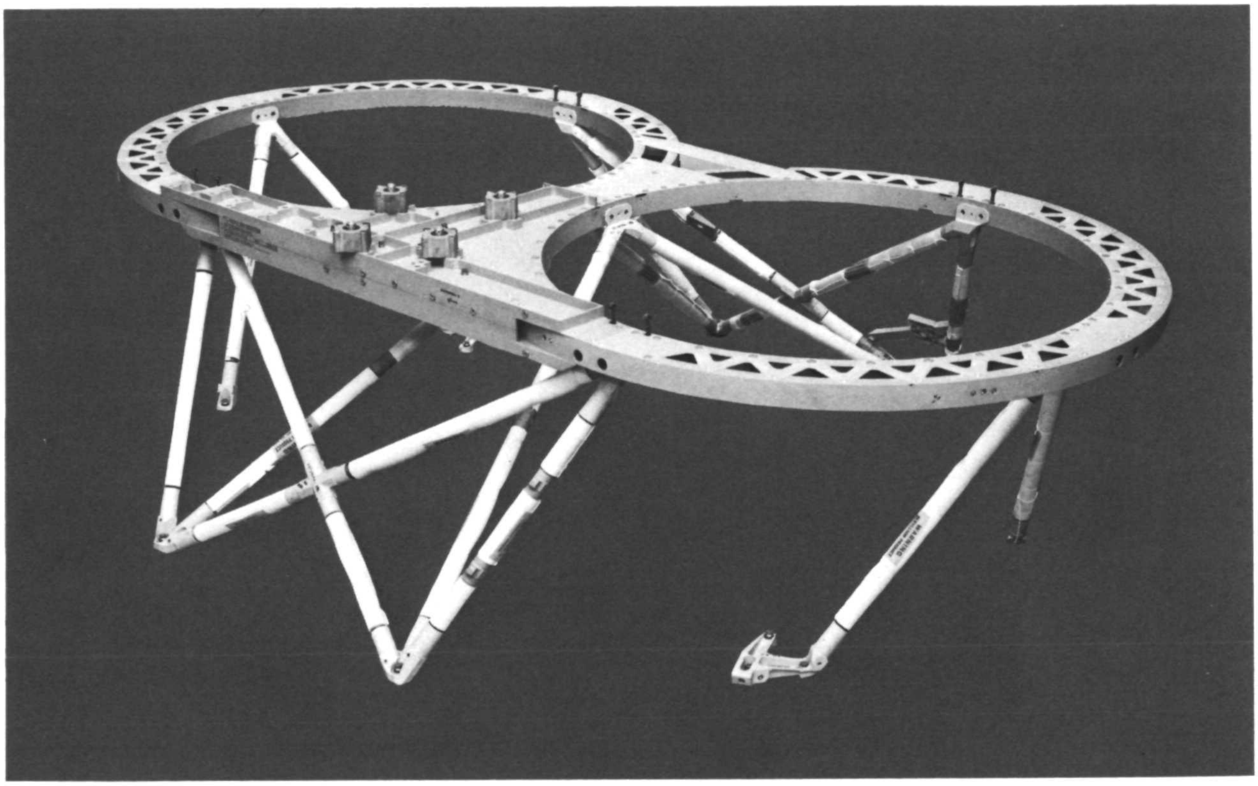


Fig. 3. Truss assembly

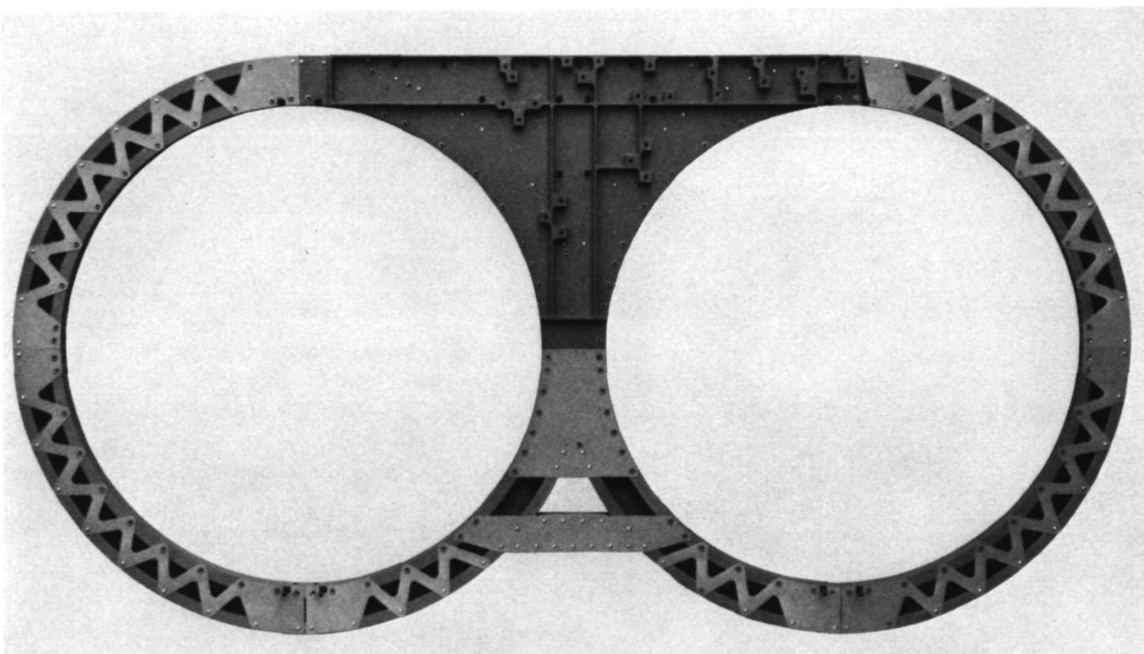


Fig. 4. Ring assembly

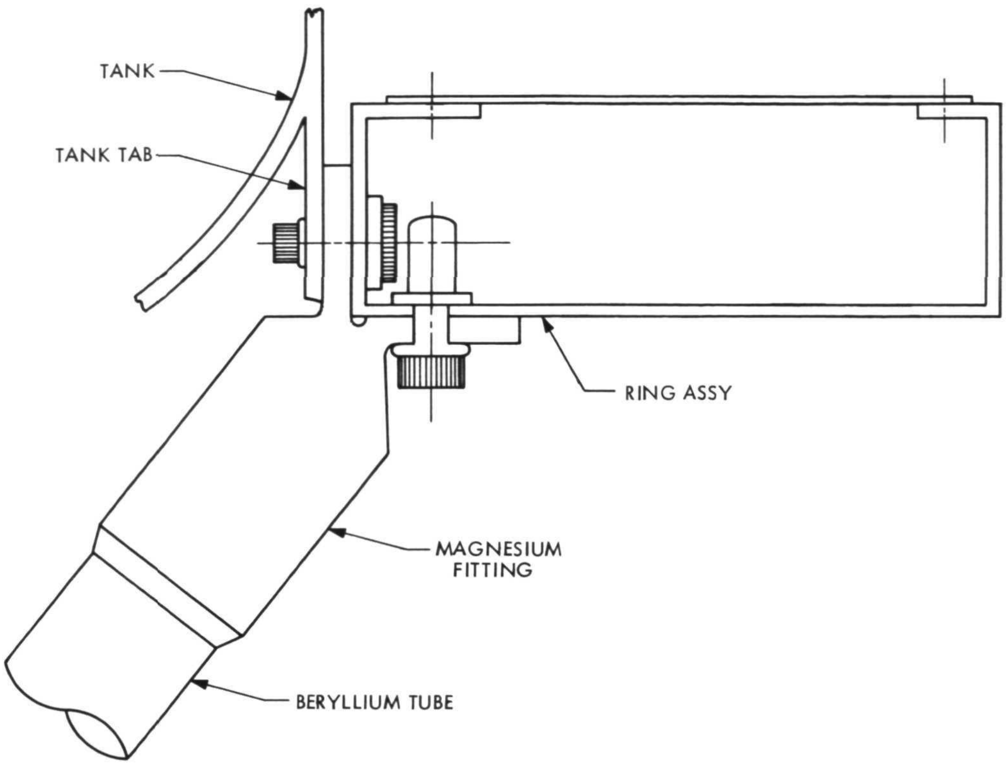


Fig. 5. Ring/truss joint

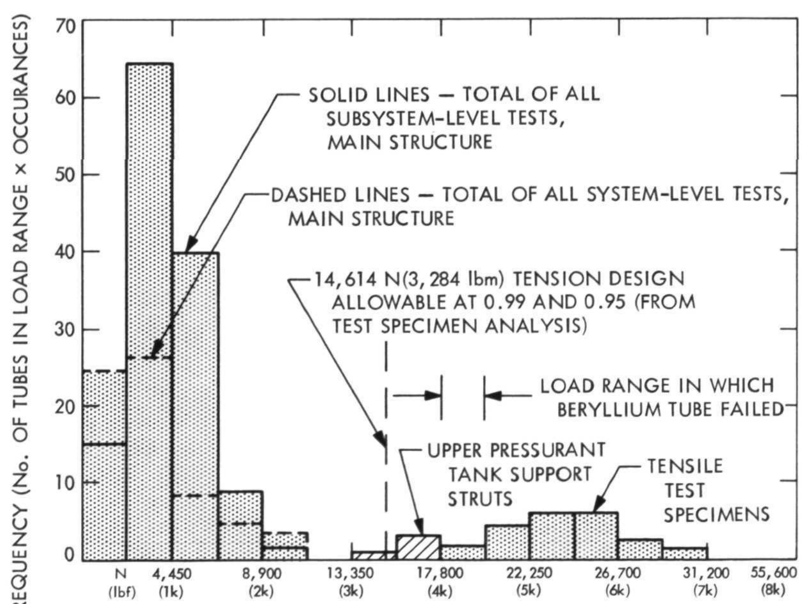


Fig. 6. Beryllium tube loading

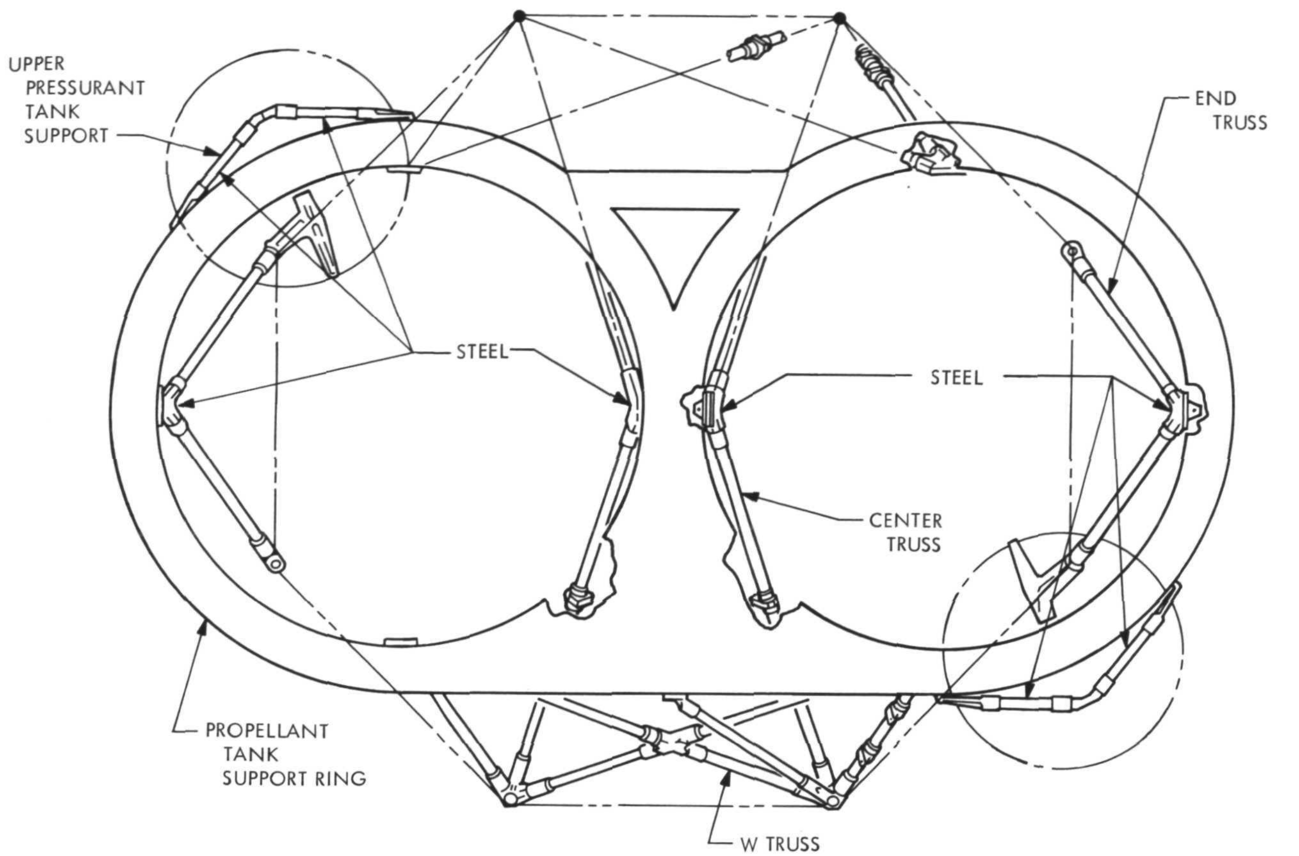


Fig. 7. Support structure steel fitting locations

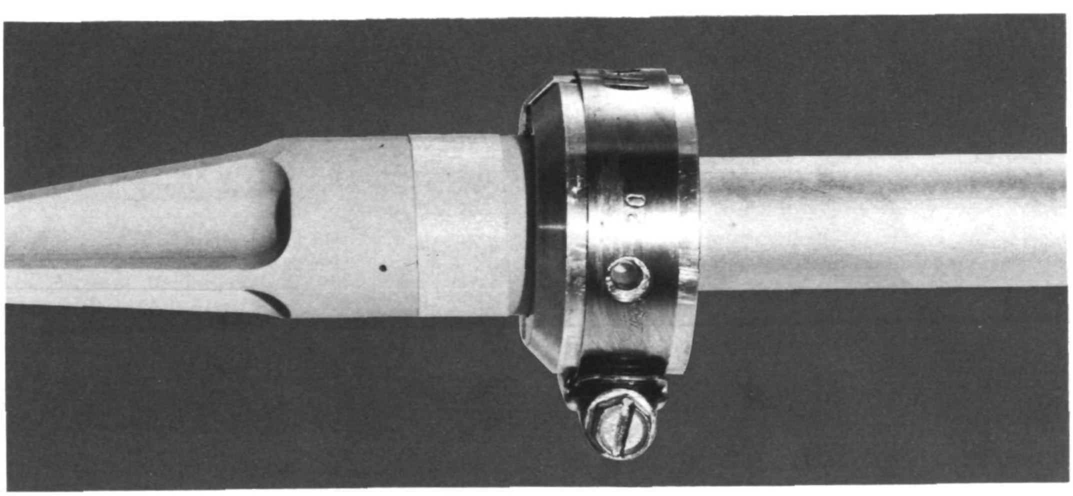


Fig. 8. Injection manifold

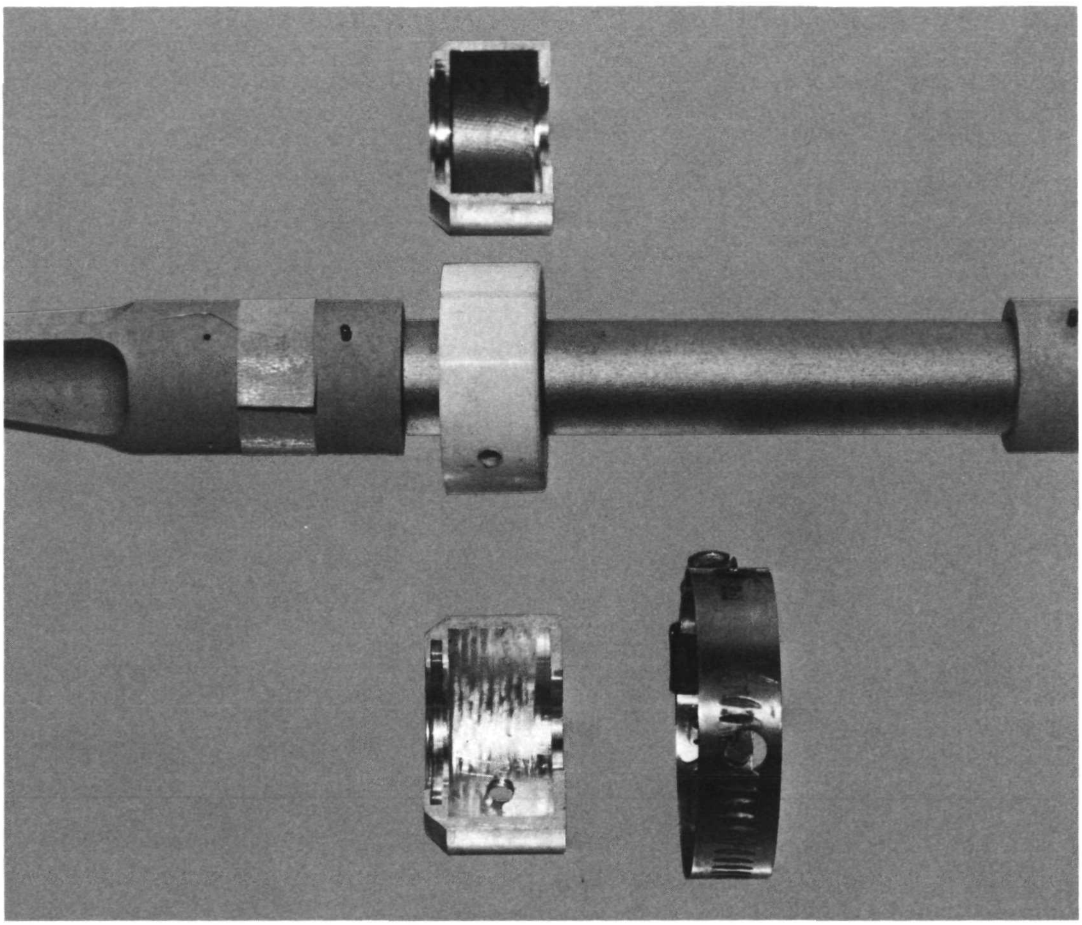


Fig. 9. Injection manifold — exploded view

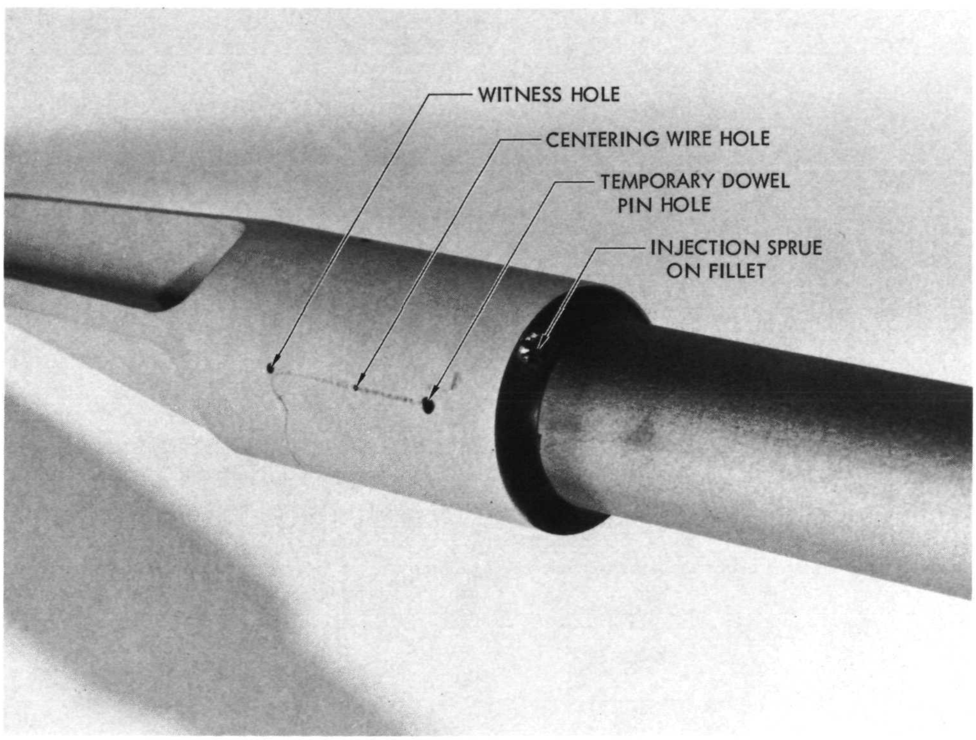
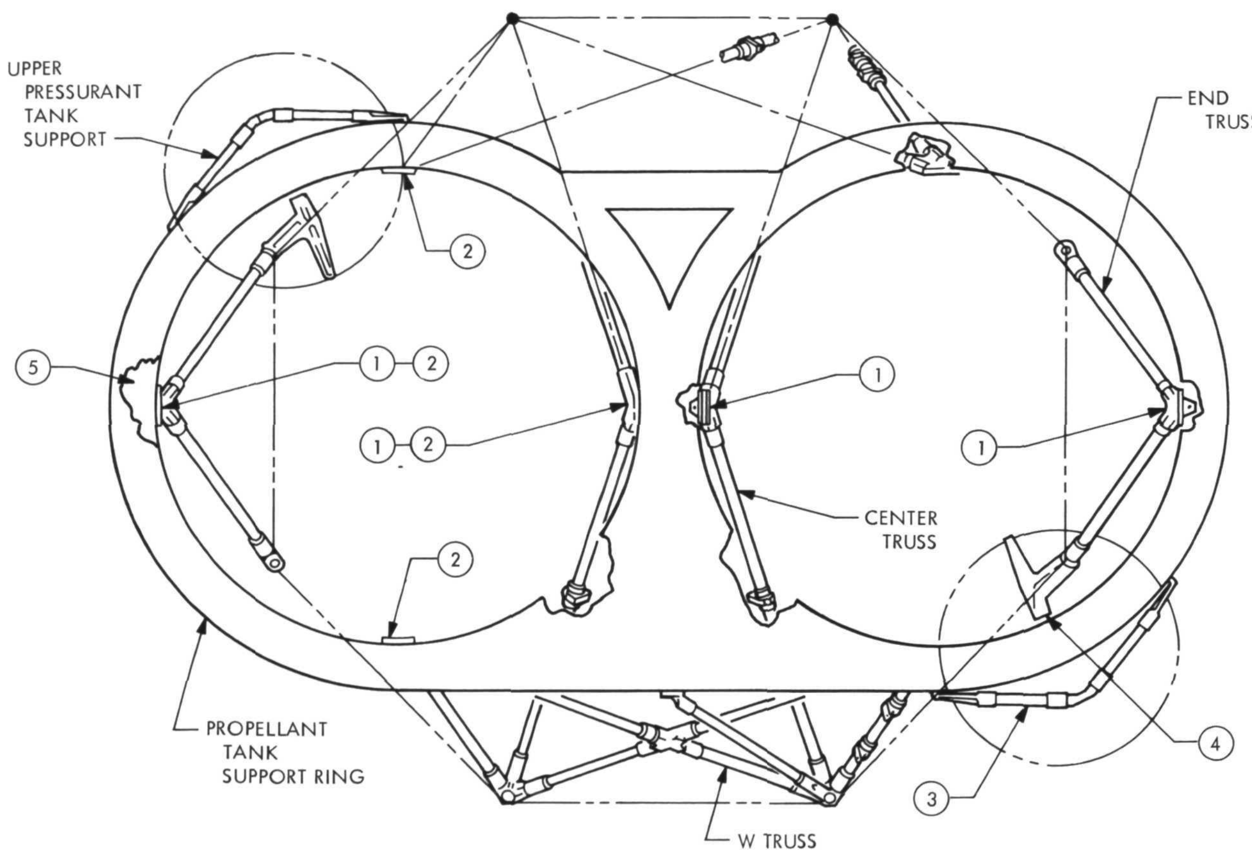


Fig. 10. Typical bonded joint



1 CRACKED FITTINGS - INSUFFICIENT FILLET RADIUS
2 BROKEN FITTINGS - OVERTEST
3 BROKEN BERYLLIUM TUBE - OVERSTRESSED
4 CRACKED FITTING - IMPROPER GRAIN ORIENTATION
5 RING/TRUSS JOINT SLIPPAGE - LOW COEFFICIENT OF FRICTION

Fig. 11. Support structure failure locations

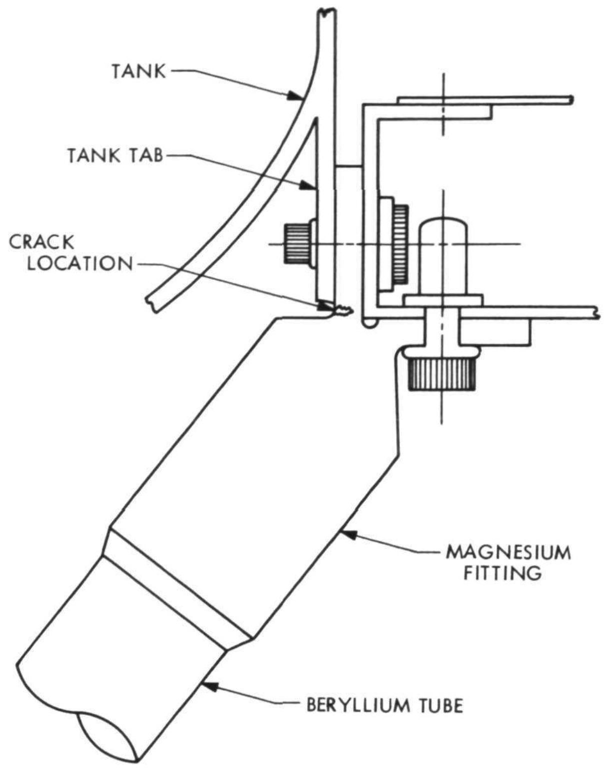


Fig. 12. Fitting crack location

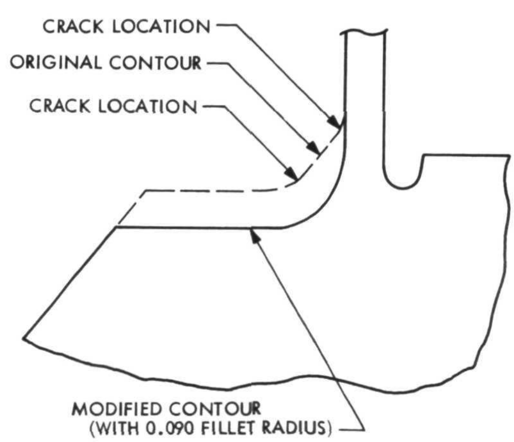


Fig. 13. Fitting fillet radius modification

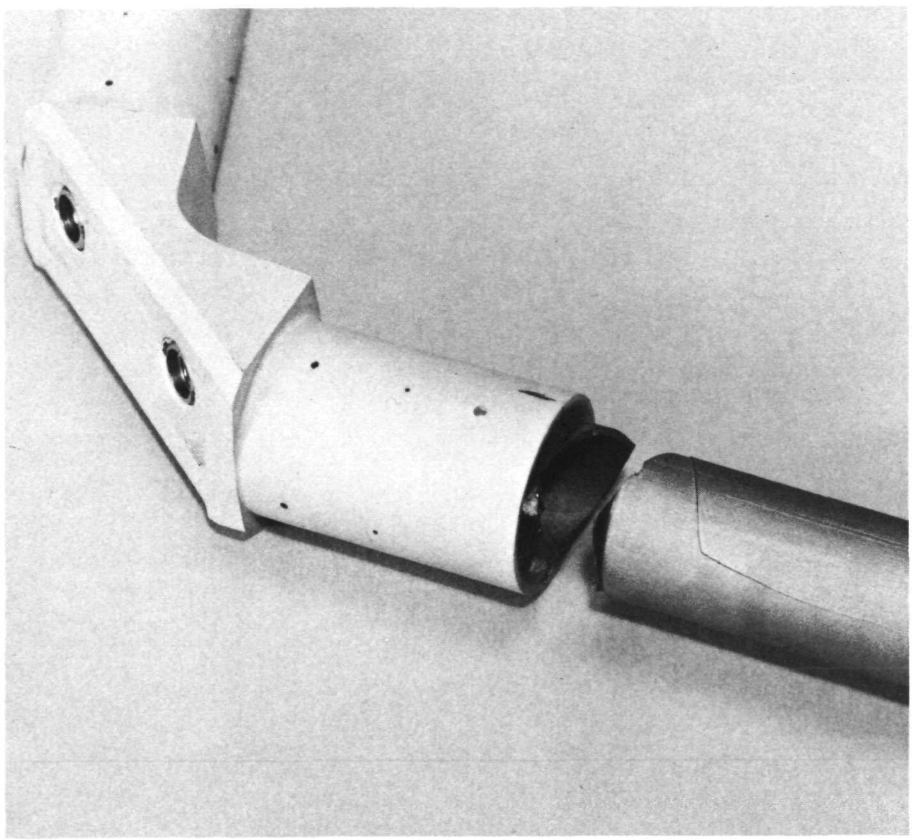


Fig. 14. Upper N_2 tank support tube fracture

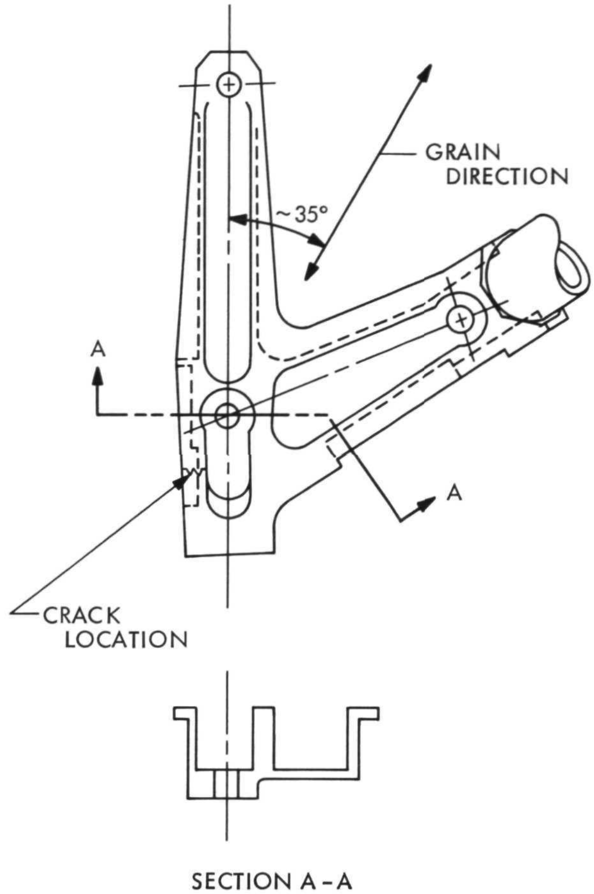


Fig. 15. Lower N_2 tank support – original configuration

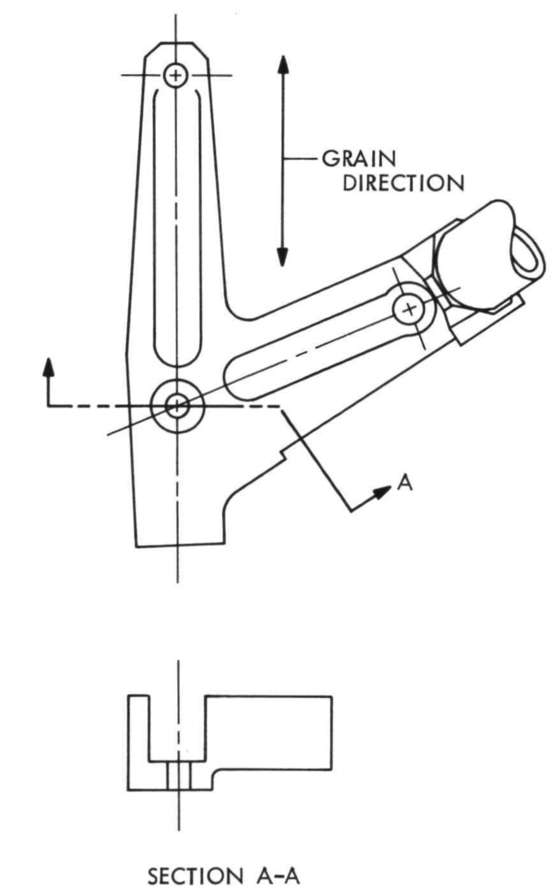


Fig. 16. Lower N_2 tank support – modified configuration

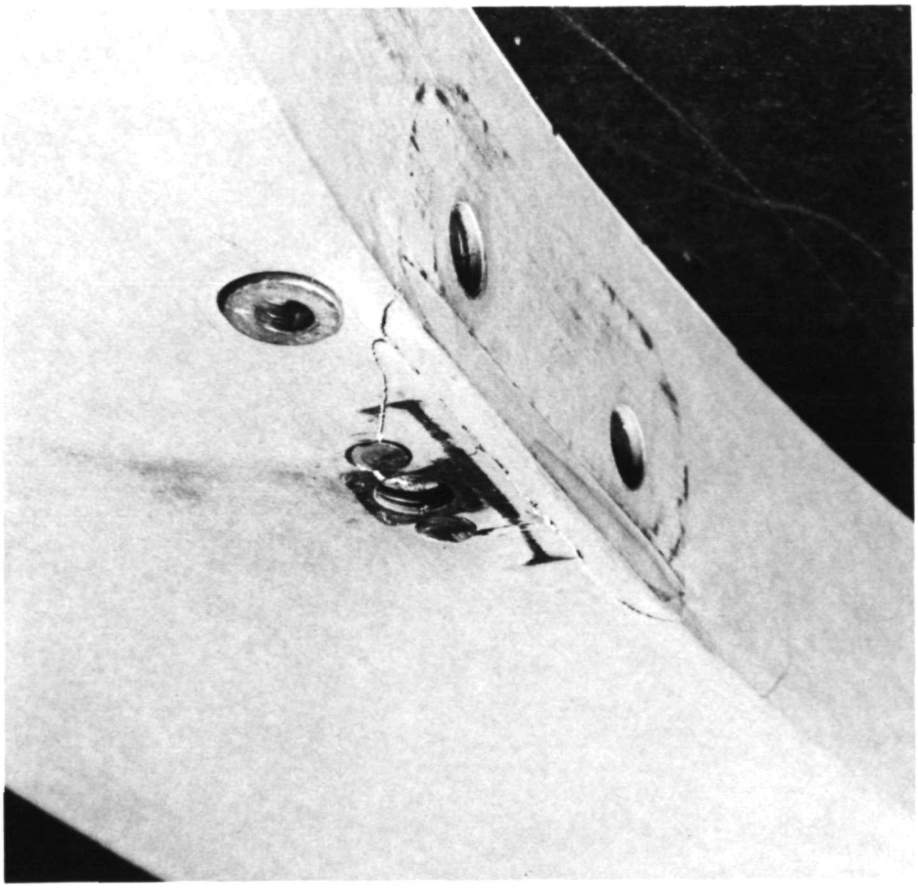


Fig. 17. Ring/truss joint damage

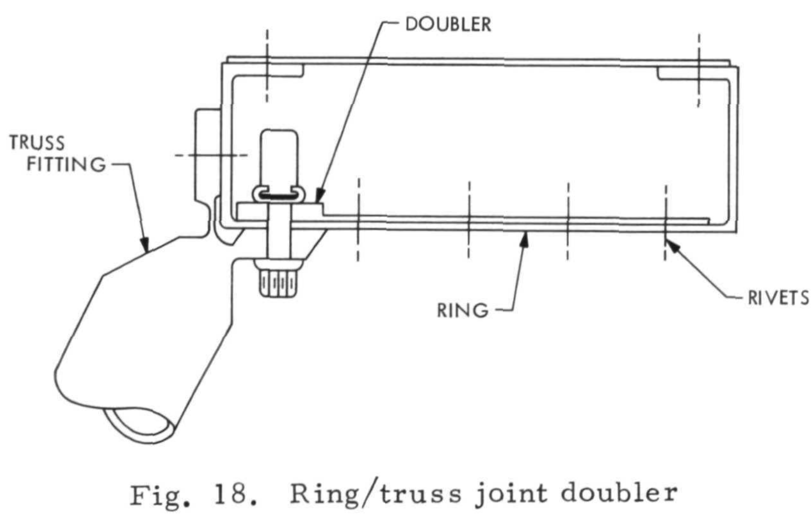


Fig. 18. Ring/truss joint doubler

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