APPENDIX C

REPORT OF MANUFACTURING AND TEST PANEL

CONTENTS

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PART C1

TASK ASSIGNMENT AND IMPLEMENTATION

Panel 2 was assigned the responsibility of reviewing manufacturing and testing associated with spacecraft equipment involved in the flight failure as determined from the review of the flight data and the analysis of the design. In particular, the Panel was to examine discrepancies noted during the fabrication, assembly, and test of components of the oxygen portion of the cryogenic gas storage system within the service module in order to determine any correlations between such preflight discrepancies and the actual inflight events.

Members of the Panel observed actual assembly of an oxygen tank and the oxygen shelf at various stages of assembly at the contractor facilities and reviewed documentation relating to the course of Apollo 13 equipment from manufacturing through test to launch. In addition, the Panel reviewed parts and material qualification data, inspection reports, reliability and quality control records, and preflight test and checkout procedures and results. Throughout the course of its review, Panel 2 concentrated on determining whether manufacturing or test procedures could adversely affect reliable conduct of flight. The steps in the manufacturing and testing of the suspected components were studied so as to evaluate various equipment acceptance procedures. Finally, the Panel attempted to relate observed flight events back to individual points in the manufacturing and testing process in order to determine if any correlation was probable.

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PART C2

ORGANIZATION

Panel 2 was chaired by Mr. H. M. Schurmeier, Jet Propulsion Laboratory, and the Board Monitor was Dr. J. F. Clark, Goddard Space Flight Center. Panel members were:

Mr. E. F. Baehr, Lewis Research Center
Mr. K. L. Heimburg, Marshall Space Flight Center
Mr. B. T. Morris, Jet Propulsion Laboratory

Specific assignments covering such areas as subsystem testing, fabrication process, and reliability and quality assurance were given to each Panel Member. In reaching Panel conclusions, however, all Members participated in the weighing and evaluation of data.

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PART C3

SUMMARY

The basic tank provides a thermally isolated pressure vessel structure that is relatively straightforward to manufacture. The manufacturing process has reasonable controls and provides tanks of high structural quality.

The manufacture of the internally mounted equipment is somewhat more complex because of the large number of parts that are required to make these assemblies. The careful use of jigs, fixtures, and the detailed Manufacturing Operations Procedures (MOP) adequately controls these steps and provides hardware fully meeting the structural design requirements as stated on the engineering drawings.

The most noteworthy manufacturability shortcoming of the design is the routing of the wires from the electrical devices within the tank. The passageways are small, adjacent metal corners are relatively sharp, and the condition of the insulation cannot be inspected after assembly. The assembly process is very difficult and even though detailed MOP's are provided and the technicians are skilled and experienced in these operations, the resultant product is of questionable quality because of the many opportunities to damage the insulation on the wires. Even in the assembled condition, the wires can be damaged because of the lack of support and restraint and the exposure to turbulent fluid during tanking, detanking, and purging operations.

Another notable shortcoming of the design is the very loose tolerances specified for the tank fill tube connecting parts. The tolerance range permitted by the engineering drawings can result in a fill tube assembly that can fall out of place if the parts are at or near the low tolerance limits. The parts cannot be assembled if their size averages much larger than nominal. Even with all parts of the fill tube assembly near the nominal sizes specified, adequate diametral clearance exists for a sizable gas leakage path.

The Globe Industries, Inc., fan motors have had a history of numerous problems. Many design changes were introduced to overcome these problems. The most prevalent problem was dielectric breakdown within the stator windings. Process changes and the addition of 300 volts rms phase-to-phase dielectric tests during stator assembly greatly reduced the incidence rate of this problem.

The standard acceptance procedures adequately cover all functional requirements for normal flight use but do not check the ability of the heater thermostats (thermostatic switches) to function under load, nor do they state a requirement for proper functioning of the fill tube assembly, which must function as a dip tube during detanking operations.

The manufacturing history of tank no. 2 of Service Module 109 (10024XTA0008) before delivery from Beech was unusual only to the extent that the tank was reworked twice after initial closure, once to replace a heater tube assembly including both motor fans and once to replace pinch-off tube assemblies used in evacuation of the annulus volume between the tank shells.

The test history was unusual only to the extent that the high but acceptable heat leak characteristic caused months of delay in tank acceptance. No direct evidence of any particular characteristic of this tank at delivery from Beech, as distinguished from any other Block II oxygen tank, was found that would correlate with the Apollo 13 flight accident.

The normal procedure at the conclusion of the heat leak tests at Beech Aircraft Corporation, Boulder, Colorado, calls for expelling the last 25 pounds of the remaining liquid oxygen through the "fill" line by applying pressure to the vent line with gaseous nitrogen. Although the tank assembly is on a weighing system which has a resolution of 0.3 pound, and the procedure calls for continuing the application of vent line pressure until both the weighing system and quantity probe indicate the tank is empty, no data were recorded that verify that remaining oxygen was expelled as a liquid. At the time no one indicated that the response of the tank to the procedures was anything but normal, and today careful review of existing data, discussions with the responsible Beech Aircraft and North American Rockwell personnel, and a special test at Beech Aircraft indicates that the detanking of the 0008 tank was most probably normal.

The manufacturing and test procedures and activities for integrating the oxygen storage tanks into the service module were thoroughly detailed and closely monitored with respect to procedures. They involved checkouts with dry gas only, until cryogenic oxygen reaches the tanks during the countdown demonstration test (CDDT) at Kennedy Space Center (KSC) a few weeks before launch. Between the tank acceptance and CDDT only pressure vessel integrity and electrically observable phenomena of the inner tank elements are tested. No tests are performed to check the ability of the thermostats to interrupt either the spacecraft-supplied heater power (about 2.8 amps at 28 V dc) or the GSE power (about 6 amps at 65 V dc).

In August 1968, oxygen shelf assemblies at North American Rockwell (NR), Downey, were scheduled to be modified to add potting to the dc-to-dc converters of oxygen tank vac-ion pumps for electromagnetic interference prevention. During factory procedures with the oxygen shelf assembly incorporating tank 10024XTA0008 in the tank no. 2 position in Service Module 106 at NR, Downey, a handling fixture incident (initiated by failure to remove an unnoticed shelf bolt) subjected this tank to unexpected jolts. These included the apparent shelf damaging contact of the tank with the fuel cell shelf and drop of the tank with the shelf to the normal oxygen mounts. Such elements as the fill tube segments appear vulnerable to this incident. No record of investigation into the internal condition of the tank other than pressure and electrical circuit test could be found. Manufacturing and test records do not show engineering assistance related to conditions internal to the oxygen storage tank.

Service Module 106 was promptly repaired and fitted with a different oxygen shelf already modified (ultimately it flew as Apollo 10). The tank and the oxygen shelf now under review were re-inspected and retested during the first 3 weeks of November 1968. They were then installed in Service Module 109 (used in the Apollo 13 flight). This service module was completed, tested, and checked out normally thereafter, so far as the oxygen system was concerned, and transported to KSC in mid-1969.

During integrated test and checkout at KSC, no major anomaly occurred until the tank-emptying phase of the CDDT, March 23, 1970. After this first cryogenic oxygen loading since February 1967, expulsion of liquid oxygen through the "fill" line under gas pressure applied through the vent line was not achieved. Evidence supporting the assumptions of leakage or dislodgment of the fill line segments (two Teflon elbows and one short Inconel tube) in the top of the quantity probe assembly within the oxygen tank was produced at KSC in the processes of emptying the tank.

Special methods used for emptying on March 27 and 28, 1970, and again on March 30, involved protracted operation of the tank heaters and fans for many hours and at maximum heater voltage. In conjunction with this heating, cyclic gas pressurization and blowdown was used to achieve rapid boiling to remove oxygen from the tank. Analyses of data taken during the early portion of these procedures confirm boiling as sufficient to detank the observed quantities.

These methods were not supported by previous comparable operations with any other Apollo CSM cryogenic oxygen storage tank. Thus it was not demonstrated separately that such operation could be accomplished without degradation or hazard in the subsequent flight use of the tank.

A review of all the evidence available indicates that this tank (at least the fill line segments) most probably arrived at the CDDT in a different condition than that in which it was last tested at Beech Aircraft Corporation.

Tests were conducted at the Manned Spacecraft Center to evaluate the effects of the sustained heater operation during the special detanking operation at KSC on March 27, 1970. These tests demonstrated that the thermostats would weld closed when they attempted to interrupt the 5.9 amps, 65 volts dc GSE power (a condition for which they were neither designed nor qualified) resulting in their failing to limit the temperature inside the tank. The tests also showed that with the heaters on continuously and as the cryogenic liquid boiled away, temperatures in the 700° to 1000° F range would exist on portions of the heater tube in contact with the motor wires. These temperatures severely damaged the Teflon insulation even in the nitrogen atmosphere of these tests. Small-scale tests subjecting Teflon insulated wires to 700° to 1000° F temperature oxygen atmosphere indicated even more severe damage to the Teflon insulation.

Therefore it is reasonable to conclude that the special detanking procedures employed on tank 0008 at KSC prior to launch of Apollo 13 severely damaged the insulation of the motor wiring inside the tank.

A more complete test is being conducted at Beech Aircraft, Boulder, Colorado, to simulate the special detanking operations used at KSC on March 27-28 and 30, 1970. This test will utilize a flight configuration tank, simulated KSC ground support equipment, and will be conducted using oxygen.

PART C-4

REVIEW AND ANALYSIS

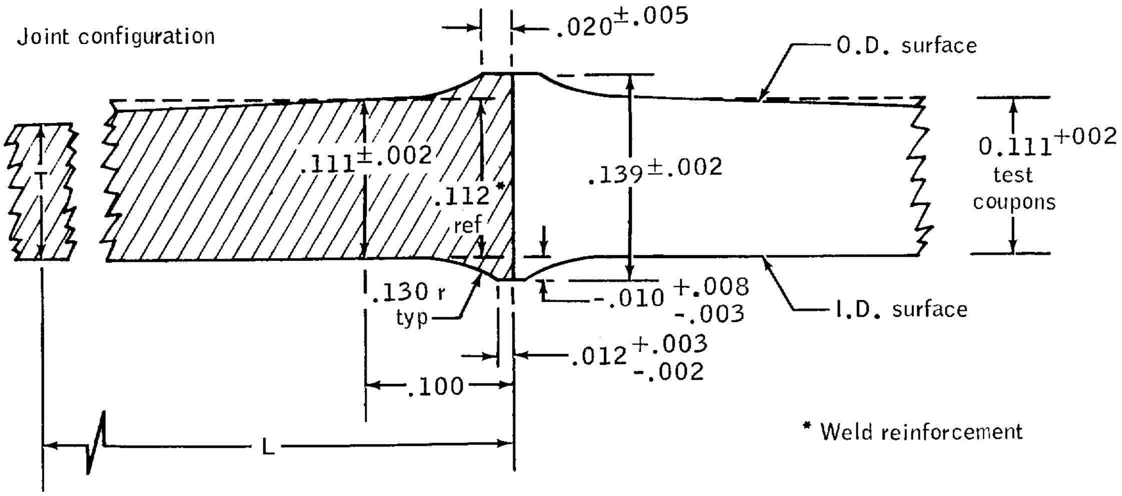
MANUFACTURE AND ACCEPTANCE TESTING OF THE CRYOGENIC OXYGEN STORAGE TANKS

The cryogenic oxygen storage tanks are manufactured by the Beech Aircraft Corporation, Boulder Division, located north of Boulder, Colorado. The tank consists of a spherical high-pressure inner vessel wrapped with multilayer insulation contained within a thin external metal vacuum jacket. Inside the pressure vessel are a heater and fan assembly (two heaters and two fans), a quantity measuring probe, and a temperature sensor. Many of the parts and subassemblies that comprise this tank are purchased by Beech from subcontractors and vendors located throughout the United States.

The detailed instructions for the manufacture and assembly of these tanks and their subassemblies at Beech are controlled by Manufacturing Operations Procedures (MOP). In addition to instructing the technicians, the MOP also calls out the presence and activities of the inspectors.

Summary of the Standard Tank Manufacturing Process

The inner pressure vessel is made from two forged hemispheres of Inconel 718 alloy. The rough-machined heat-treated forgings are supplied by the Cameron Iron Works, Houston, Texas. The physical, chemical, and metallurgical properties (X-ray, ultrasonic scan, and microstructure) of these forgings are tested and certified by Cameron. The Airite Division of Electrodata Corp., Los Angeles, California, does the final machining and electron beam welding. Prior to welding a very thorough inspection is made of each hemisphere. About 430 thickness checks are made to assure compliance to dimensional accuracy requirements. Each hemisphere is thoroughly X-rayed and dye-penetrant inspected for defects. The internal parts that support the heater probe assembly are made by Beech and supplied to Airite for installation prior to making the electron beam equatorial weld. A rather elaborate five-step welding process is used in making this equatorial weld (figs. C4-1 and C4-2). The first step is a series of tack welds. The second step is a seal weld of shallow penetration. The third step is a deep-penetration weld. The fourth step is a shallower and wider weld to blend surfaces. The fifth weld is called a cover pass which is still wider and shallower for final surface blending. The completed vessel is X-rayed and then pressure tested. A hydrostatic proof pressure of 1357 psig $^{+00}_{-35}$ is applied for 3 minutes using water. The volumetric expansion during the proof-pressure test is determined by measuring the weight increase of water contained within the test specimen. A leak test



P/M thickness L	T	Tank radius O.D.	Dimensions I.D.	
1.000	.084$^{\pm .002}$	14.808 ref$_{arc}$	12.528$^{+005}_{-0}$	Sph rad
2.000	.067$^{\pm .002}$	14.808 ref$_{arc}$	12.528$^{+005}_{-0}$	Sph rad
3.000	.059$^{+004}_{-000}$	12.587 ref$_{arc}$	12.528$^{+005}_{-0}$	Sph rad

Weld schedule (Electron beam weld)

	Pass sequence				
Parameter	1-tack	2-seal	3-pene.1	4-pene.2	5-cover
Voltage - Kv	80	80	115	95	85
Amperes - MA	1.5	1.5	6.0	4.0	3.0
Beam deflection - in.	0.012	0.012	.024/.036	.040/.080	0.110
Travel - in./min	18	⟶	⟶	⟶	⟶
Vacuum - mm hg	2×10^{-4}	⟶	⟶	⟶	⟶

Notes: (1) 0.002" gap, 0.003" offset (max typ)
(2) No weld repairs allowed
(3) Typical weld sequence shown on attached sketch

Figure C4-1.- Girth weld joint configuration and schedule.

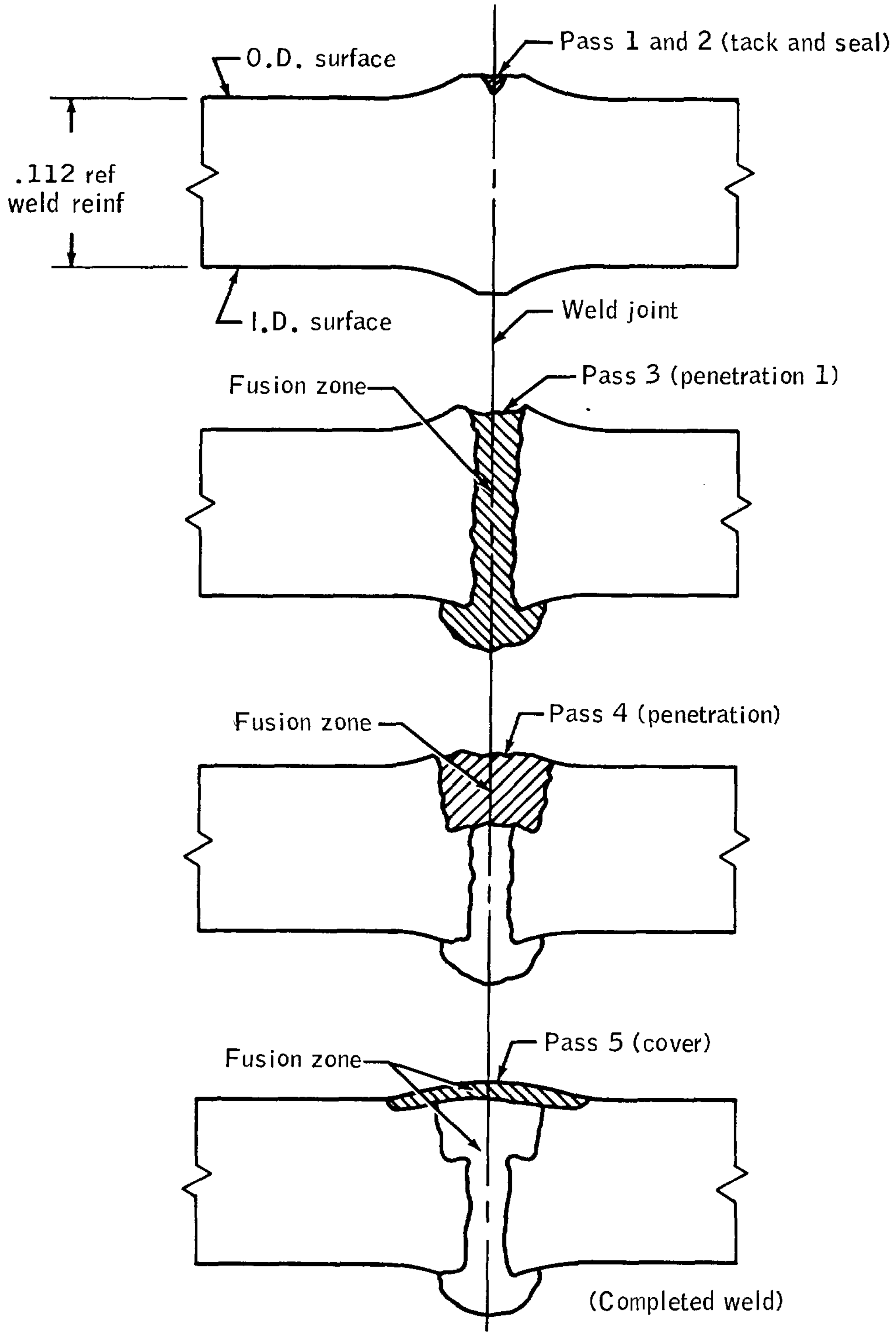


Figure C4-2.- Weld sequence.

is made at 925 psig ±15 using helium. These tests are performed by the Beech Test Department before acceptance. The completed vessels, along with substantiating data, are shipped to Beech for assembly.

The inner pressure vessel is cleaned for oxygen service and sealed in plastic. When scheduled for application of insulation, the vessel, the insulation, and the other necessary piece parts and supplies are moved to a small room annex to an area known as the Respectable Room. (The Respectable Room, its annexes, and the Ultra Clean Room together are known as the Apollo Assembly Area.)

All assembly operations performed in these rooms are in accord with standard clean room techniques, i.e., lint-free gowns, caps, and gloves. A simple entrance airlock has a motorized shoe brush and vacuum cleaner but the brushes are disabled so as not to rotate under motor power. There is no air scrub.

The insulation is applied to the inner vessel in gore panels, a layer at a time. The insulation consists of many layers of Dexiglas Insulation paper (C. H. Dextar & Son, Inc.), fiberglass, mats, aluminum foil, and aluminized Mylar. Each layer is carefully applied to the vessel, temporarily held in place with tape, trimmed for fit, and then finally held in place by thin nylon threads. After the threads are in place the tape is removed. The joints in succeeding layers are shifted so as to effectively block the flow of heat. The aluminum foil layers are checked with an ohmmeter to assure no electrical contact with inner vessel or adjacent foil layers. About halfway through the insulation process, a tube is installed which goes from the vacuum dome area to the equator, around the equator, and back to the dome area. This is called the vapor cool shield (VCS). (See fig. C4-3.)

After all the insulation is applied, the external metal jacket is installed. These parts are made by Chemtronics, Inc. The main upper and lower hemispheres are deep drawn and chem-milled. The equatorial flange is machined from a ring forging (fig. C4-4). All parts are made of Inconel 750 alloy. An assembly of the lower hemisphere and equatorial flange is made by Heli-arc welding. A shield is placed over the insulation in the region of the final closure weld between the lower hemisphere-flange assembly and the upper hemisphere shell. After these parts are positioned over the insulated pressure vessel, the circumferential weld to join them is made by the automatic Heli-arc welding process using argon gas for inerting the weld zone. The welds in the vacuum jacket are then X-ray inspected to insure integrity.

Figure C4-5 shows the major subassemblies required to complete the oxygen tank assembly. All components and piece parts required to build subassemblies are cleaned for liquid oxygen service, grouped as required

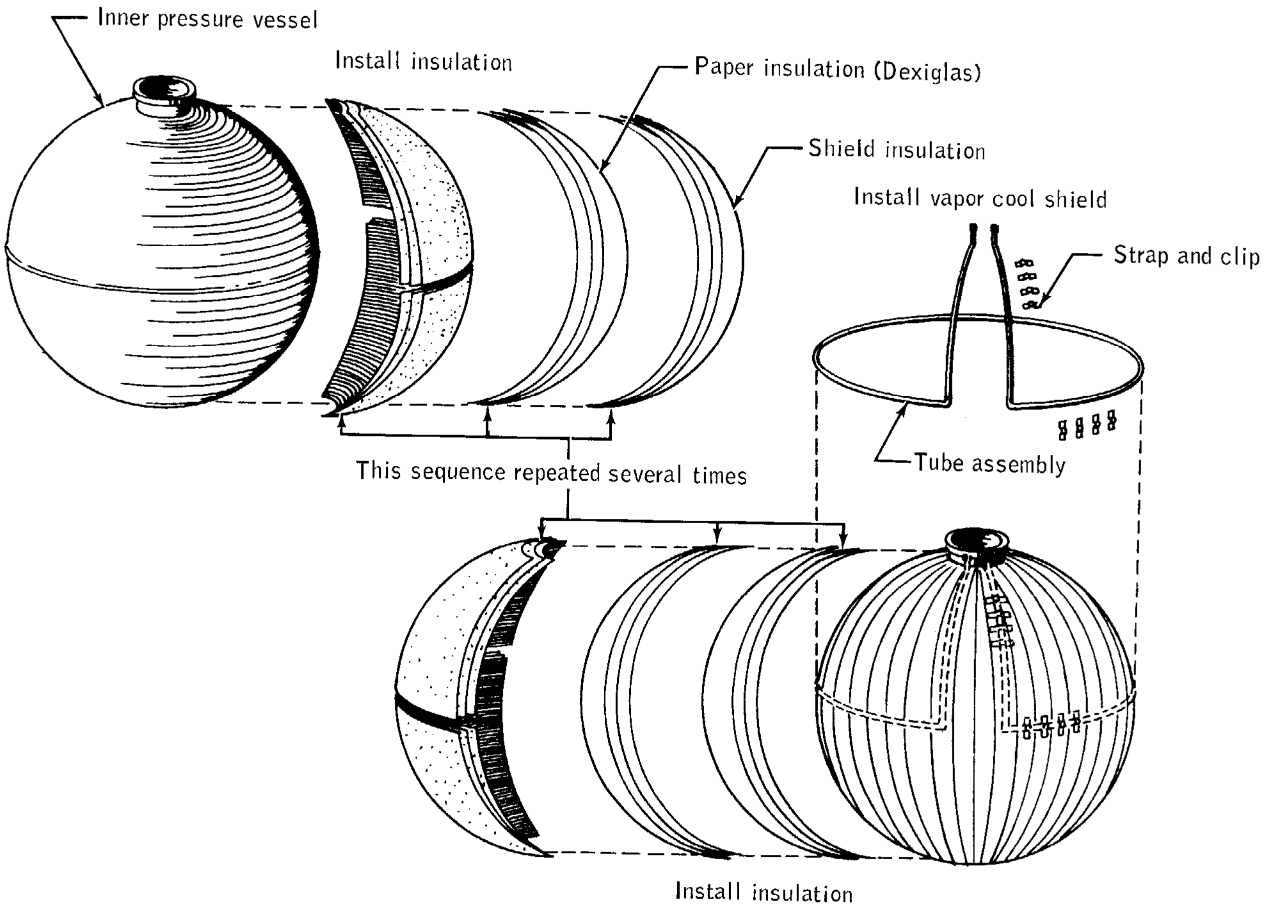


Figure C4-3.- Installation of insulation.

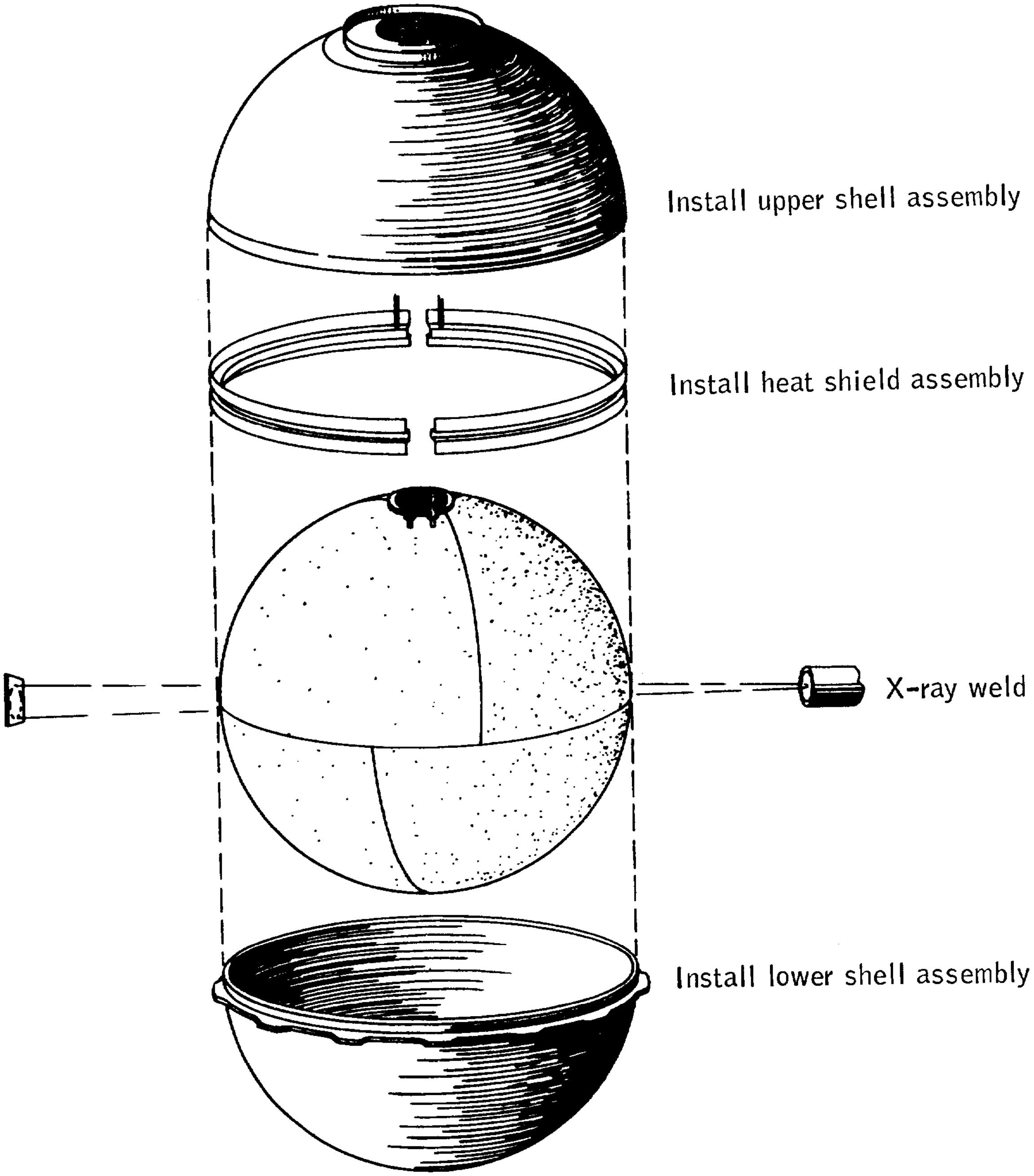


Figure C4-4.- Installation of vacuum jacket.

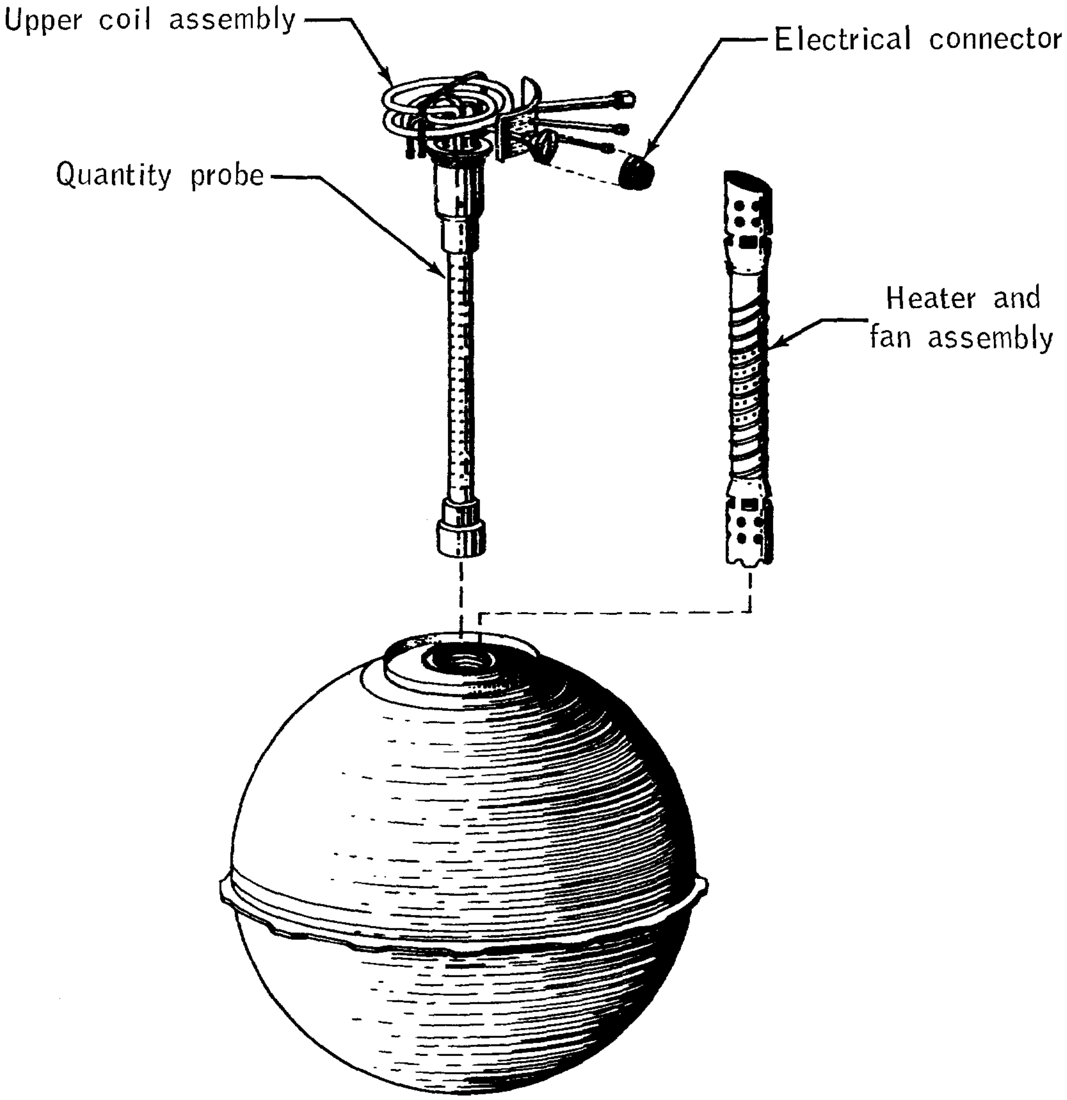


Figure C4-5.- Major subassemblies required for tank assembly.

for each subassembly (kitted), and sealed in a clear nylon plastic bag which is then sealed in a clear polyethylene bag. These kits are stored for the subassembly and assembly operations which are performed in various rooms of the Apollo Assembly Area.

The heater and fan assembly is made from numerous small parts welded, brazed, riveted, or bolted together (fig. C4-6). The first operation installs the lower pump nozzle assembly into the lower motor housing. These parts are positioned in a jig and then fusion welded in place. After this weld is X-rayed, the part is turned to trim the inside diameter and to assure roundness. The lower motor housing is then positioned and welded to the central tube. The weld zone is X-rayed and the entire assembly is pickled and passivated. The two helically preformed stainless-tube-encased nichrome heating elements are then slid in place. Before proceeding the heaters are tested for resistance and isolation from ground. The upper motor housing tube is then positioned and welded to the central heater tube. After this weld is X-rayed, the heaters are positioned and silver soldered in position. After the heater tube is thoroughly cleaned to remove any silver solder flux, the tube (conduit) that routes the wires from the lower motor past the heater elements is installed by riveting the two small clips to the inside of the central tube. Small aluminum shims are riveted to the inner surface of the heater tube to provide a flat surface for the mounting of the thermostats. The unit is then vacuum baked at 200° F to remove any moisture from the heater assembly. The resistance and insulation tests are again run to assure that the brazing has not damaged the heaters and that the units are thoroughly dry.

At this point the heater tube is ready for the installation of the thermostats. The thermostats are purchased from the Spencer Thermostat Division of Metals and Controls, Inc., Attleboro, Massachusetts. Each thermostat is subjected to detailed acceptance testing by Metals and Controls, Inc., and these data are supplied to Beech with the serialized switches. The acceptance testing consists of a 1000 V ac dielectric test for 1 minute, a visual check for workmanship, a dimensional check to drawing size callouts, a 5-minute soak in liquid nitrogen, the opening temperature, the closing temperature, a second 5-minute soak in liquid nitrogen, a recheck of the opening temperature, a recheck of the closing temperature, a leak test to check hermetic seal, a megohm test, the final inspection marking, a recording of number of cycles on the unit as shipped, the actual weight of unit, and visual packing and shipping inspection. Throughout all testing by Metal and Controls, the thermostats are checked by using 6.5 V ac and a small lamp drawing approximately 100 milliamps. Incoming inspection at Beech is limited to a visual examination.

The thermostats are inserted into the tube with their hook-type terminals extending to the outside of the heater tube and bolted in place. This heater tube assembly is then cleaned and bagged for future assembly operations.

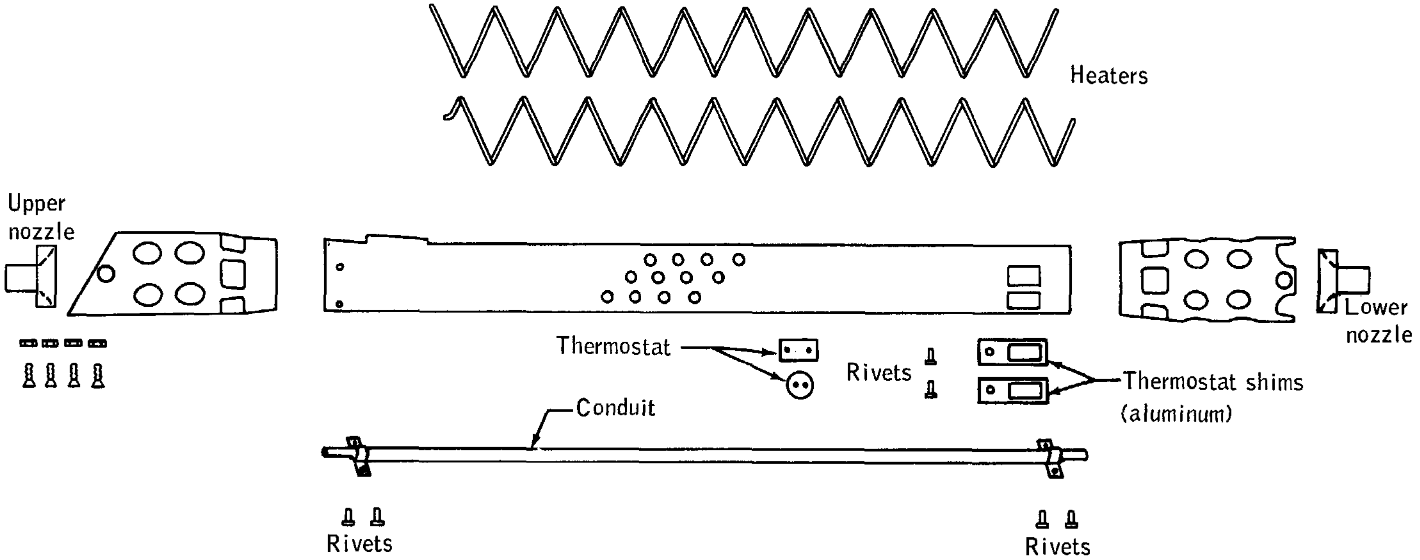


Figure C4-6.- Heater tube assembly.

The electric motor fans are purchased from Globe Industries, Inc. These motors go through a thorough acceptance test at Globe before delivery to Beech. In addition to the normal visual and mechanical inspection, the motors are functionally tested at both ambient and cryogenic conditions. A 1000 V dc dielectric strength test is applied between the windings and case. The isolation must be at least 2 megohms. The motor is then operated on 115 V ac 400 cycles, and the following characteristics are measured and recorded: (1) speed and current of motor when operating with a calibrated test fan, and (2) line current and total power both running and still. The motors are then operated in liquid nitrogen. These checks are limited to assuring that the motor starts and runs smoothly and that coastdown time is at least 30 seconds.

At Beech the normal visual incoming inspection was performed and then these parts were stored until ready to be incorporated into the heater and fan assembly.

The kits of parts and components required for the heater and fan assembly are moved to an annex room of the Respectable Area where this assembly operation is performed on a laminar flow bench. The necessary tools are cleaned and laid out for ease in the assembly process. An assembly aid is used to support the fan and heater tube in the horizontal position.

The lower electric motor is now installed. The electrical leads are provided by the motor supplier (four 26-gage nickel with Teflon insulation twisted 10 turns to the foot with a 2-inch-long Teflon sleeve adjacent to the motor) (fig. C4-7). These leads are routed parallel to the motor shaft through a shallow groove milled half in the motor end cap and half in the motor support tube (figs. C4-8 and C4-9). From this channel the wires are routed against the inner surface of the motor tube in the region of the impeller. The wires then emerge through a hole in the motor housing tube (ungrommeted). The motor is inserted in the end of the tube (fig. C4-10) and the motor end plate is installed. Shims are used as required under this motor end cap to provide 0.030-inch to 0.040-inch end clearance between the impeller and the nozzle. When the proper shims are selected and installed, the four end cap screws are torqued to the required value (fig. C4-11). The end cap is bolted to the support tube by four radial countersunk machine bolts, small segment-shaped shims, and self-locking nuts (all metal).

When the location of the lower motor is verified as having the correct impeller-to-nozzle clearance, the wire routing task continues. The wires travel axially about 2 inches (fig. C4-12) where they go inboard through a Teflon grommet into the inner conduit and travel the length of the heater section to a symmetrical location where they again emerge to the exterior through a Teflon grommet. A single insulated wire is used to pull the motor leads through this conduit route.

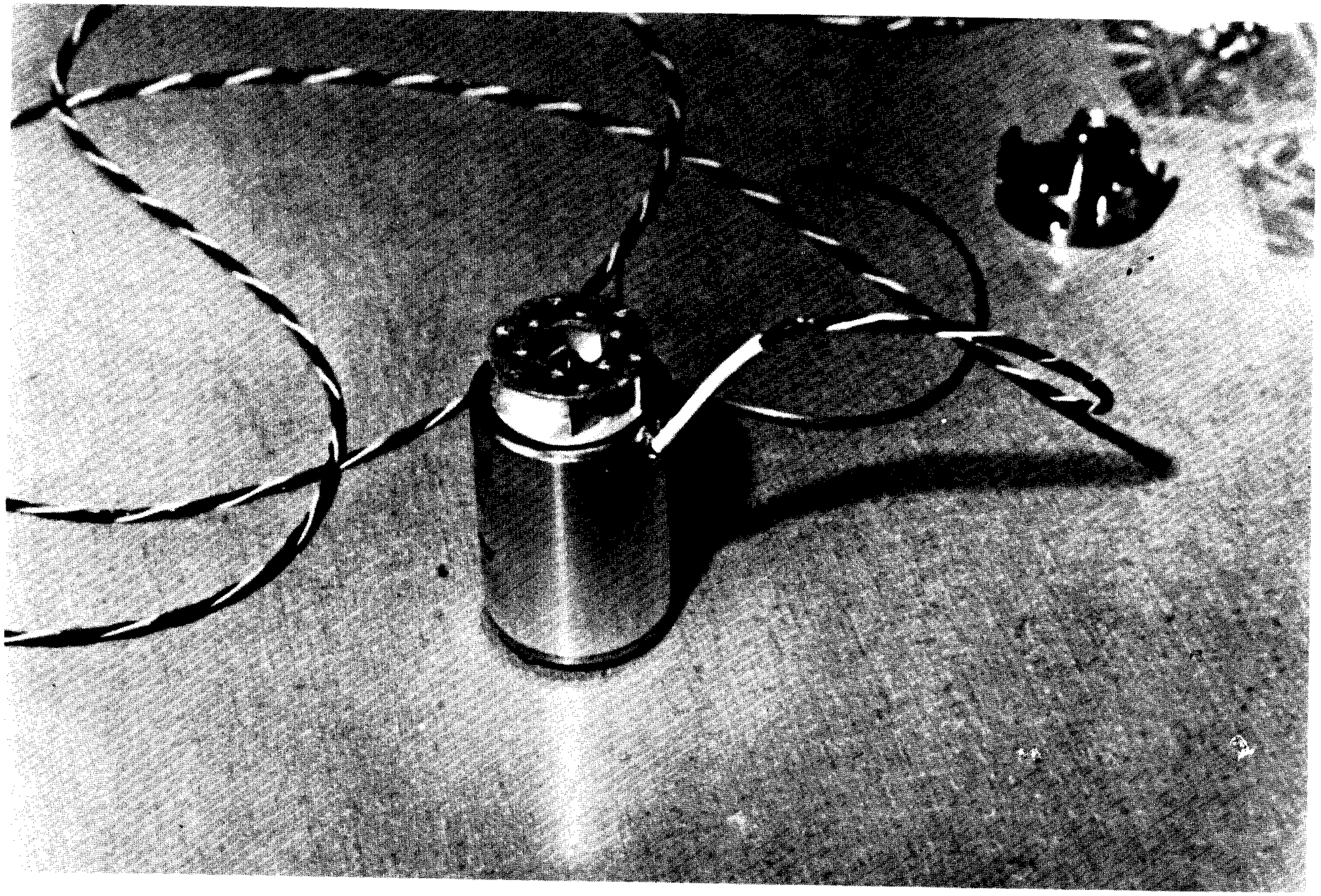


Figure C4-7.- Motor fan with long lead wires.

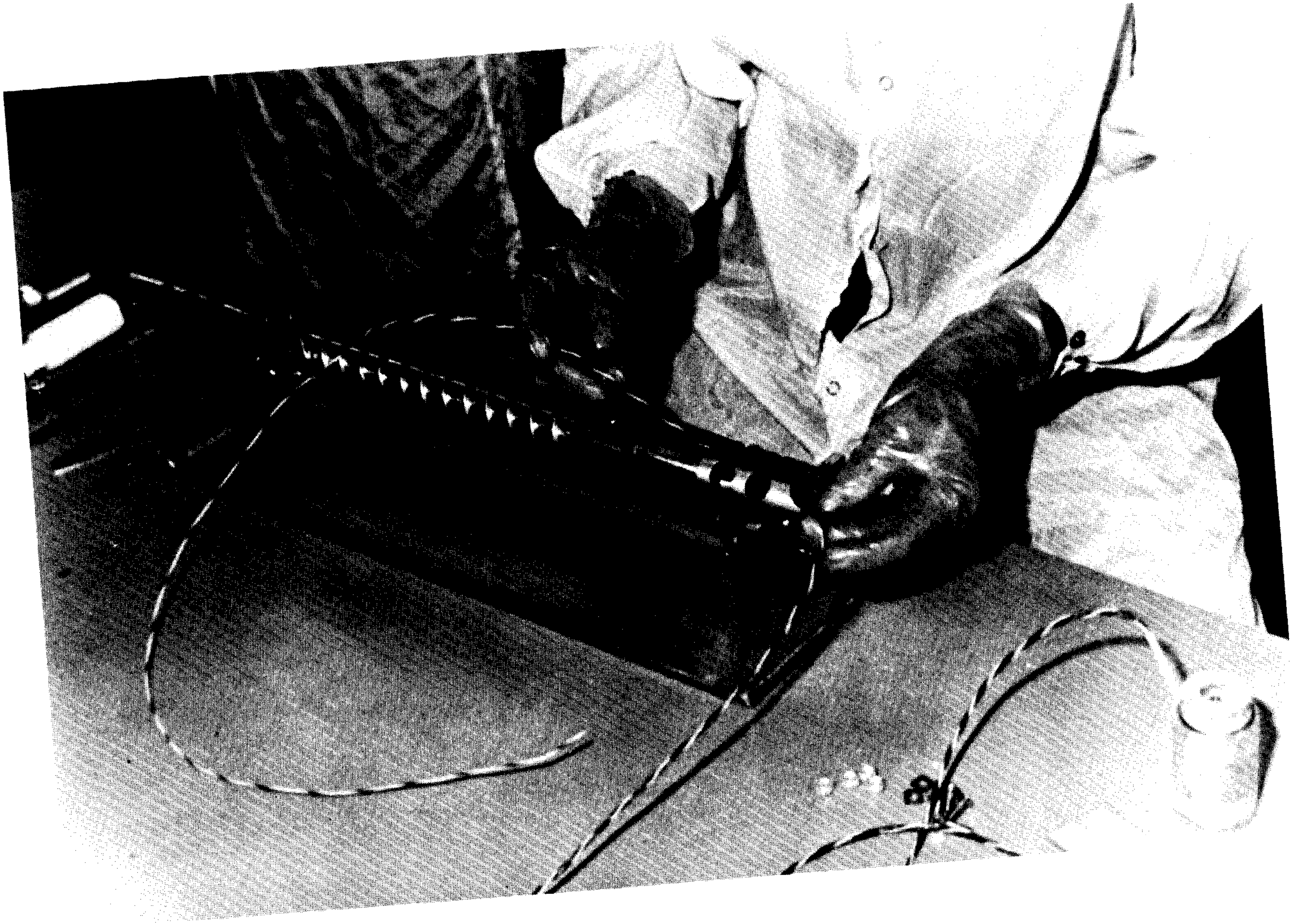


Figure C4-8.- Installing motor lead wires.

Figure C4-9.- Installing lower fan motor.

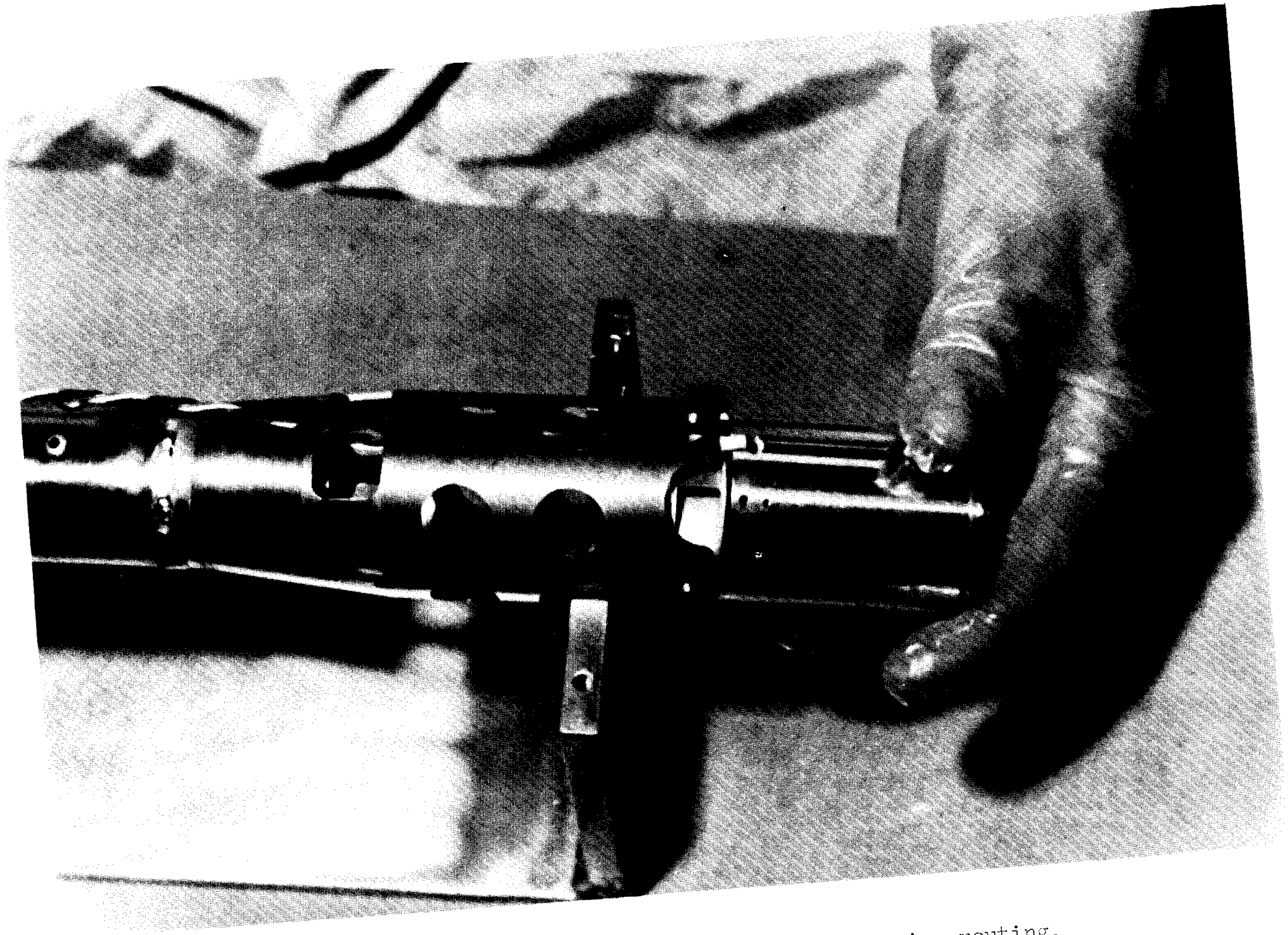


Figure C4-10.- Installing lower fan motor showing wire routing.