crack-like imperfections are sometimes introduced by the forging process, but these are relatively small and confined to the surface layers of the forging. Such defects are easy to detect and are usually removed by the machining process. It is the standard practice of the aerospace industry to reject forgings that have cracks that cannot be removed by machining. With this in mind, there is no reason to doubt the effectiveness of the final high-pressure helium proof test insofar as the pressure vessel main membrane area is concerned.

Possibility of Tank Failure During Apollo 13 Mission

On the basis of the foregoing information, it is extremely unlikely that the oxygen tank no. 2 pressure vessel ruptured at the maximum recorded flight pressure of 1008 psi and temperature of -160° F because of crack propagation. Based on the previously described ligament model, a pressure vessel passing the last high-pressure helium proof test should withstand a pressure load nearly twice that of the maximum flight pressure at -160° F. As described previously, a high-temperature blowout of the pressure vessel is entirely possible, and if this occurred the fluid released could have caused rupture of the dome or of the outer shell.

DYNAMIC TESTING

During the development and qualification of the command and service modules (CSM), a series of dynamic tests was conducted on major vehicle elements as well as subassemblies. The following sections describe those tests applicable to the cryogenic oxygen tank.

Oxygen Tank Assembly Dynamic Testing

Dynamic testing was accomplished during September 1966. Flight-type oxygen tank assembly hardware, selected as a test specimen, successfully completed this testing as documented in reference 17.

Vibration testing.- The test specimen was subjected to vibration in each of three axes, and the vibration level was maintained for 15 minutes in each axis. The specified test levels, representing the combined envelope of the atmospheric and space flight conditions, were as follows:

Frequency, Hz	g^2/Hz
10	0.003
10-90	0.003 to 0.025 at 3 dB/octave
90-250	0.025
250-400	0.025 to 0.015 at 3 dB/octave
400-2000	0.015

The test spectrum is shown as the solid line in figure D3-10. No significant anomalies were recorded during these tests. These tests qualified the oxygen tank assembly for the launch and space flight conditions.

Acceleration testing.- The oxygen tank assembly used in the vibration testing mentioned in the preceding paragraph was also tested for acceleration in each of three axes for at least 5 minutes in each direction. The acceleration was 7g in the launch axis direction and 3g in the other two orthogonal axes. These accelerations are greater than those expected during normal ground handling or during flight. No anomalies were recorded during these tests.

Apollo CSM Acoustic and Vibration Test Program

In addition to the dynamic testing previously described, the oxygen tank and shelf assemblies plus other CSM subsystems were tested as part of the Block II, Spacecraft 105/AV Certification Test Program conducted during February and March 1968 (ref. 18). These tests qualified the Block II CSM hardware against the acoustic and vibration criteria, and confirmed the structural integrity of the CSM for vibration inputs which enveloped the complete ground and flight environmental requirements as specified in reference 19.

Figure D3-11 shows the transducer locations used for both the acoustic and vibration testing. Test instrumentation in the area of the oxygen tank was as follows:

SA 110 (+X)	Oxygen shelf on bracket, 18 inches from beam 4
SA 111 (-R)	Oxygen shelf on bracket, 18 inches from beam 4
SA 112 (-T)	Oxygen shelf on bracket, 18 inches from beam 4
SA 113 (+X)	Oxygen shelf on centerline

Note: R = radial, T = tangential

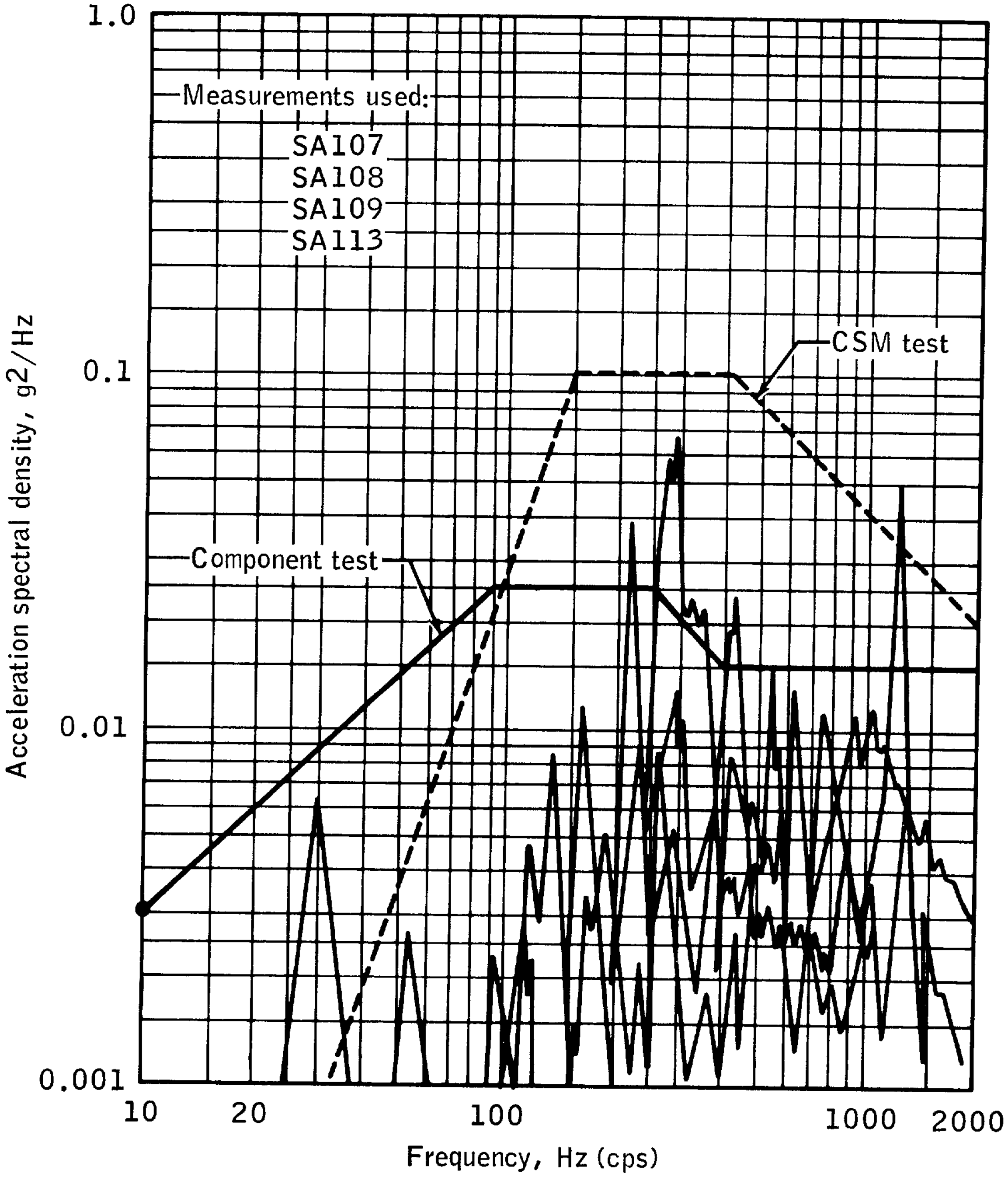


Figure D3-10.- Service module data overlays and specified test spectrum.

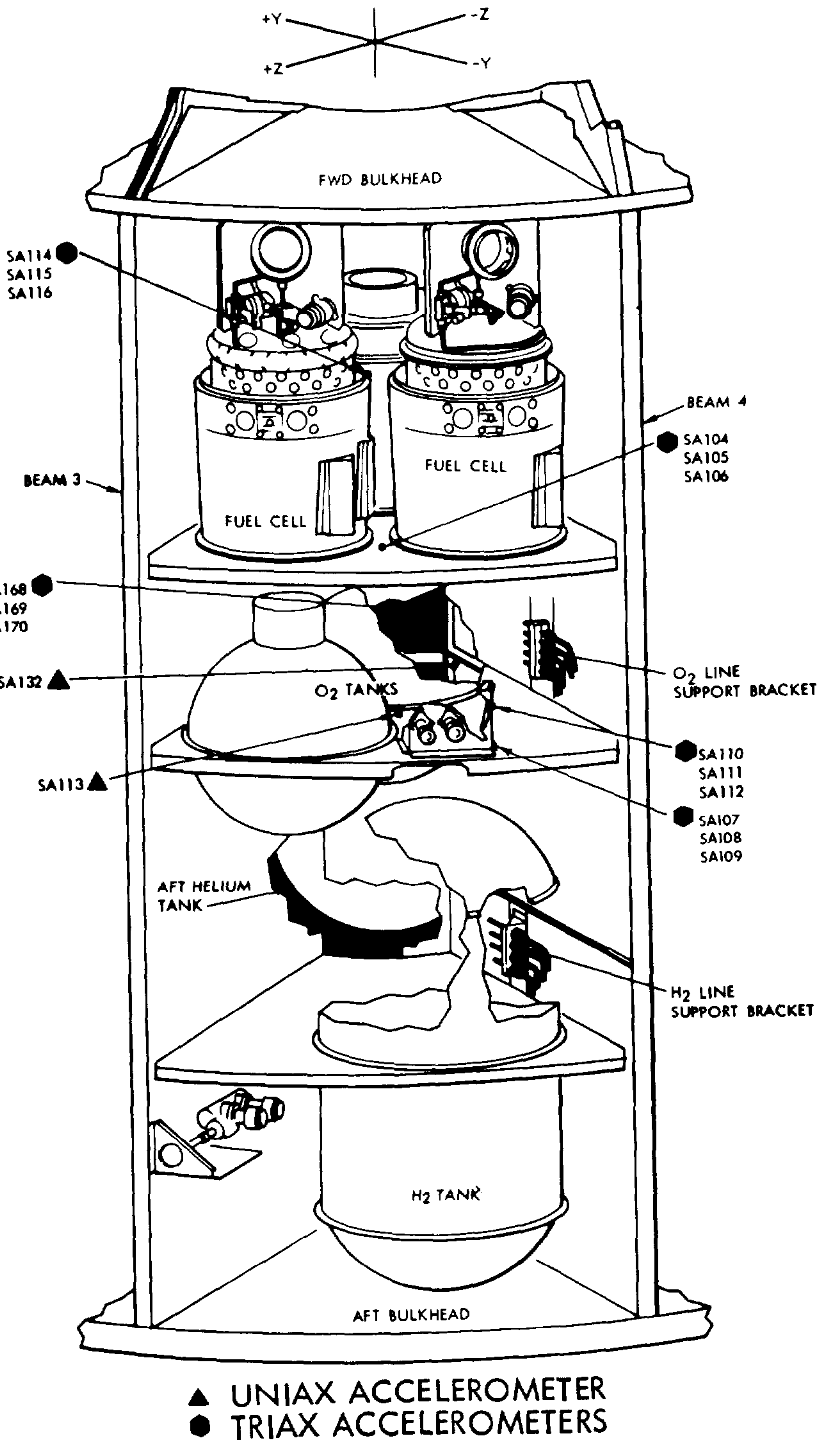


Figure D3-11.- Spacecraft 105/AV service module instrumentation, bay 4.

Vibration testing consisted of sinusoidal sweeps in the 4- to 30-Hz range, followed by sinusoidal dwells at the prominent resonance frequencies. CSM vibration response was controlled to 0.075-inch double amplitude for the 4- to 8-Hz frequency range and 0.1g peak for the 7- to 30-Hz frequency range.

Acoustic tests were performed to measure the vibratory response in the 20- to 2000-Hz frequency range. The acoustic spectrum of interest for the oxygen tank was adjusted to obtain a test spectrum as shown in figure D3-10.

The vibration and acoustic tests were completed without failures or any pertinent anomalies in the oxygen tank or tank shelf. The maximum observed accelerations during the tests are given in the following table:

Inst. no.	Vibration		Acoustic
	X-axis 4- to 30-Hz sweep, g (rms)	Z-axis 4- to 30-Hz sweep, g (rms)	X-axis 4- to 30-Hz sweep, g (rms)
SA 110	0.02	0.05	0.005
SA 111	.5	.5	.35
SA 112	.5	.6	.6
SA 113	.15	.4	.17

The responses of four transducers (SA 107 through SA 109 and SA 113) are shown in figure D3-10.

The tests confirmed the following:

1. Structural integrity of Block II CSM wiring, plumbing, bracketry, and installed subsystems when subjected to the dynamic loads resulting from spacecraft exposure to the aerodynamic noise environment expected during atmospheric flight.

2. Structural integrity of the Block II CSM when it is experiencing the low vibratory motions produced by atmospheric flight.

Based upon the results, it is concluded that the tests were adequate to qualify the CSM for flight on the Saturn V. Of course, this qualification would not necessarily cover abnormal conditions such as mishandling.

SHOCK TESTING

Although NR specification (ref. 20) requires qualification testing of the oxygen tank assembly inside its shipping container for ground handling and transportation conditions, further investigation revealed that this requirement was deleted on January 8, 1965. This deletion is documented in paragraph 3.8.4.3 of reference 21, which states, "Revised Apollo Test Requirements, no testing of transportation and ground handling environments (shall be required). Packaging is designed to preclude exposure of components to environments beyond transportation levels." The shipping container (ref. 22) was reportedly shock tested during the development program in 1964 and successfully sustained the test environment described in reference 23. From these tests it was concluded that the shock attenuation system in the shipping container was acceptable. There was no requirement for shock testing of the oxygen tank assembly outside its shipping container.

INTERNAL COMPONENTS

There are a number of components internal to the oxygen tank. These are individually discussed in the following sections.

Quantity Gage

The quantity gage capacitor (fig. D3-12) consists of two concentric aluminum tubes which are adequately mounted and supported. The inner tube of the capacitor constitutes the extension of the fill line. The outer tube is perforated to insure access of the oxygen to the space between the capacitor plates. The relative position of the two plates is maintained by insulating Teflon separators. Shorting of the capacitor at the plates within the tank requires bridging of the gap between the tubes by a conductive material. Shorting could also be induced by the contact of bare lead wires resulting from insulation damage. The power input to the quantity gage is regulated and limited by the high impedance source of the signal conditioner. The spark that could be

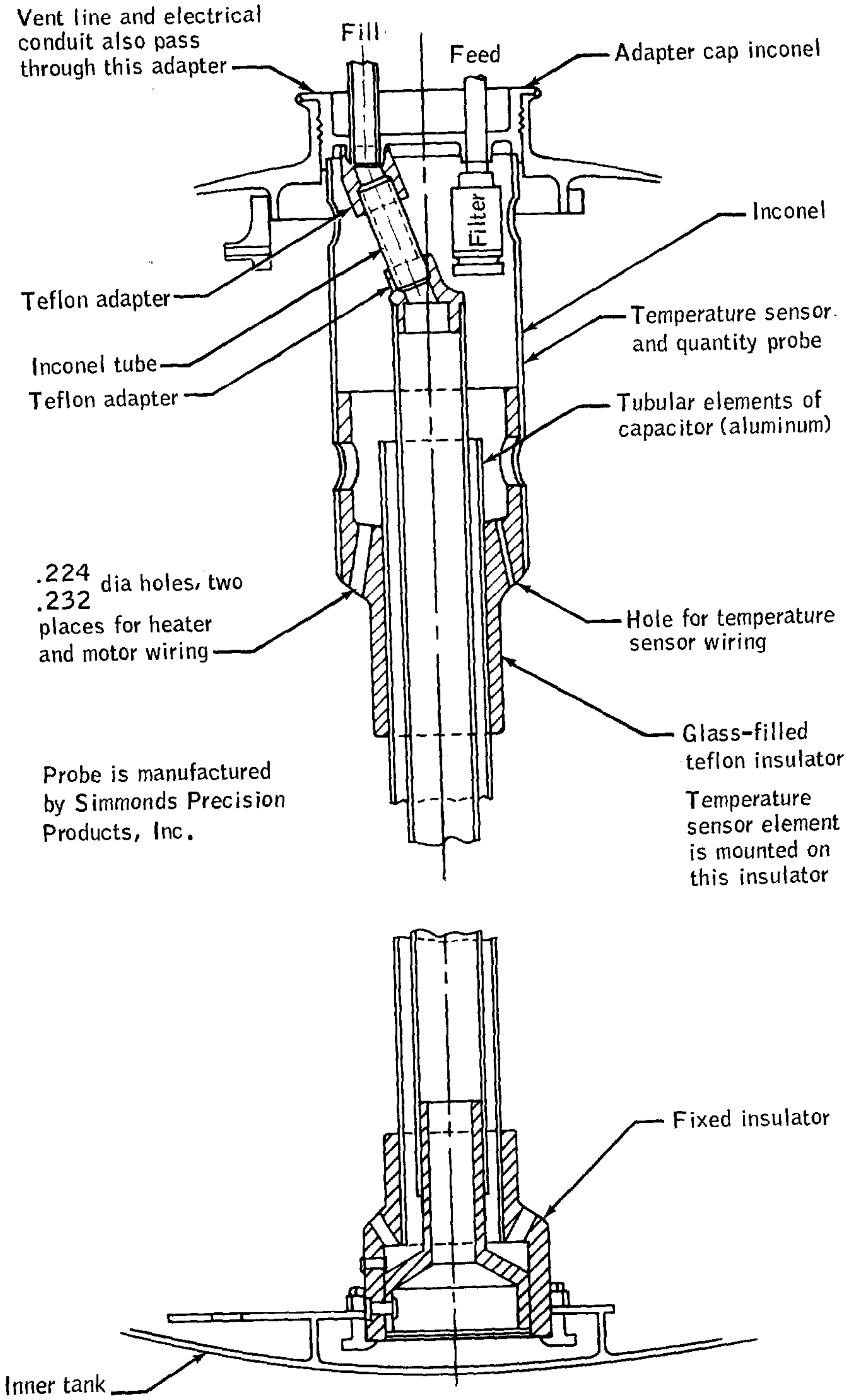


Figure D3-12.- Quantity gage.

generated is at the 7- to 10-millijoule level. The evidence provided by the data can be construed to indicate that the effects of the probe failure during flight were limited to data loss.

Heaters

The two electrical heaters (fig. D3-13) are mounted to the heater fan support tube. The heaters are nichrome resistance wire imbedded in magnesium oxide insulation encased within a sheath of stainless steel. The stainless steel sheath is spiralled and brazed to 12.0 inches of the support tube length. The specifications established by North American Rockwell for the Block II EPS cryogenic storage system (ref. 24) provide a requirement for operation of the heater circuit at 65 V dc from a GSE source for initial pressurization of the oxygen tank. For flight the specification calls for operation from a 28 V dc source. The specifications established by Beech Aircraft Corporation for the heater (ref. 25) stipulate standby operation from an ac source, later established as 65 V ac, for 50 minutes. While the heater is apparently satisfactory for its intended use, the specifications are not compatible with the intended use. The heater circuit is protected by a 15-ampere circuit breaker. Individual thermostats for each heater are also mounted on the inside of the support tube.

The thermostats were included in the heater circuit to prevent raising the pressure vessel wall temperatures above 90° F, the design temperature for the vessel walls. Such a condition (i.e., walls reaching temperature above 90° F under operating pressure) might occur if there was a very low quantity of oxygen left in the tank and it was desired to maintain pressure. There is no known instance of the thermostats ever having had to operate in flight.

A cross section of a thermostat is shown with the contacts in the open position in figure D3-14. The contacts would assume this position when the temperature of the thermostat reached 80° ± 10° F. When the thermostat temperature is reduced to 60° ± 7° F, the differential contraction of the two metals of the bimetallic disc causes the disc to snap through, assuming a convex up configuration. This forces the wave washer and the attached thrust pin to move upward. The movable arm containing the lower contact is pushed up by the thrust pin and the contacts are closed. The wave washer acts as a spring to keep the thrust pin bearing against the bimetallic disc. All of the moving parts of the thermostat are enclosed in an hermetically sealed case.

The thermostats are rated by the manufacturer as follows.

CURRENT RATING OF THERMOSTAT

Number of cycles	Applied voltage		
	30 V ac or dc	125 V ac	250 V ac
100,000	5.0 amp	2.0 amp	1.0 amp
50,000	5.5 amp	3.0 amp	1.5 amp
25,000	6.0 amp	4.0 amp	2.0 amp
10,000	6.5 amp	5.0 amp	2.5 amp
5,000	7.0 amp	6.0 amp	3.0 amp

The specifications established by North American Rockwell for the Block II EPS cryogenic storage system (ref. 24) provide a requirement for operation of the heater circuit at 65 V dc from a GSE source for initial pressurization of the oxygen tank. For flight, the specification calls for operation from a 28 V dc source. The specifications established by Beech Aircraft Corporation for the thermostat (ref. 26) stipulate a current-carrying requirement of 7 amperes without specifying voltage level or type of source (i.e., ac or dc). Acceptance test requirements imposed on the supplier by this latter document include dielectric testing, thermal shock, verification of operating temperatures of the thermostat, helium leak test, insulation resistance test, and visual and dimensional inspection. No requirement is imposed for acceptance test verification of the operational characteristics of the thermostat with respect to current-carrying capability or ability to open under load at any of the several voltages (65 V dc, 65 V ac, or 28 V dc) to which the thermostat will normally be subjected.

Qualification testing of the thermostats was accomplished as part of the overall testing of the assembled oxygen tanks. These tests included vibration, acceleration, and mission simulation. Operation of the heater circuit at Beech during the oxygen tank qualification program and for all normal acceptance testing is accomplished using 65 V ac for initial pressurization. Since this is done only when the tank is filled with liquid oxygen, it is highly unlikely that temperatures would be raised to levels that would cause operation of the thermostats. One instance of a single thermostat operating to open a heater was experienced in the First Mission Subsystem Qualification Test (ref. 27). At this time, heaters were being energized from a 28 V dc bus.

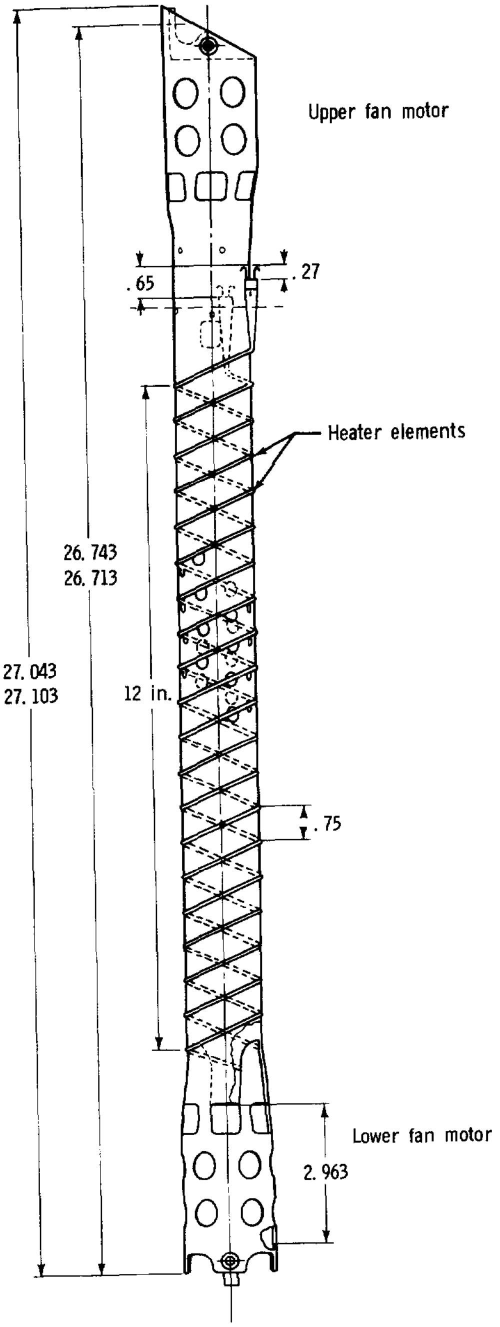


Figure D3-13.- Heater fan support.

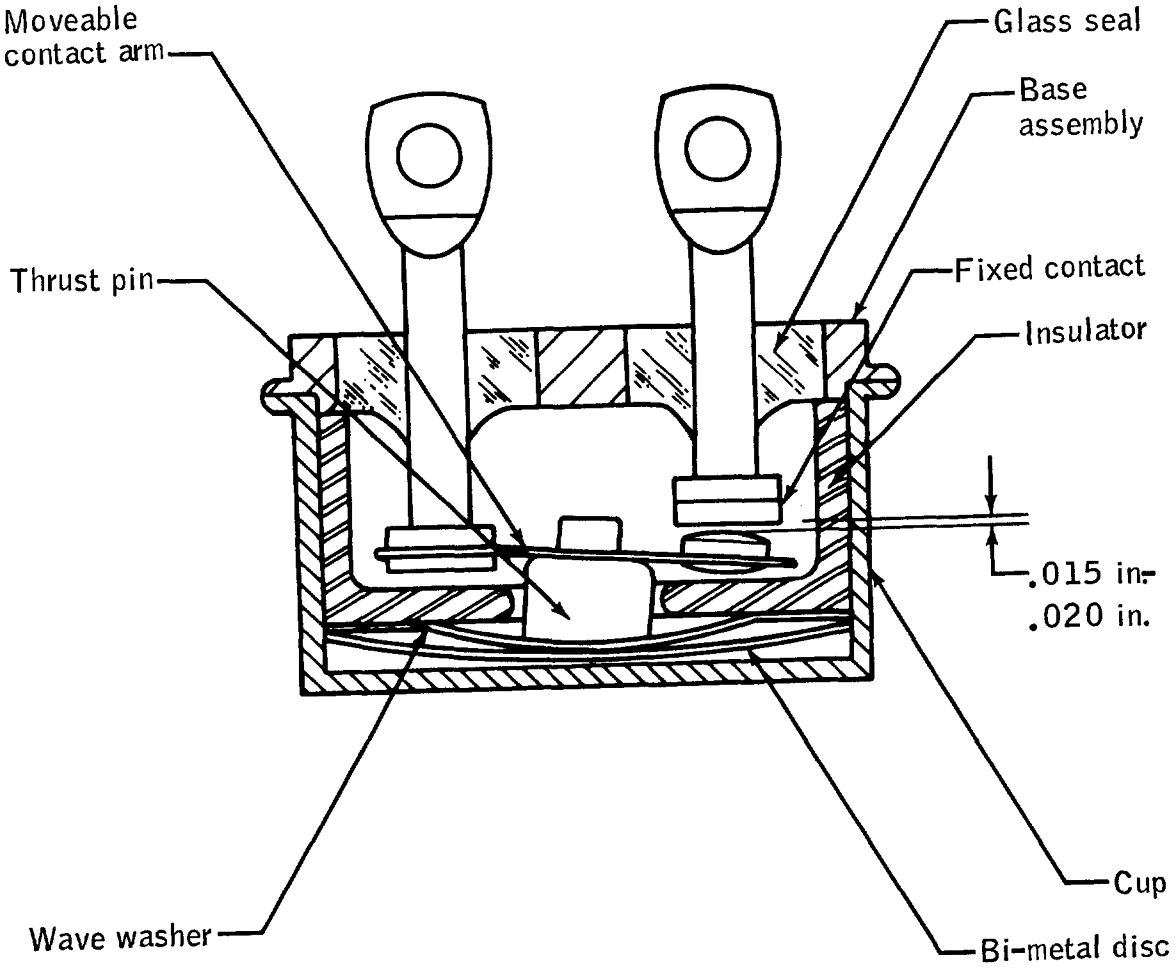


Figure D3-14.- Cross section of thermostat.

All qualification and acceptance tests identified were primarily concerned with the repeatability of the thermostat actuation at the specified temperatures. No qualification or acceptance tests have been identified which would verify the ability of the thermostats to open the heater circuit when energized at 65 V dc.

The combination of incomplete, unclear, and therefore inadequate specifications of the thermostat with respect to voltage type and level and a test program that does not verify the ability of the switch to operate satisfactorily under service conditions constitutes a design deficiency. The fact that the ratings for the thermostat by the manufacturer (preceding table) contains no entry for 65 V dc indicates that service at this voltage was not intended.

At KSC, the heater circuits were intended to be operated at 65 V dc only when the tanks were full of liquid oxygen. Under this condition, the thermostats would not be required to actuate. A discussion of the possible consequences of actuation of the thermostat under load at 65 V dc is presented in a later section of this Appendix.

Fans

At the time the tanks were first designed, the knowledge of the behavior of fluids in zero-g was limited. It was believed that significant stratification of the fluid would occur during flight. Under these circumstances a number of difficulties could arise: a rapid pressure drop in the tank would be induced by the acceleration resulting from an SPS burn; the heaters might not be able to transfer heat uniformly to the oxygen; and, finally, serious errors in quantity measurement could result. The occurrence of any of these conditions could jeopardize flight safety or mission success. For this reason, the tanks were provided with two motor-driven centrifugal fans to mix the fluid and insure its homogeneity.

The two oxygen fan motors (fig. D3-15) are three-phase, four-wire, 200/115-volt, 400-hertz, miniature, open induction motors, driving centrifugal flow impellers. The minimum speed of the motors is 1800 revolutions per minute at a torque output of 0.9 ounce-inches. The motors are mounted at each end of the motor-heater support tube by a cantilevered attachment joined to the motor back plate. The motor clearance within the support tube wall is a nominal 0.01 inch. The stator windings and bearings of the motors are exposed to oxygen.

The stator windings are fabricated with number 36 American Wire Gage (AWG) wire, using a Teflon-coated ceramic insulation. The ceramic insulation is brittle and subject to breakage if proper tension is not used in fabricating windings or if sharp bends are made at the winding

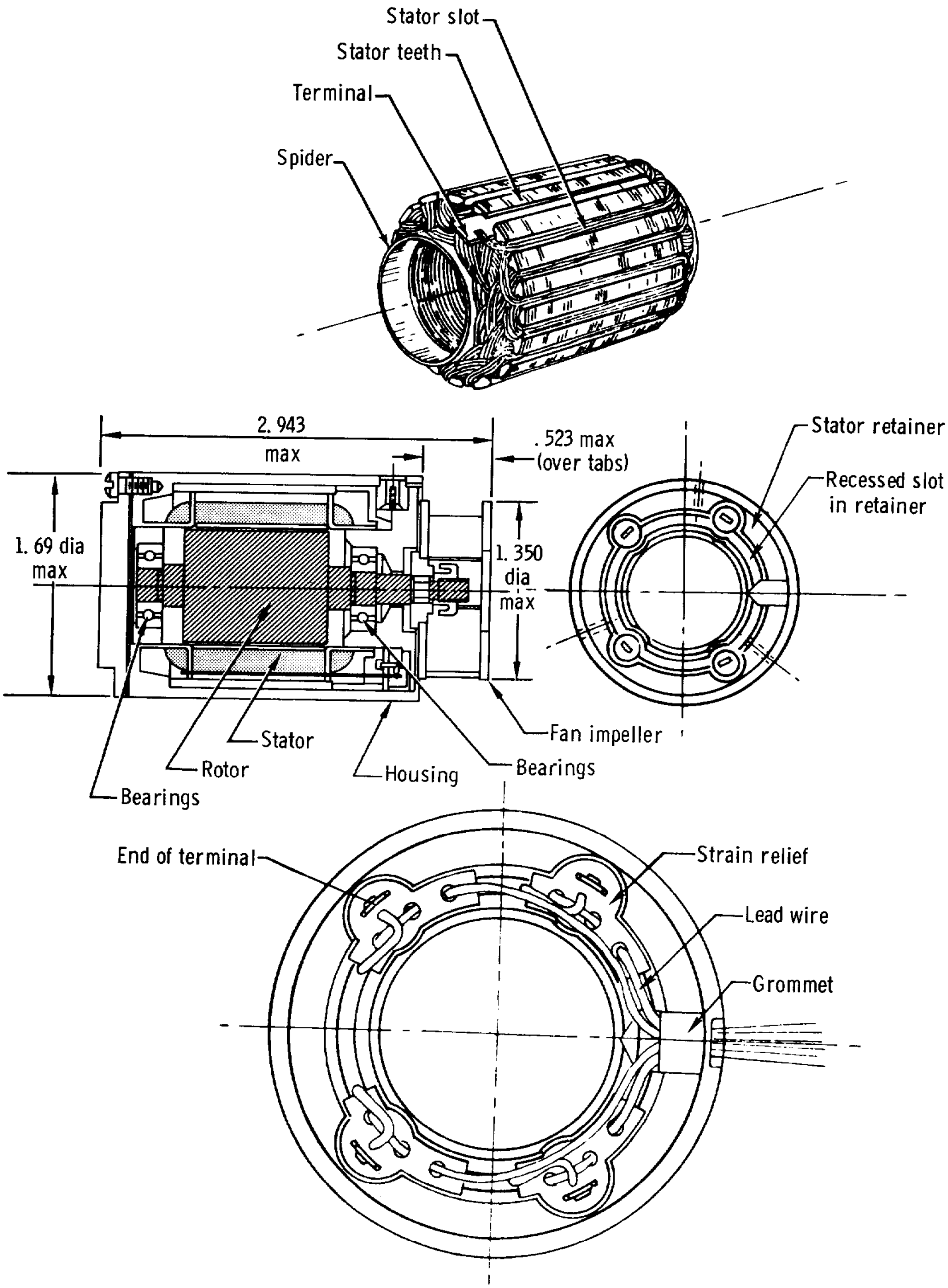


Figure D3-15.- Oxygen fan motor.

end turns. Acceptance testing of the wire is conducted on the first 100 feet of each reel. The wire is considered acceptable if no more than 10 breaks in insulation are exhibited in the sample when pulled through mercury at 25 feet per minute. The rejection rate for stator winding faults for motors processed early in the production run was substantial. Improved yield was achieved only by rigid adherence to the winding tension process control used in fabricating the windings, proper assembly techniques, and frequent in-process dielectric testing. Phase-to-phase short circuits or shorted turns within a single phase are more likely than phase-to-ground faults. A limited amount of insulation is provided between windings and ground. Phase-to-phase insulation is limited to the end turns. Considerable improvement was accomplished in the acceptance rate of motors built after the fabrication control techniques were developed (Appendix C). No problem was exhibited in the testing of the two motors finally installed for flight in oxygen tank S/N XTA0008.

The motor design uses an insulation system in the windings which is subject to failure unless carefully controlled. The individual power leads to each fan motor are protected by 1-ampere fuses.

Temperature Sensor

The temperature sensor is a calibrated resistor, the resistance of which is proportional to temperature. The sensor is mounted to the upper glass-filled Teflon fitting of the capacitor probe. Since the calibrated input to the resistor is current limited to 1.1 milliamperes under fault conditions of the sensor, no problem would be anticipated with this unit.

Wiring

Wire sizes and types of wire used within the oxygen tank are shown in table D3-IV. The insulation used in all cases is Teflon with a nominal thickness of 0.010 inch. Distribution and arrangement of the wires is shown in figure D3-16.

The insulation on all wires within the tank is specified by reference 28 to conform to MIL-W-16878, Type E. The insulation thickness requirements of this specification establish the following:

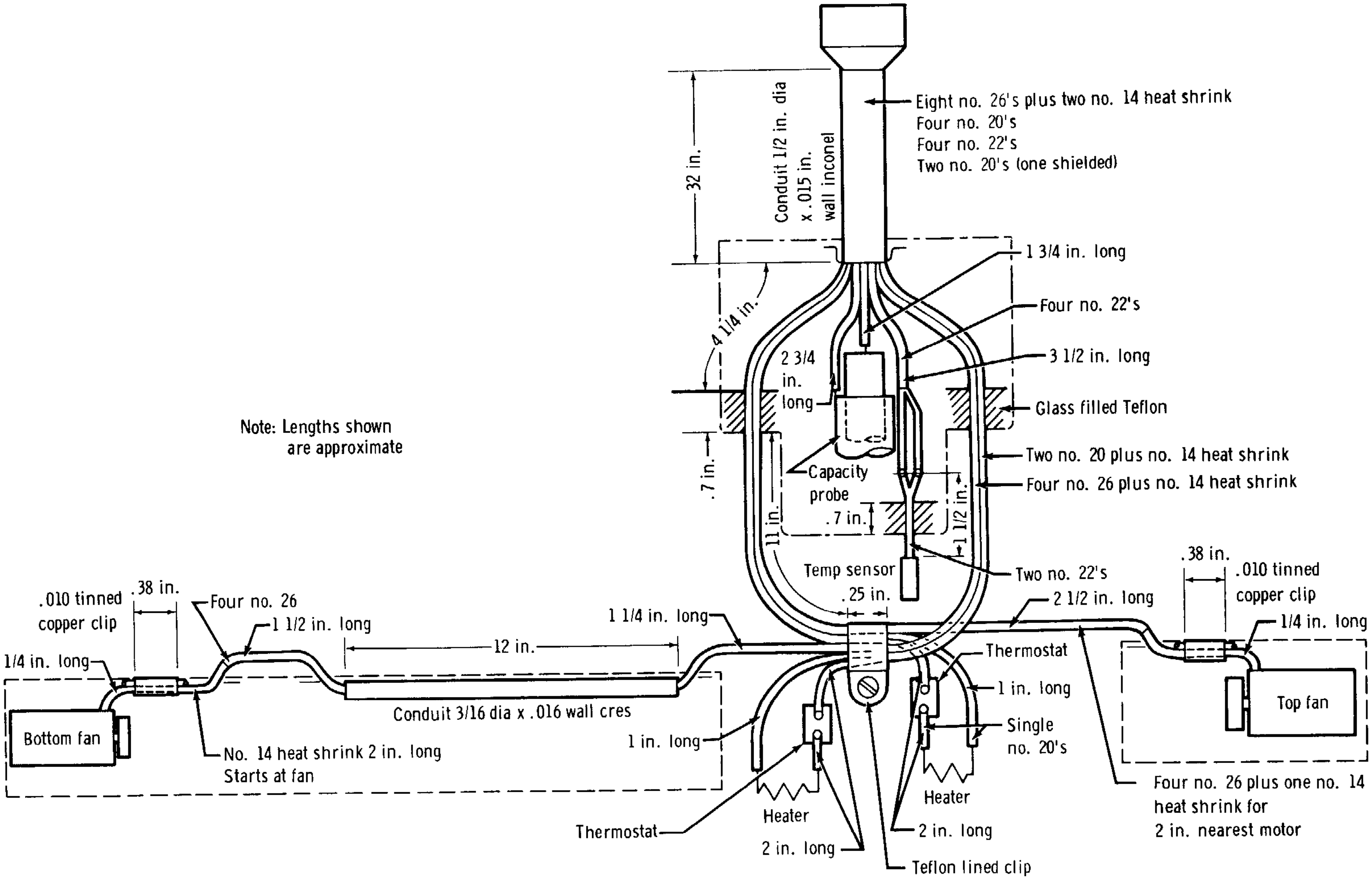
	Insulation Thickness, in.		
Condition	Minimum	Nominal	Maximum
Nominal	0.008	0.010	0.012
With out-of-center tolerance	0.007	0.010	0.014

TABLE D3-IV.- WIRES INSIDE OXYGEN TANK

Service	Number	Size	Strands	Material	Insulation (b)	Color
Heater	4	AWG no. 20	19 x 0.008	Plated copper	Teflon	Violet White/violet Brown White/brown
Quantity probe	[a]2	AWG no. 20	19 x 0.008	Grade A nickel	Teflon	White Red (shielded)
Temperature sensor	4	AWG no. 22	19 x 0.0063	Grade A nickel	Teflon	Black Orange Green Yellow
Fan motors	8	AWG no. 26	19 x 0.004	Grade A nickel	Teflon	Red White Blue Black

[a] Inner probe lead nickel shielded, Teflon sheath.

[b] All insulation to MIL-W-16878, Type E.



Note: Lengths shown
are approximate

Figure D3-16.- Oxygen tank wiring distribution.

The mechanical design of the tank with respect to provisions for wiring is considered deficient. Damage to the wiring may be either insulation damage or conductor damage, portions of which cannot be inspected or adequately tested during or after assembly.

The four number 26 AWG wires for the fan motors are encased in 0.012-inch-thick shrink-fit Teflon tubing from the motor housing to a point 0.3 inch outside the heater-fan tube. The 0.012-inch shrink-fit tubing provides the protection for the wires at the point where the four-wire bundle crosses the machined sharp edges of the access hole in the heater tube (fig. D3-17). The shrink-fit tubing does not, however, alleviate the strain on the 90-degree bend of the wires at the motor housing. During assembly of the fan to the support tube, the four-wire bundle in the shrink-fit tubing may be forced against the machined sharp edges of the support tube at point "A" of figure D3-17. Two specimens of the support tube that have been examined show no removal of burrs at this point. Between the motor and the access hole in the support tube, the wire bundle is restrained by a 0.010-inch thick soldered copper clip.

The twisted lower fan motor leads (without shrink-fit tubing) reenter the support tube and traverse a 3/16-inch-diameter conduit for 12.0 inches before again exiting the support tube. No specification restraint on slack left in the bundle contained within the heater tube conduit was noted. The motor leads are in contact with the conduit, at least at the ends of the conduit, and exposed to local heat conditions of the heater elements.

Design changes were made between Block I and Block II configurations to provide independent circuits to each motor and heater within the oxygen tanks. Provision was made in the glass-filled Teflon separator on the quantity probe for access of the extra six wires to the upper end of the probe assembly. The conduit (1/2-inch OD x 0.015-inch wall) in the dome for wiring to the connector was not, however, increased in size.

During assembly of the tank, three bundles of six wires each are sequentially pulled through the conduit. The first bundle, consisting of the two quantity gage wires and the four temperature sensor wires, is pulled through the conduit along with the pull wires for the other bundles. The second and third bundles each consist of one set of motor leads encased in 0.012-inch shrink-fit tubing and one set of heater leads. The pull wires have a break-strength of 65 pounds. Since the third bundle of wire must be forceably pulled through the conduit, damage to wires in this bundle or the others may result which may not be detectable without physical inspection. Physical inspection cannot be accomplished with this design.

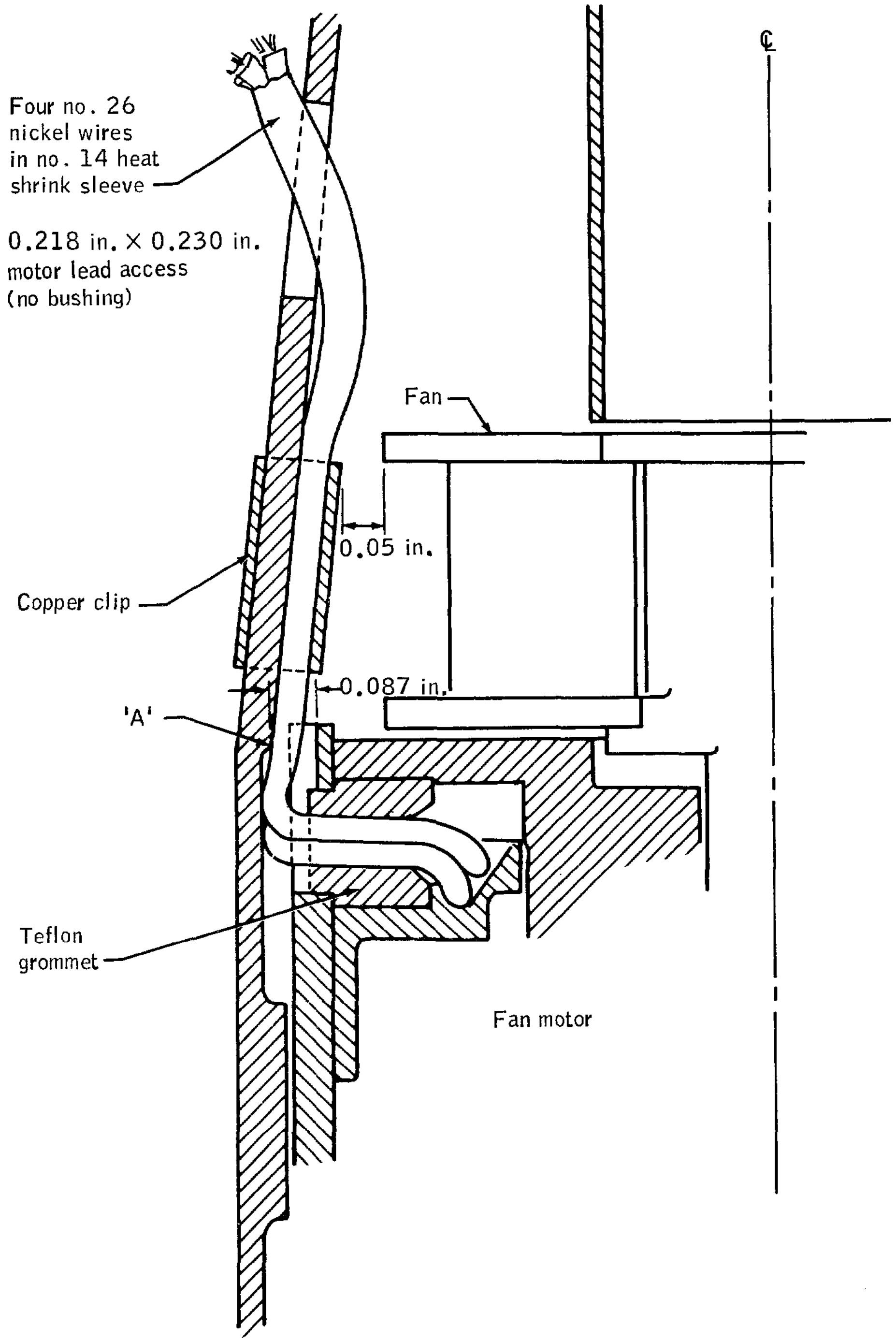


Figure D3-17.- Typical wire routing for fan motor (four times full size).

The calculated break strength of a number 26 AWG nickel wire is 11 pounds and elongation of 28 percent can be experienced before break. If the number 26 AWG wires do not share the load associated with pulling the bundle through the conduit, damage to the wire(s) will result before the pull wire breaks. Stretching of the wire results in local neck-down of both the conductor and insulation. In subsequent operation of the circuit, the locally smaller gage conductor can produce local hot spots and progressive deterioration of the insulation.

Discussion

All electrical power system wiring is protected by fuses or circuit breakers specified on the basis of wire size. Such devices will transmit their rated current without opening the circuit to either the load or a fault. The opening of the device to protect the circuit on overload is determined by an inverse time to over-current ratio that will open a large current fault in a short time, and a smaller over-current fault in a longer time. The protection afforded is to the wire and power system rather than to the connected end item.

The wiring in the oxygen tank has inherent potential for damage in assembly due to inadequate support, inadequate clearances, and thin Teflon insulation. It is well known (refs. 29 and 30) that Teflon insulation cold flows when subject to mechanical stress. The design of the tank internal installation exposes the insulation to potential progressive damage by cold flow where the wiring is placed near or at bends around sharp corners.

COMPATIBILITY OF MATERIALS WITH OXYGEN

It is well known that virtually all materials except oxides will react with liquid oxygen (LOX) under specific conditions. The tendencies to react and the rates of reaction vary widely. Most organic materials and the more active metals are sufficiently reactive with LOX to require careful attention to the condition under which they are used. Spontaneous reaction does not usually occur upon contact between a material and LOX; however, the sudden application of energy in the form of mechanical shock or electrical spark to the combination of LOX and a chemically active material will often result in violent reaction or rapid burning.

Classification Methods

A method commonly used to classify the relative reactivity of materials with LOX is described in references 31 and 32. Based upon this method, a specification, MSFC specification 106B, "Testing Compatibility of Materials for Liquid Oxygen Systems," was developed to establish acceptance criteria of materials for use in LOX and gaseous oxygen (GOX) systems. Materials meeting the requirements of paragraph 3.3 of the specification are said to be compatible with LOX. In this context it must be recognized that the term "compatible" describes only the relative reactivity of a material and does not describe an absolute situation.

Materials for use with LOX are selected from the "compatible" list of references 33 to 36 under the additional stipulation that the level of any potential mechanical shock is less than that associated with the impact test and/or that potential electrical energy sources are less than the ignition energy of the material in LOX. If a material is used with oxygen and a potential energy source, it must be determined by test that the energy available is less than that required to initiate the reaction. Furthermore, the test should represent the circumstances of use as nearly as possible.

For example, the pressures and temperatures of the oxygen to which the material will be exposed should be duplicated in the tests. Additionally, thickness and surface area of the material, as well as that of any backing material (such as may act as a heat sink, for example) should be duplicated. The latter is important because there are examples of materials changing from an acceptable rating to an unacceptable rating solely because of a change in the thickness used in a particular application. For some proprietary materials and composites whose composition may vary from batch to batch, it is necessary to repeat the compatibility tests for each batch. Elastomers are a good example of the latter category. In summary, the methodology for determining compatibility must be adhered to scrupulously to preclude self-deception.

Materials Internal to the Tank

The materials of the internal components of the oxygen pressure vessel have been identified from the records (ref. 37) and assessed as to suitability for use in the high-pressure oxygen environment. The types and estimated quantities of materials in each of these components within the oxygen tank are listed in tables D3-V through D3-IX.

Of the materials used in the tank, most have been subjected previously to compatibility testing in LOX in accordance with the methodology of references 31 and 32.

TABLE D3-V.- MATERIALS IN HEATER ASSEMBLY

Part name	Material	Estimated weight, lb
Tube assembly	321 stainless steel	1.39
Upper and lower motor support	302 stainless steel	.26
Silver braze	QQ-S-561, Class II	.062
Wire clamp	Tinned copper	.001
Thermostat doubler	QQ-A-327 (T6) aluminum alloy	.004
Grommet	Teflon (MIL-P-19462)	Negligible
Shim	321 stainless steel	.06
Bolts	302 stainless steel	.03
Screws	302 or 303 stainless steel	.04
Screws	302 or 304 stainless steel	.02
Nuts	Silver-plated 303 stainless steel	.002
Washers	321 stainless steel	.02
Washers	302 stainless steel	.007
Rivets	2117 aluminum	.001
Safety wire	304 stainless steel	Negligible
Heat shrinkable tubing	Teflon (TFE)	
	AWG no. 14 clear	.001
	AWG no. 14 white	.001
Solder	QQ-S-571, type AR Comp Sn 60-Pb40	Negligible
Screw	Stainless steel pw QQ-S-763	.04

TABLE D3-V.- Concluded

Part name	Material	Estimated weight, lb
Clamp	Stainless steel clamp with teflon cushion	Negligible
Drilube 822		Negligible
Wire	AWG no. 20, silver-plated copper	0.0278
Wire insulation and shrink fit tubing	Teflon	.0278
Disk blank*	Bi-metal (21 percent Ni 7 percent Cr Balance Fe and 36 percent Sn)	Negligible
Stationary contact*	0.010 fine silver on monel	Negligible
Movable arm*	0.004 Permanickel	Negligible
Welding cap*	Monel	Negligible
Insulator*	Alsimag 645 or Duco 9P-16	Negligible
Thrust pin*	Alsimag 35	Negligible
Mounting bracket*	302 stainless steel	Negligible
Wave washer*	Stainless steel	Negligible
Cup*	321 stainless steel	Negligible
Rivet contact* (movable)	Fine silver	Negligible
Base assembly*	321 stainless steel base	Negligible

*Thermostat parts

TABLE D3-VI.- MATERIALS IN DENSITY SENSOR PROBE

Part name	Material	Estimated weight, lb
Density sensor/assembly		1.9
Bracket	3003 Al alloy	.07
Spacer	25% glass-filled TFE Teflon	.01
Rivet	1100-H-14 Al alloy	.01
Rivet, solid	2117, 1100 Al alloy	.01
Grommet	Glass-filled Teflon	.01
Grommet	Glass-filled Teflon	.01
Sleeve	Red tubing - TFE Teflon Size 9 thin wall	.05
Spacer	25% glass-filled Teflon	.01
Solder	Tin/Lead 60/40	.01
Inner tube plug	25% glass-filled Teflon	.03
Rivet-semi-tubular	1100-H-14 Al alloy	.01
Outer tube	6063-T832 Al alloy	.20
Eyelet	Brass Comp 22 HD QQ-B-626	.01
Rivet	1100-H-14 Al alloy	.01
Terminal	Brass 1/2-H Comp. 1-QQ-B-613B	.01
Rivet, solid	110-H-14 or 2117 Al alloy	Negligible
Solder	QQ-S-571 (60/40)	.01
Sleeve, insulator top	Glass-filled TFE Teflon (25%)	.4
Rivet	1100-H-14 Al alloy	.01

TABLE D3-VI.- Concluded

Part name	Material	Estimated weight, lb
Sleeve support bottom	AMS-5542 Inconel X annealed	0.025
Insulator sleeve bottom	Fiber-filled TFE Teflon	.4
Rivet	1100-H-14 Al alloy	.01
Inner tube	6063-T832 Al alloy	.18
Terminal coax	Brass 1/2-H Comp 1-QQ-B-613B	.01
Wire	AWG no. 20, nickel, grade A	.0115
Wire, insulation and shrink fit tubing	Teflon	.0263

TABLE D3-VII.- MATERIALS IN DENSITY SENSOR PROBE TUBE ASSEMBLY

Part Name	Material	Estimated weight, lb
Tube assembly	Inconel X750	1.35
Sleeve connector	Inconel X750	.1
Electrical connector	Inconel X750	.25
Solder terminals	Gold-plated Inconel X750	.001
Tube	Inconel X750	.005
Adapter (fill) upper	Teflon (TFE)	.016
Adapter (fill) lower	Teflon (TFE)	.016

TABLE D3-VIII.- MATERIALS IN FAN MOTORS

Part name	Material	Estimated weight, lb
Screw	18-8 stainless steel	0.02
Plate, end	2024-T4 Al alloy	.04
Shim	302 stainless steel	.02
Shim	302 stainless steel	.02
Shim	302 stainless steel	.02
Bushing, bearing	303 stainless steel	.04
Bearing, ball	440C & Rulon "A"	.02
Bearing, ball	440C & Rulon "A"	.02
Spacer sleeve	303 stainless steel	.10
Lamination	Ludnum Al-4750-H no. 2 temp. RL fin.	.02
Insulator, stator slot	Teflon impreg. glass cloth	.02
Insulator, cell cover	Teflon impreg. glass cloth	.02
Terminal	Brass 1/2-H QQ-B-613	.02
Sleeving, heat shrinkable	Teflon TFE	.02
Compound, insulating	Liquinite Teflon FBC powder	.02
Wire, magnet	Teflon overcoated ceramic insulation over copper wire	.2
Housing	2024-T4 Al alloy	.2
Ring yoke	Transformer grade A silicon electrical steel	.02

TABLE D3-VIII.- Concluded

Part name	Material	Estimated weight, lb
Retainer stator	2024-T4 Al alloy	0.02
Plate, bearing	303 stainless steel	.16
Pin, spring	302 stainless steel	.02
Pin, spring	302 stainless steel	.02
Insulator	Teflon	.02
Grommet	Teflon	.02
Strain relief	Teflon impreg. glass cloth	.02
Sleeve, rotor	416 stainless steel QQ-5-763	.02
Shim, cover	302 stainless steel	.02
Plate, front	3003 aluminum alloy	.02
Vane, impeller	No. 12 brazing sheet	.02
Plate, back	No. 12 brazing sheet	.02
Hub	1100-F aluminum	.02
Lubricant	Drilube no. 822	.002
Safety wire	300 series stainless steel	Negligible
Wire	AWG no. 26, nickel, grade A	.0327
Wire insulation and shrink fit tubing	Teflon	.0518

TABLE D3-IX.- MATERIALS IN FILTER

Part Name	Material	Estimated weight, lb
Body	Inconel X750	0.016
Nut	304 stainless steel	.006
Washer	304 stainless steel	.002
Disc	302 stainless steel	.021
Seal	Teflon	.008

Some of the materials in the tables, however, have a questionable compatibility with LOX, under the criteria of MSFC specification 106B. These are the following:

60-percent tin, 40-percent lead solder
Teflon (TFE) heat shrinkable tubing
Drilube 822
Rulon A
Colored Teflon
Teflon liquinite powder

The solder is listed as incompatible in the references 33 to 36. There are no test results for heat shrinkable Teflon tubing in the references. The last four materials have given inconsistent results in compatibility tests and exemplify the "batch" problem previously discussed. In addition to the above, some of the materials within the sealed thermostats (table D3-V) have apparently not been tested.

It must be emphasized that the data in the references cited are for tests in LOX at relatively low pressures. The compatibility of the materials under the conditions of service in the tank is thus not necessarily characterized by the referenced data.

The Teflon insulation used on the wiring within the tank is a prime suspect substance that burned inside Apollo oxygen tank no. 2 (Appendix F). Over many years of use, Teflon has been proven to be one of the most satisfactory nonmetallic materials for use in LOX. It will not react with LOX unless excited by energy sources such as extremely high impact energy (above 10 Kg-M) or a spark. Adiabatic compression tests up to pressure of the order of 10 to 12 ksi have failed to ignite Teflon. However, additives to Teflon to produce color or other property changes have been known to increase the susceptibility of Teflon to react with LOX.

It must be noted that all oxygen compatibility tests are conducted with the specimens in a scrupulously "LOX-clean" condition. Cleanliness of materials within oxygen systems is vital. Something as innocuous as the oils from a fingerprint can serve as the starting point for a chain of chemical reactions that can lead to a catastrophic failure. For this reason, the same standards of cleanliness employed in compatibility tests must be applied to flight systems.

Although the quantities of incompatible materials may be small, these materials can provide the mechanism for initiating other reactions. For example, in a recent test at MSC, 2 grams of Teflon were ignited in 900 psi oxygen, temperature -190° F, by means of a hot wire. This, in turn, ignited a piece of aluminum 0.006 inch by 0.75 inch by 0.75 inch that was in contact with the Teflon.

Titanium is not listed as a material used in the oxygen system; however, a titanium clamp of the same drawing number, distinguished only by a different dash number, is used in the hydrogen tank. The clamp is made in two halves. The identifying number is stamped on only one half. The titanium halves are matched, drilled, and bagged together at the manufacturers. If a half clamp made of titanium had been placed inadvertently in the oxygen tank, it could have contributed to the fire and subsequent tank failure as the clamp is attached to the boss area of the tank. Because of the bagging and other controls, it is unlikely that a titanium clamp found its way into an oxygen tank. It is poor design practice, however, to have dimensionally identical parts of different materials that may be interchanged and then installed in a potentially hostile environment.

Although not normally exposed to supercritical oxygen, the aluminized Mylar used in the oxygen tank vacuum annulus, and within the SM, is of interest in the investigation. Aluminized Mylar is not compatible with oxygen and were the pressure vessel or the tank internal tubing to fail, the Mylar in the annulus and/or the SM would be exposed to concentrated oxygen. If an ignition source is present, the Mylar would burn. If such burning were to have occured within bay 4, it could have contributed to pressurization of the bay and consequent loss of the SM panel.

OTHER DESIGN AND SYSTEM CONSIDERATIONS

A number of other features and components of the oxygen tank system and of other spacecraft systems are discussed in the following sections.

Oxygen System Relief Valves

The oxygen tank relief valve was designed to protect the oxygen tank against the effects of potential malfunctions of the tank subsystem. Specifically, the valve was designed to relieve a pressure build-up resulting from the worst of the following three system malfunction conditions:

1. Heaters on GSE power supply at ground-rated conditions with a full tank and fans running with thermostats failing to open. This yields a heat input of 3002 Btu/hr, which would require a valve flow of 18 lb/hr to prevent exceeding 1010 psig.

2. Heaters on at spacecraft voltage level (28 V dc) and fans running with tank filled such that minimum dQ/dm exists (i.e., most critical condition for raising pressure). This yields a heat input of 685 Btu/hr and a valve flow requirement of 19 lb/hr.

3. Loss of vacuum in the annulus with the tank filled such that minimum dQ/dm exists. This yields a heat input of 935 Btu/hr which requires a valve flow capacity of 26 lb/hr.

The third condition requires the largest relief valve flow capacity and this was used to size the valve. It was also stipulated that the valve must pass this flow with the fluid at +130° F. These criteria were considered conservative because of the effects of flow through the relief valve on the heat leak, dQ/dm, and system temperatures.

A question arises from an examination of the three malfunction conditions assumed: Why was the case of heaters powered by ground support equipment (GSE) at critical dQ/dm not considered? Under such a circumstance, the heat input would be approximately 4-1/2 times that of condition 2 with a flow requirement increase in the same proportion. It was determined that it was not intended to ever use GSE power to the heaters except when the tank was full.

The design philosophy of the relief valve thus contemplated single-failure modes associated with anticipated malfunctions. It did not contemplate a catastrophic failure mode such as would be produced by combustion within the tank. This is not an uncommon design practice in the sizing of relief valves. In ground systems, however, in addition to relief valves, pressure vessels are frequently provided with large burst discs or blowout patches to protect against pressure rises that would result from conditions other than anticipated malfunctions.

The Block II relief valve was subjected to qualification testing as part of an oxygen system valve module qualification test program conducted by Parker Aircraft Company for North American Rockwell (NR) in March of 1967. Reference 38 describes the test program and the results. Briefly, the module, consisting of check valve (for no. 2 tank), relief valve, pressure switch, and pressure transducer, was subjected to the following tests: performance, vacuum, vibration, acceleration, humidity, and endurance cycling. Random vibration excitation was applied for 15 minutes for each axis. The acceleration testing was for 5 minutes in each of the +X, -X, +Y and +Z axes. During both vibration and acceleration tests, the various module elements were operated. The pressurizing medium was nitrogen at room temperature during all tests, except for one of the endurance tests which was conducted at -230° F.

The only discrepancy recorded for the test program was out-of-specification leakage of the check valve subsequent to the vibration testing. This was ascribed to the fact that fluid was not flowing through this normally open check valve during vibration which would be its condition during flight. This absence of fluid permitted the valve poppet to repeatedly strike the seat causing abnormal wear. Further, there was contamination present in the valve from the flex line used in the test setup. This aggravated the problem. Because these factors were present, the test conditions were considered not representative of actual service conditions and the check valve performance was considered acceptable (ref. 39). It should be noted that the Block I valve was tested using oxygen as the fluid medium and that the changes from Block I to Block II valves were such as to not invalidate the materials compatibility demonstrated with the Block I systems.

A number of observations are warranted. No shock testing was required for the qualification of the relief valve. In view of the fact that other valves in the service module exhibited shock sensitivity during the Apollo 13 flight and the fact that only a few thousands of an inch of poppet travel is required to open the relief valve fully, it would be valuable to determine whether the relief valve is sensitive to shock. It is possible that the relatively slow decay of oxygen tank no. 1 subsequent to the accident might be the result of a relief valve that failed to seat correctly after the shock.

In the qualification program there was no requirement for the relief valve to vent or relieve into a hard vacuum as it would have to in space. It is possible that under such conditions the oxygen would cool enough to solidify, thus plugging the orifice-like passage of the valve or the downstream lines that lead to the overboard exit, precluding further relieving by the valve. This is particularly important because the exit lines from both relief valves are manifolded prior to entering the overboard line. Were the common line to be plugged by solid oxygen by flow from one valve, it might prevent the second valve from relieving should it be required to do so. An experiment would be required to verify this.

Arrangement at Head of Tank

The head ends of the tank and the temperature sensor and quantity probe are shown in figure D3-18. One of the more significant features of the design is the arrangement of the connections in the fill line which routes the cryogenic fluid to the bottom of the tank, via the inner element of the quantity gage capacitor, and which permit the fluid to flow from the bottom of the tank during ground detanking. The manufacturing drawings of the elements of this connection, two Teflon adapters and an Inconel tube, allow a tolerance stack which is excessive. One combined worst case results in a connection which cannot reach from the fill tube connection in the tank head to the center element of the quantity gage capacitor. The other results in a connection length which prevents assembly of the probe to the adapter in the head of the tank. These are shown in figure D3-19. The tolerances on concentricity between the inner element of the capacitor and the outer shell of the probe are not known and are omitted from this figure. Inclusion would show an even worse situation than shown.

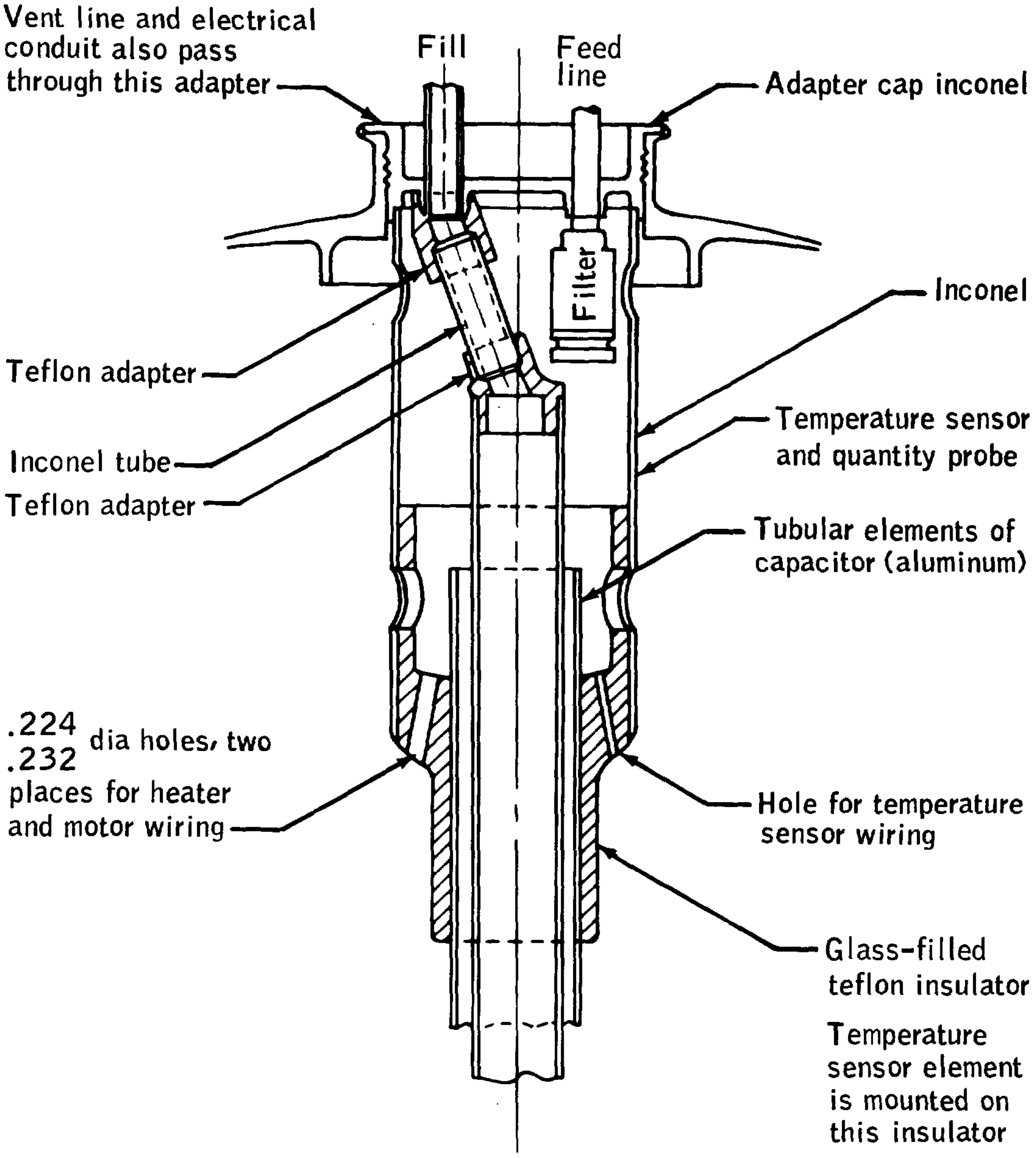
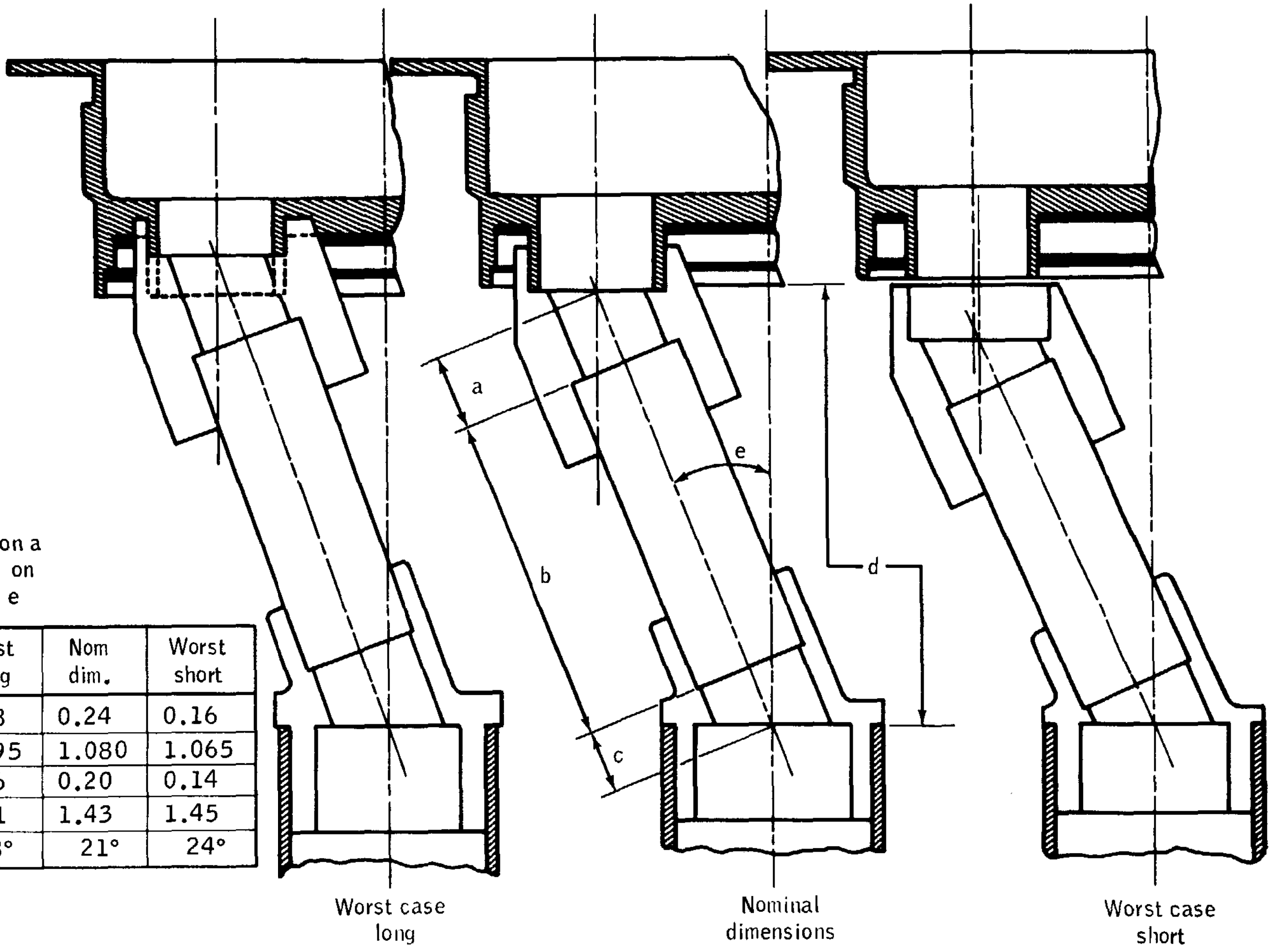


Figure D3-18.- Arrangement of head end of tank.



*Dimension a depends on value of e

Part	Worst long	Nom dim.	Worst short
a*	0.28	0.24	0.16
b	1.095	1.080	1.065
c	0.26	0.20	0.14
d	1.41	1.43	1.45
e	18°	21°	24°

Figure D3-19.- Possible variations in fill line connection.

The experience with the oxygen tank no. 2 in Apollo 13 (apparently normal detanking at Beech, but normal detanking not possible at KSC) suggests that the components used in the fill line connection were close to a worst-case short situation. Tests conducted recently at Beech show that near normal detanking is possible when considerable leakage is present at the joints in the connection, and that a substantial displacement of the top Teflon adapter relative to the fill line in the tank adapter cap is necessary to reproduce the KSC situation.

The manufacturing drawing tolerances are such that parts conforming to the drawings could result in an assembly which will not provide the proper connection. However, the probability of a combined worst case is extremely low. It is probable that the actual variations between production parts are significantly less than the drawing tolerances would permit, particularly the variations between parts within a common batch. Data have been requested on other similar parts to determine whether the variations from part to part are large or small, and whether the average tolerance stack found in practice leads to long or short connection assemblies.

The design is such that the task of assembling the probe to the adapter in the head of the tank (the connection is by four tack welds) is extremely difficult. All wiring must be loosely installed, and the majority of this originates from the fan/heater assembly which must be already installed within the tank shell. The fill line connection must be steered into place simultaneously with the insertion of the probe into the adapter, and this becomes a blind operation, complicated by the fact that thermal expansion coefficients dictate very sloppy fits between the Teflon adapters and the metal components of the fill line. This problem is dealt with at greater length in Appendix C.

One way to obviate this problem would be to redesign the internal components of the tank to permit bench assembly and thorough inspection of a single assembly, embodying all internal components and their plumbing and wiring, before introduction into the tank body. It is recognized that a redesign of this magnitude would largely destroy the foundation of experience, both ground and flight, with respect to the operational characteristics of the tank, but it is difficult to see how the internal details of the tank could be modified to provide the necessary degree of post-manufacturing inspectability without abandoning the present side-by-side arrangement of quantity probe and heater.

Dome Assembly

The tank dome assembly (fig. D3-20) forms a portion of the outer shell of the tank and houses the fluid lines and electrical conduit connecting the inner shell to the exterior of the tank. The upper surface of