REPORT OF APOLLO 13 REVIEW BOARD

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

APPENDIX F

SPECIAL TESTS AND ANALYSES

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PART F1

INTRODUCTION

An integral part of the Apollo 13 Review Board's effort included an extensive test and analysis program to evaluate in detail postulated modes of failure. The majority of these tests and analyses were conducted at the Manned Spacecraft Center (MSC) and five other NASA centers--Langley Research Center (LRC), Ames Research Center (ARC), Lewis Research Center (LeRC), Marshall Space Flight Center (MSFC), and Kennedy Space Center (KSC). Some tests at White Sands Test Facility (WSTF), North American Rockwell, Beech Aircraft, Parker Aircraft, and Boeing were also conducted. The results of this intensive test and analysis program formed, to a large extent, the basis for the development of many of the Board's findings, determinations, and recommendations.

During the review, the requests for tests and analyses were channeled through the MSC Apollo Program Office, which maintained a master file. The selection of individual tests and analyses was made after a preliminary study by Review Board specialists. In each case the request was approved by the Board Chairman or a specially designated Board monitor. In many instances the preparation and execution of tests were observed by Apollo 13 Review Board representatives.

Nearly a hundred separate tests and analyses have been conducted. The level of effort expended on this test and analysis program included a total of several hundred people over a period of about 6 weeks.

The first portion of this Appendix is a summary of those tests and analyses which most precisely support the sequence of events during this accident. This is followed by a more detailed description of these tests and analyses. This Appendix concludes with a test and analyses master list and a fault tree analysis.

It should be noted that an attempt has been made to include all tests that have been carried out in support of this review in the master list. As a result, the list includes a number of early tests which were exploratory, and in some cases inconclusive, and may not appear to lend substantive information. For each effort, there is summary information which includes identification, a statement of the objective, and a brief statement of results. More complete data on studies and tests can be found in the official files of the Apollo 13 Review Board.

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PART F2

SUMMARY OF TESTS AND ANALYSES

To assist the reader, a summary of the most significant tests and analyses is included in this part. The summary consists of a series of concise statements which are based on the results from one or more test or analysis. The summaries are presented in chronological order of the events as they occurred in the spacecraft.

DETANKING AT KENNEDY SPACE CENTER

A test simulating the conditions of the special detanking operations during the countdown demonstration test (CDDT) revealed that the thermal switches were overloaded and failed in the "closed" position. The failure of the thermostats caused very high temperatures (700° to 1000° F) inside the heater tubes. Damage to the wire insultation resulted from this overheating. Subsequent tests showed that under the conditions existing in the tank, the wire insulation would seriously degrade at temperatures between 700° F and 1000° F, thus exposing bare wire.

QUANTITY GAGE DROPOUT

Tests to determine the signal characteristics of the quantity probe under various fault conditions showed that a short between the concentric tubes would cause an off-scale high reading which would then go to zero when the short is removed, remain there for about 1/2 second, and then return to the correct indication in about 1-1/2 seconds. These are the characteristics that were observed in flight. It is not established that the failure of the quantity gage was related to the combustion that occurred in the oxygen tank no. 2.

IGNITION AND COMBUSTION PROPAGATION

The energy required to achieve the pressure rise from 887 psia to 1008 psia observed in oxygen tank no. 2 (10 to 130 Btu) can be supplied by the combustion of the Teflon wire insulation in the tank and conduit (260 Btu). Tests have also indicated that other Teflon elements and certain aluminum components inside the tank may also be ignited and thus contribute to the available energy.

Experiments show that the Teflon insulation on the actual wires in oxygen tank no. 2 can be ignited by an energy pulse which is less than the energy estimated to be available from the observed flight data.

Test of fuses in the motor power leads showed that sufficient energy to ignite Teflon insulation could be drawn through the fuses before they would blow.

The flame propagation rate experiments in supercritical oxygen indicate a rather slow burning rate along Teflon wire insulation (about 0.25 in/sec downward in one-g). Propagation rates as low as 0.12 in/sec were measured under zero-g conditions. These measurements are consistent with the slow rate of pressure rise observed in the spacecraft.

Under one-g conditions, Teflon wire insulation flames will propagate along the wire through apertures fitted with Teflon grommets.

TANK FAILURE

Several combustion tests confirmed that burning of Teflon and possibly aluminum could reach high enough temperatures to cause either the tank or the conduits into the tank to fail. Oxygen pressure was very likely lost due to the failure of the conduit.

A test in one-g in which the actual bundled Teflon insulated wire was ignited within the conduit leading from an oxygen tank and filled with supercritical oxygen resulted in bursting the heat-weakened conduit wall.

A test which contained an upper portion of the quantity probe and conduit showed that ignition of the motor lead bundle in supercritical oxygen results in flame propagation through the quantity probe insulator and into the conduit. Posttest examination showed an approximately 2-inch diameter hole had been burned out of a 3/8-inch thick stainless steel simulated tank closure plate.

PANEL LOSS

Tests with 1/2-scale honeycomb panel models in vacuum produced complete panel separation with a rapid band loaded pressure pulse in the oxygen tank shelf space. Peak pressures in the simulated tunnel volume with scaled venting were considerably lower (about 1/5) than that of the oxygen tank shelf space. These tests are consistent with the information obtained from the photographs of the service module taken by the Apollo 13 crew.

PART F3

SELECTED TESTS AND ANALYSES

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PART F3.1

THERMAL SWITCH TESTS

Objective

Determine the behavior of the thermostatic switches in the oxygen tank no. 2 under the conditions experienced during the abnormal detanking experienced at KSC. During the KSC tests, heater currents of 6.5 amperes at 65 V dc were used.

Approach and Results

Subsequent to discovering that the heater thermostatic switches most likely fused in the closed position during the KSC detanking procedures, tests were conducted to determine the power handling capabilities of these switches.

Batteries were used as a power source to test the switches. They were initially supplied with 31 V dc at currents up to 3.5 amperes. No contact degradation was observed under these conditions. When the voltage was raised to 65 V dc, some increase in contact resistance (up to about 3 ohms from a few milliohms) was noted at 1.25 amperes, although the switch continued to operate. The current was then increased to 1.5 amperes at 65 V dc; and when the switch attempted to open, it fused closed. The body of the switch was removed and the condition of the contact can be seen in figure F3.1-1.

Conclusions

Thermostatic switches similar to those in oxygen tank no. 2 will fuse closed when they attempt to open with a 65 V dc potential and currents in excess of 1.5 ampere.

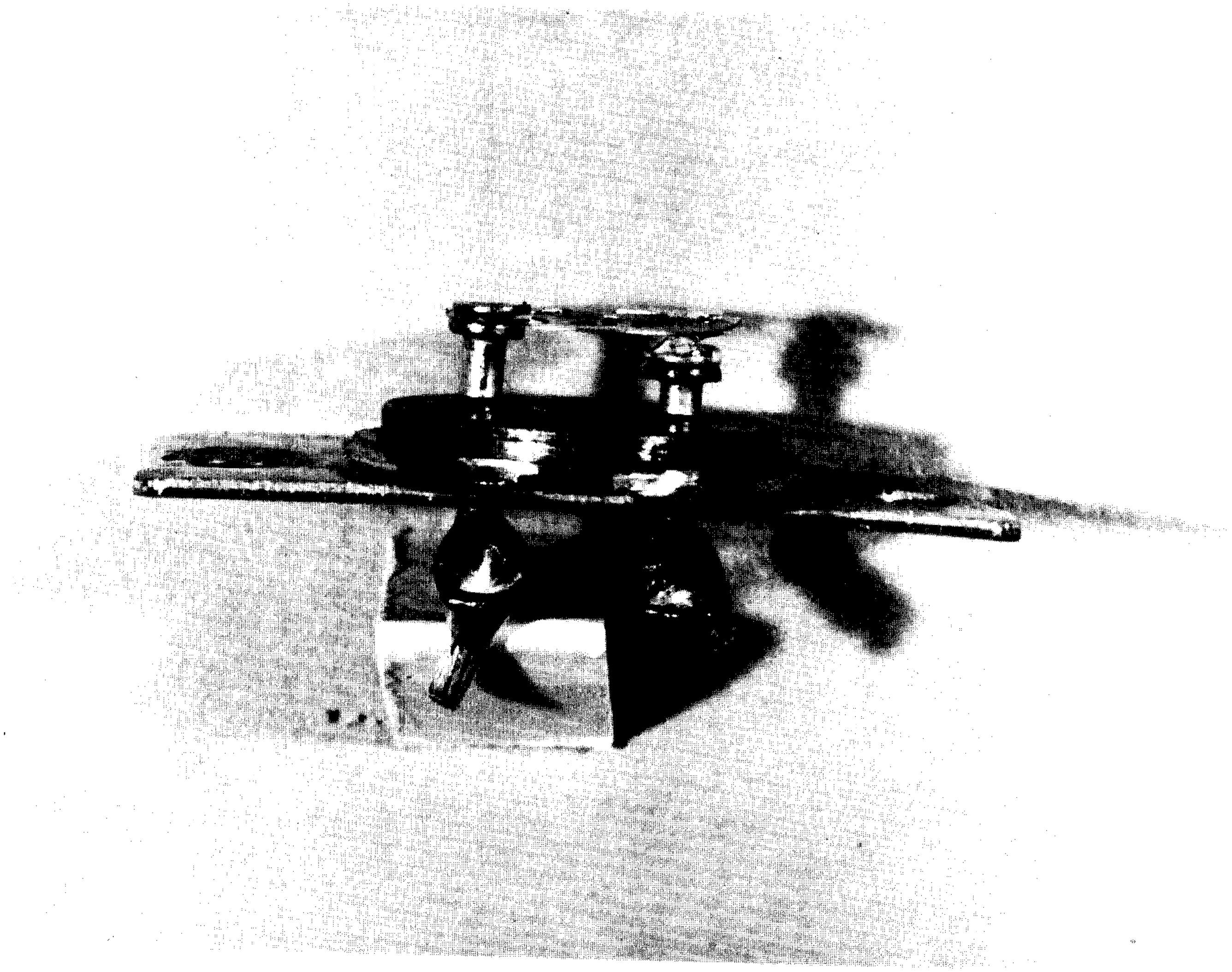


Figure F3.1-1.- Fused thermal switch control.

PART F3.2

TEFLON INSULATION DAMAGE DUE TO OVERHEATING

Objective

These tests were conducted to determine the damage that could have been done to the Teflon wire insulation during the abnormal detanking operation at Cape Kennedy.

Approach and Results

The likelihood that the equipment inside the oxygen tank was subjected to high temperatures for several hours prompted tests to reveal any changes in the thermochemistry of the remaining material. Four samples were treated in a heated oxygen flow system. The flow rate was 259 cc/sec. These samples were compared with an unbaked control sample. A typical sample of wire is shown in figure F3.2-1. The mass-loss results are given in table F3.2-I.

The relative values of heats of reaction in subsequent DTA tests in oxygen show that the degraded material is slightly more energetic per unit mass than the virgin material when oxidized.

Conclusions

The tests reveal that severe damage could have resulted to the wire insulation during the abnormal detanking procedure. In several places along the leads, bare wire was exposed which could have led to the short circuits that initiated the accident.

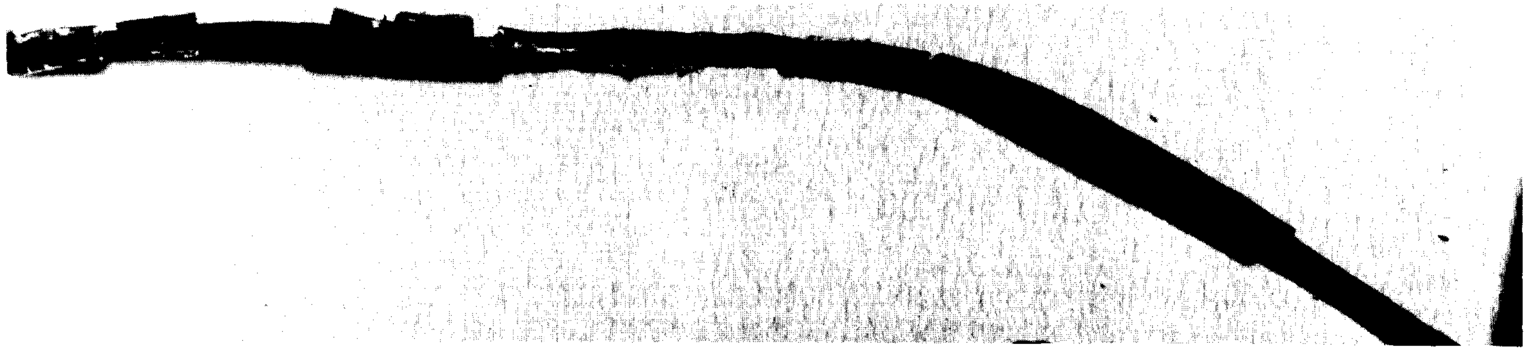


Figure F3.2-1.- Damaged Teflon insulation.

TABLE F3.2-I.- INSULATION DEGRADATION TESTS

Sample	Baking		
	Temperature, °F	Time, hr	Weight loss, percent insulation
1	77		0
2	572	2.75	+0.15
3	752	1.0	-0.08
4	860	0.5	-34.
5	932	0.5	-102.

PART F3.3

THERMODYNAMICS AND COMBUSTION ANALYSIS OF OXYGEN TANK PROCESSES

Since there is strong evidence that the failure centered around an abnormal energy addition to oxygen tank no. 2, it seems appropriate to include a special discussion of the analysis of the thermodynamics and combustion processes that may have occurred in this tank. Consideration is given here to (1) the energy required to account for the measured pressure rise, (2) the energy available in potentially combustible materials in the tank, and (3) potential ignition energy.

Energy Required to Account for Measured Pressure Rise

The measured abnormal pressure rise in oxygen tank no. 2 is presented in figure B5-3 of Appendix B. Calculations can be made for two limiting thermodynamic processes to account for this pressure rise. One process assumes that the pressure rise results from an isentropic compression of the supercritical oxygen by an expanding "bubble" of combustion products. This corresponds to the minimum amount of energy required to achieve the measured pressure rise. Another limiting process assumes that the energy addition is accompanied by complete mixing which results in homogeneous fluid properties.

Figure F3.3-1 is a pressure-enthalpy diagram for oxygen whereon point "A" is the thermodynamic state just prior to the abnormal energy addition, approximately -190° F and 887 psia. The path of the isentropic compression (minimum energy) from this state to the maximum pressure measured of 1008 psia is represented by line AB. Thermodynamic properties of oxygen presented by Weber (ref. 1) and Steward (ref. 2) were used to compute the increase in the internal energy of the oxygen. This internal energy increase of the oxygen (242 lb_m) amounts to about 10 Btu. The temperature increase associated with this process is about 1.8° F.

Figure F3.3-1 also shows the constant density path along line AC from 887 psia to 1008 psia. This process could be achieved by complete mixing of the tank contents. The internal energy increase for this case (maximum energy) is about 130 Btu. The temperature increase for this process is 2.6° F. It should be noted that this energy addition is to the oxygen in the tank. It does not include energy that might be added to other tank components such as metal parts.

The measured temperature rise of 38° F (indicated by figure B5-3 in Appendix B) during the pressure rise to 1008 psia cannot be explained by

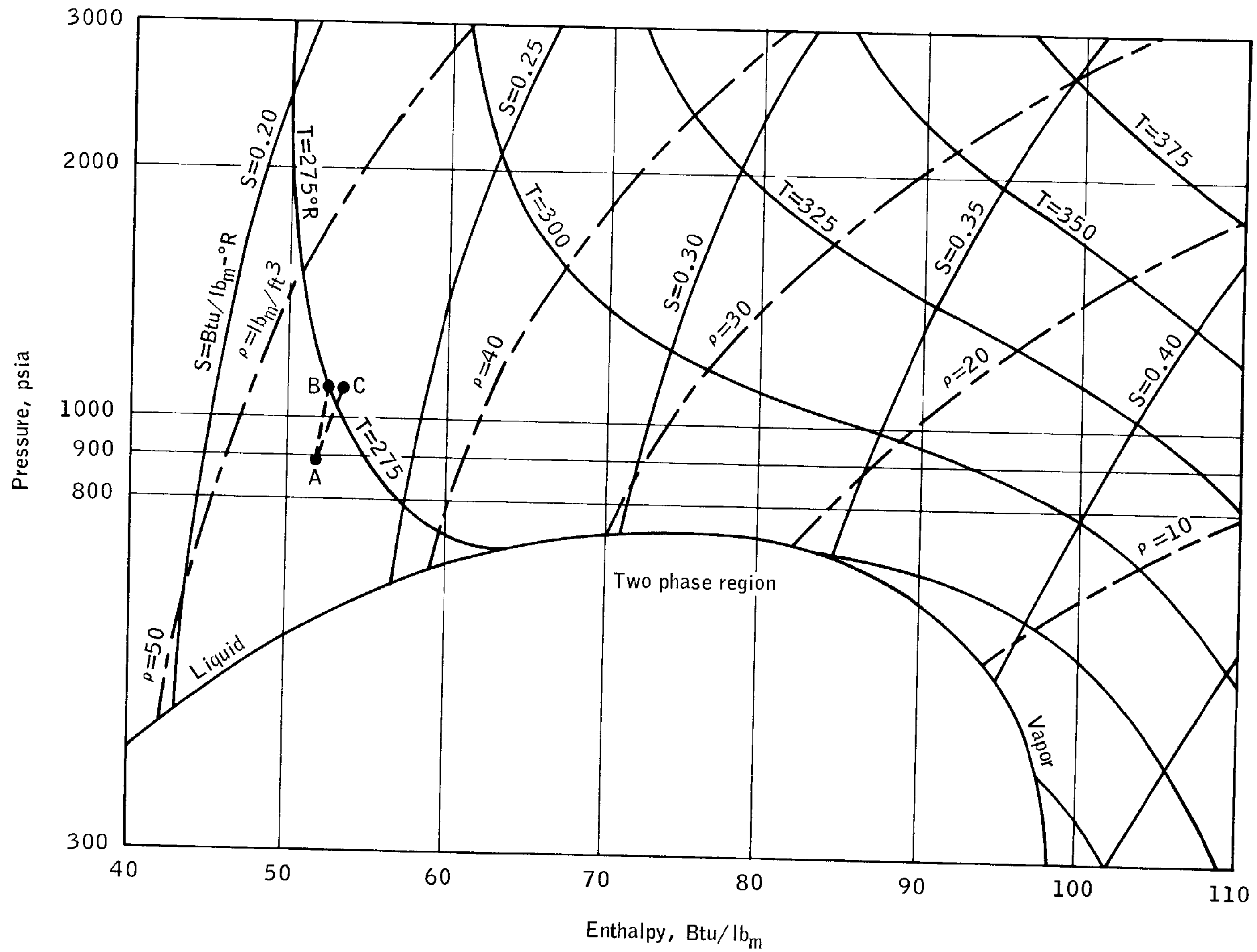


Figure F3.3-1.- Thermodynamic processes on pressure-enthalpy diagram.

either of the above-mentioned thermodynamic processes because they give a rise of only 1.8° and 2.6° F. As figure B5-3 shows, the measured temperature rise lagged the pressure rise. Both this lag and the magnitude of the temperature rise can be explained by the passage of a combustion front near the temperature sensor.

Energy Available in the Potentially Combustible Materials in the Tank

Many materials can of course react with oxygen if an ignition source is provided. Here only Teflon is considered in any detail while aluminum is mentioned briefly.

Teflon (polytetrafluoroethylene) can react with oxygen to form largely a mixture of carbonyl-fluoride, carbon tetrafluoride, carbon dioxide, and other species in small quantity, such as fluorine, depending on the stoichometry and flame temperature. The overall chemical reactions which produce these combustion products include:

$$\frac{1}{n}(C_2F_4)_n + O_2 \rightarrow 2\ COF_2\ ; \quad \Delta H_c = -1910\ \text{Btu/lb}_m\ \text{Teflon}$$

$$\frac{1}{n}(C_2F_4)_n + O_2 \rightarrow CO_2 + CF_4\ ; \ \Delta H_c = -2130\ \text{Btu/lb}_m\ \text{Teflon}$$

where the heat of combustion for these reactions is also given. For the purpose of this discussion, the heat of combustion of Teflon is taken to be -2000 Btu/lb_m Teflon. The internal energy of combustion ΔE_c is about 99 percent of ΔH_c. The amount of Teflon wire insulation in the system is about 0.13 lb_m, so that the energy available from combustion of Teflon wire insulation alone is about 260 Btu. This amount of energy is therefore more than sufficient to account for the measured pressure rise from 887 to 1008 psia.

If aluminum combustion occurs, or other tank components, the quantity of energy available is many times greater than the energy released by Teflon combustion. Experiments show that once ignited, aluminum burns readily with supercritical oxygen.

Potential Ignition Energy

Several experiments have shown that Teflon insulated wire can be ignited under the conditions that existed in the tank. A series of tests has shown that the energy required to ignite Teflon in supercritical oxygen is 8 joules or less. It was also determined that ignition was geometry dependant and in one favorable configuration combustion was the fault initiated with an estimated energy as low as 0.45 joule. In any case, the value of 8 joules is less than energy deduced from the telemetry data, as will be shown below.

The fan motors were turned on just before the event occurred. There are clear indications of short circuiting in the fan motor circuitry immediately prior to the observed pressure rise. For the moment, we will consider ignition mechanisms by electrical arcing originating in the fan circuits as being the most probable cause of the fire.

An analysis has been made of the telemetry data that permits an estimate of the total energy that could have been dissipated in a postulated short circuit which ignited the Teflon. A summary of the analysis is presented here.

The following telemetry data were used in the analysis:

1. SCS thrust vector control commands. One hundred samples per second at 10-millisecond intervals. This channel provides, in effect, a time differentiated and filtered indication of phase C of ac bus no. 2 voltage.

2. Bus no. 2 ac phase A voltage. Ten samples per second at 100-millisecond intervals.

3. Fuel cell no. 3 dc voltage at 10 samples per second.

4. Total fuel cell current at 10 samples per second.

The 115-volt fan motor circuit is shown in figure D3-5 of Appendix D. The power for the motor comes from an inverter producing three-phase, 400-cycle, 115-volt power. The motors are operated in parallel, each phase to each motor being separately fused with a 1-ampere fuse (there are a total of six fuses in the circuit). The important portions of the telemetry traces are shown in figure F3.3-2. The sequence of events postulated is as follows:

1. Fan turnon occurs at 55:53:20 g.e.t. and the phase A voltage drops from 116.3 to 115.7 volts. This is normal. The telemetry granularity is ±0.3 volt.

2. At 55:53:23, an ac voltage drop from 115.7 to 114.5 volts is observed, coincident with a fuel cell current increase of 11 amperes. This is the first short circuit that occurred after fan turnon. Since the ac voltage rose from 115.7 to 116.0 volts (as indicated by "toggling"

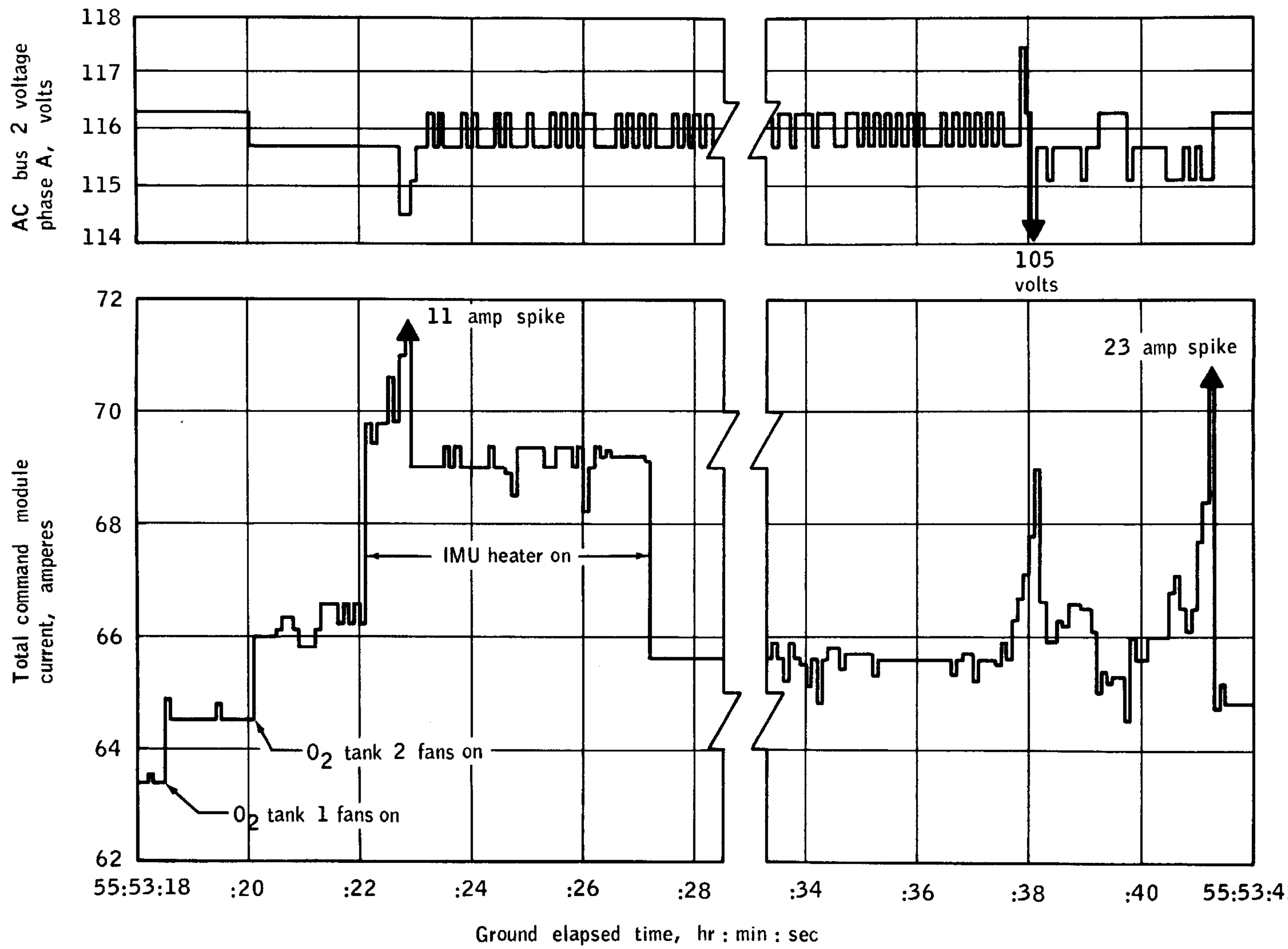


Figure F3.3-2.- Telemetry data for ac bus 2 voltage phase A and total CM current.

between 115.7 and 116.3 volts) after the event, it is probable that the short circuit involved phase A of the motor drive circuit, and all power may have been lost to one of the two fan motors at this time. This hypothesis is further supported by the coincident decrease in fuel cell current of 0.7 ampere, approximately half of the 1.5 amperes drawn by both motors.

3. At 55:53:38 another short circuit occurred, causing an ac voltage rise to 117.5 volts followed by a drop to 105 volts. The voltage rise indicates a short circuit in phase B or C as the regulator tries to bring up the voltage in a nonshorted phase. The 4-ampere dc current spike that occurs concurrently with this ac voltage rise and fall was probably much greater at some time between telemetry samples. The resultant decrease in phase A voltage may indicate an open circuit in one of the other phases of the second motor, causing phase A to draw more than normal current. The pressure in the tank starts to rise at 55:53:36 so that this short probably occurred after some combustion had commenced.

4. A final short circuit occurs at 55:53:41 as indicated by the 22.9-ampere spike on the dc current telemetry. No voltage drop is observed on the ac bus, probably because the short was of such short duration that it was not picked up by the telemetry samples. All the remaining fuses are blown (or the leads open-circuited) by this short circuit since the ac bus voltage and dc current return to the levels observed prior to initial energizing of the fans in oxygen tank no. 2.

The approximate total energy in the short circuit (arcing) can be estimated from the telemetry data. The voltage spikes indicate that the shorts were less than 100 milliseconds (the telemetry sampling interval) in duration. The fact that all the voltage and current "glitches" consisted of essentially one data point (sometimes none) means that the time of the short was very likely 50 milliseconds or less. An independent piece of evidence that bears on the time interval during which the short circuit condition exists comes from the signal on the SCS telemetry. A signal appeared on the SCS telemetry line each time a short circuit occurred on ac bus no. 2. These signals have a data rate 10 times larger than the signals from the ac and dc busses. The initial excursion of each of these SCS signals was 20 to 40 milliseconds long, and was then followed by one or two swings which are due to the SCS circuit filter characteristics. Thus, 30 milliseconds will be taken as an approximate value for the duration of the short circuits.

The current drawn during the short circuit can be estimated from the properties of the fuses used to protect the motor fan circuits. From April 18 to April 20, tests were conducted by MSC personnel to measure failure currents and failure times of the fuses using the same type inverter and fuses that were in the spacecraft. The following are the results of these measurements for a single-phase short circuit (data taken from a preliminary report of table III of the MSC Apollo 13 Investigation Team):

Volts, ac	Amperes, ac	Duration, milliseconds	Fault energy, joules
107	3.0	120	39
105	4.0	31	13
102	5.0	20	10
95	7.0	10	7
75	9.0	8	5

From these results, the most probable range of ac current in the short circuit that occurred is 3 to 5 amperes. The total energy in the short circuit is therefore between 10 and 16 joules, since it is considered unlikely that the fault persisted for more than 50 milliseconds. Thus, a most probable energy of 13 joules and a most probable ac current of 4 amperes is reasonable for those faults which blew fuses.

These values are applicable to single-phase faults to ground. For two-phase faults, the current in each phase remains the same, while the available ignition energy doubles to 26 joules.

PART F3.4

TEFLON INSULATION IGNITION ENERGY TEST

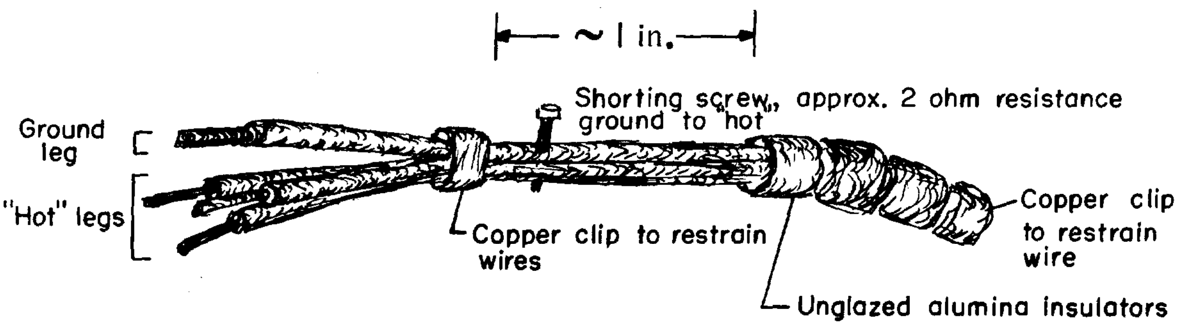
Objective

To determine the energy required to ignite the Teflon insulation by 115 volt, 60 cycle sparks on flight-qualified wire which had been subjected to the type of heating which could have occurred during the KSC detanking procedure. The spark-generating circuit was fused so that it could deliver no more energy than could have been delivered by the fan motor circuit.

Approach

Sample sections of Teflon-insulated conductors obtained from Beech Aircraft Corporation through MSC were baked in oxygen for 5 hours at 572° F, held overnight at room temperature in oxygen, and baked further for 2 hours at 842° F. The Teflon lost its pliability, cracked, and flaked off as shown in figure F3.4-1.

The test specimen consisted of four strands of degraded-insulation wires, as shown schematically below.



An adjustable short was provided by a number 80 screw driven between the strands of the "ground" wire and then adjusted so that a low-resistance short was established to one of the "hot" legs near some remaining Teflon. A replica of the test harness, made of virgin wire, is also shown in figure F3.4-1. The shorting screw and the standoff loop, installed to hold the screwhead away from the test-chamber walls, are seen in this photograph. The low resistance short was installed in series with a 1-ampere slow-blow fuse. In an independent test series, the current-carrying ability of this fuse was determined by inserting (in series) dummy resistors of various values to replace the shorted

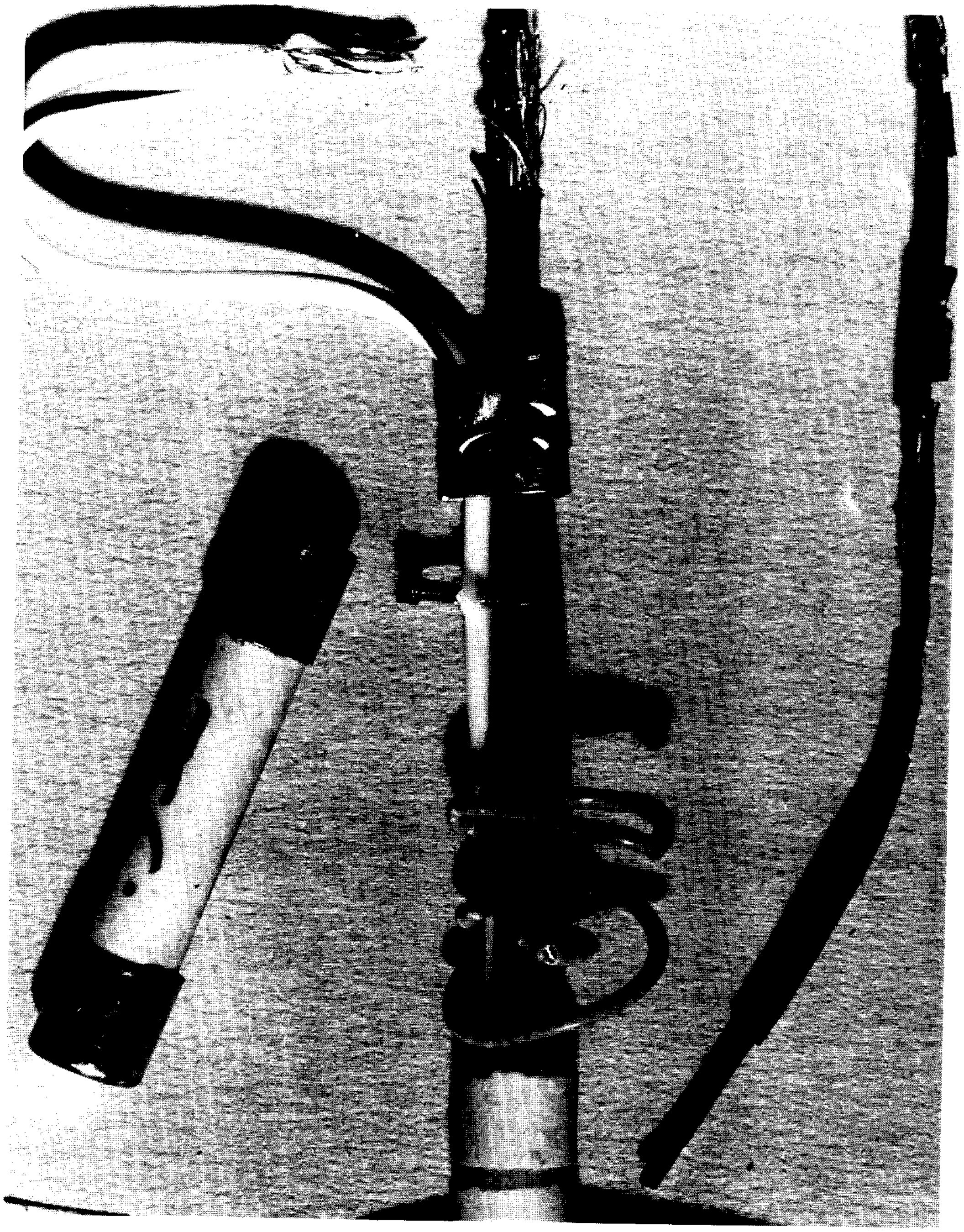


Figure F3.4-1.- Heat degraded wire and test harness replica.

test harness, and a 0.1-ohm resistor across which the voltage drop was measured. Repeated tests showed about 3.5 to 7.5 joules were required to destroy the fuse. Depending on the resistance of the remaining circuit, 10 to 90 percent of the line voltage might appear across the arc. The fault energy of the ignition tests, where the arc resistance is less than 2 ohms, is in the same range (i.e., from 3.5 to 7.5 joules).

The specimen was immersed in liquid oxygen (as before) inside the stainless steel tubing test rig shown in figure F3.4-2. The initial pressure was 920 psi.

Results

The test assembly withstood three firing pulses, 115 volts, 60 cycles, before igniting on the fourth. The 1-ampere fuse was blown each time. The short resistance was measured after each trial and was found to reduce progressively from about 5 ohms to 2 ohms, at which level ignition occurred on the next try. Approximately 1/2 second later the pressure gage showed the start of a 7-1/2 second pressure rise from 920 to 1300 psi. A thermocouple placed about 1 to 2 inches from the ignition point showed a small rise about 1 second after ignition and a large rise about 1/2 second later as the flame swept by. Much of the main conductor wire was consumed; all of the small thermocouple wire was gone. Virtually all of the Teflon was burned--Teflon residue was found only in the upper fitting where the electrical leads are brought into the test chamber. All but one of the alumina insulators vanished.

Conclusion

From the fuse energy tests and these ignition tests, it is clear that from 3.5 to 7.5 joules are adequate to initiate combustion of heat-degraded Teflon insulation. This is essentially the same as is required for unheated wire.

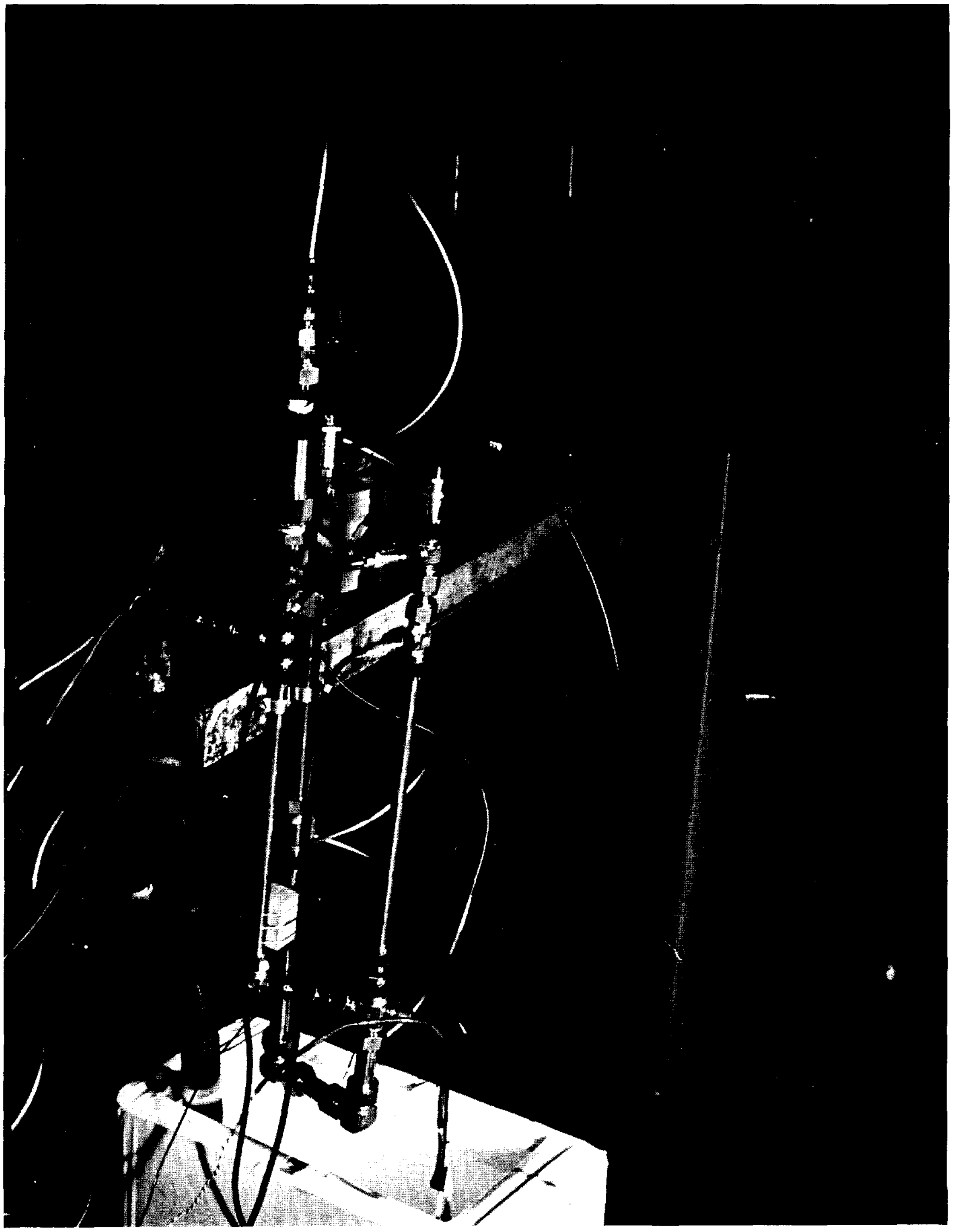


Figure F3.4-2.- Stainless steel test rig.

PART F3.5

IGNITION AND PROPAGATION THROUGH QUANTITY PROBE SLEEVE AND CONDUIT*

Objective

The purpose of this test was to determine if burning wire insulation would propagate through the upper quantity probe insulator. Another objective was to determine the failure mode of the conduit which results from the combustion of the polytetrafluoroethylene insulation.

Experimental

The chamber used for this test consisted of a schedule 80 weld-neck tee equipped with three flanges to provide a viewport, electrical and hard line feedthroughs, and conduit to quantity probe interface. The chamber, which is shown in figure F3.5-1, had a volume of approximately one-third cubic foot. A pressure relief valve was provided to maintain chamber pressure at 1050 psia during test; and, in addition, the chamber contained a rupture disc to prevent chamber failure. Supercritical conditions inside the chamber were obtained by filling with gaseous oxygen to a pressure of 940 psia and cooling externally with liquid nitrogen, using insulating foam covered with thermal blankets. Five thermocouple penetrations were provided through the chamber wall. Chamber pressure was monitored by a pressure transducer. Color motion pictures were taken through the chamber viewport at a speed of 24 frames a second. An additional camera provided external color motion pictures of the conduit-chamber interface.

The test item consisted of an upper portion of the quantity probe interfaced with a conduit assembly shown in figure F3.5-2. The quantity probe used was Block I hardware which had been sectioned for demonstration purposes. An additional hole was drilled in the probe insulator to modify it to Block II and wire was routed through it and the conduit assembly to represent the Apollo 13 configuration. Stainless steel sections were welded onto the probe to close the demonstration ports. Wiring with insulation was allowed to extend beyond the Teflon insulator approximately 4 inches. This wiring was also routed through the conduit and connected to the feedthrough pins through which power, 115 volts at 400 cycles, was supplied to both fan motor bundles by a system which had been

*Extracted from "Fuel Quantity Probe Sleeve and Conduit Assembly Flammability Report," prepared by the Manned Spacecraft Center for the Apollo 13 Review Board under TPS 13-T-06, June 5, 1970.

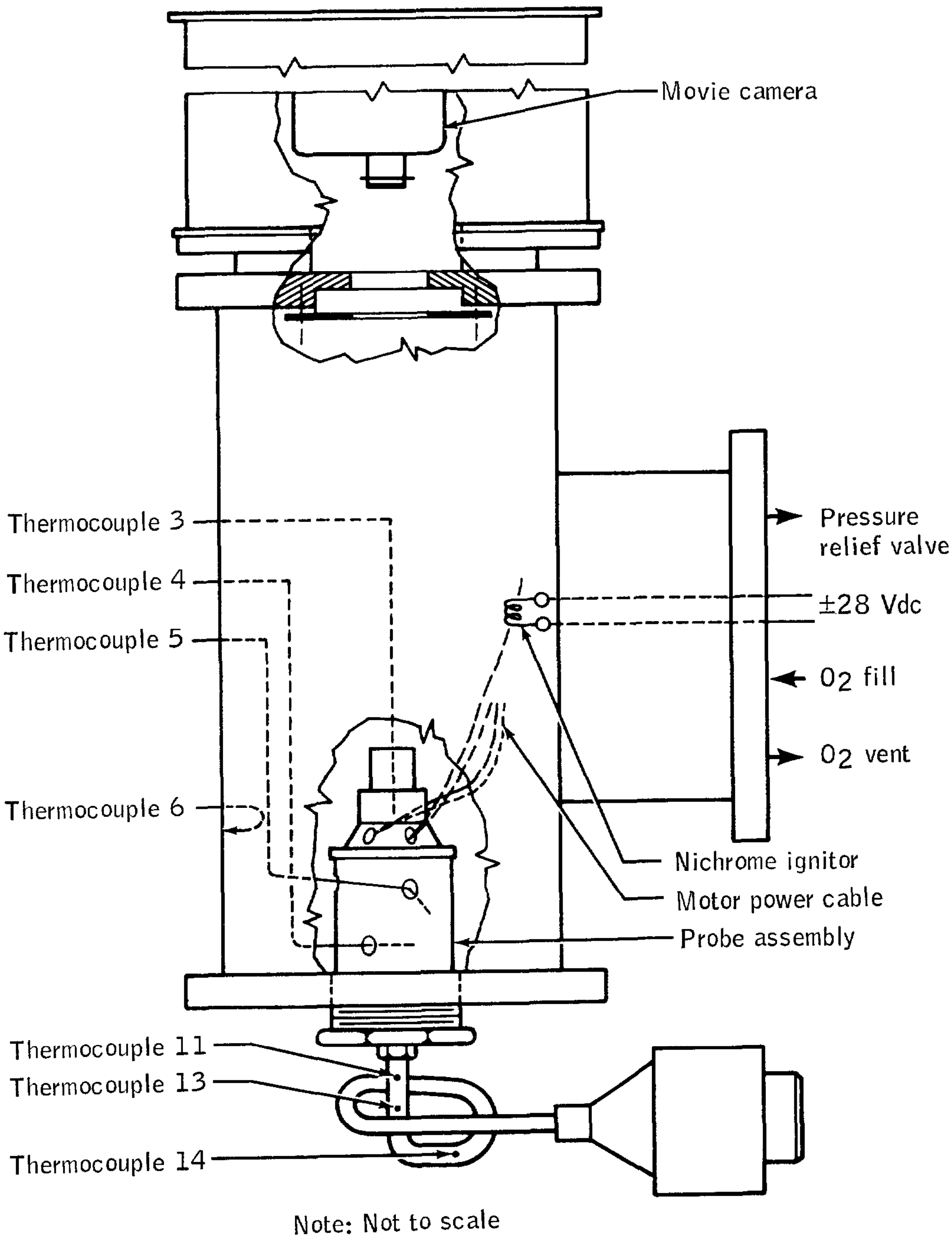


Figure F3.5-1.- Quantity probe and conduit assembly apparatus.

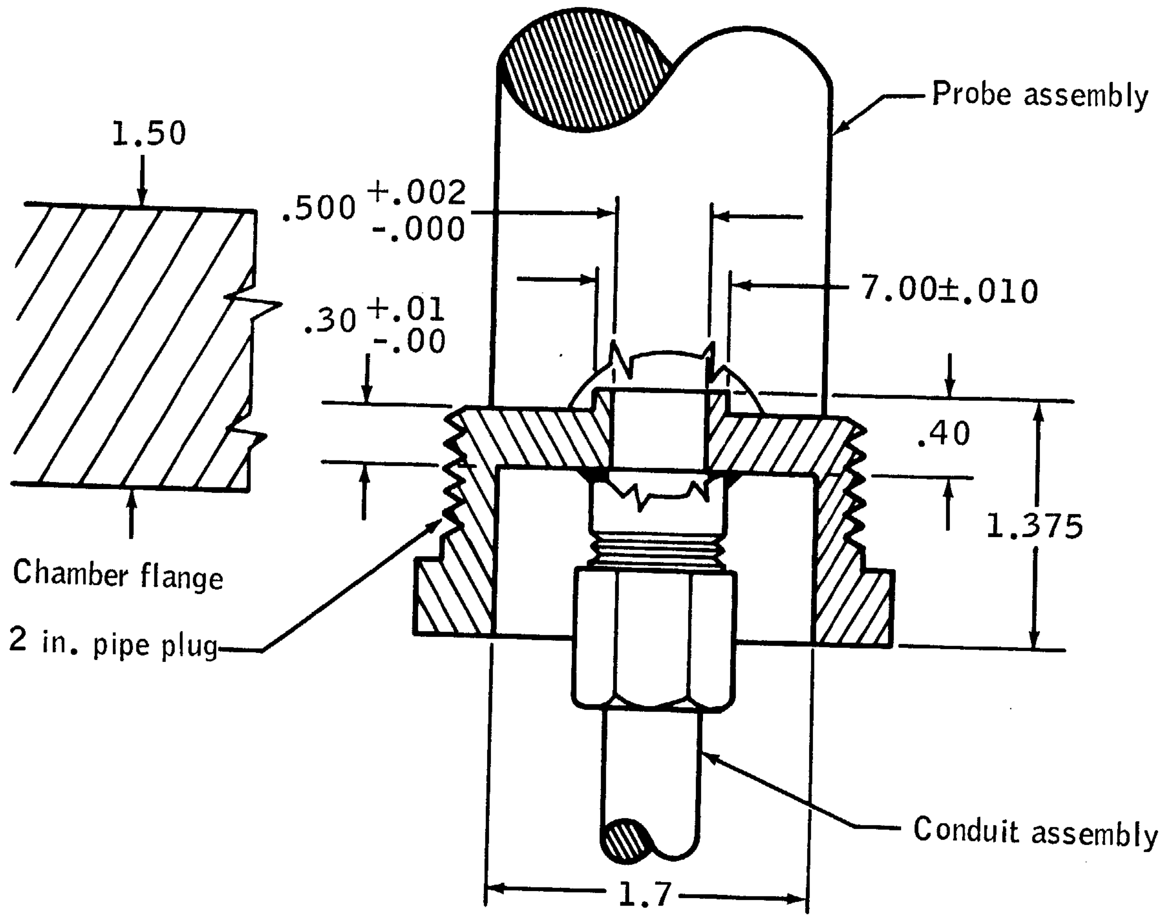


Figure F3.5-2.- Upper quantity probe - conduit interface.

fused using 1-amp fuses. One of the fan motor bundles was allowed to extend beyond the other wiring inside the test chamber and a nichrome ignitor was installed on it.

The probe conduit interface consisted of a stainless steel 2-inch pipe plug machined to the dimensions shown in figure F3.5-2. The interface was mounted on the bottom flange of the chamber so that flame propagation would be downward.

Three thermocouples were located in the region of the quantity probe as shown in figure F3.5-1. Two thermocouples were installed to measure internal chamber wall temperatures. Three thermocouples were installed on the external surface of the conduit as shown in figure F3.5-1.

After filling the chamber to 925 psia with gaseous oxygen, the chamber was cooled until thermocouple 3 shown on figure F3.5-1 indicated -138° F. Twenty-eight volts dc was applied at 5 amps to the ignitor for approximately 3 seconds. The current was increased to 10 amps for 2 seconds at which time fusion of the ignitor occurred.

Results

Pressure history of the chamber is shown in figure F3.5-3. The first relief valve opening occurred at approximately 28 seconds. It subsequently reopened 15 times before failure occurred. Fusion of the ignitor is shown on the graph to indicate ignition of the insulation.

Temperature histories of both internal and external portions of the test apparatus are shown in figures F3.5-4 and F3.5-5. Thermocouple placements in each of these areas are included in the legend figures of each of these graphs. It should be noted that two types of thermocouples were used, one with good sensitivity at low temperatures, copper-constantan, and one with good sensitivity at high temperatures, chromel-alumel. These two types are also indicated in figures F3.5-4 and F3.5-5.

The propagation observed in the color motion picture coverage internally proceeded from the ignition site (fig. F3.5-6) vertically downward. Figure F3.5-7 shows burning of the insulation on the fan motor wire bundle just before reaching the other wire bundles. Figure F3.5-8 shows the burning of several of the wire bundles. Figure F3.5-9 shows the burning of the wire bundles just prior to reaching the Teflon insulator, and figure F3.5-10 shows the more subdued fire after the propagation had progressed further into the upper probe region. Figure F3.5-11 shows the dense smoke after propagation of the burning into the insulator.

Figure F3.5-12 shows the conduit and chamber interface burnthrough scenes taken from the external movie coverage. The time for this sequence (24 frames) is 1 second. The small amount of external burning resulted from ignition of the Mylar film used to insulate the test chamber.

Visual observation of the failure of the conduit through a test cell window revealed that a flame front resulted as far away as 3 or 4 feet from the chamber.

After the test, the section of conduit was found approximately 8 feet from the chamber. Several pieces of the Teflon insulator, two pieces of the conduit swedgelock nut, and one piece of conduit tubing were gathered from a 20-foot radius around the test area (fig. F3.5-13). The only item remaining in the test chamber was a portion of the Inconel section of the capacitance probe (fig. F3.5-14). The stainless steel portion was completely gone and a portion of the Inconel was burned. No remains of the aluminum portion of the probe could be found. The conduit-chamber interface was torched out to a maximum diameter of 1-7/8 inches (see figs. F3.5-15 and F3.5-16).

Conclusions

It is quite evident from the results of this test that the insulation burning on the electrical conductors did propagate through the probe insulator even in downward burning and proceeded into the conduit. It is difficult to determine if the insulator was ignited and what time was required for the burning to propagate through the insulator. However, failure of the conduit occurred in approximately 10 seconds after burning had proceeded to the insulator-wire bundle interface. After the initial failure of the conduit, the contents of the tank (1/3 cubic foot) were vented in approximately 0.5 second with a major portion of the burning of metal occurring in 0.25 second. Venting of larger amounts of oxygen would not necessarily take longer since continued oxygen flow should produce considerably larger "torched out" sections. In order to produce the heat necessary for the effects observed here, metal burning must have occurred.

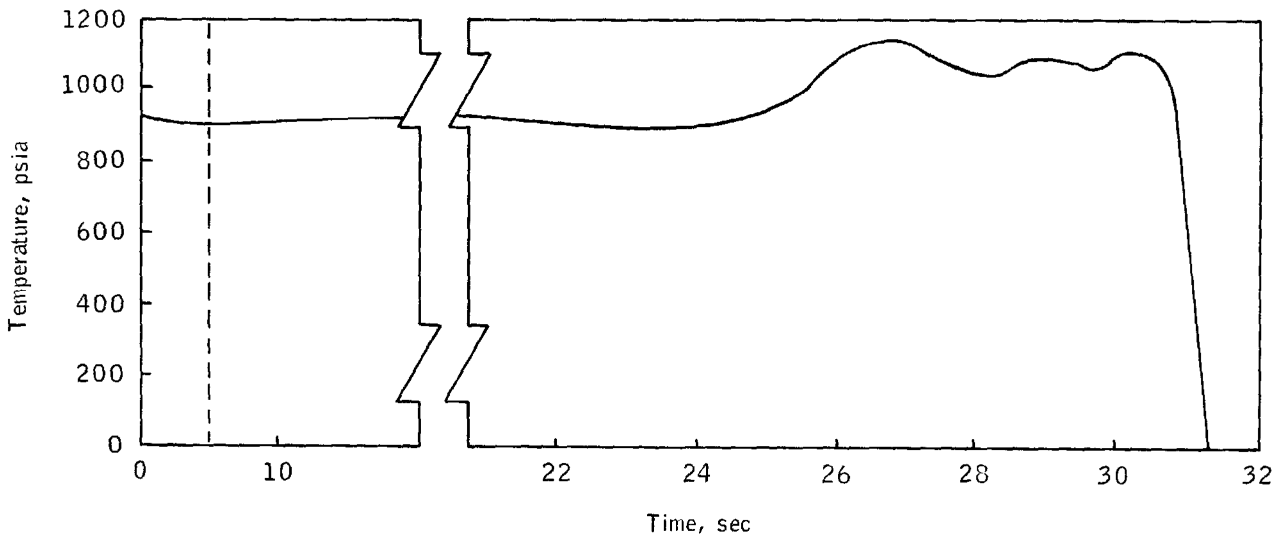


Figure F3.5-3.- Quantity probe and conduit assembly test pressure history.