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"A REVIEW OF CRYOGENIC TESTING PERFORMED BY THE THERMOCHEMICAL TEST BRANCH, MANNED SPACECRAFT CENTER IN SUPPORT OF APOLLO 13 AND 14"

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ABSTRACT

The Apollo 13 anomaly provided considerable impetus for a variety of types of cryogenic and ignition tests. This presentation will treat the logic of the various test program designs, the test techniques, and their final impact upon the investigation findings. In addition, the presentation will cover several test programs initiated to determine the thermal performance and general performance characteristics of the redesigned Apollo 14 cryogenic storage system.

INTRODUCTION

This paper is a brief summary of the Apollo 13 and Apollo 14 oxygen cryogenic storage system (CSS) tests performed at the Thermochemical Test Area, Manned Spacecraft Center. This area includes five unique facilities which provided the many specialized test environments and fixtures necessary to accomplish the subject test programs. There were 25,000 manhours invested in 30 test programs of which 50% were completed between April 14 and May 22, 1970 in direct support of the Apollo 13 anomaly and the requirements for redesign of the Apollo 14 CSS were made; however, this paper will treat only the test planning logic and the highlights of the more informative tests. The Apollo 13 and Apollo 14 test programs were concerned with ignition and combustion phenomena and the Apollo 14 tests were additionally concerned with determining the operational characteristics of the redesigned CSS.

APOLLO 13 TESTS

The Apollo 13 Anomaly Investigation was a very intense series of test programs and group discussions. The testing was controlled from a single point for the purpose of avoiding redundant and unproductive testing. The control of testing was effective and the pattern which evolved was as described below:

Baseline Tests

These tests were performed for the purpose of basic orientation of the Apollo 13 Review Board, the Observers, and many of the Panel members on the combustion characteristics of the various CSS materials and the operational characteristics of the CSS components and instrumentation.

The materials combustion tests were conducted in high pressure oxygen gas, supercritical oxygen, and subcritical oxygen. There were several informative movies taken during these tests which helped considerably to approximate combustion rates and ignition energy values for teflon wire insulation in 900 psi supercritical oxygen, as well as to establish a graphic understanding of this combustion process.

There were also several test programs conducted for the purpose of characterizing the CSS components and instrumentation in order to more beneficially interpret the data recorded pertinent to the Apollo 13 accident. The TTA test assignments were designed to evaluate the Apollo CSS fluid flow dynamics and its associated valves, pressure transducers, and flowmeter response times. The results of these test programs confirmed that the analysis methods being used on the Apollo 13 data were correct.

At this point, it was evident that combustion of the teflon insulation was a realisitc consideration and the energy released could easily be sufficient to provide the pressure rise rates recorded on the Apollo 13 data. Therefore, it was determined that while ignition and combustion studies continued, an effort to determine the ignition source would be initiated. This included the examination of all aspects of the CSS handling prior to flight.

Simulations of CSS Preflight Servicing

The TTA tests were simulations of the Apollo 13 #2 oxygen tank special detanking procedures which were used by KSC to cope with a detanking problem. This was caused by a displaced inner tank coupling which disallowed simple pressure application for liquid detanking and caused them to detank principally by evaporation. It was suspected that the prolonged and abnormal operation of the tank heaters during detanking was directly related to the ultimate failure. As shown in figure 1, this testing revealed that the heater thermostat switch contacts welded in the closed position. Consequently, heaters were continuously adding energy to the system during the simulated detanking operation which allowed temperatures on the heater probe assembly to rise as high as 1000° F (see figure 2), which is grossly in excess of the

+80° F thermal switch set point. The insulation of the destratification fan motor wires located in this area was severely degraded as shown in figures 3 and 4. This information was very significant for incident reconstruction. As a result of this finding, it was reasonable to postulate that ignition took place somewhere within the heater probe assembly near the degraded fan motor wires after which combustion continued until CSS failure.

Component Level Ignition Studies

This category of tests was designed to deliberately ignite the teflon insulation in a simulated CSS to determine the potential CSS failure modes and to gain a better understanding of system combustion propagation and pressure rise rates. These tests indicated that the flight structural failure occurred within the electrical conduit section between the pressure vessel and the outer shell of the accessory dome. Figure 5 shows the results of these tests. Considerations were now being given to performing a full simulation test using all the flight type hardware possible. However, there were still many reservations concerning the types and quantities of energy releases that could take place after ignition of an "all up" configuration. Therefore, additional tests were performed to determine if there would be gross amounts of energy released from the combustion of metals within the CSS. For these tests, TTA responsibility was primarily the CSS heater/fan motor probe assembly. Every reasonable effort to ignite the fan motors was attempted but no metal combustion was evidenced. Figures 6 and 7 show the results of some of these tests.

Full Simulation O_2 CSS Ignition Test

Subsequently, the "all up" test configuration was established and the test objectives defined. The primary objective was to determine the pressure and temperature time history of the combustion of the teflon wire insulation and the extent of propagation to other materials when the wire insulation was forcibly ignited near the lower fan motor. The test article was a flight configured CSS tanked with approximately 900 psi, -190° F supercritical oxygen. The results of this test were generally as expected. The conduit ruptured 1/4 inch from the pressure vessel (see figure 8) within 58 seconds after ignition. The combustion time history, shown in figure 9, was in agreement with the results obtained from previous component level tests, and was a remarkable facsimile of the Apollo 13 accident time history which occurred within a 75 second period. The difference between one "G" and zero "G" burning rates for the teflon as well as the uncertainty of the exact ignition location easily allows for the 17 seconds difference. The relief valve functioned normally at 1006 psia and the maximum pressure recorded was 1170 psia. As shown in figure 10, post-test inspection of the CSS interior showed that essentially all teflon burned except the lower capacitance probe insulator.

APOLLO 14

Material Ignition and Combustion Tests

During the Apollo 13 investigation, and throughout the resulting Apollo 14 redesign period, the materials test programs continued to provide useful data. The ignition and combustion tests were performed at several MSC locations,* with the TTA responsibility being primarily that of spark ignition studies. Several methods of controlling and measuring spark energy releases were developed, and spark testing was performed over a range of voltages, energies, and specimen types. The test apparatus shown is shown in figure 11, a typical spark ignition device schematic is shown in figure 12, and the results of igniting an aluminum specimen are shown in figure 13. The test results may be generalized as follows:

1. Short term sparking is probable with wire breaks and intermittent shorts and is very difficult to protect against. Normal fusing techniques are too slow to provide adequate protection.

2. Lowering the voltage available at the gap makes it more difficult to transfer spark energy at rates sufficient to cause combustion.

3. Practical values for the spark ignition threshold of materials are very difficult to obtain because they are very dependent on geometries from the viewpoints of ease of sparking, and heat retention properties. That is, sharp points and/or low mass extrusions are more easily ignited than blunt large mass objects.

4. Some ignition threshold values considered useful which were developed by sparking from needle point geometries in an ambient temperature high pressure O_2 environment are 0.25 joules for teflon, approximately 3 joules for poor conducting metals, and somewhat higher energies for good conducting metals.

5. Each design configuration must be independently evaluated to determine its vulnerability to spark ignition.

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*Flammability Testing Conducted in Support of Apollo 13, by L. J. Leger, Materials Technology Branch, MSC, and R. W. Bricker, Structural Test Branch, MSC.

The Apollo 14 redesigned CSS excluded the destratification fan motors thereby eliminating a potential high energy spark source. In addition, all teflon wire insulation was deleted which eliminated most of the easily ignitable combustible material. The new design incorporated extensive use of stainless steel sheathed, silicone dioxide insulated conductors which provided considerably less vulnerability to damage and combustion than the Apollo 13 installation. All of the elements incorporated in the redesign which would be exposed to oxygen were spark ignition tested under many failure mode simulations. The results were that the Apollo 14 redesign spark tests produced no ignitions when a circuit with resistances and fuse protection like that in the spacecraft was included.

Alternate Destratification Methods

Following the elimination of the destratification fans, two courses of investigation were followed: one, providing a substitute for the loss of the fans, and two, investigating the problems associated with having no destratification devices.

One of the more promising substitutes considered was an external recirculation loop concept. A test was performed to determine the feasibility of using a modified version of the Apollo Environmental Control System (ECS) coolant pump to circulate the fluid to destratify the oxygen in the CSS. Figure 14 shows the disassembled pump. The pump electrical parts were excluded from contact with the fluid by use of a magnetically coupled fluid impeller. In the test setup, the pump was installed such that the oxygen would flow from the vent to the fill line of an Apollo cryogenic storage vessel. For this test an unmodified coolant pump was used, and nitrogen was substituted for oxygen. Various gaseous and supercritical fluid conditions were tested to simulate the full mass quantity spectrum. A normal usage outflow of 1.5 pounds per hour was provided during the test. The feasibility was clearly demonstrated in a low density or 5 pounds per cubic foot test, in which purposely induced stratification was eliminated by operation of the external loop.

To aid in determining the effects of having no destratification devices in the cryogenic storage vessel, tests were performed in which KSC prelaunch tanking procedures were duplicated both with and without heater operation, without the use of destratification fans, and with the vessel in a normal vertical configuration. Following each test, the vessel was agitated to simulate launch vibration; this resulted in a maximum of 10 pounds per square inch decrease from 900 pounds per square inch absolute pressure. These pressure decreases were accompanied by 3° F decreases in indicated temperature and a 2% decrease in indicated quantity.

Additionally, an investigation of stratification at low fill densities was conducted by depleting the cryogenic storage vessel to 35%, establishing normal usage flow and maintaining pressure for 24 hours. The vessel was then agitated to simulate engine firing accelerations and vibrations and no appreciable pressure decay was observed.

The final test in this series was to determine the operational time available when depleting at the maximum expected flowrate to 150 pounds per square inch absolute without the use of heaters and starting at a low fill density (20% full).

The results indicate a time to minimum pressure of 49 hours with the vessel located in a 60° F environment. Even though two phase fluid existed somewhere between 554 and 501 pounds per square inch absolute pressure, it did not cause any operational problems.

Flight Support Tests

To meet a specific Apollo 14 in-flight test objective, it became necessary to determine the best method for filling the newly configured cryogenic storage vessel to approximately 60%. In the first method tested, the vessel was filled with liquid oxygen, dumped to 61% using gaseous oxygen pressure, fully pressurized with ambient temperature gaseous oxygen (quantity increased to 74%), and depleted at one pound per hour for 40.5 hours. During the depletion phase, the pressure decreased below the minimum operational limit and required 5.5 hours to recover although the heaters were on. Figure 15 is a plot of the pressure versus time for this period. The vessel was subsequently agitated but no pressure decay was experienced.

In the second method attempted, the vessel was filled with liquid oxygen, pressurized with heaters, depleted at 1.55 pounds per hour for 63 hours, and further depleted for 44 hours with equilibrium flow to maintain normal pressure. No abnormal pressure decay resulted from depletion flows or from agitation of the vessel.

A third method was implemented whereby the vessel was filled with liquid oxygen, dumped to 51%, pressurized to normal pressure with gaseous oxygen, and maintained at normal pressure by inflow of gaseous oxygen for 10 hours. Agitation produced a pressure decrease of 249 pounds per square inch and subsequent repressurizations with heaters followed by agitations continued to show pressure decreases.

Of the three methods, the second method was chosen since it fit within launch pad operational constraints and produced no instability in the vessel.

CONCLUDING REMARKS

The test programs conducted at the TTA, MSC, in support of the Apollo 13 investigation provided very fast, accurate insight into the cause of the flight anomaly, as well as important guidelines for the Apollo 14 CSS redesign. These test programs also provided the operational information necessary to gain a high confidence level in the redesigned Apollo 14 CSS.

Some specific conclusions from these tests, which are of interest to cryogenic systems designers, are as follows:

1. Electrical circuits included in oxygen storage vessels may be hazardous unless special engineering precautions are taken to limit the availability of electrical energy and/or to provide geometries demonstrated to be safe.

2. Potentially detrimental fluid stratification effects may be minimized by using external loop circulation techniques and/or by special filling and operational methods such as those developed for Apollo 14.

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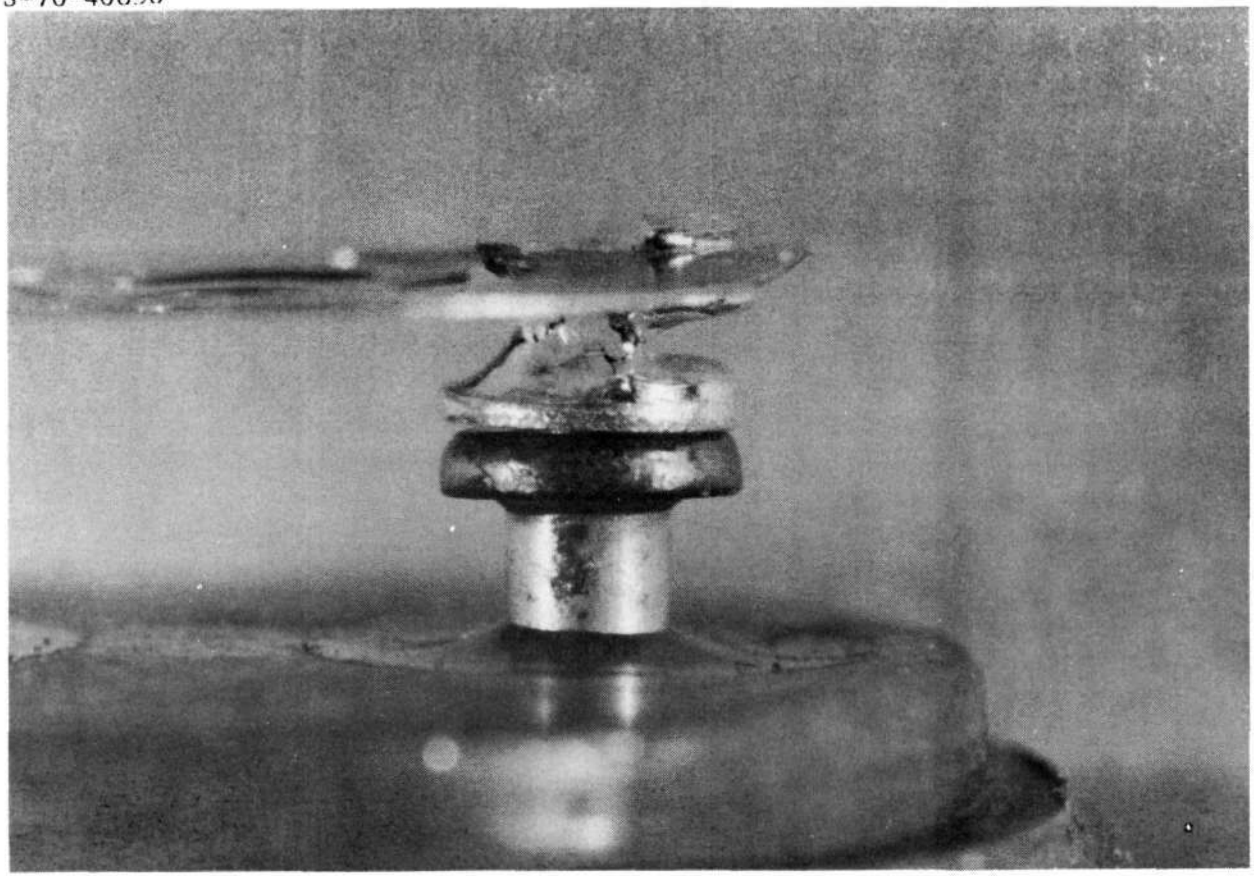

Figure 1.- Welded heater thermostat switch contact

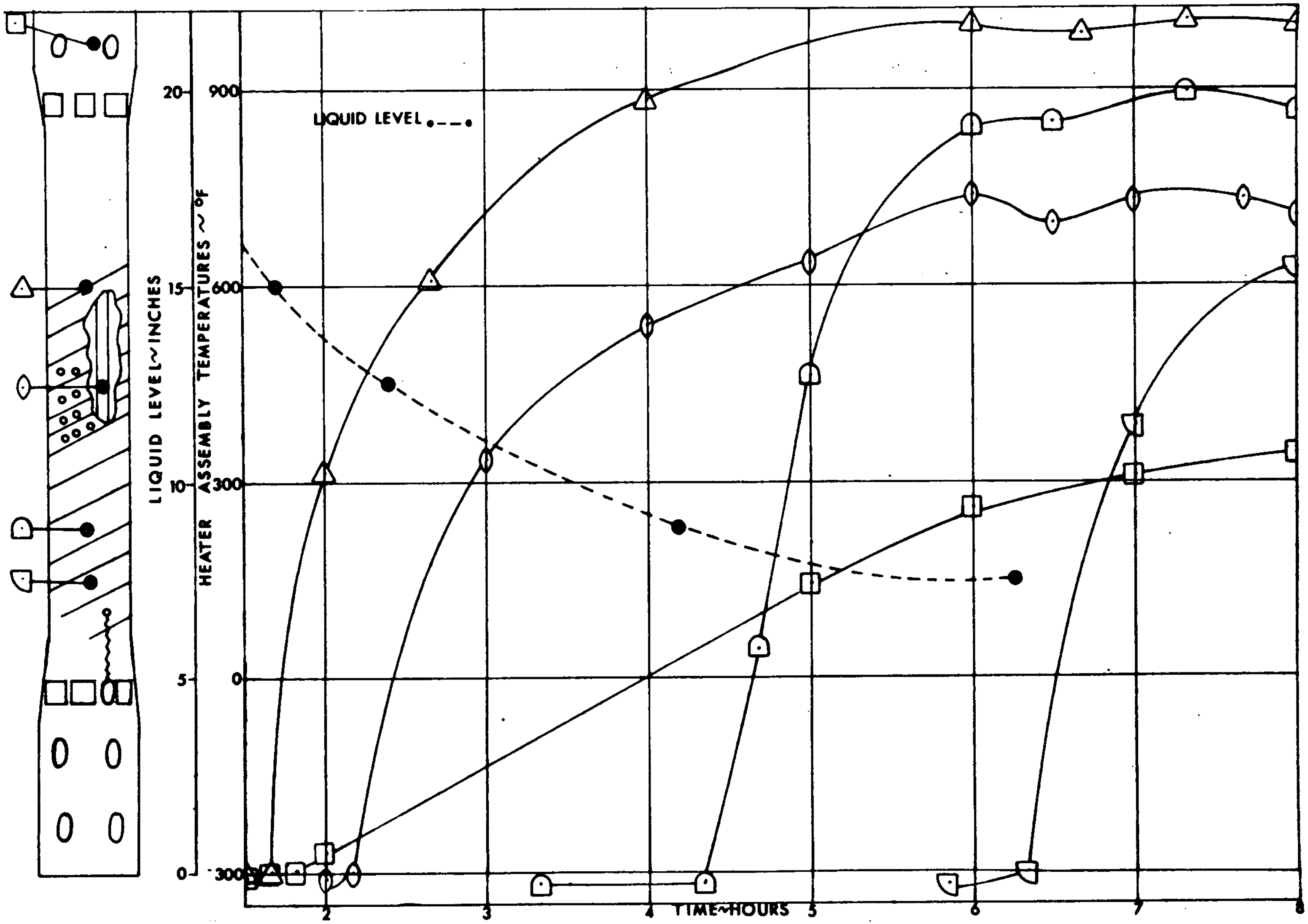

Figure 2.- Detanking heater temperature profile

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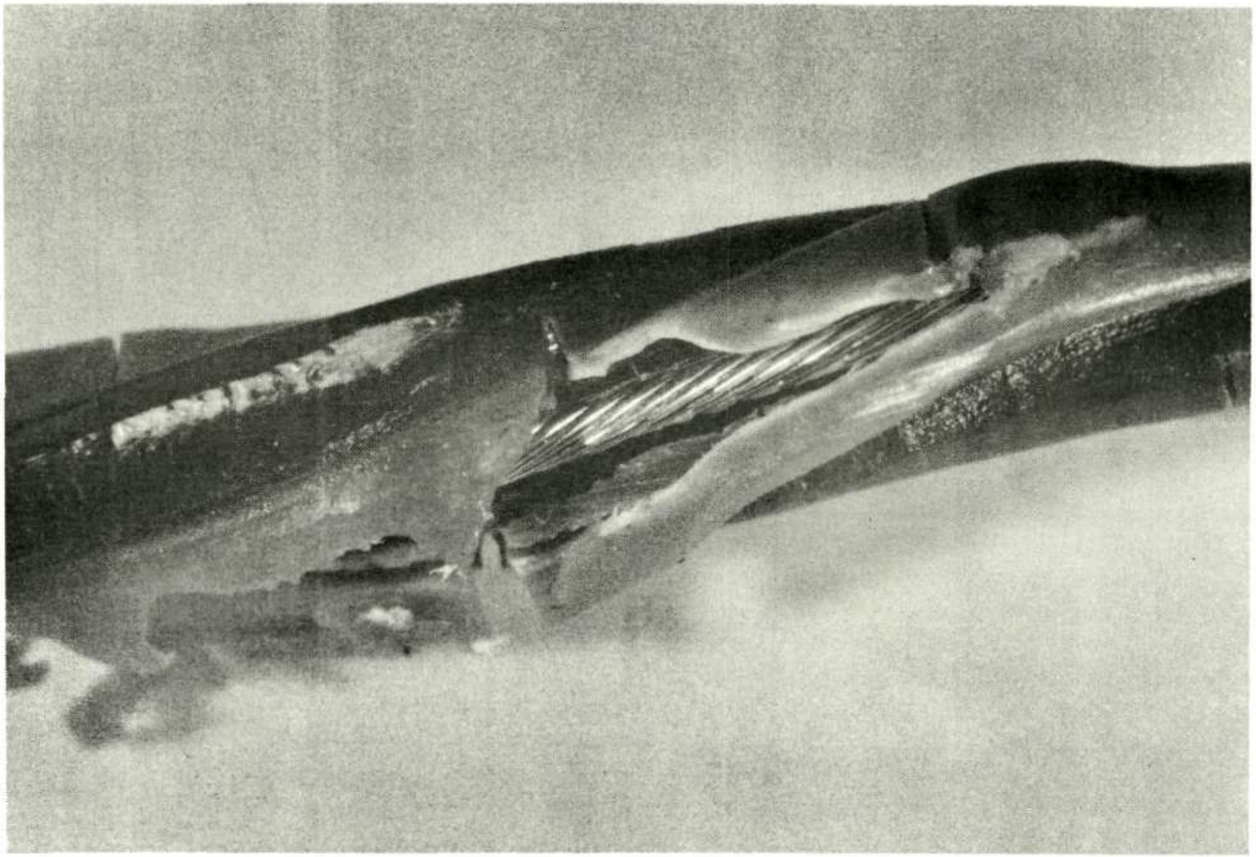

Figure 3.- Most severe degradation to fan motor wire insulation

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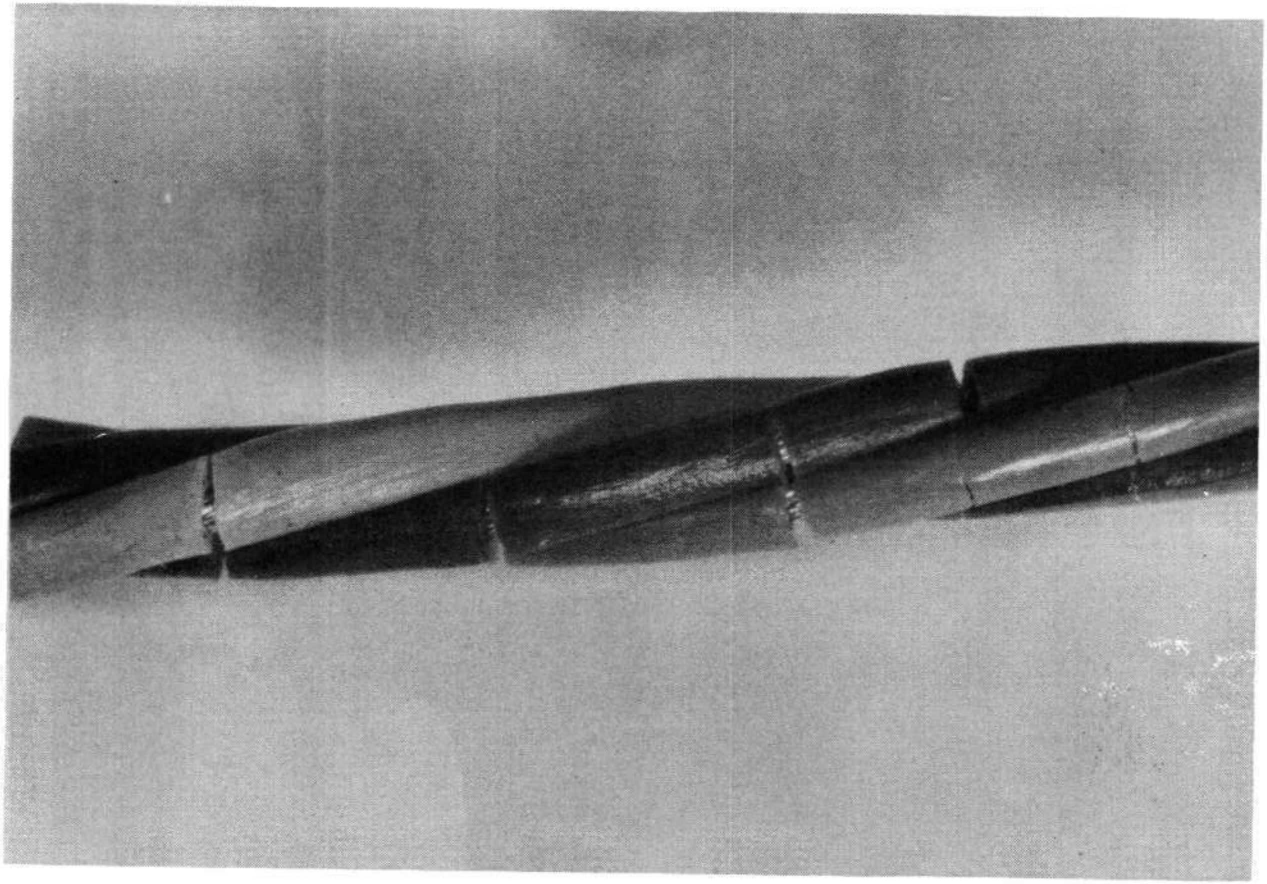

Figure 4.- Average degradation to fan motor wire insulation

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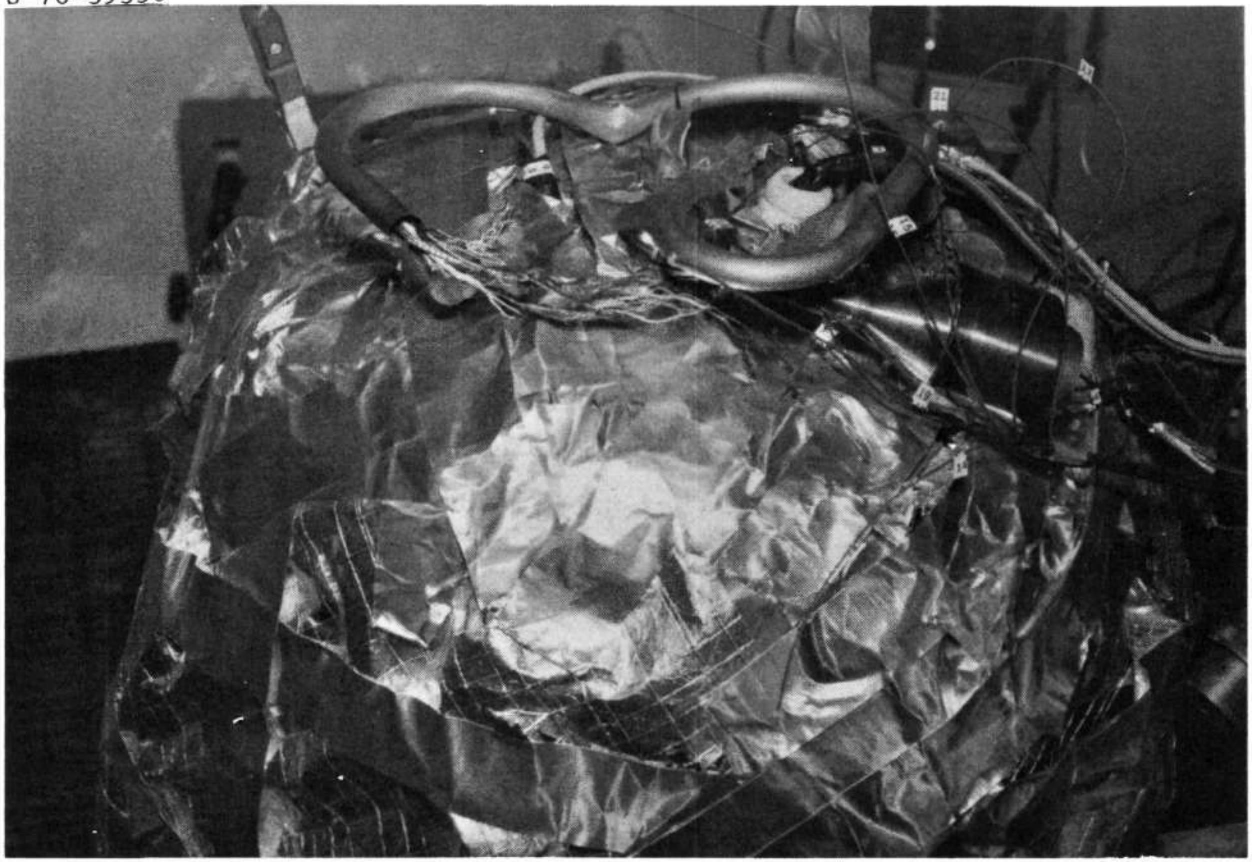

Figure 5.- Electrical conduit after rupture

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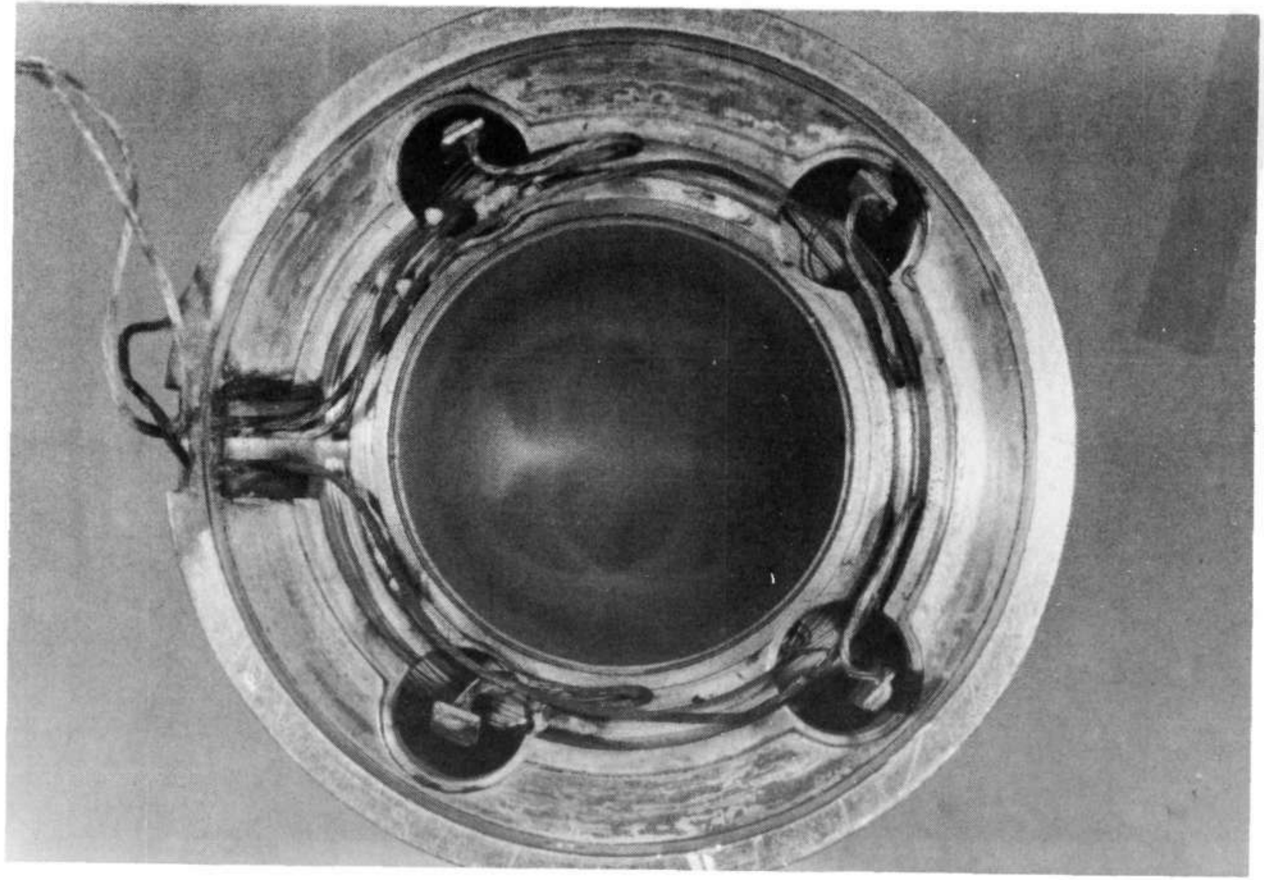

Figure 6.- Fan motor wire and terminal insulation combustion from upward burning

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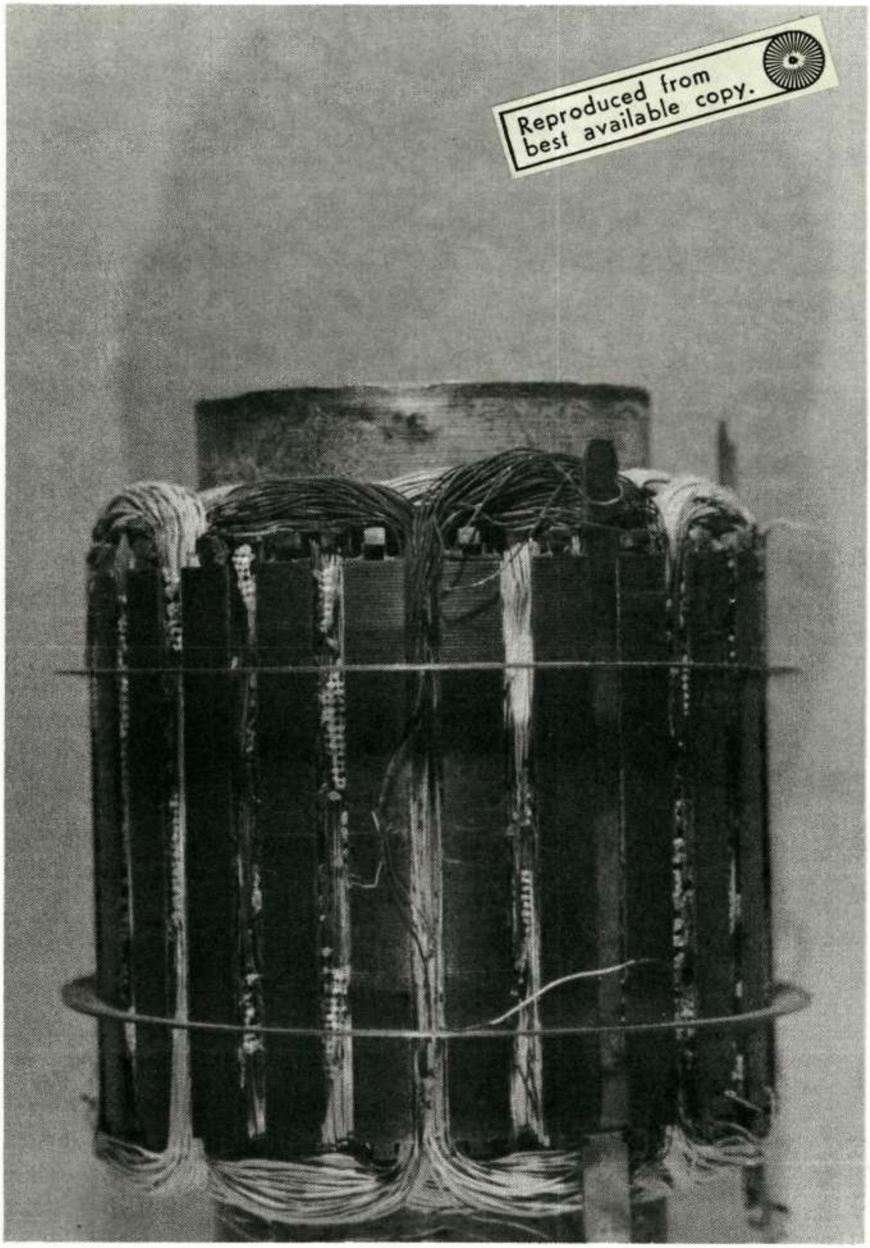

Figure 7.- Fan motor charred stator winding insulation from upward burning

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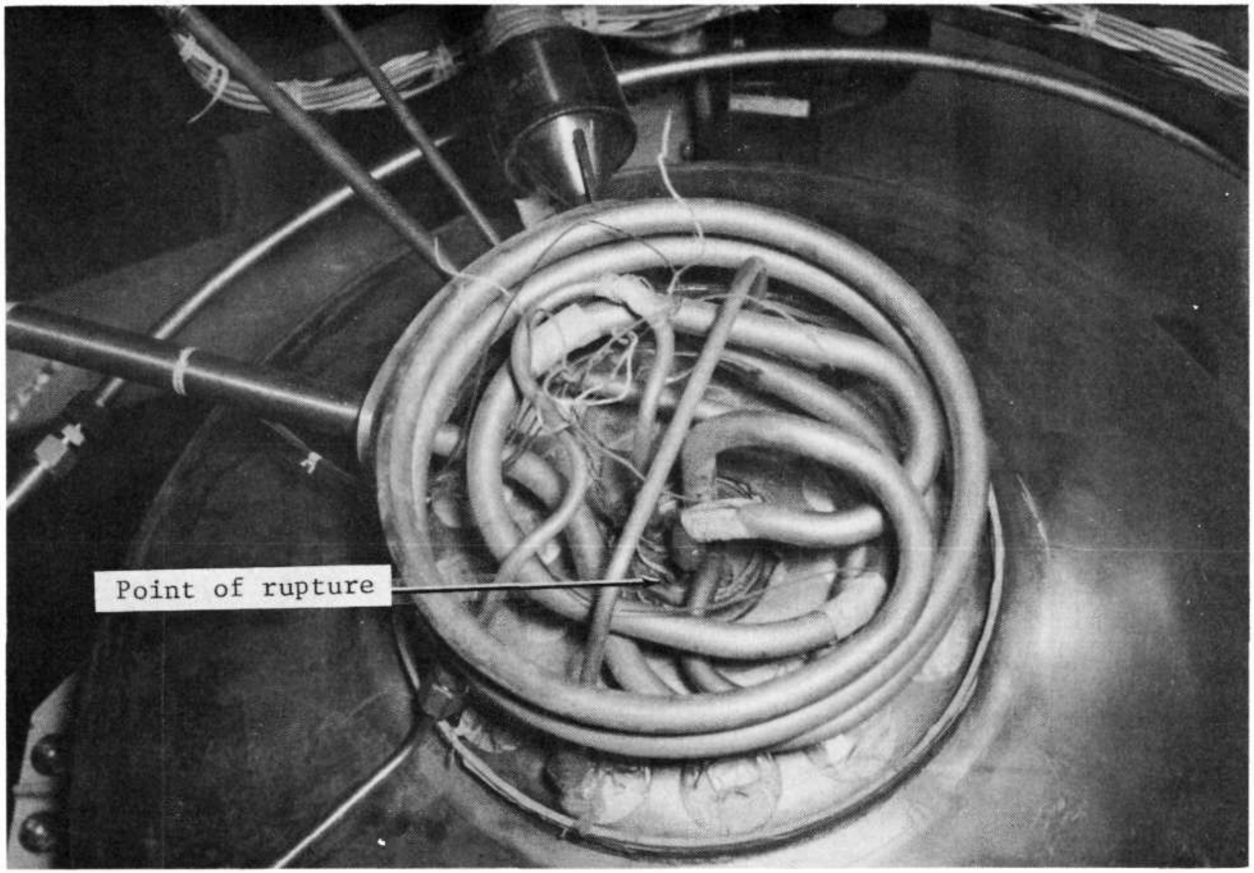
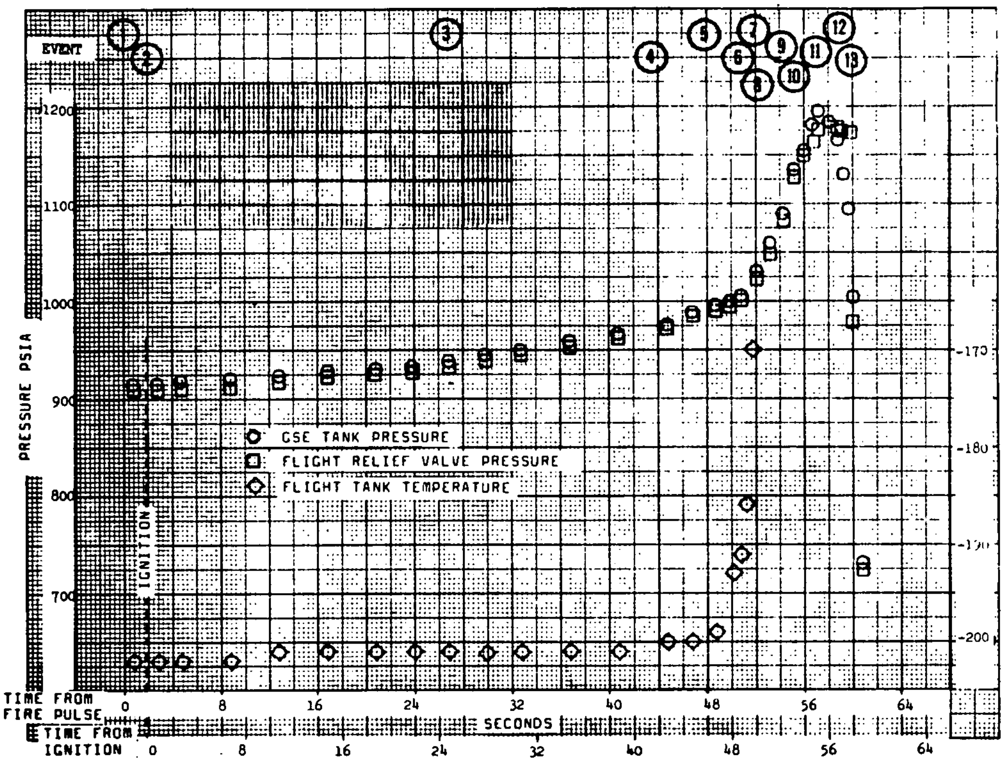


Figure 8.- Electrical conduit rupture after "all up" test



Event number	Event	Time from fire pulse, seconds	Time from ignition, seconds
1	Fire pulse applied to igniter on lower fan motor wires	0.0	-1.99
2	Lower fan motor fuses blown	1.99	0.0
3	Upper fan motor fuses blown	26.70	24.71
4	Wire loop temp. sensor indicated slow temp. rise	43.33	41.34
5	Flight position temp. sensor indicated slow temp. rise	47.93	45.94
6	Flight relief valve opens at 1006 psia	50.86	48.87
7	Wire loop temp. sensor offscale	51.92	49.93
8	Flight position temp. sensor offscale	52.03	50.04
9	GSE relief valve opens at 1095 psia	54.14	52.15
10	GSE relief valve opens at 1129 psia	55.14	53.15
11	Maximum tank pressure achieved (1197 psia)	57.03	55.04
12	Max. flow thru flight relief valve - 100.2 no./hr.	59.02	57.03
13	Tank rupture at 1134 psia	59.99	58.00

Figure 9.- "All up" test time history

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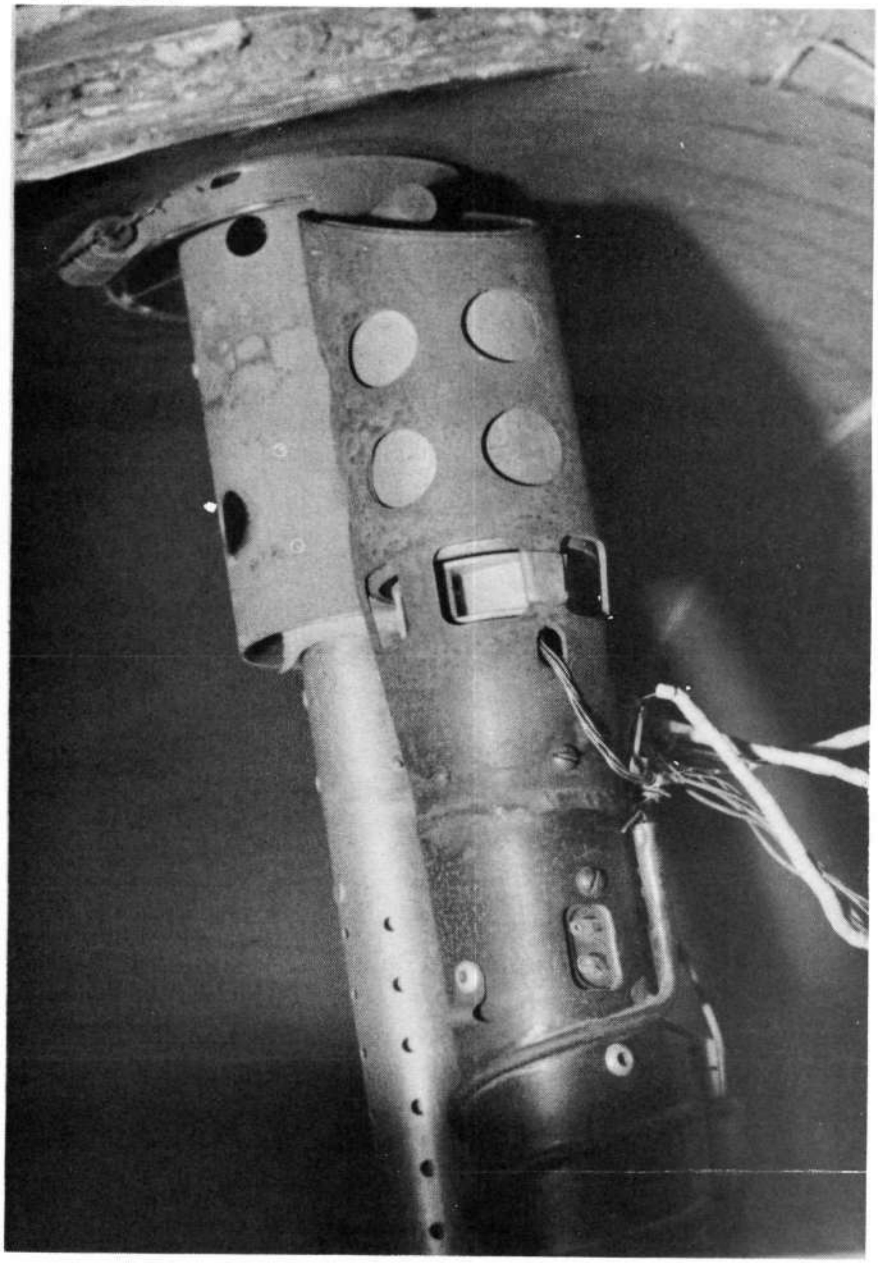

Figure 10.- Top of heater and capacitance probe assembly after "all up" test

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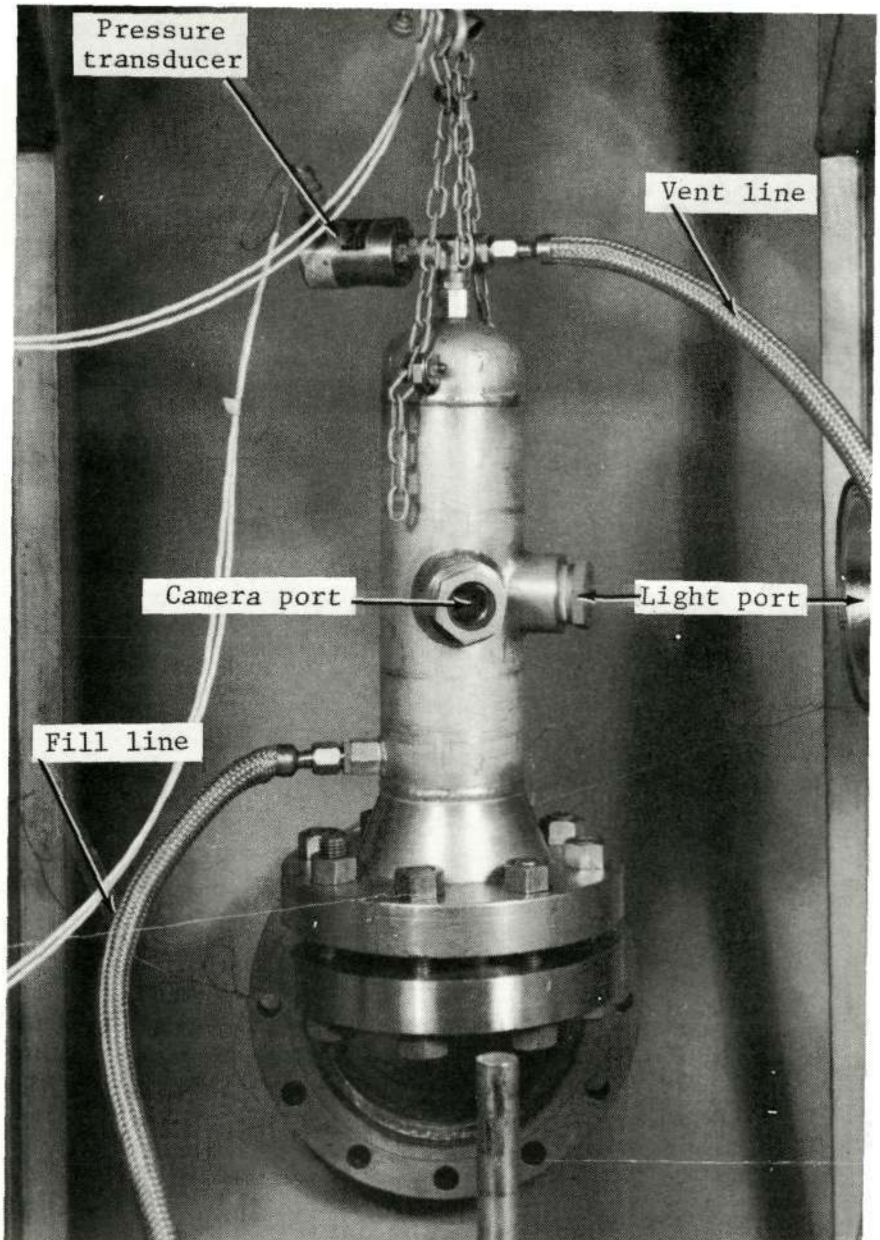

Figure 11.- Supercritical oxygen spark ignition test apparatus

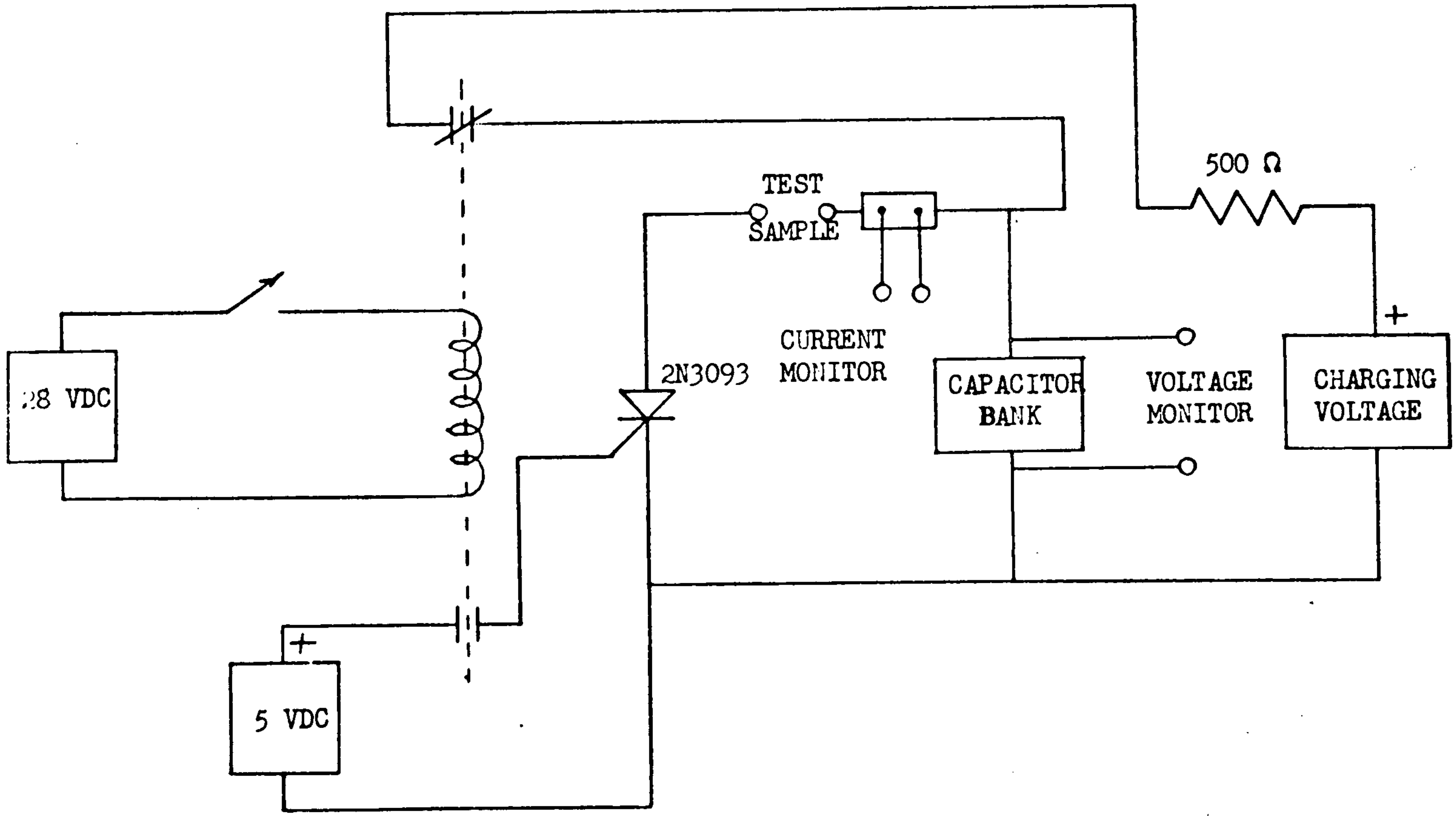

Figure 12.- Capacitor discharge spark ignition test system schematic

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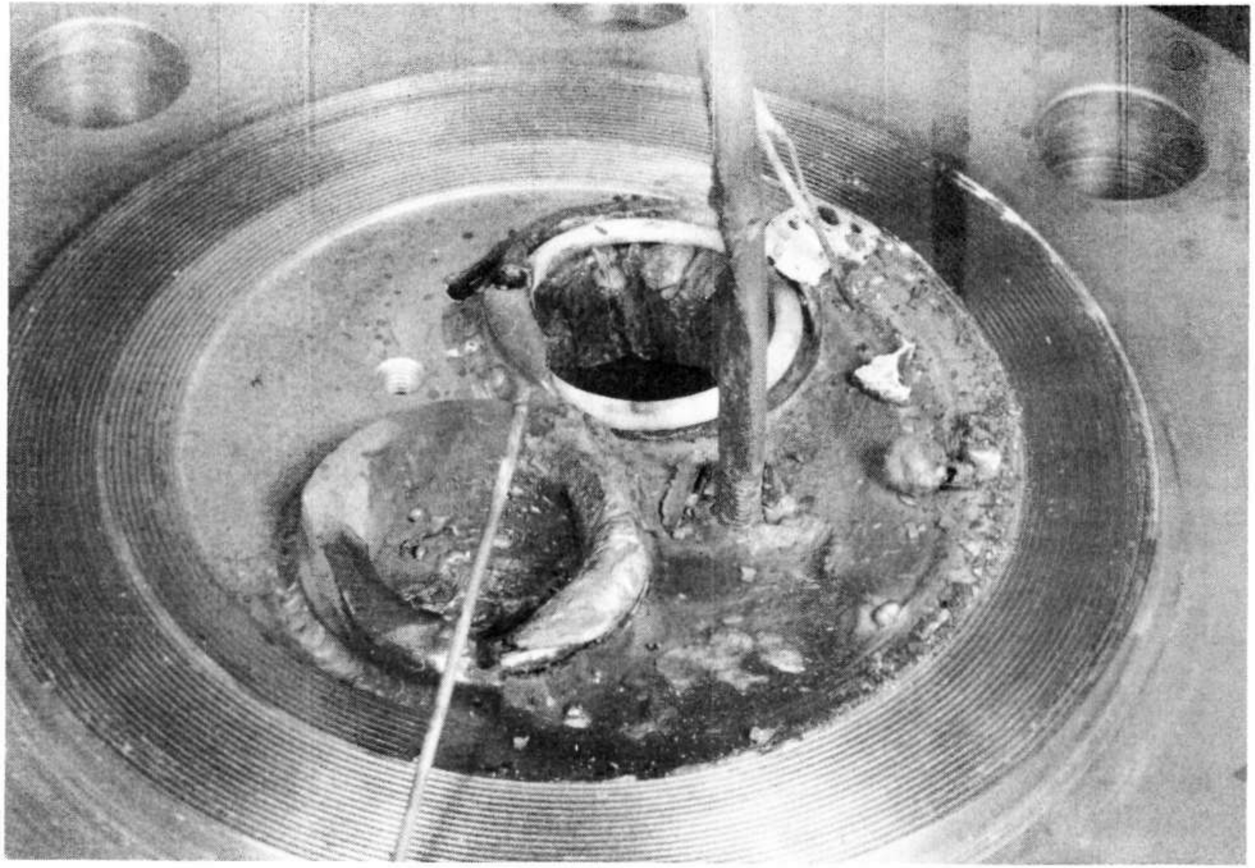

Figure 13.- Results of aluminum burn after spark ignition in a stainless steel test vessel

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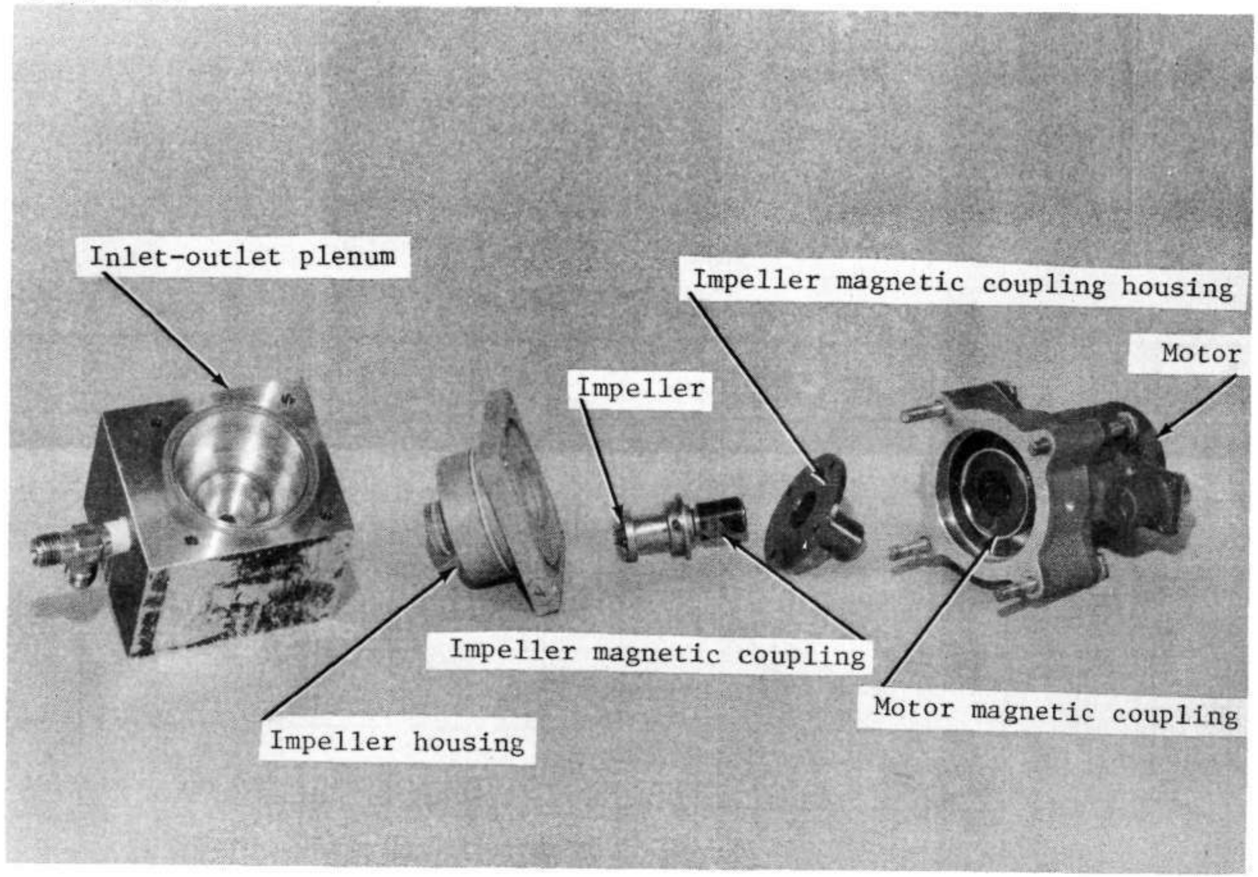

Figure 14.- Disassembled recirculation pump

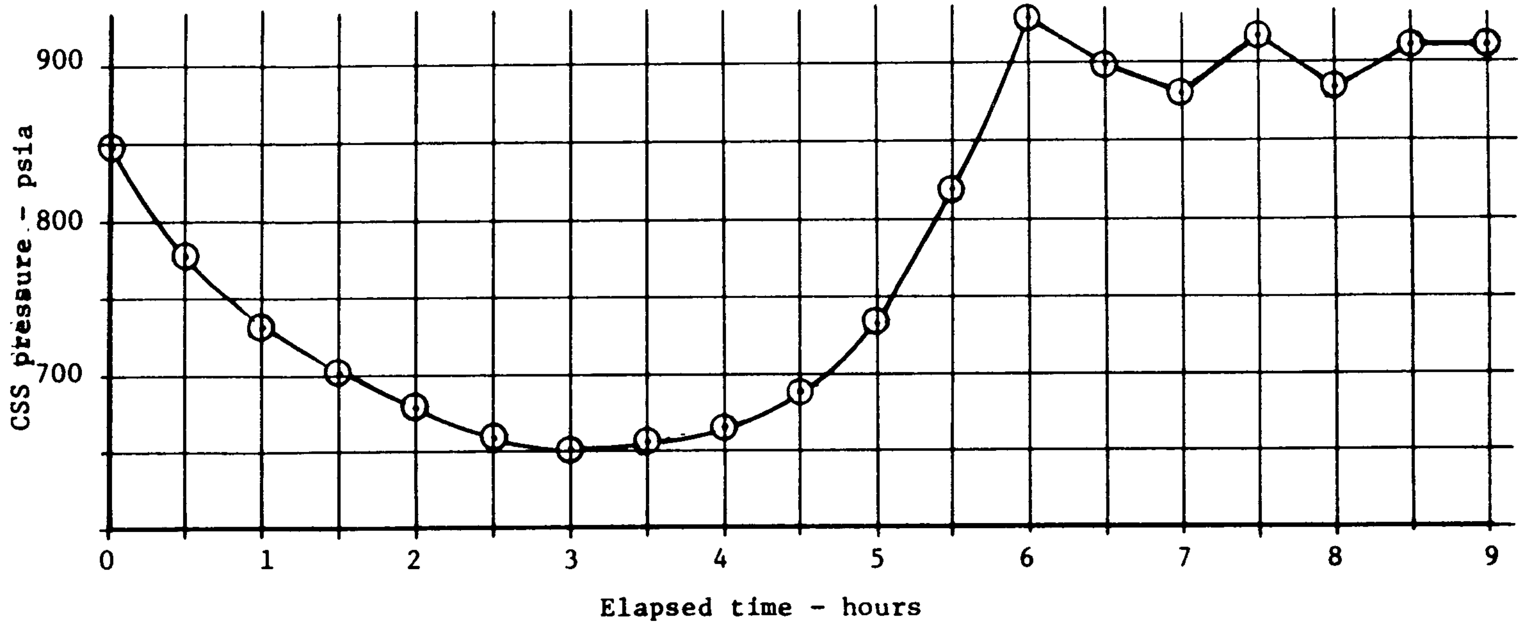

Figure 15.- CSS pressure for 1st partial fill method