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INVESTIGATION OF AIRCRAFT FUEL TANK EXPLOSIONS AND NITROGEN INERTING REQUIREMENTS DURING GROUND FIRES

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FINAL REPORT

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16. Abstract

Nitrogen inerting was investigated as a means of preventing or minimizing explosions and/or reactions in aircraft fuel tanks under simulated crash-fire conditions. Tests were conducted on both small and large volume tanks, inerted to various concentrations (expressed in terms of O_2 concentration by volume), containing different amounts of Jet-A or JP-4 fuel and heated at different rates.

Results of these tests indicated that internal fire or explosion would not result from external heating or internal high-energy spark when the tank was inerted to an oxygen concentration lower than 10 percent.

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PREFACE

The authors would like to thank E. P. Klueg and G. E. Chamberlain for their initial planning and help during the performance of this test program. We would also like to express our appreciation to the technicians who made the completion of this project possible--they were W. E. Neese, J. Demaree, and C. R. Cole.

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INTRODUCTION

PURPOSE.

The main objectives of the test program were as follows:

1. Phase I:

- To determine the maximum oxygen concentration (when nitrogen inerting is used to reduce the O_2 concentration) which will not support an internal tank reaction (explosion) due to hot-surface ignition, tank burn-through, or a high-energy spark in the tank during a post-crash ground fire.

- To determine the effects of elevated fuel vapor temperature on the amount of nitrogen inerting (expressed in oxygen concentration) needed to avoid any noticeable tank reaction.

2. Phase II: To demonstrate by large-scale testing, the results of phase I, thereby giving confidence in using the results of small-scale tests for full-size fuel tanks.

BACKGROUND.

A project was conducted at the National Aviation Facilities Experimental Center (NAFEC) to determine the capability of nitrogen inerting in preventing fuel-tank explosions during post-crash ground fires. Airplane accidents, including survivable crashes, have occurred where ground fires have caused intact fuel tanks to explode, producing a more intense fire that hinders or precludes evacuation of passengers from the aircraft.

Prior to the work included in this report the Federal Aviation Administration (FAA) had completed two projects at NAFEC related to the use of a liquid nitrogen fuel tank inerting system. Report FAA-RD-71-42, "Inerted Fuel Tank Oxygen Concentration Requirements" by Samuel V. Zinn Jr., 1971, shows the results of a literature search conducted to investigate the extent of experimental work and studies that were performed for determining and evaluating safety parameters of jet fuels in aircraft tanks when using nitrogen as an inerting agent. Report FAA-RD-72-53, "Performance of a DC9 Aircraft Liquid Nitrogen Fuel Tank Inerting System," by E. P. Klueg, W. C. McAdoo, and W. F. Neese, 1972, shows the development and installation of a liquid nitrogen fuel tank inerting system on an FAA DC9-15 aircraft. The DC9 report shows the evaluation of the instrumentation equipment and measurement techniques for evaluating the installed fuel tank inerting system performance. Also given in the report are the results of a flight test program conducted to demonstrate compliance of the DC9 inerting system with applicable airworthiness standards, to evaluate oxygen concentration measurement techniques, and to verify that the installed inerting system maintained an explosion-safe mixture in the fuel tanks over the entire flight envelope.

SMALL-SCALE TEST EQUIPMENT AND CONFIGURATION

FACILITY AND TEST ARTICLE DESCRIPTION.

TEST SITE. A test site specifically for this small-scale test program was constructed in the rear of one of the permanent fire test facilities at NAFEC (figure 1). It consisted of a square concrete pad surrounded by a plywood wind barrier. The test tank and the burner assembly were installed in the center of this pad. A mobile instrumentation trailer was positioned to overlook the pad with an approximate separation of 60 feet. The trailer housed data collection and recording equipment and provided a small workshop area for project personnel. The burner assembly beneath the test article, test tank inerting and purging, internal tank ignition, and site fire protection units were also controlled from within the trailer.

TEST TANK. The test tank had internal dimensions of 35X35X12 inches (50-gallon capacity), and was constructed of aluminum channel sidewalls, aluminum plate top and an aluminum or stainless steel bottom of various thicknesses, depending on test requirements.

The top plate incorporated a 10X18-inch opening that was covered with an 0.003-inch thick replaceable 12X20-inch aluminum foil blowout panel, designed to rupture when tank internal pressure rose to 4 pounds per square inch gage (lb/in^2g). This burst pressure would vary slightly due to rate of pressure build up and/or temperature rise, but would never exceed 5 lb/in^2g.

A vent line, sized proportionately to tank capacity (19/64-inch inside diameter), was installed in one wall of the test tank, connecting the tank ullage with the atmosphere. Instrumentation lines (pressure and sample lines and thermocouple leads) penetrated the tank sidewall. Fire-detection photocells and a Fenwal detector eye, inerting and purging lines, tank fill and drain lines, and the internal ignition spark ignitor plug were also mounted on or through the tank walls (figure 2). The test article was suspended above the burner assembly by a 6-foot-high tank support rack constructed of 3-inch diameter steel pipe. Mounting provisions enabled the tank to be installed on the rack at various heights and angles above the burner, depending on the desired test configuration.

TANK INTERNAL SPARK IGNITION. Test tank internal ignition capability was provided by using one segment of a Pratt and Whitney PWA246570C J-57 turbojet engine ignition system (figure 3). A switch in the instrumentation trailer directed 28 volts direct current (Vd.c.) to a General Laboratory 15700-10 10,000-volt ignition transformer installed on the top wall of the test tank. This transformer provided an intermittent spark of 2 joules at the ignitor plug electrodes. This plug was inserted into the upper portion of the tank ullage through an adapter screwed into the tank sidewall.

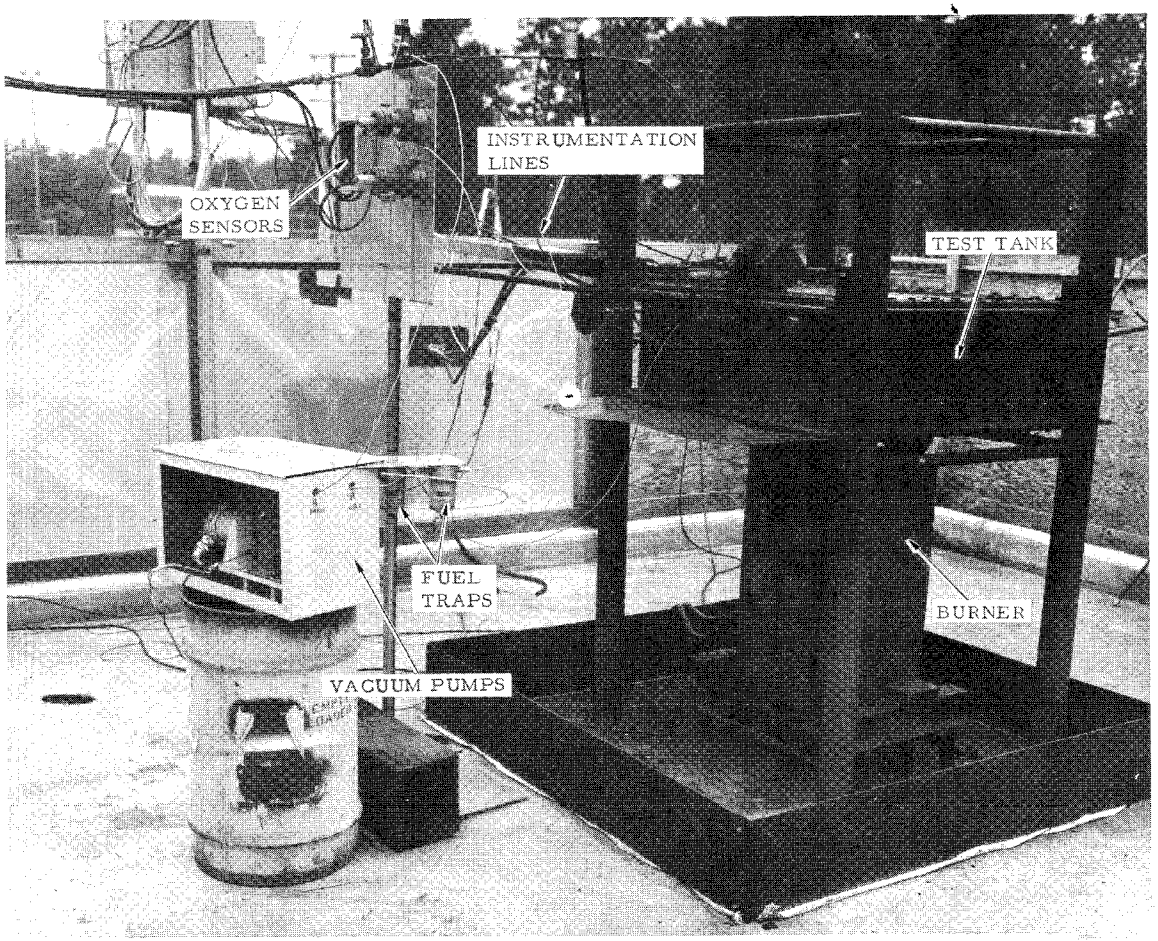

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FIGURE 1. SMALL-SCALE TEST CONFIGURATION

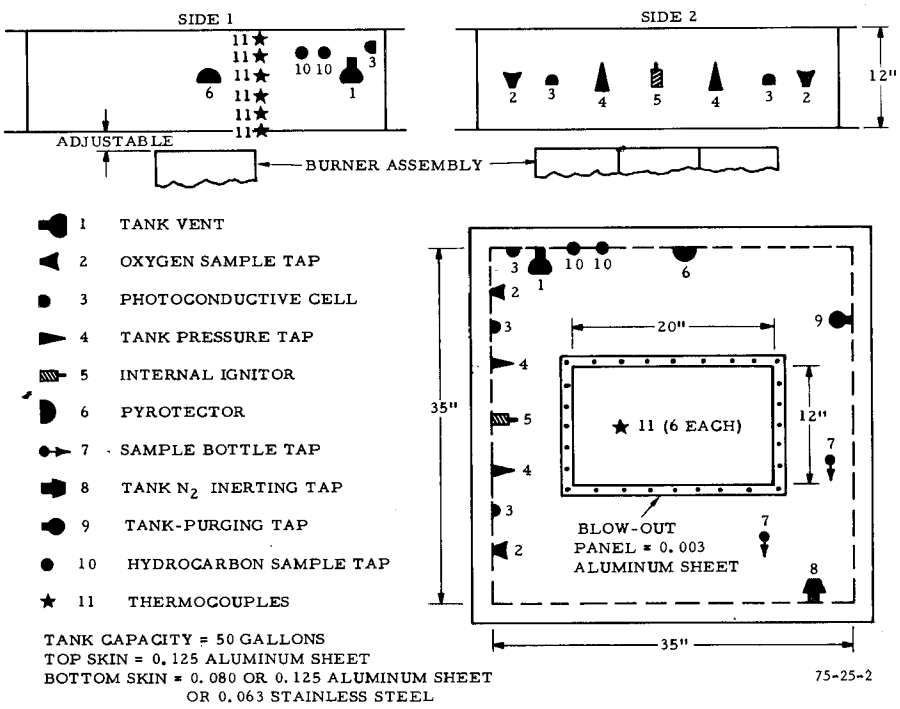


FIGURE 2. TEST TANK INSTRUMENTATION LOCATIONS

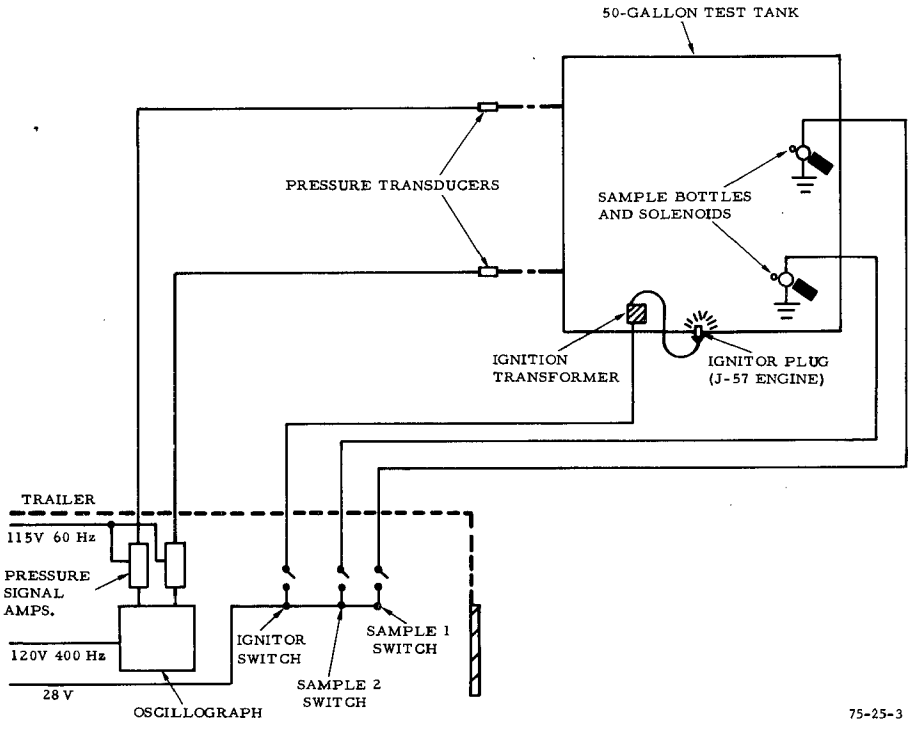


FIGURE 3. PRESSURE SENSING, INTERNAL TANK IGNITION, AND SAMPLE BOTTLE LOCATION SCHEMATIC

TANK INERTING SYSTEM. The ullage in the test tank was inerted, when required, using water-pumped gaseous nitrogen (GN_2) supplied from a 251-cubic-foot capacity 2,000 lb/in^2g storage cylinder. A pressure regulator installed on this cylinder was adjusted to provide a 50 lb/in^2g output, through an 0.250-inch diameter tube to a solenoid valve. When inerting was required, actuation of a switch in the instrumentation trailer provided 28 Vd.c. to open this valve. The inerting line inlet was in one wall of the test tank, near the top surface of the tank. The displaced air from the ullage exited the tank through the 19/64-inch diameter tank vent line. Various test configurations required a 1.5 lb/in^2g relief valve to be installed in this vent line. At this time the nitrogen cylinder regulator was adjusted to a 5 lb/in^2g output to prevent overpressuring the test tank and rupturing the blowout panel. Originally an 0.50-inch-diameter stainless steel perforated discharge tube (eight 0.0980-inch diameter outlet holes) was installed in the tank. After completion of the baseline tests, this tube was removed, and nitrogen was discharged into the ullage directly from the sidewall bulkhead fitting.

SMALL-SCALE TEST BURNER ASSEMBLY. A locally-fabricated burner assembly (figure 4) was placed beneath the test tank to simulate conditions encountered during a post-crash fire (figure 5). This burner was constructed of 0.125-inch thick steel plates arranged to form three flues approximately 36 inches high, with a total heat outlet area of 180 square inches. Near the bottom of each flue was a pneumatic atomizing fuel/air nozzle capable of delivering a 2.53 gallon per hour fuel flow at 40 lb/in^2g air pressure settings. These pressure settings were the result of computations made to calculate the amount of fuel required in this installation to produce a $Btu/ft^2/s$ radiant heat output similar to that generated by a post-crash fire on a reduced scale The nozzles directed a cone-shaped fuel spray vertically toward the lower surface of the test tank. Each flue had a crossfire hole connecting it to the interior of the adjacent flue. The end flue contained the ignition spark electrode assembly. This spark would ignite the fuel spray in this flue and the flames would instantly propagate through the crossfire holes to ignite the fuel spray in both adjacent flues. Spark energy was produced by a universal domestic oil burner-type ignition transformer. Burner fuel (JP-4) was supplied from a pressurized fuel tank. Burner air pressure was supplied at the proper setting by a portable air compressor that also provided post-test tank purging air when required. Burner operation was controlled from the instrumentation trailer.

The following burner temperatures were used throughout the test program: 1,000° F, 1,300° F, 1,600° F, 1,800° F, and 2,000° F. The flames were calibrated using a radiant heat transducer. The following are the results of the calibration: 1,000° F - 0.80 $Btu/ft^2/s$, 1,300° F - 1.05 $Btu/ft^2/s$, 1,600° F - 1.5 $Btu/ft^2/s$, 1,800° F - 1.75 $Btu/ft^2/s$, and 2,000° F - 2.25 $Btu/ft^2/s$.

The total Btu input into the test tank was checked for the 2,000° F and 1,600° F flames. The average Btu input into the tank over its entire bottom surface during the first two minutes was 0.95 $Btu/ft^2/s$ for the 1,600° F flame, and

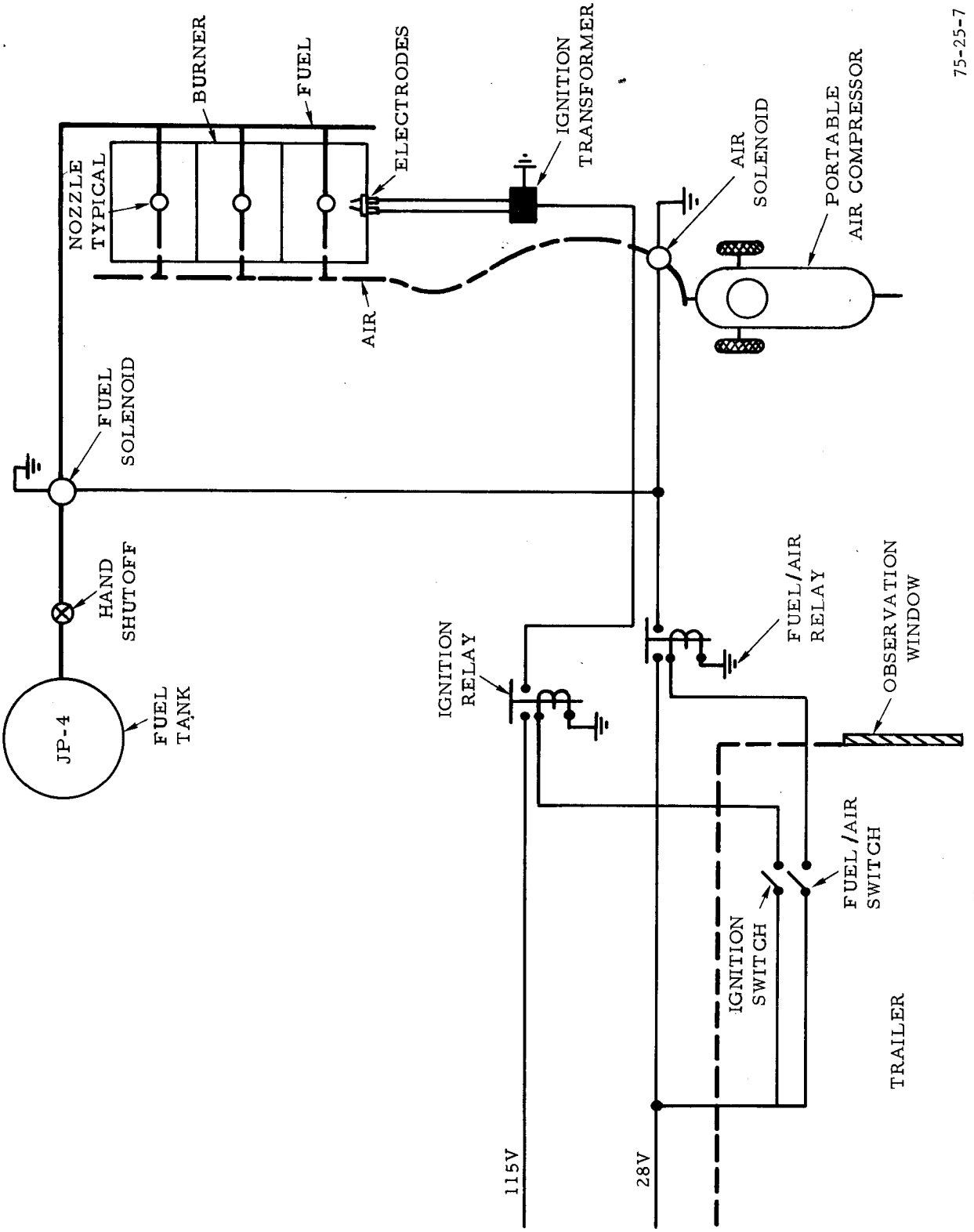


FIGURE 4. SMALL-SCALE BURNER SCHEMATIC

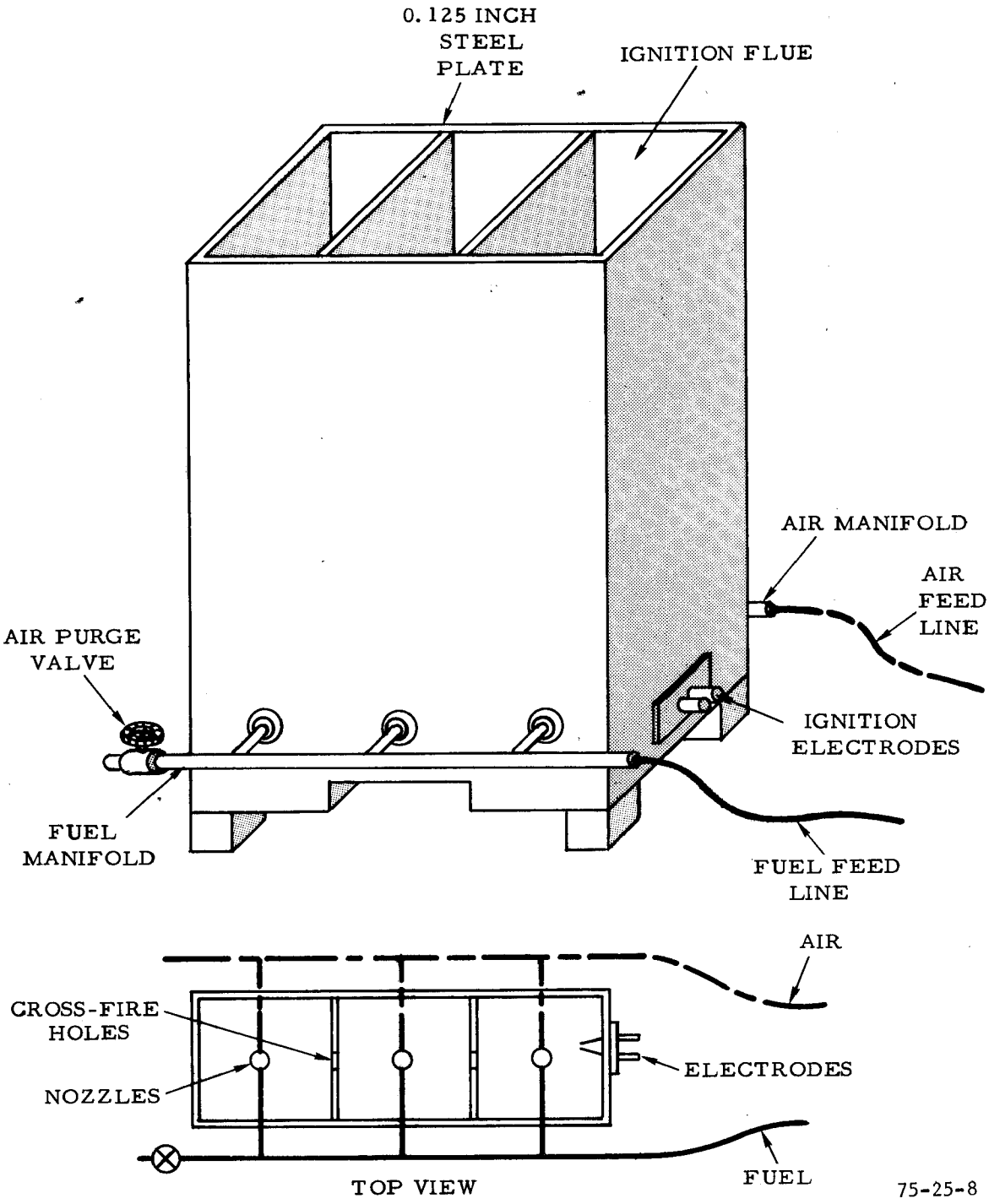


FIGURE 5. SMALL-SCALE BURNER ASSEMBLY

1.1 Btu/ft^2/s for the 2,000° F flame. For the next two minutes the average was 1.37 Btu/ft^2/s for the 1,600° F flame and 1.79 Btu/ft^2/s for the 2,000° F flame.

The Btu input into the tank increased with time as the burner and tank heated up.

TEST INSTRUMENTATION.

HYDROCARBON CONCENTRATION MEASUREMENTS. The hydrocarbon content of the vapor in the ullage of the test tank was measured by drawing a vapor sample through a modified Mine Safety Appliance LIRA® model 300 infrared analyzer (figure 6). This analyzer operated on the principal of infrared absorbtion and examined the infrared spectra of the components in the sample stream to locate an infrared absorbtion band unique to hydrocarbons. The analyzers were calibrated to analyze aviation turbine fuel, type A, from zero to 6 percent by volume in air. This calibration was periodically checked during the test program by flowing a 30 percent ethane-in-nitrogen calibration gas through the sampling system and observing the instrumentation for correct analyzer response.

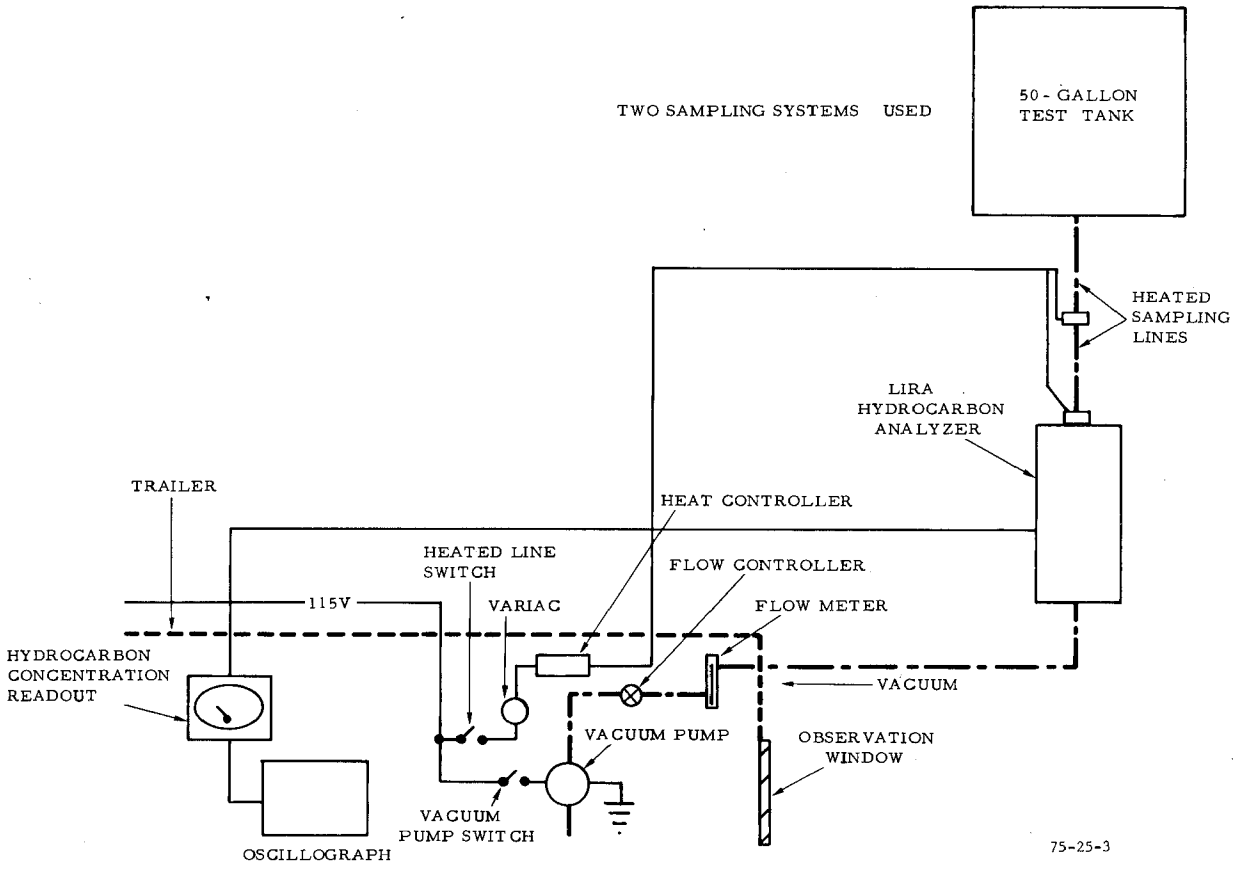


FIGURE 6. HYDROCARBON CONCENTRATION ANALYZER SCHEMATIC

Normally, this analyzer operates at atmospheric pressure or above, with the analyzer cell block heated to a temperature of 158° F. However, to enable measurement of higher volumetric concentrations than normally possible with this unit, the analyzers were modified by increasing the cell temperatures to 180° F and reducing operating pressures to half an atmosphere (approximately 8 lb/in^2 absolute). To assist in maintaining proper cell temperatures, the analyzers were housed in an insulated equipment case, internally heated to a temperature of 135° F. Approximately 12 feet separated the analyzers and the test article.

Hydrocarbon sampling system flow was produced by creating a partial vacuum in the system created by a pump installed in the instrumentation trailer. After being withdrawn from the tank ullage the vapor samples passed through electically heated 0.125-inch diameter lines to the analyzers. These lines were heated to 250° F to prevent the vapor from condensing out before reaching the analyzers. A flow rate of 200 cubic centimeters per minute through the sampling system was determined to be a prerequisite for accurate analyzer operation. This flow was regulated by pre-adjusted metering valves installed inside the test article at the inlet of the sample lines. The required operating pressure (8 lb/in^2 absolute) was maintained by an adjustable subatmospheric pressure regulator, located in the instrumentation trailer.

Once the vapor samples had passed through the analyzers, condensation would occur due to the rapid cooling of the sample stream. To prevent this liquid fuel from entering the flow control components in the trailer, traps were installed in the system downstream from the analyzers. From the traps, the sample passed through the vacuum pump to ambient. Output signals from the LIRA® analyzers and all other data-producing components described in this segment of the report were recorded on a Honeywell Visicorder® Oscillograph, model 1108. This is a direct-reading oscillograph that simultaneously records up to 24 channels of data at frequencies from direct current (d.c.) to 5,000 cycles per second (Hz). A record speed of 0.5 inches per second was normally used throughout the entire inerting test program.

Hydrocarbon concentration measurements were discontinued approximately half way through the small-scale test program. A varnish-like deposit formed in the flow-metering valves during the small fuel quantity tests when tank lower skin temperatures exceeded 400° F. This deposit clogged the valves, preventing proper sample flow and causing erroneous analyzer readings. It was decided to discontinue measurements during this phase of testing and reactivate them during large-scale testing when this condition would not be present.

OXYGEN CONCENTRATION MEASUREMENTS. Volumetric oxygen concentrations within the ullage of the test tank were monitored and recorded during the entire test program (figure 7). Vapor samples drawn from this area were directed to two Beckman® model 715 process oxygne sensors. These instruments were the same as those used on the DC9 test program. The volumetric oxygen concentration of the vapor sample passing through the sensors was measured by the diffusion of sample oxygen content through a gas-permeable membrane exposed to the sample stream.

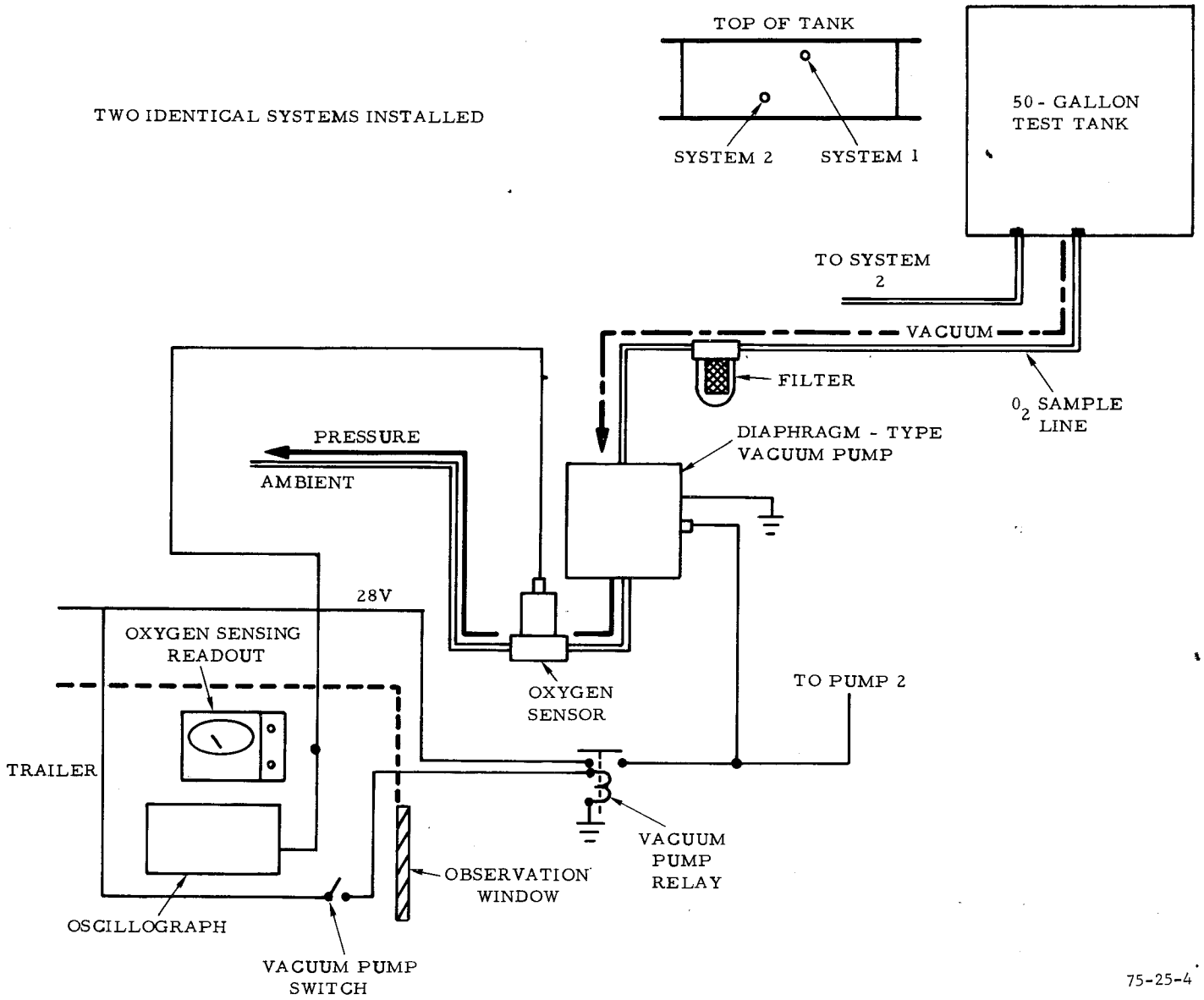


FIGURE 7. OXYGEN-MEASURING SYSTEM SCHEMATIC

This resulted in an electro-chemical reaction within the sensor, producing a current flow proportional to the partial pressure, and, therefore, the concentration of oxygen in the sample. The output signal from the sensors was amplified and read directly in volumetric percentage on an indicator in the instrumentation trailer and also recorded on the oscillograph. Originally, sampling system flow pattern was arranged to direct the vapor samples to the sensors under a partial vacuum, utilizing the hydrocarbon measurement system sampling lines. However, this method proved impractical, and the oxygen sampling system was made independent of the hydrocarbon system. This was accomplished by installing two vacuum pumps in the oxygen sampling lines between the test tank and the sensors. The sample was withdrawn from the tank by the partial vacuum created by these pumps and directed to the sensors from the pressure side of the pumps. Fuel traps located upstream of the pumps prevented liquid fuel from entering the pumps and the sensors. After passing through the sensors, the vapor samples were exhausted to ambient. The sensor outlets were not restricted, consequently, no pressure build up occurred in the sensor lines.

TEST TANK INTERNAL PRESSURE MEASUREMENTS. Internal pressure within the tank cavity was constantly measured and recorded during the small-scale tests (figure 3). Two Statham transducers were connected to the tank ullage by 0.250-inch diameter copper tubes approximately 5 feet in length. The transducers were encased in an instrumentation wire carrier that protected them from the heat radiating from the fire in the burner assembly. Output signals from the transducers were transmitted to two signal-conditioning modules for amplification and then to the oscillograph. No direct readout instrumentation was used to monitor pressure build up.

INTERNAL TANK TEMPERATURE MEASUREMENTS. The temperatures of the tank lower skin, the ullage, and, when possible, the fuel were constantly monitored and recorded during the entire small-scale test phase. Chromel/Alumel type-K Ceramo thermocouples were secured to the tank bottom plate to monitor skin temperature (figure 8). Ullage thermocouples, identical in type, were arranged so as to indicate the temperature of the vapor space at various levels above the tank floor. Fuel temperature-sensing thermocouples were also identical type and were mounted 0.250 inch above the tank floor. This height enabled fuel temperature measurement only at the higher fuel quantities, so during the majority of tests they sensed ullage temperatures. All skin temperatures mentioned in this report were internal to the test article. Approximate locations of all thermocouples are shown in figure 8. Thermocouple output signals were directed to a thermocouple amplifier in the instrumentation trailer. This instrument eliminated the need for an external cold junction-compensating network and also provided seven measurement ranges. Temperature information was recorded on the Honeywell oscillograph, and direct readout information was attained utilizing a temperature-indicating meter connected to the thermocouples through a rotary selector switch. This method allowed visual monitoring of the temperatures on an individual thermocouple basis.

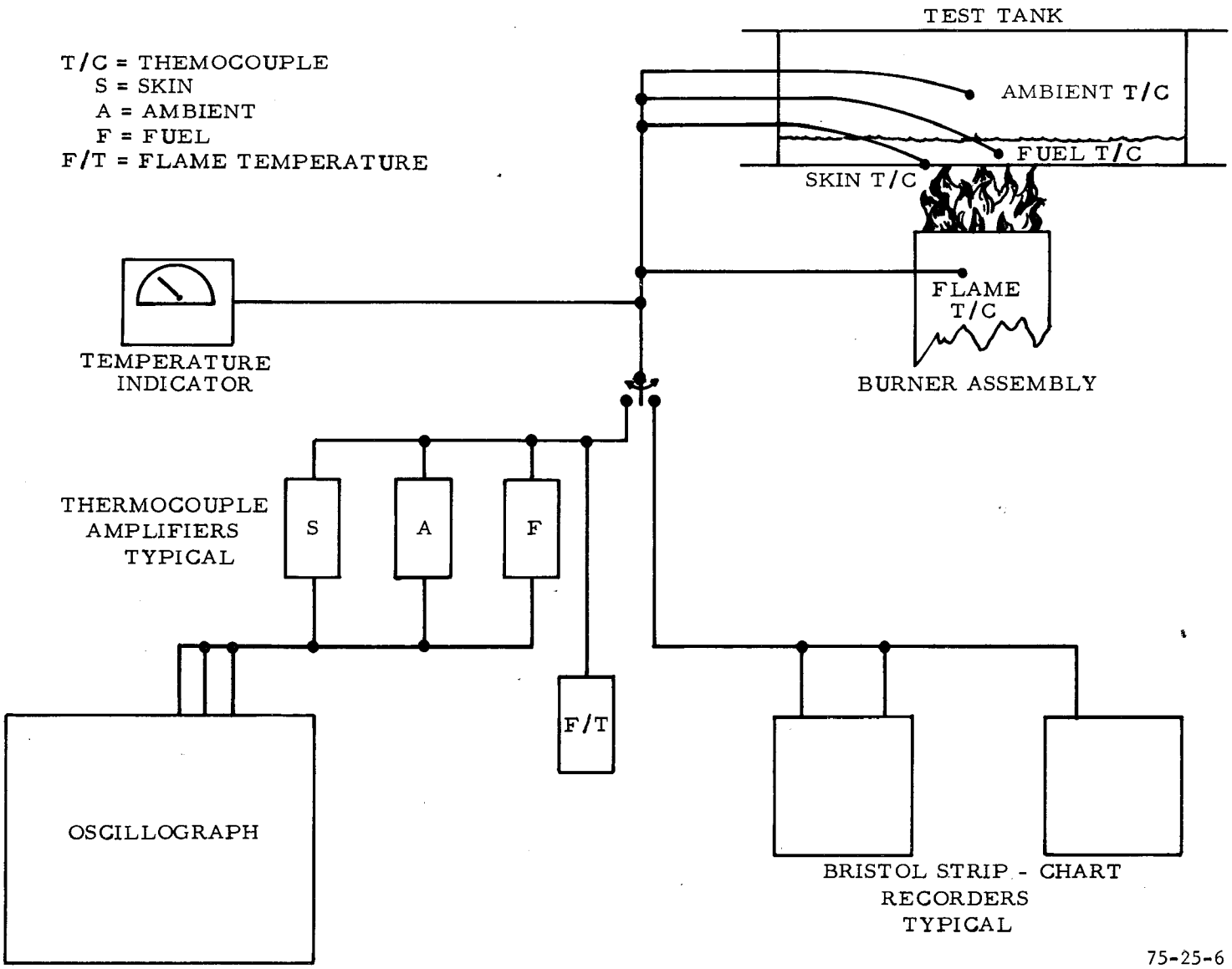


FIGURE 8. SMALL-SCALE THERMOCOUPLE SCHEMATIC

FIRE-DETECTION INSTRUMENTATION. Three Clairex model CL603 photo-conductive cells and one Fenwal fire detector provided flame detection in the test tank (figure 2). All units operated on the principal the detection of infrared radiation.

One photocell surveyed the area of the internal tank ignition spark and the remaining two were installed to observe the entire ullage of the tank. The Fenwal detector was inserted in the tank wall 90° from the photocells and therefore, observed the same area, but from a different angle. Photocell power was provided by two "D" cell batteries located in a control box in the instrumentation trailer. Their output signals were directed back to the Honeywell oscillograph in the trailer. The Fenwal detector was powered by a 28-Vd.c. output signal directed to a red indicator light on the trailer control panel. A test switch installed in the detector circuit provided a rapid check of system operation.

DISCUSSION AND RESULTS (SMALL-SCALE)

BASELINE TESTS.

A series of "baseline" tests were run varying the quantity of fuel (10-percent full (5 gallons), 30-percent full (15 gallons), and 80-percent full (40 gallons)); the burner flame intensity (1,000° F, 1,300° F, 1,600° F, and 2,000° F); and initial fuel temperature. These tests were designed to show variations in oxygen concentration, and fuel vapor concentration when an intact-fuel tank was exposed to a ground fuel fire. All the baseline tests were run using Jet "A," sample 5 as the test fuel (see appendix).

A 1.5 lb/in^{2}g check valve was installed in the vent for all the baseline tests (this valve was removed and not used for other test series except where noted). The tank was inerted with nitrogen until the oxygen concentration was reduced to near zero (except in a few cases where 21 percent O_2 at the start of the test was used). The tests were terminated when the fuel vapor/air mixture became overrich or the pressure in the tank began to rapidly rise. On occasion, rapidly boiling fuel caused a rupture of the blowout panel (this occurred even when the check valve was not installed). Even though the oxygen concentration in the tank was near zero when the tank ruptured, a fuel mist emanated, forming a large cloud over the tank, which on occasion was ignited by the ground fire, and producing a large fireball.

Table 1 shows a list of tests run in this series. The larger the quantity of fuel the lower the fuel temperature at which time the mixture became overrich. Since the fuel contained dissolved oxygen the O_2 increased in the tank when heated. The larger the quantity of fuel the greater the amount of O_2 released into the ullage. The only difference the elevated fuel tank temperatures at the test start made was to reduce the test time.

TABLE 1. BASELINE TEST DATA

	Burner Flame Temperature °F	Fuel Quantity Gallons (Jet "A", Sample 5)	Initial Fuel Temperature °F	Final Fuel Temperature °F	Oxygen Concentration Initial Percent By Volume	Oxygen Concentration Final Percent By Volume	Hydrocarbon Concentration Initial Percent By Volume	Hydrocarbon Concentration Final Percent By Volume	Test Time Min/Sec
	2,000	40	73	321	0.50	8.5	0.54	11.0	20:29
	2,000	40	105	324	0.83	8.5	0.84	10.5	18:58
	1,600	40	40	249	0.92	9.2	0.11	†	21:31
	1,000	40	55	258	1.0	12.4	0.13	7.7	49:00
	1,000	40	176	302	6.5	12.0	1.40	9.2	25:29
	1,000	40	57	241	0.42	4.5	0.0	8.5	33:00
*	2,000	15	102	419	1.0	1.4	0.20	12.2	11:39
	2,000	15	63	412	0.7	1.7	0.10	6.1	14:12
	2,000	15	188	385	1.0	1.4	2.20	7.3	8:40
	2,000	15	140	371	0.6	1.6	1.10	11.2	9:12
	2,000	15	109	410	1.8	2.3	0.33	6.9	10:32
	1,600	15	172	318	3.2	3.5	4.10	6.2	5:39
	1,600	15	135	370	3.7	4.2	1.60	5.9	7:48
	1,600	15	70	436	1.3	1.1	0.20	8.1	10:58
	1,600	15	88	349	4.3	4.5	1.40	5.8	9:00
	1,600	15	63	409	0.8	2.0	0.10	7.5	15:58
	1,300	15	183	340	1.8	2.5	1.8	11.1	19:05
	1,300	15	42	320	0.5	0.9	0.10	6.4	18:59
	1,300	15	143	248	0.7	1.3	1.0	17.6	13:45
	1,300	15	107	359	1.0	2.1	0.40	6.9	17:56
	1,000	15	59	308	0.9	1.3	0.10	6.6	21.15
	1,000	15	97	385	0.4	10.0	0.20	†	33:15
	1,000	15	145	332	2.8	4.0	0.90	5.7	15:52
	1,000	15	180	341	1.3	2.3	1.0	†	12:50
	2,000	5	190	419	0.8	1.0	1.90	6.5	6:39
	2,000	5	66	419	1.0	1.3	0.0	10.6	10:28
	2,000	5	150	419	0.9	0.9	0.80	18.8	8:15
	2,000	5	108	418	0.9	0.9	0.30	12.2	6:48
*	1,600	5	64	153	21.0	21.0	0.18	2.0	5:18
	1,600	5	183	406	2.3	2.4	1.60	6.8	8.19
	1,600	5	154	403	2.0	2.1	1.30	7.0	8.19
	1,600	5	72	268	21.0	15.2	0.0	11.5	5:44
	1,600	5	94	410	2.6	2.8	0.20	7.6	8:40
	1,600	5	61	406	0.9	1.2	0.0	7.2	12:01
	1,600	5	183	400	0.8	0.8	0.11	†	6:00
	1,600	5	72	238	0.0	0.58	0.43	76.3	6:20
	1,600	5	47	366	21.0	20.8	0.18	27.4	6:48
	1,600	5	81	332	20.8	20.4	0.38	†	5:59
	1,600	5	84	371	17.6	16.8	0.36	3.5	6:30
	1,600	5	59	386	20.8	20.0	0.0	8.5	9:11
	1,300	5	102	411	0.0	0.0	0.45	5.89	10:07
	1,300	5	182	400	2.5	2.5	2.90	6.2	8:20
	1,300	5	137	403	0.7	1.5	0.90	11.0	7:27
	1,300	5	173	350	2.4	2.3	3.10	5.8	6:17
	1,000	5	173	378	0.7	0.7	2.30	7.8	18:30
	1,000	5	90	328	0.8	0.5	0.20	7.4	11:18
	1,000	5	146	367	2.0	2.0	1.00	7.1	10:31
	1,000	5	70	394	0.3	0.6	0.0	6.9	14:22
	1,000	5	75	246	0.0	0.83	1.20	10.0	7:34

† ~ Denotes Off Upscale
* ~ Denotes Rupture Of Blowout Panel

HOT-SURFACE IGNITION TESTS.

A series of tests was run to determine: (1) the characteristics of hot-surface ignition in an uninerted fuel tank, and (2) the minimum nitrogen inerting (expressed in oxygen concentration) which would prevent hot-surface ignition.

All tests in this series utilized Jet-A type fuel (sample 5 in the appendix). Because of the time consumed in changing the tank bottom skin after a burn-through, the majority of tests were run using a stainless steel bottom. A few specified tests were run using aluminum bottoms to verify the result of the tests using steel. A partial listing of tests run in this series is shown in tables 2 and 3. It should be noted that although this is a partial listing of hot-surface ignition tests (test runs for which all data are not available have been omitted, e.g., 0_2 sensor failure during test, thermocouple failure, burner failure, or partial failure); in all, over 50 tests were run and there were no test results conflicting with those shown in tables 2 and 3.

Tests were run, first varying the burner temperature (1,600° F and 2,000° F), then the fuel quantity (8 to 3/4 ounces), and finally the oxygen concentration (from 21 to 10.5 percent). The following results were obtained from this test series:

When the test article containing fuel quantities greater than 1 ounce was rapidly heated with the 2,000° F flame, an explosion (rupture of the blowout panel) occurred. Figure 9 shows a comparison of results for fuel quantities of 2, 5, and 8 ounces heated with the 2,000° F flame. Note that although the time to explosion increased as the fuel quantity increased the hot-surface ignition temperature of the bottom skin surface remained constant at approximately 500° F. For all tests run in this series using more than 1 ounce of fuel and a 2,000° F flame hot-surface ignition occurred, and it occurred with a measured bottom skin temperature between 460° F and 520° F (two skin thermocouples were used to record the internal bottom skin temperature with the highest temperature recorded used).

When the test flame was reduced to 1,800° F no explosion occurred. However, a pressure build up was noted when the bottom skin temperature reached 500° F. This was coupled with a rapid loss of 0^2 and a slight rise in ullage temperature (figure 10). When the test flame was reduced to 1,600° F, only a very slight pressure rise could be seen (in some tests none at all) with little or no drop in oxygen or rise in ullage temperature. Figure 11 shows the rate of temperature rise for which hot-surface ignition did and did not occur.

In order to properly evaluate what was occurring during these tests, fuel vapor samples were taken from the ullage of the tank just prior to the skin temperature reaching 480° F under various heating rates. The samples were then analyzed using an infrared spectrophotometer to identify chemical compounds in the fuel/air ullage mixture. Figure 12 represents a comparison of compounds identified in the ullage when 2 ounces of Jet A, and an 0_2 concentration of 21 percent were heated by the 2,000° F and the 1,600° F flame. A strong concentration of methane and acetylene was noted in the exploding tank whereas these were replaced by carbonyl and alkene in the nonexploding tank. This

TABLE 2. HOT-SURFACE IGNITION TESTS, STAINLESS STEEL BOTTOM

Test Number	Flame Temperature (°F)	Fuel Quantity Sample 5 (Ounce)	O_2 Start (Percent) By Volume	O_2 at Reaction or End of Test (Percent by/ Volume/Time)	Reaction (lb/in^2g/Time)
12	1,600	2	21	19 @ 2 min. ~ 9 @ 8 mim.	No
13	2,000	2	21	21	Yes
14	2,000	2	21	21	Yes
15	2,000	2	21	21	Yes
16	2,000	5	21	21	Yes
17	2,000	5	21	21	Yes
18	2,000	8	21	21	Yes
20	2,000	2	10.5	10.5 @ 1 min. 20 sec. ~ 9 @ 2 min.	No
21	2,000	5	10.5	10.5 @ 1 min. 10 sec. ~ 3 @ 3 min.	No
22	2,000	2	12.5	12.50 @ 1 min. ~ 9.5 @ 3 min.	No
23	2,000	2	13.5	13.7 @ 1 min. ~ 11.5 @ 3 min.	Slight Pressure Build Up @ 40 sec.
25	2,000	2	15	15 @ 40 sec. ~ 12 @ 2 min.	0.20 @ 40 sec.
26	2,000	5	15.7	15.7 @ 1 min.~ 5 @ 1 min. 30 sec.	1.0 - Slow Reaction
27	1,600	5	21	21 @ 1 min. ~ 8 @ 9 min.	No
29	1,800	2	21	21 @ 1 min. ~ 10 @ 1 min. 30 sec.	1.0 lb/in^2g
30	2,000	2	21	21	Yes
32	1,600	2	21	21 @ 1 min. 30 sec. ~ 15.5 @ 8 min.	0.1 @ min. 10 sec.
33	2,000	2	16.3	16.3 @ 1 min. ~ 15 @ 1 min. 30 sec.	0.15 @ 40 sec.
34	2,000	2	18	18 @ 1 min. ~ 14 @ 2 min.	0.15 @ 40 sec.
35	2,000	2	21	21	Yes
36	2,000	2	18	18 @ 50 sec.	0.15 @ 40 sec.
37	2,000	1	18	18 @ 1 min.	0.1 @ 30 sec.
38	2,000	1	21	21 @ 1 min.	0.1 @ 40 sec.
40	1,600	3/4	21	17 @ Reaction ~ 5 min. 20 sec.	Yes
41	1,600	3/4	21	17 @ Reaction ~ 6 min. 20 sec.	Yes
42	1,600	3/4	21	20 @ Reaction ~ 2 min. 45 sec.	Yes:2 @ 30 sec.

TABLE 3. HOT-SURFACE IGNITION TESTS, ALUMINUM BOTTOM

Test Number (-)	Flame Temperature (°F)	Fuel Quantity Sample 5 (Ounce)	O_2 Start (Percent) By Volume	O_2 at Reaction or End of Test (Percent by/ Volume/Time)	Reaction (-)
71	2,000	5	21	21 1 min. 10 sec.	Yes
72	2,000	5	21	21 1 min. 10 sec.	Yes
NT45	2,000	2	21	21 1 min.	Yes
NT46	2,000	2	21	21 45 sec.	Yes
NT47	2,000	2	13.8	Burn-through	-
NT48	2,000	2	13.8	Burn-through	-
NT49	Slow Heat	2	21	Burn-through	-
NT50	2,000	2	21	21 55 sec.	Yes

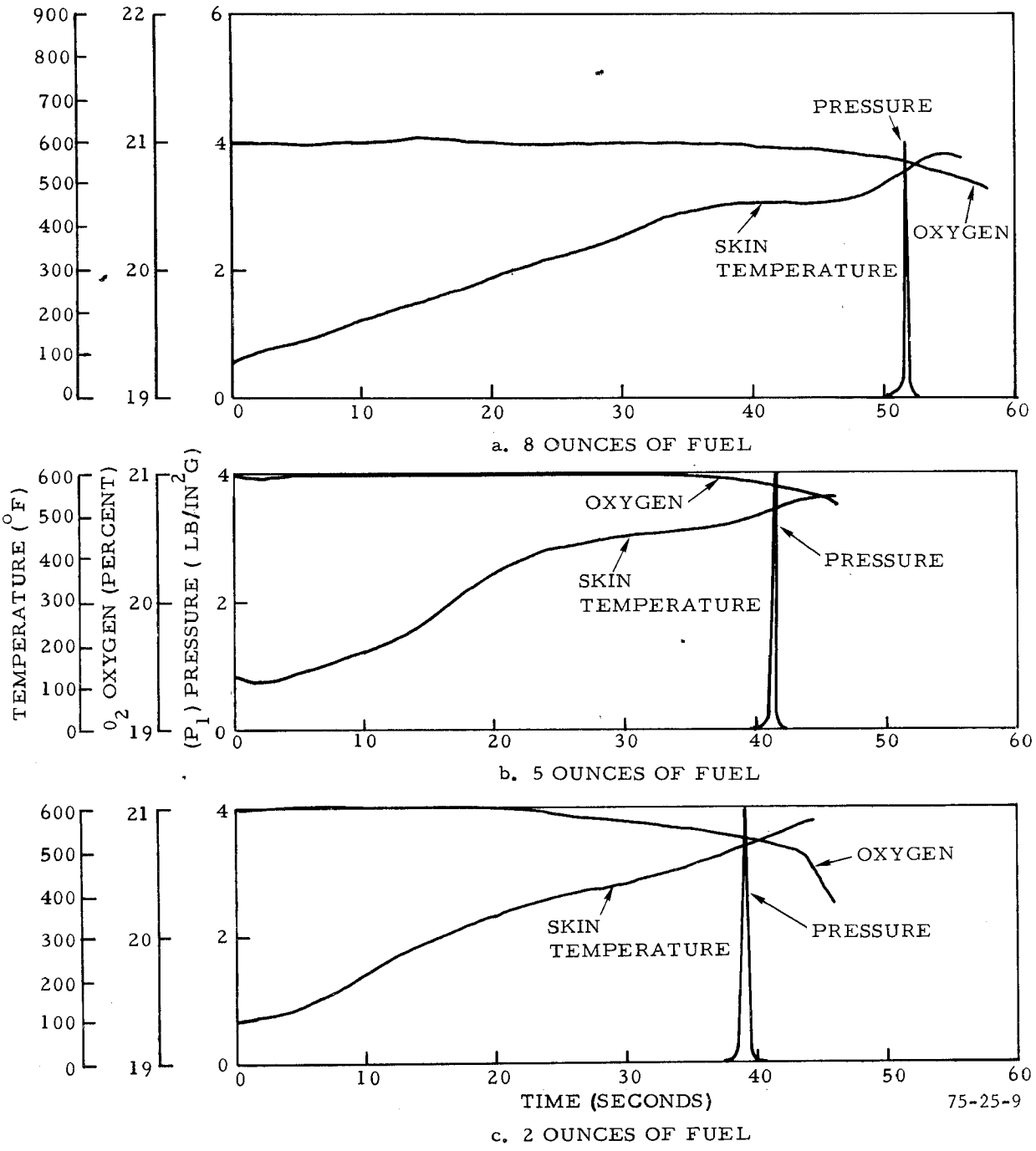
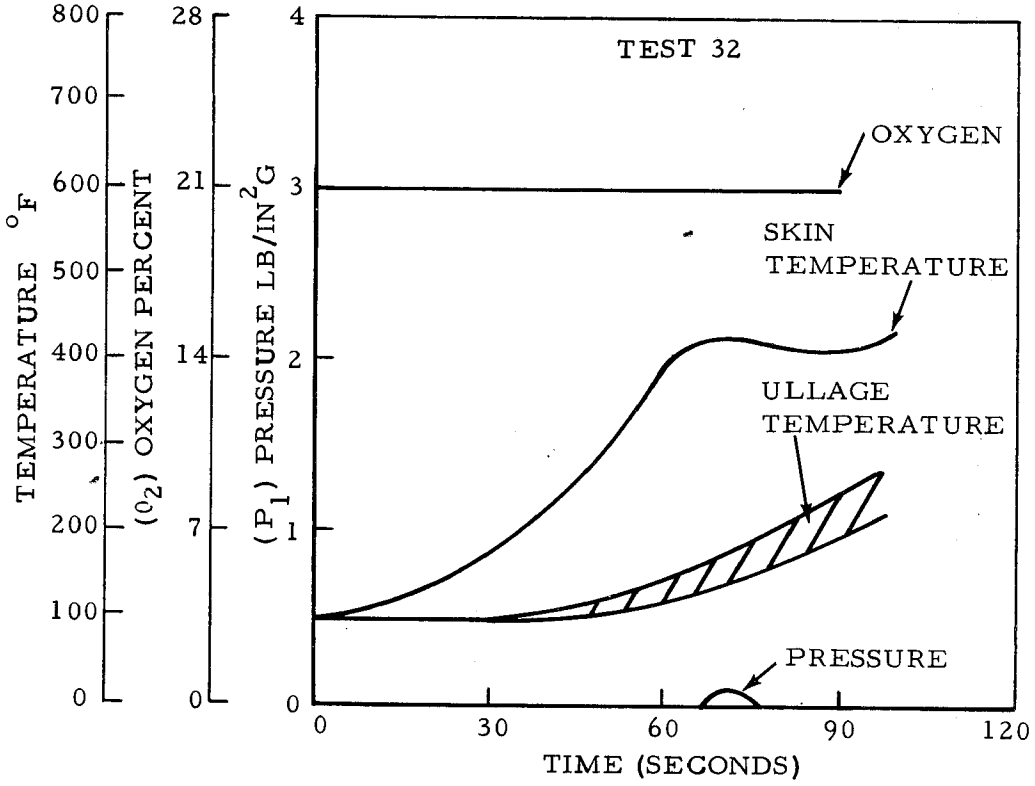
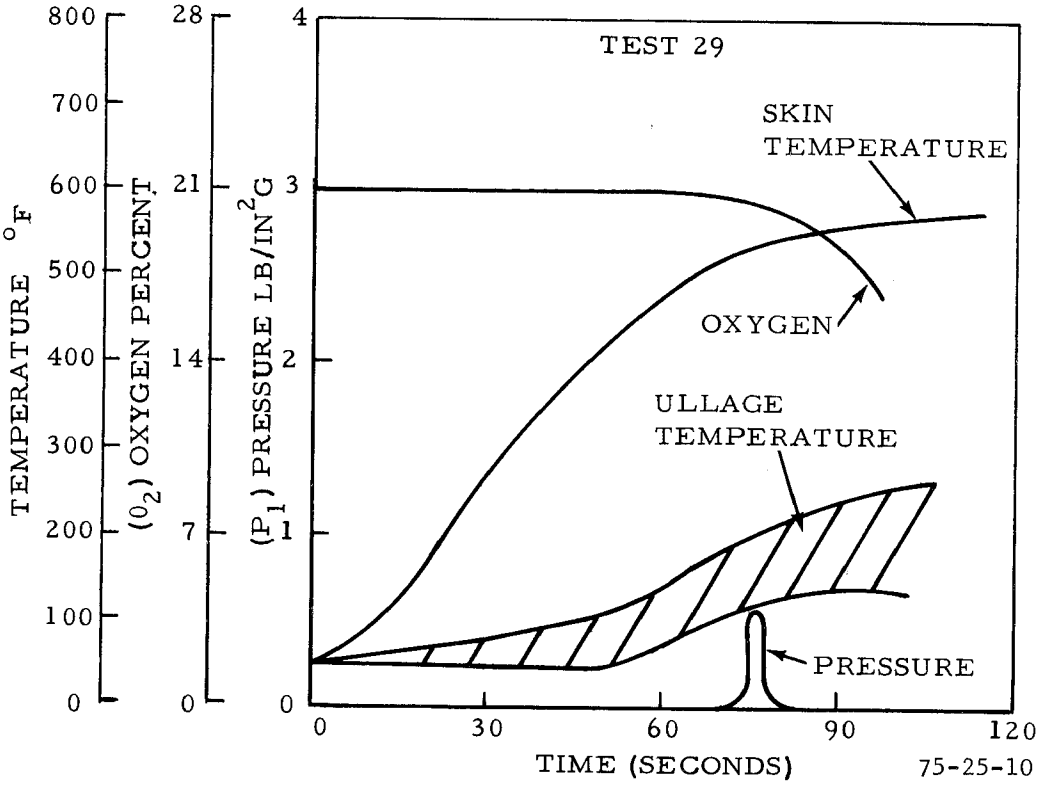


FIGURE 9. EFFECTS OF HEATING VARIOUS SMALL QUANTITIES OF JET "A" TYPE FUEL



a. 1600°F FLAME



b. 1800°F FLAME

FIGURE 10. RELATION OF HOT-SURFACE IGNITION TO FLAME INTENSITY

seemed to indicate that when the tank was heated at the slower rate, the hydrocarbons combined with the oxygen in the tank thus tending to prevent an explosion from hot-surface ignition (a 2-joule spark, internal to the tank, would cause an explosion in either case, as will be shown in a later series).

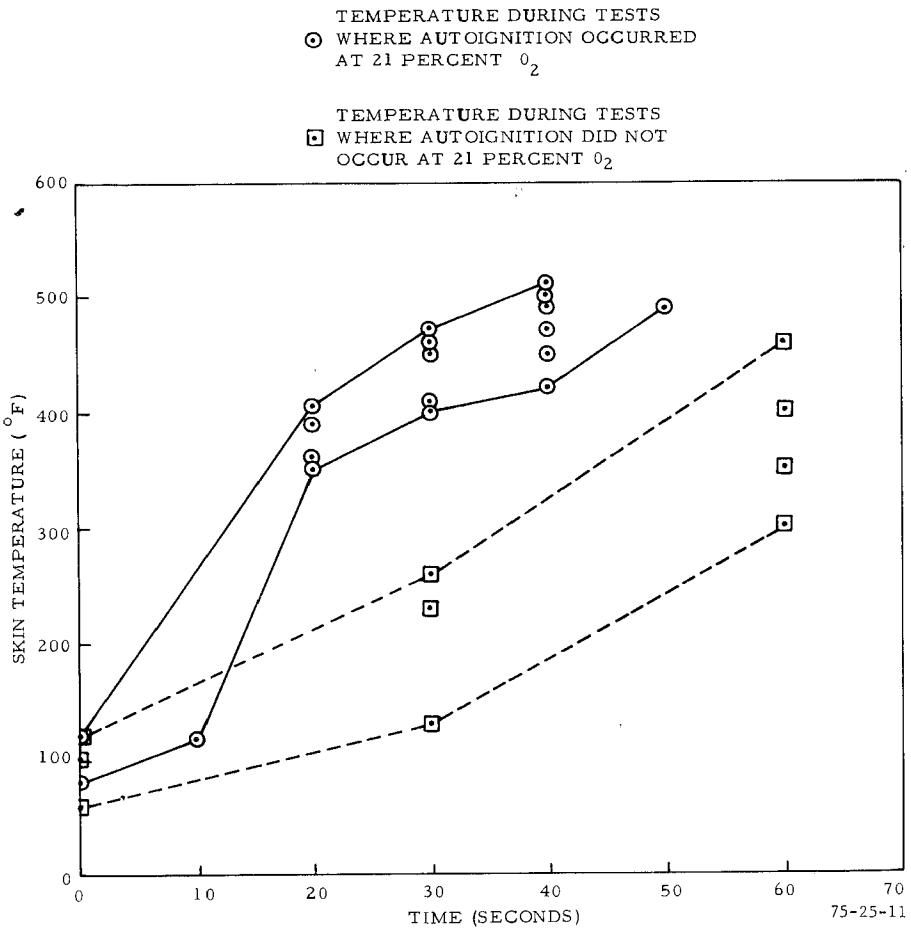


FIGURE 11. AUTOIGNITION AS A FUNCTION OF RATE-OF-RISE OF SKIN TEMPERATURES

It was also noted during the lower temperature tests (1,600° F and 1,800° F) that after the bottom skin temperature reached approximately 500° F, the oxygen concentration in the tank began to drop (figure 13). This could also be explained by the oxygen in the ullage combining with the cracked hydrocarbons from the fuel forming various compounds (a slow oxidation process). This slow oxidation process could also be seen in inerted tests where an explosion from hot-surface ignition did not occur and the bottom skin temperature was allowed to go above 500° F.

With a little insight into the characteristics of the hot-surface ignition phenomenon, tests were begun to determine the amount of nitrogen inerting needed to suppress an explosion and/or reaction from hot-surface ignition in an aircraft fuel tank during a post-crash fire.

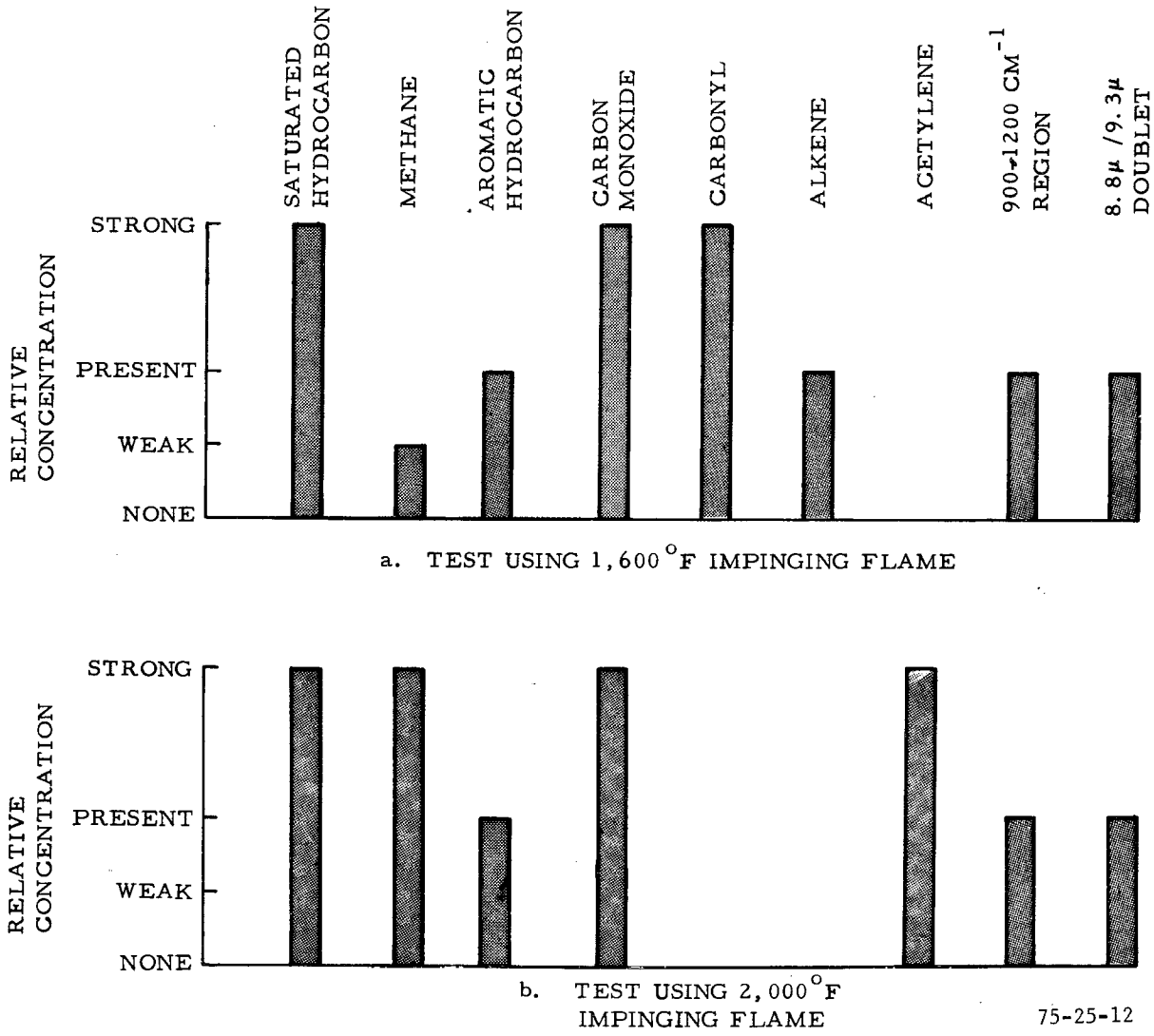


FIGURE 12. INFRARED SPECTROPHOTOMETRIC IDENTIFICATION OF ULLAGE VAPOR FOR TWO HEATING RATES

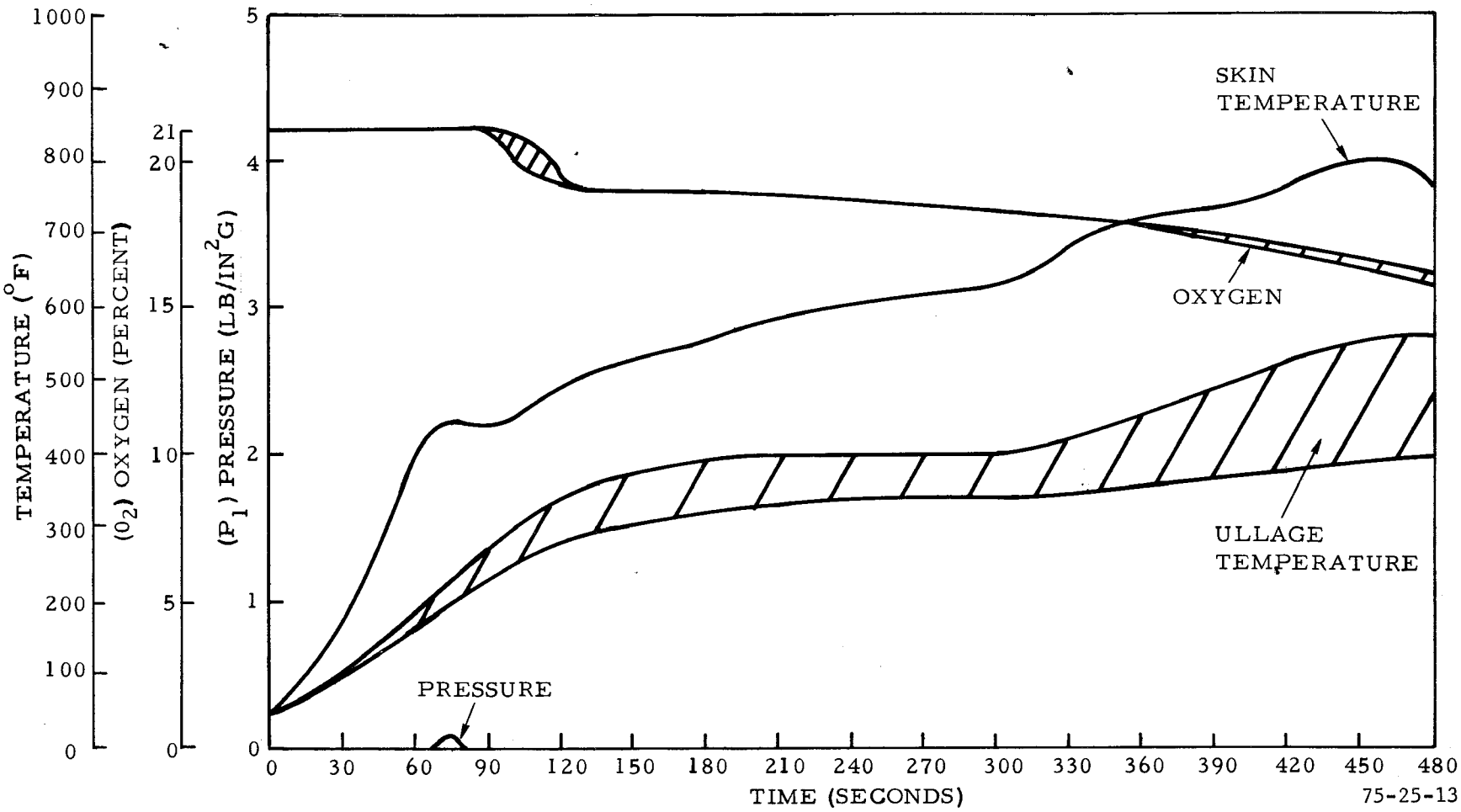


FIGURE 13. OXYGEN DEPLETION AT ELEVATED TEMPERATURE

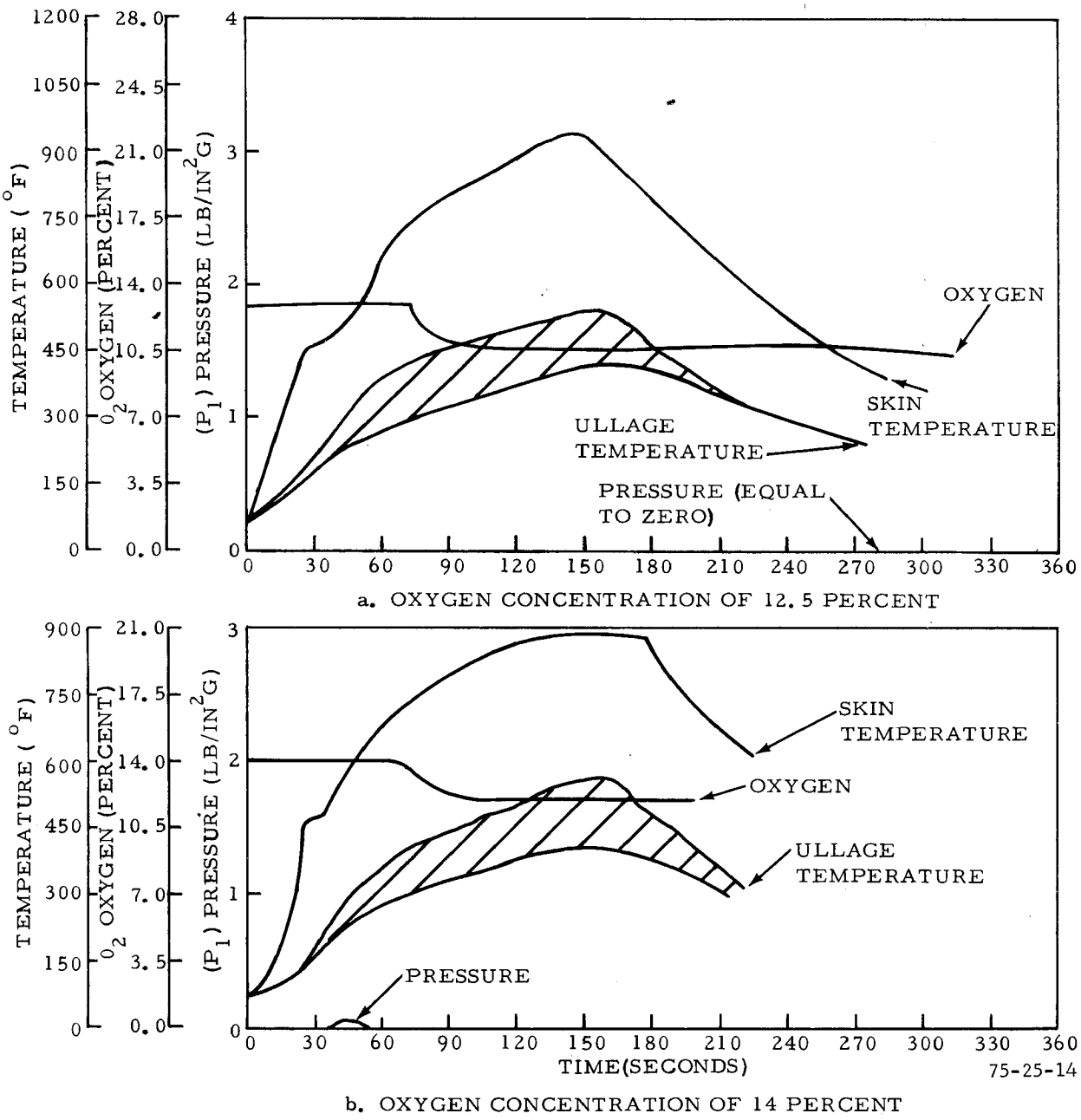


FIGURE 14. OXYGEN CONCENTRATION LIMITS FOR HOT-SURFACE IGNITION

The lowest oxygen concentration at which a reaction (a reaction is hereby defined as a pressure build up of at least 0.01 lb/in^2g caused by oxidation) occurred due to hot-surface ignition was 14.0-percent O_2 (figure 14). There was no reaction when the O_2 concentration was lowered to 12.5 percent O_2 (figure 14). Although reaction occurred with an oxygen concentration as low as 14.0 percent, no explosions (rupture of the blowout panel) could be obtained with the 2, 5, or 8 ounces of fuel when the oxygen level was lowered to 18 percent. The only explosions to occur with these quantities of fuel were at an oxygen concentration of 21 percent.

In order to study the effects of inerting at tank skin temperatures of over 500° F, smaller quantities of fuel were used (3/4-1 ounce). This allowed the test to progress past the 500° F skin temperature because the mixture was not yet rich enough to ignite. As the temperature in the ullage increased, the lean explosive limit decreased, thus creating an explosive mixture at an elevated temperature.

Hot-surface ignitions did occur during these elevated temperature tests (using a 1,600° F flame), with explosions occurring with an O_2 concentration of 17 percent. The skin temperature at the time of this explosion was 850° F and the ullage was over 600° F (figure 15). Although this explosion occurred at 17 percent O_2 it should be noted that the oxygen concentration was 21 percent at the start of the test and dropped due to the process previously described. In tests where the initial oxygen concentration was lowered to 18 percent no reaction occurred due to hot-surface ignition.

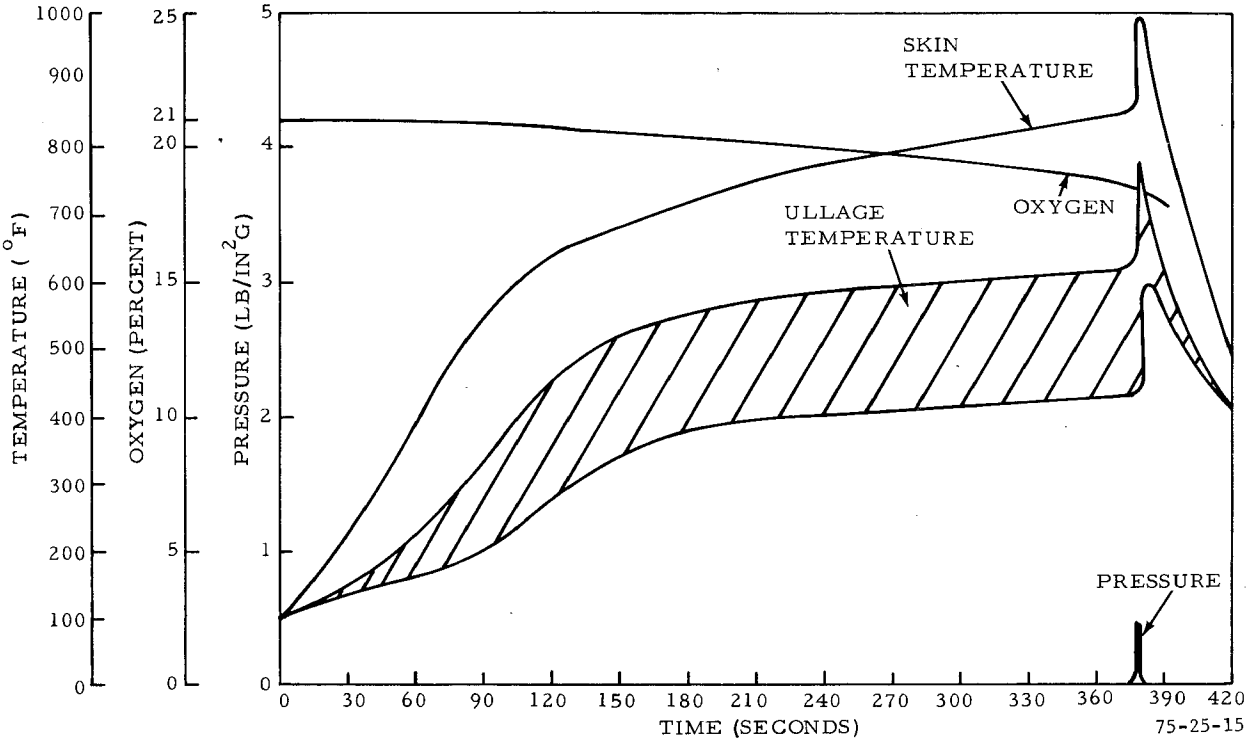


FIGURE 15. HOT-SURFACE IGNITION AT ELEVATED TEMPERATURES

Because of the self-inerting phenomenon (slow oxidation) that occurred above a skin temperature of 500° F, hot-surface ignition tests at specific O_2 concentrations and temperatures were impossible. Therefore, a number of tests were run, starting with an O_2 concentration of 21 percent and using the 2,000° F flame, to determine if hot-surface ignition would occur at lower oxygen concentrations and elevated temperatures. No hot-surface ignitions occurred below 17 percent O_2. Skin temperatures were allowed to reach the melting point of aluminum and O_2 concentrations dipped below 5 percent. The history of a typical elevated temperature test is shown in figure 16. During that test a spark ignition was activated at an O_2 concentration of 10.5 percent to show that an explosive mixture was present in the tank. At the time of the explosion the skin temperature was 1,050° F and the ullage 800° F. Similar tests had been run in which no spark was used and no reactions occurred, with the test being terminated when the O_2 concentration dropped to near 5 percent.

A curve showing the expected results of a hot-surface ignition for various O_2 concentrations is given in figure 17. Because the elevated temperature tests represent only a few out of an almost infinite number of possible tests varying O_2, temperature, rate-of-rise of temperature, and dwell time, an exact concentration of O_2 which will support an explosion at elevated temperature could not be determined. But, as will be seen in the next section, results at elevated temperatures using a spark ignitor were able to define a maximum allowable O_2 concentration, and since all tests indicated that the internal tank spark was a much more severe test than hot-surface ignition, the O_2 concentration found to protect against a spark would also protect against any hot-surface ignition.

SPARK IGNITION TESTS.

A series of tests were run to determine the maximum oxygen concentration which will not support a reaction, due to an internal tank spark during a ground fire. Table 4 is a partial listing condensed from the more than 50 spark ignition test runs. All tests shown in the table were skin temperatures of less than 600° F and ullage temperatures below 400° F, and used Jet "A" (sample 5) fuel. It was found that 4 ounces of fuel created the most hazardous condition. Tests using 6 to 8 ounces gave similar results as the 4 ounce tests, and larger quantities of fuel provided less hazardous conditions. As can be seen from table 4, a 14.3 percent O_2 concentration would not support a reaction in the tank when 2 ounces were used, but when 4 ounces were used the O_2 concentration had to drop below 12.5 percent O_2. No reaction occurred below a 12.5 percent O_2 concentration under any test conditions at these lower temperatures. Figure 18 shows a comparison of test NT6 and NT10, and figure 19 is a comparison of NT15 and NT18.

A number of elevated temperature tests were run using 3/4 ounce of Jet-A fuel as previously described in the hot-surface ignition tests. Explosions occurred with O_2 concentrations as low as 10.5 percent at skin temperatures approaching the melting point of aluminum and ullage temperatures of approximatly 800° F

TABLE 4. SPARK IGNITION TESTS

Test Number	Flame Temperature (°F)	Fuel Quantity (Ounce)	O_2 @ 1st Spark (Percent)	O_2 @ Reaction (Percent)	Reaction Press (lb/in^2g)	Reaction
NT1	2,000	2	19	19	4.3	Yes
NT2	2,000	2	14	-	-	No
NT5	2,000	2	14.5	14.5	4.3	Yes
NT6	2,000	2	14.3	-	-	No
NT7	2,000	2	16.2	16.2	2.3	Yes
NT8	2,000	2	15	14.8	4.6	Yes
NT9	2,000	2	13.1	-	-	No
NT10	2,000	2	14.4	14.4	2.7	Yes
NT11	2,000	2	14.3	-	-	No
NT12	2,000	2	13.9	-	-	No
NT13	2,000	2	14.8	14.8	3.3	Yes
NT14	2,000	4	13.9	13.9	4.1	Yes
NT15	2,000	4	12.5	12.5	0.8	Yes
NT16	2,000	4	11.4	-	-	No
NT17	2,000	4	12.5	-	-	No
NT18	2,000	2	12.3	-	-	No
NT19	2,000	4	12.5	-	-	No
NT20	2,000	4	13.5	13.5	0.5	Yes

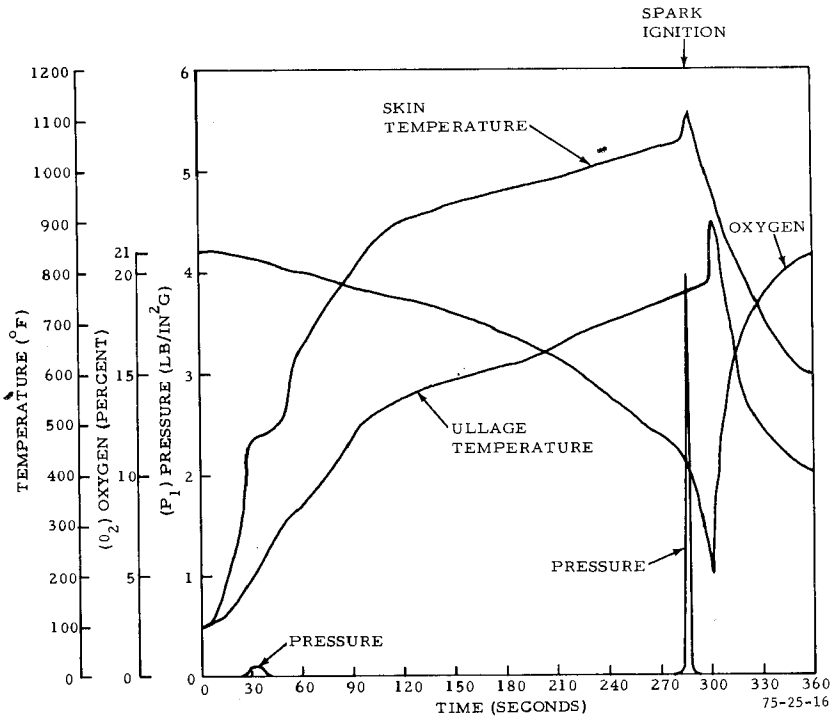


FIGURE 16. ELEVATED TEMPERATURE TESTS WITH NO AUTOIGNITION

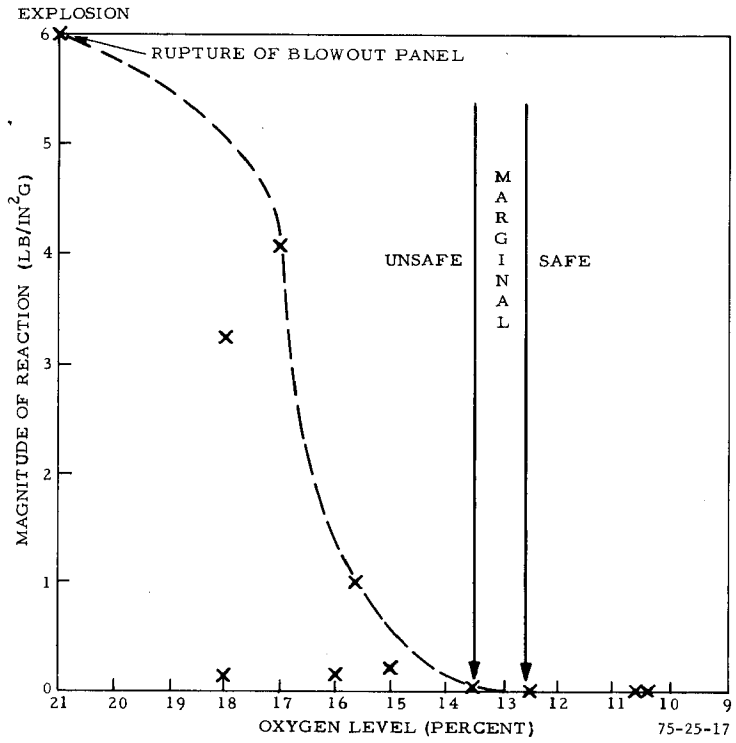
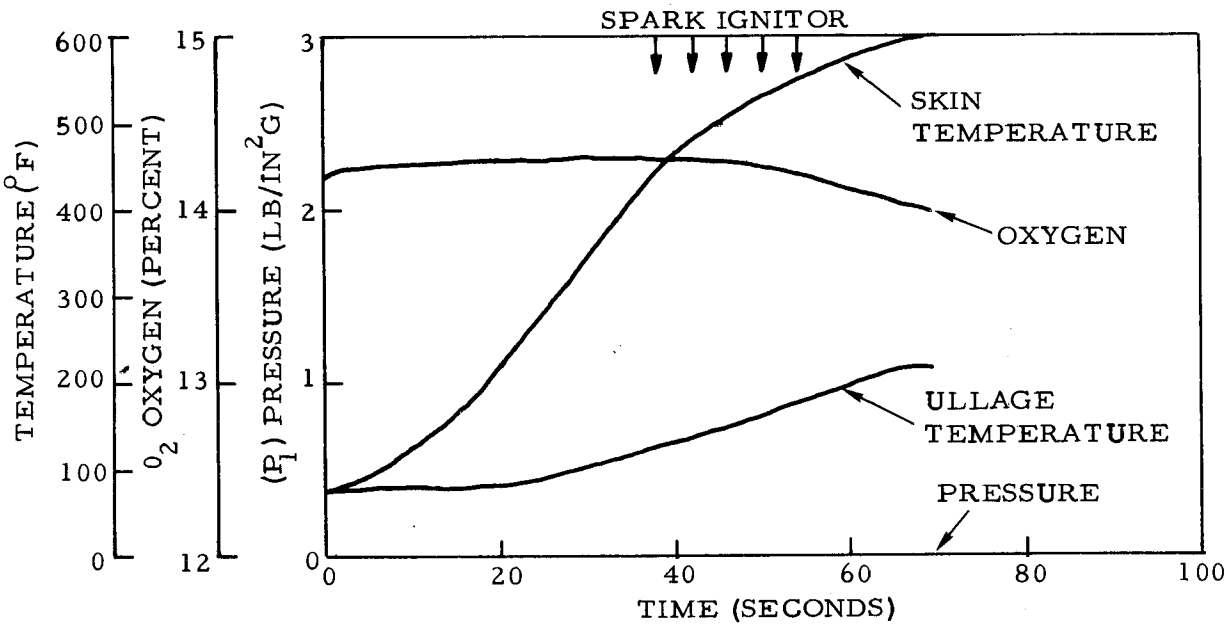
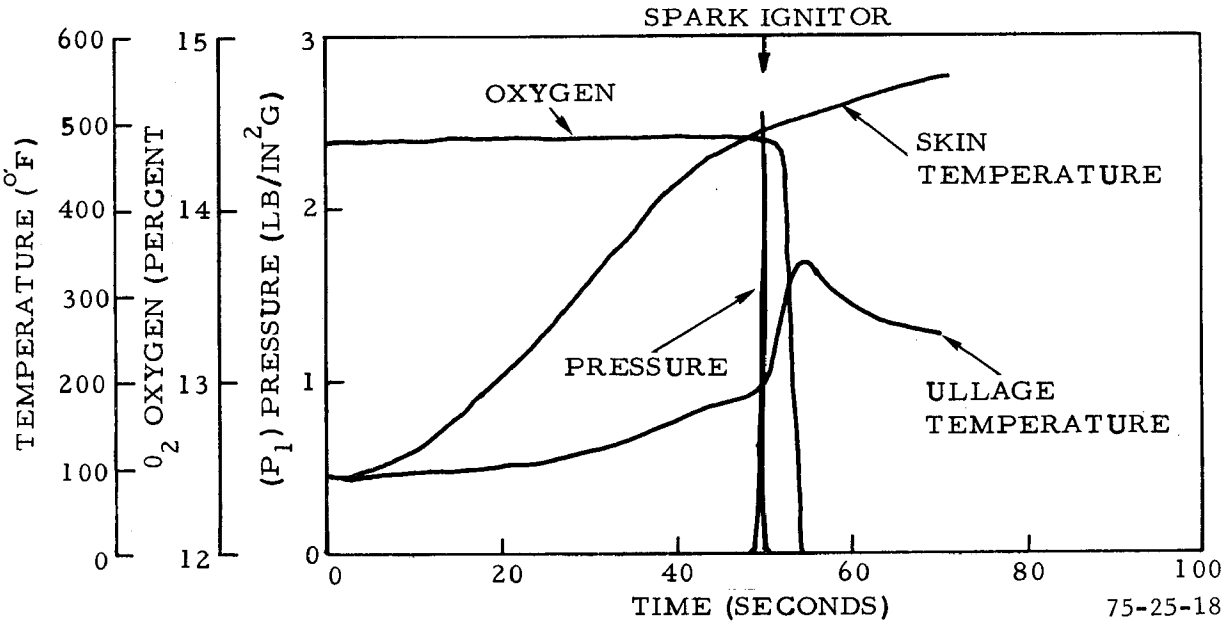


FIGURE 17. THE EFFECT OF OXYGEN LEVEL ON MAGNITUDE OF REACTION FROM AUTOIGNITION

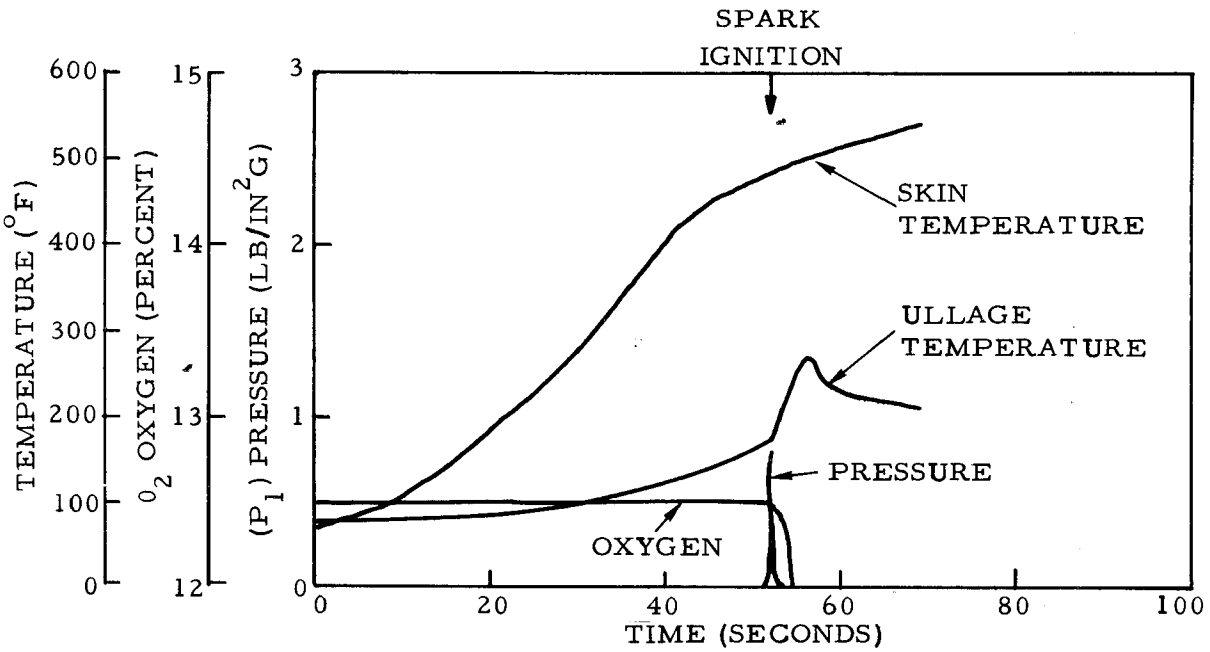


a. OXYGEN 14.3 PERCENT

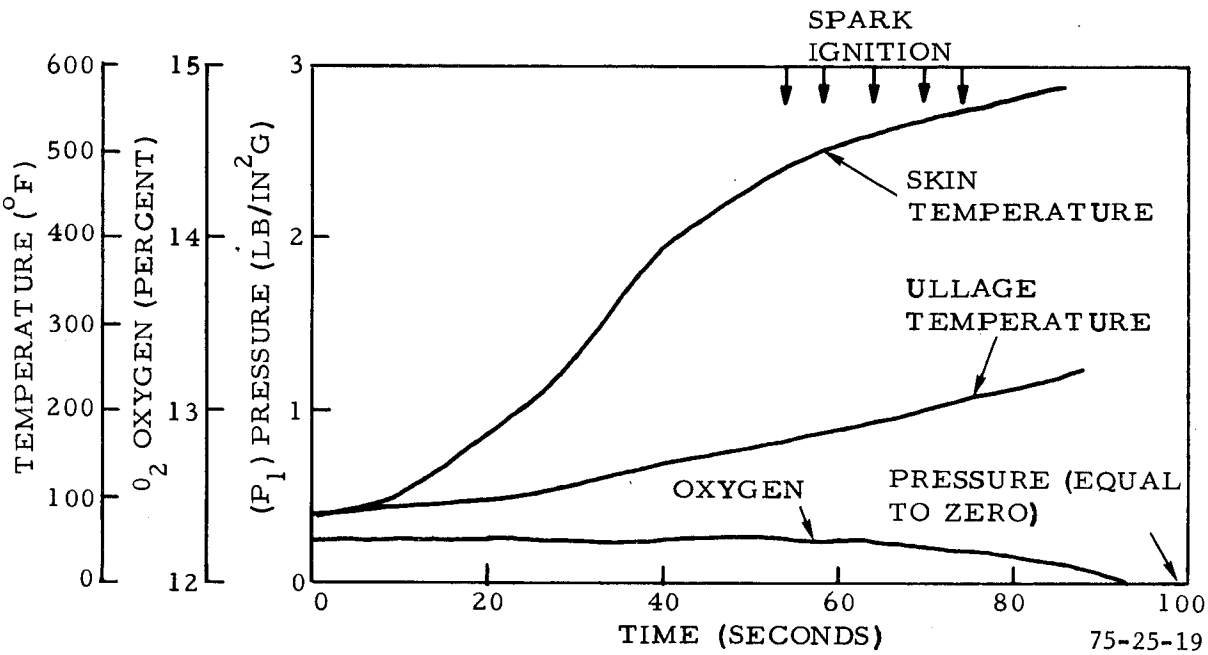


b. OXYGEN 14.4 PERCENT

FIGURE 18. OXYGEN CONCENTRATION LIMITS FOR SPARK IGNITION



a. OXYGEN 12.5 PERCENT



b. OXYGEN 12.3 PERCENT

FIGURE 19. OXYGEN CONCENTRATION LIMITS FOR SPARK IGNITION AT ELEVATED TEMPERATURES

(refer to figure 16). Reactions at these elevated temperatures could be seen at an 0_2 concentration of 10 percent. Figure 20 shows a test where a series of reactions occurred with the 0_2 concentration at 10 percent. As a reaction occurred the 0_2 was lowered below 10 percent and the reaction quenched the pressure which had risen, fell, and actually became slightly lower than ambient, thus causing air (containing 21 percent 0_2) to enter the tank. The 0_2 concentration was increased in the tank, and again a 10 percent concentration was obtained. With the spark still being activated in the tank the process repeated itself. This process repeated itself several times. During all tests no reactions were observed when the oxygen concentration was below 10 percent.

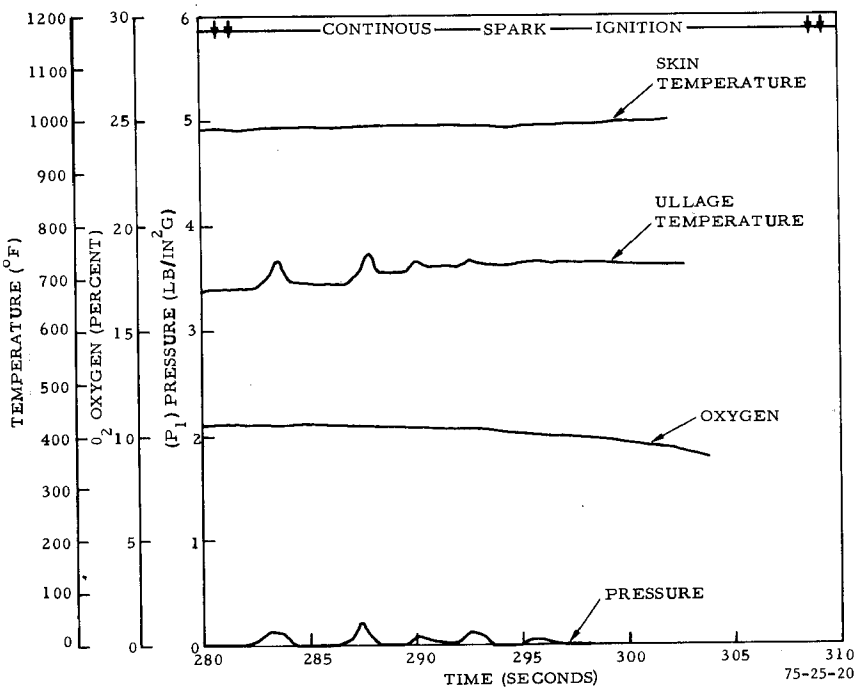


FIGURE 20. SPARK IGNITION REACTION AT 10-PERCENT OXYGEN CONCENTRATION

Figure 21 shows the expected reaction at various oxygen concentrations, due to a spark ignition of an explosive mixture of Jet-A in a fuel tank during a post-crash fire.

BURN-THROUGH TESTS.

A series of tests were run to determine the maximum oxygen concentration that would suppress an explosion due to tank burn-through. A number of burn-through tests were run using 5 gallons of fuel in the test article and having the test article tilted such that the flame impinged on both wetted and dry areas of the bottom surface. There was no difference noted between a burn-through into a tank with a 21 percent 0_2 concentration or a tank having a zero percent 0_2 concentration. Expanding gasses from the heated tank would exit the burn-through opening creating a torch-like flame. No reactions were recorded in the tank.

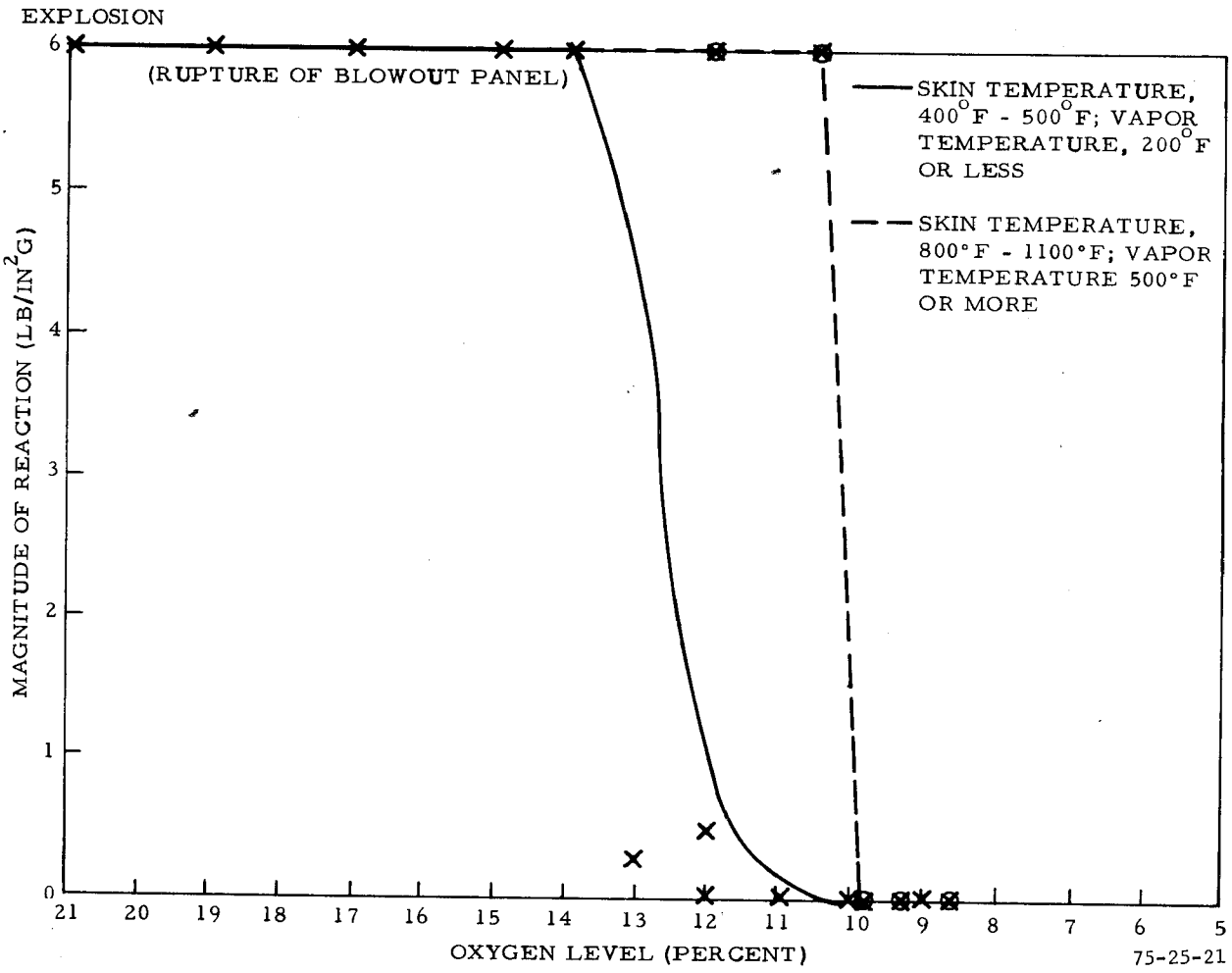


FIGURE 21. MAGNITUDE OF REACTION Vs. OXYGEN LEVEL DUE TO SPARK IGNITION

Burn-through tests were also run using a small amount of fuel (2 ounces) in order to insure an explosive mixture at burn-through. Again the results were the same with the inerted tank as with the uninerted. Figure 22 shows a comparison of results for O_2 concentrations of 21, 13.8, and zero percent. Note that in all cases there is a rise in ullage temperature, drop in O_2 (except where it is already zero) and no increased pressure. This indicates a burning in the tank but was not accompanied by a measurable pressure rise.

Since there were no reactions caused by burn-through during this test program, the only advantage, concerning burn-through, to be achieved by inerting would be to limit the burning inside the wing, after burn-through occures.

JP-4 FUEL TESTS.

Similar results were achieved when JP-4 was used in the tests in place of Jet-A. A hot-surface ignition occurred with the O_2 concentration at 21 percent, causing rupture of the tank blowout panel (figure 23). When the O_2 was lowered to 18 percent a reaction occurred but there was no rupture of the blowout panel (figure 24). A slight pressure rise was noted at an O_2 concentration of 13.4 percent due to hot-surface ignition. Using spark ignition, slight

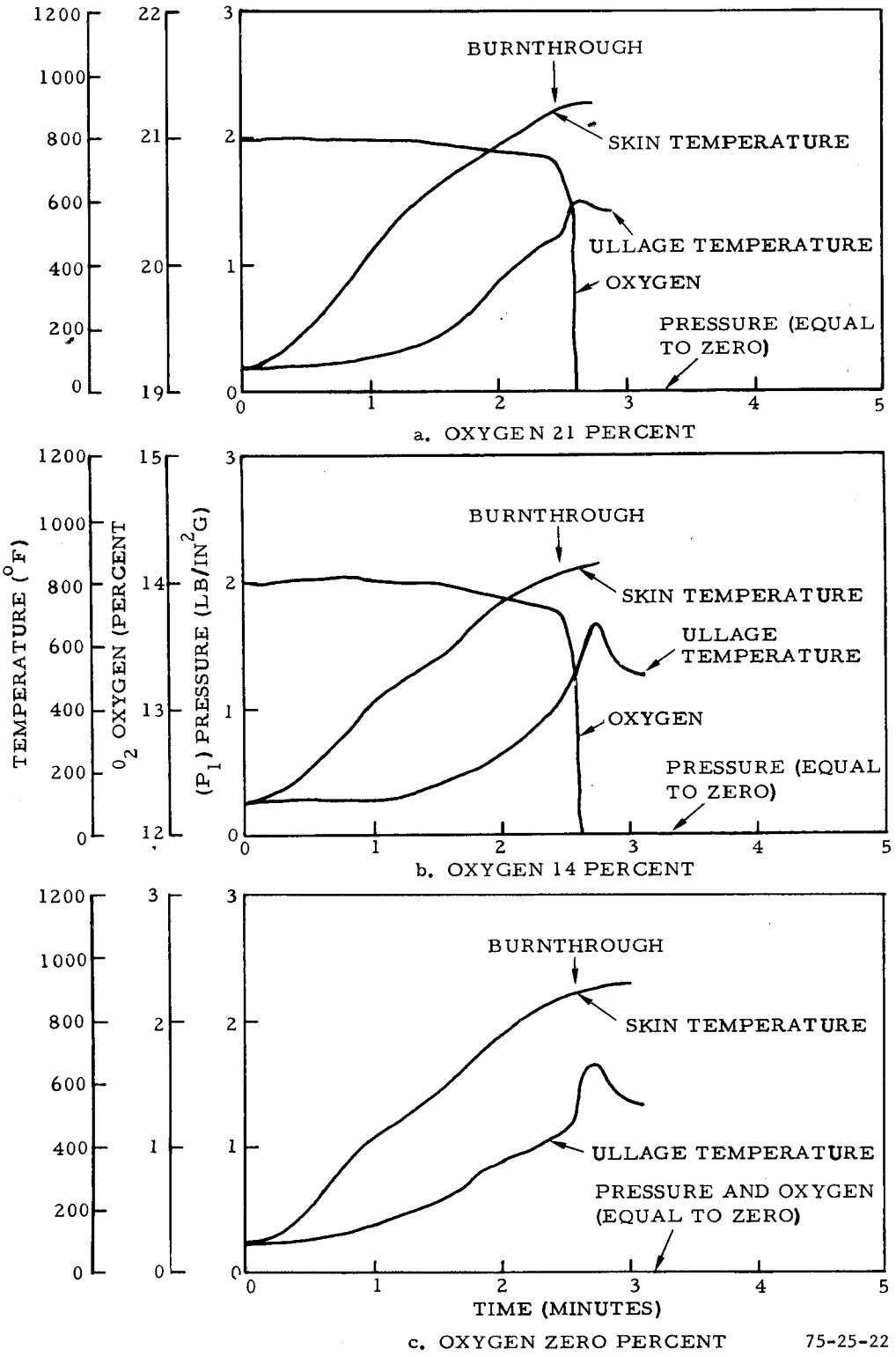


FIGURE 22. BURN-THROUGH REACTION FOR VARIOUS OXYGEN CONCENTRATION LEVELS

pressure rises were obtained (for skin temperatures below 600° F and ullage temperatures below 400° F) as low as 12 percent O_2. Rupture of the blowout panel was obtained with O_2 concentrations of 14 percent or greater by spark ignition.

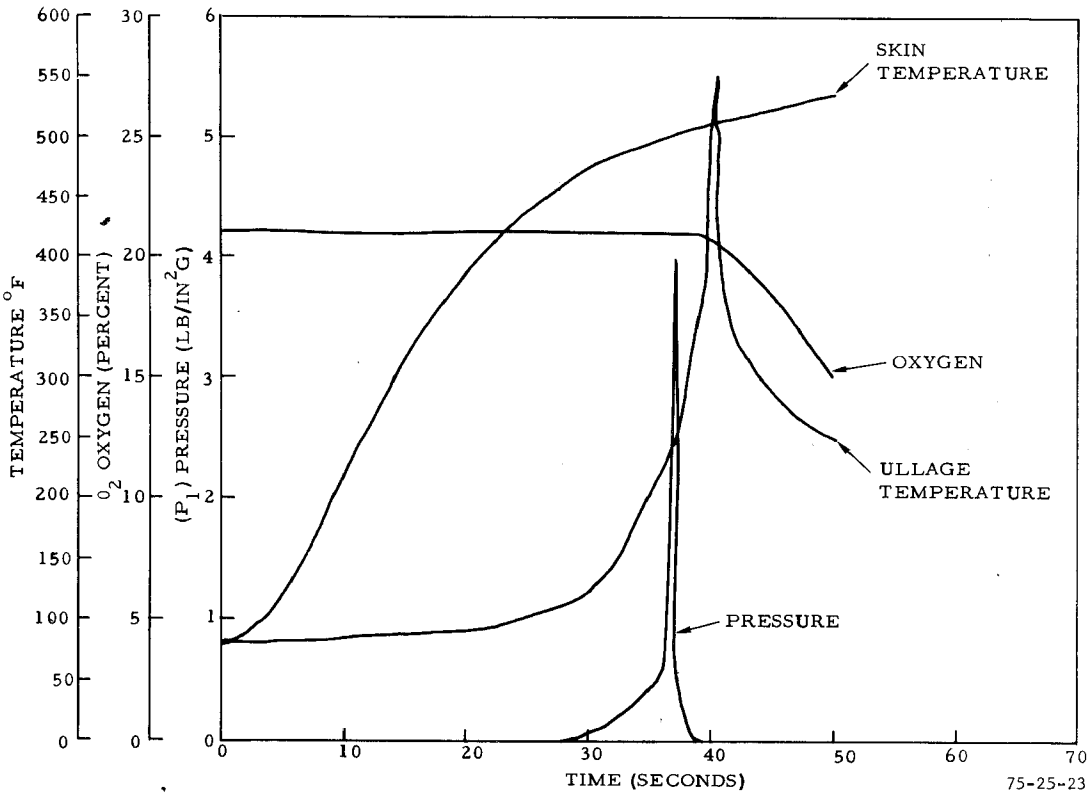


FIGURE 23. JP-4 AUTOIGNITION AT 21-PERCENT OXYGEN CONCENTRATION

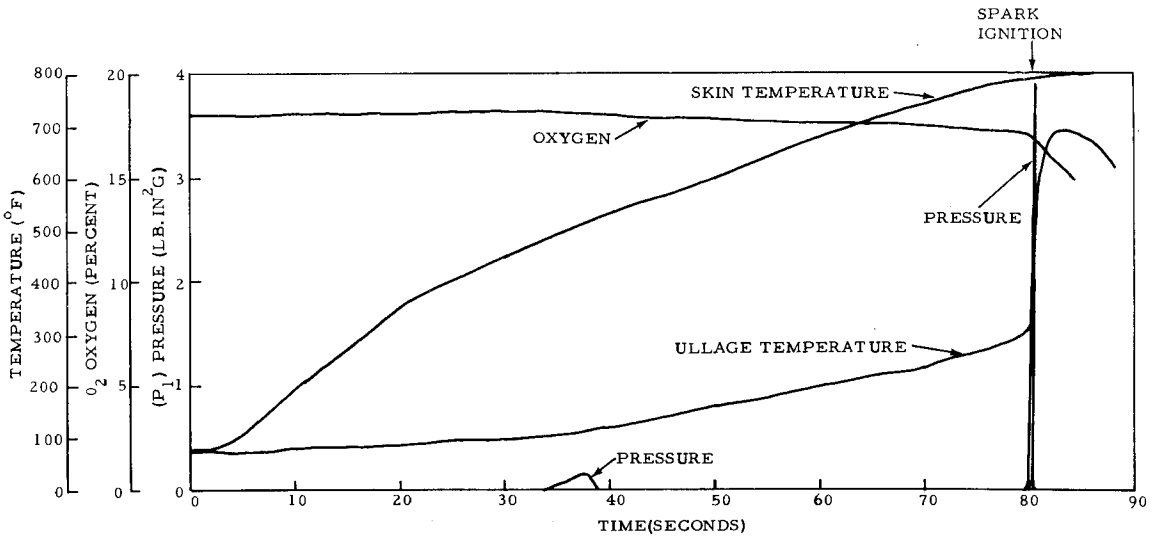


FIGURE 24. JP-4 AUTOIGNITION AT 18-PERCENT OXYGEN CONCENTRATION

Two elevated temperature tests using JP-4 fuel were run, with the results being shown in figure 25. The results were similar to that of Jet-A; e.g., a slow drop in O_2 concentration and a reaction at 13.5 percent O_2 with the skin temperature of 920° F and ullage temperature of 540° F, when the spark ignitor was activated, and no reaction when the spark was activated with a 9 percent O_2 concentration and slightly higher temperatures.

COMPARISON OF VARIOUS FUELS.

A series of tests was run, using a variety of Jet-A type fuels obtained from commercial airline flights arriving from various parts of the country and the world (see appendix for a list of fuels used), to determine if any differences could be obtained in the test results due to the differences of the fuels within the Jet-A specifications. In all, over 40 tests were run using the various fuels. All test results indicated the amount of inerting (oxygen concentration) needed to prevent any explosion and/or recorded reactions were the same as previously reported.

The only difference between the fuels noted was the pressure build up of the Avtur-50 fuel as compared to the domestic. The Avtur-50 fuel (sample 2) had a slower rate of pressure rise due to hot-surface igniton than the domestic fuels. This rate of rise fell between that of the domestic Jet-A and that of JP-4. JP-4 tests showed that it had a much slower rate of pressure rise from hot-surface ignition than did the Jet-A's. Figure 26 shows a comparison of the rate of pressure rise for the three fuels. The faster the rate of pressure rise the lower the pressure it took to rupture the blowout panel.

In order to determine what might occur in an actual fuel tank that did not contain a blowout panel, a 0.020 aluminum plate was used in place of the 0.003 aluminum blowout panel. Tests were run using both domestic Jet-A (sample 5) and JP-4 (sample 1).

Hot-surface ignition of the Jet-A sample again caused a rupture of the aluminum plate. The JP-4 sample ignited from the hot-surface and a slow pressure rise was recorded. The pressure peaked at 10 lb/in^2g, remained at that level for about 1 second and then returned to zero. The O_2 concentration dropped well below 9 percent in the tank, and the tank remained intact.

It should be noted that the differences in the rate of pressure rise for the various fuels was found only during hot-surface ignition. When the ignition was caused by a spark, all fuels tested responded with a rapid pressure rise.

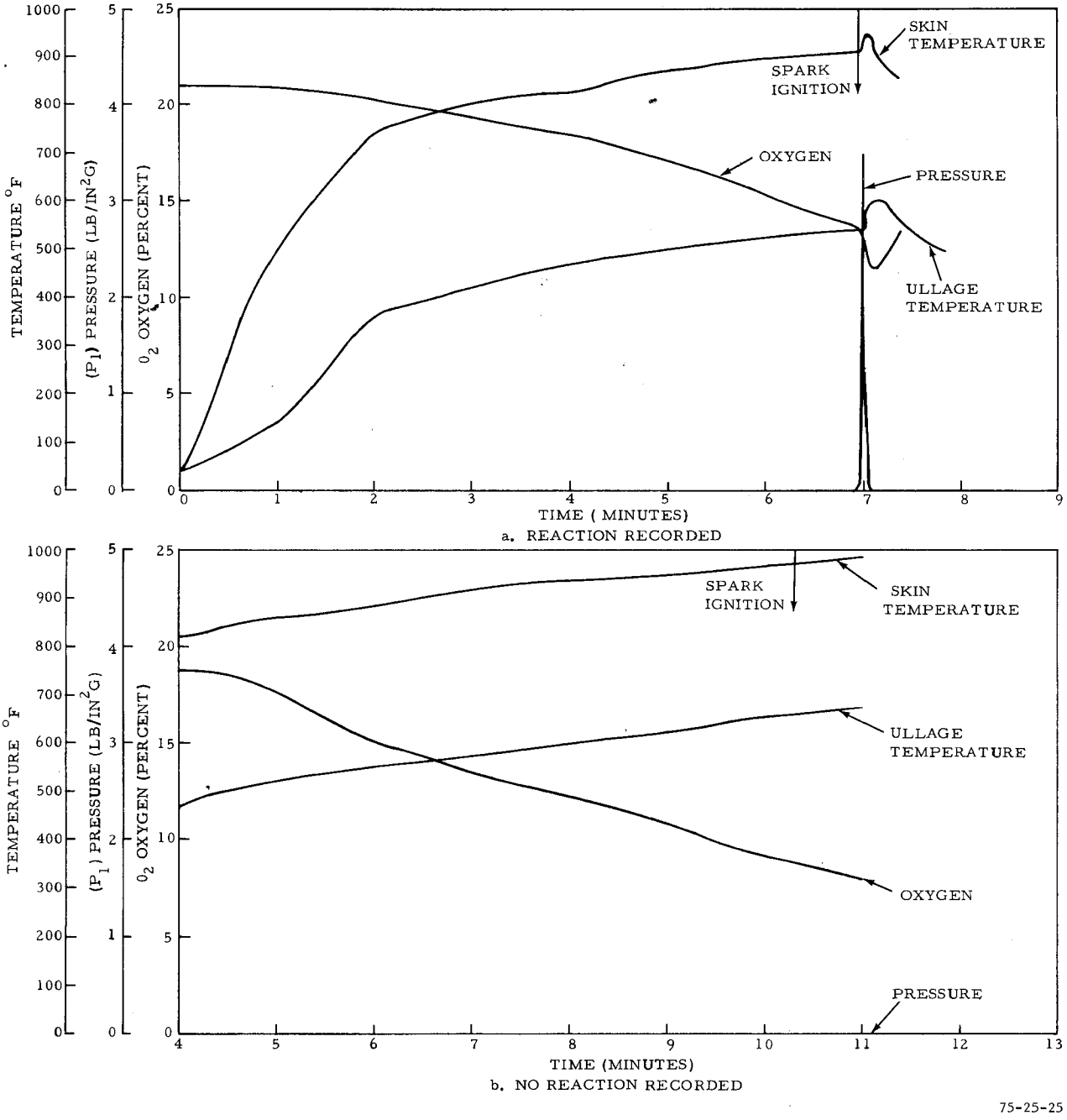


FIGURE 25. EFFECTS OF JP-4 HEATED TO ELEVATED TEMPERATURES

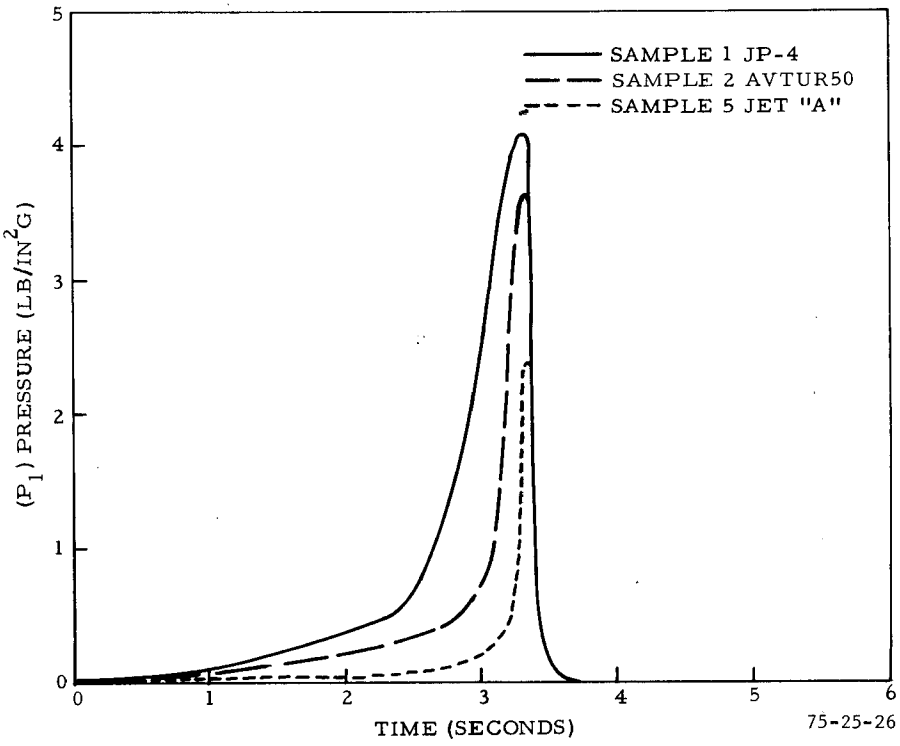


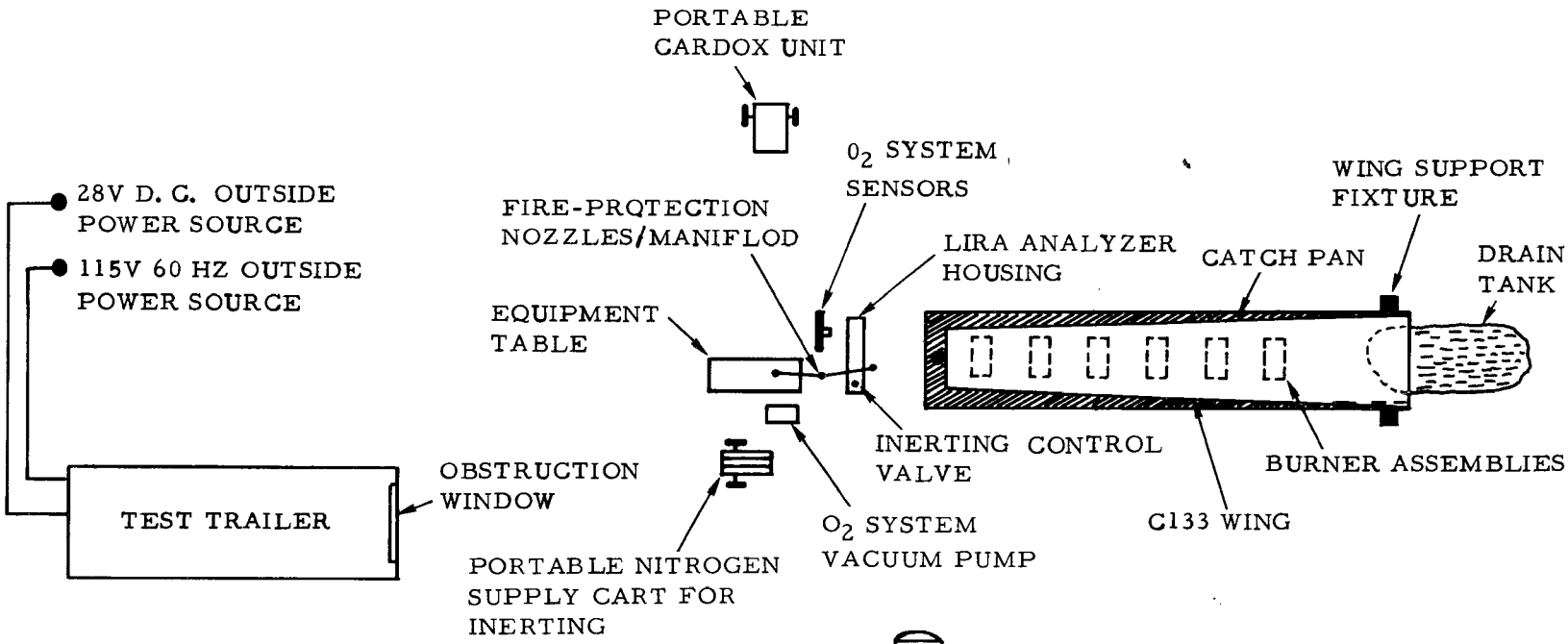
FIGURE 26. PRESSURE RISE FROM VARIOUS FUELS DUE TO HOT-SURFACE IGNITION

LARGE-SCALE TEST EQUIPMENT AND CONFIGURATION

FACILITY AND TEST ARTICLE DESCRIPTION.

TEST SITE. The test site was located in a remote area of NAFEC. Equipment used for the readout and recording of all the test data was housed in an instrumentation trailer located at the test site. In addition to housing the data acquisition equipment, the actuation of the simulated crash-fire burner assemblies, fire-extinguishing system, internal ignitor in the test wing, and the wing nitrogen inerting system was controlled from within the trailer. To provide a safe separation in the event of a violent reaction, the trailer was located approximately 200 feet from the test wing (figure 27).

Various instrumentation components (LIRA analyzers and oxygen measuring sensors), the inerting control valve, and sample line vacuum pumps were located between the trailer and the wing, approximately 30 feet from the wingtip.



INSTRUMENTATION TRAILER CONTAINING:

1. OXYGEN CONCENTRATION READOUTS
2. HYDROCARBON CONCENTRATION READOUT
3. OXYGEN SAMPLING SYSTEMS FLOW CONTROL BENCH
4. THERMOCOUPLE AMPLIFIERS
5. WING BURNER ASSEMBLY FUEL/AIR AND IGNITION CONTROLS
6. OSCILLOGRAPH
7. BRISTOL RECORDERS
8. PRESSURE AMPLIFIERS

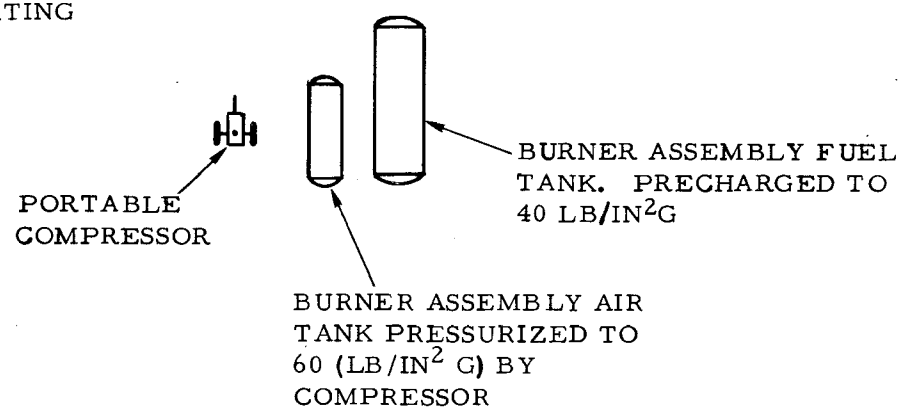


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FIGURE 27. FULL-SCALE TEST FACILITY

A 10-foot wide steel catch-pan, extending the entire length of the test article, was provided beneath the wing to contain any fuel that might escape the wing due to a burn-through or rupture. This pan channeled the fuel to a drain tank installed in the ground to prevent soil contamination by fuel.

The test wings were suspended above the burner assemblies utilizing a support stand that was pivotable around a horizontal axis attached to the wing root. During the DC7 tests a rigid 4-inch diameter pipe provided support of the wing at the tip end. A telescoping, adjustable support tube was used for wingtip support during the C133 tests. This enabled the test article to be tilted spanwise for varying test configurations. Support stand height at the wing root end provided a 6-inch minimum separation between the top of the burner flues and the wing bottom skin.

DC7 TEST WINGS. The DC7 wings were of full-cantilever, multicellular, all-metal stressed skin construction. Only the outer panels of the wing assemblies were utilized for test purposes. Principal structural components of these panels were spars, bulkheads, ribs, stringers, and skin. Two spars, which were continuations of the aircraft center wing section front and center spars, formed the front and rear walls of this section. The spars, their interconnecting bulkheads, and the top and bottom skin plates were so constructed as to constitute an integral fuel tank of 512 U.S. gallon capacity. The ailerons, which are normally installed on this section, were removed.

C133 TEST WINGS. The C133 wings were also full-cantilever, stress-plated outer wing sections. The outer panel normally incorporated the ailerons (which were removed for test purposes) and an integral fuel tank extending from root to wingtip. The structure consists of two spanwise spars, spanwise panel stiffeners and chordwise ribs and bulkheads. Stressed doors are provided in the wing structure to permit access to the fuel tanks. The fuel capacity of this outer wing panel is 1,390 U.S. gallons. The existing tank vent line was utilized, with a 1.5 lb/in^2g check valve installed in the outlet during the inerting tests only. A filler opening for tank fuel servicing and a drain outlet for post-test draining were installed in the test wing, as there were no provisions for either in this section of the wing.

INTERNAL WING INERTING SYSTEM. The wing tank inerting system consisted of six, 251-cubic-inch capacity, gaseous, water-pumped nitrogen (GN_2) cylinders mounted on a mobile cart, a shut-off valve, and the necessary tubing (figure 28).

Each nitrogen cylinder had an individual regulator pre-adjusted to 50 lb/in^2g. These regulators were connected to one another by a common manifold. The manifold was, in turn, connected to an electrically-operated solenoid control valve, actuated from the instrumentation trailer. Opening this valve would permit nitrogen to flow to the wing through a 0.250-inch inside diameter tube attached to a bulkhead fitting penetrating the wingtip wall; connected internally to a 0.500-inch inside diameter aluminum tube, containing thirteen equally spaced 0.0980-inch diameter holes. This tube was installed in the forward portion of the tank, near the upper wall. The thirteen holes were positioned to direct the nitrogen gas upward toward the tank top wall. One hole was provided

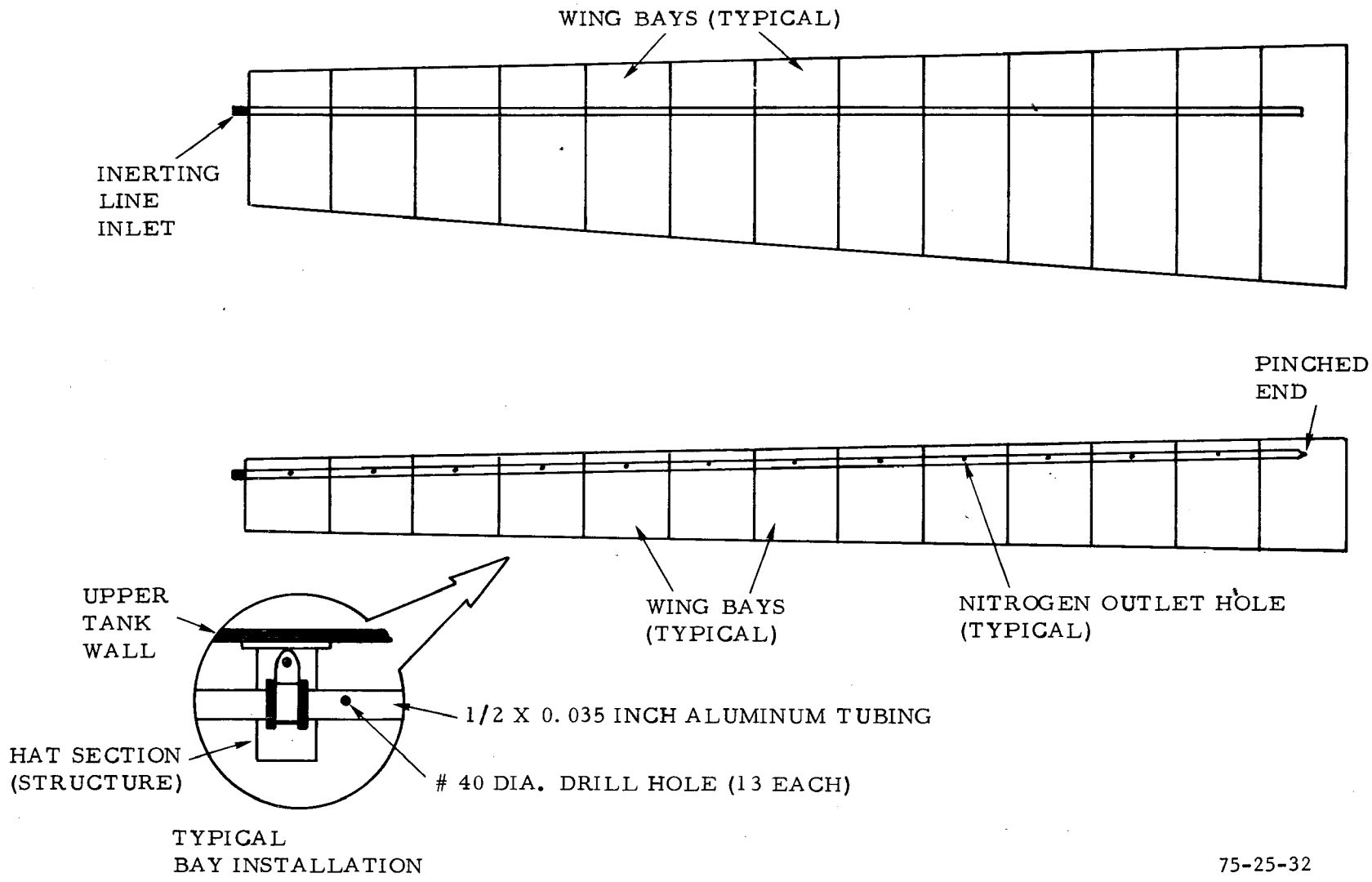

FIGURE 28. C133 WING-INERTING LINE INSTALLATION

in each tank bay. The inerting line terminated approximately 18 inches from the wing root wall. The Beckman oxygen-sensing instruments were used to monitor the inerting operation effect on tank oxygen concentration and to determine the termination point.

FULL-SCALE TEST BURNER ASSEMBLIES. A simulated post-crash fire was created beneath the test article by the use of locally-fabricated burner assemblies. The assemblies were constructed of 0.125-inch-thick plate steel, assembled in such a manner as to form six flues in each unit (figure 29). Each flue had a nozzle that directed fuel in a cone-shaped spray vertically toward the lower surface of the test wing. An ignitor assembly consisting of two converging universal oil burner-type electrodes was installed in one center flue of each burner assembly. Fuel spray from the nozzles would be ignited from the electrode spark, and the flames from the ignition flue would instantly propagate to the remaining five flues through crossfire holes cut in the flue walls. Since the fuel/air control valves and ignition spark for all burner assemblies were activated by a single switch for each in the instrumentation trailer, ignition occurred in all burners simultaneously.

Burner fuel nozzles were pneumatic atomizing liquid/air type (Spraying System Company, set-up 13-A) providing a 2.53 U.S. gallon per hour fuel flow at fuel and air pressures pre-set prior to the test. This fuel flow was calculated to provide a fire that would produce a Btu output similar to that of a postcrash fuel pool fire. The burners were calibrated at a radiant heat output of 2.25 $Btu/ft^2/s$ for the condition used in the full-scale tests. Burner fuel (JP-4) was supplied from a 1,000-gallon storage tank pressurized to 40 lb/in^2g using air from a portable air compressor. Due to the vast ullage of the tank, pretest tank pressurizing was sufficent to maintain this pressure setting during the test. Air for the burner was supplied from a 140-cubic-foot capacity storage tank pressurized to 60 lb/in^2g. This pressure was reduced to 30 lb/in^2g by pressure regulators, installed between the tank and the nozzles. Burner ignition spark was generated at the electrodes, utilizing a universal oil-burner type 120/10000-volt transformer (figure 30).

The burner assemblies were placed in a line, spanwise, beneath the test wing. During testing of the DC7 wings, three burners were used. Six burners were used for the C133 tests.

TEST INSTRUMENTATION.

The test instrumentation used in the large-scale DC7 and C133 wing tests was essentially the same as that used in the small-scale test previously described. The following paragraphs pertain primarily to the C133 tests. The DC7 wings, being preliminary test articles, were not as fully instrumented as the C133's.

HYDROCARBON CONCENTRATION MEASUREMENTS. Hydrocarbon concentration was measured using two Mine Safety Appliance LIRA model 300 infrared analyzers (figure 31). Sampling system flow was generated by inducing a partial vacuum in the system utilizing a vacuum pump which was installed in the instrumentation trailer.

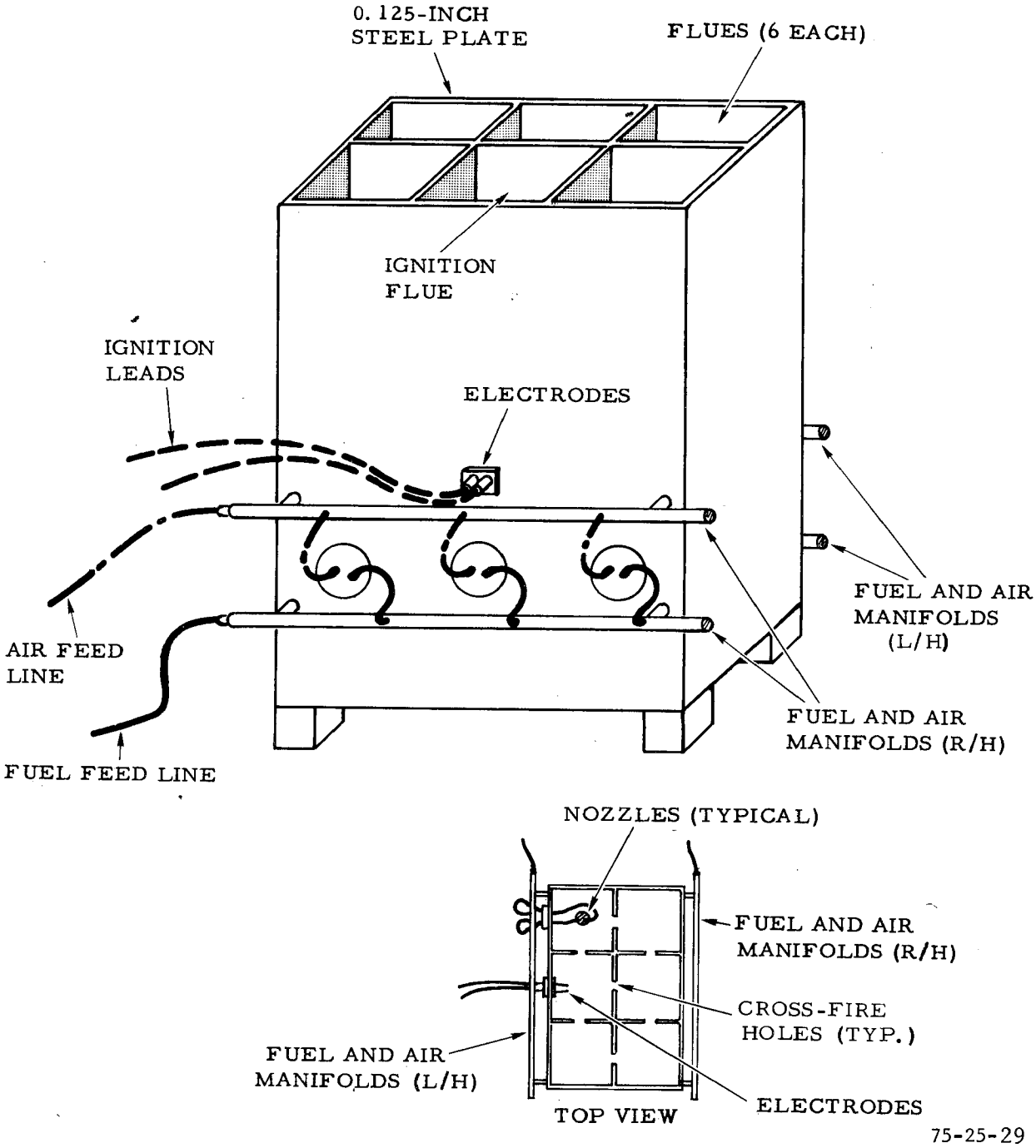

FIGURE 29. FULL-SCALE BURNER ASSEMBLY

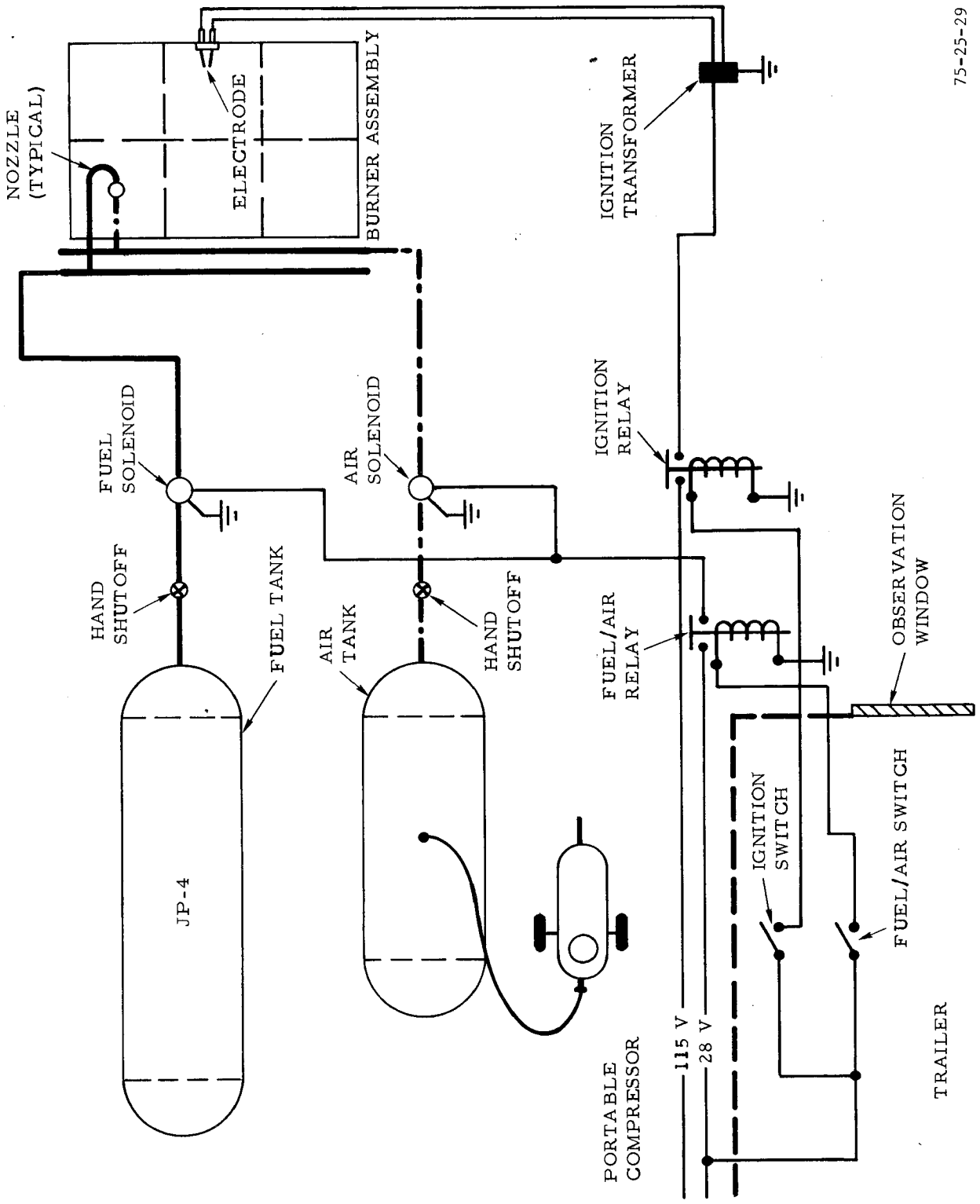

FIGURE 30. FULL-SCALE BURNER ASSEMBLY

The samples were drawn from two locations in the ullage in the wing through 0.125-inch inside diameter lines connected to metering valves mounted on the outboard wall of the wingtip. These valves were adjusted to maintain a 200 cubic centimeter per minute (cm^3/min) flow through the analyzer cell. The sample was then drawn through heated (250° F) tubes to the analyzer, where continuous hydrocarbon measurements were taken.

Concentration information was displayed on a direct readout meter and recorded on a Honeywell model 1180 visicorder oscillograph in the instrumentation trailer.

From the analyzer the sample was then drawn through the system to an absolute pressure regulator, on the instrumentation trailer control panel, that maintained 8 lb/in^2g absolute pressure in this system, this setting being required for proper operation of the LIRA® analyzers. Flowmeters on the control panel enabled constant monitoring of the 200 cubic/centimeters per minute system flow. The sample then entered the inlet (vacuum) side of the diaphragm-type vacuum pump and was discharged from the outlet (pressure) side of the pump, out of the trailer, to ambient.

OXYGEN CONCENTRATION MEASUREMENTS. The oxygen concentration measurements were taken from the ullage in the wings utilizing three Beckman® model 715 oxygen sensing systems. Samples (figure 31) were drawn from four locations in the wing by applying a partial vacuum at the sensing line inlets created by motor-driven vacuum pumps installed between the wing and the oxygen-sensing units. The samples passed through 0.125-inch inside diameter lines from the wing to that prevented liquid fuel from entering the oxygen sensors and vacuum pumps. From the traps it entered the inlet side of the pumps, then out the pressure side to the sensors, where continuous measurements were taken. This information was permanently recorded on the Honeywell oscillograph and displayed on a direct readout meter. After passing through the sensors the samples were exhausted to the atmosphere.

TEMPERATURE MEASUREMENTS. The internal temperature of portions of the lower wing skin, the ullage in the wing, and the wing fuel load were constantly monitored and recorded. Fifteen chromel/alumel (type K) ceramo thermocouples were installed in the wing (figure 32). Only twelve were utilized, the three in the wing root section were not considered to be in a critical area and were not used.

The Ceramo thermocouples were connected to extension wires by standard connectors. The extension wires were, in turn, connected to a patch-board in the instrumentation trailer. The patch-board provided a means of switching the incoming temperature signal to either a bank of Bristol 760 strip-chart recorders or to the Honeywell oscillograph, utilizing individual Brush Company thermocouple amplifiers to strengthen the signal. Direct read-out temperature information was available through a temperature-indicating meter connected to a rotary selector switch that provided individual thermocouple selection.

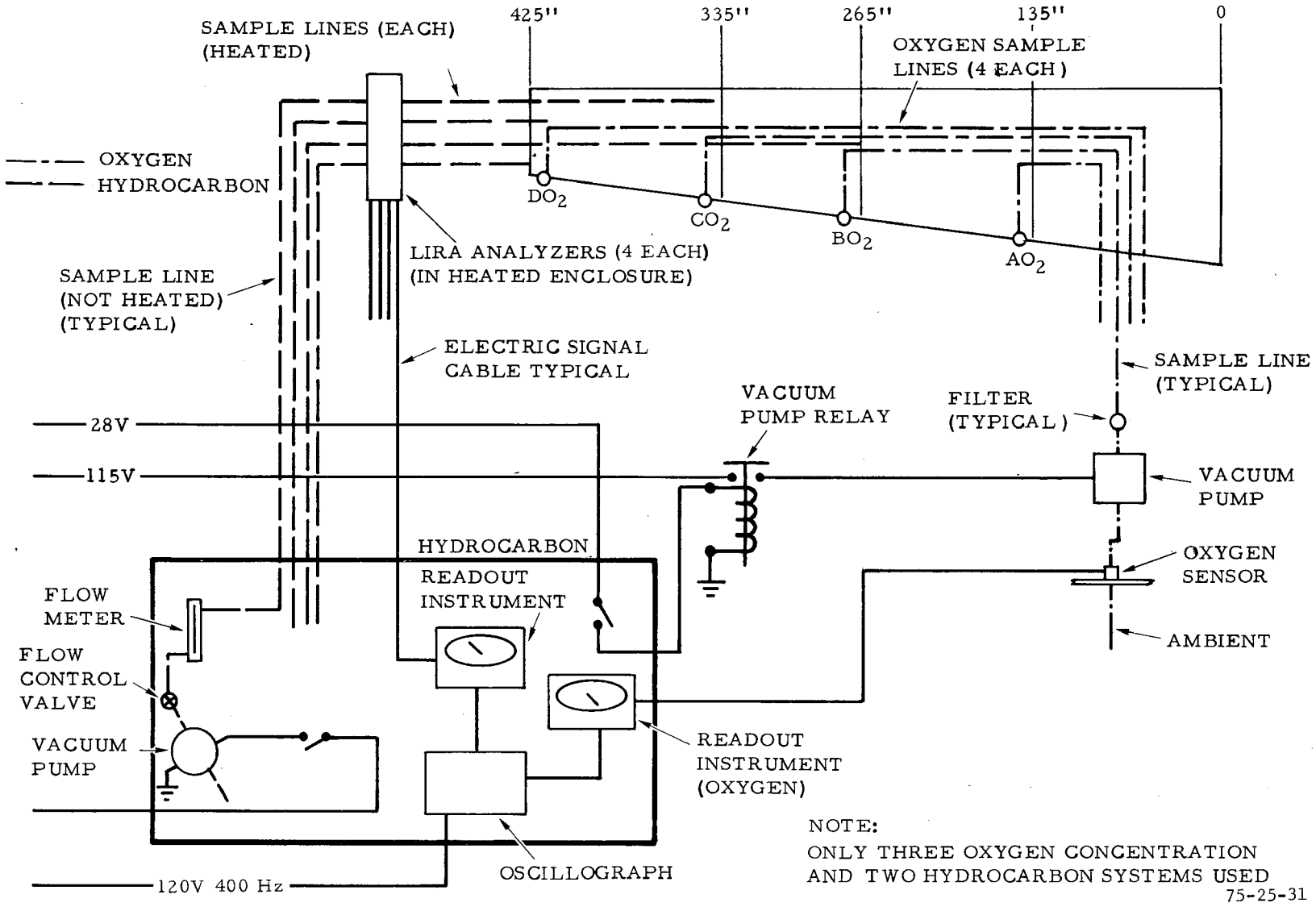

FIGURE 31. OXYGEN CONCENTRATION AND HYDROCARBON SAMPLING SYSTEMS

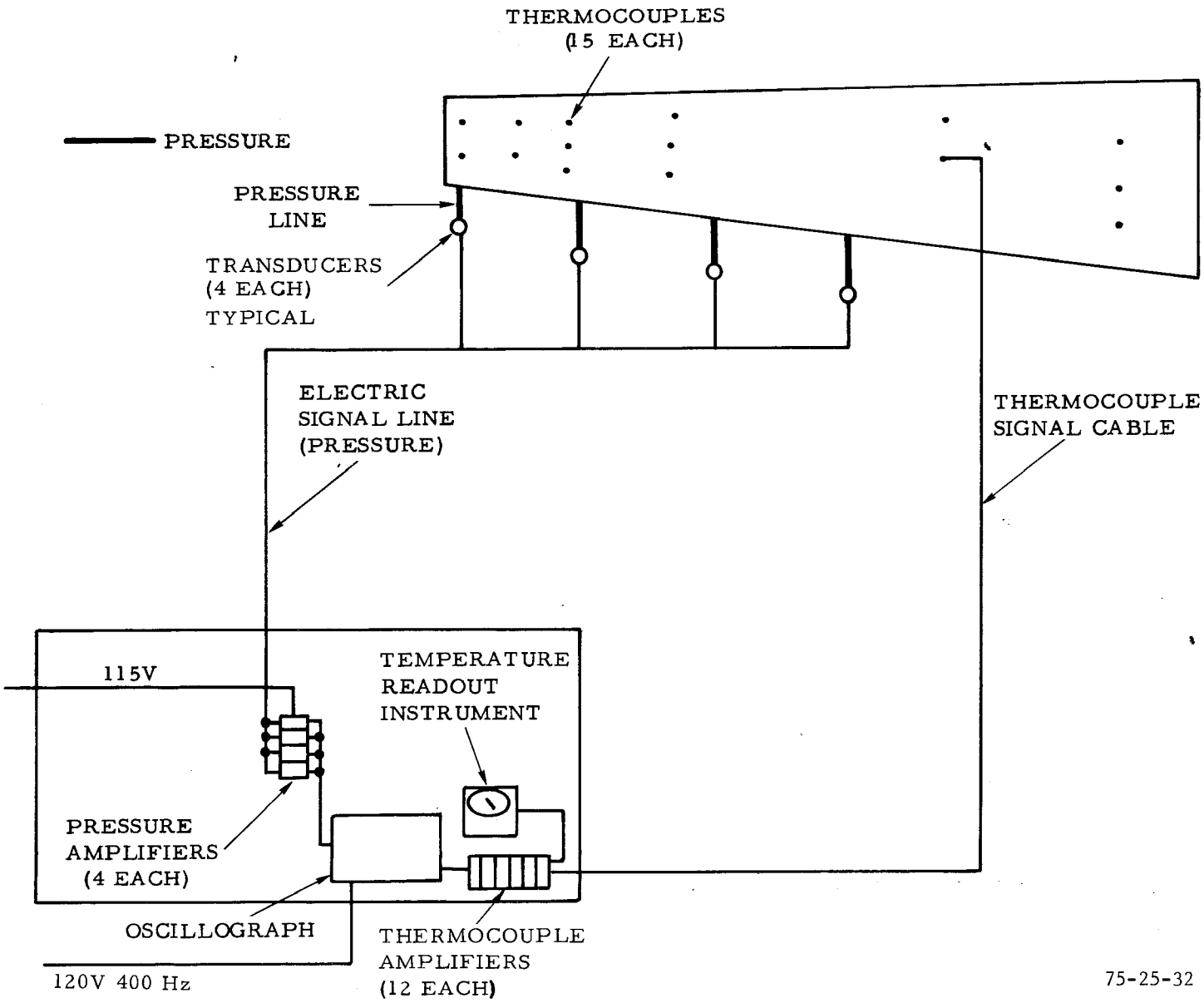

FIGURE 32. TANK INTERNAL PRESSURE AND TEMPERATURE-MEASURING SYSTEMS

TANK PRESSURE MEASUREMENTS. Test article internal pressures were measured using four pressure transducers connected to the wing's internal cavity by 0.250-inch inside diameter lines through bulkhead fittings installed in the wing rear spar.

Transducer-measuring ranges were from zero to 10 and 50 lb/in^2g. Transducer electrical output was directed to a signal amplifier in the instrumentation trailer. This unit was connected to the Honeywell oscillograph where pressure levels were continuously recorded. No direct read-out pressure indicators were utilized.

FIRE-DETECTION SYSTEM. Wing internal fire detection was accomplished using five Clairex photo-conductive cells installed in the upper portion of the rear spar and positioned to survey the entire tank cavity. Photo-cell reaction electrical impulses were directed to a locally-fabricated amplifier unit and, in turn, to the Honeywell oscillograph. The fire-detection system was installed to obtain test information only, as there were no provisions on the test article for either fire prevention or control.

DISCUSSION AND RESULTS (FULL-SCALE)

PRELIMINARY DC7 WING TESTS.

Two preliminary tests were run, using DC7 wing tanks as test articles. The tanks were sparsely instrumented (two thermocouples, one oxygen sensor, one hydrocarbon analyzer, and one pressure probe). The purpose of the preliminary tests was to determine any problems that might arise in the instrumentation or operating procedures prior to testing the fully instrumented C133 wing tanks.

Because of the size of the DC7 wing tanks (512-gallon capacity) as compared to the C133 tanks (1,390-gallon capacity) only three of the six burners were used in the preliminary tests. Figure 33 shows the test configuration of the

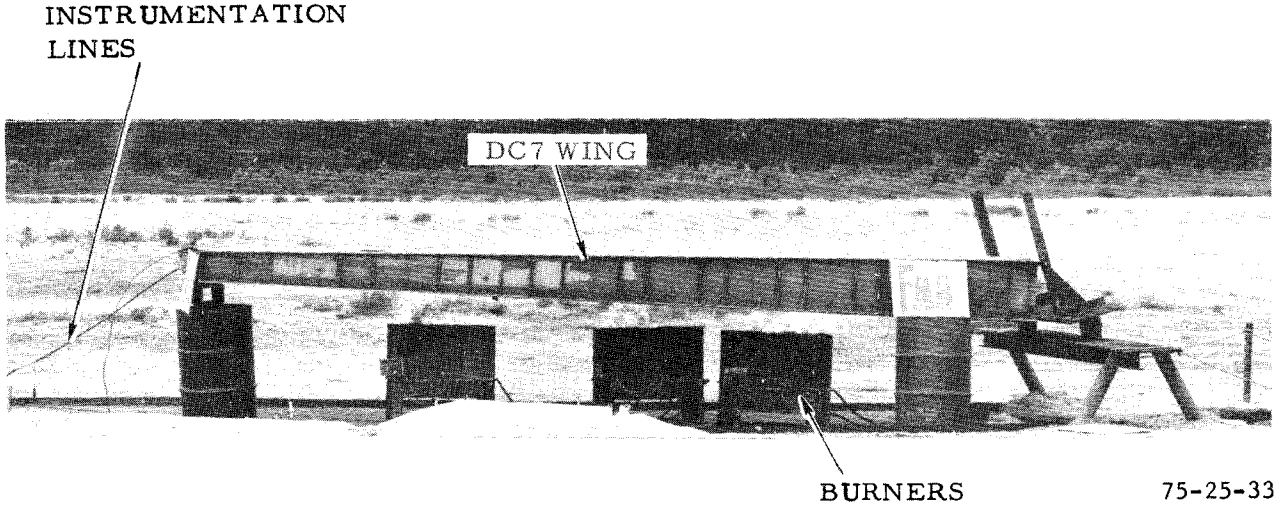

FIGURE 33. DC7 TEST ARTICLE

first preliminary test. One hundred gallons of Jet-A type were was used. The approximate fuel level and burner location are shown in figure 34. It should be noted that the entire bottom surface of the fuel tank was wetted, with a depth at the wing root of approximately 2 inches and at the tip of less than an eight of an inch. Figure 35 shows the location of instrumentation

TEST NUMBER ONE. The start of the first preliminary test can be seen in figure 36. The instrumentation lines were connected to the wing at the tip. No inerting was used in the preliminary tests, therefore, the oxygen concentration at the start of the test was 21 percent.

Approximately 13 minutes after the start of the test the wing burnt through, and continued to burn even after the test was terminated and the burners extinguished. There was evidence of an internal fire throughout the wing (figure 37). The entire top surface of the wing had buckled and small burn-through's had occurred at various places on the surface. Shortly after burn-through the oxygen concentration in the wing fell to near zero. Figure 38 shows the remains of the wing after the test. The results of this test are similar to those obtained in the small-scale burn-through tests.

TEST NUMBER TWO. The configuration of the second preliminary test is shown in figure 39. Fuel quantity in the second test was 25 gallons, thus providing both wetted and dry areas of the wing.

Two minutes from the start of the test a violent reaction (explosion) occurred in the tank, The entire top of the wing was destroyed by the reaction (figure 40), and a large fireball engulfed the wing. Because of the violent nature of the reaction no data during and after the explosion were obtained. This was due to the loss of sample lines and wiring connecting the wing with the instrumentaion. Figures 41 and 42 show the remains of this preliminary test. After examing the available data and the wreckage of the wing the probable cause of the reaction was determined to be hot-surface ignition. The reaction in this test was the same as in the small-scale tests when a small amount of fuel was heated with 2,000° F flame.

PRIMARY C133 WING TESTS.

Breakaway fittings were installed in the sample lines (this was done to protect instrumentation in the event of an explosion) and separate sample lines for the oxygen analyzers were installed. In the second preliminary test the flow-metering valve for the hydrocarbon analyzer became clogged, the same problem that had materialized during the small scale tests. It had been planned to use the hydrocarbon sample lines for the oxygen sensors; hence, the need to install separate sample lines.

The test configuration selected for the four C133 wing tests were chosen so as to best demonstrate that the results of the small-scale tests could be extrapolated to full-scale fuel tanks. Because of the vast size of the wing tanks and the amount of instrumentation used, these tests, and the data obtained, should be looked upon as a demonstration only, and used accordingly.

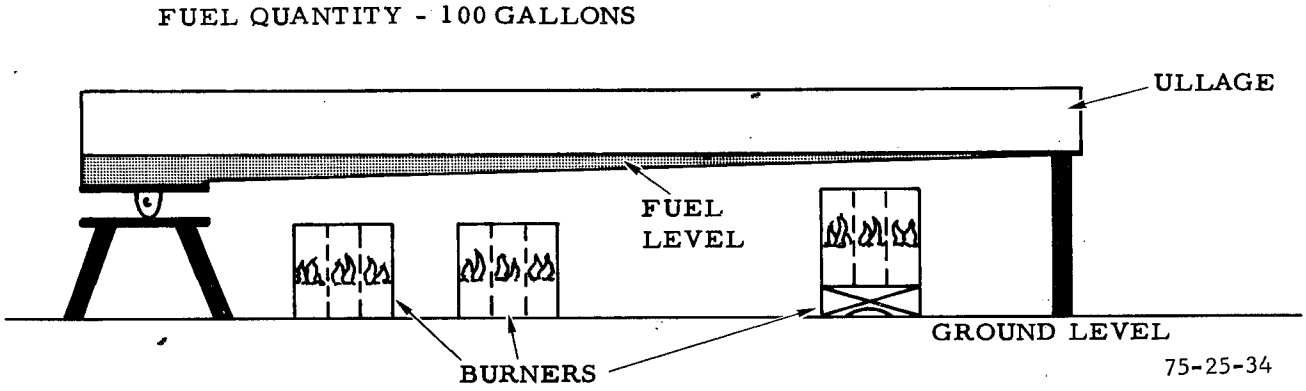

FIGURE 34. FIRST DC7 TEST CONFIGURATION

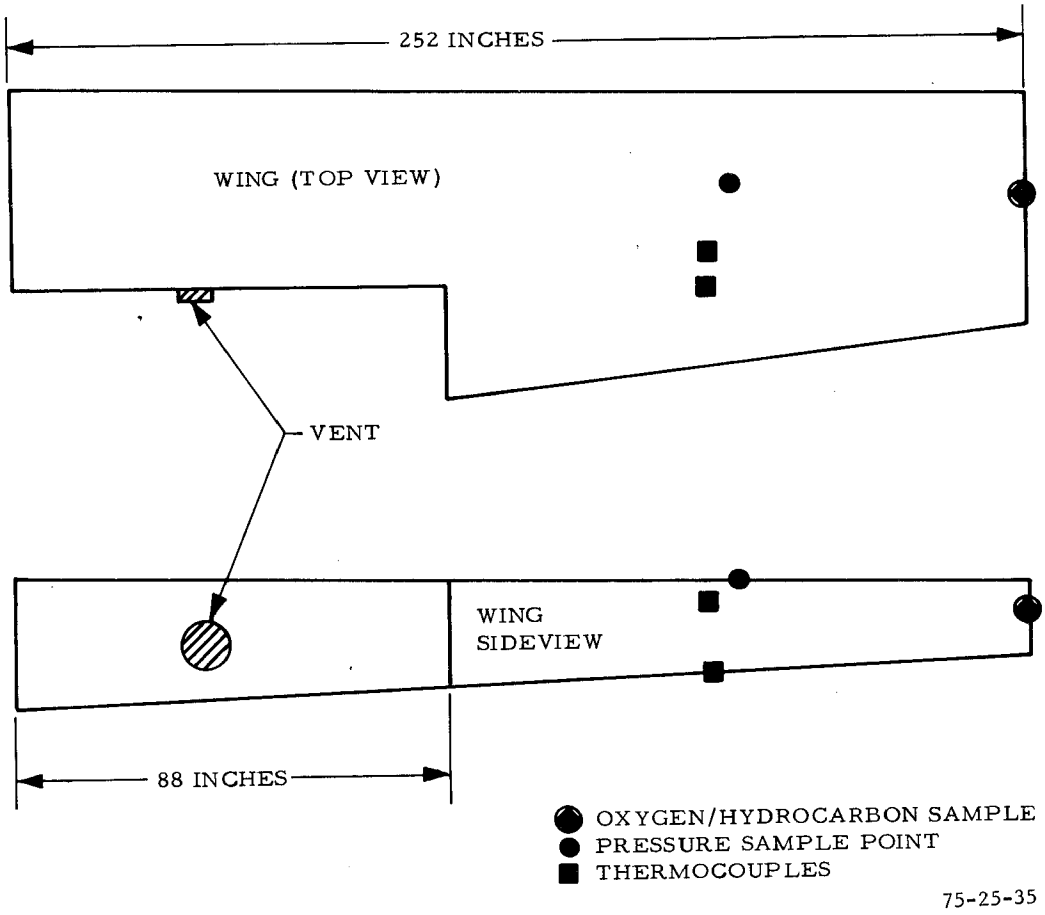

FIGURE 35. DC7 WING INSTRUMENTATION LOCATION

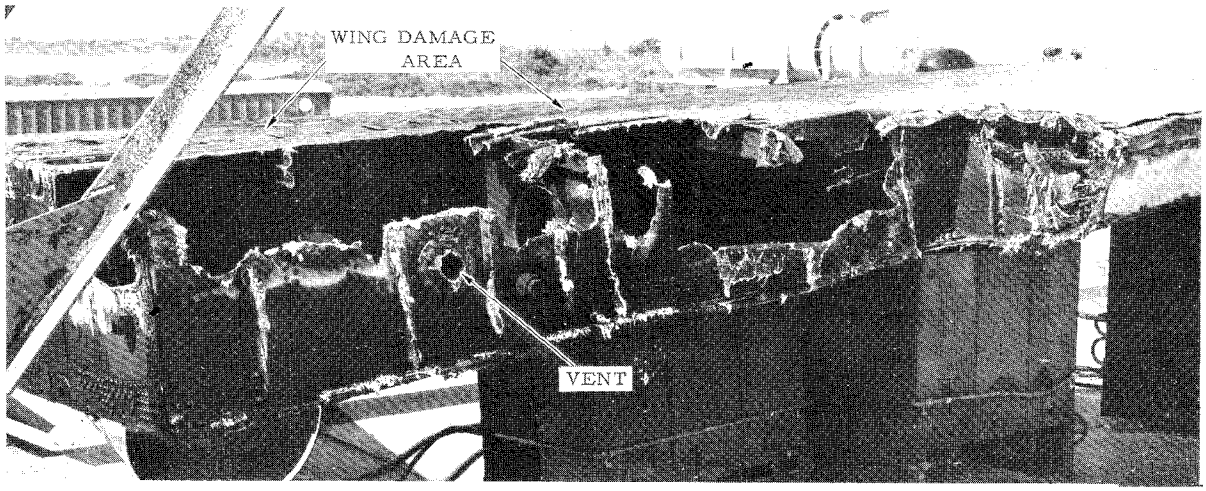

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FIGURE 36. INITIATION OF FIRST DC7 TEST

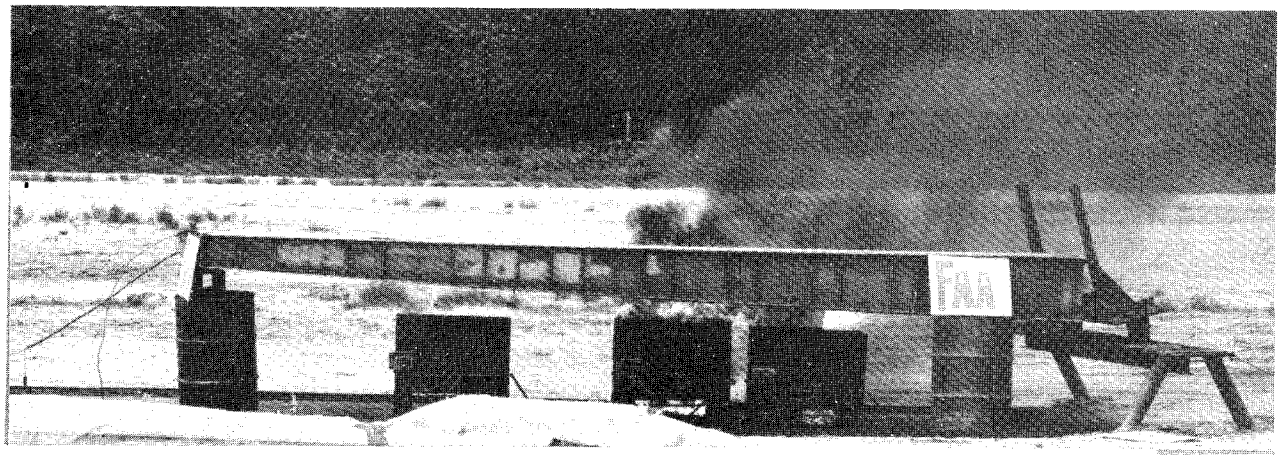

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FIGURE 37. POST-TEST VIEW, FIRST DC7 TEST

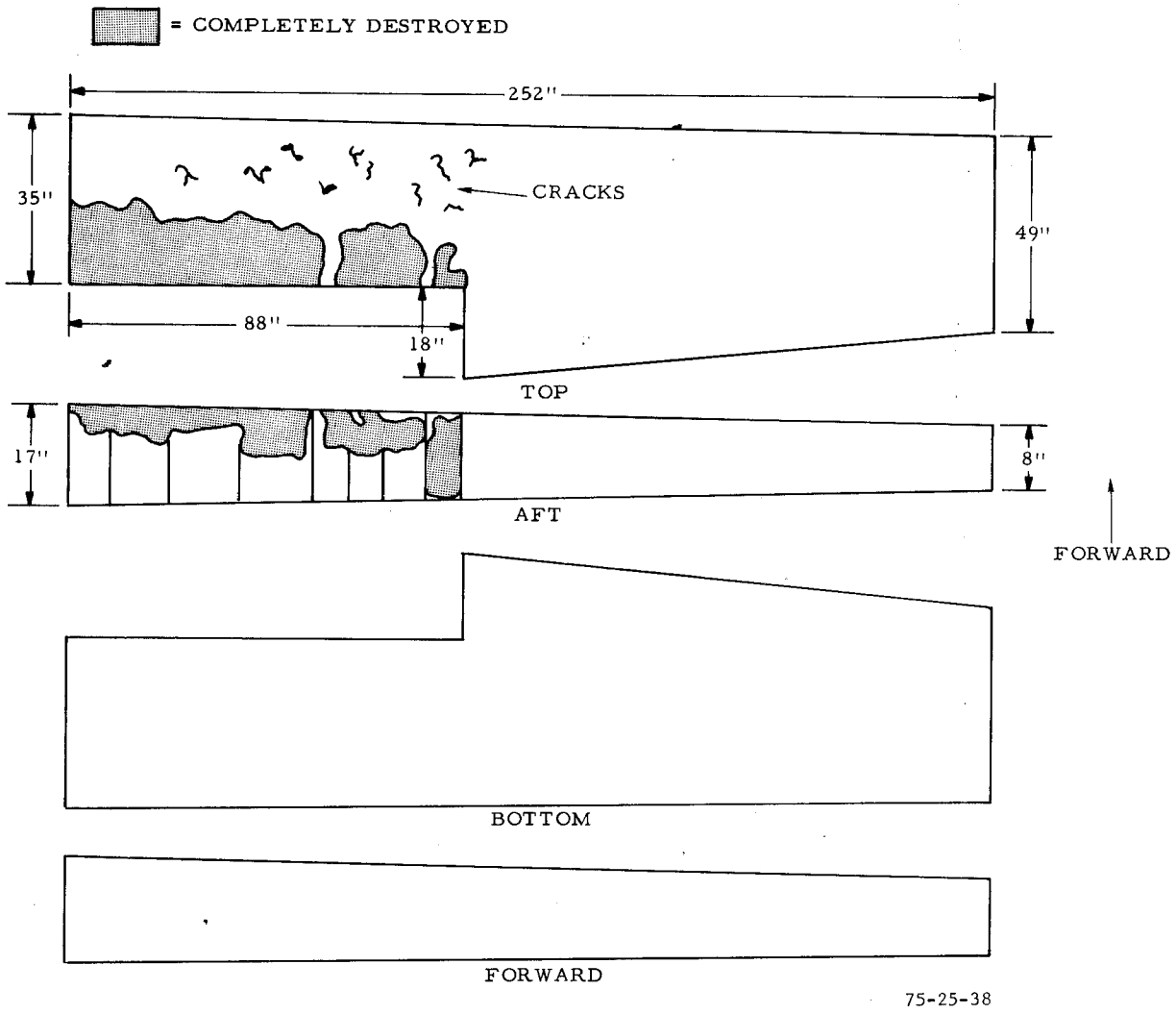

FIGURE 38. RESULTANT DAMAGE, FIRST DC7 TEST

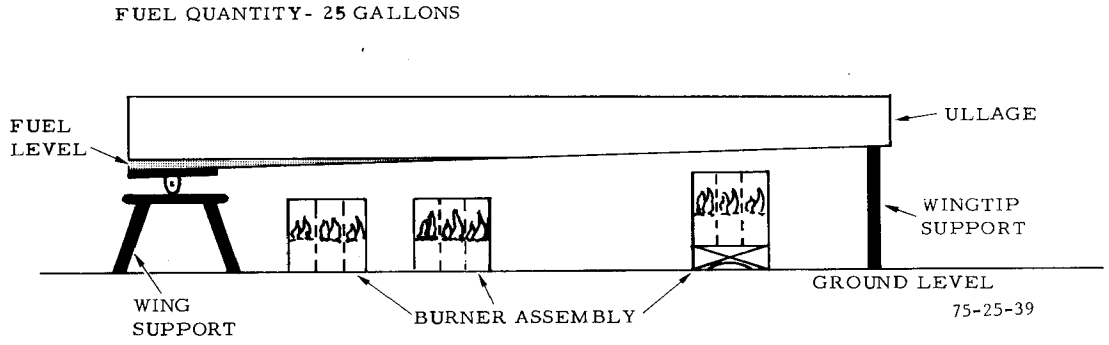

FIGURE 39. SECOND DC7 TEST CONFIGURATION

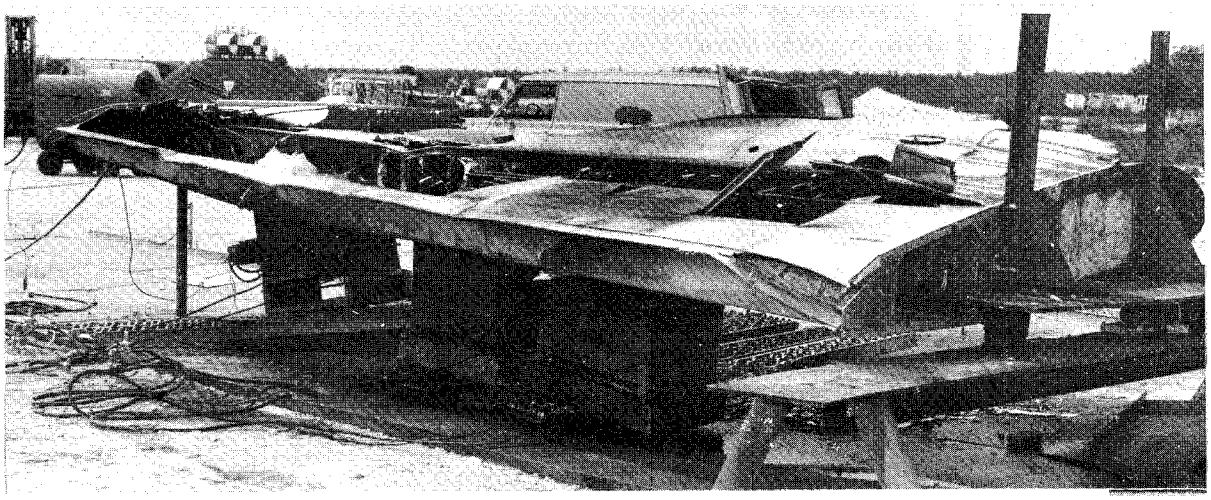

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FIGURE 40. POST-TEST VIEW, SECOND DC7 TEST

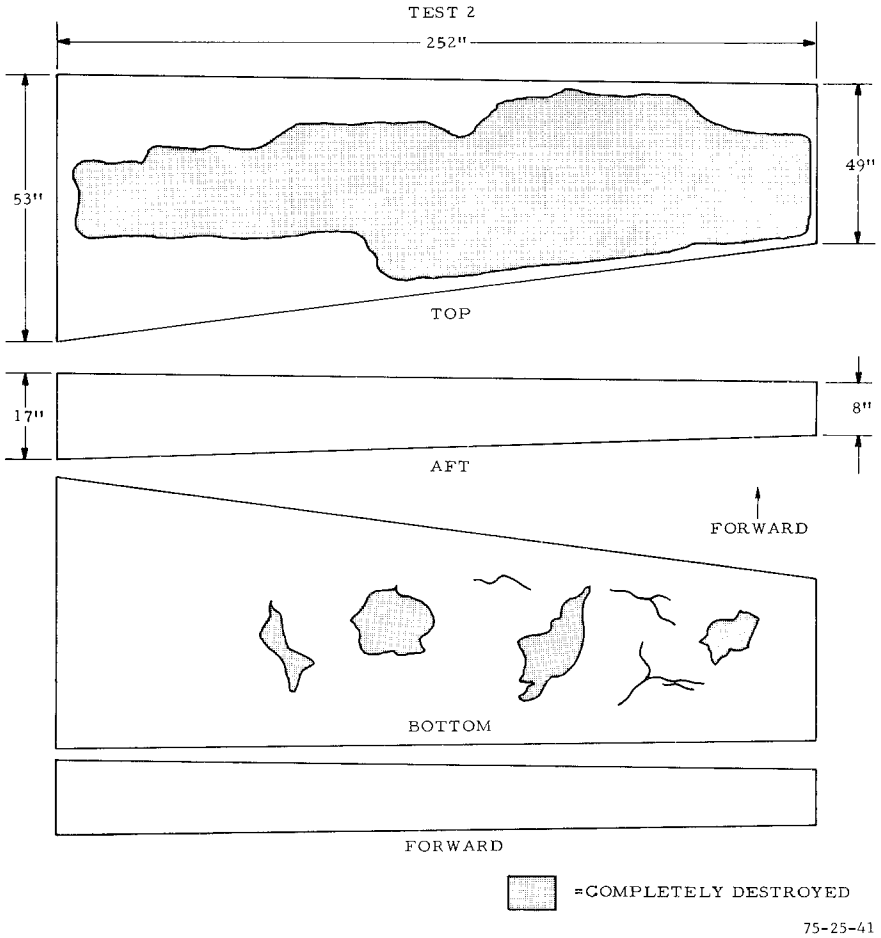

FIGURE 41. RESULTANT DAMAGE, SECOND DC7 TEST

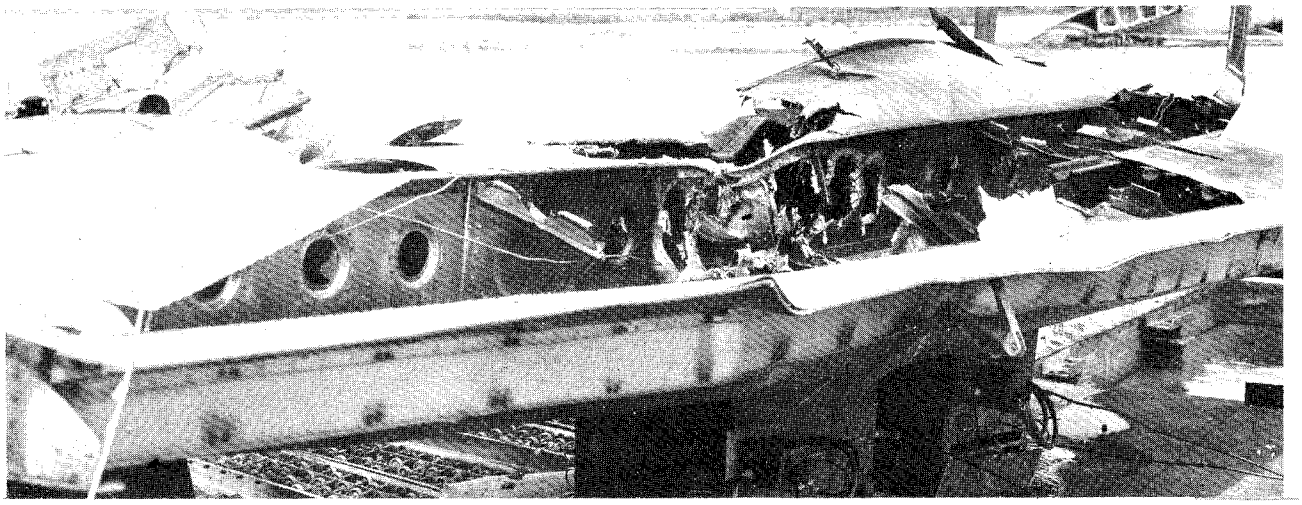

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FIGURE 42. CLOSEUP VIEW, POST-TEST DAMAGE, SECOND DC7 TEST

TEST NUMBER ONE. The first C133 wing test was set up as shown in figure 43. Wing instrumentation locations for all C133 wing tests are shown in figure 44. The tank was uninerted and had a fuel load of 55 gallons. All six burners were used and spaced evenly under the wing. Flames from the burners impinged on both wetted and dry areas of the bottom wing skin.

Approximatly 95 seconds from starting the test a violent reaction occurred which completly destroyed the wing. A sequence of this reaction can be seen in figure 45. The photos were taken from successive frames of a 16-mm film shot at 24 frames a second. The resultant damage to the wing is shown in figure 46. The entire top portion of the wing was destroyed. Various portions of the wing were hurled up to 100 yards from the original position. Figures 47 and 48 show the remains of the wing after the test. Note that the entire wing somersaulted, landing bottom side up. The bottom skin of the wing was entirely intact except for structural failure near the wingtip which was due to the violent reaction and impact with the ground.

From analyzing the films and data obtained from the test (figure 49) it was determined that hot-surface ignition had occurred and had been the cause of the violent explosion. The highest recorded skin temperature was 460° F. Four hundred and sixty degrees is in the range of skin temperature where hot-surface ignition occurred during the small-scale tests. Since no burn-throughs occurred and the tank vent was not located within the ground fire, hot-surface ignition was considered to be the cause of the reaction.

It should also be noted that the oxygen concentration dropped in various portions of the wing. This also corresponds to the self-inerting phenomenon encountered in the small-scale tests.

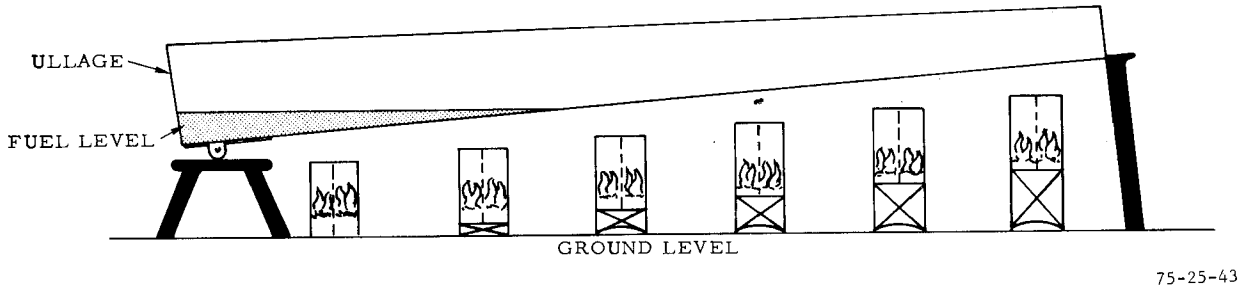


FIGURE 43. C133 WING TEST, FIRST AND SECOND TEST CONFIGURATION

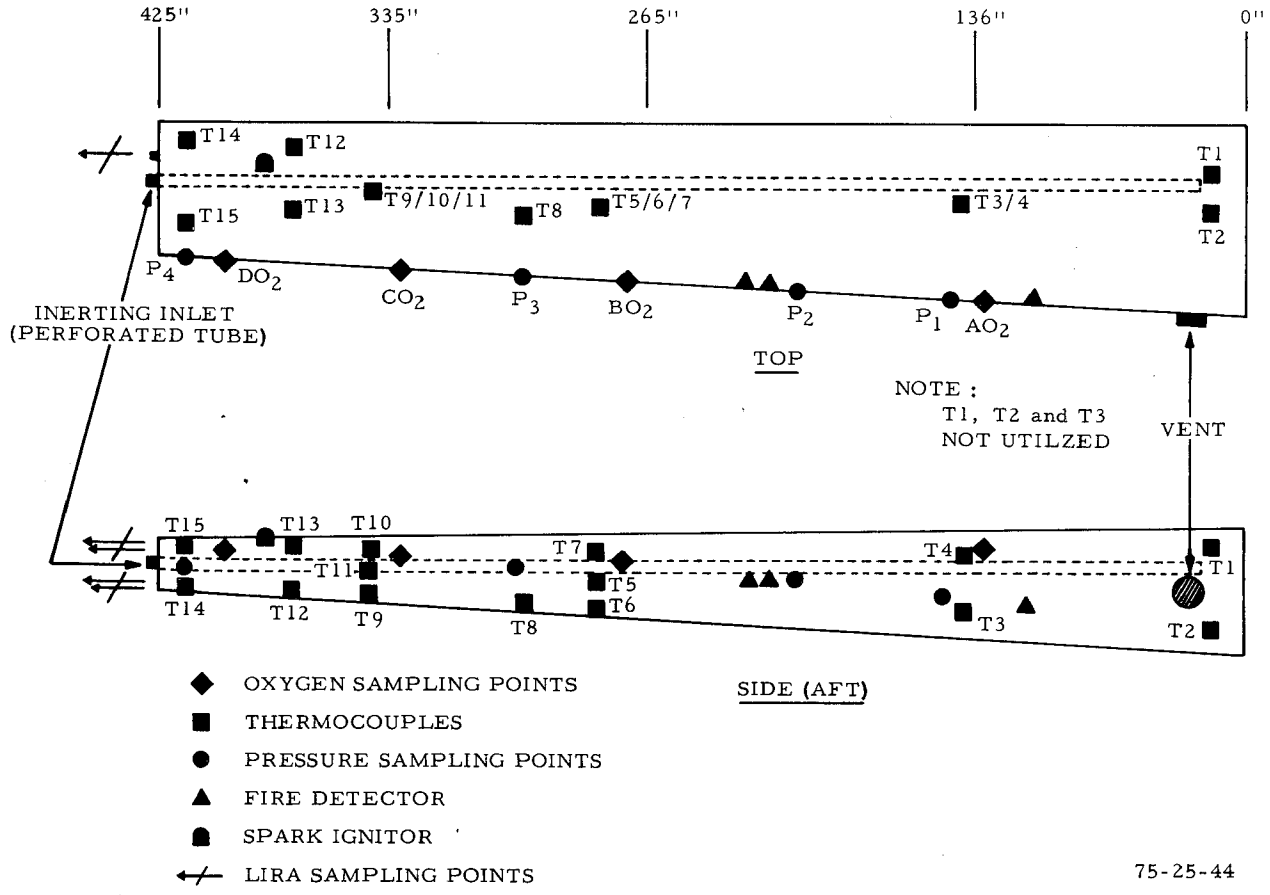
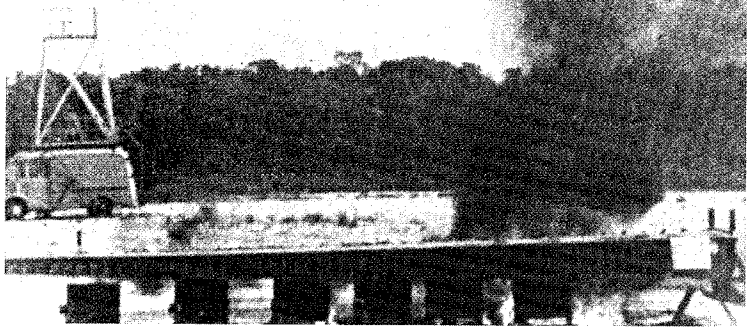
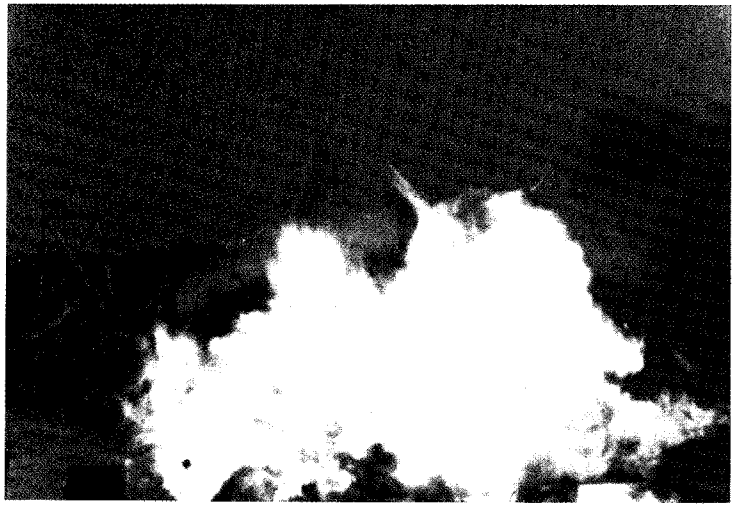


FIGURE 44. C133 WING INSTRUMENTATION LOCATION

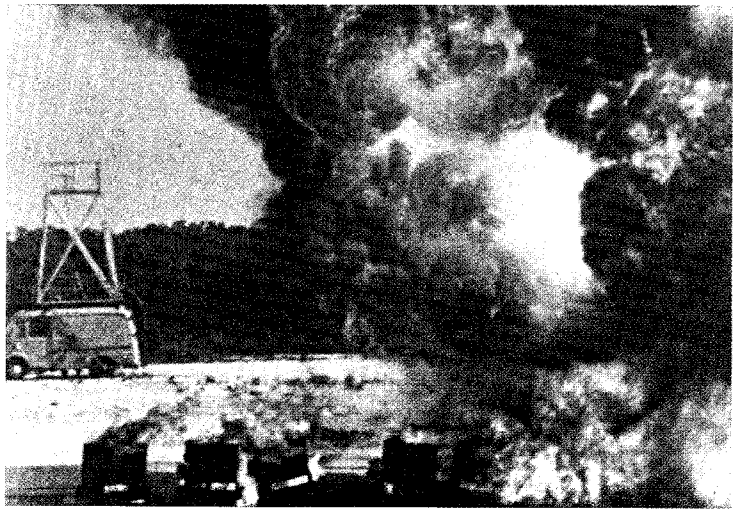


a. PRIOR TO EXPLOSION



b. EXPLOSION FIRST STAGE

c. EXPLOSION SECOND STAGE



d. EXPLOSION THIRD STAGE 75-25-45

FIGURE 45. SEQUENCE OF TANK EXPLOSION, FIRST C133 TEST

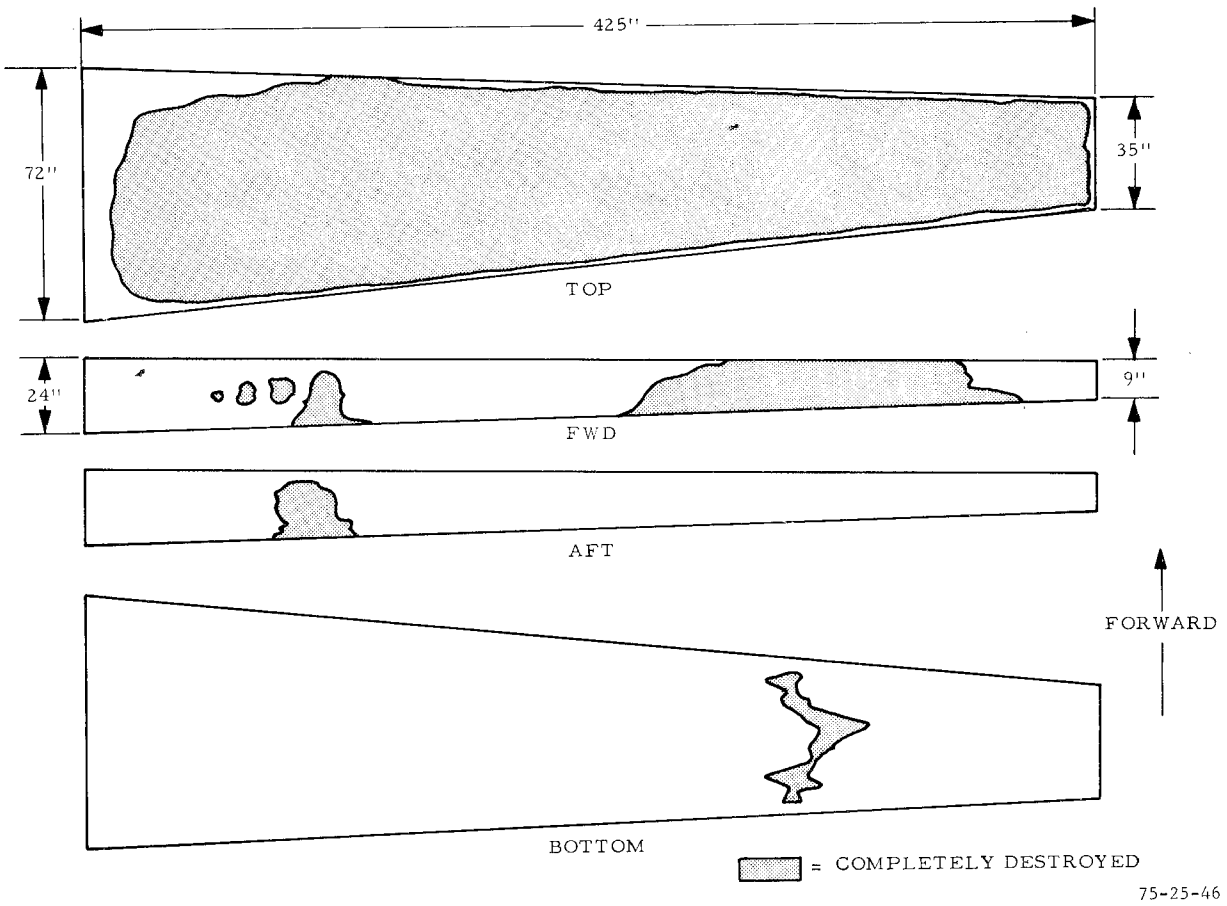


FIGURE 46. RESULTANT DAMAGE, FIRST C133 WING TEST

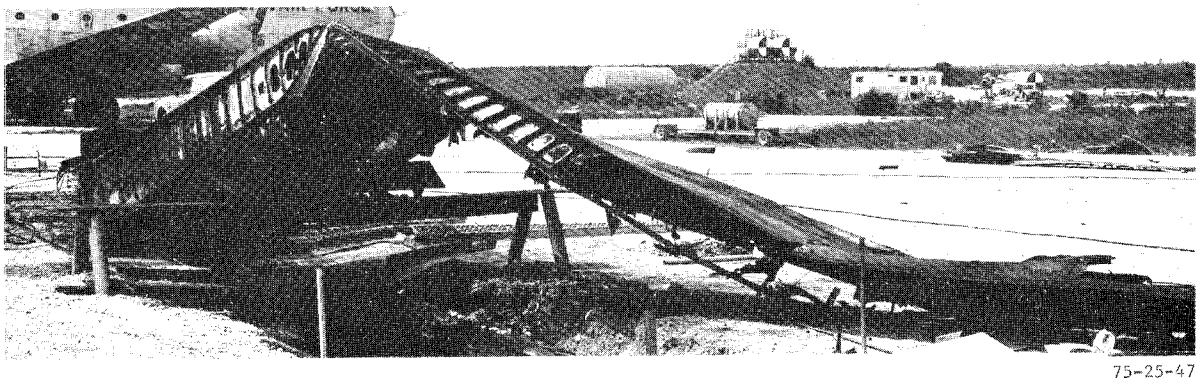


FIGURE 47. POST-TEST DAMAGE, FIRST C133 TEST (FORWARD)

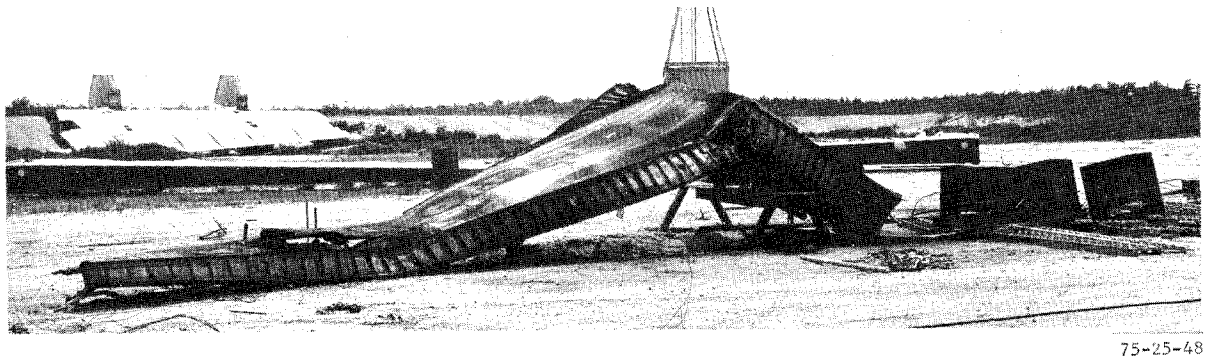


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FIGURE 48. POST-TEST DAMAGE, FIRST C133 TEST (AFT)

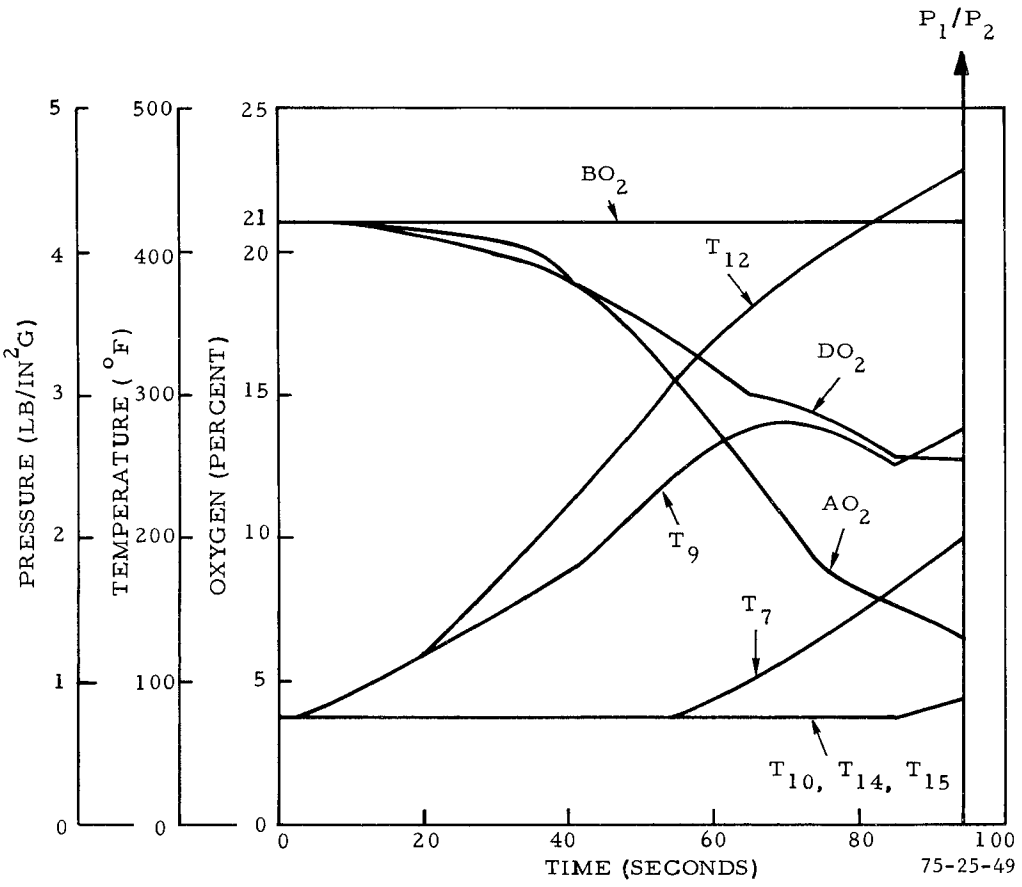

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FIGURE 49. FIRST C133 WING TEST RESULTS

TEST NUMBER TWO. The second C133 test was conducted under the same conditions as the first test, with the only changes being the inerting of the wing to obtain a nominal 9-percent oxygen concentration in the tank ullage, and the installation of a 1.5 lb/in^2g check value at the exit of the tank vent.

Three minutes and fifteen seconds after start of the test a burn-through occurred in the bottom skin of the wing. No reaction was noted in the wing at this time. Figure 50 shows the oxygen concentrations, pressures, and skin and vapor temperatures in the area near the burn-through, from the beginning of the test until after burn-through occurred. Burn-through of the wing was marked by a drop in internal tank pressure and the failure of skin thermocouple T_8 as it neared the melting point of alumimum. It should be noted that the oxygen concentration in the wing varied from 6 to 12 percent, the highest reading being near the bottom skin in the vicinity of the initial burn-through.

The probable cause of this variation in oxygen concentration was the method in which it was introduced into the tank. The inerting line was located near the top of the wing, with the exit holes aimed towards the top surface.

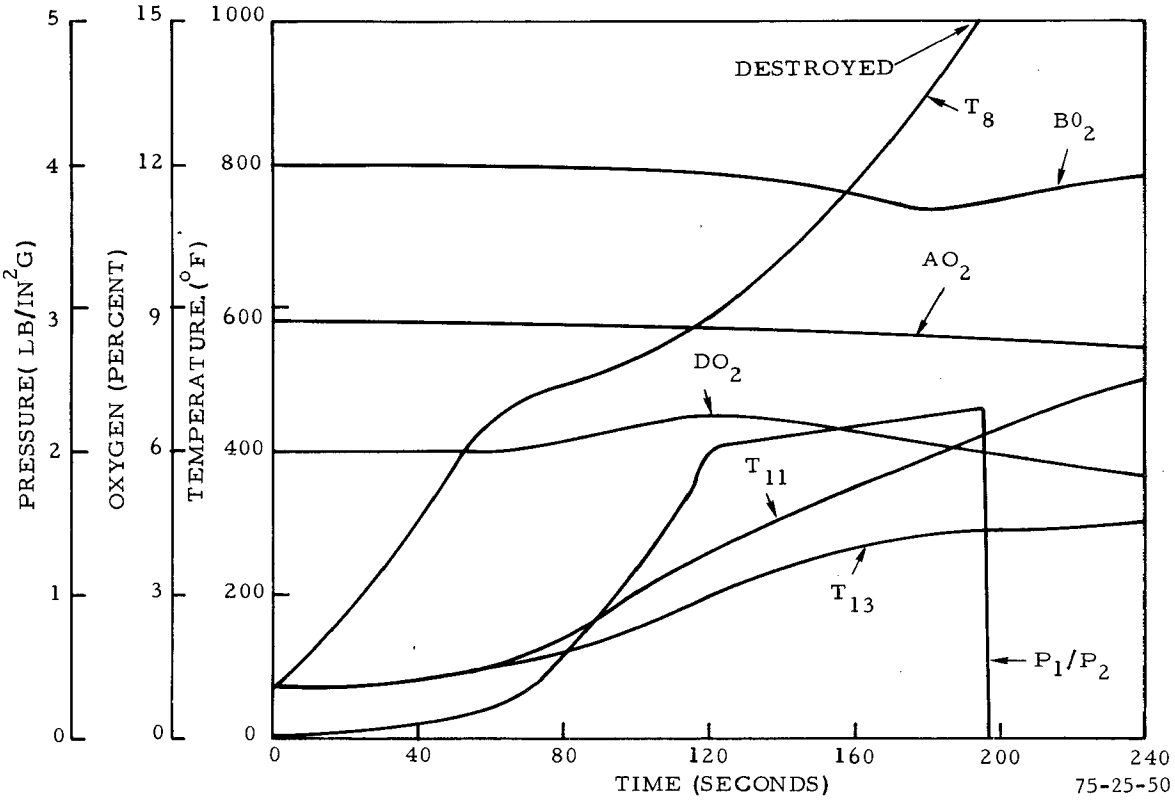


FIGURE 50. SECOND C133 WING TEST RESULTS

Although this condition prevented the desired 9-percent oxygen concentration throughout the wing being attained, it was decided to continue the test. This was done for two reasons, (1) the average concentration was 9 percent, and (2) the highest concentration of oxygen (the most conducive to a reaction) was located just above the bottom skin over a dry area of the wing. That area was the most likly place for hot-surface ignition to begin. Thus the variation in oxygen concentration made the test a more severe measure of the ability of nitrogen inerting to suppress a reaction due to hot-surface ignition.

The oxygen concentration in the intact portion of the wing slowly dropped to near zero (figure 51). The burners remained on for 18 minutes and the wing was allowed to burn for another 6 minutes after the burners had been extinguished. Figure 52 depicts the damage to the wing and figure 53 shows the remains after the test. It should be noted that there was no damage to the intact portions of the wing; that is, burn-throughs or buckling of the top skin (as seen in the first DC7 test), thus indicating that inerting had prevented burning inside the wing.

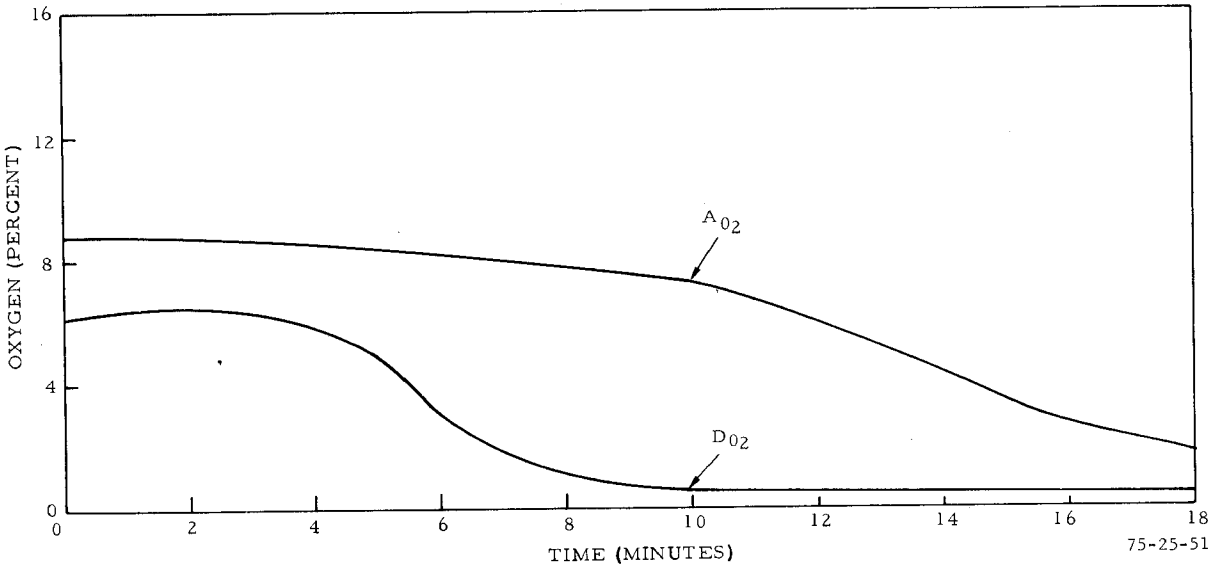


FIGURE 51. OXYGEN CONCENTRATION DURING SECOND C133 WING TEST

TEST NUMBER THREE. The configuration of the third test is shown in figure 54. Two hundred and seventy-five gallons of Jet-A type fuel were used (enough to cover the entire bottom skin of the wing). Because of the inability to obtain a homogeneous mixture of the nitrogen in the second test, a much slower rate of nitrogen flow and a longer "sit time" were employed for the third test. It was decided that in the third test a maximum of 9-percent oxygen concentration should be allowed in any monitored area of the wing. The deviation obtained during the test can be seen in figure 55, varying from a maximum of 9 percent to a minimum of 7 percent at the outset of the test.

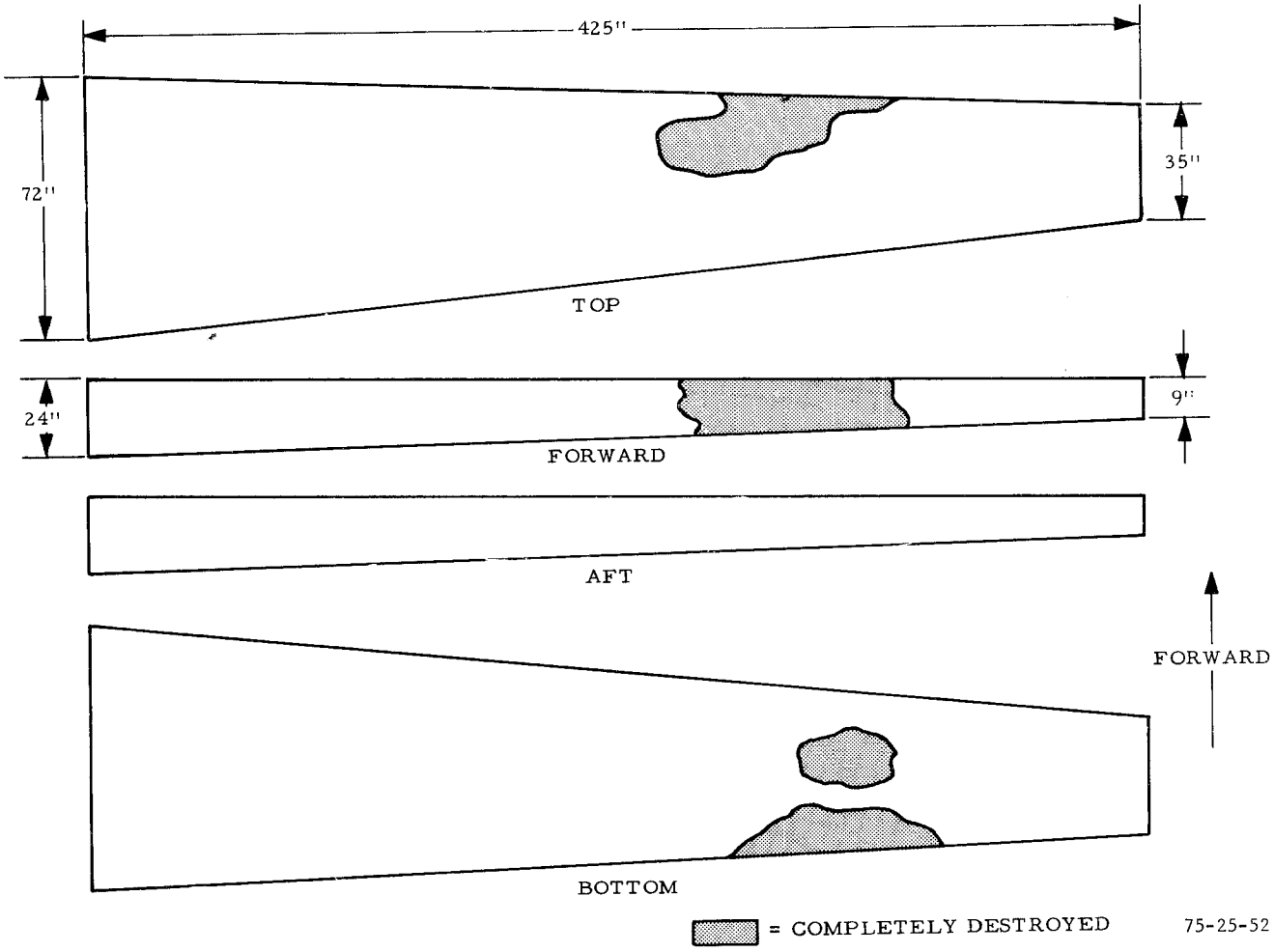
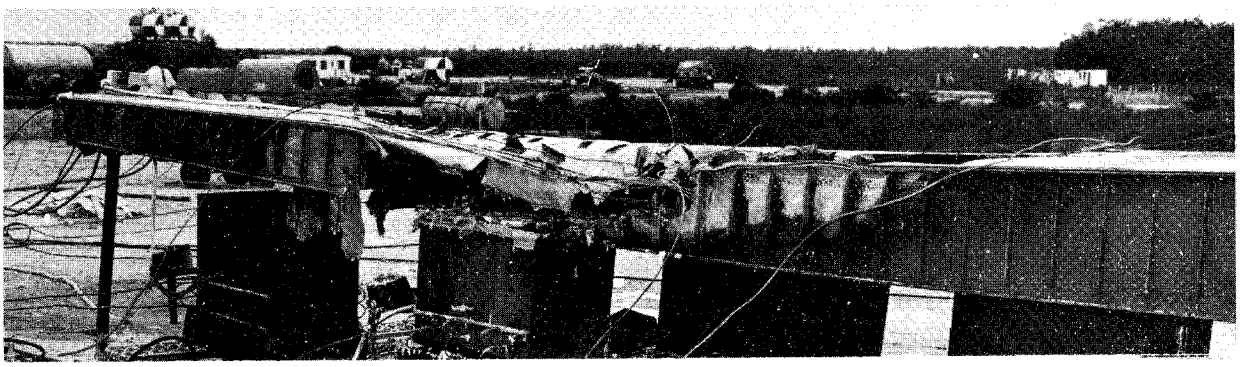


FIGURE 52. RESULTANT DAMAGE, SECOND C133 TEST



75-25-53

FIGURE 53. POST-TEST VIEW, SECOND C133 TEST

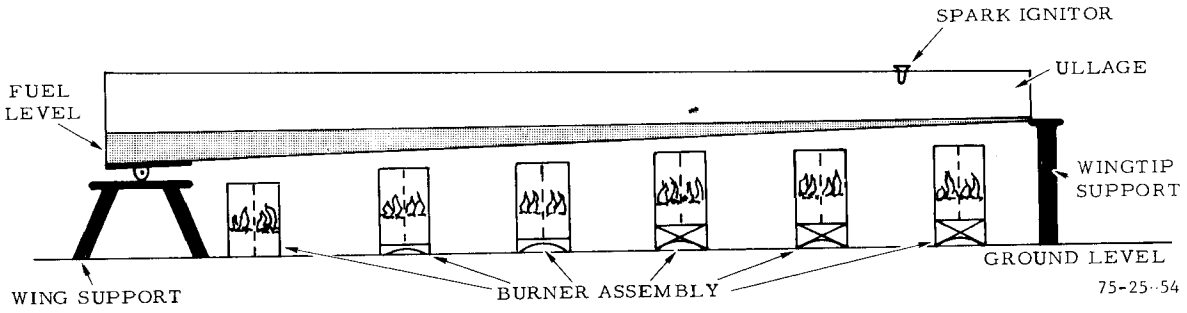


FIGURE 54. C133 WING TEST, THIRD AND FOURTH TEST CONFIGURATION

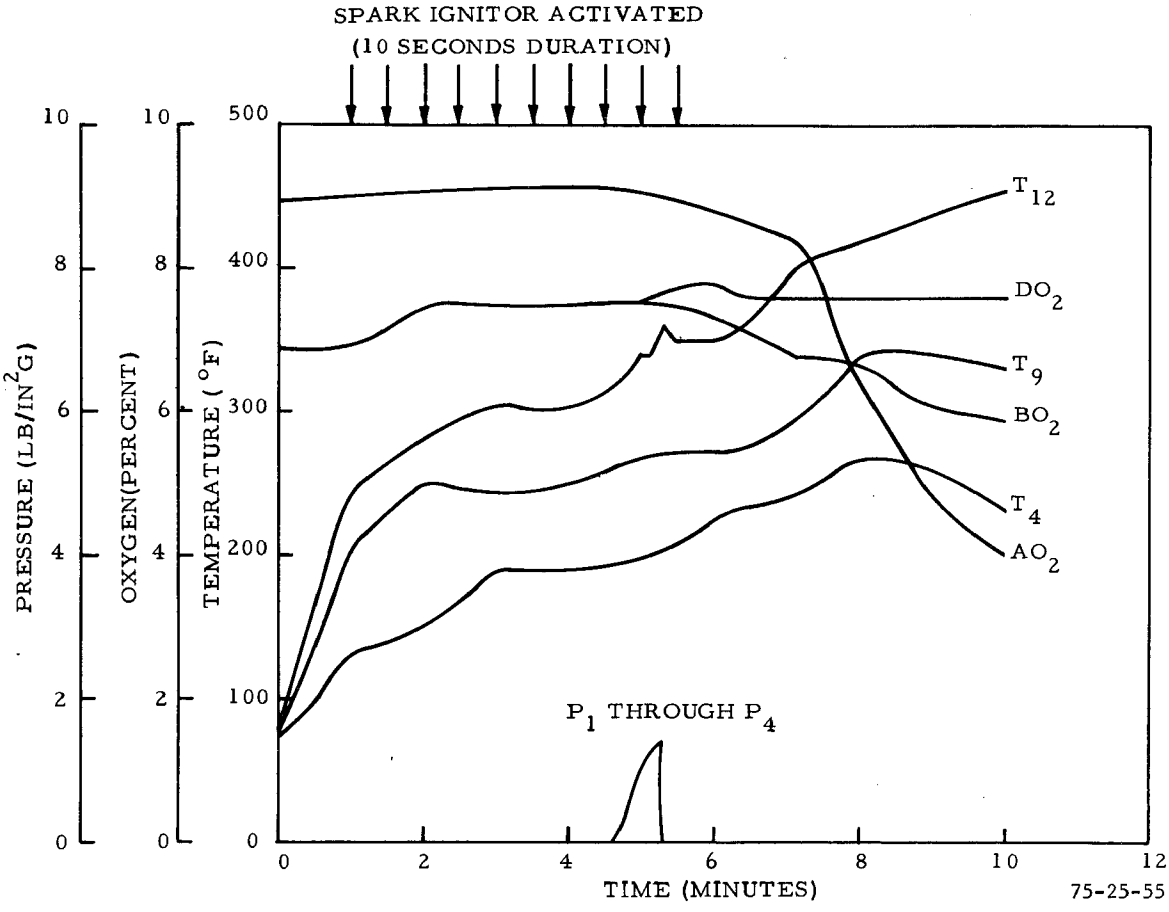


FIGURE 55. THIRD C133 WING TEST RESULTS

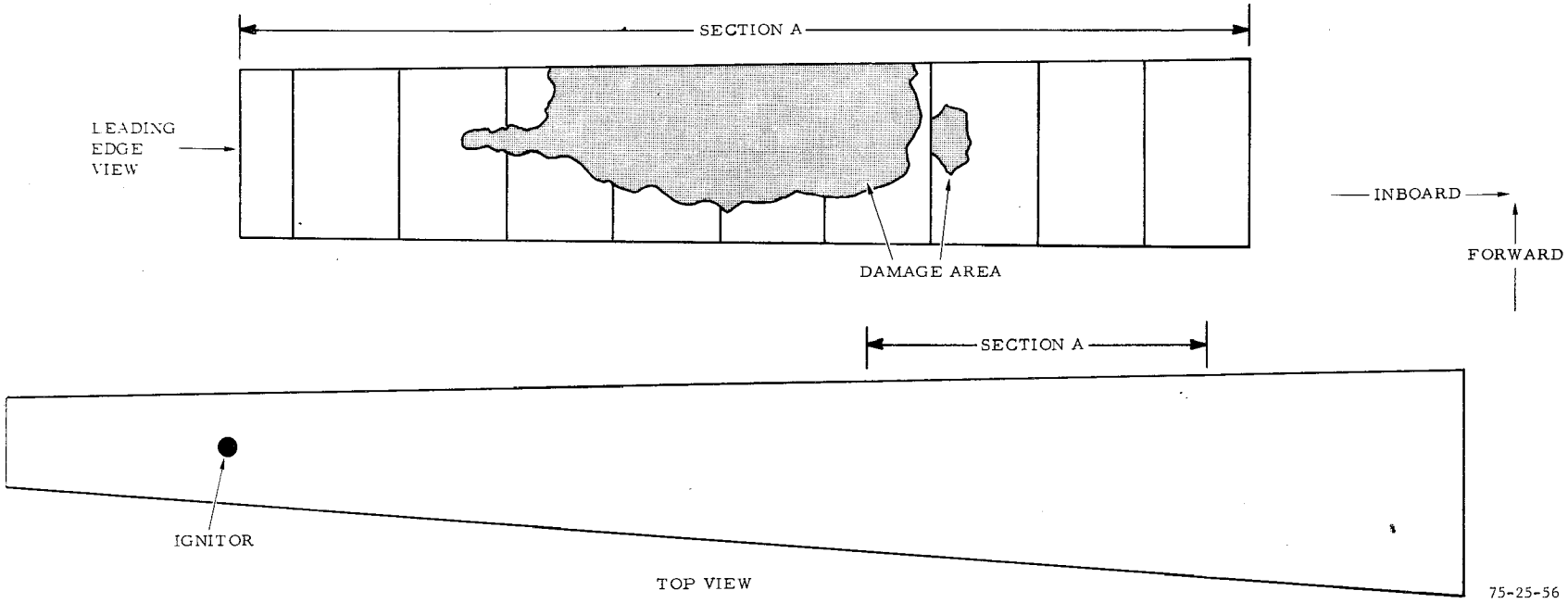


FIGURE 56. RESULTANT DAMAGE, THIRD C133 TEST

A high-energy (2-joule), intermittent spark was generated in the tank every 30 seconds (for a duration of 10 seconds), from 1 minute after the start of the test until just after burn-through occurred. There was no reaction in the tank as a result of the spark. Burn-through occurred at approximately 5 minutes and 15 seconds into the test. The burn-through was located in the tank forward sidewall, above the fuel level (figure 56). A slight temperature and oxygen rise (figure 55) accompanied the pressure loss due to burn-through. Torching was seen emanating from the burn-through opening during the test, and continued after the burners were extinguished. As with the second C133 test, there was no indication of any internal fire in the wing (figure 57). The torching had the same effect as seen in the small-scale tests when burn-through occurred.

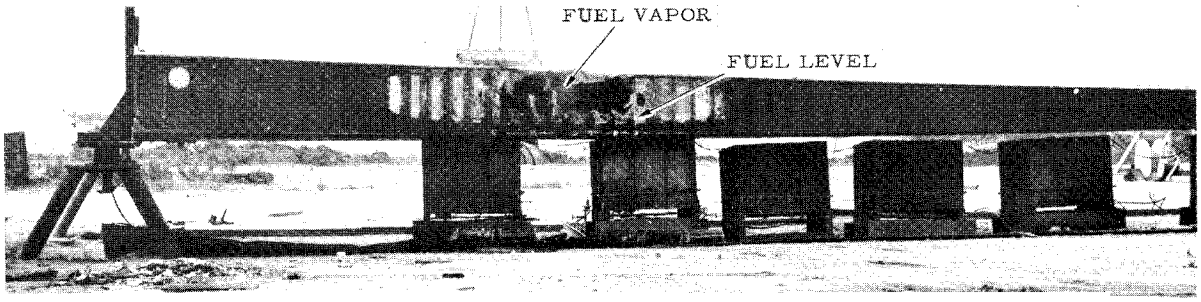


FIGURE 57. POST-TEST VIEW, THIRD C133 TEST

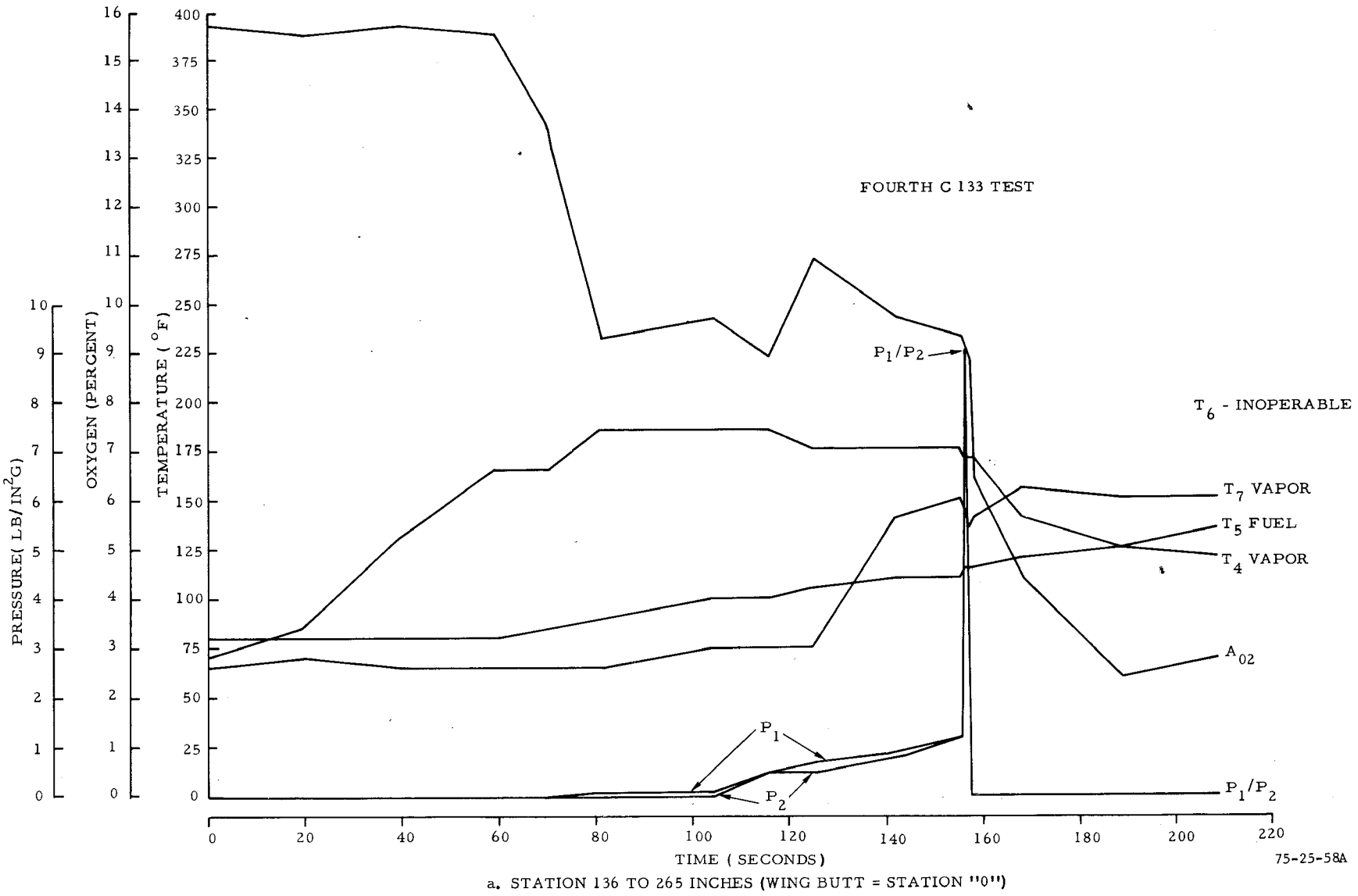
TEST NUMBER FOUR. The final large-scale test (fourth C133 test) was a repeat of the third C133 test except that a nominal 15-percent oxygen concentration was used. As in the third test, 275 gallons of Jet-A type fuel were used and a 2-joule spark was activated at intervals in the tank during the test. The oxygen concentration, at the start of the test, varied from 14.5 to 16 percent (figure 58).

The first activation of the spark ignitor brought no reaction. The second activation of the spark caused a 10 lb/in^2g reaction in the wing. The tank aft sidewall was ruptured and a large torching flame emanated from the opening and self-extinguished almost instantly.

The sharp drop in the oxygen concentration recorded on sensor AO_2 prior to the reaction can probably be explained best by the fact that the burner flames were impinging on the AO_2 sample line.

Figure 59 represents the damage to the wing caused by the reaction, and figure 60 is a photo taken after the test.

Upon analysis of the data, the reaction was analyzed as follows: At time "0" ($\approx$ 155 seconds into the test) a 2-joule spark was generated near the top skin of the wing, as shown in figure 61. Five-tenths of a second after initial activation of the spark, the fuel vapor in the immediate vicinity



a. STATION 136 TO 265 INCHES (WING BUTT = STATION "0")

FIGURE 58. FOURTH C133 WING TEST RESULTS (Sheet 1 of 3)

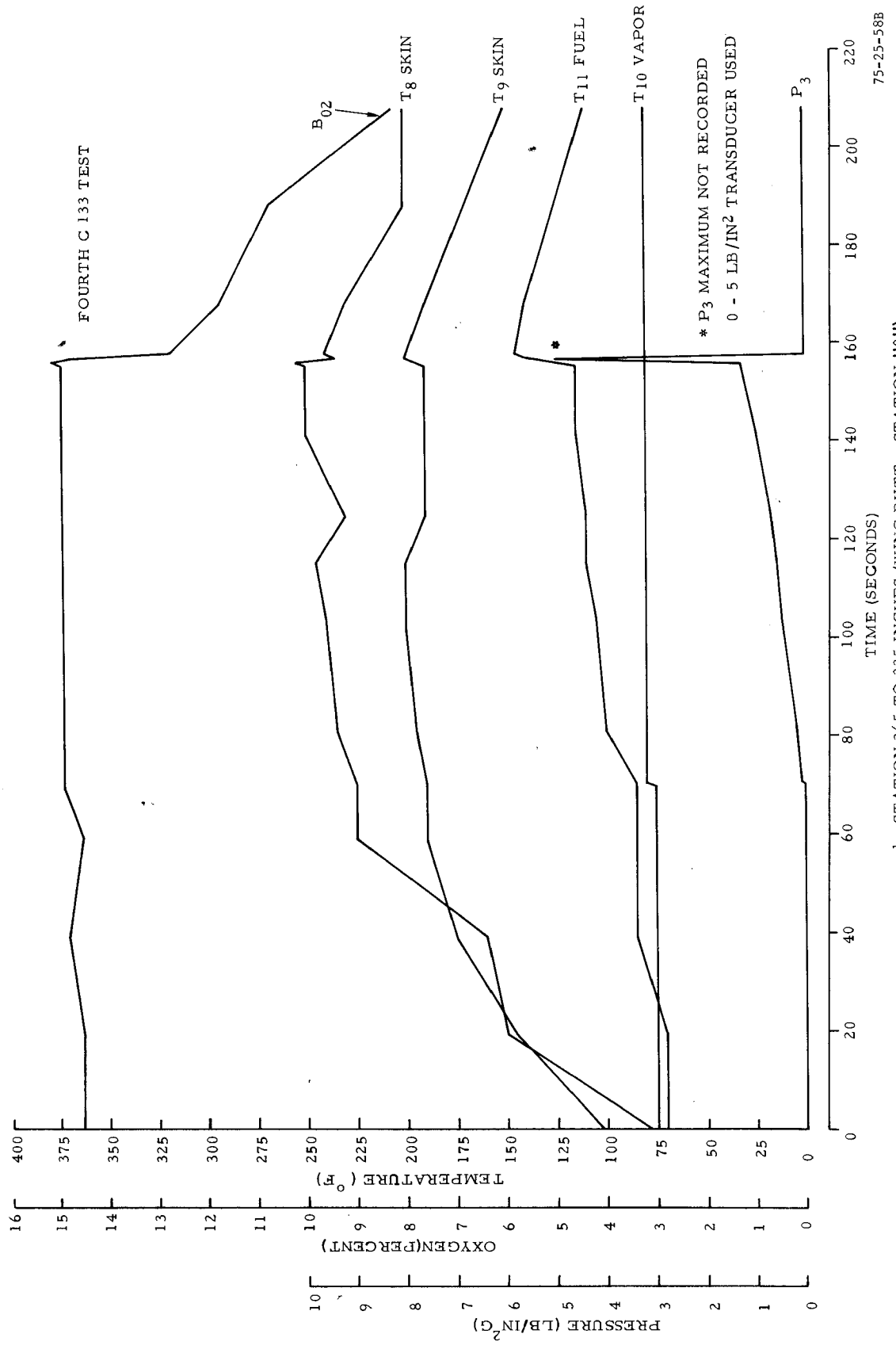
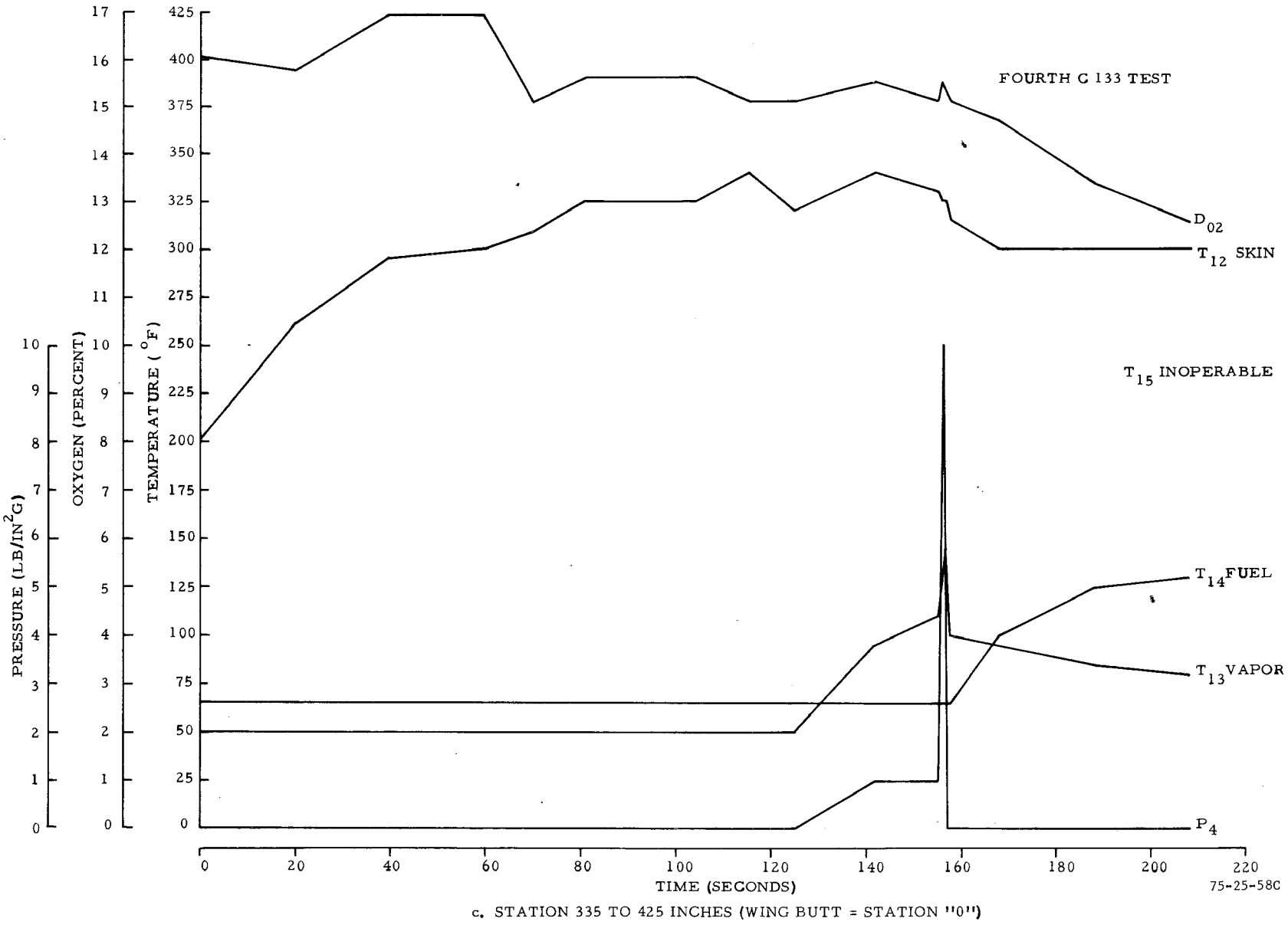


FIGURE 58. FOURTH C133 WING TEST RESULTS (Sheet 2 of 3)



c. STATION 335 TO 425 INCHES (WING BUTT = STATION "0")

FIGURE 58. FOURTH C133 WING TEST RESULTS (Sheet 3 of 3)

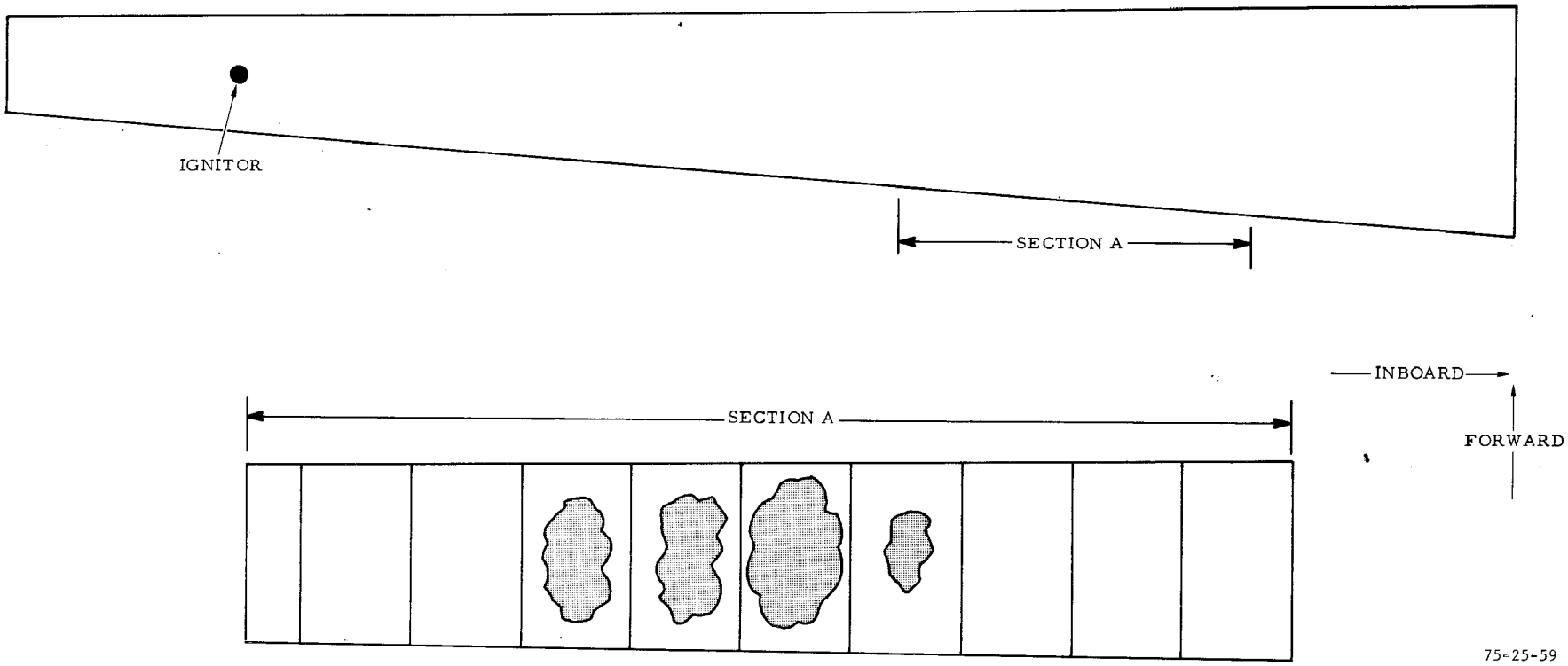


FIGURE 59. RESULTANT DAMAGE, FOURTH C133 TEST

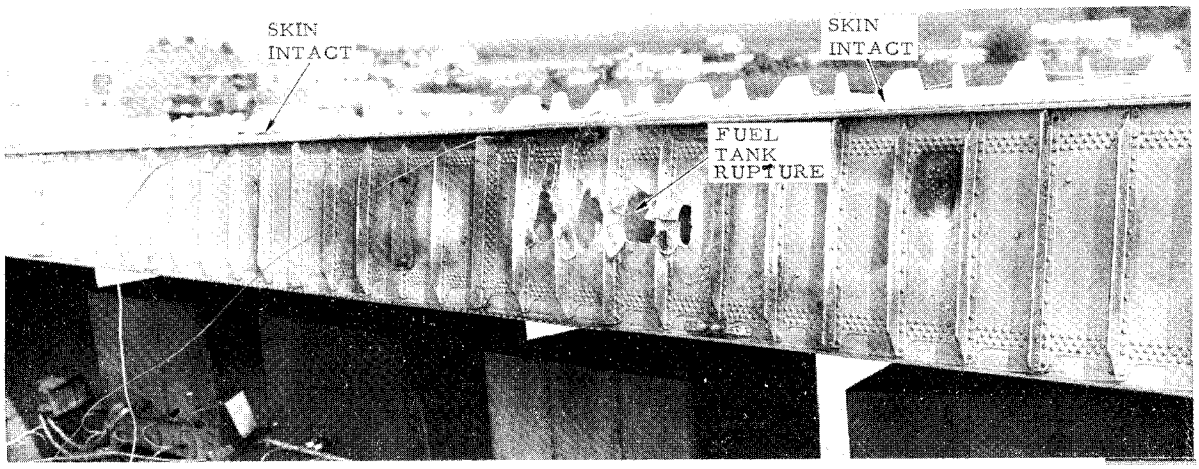


FIGURE 60. POST-TEST VIEW, FOURTH C133 TEST

of the spark ignited. At 0.75 seconds the flame front had moved approximately 4 feet down the wing, and the pressure began to build in the vicinity of the ignitor. One second after spark activation the pressure front began to propagate down the wing. By 1.25 seconds the pressure front had reached half-way down the wing with the temperature front lagging behind. The pressure front had reached both ends of the wing by 1.50 seconds with the thermal front being only about half-way down the wing. When rupture of the tank occurred, at 1.66 seconds, the pressure had reached between 9 and 10 lb/in^2g throughout the wing, but the thermal front had only propagated as far as the rupture in the tank, station 291. No significant increase in temperature was noted between stations 291 and 425 due to the reaction in the tank.

The fourth C133 test showed the usefulness of partial inerting. With a nominal oxygen concentration of 15 percent the reaction was greatly reduced, although not completly averted.

COMPARISON OF RESULTS (SMALL-SCALE AND FULL-SCALE)

The results of the full-scale tests show that the small-scale test results should be valid for full-size aircraft fuel tanks. Burn-throughs into an uninerted tank failed to produce any significant reaction in either full- or small-scale tests. Hot-surface ignitions were obtained in uninerted tanks in both test phases. No reaction was noted in either the full- or small-scale tanks, from hot-surface or spark-ignition, when the O_2 was 9 percent or lower. A full-scale test, using a spark ignition, at 15 percent O_2 concentration produced a mild explosion. Small-scale tests under similar conditions produced rupture of the blowout panel. Since the blowout panel was designed to relieve at 4 lb/in^2g, no difference could be seen in the small-scale tests between an explosion at 21 or 15 percent although a difference could have and probably did exist. Similarities could also be seen between the two phases in the drop in O_2 concentrations due to a slow oxidation.

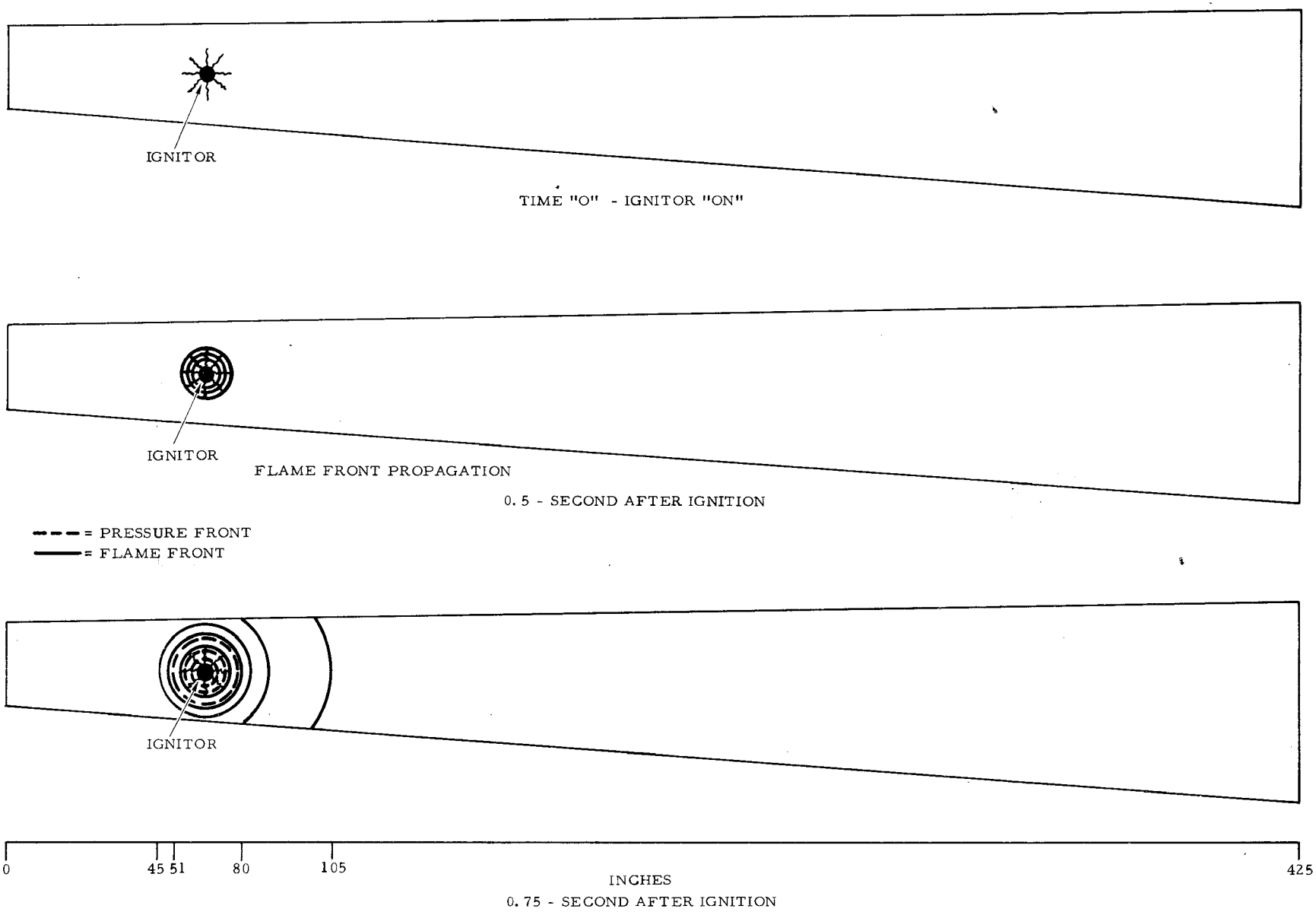


FIGURE 61. FOURTH C133 TEST IGNITION SEQUENCE (Sheet 1 of 3)

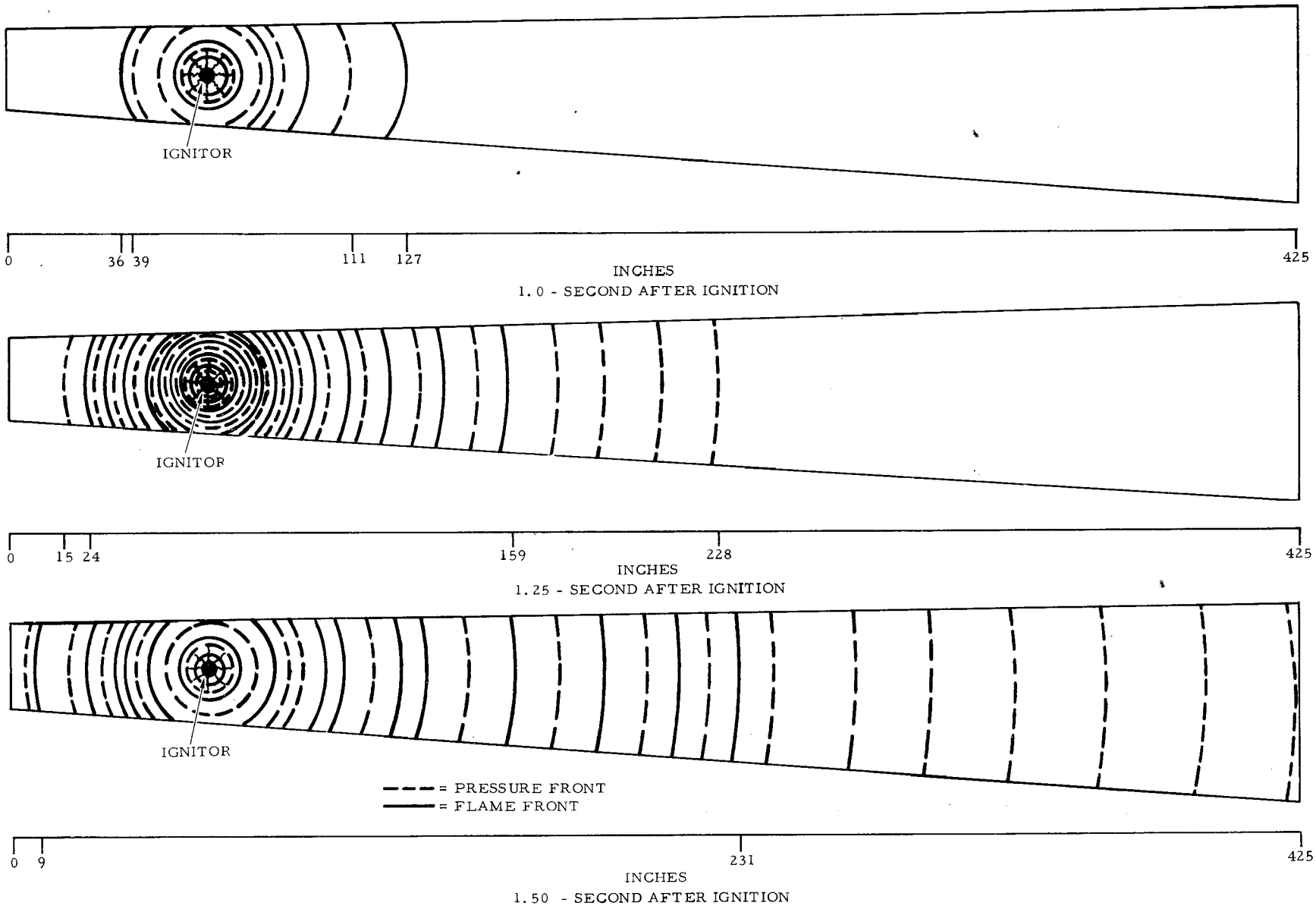


FIGURE 61. FOURTH C133 TEST IGNITION SEQUENCE (Sheet 2 of 3)

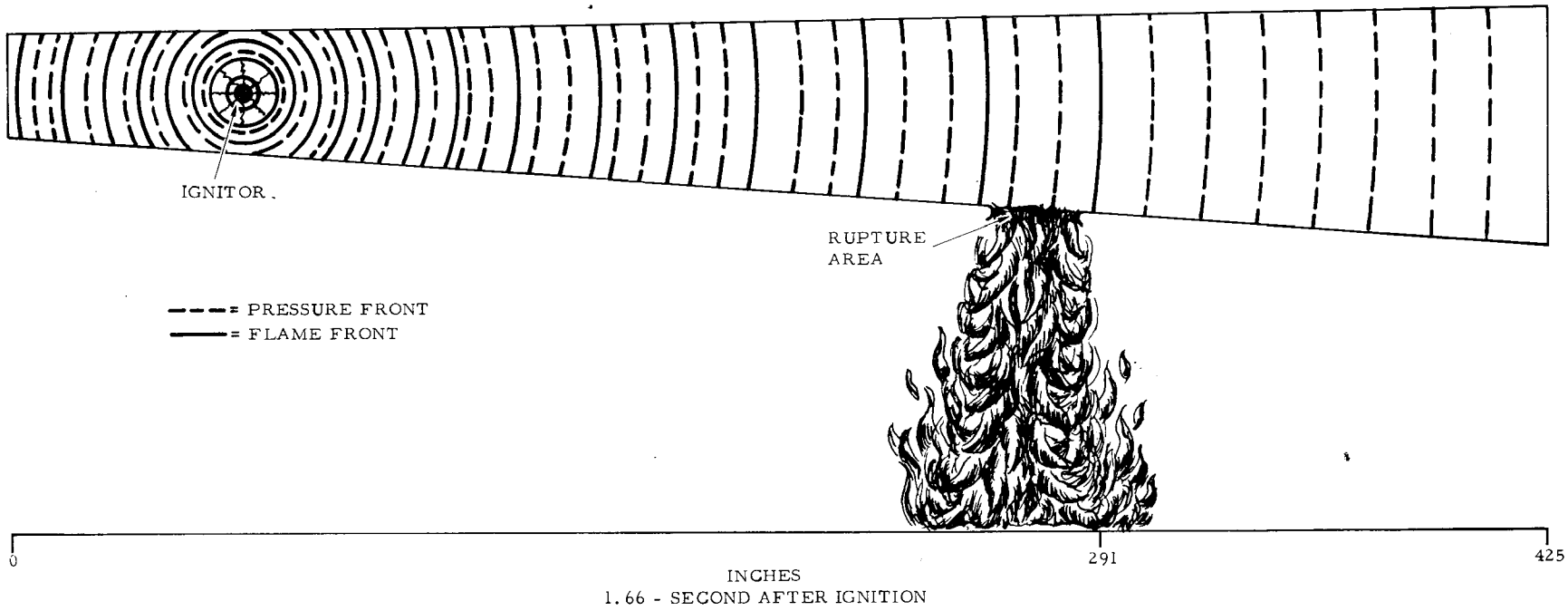


FIGURE 61. FOURTH C133 TEST IGNITION SEQUENCE (Sheet 3 of 3)

SUMMARY OF TEST RESULTS

The results of the test program conducted are as follows:

SMALL-SCALE TESTS.

1. Explosions at fuel tank skin temperatures of less than 500° F and ullage temperatures of less than 300° F, from hot-surface ignition, did not occur when the O_2 concentration was lowered to 18 percent or below.

2. Reactions at fuel tank skin temperatures of less than 500° F and ullage temperatures of less than 300° F, from hot-surface ignition, did not occur when the O_2 was lowered to 12.5 percent or below.

3. Elevated temperature tests (skin temperatures above 500° F and ullage temperatures higher than 300° F) showed that tank explosions could occur at a O_2 concentration of 17 percent, due to hot-surface ignitions.

4. Tests using a spark ignitor proved it to be a more severe ignition source than a hot surface ignition source. For the conditions described in the first result listed above, explosions were recorded with an O_2 concentration as low as 14.5 percent and reactions were recorded as low as 12.5 percent.

5. Elevated temperature tests using a spark ignitor showed that a 10.5-percent O_2 concentration supported an explosion and 10-percent O_2 was the lowest point at which a recorded reaction occurred.

6. There were no recorded reactions during any of the burn-through tests.

7. The rate at which a fuel tank was heated was found to be a determining factor in whether the tank would experience hot-surface ignition (and the intensity of reaction) or not. Slow heating rates produced a compound which formed with the oxygen, and no hot-surface ignition occured. Fast heating rates produced methane and acetylene and a strong autoignition occurred.

8. A slow oxidation occurred when the skin temperature was allowed to rise above 500° F, and the tank began to self-inert.

9. The rate of pressure rise due to hot-surface ignition varied with the type of fuel. JP-4 had the slowest rise, Avtur-50 next, and domestic Jet-A the fastest rise.

10. Based on the data collected and presented in the report it was found the inerting requirements for small-scale tests are as presented in table 5.

TABLE 5. INERTING REQUIREMENTS IN SMALL-SCALE TESTS

Type of Ignition Source	Tank Temperature Range	Oxygen Limit No Explosion (Percent)	Oxygen Limit No Reastion (Percent)
Hot Surface	Skin Less Than 500° F Ullage Less Than 300° F	18	12.5
Hot Surface	Skin Greater Than 500° F Ullage Greater Than 300° F	Less Than 17	Not Determined
Spark	Skin Less Than 500° F Ullage Less Than 300° F	14	12
Spark	Skin Greater Than 500° F Ullage Greater Than 300° F	10.4	9.9
Burn-through	Skin Greater Than 500° F Ullage Greater Than 300° F	No Explosion	No Reaction

TABLE 6. LARGE-SCALE TEST RESULTS

Type of Ignition Source	Tank Temperature Range	Oxygen Concentration (Percent)	Results
Burn-through	Skin Greater Than 500° F Ullage Greater Than 300° F	21	Fire in Wing No Pressure Rise Noted
Hot Surface	Skin Less Than 500° F Ullage Less Than 300° F	21	Explosion
Hot Surface	Skin Less Than 500° F Ullage Less Than 300° F	21	Explosion
Hot Surface	Skin Greater Than 500° F Ullage Greater Than 300° F	9	No Reaction Noted
Spark	Skin Greater Than 500° F Ullage Greater Than 300° F	9	No Reaction Noted
Spark	Skin Less Than 500° F Ullage Less Than 300° F	15	Explosion (10 lb/in^2) Reaction

LARGE-SCALE TESTS.

1. Full-scale test results confirmed the validity of the small-scale work and its correlation to full-scale fuel tanks.

2. A full-scale wing tank explosion from hot-surface ignition was demostrated. The ability of a 9-percent O_2 concentration to prevent this occurrence was also demonstrated.

3. The ability of 9-percent O_2 concentration to prevent a reaction in a full-scale wing due to a high-energy spark was also demonstrated.

4. A 15 percent O_2 concentration allowed an explosion due to a high-energy spark, but the magnitude of the explosion was much less than the uninerted wing explosion.

5. Based on the data collected and presented in the report it was found the inerting requirements for large-scale tests are as presented in table 6.

CONCLUSIONS

1. The results of the full-scale tests did not disagree with the results of the small-scale tests, thus giving confidence in the extrapolation of the small-scale test results to larger fuel tanks.

2. A 9-percent or lower O_2 concentration will provide undamaged tank explosion protection during a post-crash fire under all conditions tested.

3. Concentrations as high as 18 percent O_2 will provide limited protection under certain conditions during a post-crash fire.

4. Concentrations of oxygen lower than 12.5 percent will give protection against most conditions experienced during a ground fire.

5. Even though the elevated temperature environment provides the most severe explosive condition and a need for an O_2 concentration of 9 percent or lower, it is also the condition which produces a slow oxidation or self-inerting in the tank. This self-inerting would provide a margin of safety if a 9-percent O_2 concentration was used.

APPENDIX

FUEL ANALYSIS

APPENDIX

FUEL ANALYSIS

SAMPLE No. ⟶	1	2	3	4	5	6
Gravity Specfic 60/60° F	0.7608	0.7932	0.8128	0.8179	0.8155	0.8090
Gravity °Api 60/60°F	54.5	46.9	42.6	41.5	42.0	43.4
Reid Vapor Press. (lb/in^2)	2.04	0.27	0.01	0.01	0.01	0.00
Distillation I.B.P. °F	160	280	300	302	312	314
Percent Over °F						
5	198	326	348	344	355	346
10	212	340	360	354	370	358
20	236	352	374	364	388	372
30	257	362	386	378	404	386
40	280	373	398	389	416	399
50	303	382	410	400	427	414
60	324	392	424	412	440	428
70	344	402	440	428	452	440
80	370	416	458	448	466	454
90	410	436	480	478	486	473
95	456	456	499	502	504	491
End Point	466	472	516	519	521	504
Recovery % Vol.	97.0	98.0	98.7	98.7	98.2	97.0
Residue % Vol.	1.5	1.0	1.3	1.3	1.3	1.5
Loss % Vol.	1.5	1.0	0.0	0.0	0.5	1.5
F.I.A. Saturates % Vol.	81.32	80.13	78.26	77.14	78.50	78.74
Olefins % Vol.	1.00	0.66	1.24	1.43	1.87	1.97
Aromatics % Vol.	17.58	19.21	20.50	21.43	19.63	19.29
Freeze Point °F	N/A	-71.3	-56.7	-74.4	-50.5	-57.3
Flash Point °F	Below RT	119-120	137	135	150	140
Luminometer No.	62	52	44	42	42	61
Auto Ignition Temp. °F	446	437	446	437	437	437

SAMPLE IDENTIFICATION

No.	Fuel	Carrier	A/C Type	A/C No.	Origin	Remarks
1	JP-4				FAA/NAFEC	
2	Avtar-50	TWA	B747	N93109	London	Equivalent to Jet-A-1
3	Jet-A	TWA	DC9	N5329	Chicago	
4	Jet-A-1	TWA	B707	N7587TW	San Francisco	
5	Jet-A				FAA/NAFEC	
6	Jet-A	TWA	DC9	N1070T	Cincinnati	