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Report No. NA–69–32

(DS–68–20)

FINAL REPORT

Contract No. FA67WA–1704

Project No. 520-002-07X

STUDY OF FLAME PROPAGATION THROUGH AIRCRAFT VENT SYSTEMS

AUGUST 1969

PREPARED FOR

DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION
NATIONAL AVIATION FACILITIES EXPERIMENTAL CENTER
Atlantic City, New Jersey 08405

by

FENWAL INCORPORATED
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Ashland, Mass. 01721

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Prepared by:
J. P. Gillis

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FOREWORD

The report was prepared by Fenwal Incorporated, Division of Walter Kidde and Company, for the Federal Aviation Administration. The work was part of a program of the Engineering and Safety Division, Aircraft Development Service, Washington, D. C. Technical direction and review for the project was furnished by the Instruments and Equipment Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

ABSTRACT

A study was made of flame propagation in a simulated aircraft vent system to provide design criteria for future vent system installations in aircraft. Determinations were made of flame speeds in various sections of the vent system under conditions of ascent, descent and aircraft-on-ground. Temperature and altitude effect on flame speed were also investigated.

The geometric configuration of the simulated vent system caused momentary flame speeds in excess of 1000 feet per second and the associated pressures developed in some instances exceeded the structural limitations of typical aircraft vent ducts.

Conclusions indicate methods of reducing flame propagation speed in aircraft vent systems.

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INTRODUCTION

The purpose of this program was to investigate flame propagation in the vent systems of turbine aircraft under simulated flight and ground operating conditions. The function of a venting system is to keep the pressure differential across the walls of aircraft fuel tanks to a minimum during refueling and during the most rapid altitude changes that the aircraft can experience. The vent systems are often designed to prevent spillage of liquid fuel from the aircraft by the utilization of dead-ended sections of vent ductwork and/or fuel slosh collection tanks.

The hazard associated with aircraft fuel vent systems is attributed to the fact that the fuel vapors handled by the vent systems are flammable in air under certain conditions. When these conditions exist and an ignition source of sufficient energy is present, the fuel vapor-air mixture will ignite. The combustion process following ignition in a mock-up aircraft vent system has been investigated and is the subject of this report.

The presence of a flammable fuel vapor-air mixture in an aircraft vent system is dependent on a multitude of variables such as the type and condition of the fuel, the fuel/air ratio, the fuel temperature, aircraft altitude and condition of flight and many others. The complexity and broad range of these variables make it extremely difficult to predict the presence or absence of a flammable mixture in an aircraft vent system at specific conditions of flight. The effects of these variables are discussed in this report. In the test portion of this program, however, a concerted effort was made to simulate the most hazardous flammable mixtures that could be achieved in a typical aircraft vent system.

ASPECTS OF FUEL FLAMMABILITY

Limits of Flammability

The flammable limits of a combustible vapor in air may be defined as a range of combustible concentrations, expressed in volume percent, in which flame will propagate independent of the initial ignition source. The combustible-lean end of this range is known as the lower limit of flammability and the most concentrated vapor end of the range is called the upper flammable limit.

The determination and reporting of flammable limits of vapors and gases normally assumes standard conditions of temperature and pressure. In the case of vaporizing liquids, the vapor fractions attainable at a specific temperature are limited by the vapor pressure exerted by the liquid at that temperature. This may dictate that the upper flammable limit or both lower and upper limit be determined at an elevated temperature. As a result, the flammable limits of vaporizing liquids are often expressed in terms of a temperature range. The flammable temperature range is defined as the liquid temperature range at sea level, within which the vapor in equilibrium with the fuel will form a flammable mixture with air.

The approximate flammable temperature range for JP-4 fuel is $-20^{\circ}F$ to $+60^{\circ}F$ and for JP-5 fuel is $110^{\circ}F$ to $180^{\circ}F$.

Altitude Effect

The flammable temperature range of aircraft fuels at equilibrium conditions narrows with increasing altitude and the entire range shifts slightly in the direction of lower temperatures. This downward shift is attributed to the fact that at a given temperature, the fuel vapor pressure remains constant and as the total mixture pressure decreases, the fuel vapor concentration increases. Both the lower and upper flammable concentrations are obtained at lower temperatures.

Another important influence exerted by altitude on fuel flammability is its effect on solubility of gases in the liquid fuel. All hydrocarbon fuels have the capacity to dissolve gases. The solubility is dependent on the partial pressure exerted on the fuel by the gas. When the partial pressure of the gas above the fuel is reduced, the dissolved gas begins to be released from solution. Oxygen is more soluble in hydrocarbon fuels than nitrogen. Thus the vapor space in the fuel tank of an ascending aircraft can become oxygen enriched when dissolved gases are released from solution. The presence of the additional oxygen tends to widen the flammable temperature range.

Turbulence Effect

The flammable temperature limits of aircraft fuels have been determined and reported by various laboratories and agencies. Although some discrepancies have been observed in the data obtained, most of the data appear to be in agreement within the normal tolerances of accuracy associated with experimental procedures. It is important to realize that the majority of the published information relates to flammability limits determined under static conditions whereas the fuel in an aircraft tank is subject to dynamic conditions. Dynamic conditions in a fuel tank can produce sprays which cause a significant expansion (at least 50%) of the temperature range at which the tank vapor space is in a flammable condition. This expansion occurs at the lean limit of the flammability envelope.

During aircraft climb the concentration of fuel vapors in a tank can be lower than that which would exist under equilibrium conditions. During aircraft descent, an overrich fuel air mixture is fed with air which can cause the mixture to become flammable until the temperature increases and attains a new overrich equilibrium condition appropriate to the fuel.

The difficulties of theoretically determining the conditions of flammability within an aircraft fuel tank are further compounded by a number of other variables such as fuel storage temperature, fuel weathering, vapor stratification and the use of two different fuels in the same tank. It is therefore not unreasonably conservative to assume that flammable conditions may exist in aircraft fuel tanks and associated vent systems during all modes of flight. The effect of altitude on the range of flammability is shown in Figure No. 1.

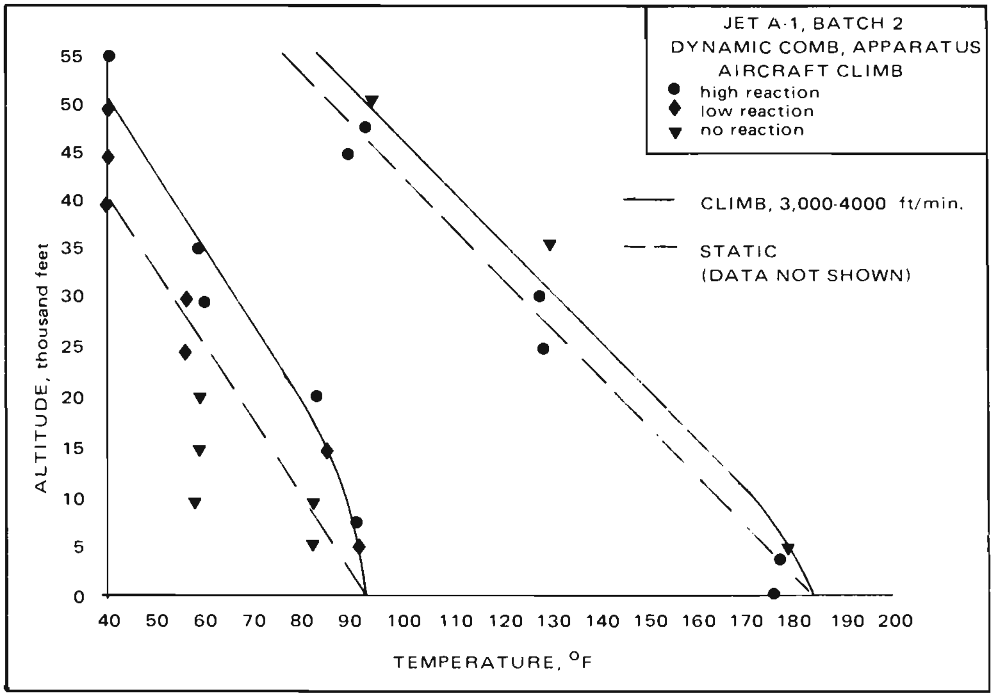

FIGURE 1. - The Relative Flammability Envelope of Jet A-1 During Aircraft Climb.

TESTS IN LARGE SCALE MOCK-UP

Apparatus

Flame propagation studies were conducted in a full scale mock-up of a typical aircraft fuel vent system. Three fuel tanks were simulated by tanks constructed of eight gauge carbon steel, each measuring 48 by 60 by 40 inches. This volume (500 gallons) represents the ullage space which would exist in an aircraft tank under near full conditions. Each tank was provided with an 18 inch diameter vent port which was covered with aluminum foil held in place by a clamp ring. The static vent port relief pressure was approximately 1.0 psig.

The rectangular vent duct, which constituted most of the vent system was constructed of eight gauge carbon steel and measured 2 1/2 by 4 inches in cross section. That portion of the vent system which was composed of circular cross sectional vent ducts was fabricated of 2-5/8 inch O. D., 0.065 inch wall steel tubing.

The vent system was completed with a wing section. This section of wing includes the wing tip, S-tube with vent scoop, fuel slosh collection tank, and outboard reserve tank. The aforementioned components were assembled to this wing section.

Instrumentation

The vent system was equipped with ionization probes so that a determination of flame propagation and velocity could be made. The number and location of the ionization probes was varied throughout the testing so that the maximum amount of useful data could be obtained.

Ionization probes were fabricated from 14 millimeter automotive spark plugs. The center electrodes were extended with stainless steel rods and sharpened at their ends. They were installed in the duct work by screwing them into bosses welded on the side of the duct. At 90 degrees to each installed pair of electrodes, a hole was provided for use in obtaining the proper ionization gap. This hole was closed with a pipe plug when not in use. All of the ionization probes were powered with 510 VDC power supplies. The ionization voltage was fed directly to a recording oscillograph.

The vent duct and fuel tanks were equipped with strain gauge type pressure transducers. The number and location of transducers was also varied throughout testing to provide a complete pressure profile during flame propagation. The transducers were periodically calibrated throughout the test program with a dead weight tester to assure readout accuracy within ±1 psig.

The ignition source was constructed using a pair of ionization probes as electrodes. It was powered by the discharge of two series-wired 525 micro-farad capacitors charged to 900 volts through a 15,000 volt luminous tube transformer. The ignition energy created is approximately 100 joules. Provisions for installing these ignition electrodes were made at the vent scoop outlet, within the fuel tanks and within the duct work.

Ignitor operation, ionization probe operation, and explosion pressure development were monitored and recorded by a Consolidated Electrodynamics Corporation (CE) Type 5-124A Oscillograph. Timing markers were electronically superimposed on the oscillograph chart to provide a time base for all of the events recorded during a test. A sketch of the apparatus is shown in Figure No. 2. Photographs of the apparatus are shown in Figure Nos. 3 and 4.

Auxiliary Test Apparatus

An auxiliary flame propagation apparatus was constructed using the 2-1/2 inch by 4 inch rectangular duct work. The apparatus was 20 feet long and closed at both ends. At one end, which was permanently sealed, the aforementioned ignitor was installed. Six inches from the opposite end, a pair of ionization probes was installed. This apparatus was used to establish that given flammable mixtures will burn and propagate in vent systems. Specifically it was used to establish flame propagation at simulated high altitudes using JP-4 and kerosene as combustibles. The duct end adjacent to the ionization probe was sealed with an aluminum plate. This plate was held in place by pressure differential alone during all of the simulated altitude runs, and was replaced by a foil burst disc during atmospheric pressure experiments. The 20 feet of rectangular duct work was suspended inside of 24 feet of 12 inch diameter circular duct for the purpose of conducting high ambient temperature experiments, i. e. with skin temperatures as high as 140 to 150 degrees Fahrenheit. The 12 inch diameter duct was equipped with thermocouples and a hot air heating system. The closed end of the rectangular duct was also equipped with valves and a manifold for use in evacuating and introducing flammable materials, and for installation of pressure measuring devices. A sketch of this test apparatus is shown in Figure No. 5.

Equipment for Generating Flammable Vapor

Saturated fuel vapor was generated from its liquid phase in a cylindrical shaped steel pressure vessel having a working pressure of 150 psig. The base of the vessel was equipped with a heating jacket. Mechanical mixing of vapor with air in the vessel was provided by a 10 inch stainless steel fan mounted on a pressure tight shaft and feed-through unit, and driven by a 1/3 HP externally mounted electric motor. An air compressor, a laboratory test gauge, and a mercury manometer were connected to the mixing vessel. A pressure transducer was mounted on the vessel for use in measuring pressure decay rate when mixture flow rate determinations were required. After being blended, flammable mixtures were conducted from the cylindrical mixing vessel through a 3 inch ball valve attached to the vessel, and then through 3 inch pipe to an appropriate point in the vent system for use in flame propagation tests. This

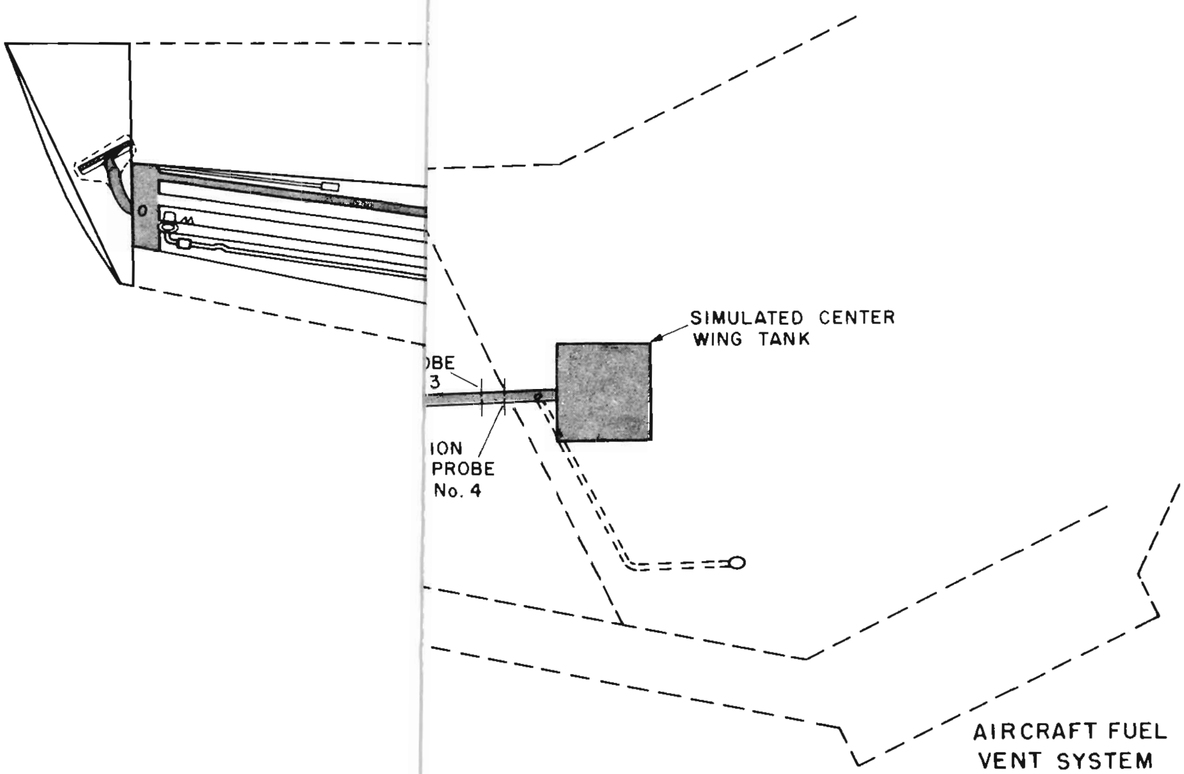

FIGURE 2. - Center Wing Tank
Test Configuration

FIGURE 3. - Simulated Aircraft Vent Systems

FIGURE 4. - Test Apparatus

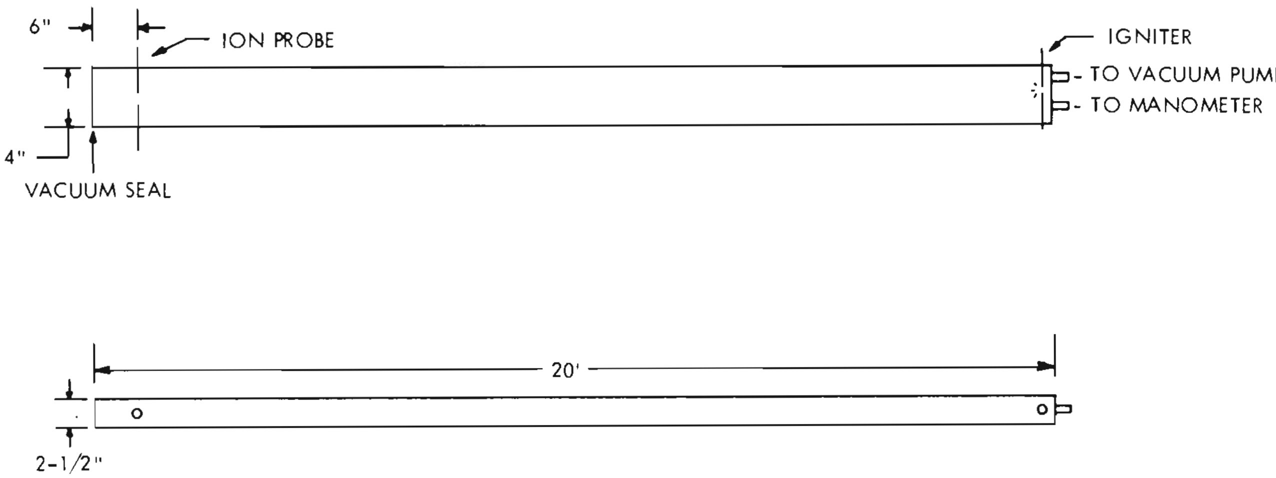

FIGURE 5. - Apparatus for Altitude Tests

vessel enabled the blending of up to 160 cubic feet of stoichiometric (3.5 to 4.0 percent) fuel air mixtures from about ten gallons of the liquid fuel depending on prevailing ambient temperatures. A photograph of this holdup vessel is shown in Figure No. 6.

Procedure

Full Scale Tests

Flame propagation in the large scale mock-up was initially studied by treating each of the three vent system paths as a separate system. This was done to concentrate the instrumentation, and to simplify the creation of fuel mixtures within the vent system. A detailed description of selected tests representing each of the various flight conditions is given below. Data for all tests is given in Appendix I.

Aircraft on Ground

The initial test simulated an aircraft on ground condition with a stationary flammable mixture in the vent system, and with the ignition source in the vent scoop outlet. The first vent system tested served the center wing tank. Four ionization

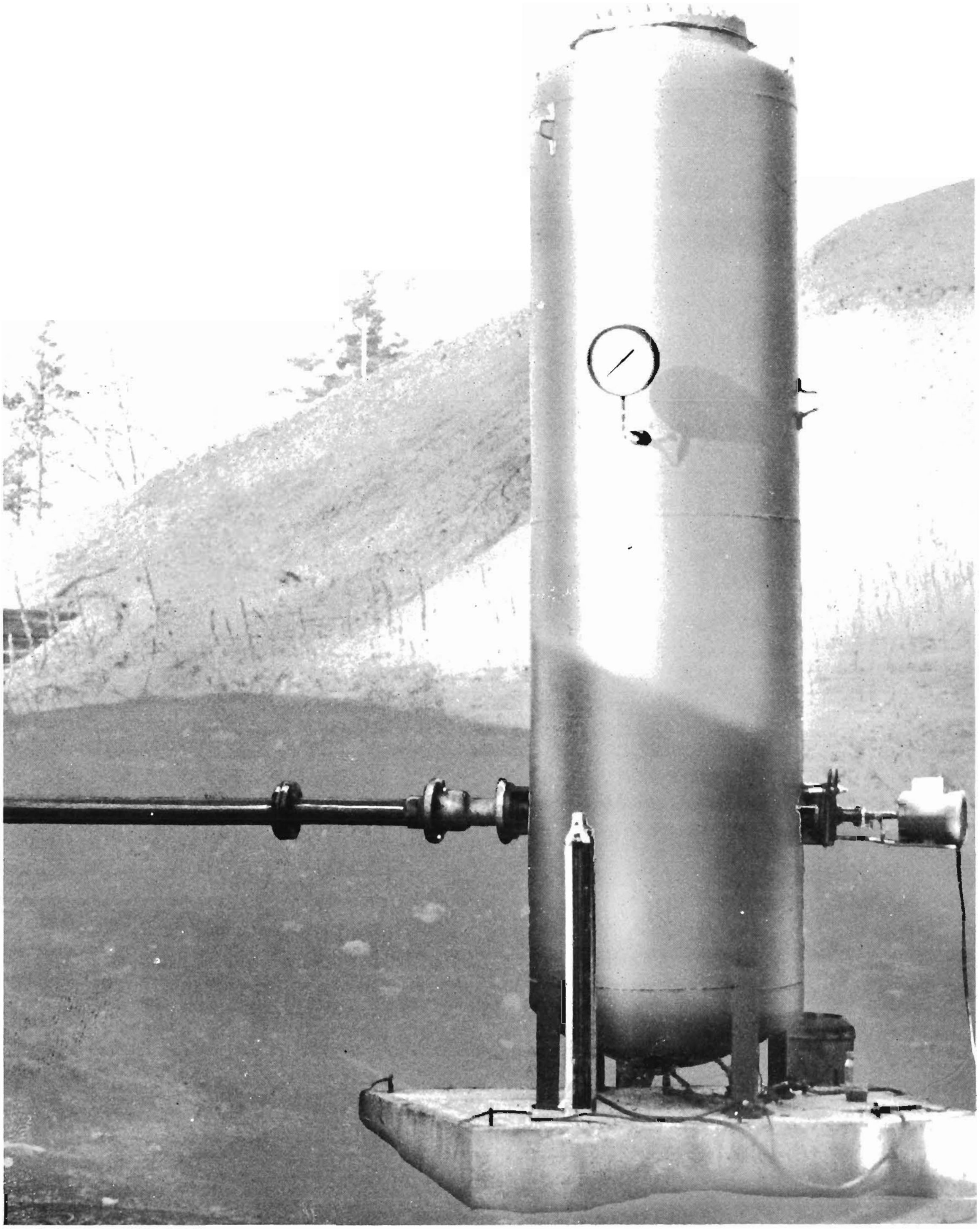

FIGURE 6. - Holdup Vessel for Combustible Mixtures

probes were used, and their locations are indicated in the Table of Results, Run No. 1, and are shown by their designated numbers on the vent system diagram for this test - Figure No. 2. No pressure transducers were used. This test was conducted on a sunny day with an ambient temperature of 80°F. Flame travelled from the point of ignition to probe P_1 in 125 milliseconds for an average flame velocity of 20.8 feet per second. It travelled from ionization probe P_1 to ionization probe P_2 in 290 milliseconds at an average velocity of 3.5 feet per second. From probe P_2 to probe P_3, average flame velocity was 49.7 feet per second. From probe P_3 to probe P_4 the flame travelled at an indicated velocity of 500 feet per second. In this report all instrumentation is located with respect to Aircraft Wing Station Number and is so shown in the Figures and Data Sheets. Wing station numbers are referenced to the fuselage center line and are inches of actual wing length.

A similar test, Run No. 2 on the data sheet, was performed under the same conditions to establish propagation through the vent duct serving main tank No. 4. The test configuration is shown in Figure No. 7.

Flame propagation was then established in the duct serving main tank No. 3. The test configuration is shown in Figure No. 8 and the data given in Run No. 3 of the data tables.

Additional tests were conducted to establish the repeatability of the aforementioned results.

At this point in the test program it became evident that more instrumentation would be necessary to fully determine the nature of the flame propagation. The additional instrumentation consisted of ionization probes and pressure transducers at additional locations to provide more complete data. It was felt that flame velocities previously obtained were not representative of those occurring in the entire duct length. The ionization probes only served to establish the extent of flame propagation. Velocities and acceleration could be determined more precisely with the additional instrumentation.

The fuel vent system was fitted with additional ionization probes and their relative positions are shown in Figures 7, 8 and 9 which show the apparatus and flammable vapor configuration for each of the three vent system paths as they were individually tested. Four pressure transducers were installed, and were placed in the relative positions shown in Figures 7, 8 and 9.

With the new instrumentation installed, a test, Run No. 7 was conducted in the vent system serving the center wing tank. The ambient temperature was 70° and the weather was sunny. The operating condition was that of an aircraft on the ground. The test configuration is depicted in Figure No. 9.

There was no fuel vapor flow. Flame propagated throughout this leg of the vent system. Flame travelled from the vent scoop to the first ionization probe P_1 at an average speed of 7.7 feet per second. It travelled from probe P_1 to probe P_2 at 11.5 feet per second. It travelled from probe P_2 to probe P_3 at 6.7 feet per second. It travelled from probe P_3 to probe P_4, a distance of about seven feet, at an average velocity of 26 feet per second. It passed through the crossover from probe P_4 to probe P_5 at an average velocity of 14-1/2 feet per second. From probe P_5 to probe P_6 an average rate of 28.2 feet per second. From probe P_6 to probe P_7 at an average rate of 94 feet per second, and from probe P_7 to probe P_8 at an indicated rate of 500 feet per second.

In all tests up to this point, the flame could be heard propagating in the vent duct. The audible indication was that the flame decelerated markedly as it passed through the crossover pipe located at the No. 4 main tank before accelerating again in the second length of long duct.

The next test, Run No. 8, was conducted in that section of vent duct serving the center wing tank. The test configuration was that of Figure No. 9. The ambient temperature was 95°F. The weather was sunny. The ignition source was located in the rectangular vent duct at Wing Station No. 663. The ignition source was placed within the duct to simulate a penetration caused by a lightning strike causing subsequent ignition of the JP-4 air mixture contained in the vent duct. There was no flow of vapor in the vent duct at the time of ignition. Flame accelerated from the ignition point to probe P_3 at an average rate of 22.3 feet per second, probe P_3 to probe P_2 at 66.7 feet per second, and probe P_2 to probe P_1 at 130 feet per second. In the opposite direction, the flame accelerated from ignition to probe P_4 at 76.5 feet per second and decelerated from probe P_4 to probe P_5 (through the crossover bypass) to 2.7 feet per second after which the combustion continued in two directions, one direction four feet to a blank end. As the flame started accelerating in the inboard section of rectangular duct, it travelled from probe P_5 to probe P_6 at a rate of 6.9 feet per second, from probe P_6 to probe P_7 at a rate of 200 feet per second and from probe P_7 to probe P_8 at an indicated 500 feet per second. The pressure reached 6.4 psig at position Pr_2 at the end of the first long stretch of rectangular duct work. Pressure in the middle of the duct reached 6.3 psig at position Pr_1 while the pressure in the second leg of long duct work reached 5.7 psig at position Pr_3 and in the simulated center tank itself reached 3.5 psig at position Pr_4.

A test, Run No. 10, under the same condition was conducted in the leg of duct work serving No. 3 main tank. The test configuration was that shown in Figure No. 8. The point of ignition was inside the duct at Wing Station No. 203.

Repeats of tests, described above, were conducted and are listed in the data tables with their results.

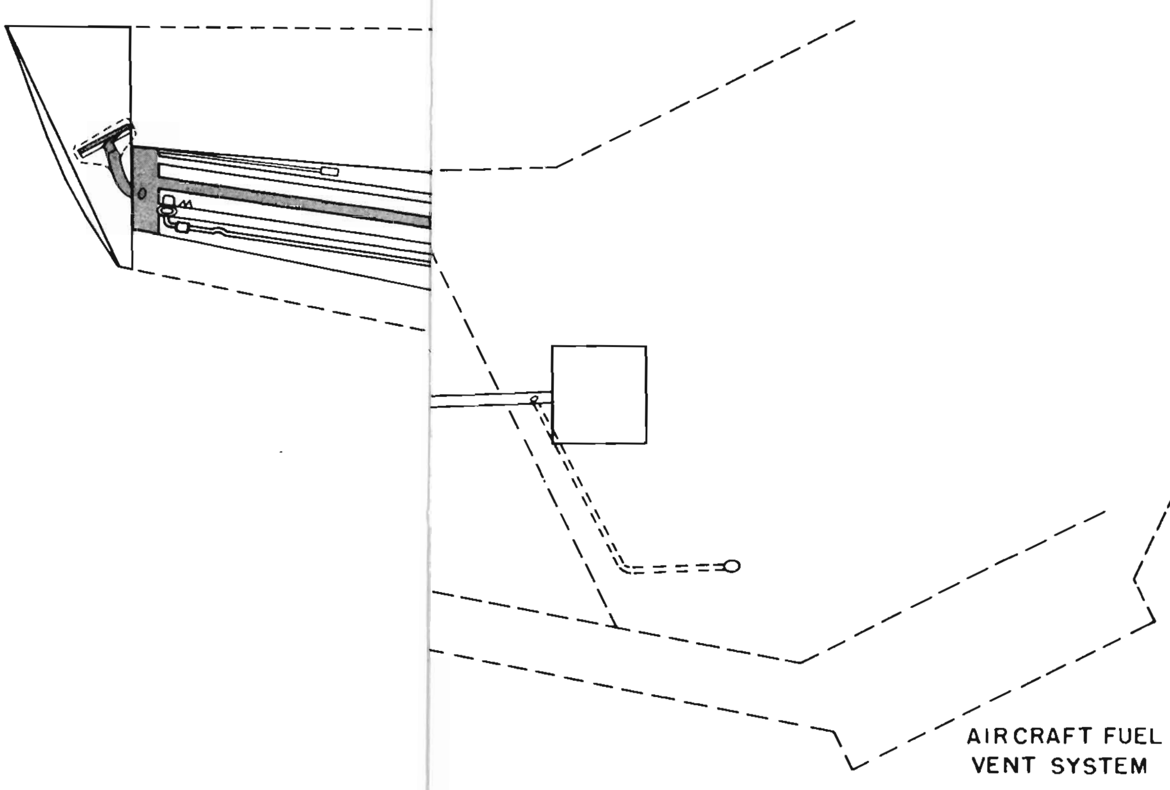

FIGURE 7. - No. 4 Main Tank
Test Configuration

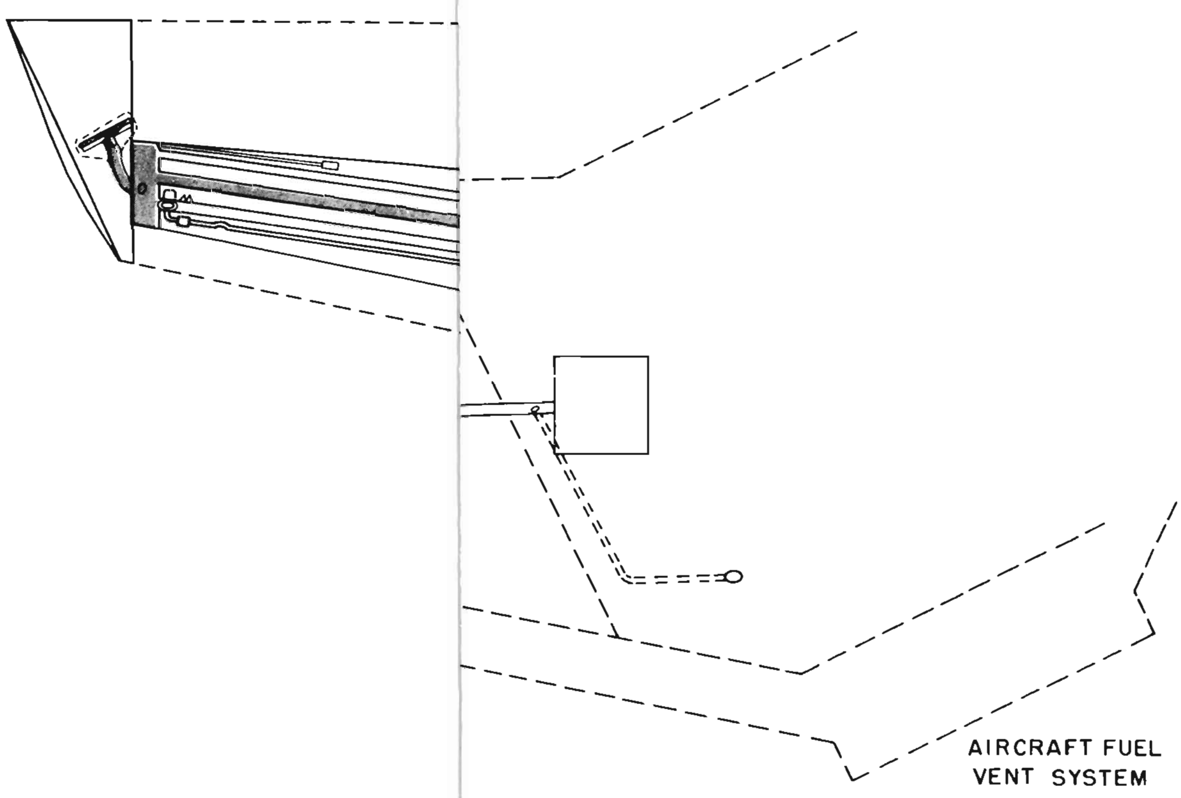

FIGURE 8. - No. 3 Main Tank
Test Configuration

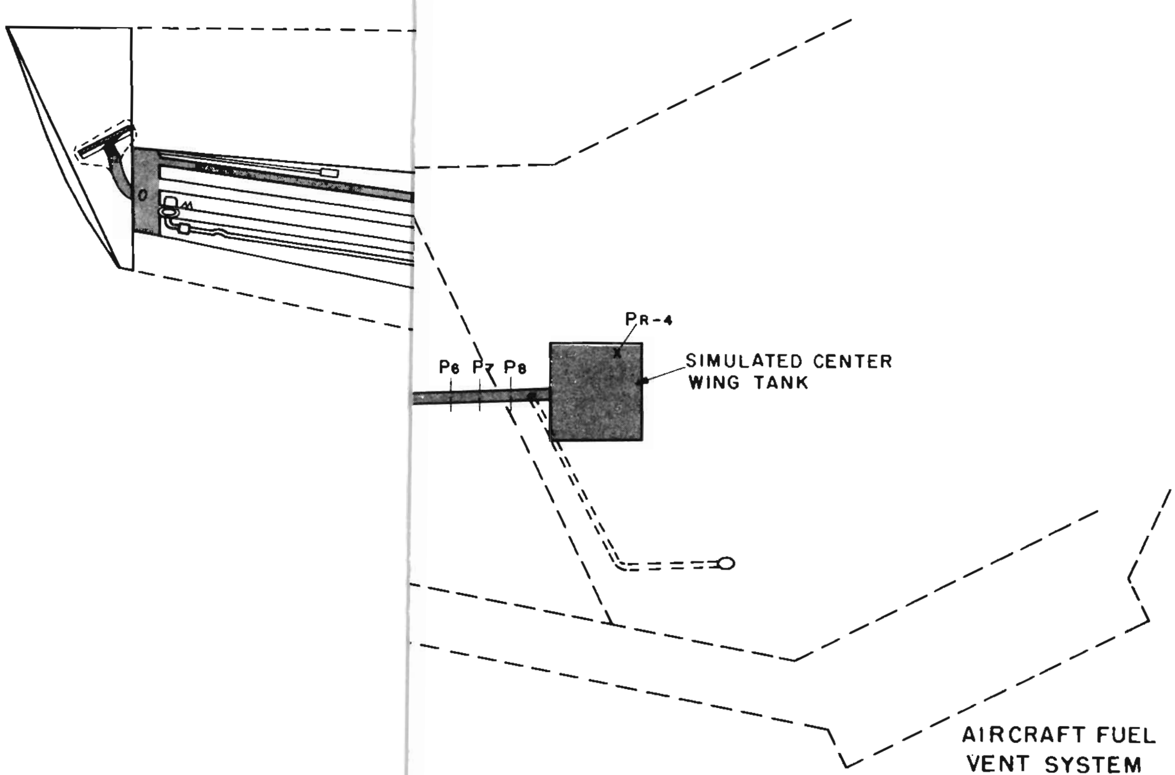

FIGURE 9. - Center Wing Tank
Test Configuration

Aircraft in Climb Condition

A test was conducted in the vent system serving the center wing tank simulating an aircraft gaining altitude at a high rate. The rate of climb simulated produced an outward flow of vapor from the vent scoop of 22 feet per second, a design parameter of the vent system. This test, Run No. 13, was conducted on a cloudy day with an ambient temperature of 75°F. The test, using the Figure No. 9 configuration, simulated a lightning strike at the vent scoop outlet. The flame travelled from the point of ignition in the vent scoop to the probe P_1 position at an average rate of 42 feet per second, from probe P_1 to probe P_2 at 49 feet per second, probe P_2 to probe P_3 at 16.5 feet per second, probe P_3 to probe P_4 at 4.6 feet per second and probe P_4 to probe P_5 through the crossover at 9.2 feet per second. Having passed through the crossover, flame accelerated between probe P_5 and probe P_6 to an average of 15.8 feet per second, from probe P_6 to probe P_7 at 333 feet per second, probe P_7 to probe P_8 which are spaced one foot apart, indicating flame speed was 1,000 feet per second.

Under this test condition also, the burned gases did not have sufficient vent area through which to escape, and there was a pressure buildup in the vent duct. This pressure buildup created the mechanism for an increase in flame speed. The pressure piling effect coupled with a lower ambient temperature produced destructive supersonic flame velocities. The pressure at the blank end of the vent ducts just before entering the crossover at Pr_2 was in excess of 8 psig, the highest attained at any point in the system.

In Run No. 15, which is a duplicate of Run No. 13, except that ambient temperature was 55°F, destructive supersonic velocities were attained throughout the vent system including the crossover pipe serving the center wing tank. A marked decrease in flame speed was observed in Run No. 13 when flame velocity, prior to entering crossover, was moderate. In this test, the flame velocity entering the crossover pipe was supersonic and no measurable hesitation of flame travel was detected in the crossover. The flame continued at supersonic speeds through the second section of duct to main tank No. 3 igniting its contents and venting it. Pressures and speeds attained exceeded the range of the instrumentation, and are recorded as "in excess of" the maximum measurable range.

Aircraft in Descent Condition

Run No. 20 was conducted in the vent system serving the No. 3 main tank to simulate a lightning strike at the vent scoop while the aircraft was in an emergency descent condition. Inflow was 22 feet per second. This test was conducted on a cloudy day at an ambient temperature of 40°F. The flame travelled from its ignition source to probe P_1 at an average rate of 20 feet per second from probes

P_1 to P_2 at greater than 1,000 feet per second, and from then on to probe P_8 at greater than 1,000 feet per second. The supersonic velocities which occurred destroyed some of the instrumentation and expanded the duct work from a rectangular to an elliptical cross section.

Aircraft on Ground Refueling

This test was conducted in the vent system serving the main tank No. 4, and is recorded as Run No. 22. Approximately 9 gallons of JP-4 was put in a steel sphere and the sphere pressurized to 300 psi with air. This sphere was then mounted on the tank simulating main tank No. 4. The test configuration is shown in Figure No. 7.

Previous to the mounting of this sphere, tests were conducted to determine at what rate fuel could be discharged through its 3 inch diameter opening. The fill and pressure ratio were adjusted so that this flow would equal 250 gallons per minute, simulating a fueling rate used for refueling aircraft. The pressurized sphere was opened with a fast operating pyrotechnic device. A spark type ignition source was created within the fuel tank about two feet and below the sphere mounting. This ignition source was programmed to actuate after the 250 gallon per minute flow had been established. Prior to performing the tests, the fuel tank and vent system were completely purged with a pre-mixed JP-4 air mixture.

The fuel was discharged into the tank as the ignition source actuated. The tank vented itself carrying the flame and unburned flammable vapor out through the opening. The subsequent in-rush of air "leaned out" the remaining fuel air mixture rendering it non-flammable, and no flame propagated into the duct. The explosion pressure developed in the tank exceeded 10 psig.

Effectiveness of Reticulated Foam as a Flame Arrestor

The effectiveness of two types of reticulated polyurethane foam supplied by FAA as flame arrestors was determined. One type of foam had 10 pores per inch (ppi) and the second type had 20 ppi. The first test, Run No. 91, was conducted in the twenty foot long 2-1/2 inch by 4 inch rectangular duct used in the altitude tests. A 2-1/2 inch by 4 inch by 7 inch block of the foam (20 ppi) was placed in the duct. Ionization probes were provided on either side of the block to establish flame propagation and passage of flame through the material if any. The entire duct was evacuated prior to a test and filled with premixed JP-4 air mixture at atmospheric pressure. The mixture was ignited and the flame ionization probes monitored on the oscillograph. The flame reached it and burnt its way through the reticulated polyurethane foam in a tortuous path, and passed through to the other side actuating both ionization probes. A second test, Run No. 92, was conducted in which the foam (20 ppi) was packed more tightly into the rectangular duct. Again the mixture was ignited, and in this run the material was effective in arresting the flame. A third test, Run No. 93, was conducted on the 10 ppi foam. A block of the same size was cut and put into the rectangular duct work. The 20 foot duct was evacuated and filled with JP-4 air as before. The mixture was ignited, the flame propagated to the first ionization probe but did not pass through the foam.

Three additional samples of 10, 40 and 60 ppi reticulated foam were provided for testing as flame arrestors and were installed in the fuel slosh collection tank. Effectiveness was established by monitoring flame ionization probes on both sides of the tank in the full scale vent system. Flammable mixtures of JP-4 in air propagated through the foam when ignited at the vent scoop. The fuel slosh collection tank was opened and examined. It was found that the interior geometry of the tank did not lend itself to effective utilization of the foam. The "S" tube enters the fuel slosh collection tank through a 90° elbow. This elbow terminates so close to the vent duct penetrations in the fuel slosh collection tank as to reduce the effective thickness of foam to about an inch - not enough to arrest flame propagation. Each sample was tested.

A twelve inch plug of foam installed in the "S" tube portion of the system proved effective in arresting flame propagation.

Propagation in the Entire Vent System

A test, Run No. 18, was conducted to establish flame propagation throughout the entire fuel vent system simultaneously so as to verify the validity of the single leg analysis approach used in most of the investigation. The test configuration is shown in Figure No. 10. Ignition in the system was provided at the vent scoop and flame propagation was complete.

This test was repeated, Run No. 94, with ignition in the center wing tank to establish that flame which had propagated from the opposite wing to the center tank would continue on out through the other wing entering all tanks in the process.

Testing in the Twenty Foot Auxiliary Flame Propagation Apparatus

Flame propagation was established in the twenty foot Auxiliary Flame Propagation apparatus under the following conditions:

JP-4-in-Air at 7,500 feet and 85°F - Run No. 23

JP-4-in-Air at 17,500 feet and 85°F - Run No. 24

JP-4-in-Air at 35,000 feet and 85°F - Run No. 25

JP-4-in-Air at 7,500 feet and 35°F - Run No. 26

JP-4-in-Air at 17,500 feet and 35°F - Run No. 27

JP-4-in-Air at 35,000 feet and 35°F - Run No. 28

JP-5-in-Air at sea level and 110°F - Run No. 29

JP-5-in-Air at 7,500 feet and 110°F - Run No. 30

JP-5-in-Air at 17,500 feet and 110°F - Run No. 31

JP-5-in-Air at 35,000 feet and 110°F - Run No. 32

In establishing flame propagation in the twenty foot Auxiliary Flame Propagation apparatus, propagation in the complete Fuel Vent System Mock-up was established by analogy. These tests eliminate the expensive and time consuming procedure of conducting tests in the complete system inside an environmental test chamber.

All fuel-air mixtures used in these tests were blended in the aforementioned cylindrical shaped steel pressure vessel. The twenty foot auxiliary apparatus was evacuated to approximately 5 mmHg absolute, and filled with fuel-air mixture to a pressure which corresponded to the altitude condition desired. The mixture was then ignited and the extent of propagation established.

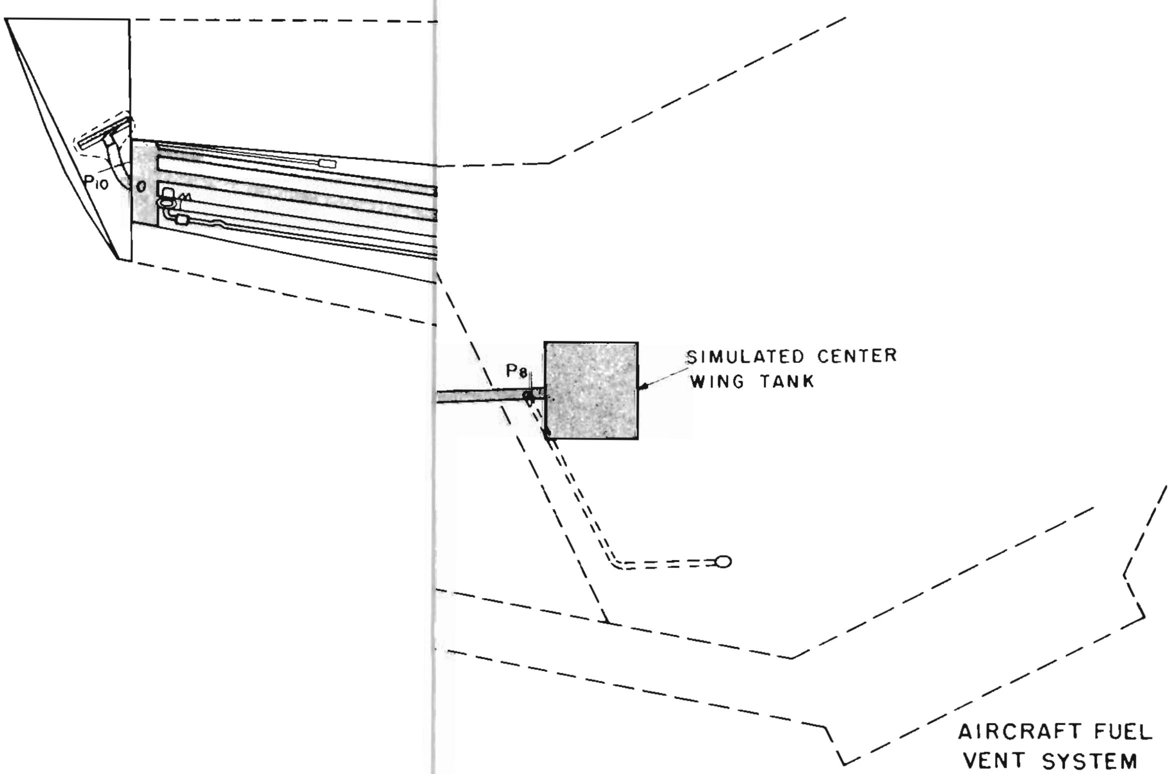

FIGURE 10. - Simulated Aircraft Vent System

TESTS IN SMALL MOCK-UP

A simplified apparatus was constructed with a geometry that would lend itself to theoretical analysis. It consisted of a 2 by 2 by 4 foot pressure vessel and lengths of 2-1/2 by 4 inch rectangular duct equipped with flame ionization probes. One end of a 20 foot section of the duct was welded flush to one side of the vessel at a 90 degree angle. A four foot section of duct was welded to the opposite side so as to protrude into the vessel interior, a distance of six inches. The vessel was equipped with a 12 inch diameter, 25 psig pressure relief vent. Ionization probes and pressure transducers were installed and are shown schematically with the test apparatus in Figure No. 11.

The first system variable investigated was the effect of ambient temperature on flame velocity. A series of tests was conducted at temperatures from 30°F to 160°F and consisted of explosions of 5% propane-in-air produced in the apparatus so that flame speed and pressure rise could be measured. The results are listed in Appendix II.

The second system variable investigated was that of system configuration. Specifically, this involved a determination of the effect of a blank end on the 20 foot duct preceded by a 90 degree change in direction and a change in cross section configuration. This change was designed to simulate that section of the full scale vent system where destructive flame velocities occurred, namely, near the circular shaped vent crossover tubes. An eight inch section of rectangular duct was closed at one end and flanged at the other to adapt to the 20 foot section. Six inches from the closed end, a two foot section of 2-5/8 inch inside diameter pipe was centered and welded. This piece was added to the test apparatus and instrumented as shown in Figure No. 12.

A series of tests was conducted in which temperature was varied from 30°F to 160°F and consisted of 5% propane-in-air explosions produced in the test apparatus so that flame speed and pressure rise could be measured. The results are listed in Appendix II. Low temperature and this configuration combined to produce supersonic velocities.

A third system variable investigated was that of ignition location. This variable was introduced by moving the ignition source to the geometric center of the 2 by 2 by 4 foot tank and conducting the tests then moving the ignition source to the position occupied by probe No. 4 and then to the position occupied by probe NO. 5.

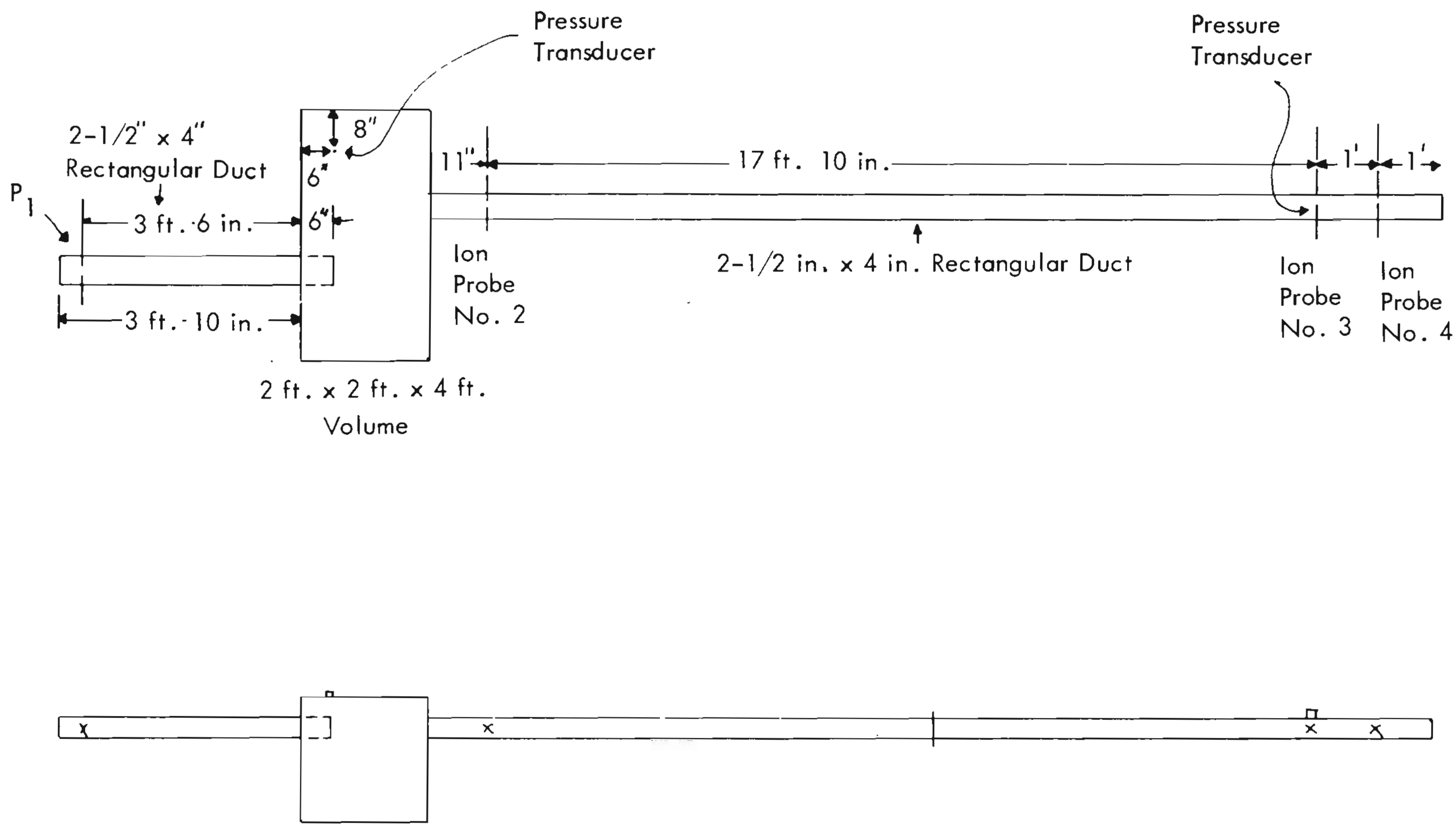

FIGURE 11. - Fuel Tank Vent System Analysis Configuration I

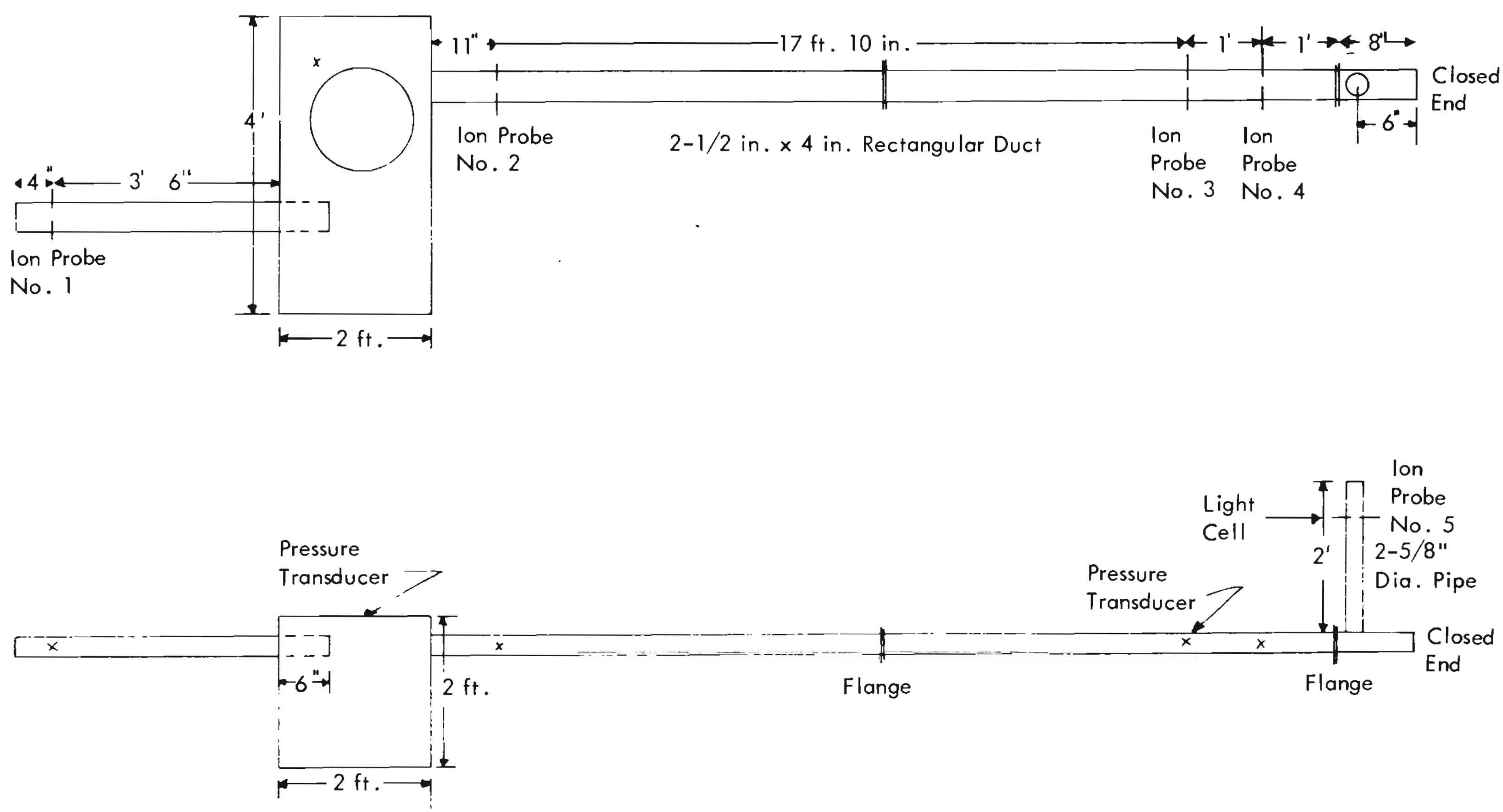

FIGURE 12. - Fuel Tank Vent System Analysis Configuration II

The tests consisted of 5% propane-in-air explosions produced in the test apparatus so that flame speed and pressure rise could be measured. The results are listed in Appendix II.

The effect of combustible as a system variable was investigated. This variable was introduced by hydrocarbons of different structure to determine what change in flame speed would result. It was felt that temperature dictated the presence of supersonic velocitites in the flame propagation tests by controlling the makeup of the vapor phase. Lower boiling compounds would be present in higher concentration in 4% JP-4-air mixtures at lower temperatures.

Slightly richer than stoichiometric mixtures of the following hydrocarbons in air were ignited in the test apparatus:

Methane

Ethane

Propane

Pentane

These tests were conducted in the apparatus shown in Figure Nos. 13 and 14. The results are listed in Appendix II.

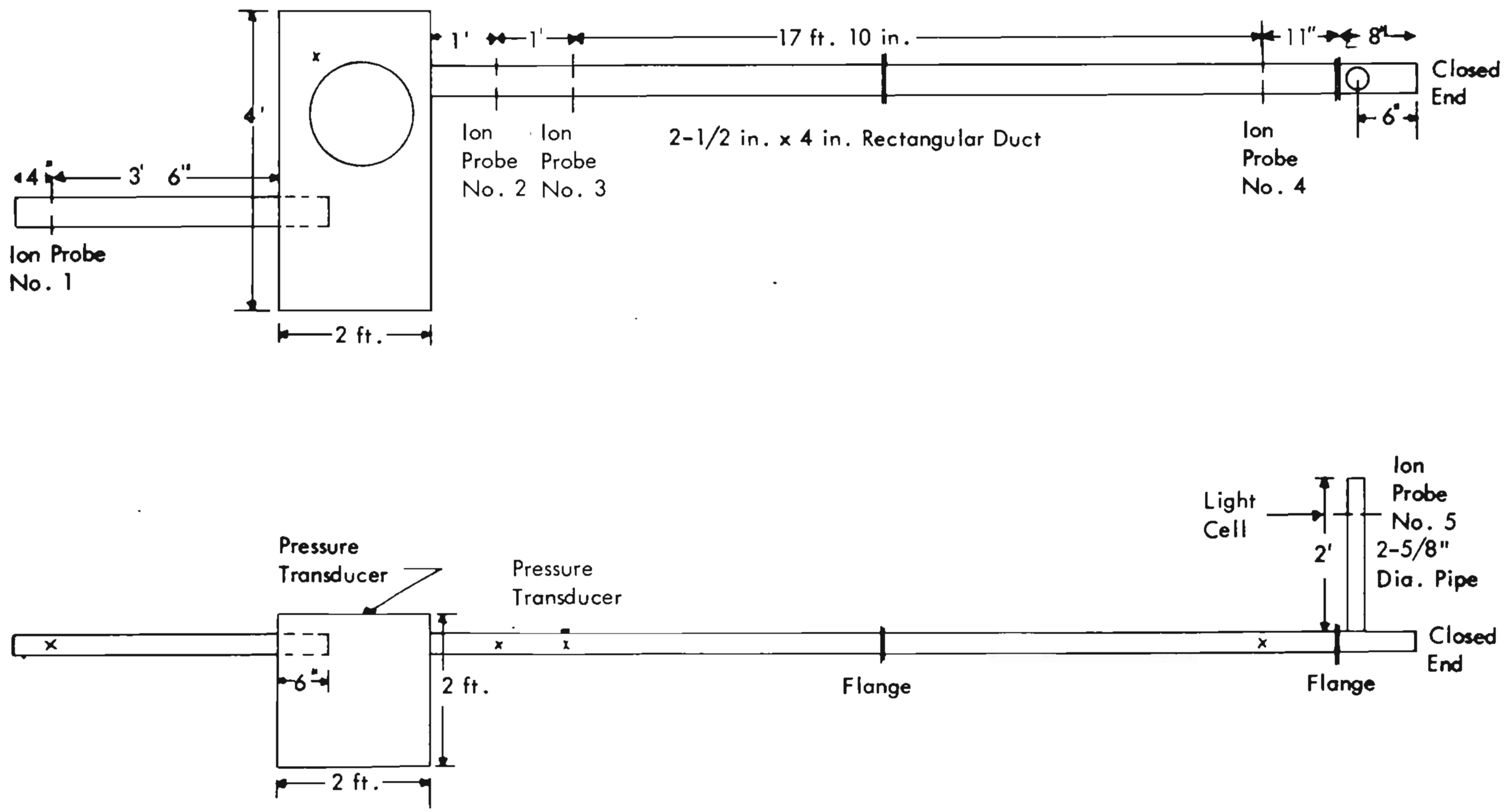

FIGURE 13. - Fuel Tank Vent System Analysis Configuration III

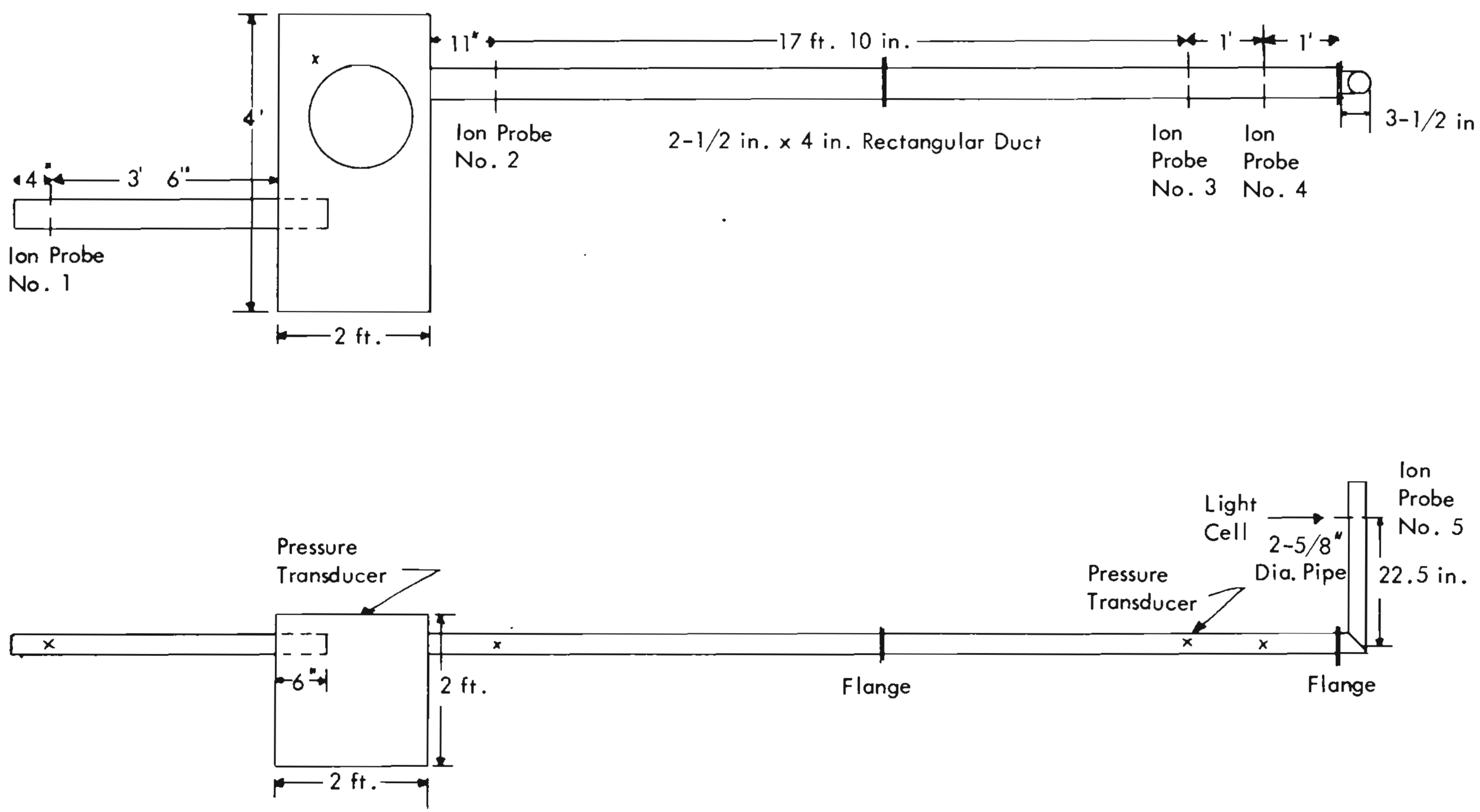

FIGURE 14. - Fuel Tank Vent System Analysis Configuration IV

DISCUSSION

Ignition of flammable vapors at the vent scoop of the large scale vent mock-up under static conditions produced flame velocities in the order of 1000 feet per second in various sections of the vent system. The total number of successful tests conducted under these conditions in the individual vent systems was 13, ten using the center wing tank vent system, two using the No. 3 tank vent system and one in the No. 4 tank vent system. In 11 of these tests, the flame velocity measured reached 500 feet per second or greater in the vent system. The development of such high flame velocities is better understood by considering the combustion process in long ducts.

When an explosive gas is confined in a channel and ignited, the flow induced by the thermal expansion of the gas in the combustion wave is restricted by the channel wall. Consequently, the flow attains much higher velocities than under conditions of free expansion in an open flame and flame and flow commonly augment each other by a feedback mechanism as follows: stream turbulence, however slight it may be initially, produces a wrinkling of the combustion wave surface; the resulting increase of surface increases the amount of gas burning per unit time, namely, the flow of gas in the channel; this in turn produces more turbulence and hence, increased wrinkling of the wave, and so on, so that the progress of the combustion wave becomes nonsteady and self-accelerating. In addition, the burning velocity increases as the unburned gas ahead of the flame is preheated and precompressed by the compression waves that are generated by the mass acceleration in the combustion wave. The compression wave is initially a comparatively weak pressure wave, which is overtaken and reinforced during its travel by numerous other pressure waves originating in the combustion zone. The coalescence of these pressure waves into a strong shock front in a configuration which is dead-ended can result in a reflection of the shock wave back toward the combustion zone. The effect of the passage of this reflected shock wave through the combustion wave is similar to the effect of a sudden release of pressure by a rupture of a diaphragm. A rarefaction wave propagates backward into the unburned gas and a jet of unburned gas develops which penetrates deeply into the burned gas. The shear between burned and unburned gas in this flow configuration produces extreme turbulence so that a sudden large increase in the burning rate occurs.

In three of the 13 tests mentioned above, localized pressures were developed in the rectangular vent duct of sufficient intensity to distort three to five foot sections of the duct. A subsequent hydrostatic pressurization of a three foot section of similar duct showed that a pressure of approximately 475 psig was required to produce similar distortion.

The ambient temperature in these three tests ranged from 30^{o}F to 50^{o}F whereas the temperatures in the 10 non-destructive tests ranged from 65^{o}F to 80^{o}F. The effect of lower ambient temperature is two-fold; first, it predicates a greater mass of combustible mixture at atmospheric pressure and, therefore, a greater release of energy during combustion; secondly, it alters the hydrocarbon content of the fuel vapor in the combustible mixture so that the mixture contains a greater percentage of the more volatile, faster burning hydrocarbons.

Distortion of the vent duct occurred in three other tests in the large scale mock-up. The ambient temperature in two of these tests was 40^{o}F and in the third was 75^{o}F. However, all three tests simulated a descending aircraft with a flow of combustible mixture inboard through the vent duct of 22 feet per second. The localized destructive pressures obtained are attributed to the extreme turbulence of the combustible mixture flowing through the vent system.

An additional factor contributing to the high flame velocities developed in the large scale mock-up is the presence of a fuel slosh collection tank located approximately three feet inboard of the vent scoop. When a mixture is ignited at the vent scoop and flame propagates into the collection tank, the entire mixture in the tank becomes involved in the combustion. The relief paths for the pressure developed in the tank are outboard through the vent scoop and inboard through the fuel tank vents. The inboard flow creates turbulence in the vent ducts and serves as a driving force to accelerate flame propagation in the ducts.

There are a number of tests listed toward the end of Table No. 1 in which ignition of the combustible mixture was not obtained or in which combustion did not occur throughout the entire vent system under test. These tests, not listed in chronological order, represent the effort expended early in the program to devise a reliable method of preparing JP-4 vapor-air mixtures and of thoroughly purging the vent systems with the mixture.

Difficulties were encountered in obtaining JP-4 fuel in drums which exhibited the proper vapor pressure characteristics. Apparently, the low boiling constituents of the fuel had evaporated during the storage and/or drumming process. The problem was eliminated by obtaining fuel in bulk quantity and storing it underground. A fuel sample was submitted to New England Laboratories of Newton, Massachusetts, for analysis. The results of this analysis are presented in Appendix III.

The first series of tests conducted in the apparatus shown in Figure No. 11 were designed to determine the effect of ambient temperature on the velocity of the flame propagating through the vent duct. A propane-air mixture was used with ignition in the short section of duct at location P_1. Flame velocities between 500 and 1000 feet per second were obtained in all tests although the temperature was varied from 30°F to 160°F. The same results were obtained when the ignition source was moved to the center of the tank. These consistently high flame speeds, apparently independent of ambient temperature are attributed to the extreme turbulence and impetus imparted to the combustion wave by the combustion which occurred in the tank. When the ignition source was moved to location P_4 of the apparatus, the flame velocities obtained were substantially lower and exhibited a temperature dependence, e.g. 185 feet per second at 32°F and 11.1 feet per second at 160°F.

The effect of ambient temperature on flame velocity was investigated in an apparatus which had both a dead-ended section and a right angle extension. A sketch of the apparatus is shown in Figure No. 12. High flame speeds were achieved between 70°F and 160°F due to the tank combustion driving force, turbulence and shock wave reflection. At temperatures of 30 - 32°F, precompression of the unburned gas caused auto-ignition of the gas at the dead-ended section in four of the five tests conducted. In one test, excessive pressure ruptured the dead-ended section. Ignition near the opposite end of this apparatus, at locations P_4 and P_5 produced relatively low flame velocities which did exhibit a temperature dependence, e.g. 308 feet per second at 32°F and 8.1 feet per second at 160°F.

Three valid tests were conducted in the apparatus shown in Figure No. 14. High flame velocities were obtained in two of these tests and auto-ignition due to precompression occurred in the third.

A final series of tests was conducted in the three test configurations shown in Figures Nos. 11, 12, and 13. A number of hydrocarbons were investigated in order to determine the effect of combustible mixture composition on flame velocity at various temperatures. The specific hydrocarbons tested were methane, ethane, propane and pentane. As before, the turbulence and driving force created by combustion in the tank tended to obscure the effects of combustible type and temperature.

The propagation rate of flame through an entire section of the vent system, from the vent scoop to the fuel tank, was not easily reproduced. This is attributed to slight variations in ambient temperature, test apparatus wall temperature, fuel/air ratio and fuel-air mixture temperature. Although a wide range of flame speeds was obtained for each specific section of the vent system, the average of the flame speeds obtained for each section indicated a definite propagation pattern.

The diagram in Figure No. 15 shows the maximum, minimum and average flame speeds obtained in five identical tests conducted in the vent duct of the center wing tank. The ambient temperature for the five tests ranged from 65°F to 80°F. In each test a stoichiometric JP-4 fuel-air mixture was introduced into the vent system and ignited at the vent scoop. Flame speeds were determined at eight locations in the

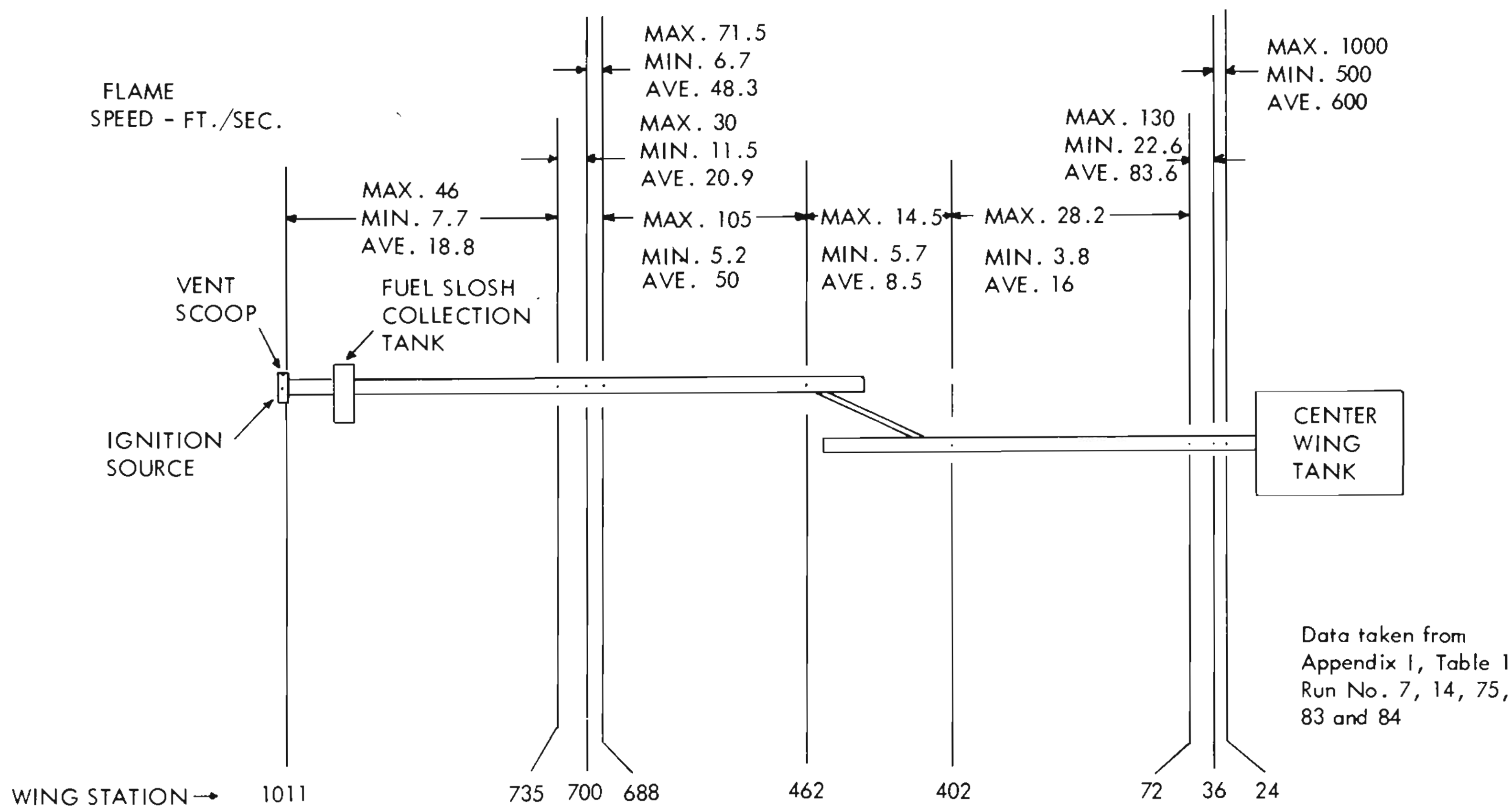

FIGURE 15. - Maximum and Minimum Flame Speeds in Vent Duct for Center Wing Tank

system. A similar analysis for the No. 4 main tank and No. 3 main tank could not be obtained because of an insufficient number of test runs under identical test conditions.

The average flame speed from the point of ignition to wing station 735 was found to be 18.8 feet per second. The initial flame propagation rate through the vent tube to the fuel slosh collection tank is relatively slow because of the incubation time required for the combustion process to be established from a point ignition source and also because of the proximity of the burned gases to the open vent scoop which effectively vents the burned gases to the atmosphere. As the flame front moves into the fuel slosh collection tank, the flammable mixture within the tank burns creating a rise in pressure which in turn causes a slight compression of the unburned gases in the inboard vent duct. The flame front then begins to accelerate as it travels down this duct section. The five-test average flame speed for the final straight section of the duct, wing station 688 to wing station 462, was 50 feet per second.

At this point the flame front leaves the rectangular duct and enters a duct having a circular cross-section of approximately one half the area of the rectangular duct. The result was a drastic reduction in flame speed through the circular duct. The average flame speed dropped from 50 to 8.5 feet per second as a result of the transition from the rectangular to the circular duct. The reason for this deceleration is not immediately apparent.

At wing station 402, the circular duct leads into a rectangular duct once again. The slow moving flame from the circular duct passes into the rectangular duct and begins to accelerate. The condition here begins to simulate a closed end ignition because of the great distance between the flame and the vent scoop. The burned gases are not effectively vented from the duct and the unburned gas mixture ahead of the flame becomes compressed and burns more rapidly. At the last section of the duct, from wing station 36 to wing station 24, the average flame speed was 600 feet per second.

Altitude and temperature have a pronounced effect on flame propagation characteristics of flammable vapor-air mixtures. The altitude effect is shown for both JP-4 and JP-5 in Figure No. 16. As applied to the vent system discussed above, the data indicates that substantial reductions in flame speeds would be encountered in the vent system at the higher altitudes. The temperature effect is shown in Figures No. 17 and 18. Propane was used as the combustible to eliminate the variable associated with a multi-constituent fuel such as JP-4. Flame speeds were observed to increase with a reduction in temperature.

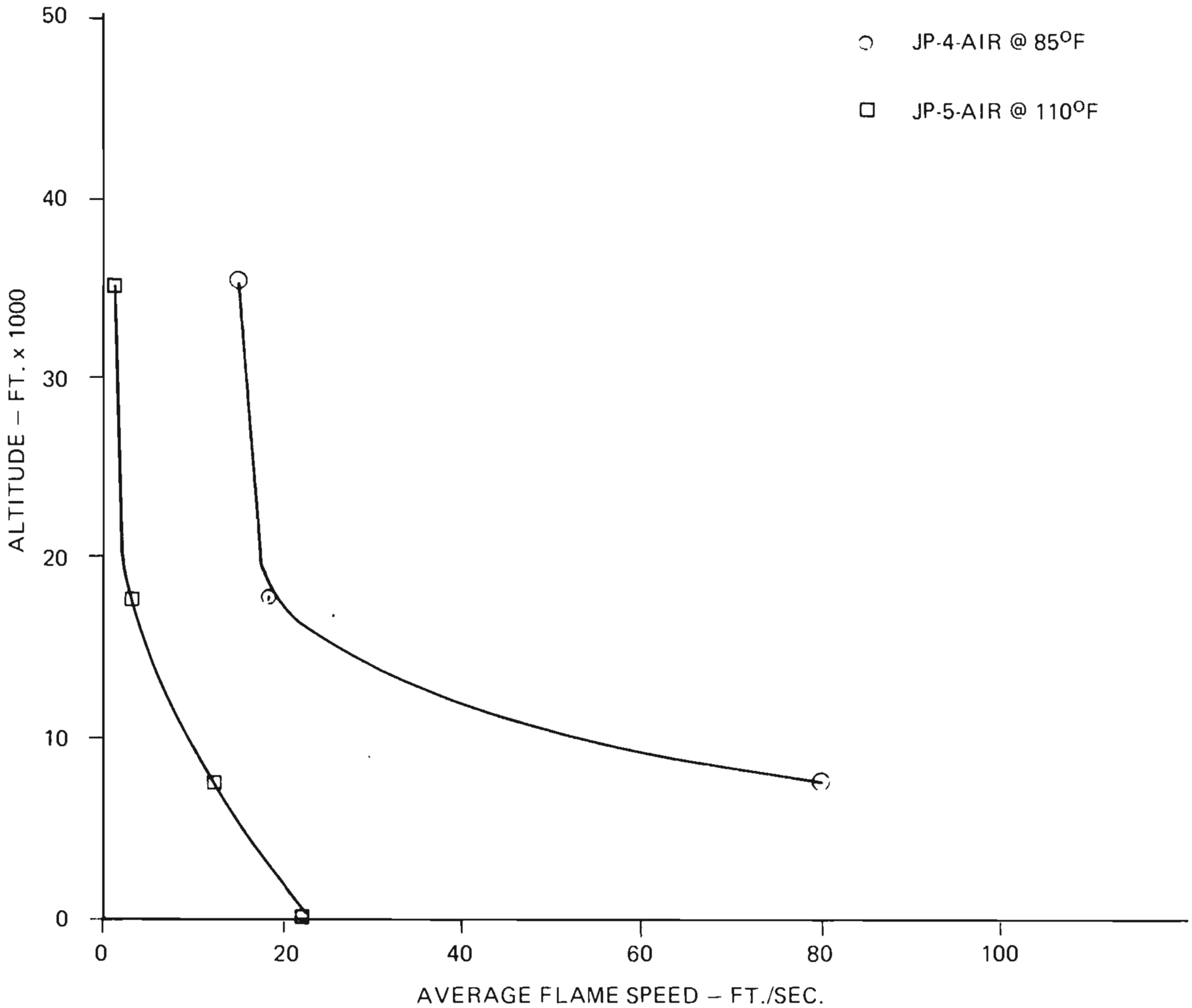

FIGURE 16. - Effect of Altitude on Flame Speed in 20' Duct Section with Closed End Ignition

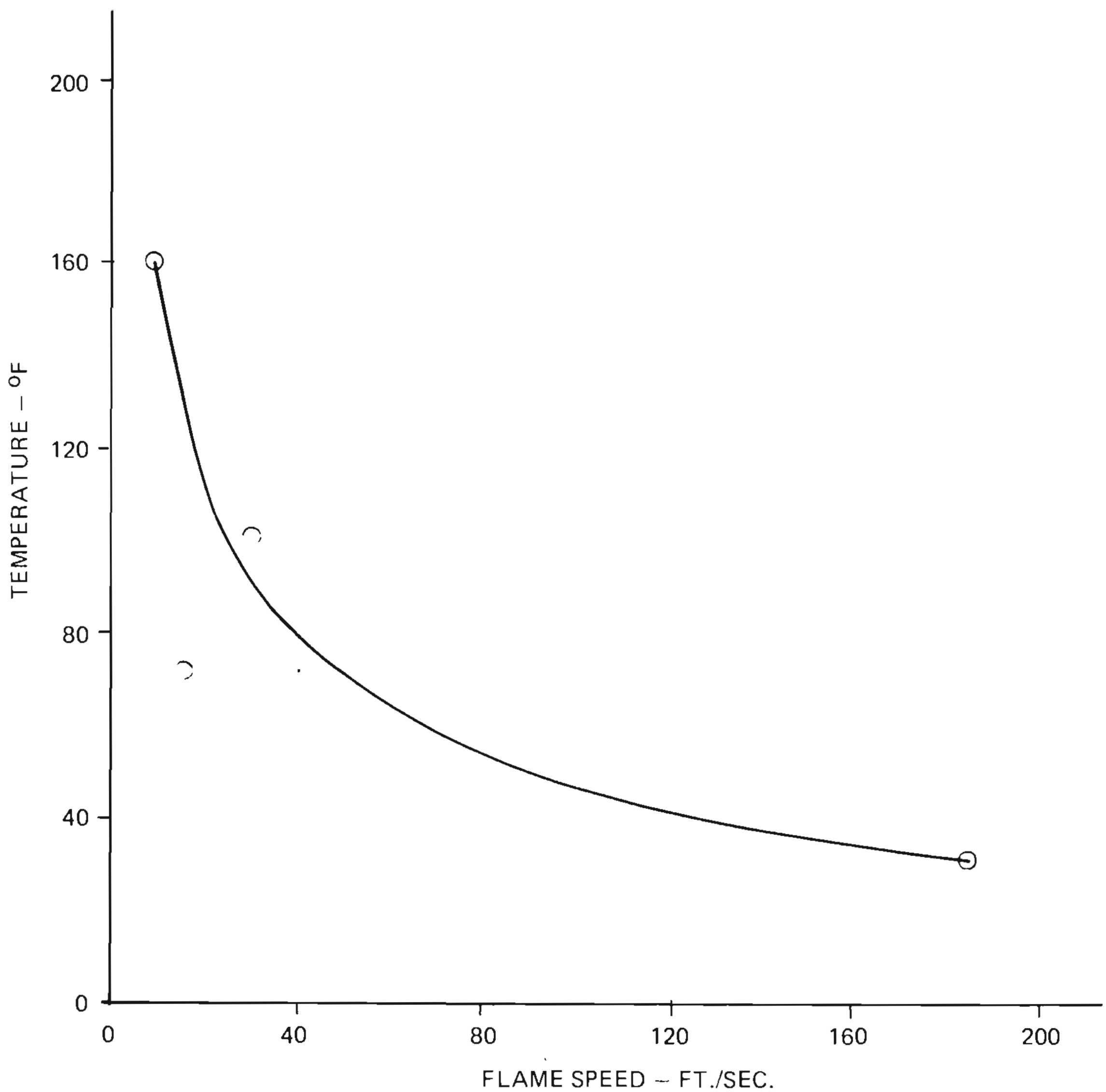

FIGURE 17. - Effect of Temperature on Flame Speed on Propane-Air Mixtures with Open End Ignition - Configuration I

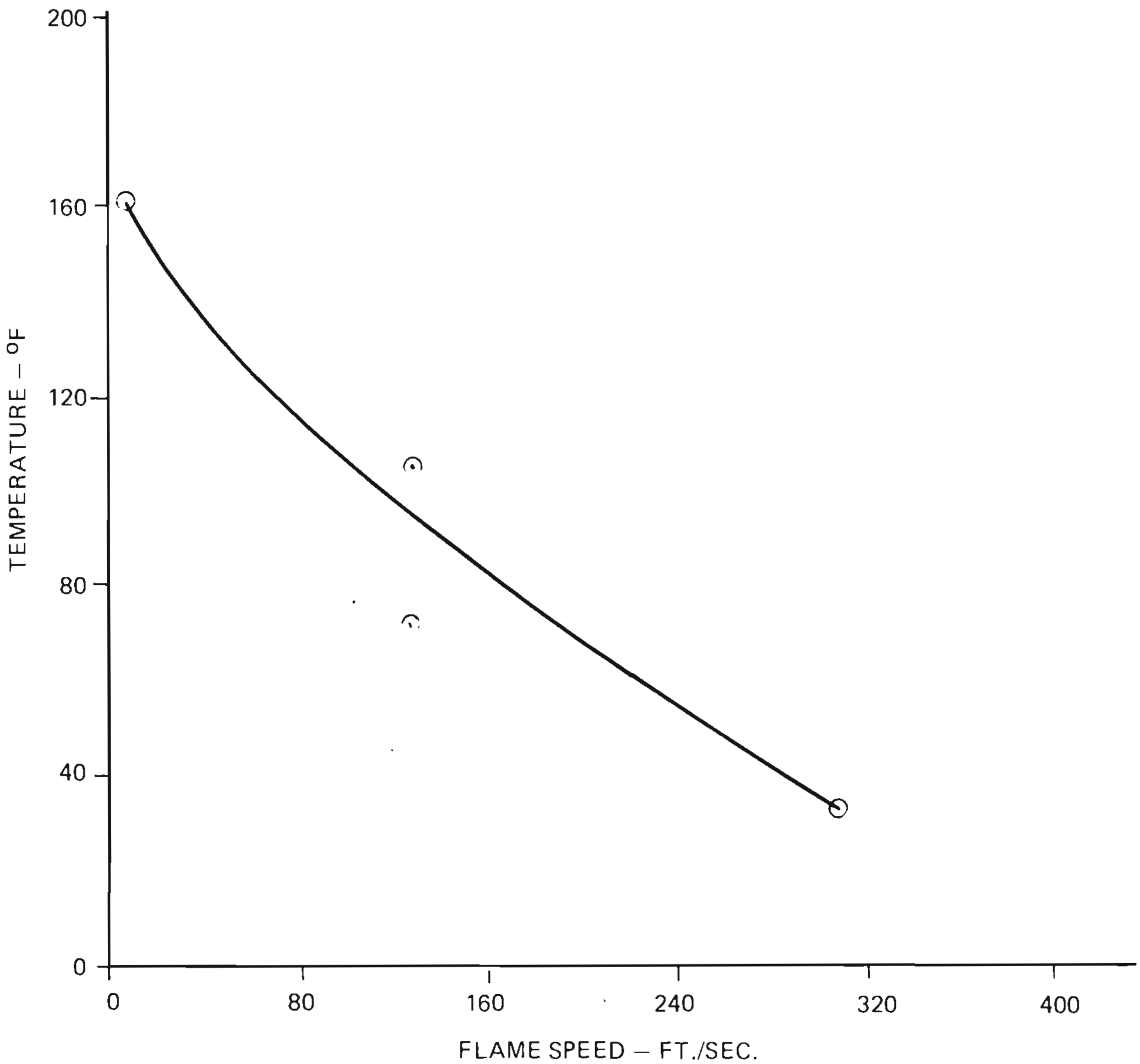

FIGURE 18. - Effect of Temperature on Flame Speed of Propane-Air Mixtures with Open End Ignition - Configuration II

CONCLUSIONS

1. Under all flight and ground operating conditions where sufficient fuel and oxygen is present to support combustion, a flame will propagate at varying velocities through a typical vent system when ignited at the outlet.

2. Momentary flame speeds exceeding 1000 feet per second were caused by the vent configuration, which reinforced the combustion wave.

3. Pressures exceeding the structural limitations of typical aircraft vent ducts can be obtained at the points where high flame speeds are obtained.

4. Changes in the vent configuration, which reduce the flame front reinforcement, will reduce the rate of flame propagation.

5. Sharp transitions in duct shape, diameters, direction of travel, dead ended sections, etc., are characteristics which contribute to wave reflections that reinforce flame propagation and should be eliminated. Where duct transitions are necessary, they should be smooth and gradual.

6. Vent systems should not incorporate fuel slosh collection tanks since they provide a driving force which accelerates the flame propagation rates.

7. The temperature variation effect on the composition of the vapors of aircraft turbine fuel and the mass of the vapors has a significant effect on the flame speeds.

8. Properly installed reticulated foam will serve as a flame barrier in a vent system when located in an area of low flame speeds.

9. The geometric complexity of the vent system, which can give rise to secondary effects such as reflections, precludes establishment of analytical procedures to predict the flame propagation characteristics in the vent system. The present state of knowledge of propagating flames allows predictions only in constant area straight ducts.