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Limiting Oxygen Concentration Required to Inert Jet Fuel Vapors Existing at Reduced Fuel Tank Pressures

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16. Abstract

This report discusses experiments to determine the reduction in oxygen concentration required to prevent a fuel tank explosion. A simulated aircraft fuel tank containing JP-8 fuel of an amount equivalent to a mass loading of approximately 4.5 kg/m^3 was used to determine the limiting oxygen concentration (LOC) at pressures corresponding to altitudes ranging from 0 to 38 kft. In addition, the peak pressure rise was measured at various altitudes (pressures) due to ignition occurring at O_2 levels approximately 1% to 1.5% above the LOC.

A wide range of ignition sources were used throughout the testing. An oil burner transformer connected to an analog timer provided a low power arc of both short (0.1 second) and long durations (1 second), a spark igniter taken from a J-57 engine provided a very short duration (175 μseconds) high powered spark, and a heated metal block was used as a hot surface ignition source. These varied capabilities allowed for an evaluation of the variation in the LOC due to a specific type of ignition source.

From these tests, it was determined that the LOC at sea level through 10 kft is approximately 12% O_2, while exhibiting a linear increase from 12% at 10 kft to approximately 14.5% at 40 kft. Tests with various sparks/arcs as ignition sources at sea level showed little variation in results, with the LOC ranging from 12.0% to 12.8%. Also, a heated surface capable of igniting a fuel air mixture proved insufficient for ignition in a tank inerted to just 14%. Peak pressures resulting from ignition at oxygen concentrations 1% to 1.5% above LOC values decreased as the altitude was increased to 30 kft, while the duration to reach the peak pressure increased.

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EXECUTIVE SUMMARY

Aircraft fuel tank protection has become of great interest within the aviation community since the fatal accident of TWA 800, a B747, over East Moriches, NY, in July 1996. The National Transportation Safety Board determined that the "probable cause of the TWA flight 800 accident was an explosion of the center wing fuel tank (CWT), resulting from ignition of the flammable fuel-air mixture in the tank." As a result, the Federal Aviation Administration (FAA) is currently conducting research aimed at reducing or eliminating the flammability exposure time of high flammability fuel tanks. Much consideration is being given to the design and optimization of a system involving nitrogen inerting. In this process, nitrogen or nitrogen-enriched air would be used to reduce the oxygen concentration within the fuel tank to a level at which ignition could not be supported by flammable ullage vapors. This type of system has been implemented in several military aircraft; however, high cost and weight factors combined with low-reliability factors make those designs impractical for transport category aircraft. Recent advances in gas separation technologies may make it possible to design an economic and reliable means of inerting commercial aircraft fuel tanks. However, in order to optimize such a system, more data concerning fuel flammability and inerting gas requirements were needed. The goal of the research effort discussed herein is to determine the oxygen concentration necessary to render the fuel tank ullage inert. This value is termed the limiting oxygen concentration (LOC).

The tests were conducted at the FAA William J. Hughes Technical Center, Atlantic City International Airport, Atlantic City, NJ, in a facility capable of creating pressures corresponding to altitudes ranging from 0 to 38 kft. From these tests, it was determined that the LOC at sea level through 10 kft is approximately 12% O_2, with a linear increase from 12% at 10 kft to approximately 14.5% at 40 kft. Tests with various sparks and arcs as ignition sources at sea level showed little variation in results, with the LOC ranging from 12.0% to 12.8%. Also, a heated surface capable of igniting a fuel air mixture proved insufficient for ignition in a tank inerted to just 14%. Peak pressures resulting from ignition at oxygen concentrations 1% to 1.5% above LOC values decreased as the altitude was increased to 30 kft, while the duration to reach the peak pressure increased. Further experiments to examine the trend of peak pressure rise as a function of both altitude and oxygen concentration are needed. The results contained in this report should be useful in the design, sizing, and optimization of future aircraft inerting systems and add to the overall knowledge base of jet fuel flammability characteristics.

1. INTRODUCTION.

1.1 BACKGROUND.

Aircraft fuel tank protection has become of great interest within the aviation community since the fatal accident of TWA 800, a B747, over East Moriches, NY, in July 1996. The National Transportation Safety Board (NTSB) determined that the "probable cause of the TWA flight 800 accident was an explosion of the center wing fuel tank (CWT), resulting from ignition of the flammable fuel/air mixture in the tank [1]". The NTSB [1] further concluded that contributing factors to the accident were that the design and certification of the aircraft required only the preclusion of all potential ignition sources in order to prevent a fuel tank explosion. No measures were taken to reduce heat transfer or inert the fuel tank.

In several aircraft configurations, including the B747, the environmental conditioning system packs are located beneath the CWT. The hot bleed air from this system, passing directly underneath of the tank, is the driving force behind the generation of flammabable fuel vapor in the ullage. In fact, the Aviation Rulemaking Advisory Committee's Fuel Tank Harmonization Working Group [2] found that heated CWTs contain a flammable fuel-air mixture 30% of the total flight time as compared with only 4%-6% of the flight time for unheated CWTs and 2%-4% for typical unheated main wing tanks.

The Federal Aviation Administration (FAA) is currently conducting research aimed at reducing or eliminating the flammability exposure time of CWTs. Much consideration is being given to the design and optimization of a system involving nitrogen inerting. In this process, nitrogen or nitrogen-enriched air would be used to reduce the oxygen concentration within the fuel tank to a level at which ignition could not be supported by the flammable vapors. Inerting systems have been implemented in several military aircraft; however, high cost and weight factors of those designs combined with low reliability factors make military designs impractical for transport category aircraft. Recent advances in gas separation technologies may make it possible to design an economic and reliable means of inerting aircraft fuel tanks. However, in order to optimize such a system, more data concerning fuel flammability and inerting gas requirements are needed throughout the operational envelope of a fuel tank, including various possible ignition sources.

1.2 AVIATION FUEL SPECIFICATION AND CHARACTERISTICS.

In the United States, specific requirements relative to aviation turbine fuel properties is set forth by the American Society of Testing and Materials (ASTM) Standard D 1655. This standard limits itself to the commercial grade fuels Jet A, Jet A-1, and Jet B. Jet A and Jet A-1 are the most commonly used aviation fuels, differing only in their freezing point (-40°C for Jet A and -47°C for Jet A-1). Both are derived from kerosene and have a relatively high flash point, set at a minimum of 38°C (100°F).

Jet B fuel, on the other hand, is rarely used today. Jet B is essentially the same as JP-4, a standard U.S. military fuel that was used until 1988 when a transition to JP-8 (a fuel which is very similar to Jet A) was initiated [3]. In addition, the U.S. military also currently uses the high-flash point (60°C), kerosene-based JP-5 fuel for Navy carrier-based aircraft. While ASTM D 1655 does not control the specifications for these military fuels, a listing of their

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corresponding requirements can be found in the Handbook of Aviation Fuel Properties [4]. These specifications, for JP-4, -5, and -8, as well as those from ASTM D 1655 for Jet A, Jet A-1, and Jet B, are given in appendix A of this report for convenience.

The fuel used in the experiments discussed within this report was JP-8, which can be treated approximately as Jet A (see appendix A). With regards to the chemical composition of Jet A, ASTM D 1655 states that these fuels "shall consist of refined hydrocarbons derived from conventional sources including crude oil, natural gas liquids, heavy oil, and tar sands." There are no provisions given for the exact composition of the fuel, and as such, the properties of any given fuel batch can vary from that of any other, provided that they meet the minimum specifications set forth in ASTM D 1655. This lack of a definitive composition results in fuels that consist of hundreds of chemical species.

Regarding the flammability properties of aviation fuels, the two most widely used parameters are the fuel's flash point and flammability limits, given in terms of altitude and temperature data.

The flash point of a liquid fuel is defined as the lowest temperature, at atmospheric pressure, at which sufficient vapor is released by the fuel to support ignition. The current standardized methods for determining the flash point are ASTM D 56 and ASTM 3828. Both methods place a sample of fuel in a closed cup and heat it at a constant rate. A small flame is introduced into the cup, and the lowest temperature at which ignition is observed is referred to as the flash point. Figure 1, as taken from reference [4], shows a graph of approximate flash points versus blends of Jet A and Jet B fuels.
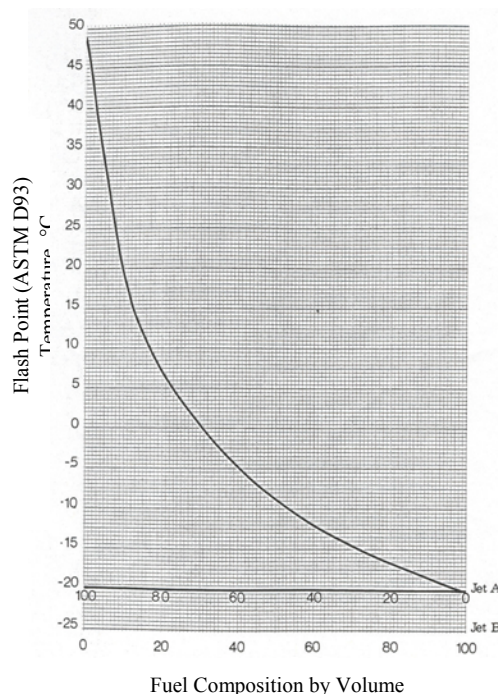

FIGURE 1. TYPICAL FLASH POINT TEMPERATURES OF JET A AND
JET B FUEL BLENDS

The flammability limits of a given fuel provide more information than the flash-point measurement, especially when presented as regions of flammability in terms of altitude and fuel temperature. At any given altitude (pressure), a fuel will have a lean (or lower) flammability limit (LFL) and a rich (or upper) flammability limit. Within these limits, ignition of vapors may occur, while outside the limits there should be no observed combustion phenomenon. Over the years, there have been numerous experiments to determine the flammability limits of aviation turbine fuels. A typical plot of these limits, including ignition energies, for Jet A and Jet B fuels is shown in figure 2, as taken from reference [3].
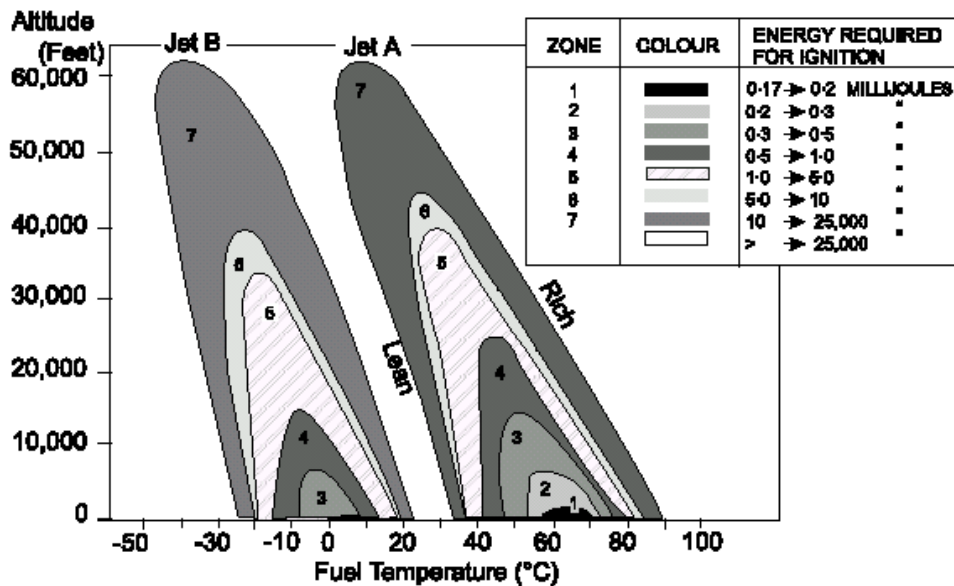
FIGURE 2. TYPICAL INDUSTRY-ACCEPTED PLOTS OF JET FUEL
FLAMMABILITY LIMITS

Both the flash point and flammability limits given above assume isothermal and equilibrium conditions, not taking into account such things as possible condensation of the fuel vapor and variation of the ullage composition. In order to provide useful data for fuel tank inerting requirements, data on the reduction of fuel flammability as a function of oxygen depletion are needed.

1.3 SCOPE OF EXPERIMENTS.

The purpose of the experimental research discussed in this report is to further quantify the oxygen concentrations required to protect against the ignition of JP-8 fuel vapors at altitudes ranging from 0 to 38 kft. This data will aid in the design of nitrogen inerting systems for use in aircraft fuel tanks. Throughout the experiments, the lowest oxygen concentration resulting in ignition of the ullage fuel vapors is referred to as the limiting oxygen concentration (LOC).

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2. EXPERIMENTAL APPARATUS.

2.1 TEST ARTICLE.

The experiments discussed within this report were conducted at the FAA William J. Hughes Technical Center's Pressure Fire Modeling Facility. This facility houses a 10-m^3 vessel capable of withstanding a maximum working pressure of 650 psi. An attached vacuum pump evacuated the chamber to pressures corresponding to desired altitudes.   The pressures corresponding to each altitude tested can be found in table 1.

TABLE 1. ALTITUDE-PRESSURE DATA

Altitude (kft)	Pressure (psia)
0	14.70
10	10.25
20	6.97
30	4.61
38	3.22

The vented fuel tank test article placed within the 10-m^3 vessel was approximately 0.25 m^3 (9 ft^3) in volume. It was equipped with 12 K-type thermocouples, sample lines for hydrocarbon and oxygen vapor sampling, thermostatically controlled hot plates with a capacity of 1650 watts, and a 6-in.-diameter mixing fan used to ensure a homogeneous ullage vapor mixture. A fuel pan, measuring 9.5 by 9.5 in., was placed in the center of the fuel tank. A 10- by 10-in. opening in the fuel tank's roof was fitted with interchangeable pressure relief mechanisms of either a spring-loaded 1/4-in.-thick aluminum plate or a foil diaphragm.

The aluminum plate mechanism was used in the early phases of testing to gain general knowledge of the LOC at each altitude, while the diaphragm was used to more accurately determine the LOC. In the case of the aluminum plate, an ignition was said to occur if there was noticeable movement of the plate; whereas, with the latter mechanism, ignition was said to occur if the diaphragm was ruptured during the test. Ignition was also evident from the appearances of flames of various size and color.

In addition, two piezoresistive pressure transducers installed in the tank were used at oxygen concentrations approximately 1%-1.5% above the LOC at each altitude.   These tests were performed in hopes of providing more knowledge of the pressure rises associated with these low-level oxygen tests so as to increase confidence that any chemical reactions near the LOC would not result in pressure increases that might impact the structural integrity of the tank.

A bank of nitrogen bottles, connected to the fuel tank and controlled via a solenoid valve, served the dual purpose of controlling the ullage oxygen concentration and extinguishing any flames resulting from ignition of the ullage vapors.   In addition, a bottle of 100% methane was connected to the fuel tank, for use during the validation tests, in which the LFL for methane was determined and compared to published data [5].

The 12 thermocouples were used to record liquid fuel, ullage, and tank wall temperatures for the purpose of test monitoring and for use in future fuel vapor modeling work. Two thermocouple trees, placed within the tank, held a total of four ullage thermocouples. There were two thermocouples on each tree, which were placed a third of the way up from the bottom of the tank and a third of the way down from the top. Two thermocouples were placed on the floor, directly above the two heating elements, and one in the middle of the floor, directly under the fuel pan, in between the two heating elements. In addition, one thermocouple was used to record the liquid fuel temperature, and another thermocouple was placed at the center of each sidewall.

A spark/arc gap was located in the front left corner of the fuel tank. This gap consisted of two 1/16-in.-diameter tungsten electrodes that used a micrometer for gap width control and adjustment springs for electrode alignment. The gap width was set at approximately 7 mm throughout testing as this has been shown to be the optimum electrode spacing for ignition testing with methane [6]. Throughout testing, these electrodes were powered by two different spark/arc generators—an arc generating oil burner transformer and a J-57 engine spark igniter. In addition to these two ignition sources, a hot surface was also used in a brief set of tests concerning hot surface vapor ignition (HSVI). All of these ignition sources are discussed in detail in section 2.4 of this report, and a discussion of the methods used and results of energy calculations of the spark/arc generators is provided in section 2.5.

All test equipment was controlled through solid-state relays, powered by toggle switches located within a trailer directly outside the test facility. The trailer also housed all computer and data acquisition equipment. Schematics of this test setup, including thermocouple placements, are shown in figures 3 and 4.
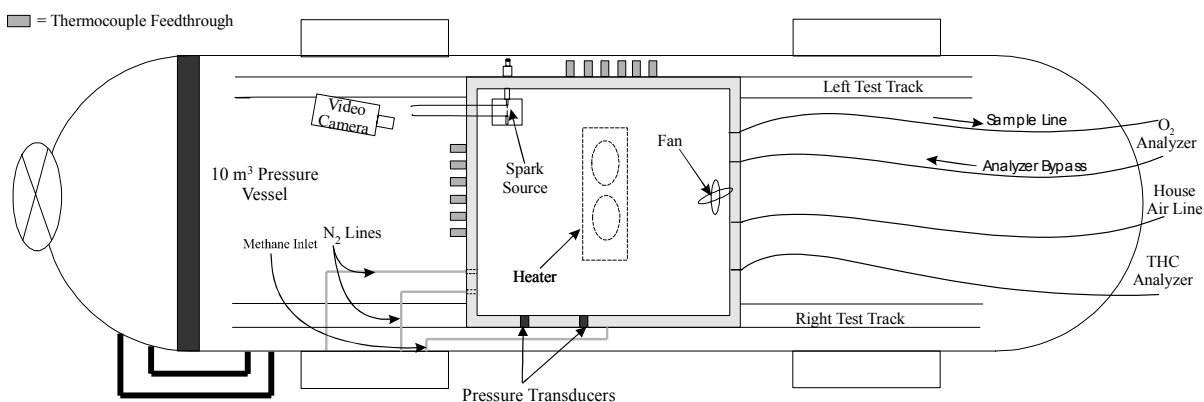

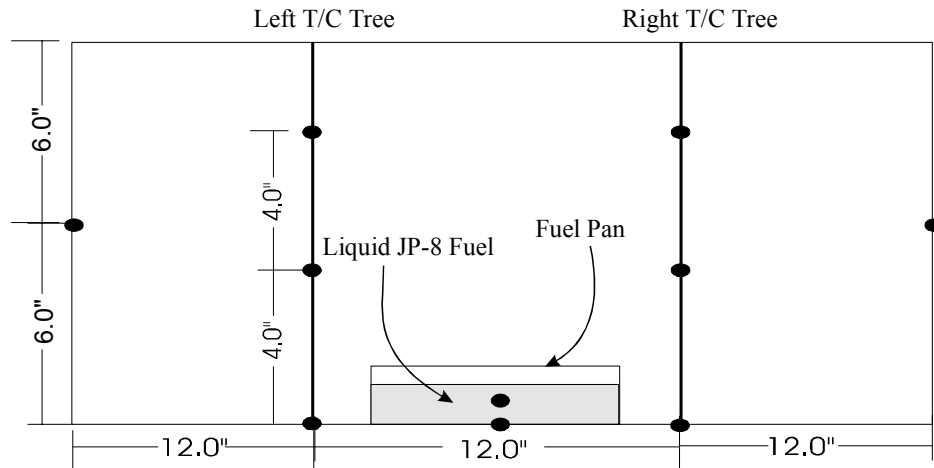FIGURE 3. SCHEMATIC OF EXPERIMENTAL SETUP (PLAN VIEW)

FIGURE 4. THERMOCOUPLE LOCATIONS

2.2 PRESSURE MEASUREMENT.

Two piezoresistive pressure transducers were used in testing at ullage oxygen concentrations approximately 1%-1.5% greater than the determined LOC at each altitude. A Kulite model XT-130 and an Endevco model 8530C were employed and both were operated at a frequency of 1 kHz. Though manufactured by different companies, both have similar electronics and work on the same theory of operation, thus, giving similar readings. In a method similar to Shepherd, et al. [7], to protect these transducers from the high temperatures associated with the ignition, it was necessary to place them in protective housings with a 3/8-in.-thick, sintered porous metal disc in front of the diaphragms. These protective housings act as a flame arrestor, protecting the transducers from the impinging flame front.

2.3 VAPOR MEASUREMENT.

Ullage hydrocarbon and oxygen concentrations were measured with dedicated hydrocarbon and oxygen analyzers connected to the test article via 1/4-inch sample lines. Among the considerations taken into account when designing the sampling systems were condensation of the fuel vapors, fouling of the sensors, depletion of the sample, and maintaining the necessary pressures and flow rates for each of the analyzers. A schematic of the sample trains employed are shown in figure 5, and detailed descriptions of each are given in sections 2.3.1 and 2.3.2 as well as brief summaries of the measurement principles of each analyzer.
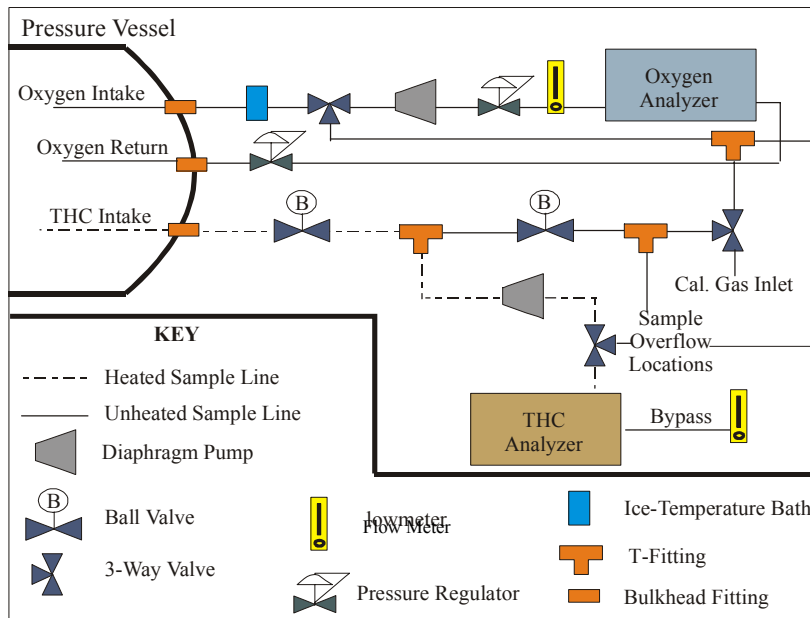
FIGURE 5. ULLAGE VAPOR SAMPLING SYSTEM

2.3.1 Hydrocarbon Analysis.

Hydrocarbon concentrations were measured throughout all tests with a total hydrocarbon (THC) analyzer using flame ionization detector (FID) technology. The full length of the sample line was maintained above 300°F with analog temperature controllers. This sample line was routed outside the rear of the vessel, into a series of ball valves, and into the hydrocarbon analyzer. The ball valves were used to switch the sampling process from inside of the fuel tank to the ambient air outside of the pressure vessel. This was done for two reasons. First, it was necessary to ensure that during ignition, the analyzer was not sampling from the fuel tank because it would damage the sensor. Second, it was necessary to intermittently draw a vapor sample from the tank because continuous sampling would result in a severe depletion of the sample. In addition, for tests at altitude, an external diaphragm-type pump was used between the ball valves and the analyzer to achieve the necessary flow rate through the detector. A flow meter on the bypass end of the analyzer was used to confirm the required sample flow rate. Limitations of the sample pump prevented experiments above altitudes of 38 kft. Testing at higher altitudes resulted in insufficient flow on the outlet of the pump. This caused a reversal in flow direction at the sample overflow location, thus, diluting the vapor sample.

Calibration of the THC analyzer was performed by flowing mixtures of varying propane concentration directly into the calibration ports of the analyzer. This calibration was then checked by allowing the calibration gas to flow through the pump into the sample inlet to ensure that there was no variance between the sample line and the calibration line.

The measurement principle of a FID analyzer is based on the ionization of organically bound carbon atoms in a hydrogen flame. The vapor sample is mixed with a hydrogen fuel mixture prior to reaching the burner, where the high temperature of the hydrogen flame causes reaction of the hydrocarbon compounds. Ions produced by this combustion are detected by the electrodes of

the FID, and the resulting current is amplified and outputted. This output is proportional to the number of carbon atoms for all hydrocarbon molecules and provides accurate total hydrocarbon measurements in terms of a volumetric concentration relative to the calibration gas.

2.3.2 Oxygen Analysis.

A Rosemount OM-11 EA oxygen analyzer was used to record the tank oxygen concentrations throughout the test program. Using a diaphragm-type pump in conjunction with a pressure regulator and flow meter to maintain a steady flow and pressure, the sample was drawn from the tank through an ice-temperature bath, into the analyzer, and then recirculated back into the tank. A backpressure regulator on the return side ensured positive flow back into the test article. The ice-temperature bath was used to condense out the hydrocarbons from the sample prior to reaching the oxygen sensor, which was found to be sensitive to these liquids. Calibration was performed by inserting mixtures of varying oxygen concentration into the sample line upstream of the diaphragm pump.

The OM-11 is, in essence, a partial pressure-sensing device. It uses a polarographic oxygen analysis technique, whereby two electrodes, immersed in potassium chloride gel, permit the diffusion of oxygen across a Teflon membrane. The rate of this diffusion is proportional to the partial pressure of oxygen on the outside of the membrane. The OM-11 converts this partial pressure into a reading of volumetric percent oxygen concentration, having an output on a scale of 0 to 5 Vdc.

2.4 IGNITION SOURCES.

Throughout testing, several ignition sources were used. An oil burner transformer connected to an analog timer provided a low-power arc of both short (0.1 second) and long durations (1 second), a spark igniter taken from a J-57 engine provided a very short duration (175 μseconds) high-powered spark, and a heated metal block was used as a hot surface ignition source. The heated metal block, which measured 1″ x 3″ x 6″ long, was heated by two 0.75″ diameter heating rods that passed through the unit and was monitored by a thermocouple mounted to the top surface. These varied ignition energy characteristics allowed for the verification of any variation in the LOC due to a specific type of ignition source.

2.5 SPARK/ARC ENERGY CALCULATION METHOD AND RESULTS.

For better characterization of the sparks and arcs used in testing, measurement of both voltage and current at the point where the high voltage leads entered the fuel tank were made. A Tektronix P6015A high-voltage probe was used for voltage measurement and an Ion Physics model CM-10-L was used for current measurement. Both probes were connected to a Tektronix THS730A oscilloscope which was used to record the two traces and transport them to a PC where calculations could be performed. With the voltage and current data, the energy deposited into the gap could then calculated by

$$E = \int_0^{t_1} VI \, dt \tag{1}$$

These tests and calculations were performed for both the short and long duration oil burner transformer arc as well as for the engine igniter spark. The results of these measurements can be found in table 2, while the voltage and current traces for the engine igniter and portions of the traces for the oil burner transformer are shown in figures 6(a) and 6(b).

TABLE 2. ESTIMATED SPARK/ARC ENERGIES

Ignition Source	Time Duration (s)	Estimated Energy (Joules)
Oil Burner Transformer	1.0	0.5
Oil Burner Transformer	0.1	0.08
J-57 Engine Igniter	0.000175	0.5
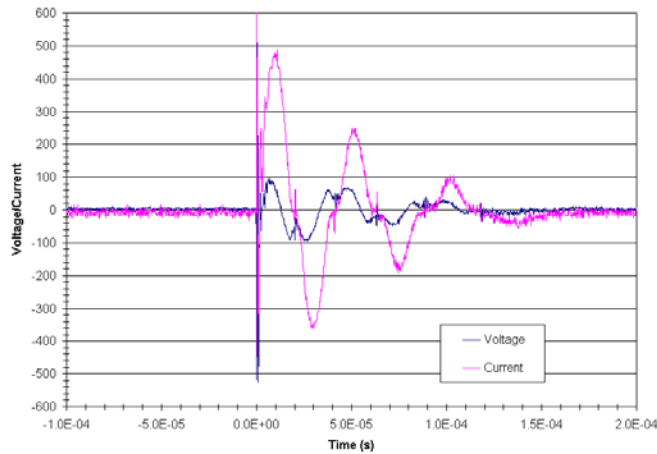
(a)
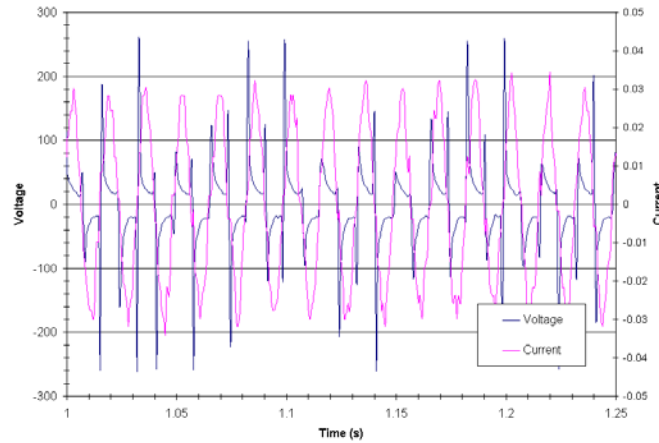
(b)

FIGURE 6. VOLTAGE AND CURRENT TRACES OF (a) J-57 ENGINE IGNITER AND (b) OIL BURNER TRANSFORMER IGNITION SOURCES

In addition, noise tests were conducted to determine if noise levels on either of the probes were large enough to effect this energy calculation. These tests clearly indicated that any noise on either of the probes was insufficient to have affected energy calculations in any significant way.

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3. EXPERIMENTAL PROCEDURES.

3.1 METHANE VALIDATION TESTS.

Prior to each test, the test article was purged with shop air in order to remove any remaining methane vapors. The hydrocarbon analyzer was calibrated with a certified bottle of 5-percent methane balanced in nitrogen and was zeroed with 100% nitrogen. The vessel door was closed and sealed, and data acquisition was initiated. A solenoid valve was opened to introduce methane into the test article. The ullage vapors were monitored with the hydrocarbon analyzer, providing time for complete mixing of the methane vapors. Once the desired methane concentration stabilized, a 1-second spark initiated the combustion process. This was repeated at numerous methane concentrations until ignition, defined in these tests as visual observation of movement of the blowout plate, was unobtainable. This level was then noted as the LFL and was compared to published data [5].

3.2 JP-8 LIQUID FUEL TESTS.

Prior to each test, the test article was purged of any remaining vapors with shop air until the ullage oxygen content was approximately 20.9% and the hydrocarbon concentration was below 2000 ppm-C_3H_8. The hydrocarbon analyzer was calibrated and linearized with certified bottles of 2-, 3-, 4-, and 6-percent propane balanced in nitrogen. The oxygen analyzer was subsequently calibrated with certified bottles of 12% and 16% oxygen with a nitrogen balance. In addition, both analyzers were zeroed with a bottle of 100% nitrogen.

Following this calibration and a check of all critical devices, 3/8 of a gallon of JP-8 fuel was carefully measured, poured into the fuel pan, and placed in the center of the fuel tank. The pressure vessel was hydraulically sealed and the vacuum pump was used to evacuate the chamber to the approximate pressure corresponding to the desired altitude. Data collection was initiated. The nitrogen solenoid valve was opened to introduce nitrogen into the tank. The flow of nitrogen was introduced in stages, while monitoring the ullage oxygen concentration. When the desired oxygen concentration was achieved, all nitrogen flow was terminated, and the fuel heating process was started.

The oxygen and hydrocarbon concentrations within the fuel tank were periodically checked throughout the test, with the fan being used to ensure a well-mixed ullage vapor space. Upon achieving the desired ullage vapor concentration, the oxygen analyzer pump was turned off, and the hydrocarbon analyzer was switched to sample from ambient air. This was done to prevent combustion products from fouling the gas analyzer sensors.

At this point, video tape recording was initiated and the fuel vapor mixture was subjected to several sparks/arcs. In the case of the HSVI tests, the heated block was running and monitored throughout the test at between 50%-70% full load and turned to full load as the desired ullage vapor concentration was achieved. The hot surface temperature (HST) was monitored throughout. In all test cases, if ignition, as defined in section 2.1, was not observed the test was terminated and the tank was considered inert under these conditions.

In order to obtain worst-case scenario data, it was desired to perform testing at near-stoichiometric mixtures. Calculations of the stoichiometric mixture were performed by approximating the fuel vapor as C_xH_y. Using an existing computer model developed by Ivor Thomas, the FAA's Chief Scientific and Technical Advisor for Fuel Systems, a ratio of y:x was obtained, as well as the vapor's molecular weight. These calculations, with the input of a stoichiometric fuel-air mass ratio (FAR) of 0.068, resulted in y/x = 1.99 and MW_{vapor} = y + 12x = 126.54. With this information, it was then determined that the approximate fuel vapor was $C_{9.05}H_{18.01}$. This could then be substituted into a stoichiometric chemical equation

$$C_{9.05}H_{18.01} + a[O_2 + 3.76N_2] \rightarrow bCO_2 + cH_2O + dN_2$$

Solving this equation for the coefficients a, b, c, and d results in

$$C_{9.05}H_{18.01} + 13.55[O_2 + 3.76N_2] \rightarrow 9.05CO_2 + 9H_2O + 50.96N_2$$
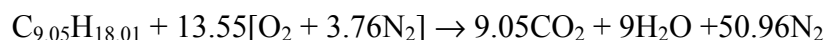
From this, the fuel-air mole ratio can be determined as

$$\frac{mol_{fuel}}{mol_{air}} = \frac{1}{1 + (4.76)(13.55)} = 1.53\%$$

Therefore, the stoichiometric mixture in terms of part-per-million of fuel vapor (ppm_{fuel}) is given by 15267 ppm_{fuel}. To obtain this value in terms of propane, it is simply multiplied by the carbon ratio, in this case $\frac{9.05}{3}$. This then results in an approximate stoichiometric mixture of 46155 ppm-C_3H_8. Performing this same set of calculations for a 12% O2 environment, one could find a stoichiometric 12% O_2 air mixture of approximately 24000 ppm-C_3H_8. As testing showed and as discussed in section 4.2.2, this stoichiometric mixture at a reduced O_2 concentration resulted in the lowest values of the LOC despite initial thoughts that a stoichiometric 21% O_2 air mixture would be needed.

4. DISCUSSION OF RESULTS.

4.1 METHANE VALIDATION TESTS.

As discussed previously, prior to performing any ignition experiments with aviation fuel, a series of validation tests were performed with methane in air mixtures. Because pressure was not measured in these experiments, ignition was defined by visual observation of the movement of the blowout plate, which resulted from a pressure buildup within the tank.

The experimental data for this series of tests is shown in figure 7, in terms of ignition and nonignition criteria. The data shows that the LFL of methane lies somewhere between 5.3% and 5.35% methane, matching closely the value 5.3% given by Lewis and von Elbe [5]. Therefore, it was concluded that the experimental apparatus and methods employed were suitable for ignition testing.
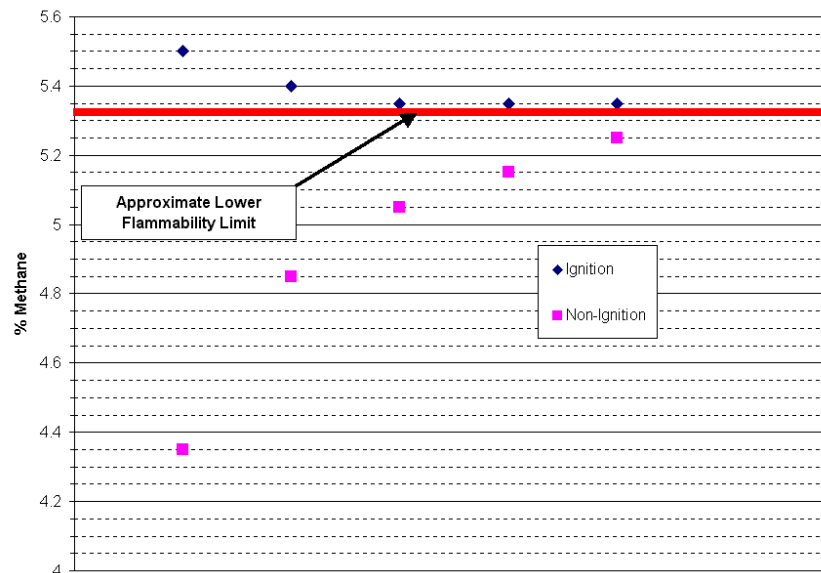
FIGURE 7. EXPERIMENTAL METHANE LFL DATA

4.2 JP-8 LIQUID FUEL TESTS.

The majority of tests with liquid JP-8 fuel were conducted using the oil burner transformer as the ignition source with an arc duration of 1 second. These tests were conducted with both the 1/4-in. aluminum plate and foil diaphragm pressure relief mechanisms and at altitudes ranging from 0 to 38 kft. Subsequent tests used the other various ignition sources in an attempt to verify any dependency of the LOC with ignition source. Tests with the short duration oil burner transformer, engine igniter, and hot surface focused on sea level conditions because this is the region which drives the design criteria for an inerting system.

4.2.1 Long Duration Oil Burner Transformer Tests.

The initial oil burner transformer tests were conducted with a spring-loaded, 1/4-in. aluminum plate used as the pressure relief mechanism and a 1 second arc duration. As noted previously, ignition under these test conditions was characterized by movement of this blowout plate. The tests were conducted in the range of 0 to 30 kft, in increments of 10 kft. At each altitude, ignition was attempted at an initial ullage concentration of 20.9% O_2 followed by reduced oxygen concentrations until ignition was no longer observed under the given test conditions. The results from this set of tests are shown in figure 8 as oxygen concentration plotted against altitude.

The data in figure 8 clearly indicates that LOC increases with increasing altitude. However, the precise nature of this trend could not be established due to data scatter and an insufficient ignition and nonignition criterion. These results were useful in subsequent tests to determine the LOC as a function of altitude. The upward trend in LOC is not observed at 30 kft in figure 8 due to an insufficient hydrocarbon sample flow at this low pressure. Prior to continuing with further testing, this issue was resolved.
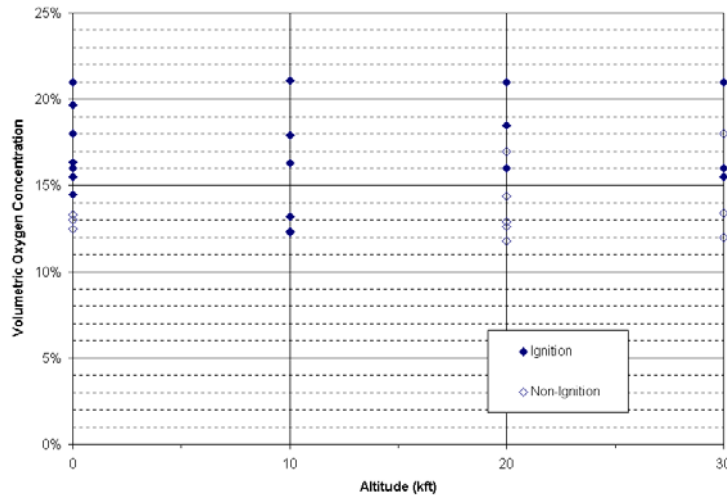
12

FIGURE 8. LIMITING OXYGEN CONCENTRATION DATA
RESULTS—ALUMINUM PLATE RELIEF MECHANISM

To better define the LOC, the aluminum plate pressure-relief mechanism was replaced with a foil diaphragm. With this new relief mechanism, ignition was defined simply by rupture of the foil, allowing for a more definitive measure of ignition and nonignition. These tests were carried out in a similar fashion as those depicted in figure 8, with the upper limit of testing being at or slightly above the LOC determined from the previous tests. This set of tests was also expanded to include a higher altitude of approximately 38 kft, the upper limit at which the instrumentation was capable of accurate vapor measurement. The results are presented in figure 9, again as oxygen concentration plotted against altitude. In addition, figure 10 shows the minimum O_2 concentration resulting in ignition along with the maximum O_2 concentration resulting in nonignition at each altitude.
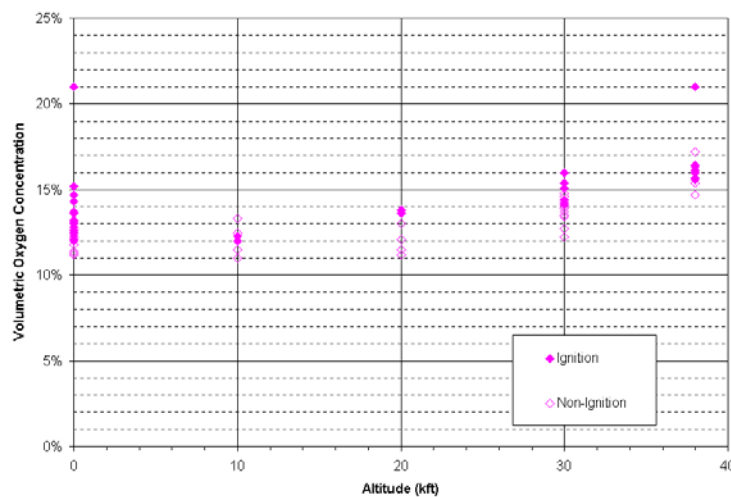

FIGURE 9. LIMITING OXYGEN CONCENTRATION DATA RESULTS—
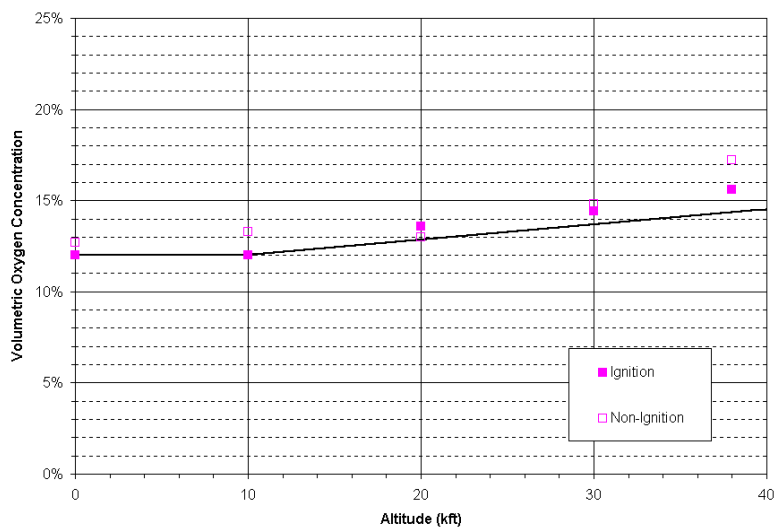FOIL DIAPHRAGM RELIEF MECHANISM

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FIGURE 10. LIMITING OXYGEN CONCENTRATION DATA RESULTS—
MINIMUM/MAXIMUM VALUES FOR IGNITION AND NONIGNITION

From these results, there is a clear indication that an increase occurs in the LOC as altitude is increased. The LOC rises steadily from a value approximately 12% O_2 at sea level and 10 kft to approximately 14.5% O_2 at 40 kft.

The sea level LOC data is consistent with previous data, such as Zinn's work in 1971 [9], in which he performed an extensive literature search of several inerting level requirement datasets. Zinn found that the resulting LOC determined by these experiments varied approximately 1 percent, falling in the 11.5%-12% O_2 range. Many aircraft inerting systems, however, have used a level approximately of 9% as their design criteria as a result of a Bureau of Mines suggestion of using a 20% safety margin [10].

While there is not much data available for the LOC at altitude, Stewart and Starkman [11] did perform some altitude work with both carbon dioxide and nitrogen inerting. Their data, however, was generated by using flame propagation as the ignition and nonignition criteria. If any visible flame front occurred within the tank, it was considered an ignition. The resulting pressure rise was not used as a criterion, and it is noted in their report that at times flame propagation occurred with little or no resulting pressure rise. As a result of this difference in criterion, Stewart and Starkman's data set tends to be lower than the data generated here, starting at approximately 9.8% O_2 at sea level and increasing to approximately 10.8% at 30 kft and 13% at 60 kft. While the disparity in criteria does not allow for direct comparison of this data to the data presented in this report, it does verify the trend of decreasing inerting level requirements (higher LOC) as altitude is increased.

Figures 11-15 depict the data from these tests as approximated fuel-air mass ratio and volumetric fuel vapor concentration versus volumetric oxygen concentration for each of the five altitudes tested. A large majority of the tests were conducted at sea level, because this is the most important region in the design of an inerting system. From the 50 tests conducted at sea level, 18

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were conducted in the range of 11%-12.5% O_2. Of these 18 tests, only four resulted in ignition, and only one of the nine tests at or below 12% O_2 ignited.

FIGURE 11. LIMITING OXYGEN CONCENTRATION DATA RESULTS—FUEL-AIR RATIO AND FUEL VAPOR CONCENTRATION VS OXYGEN CONCENTRATION (SEA LEVEL)

FIGURE 12. LIMITING OXYGEN CONCENTRATION DATA RESULTS—FUEL-AIR RATIO AND FUEL VAPOR CONCENTRATION VS OXYGEN CONCENTRATION (10 kft)
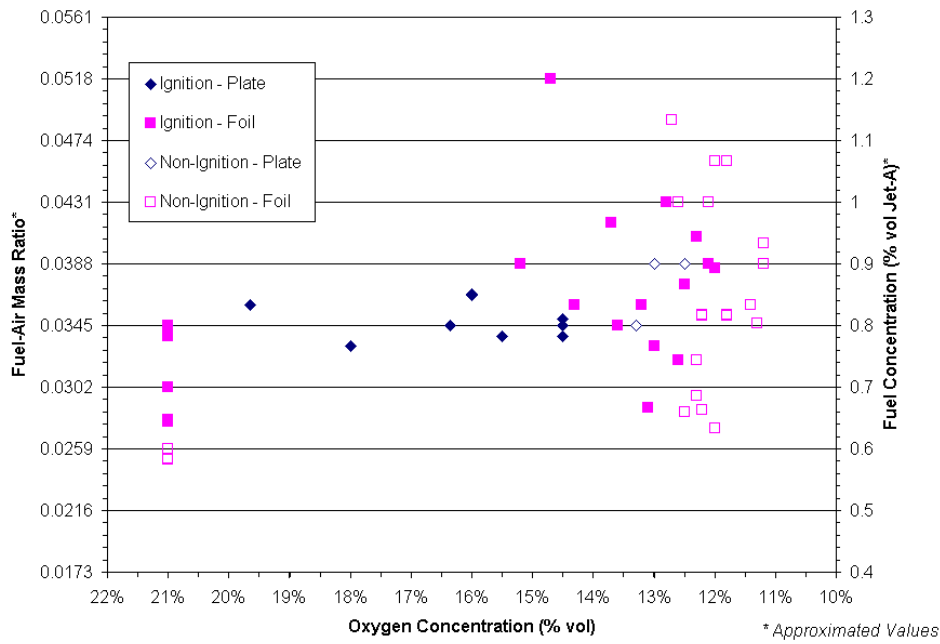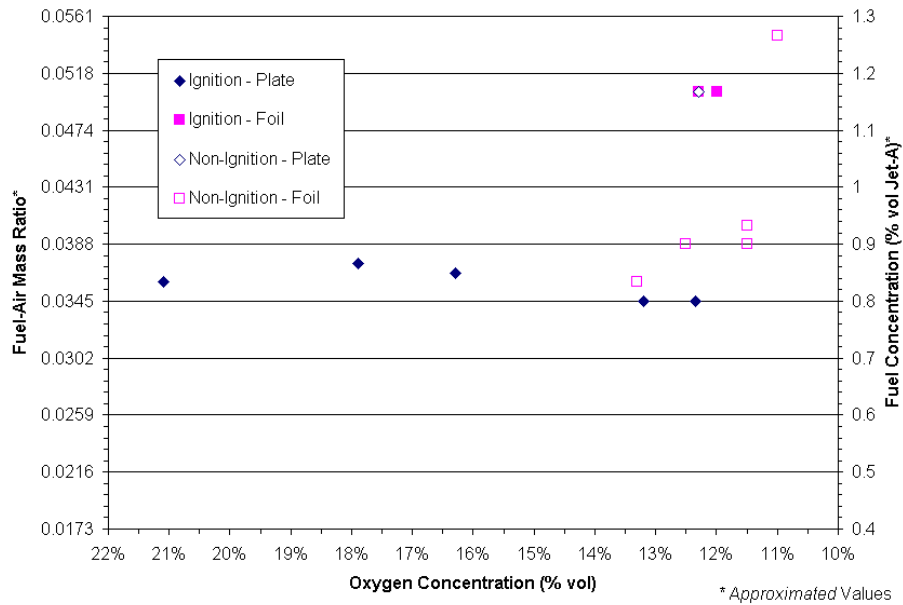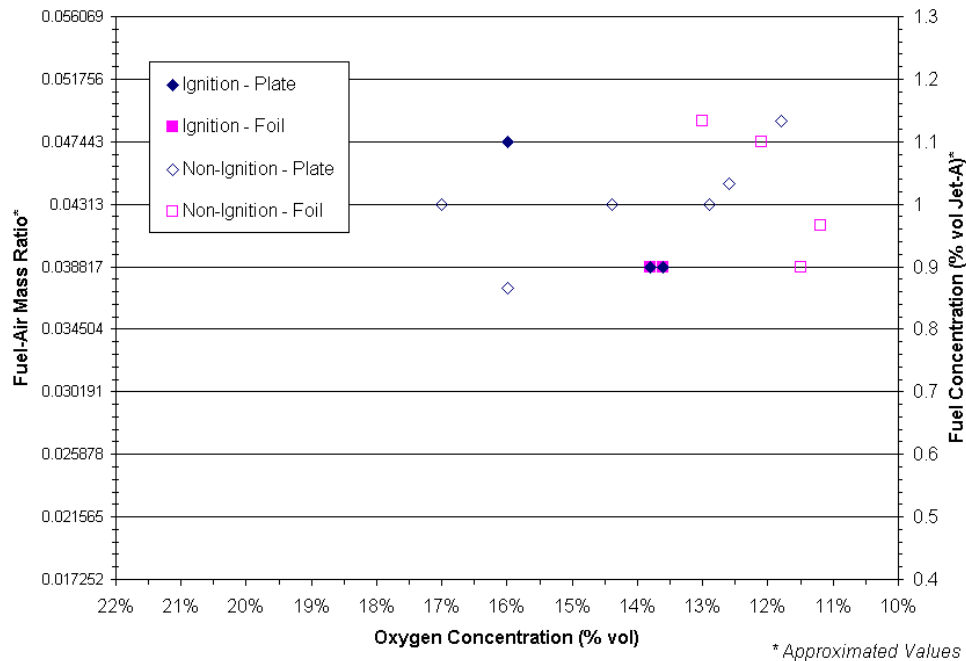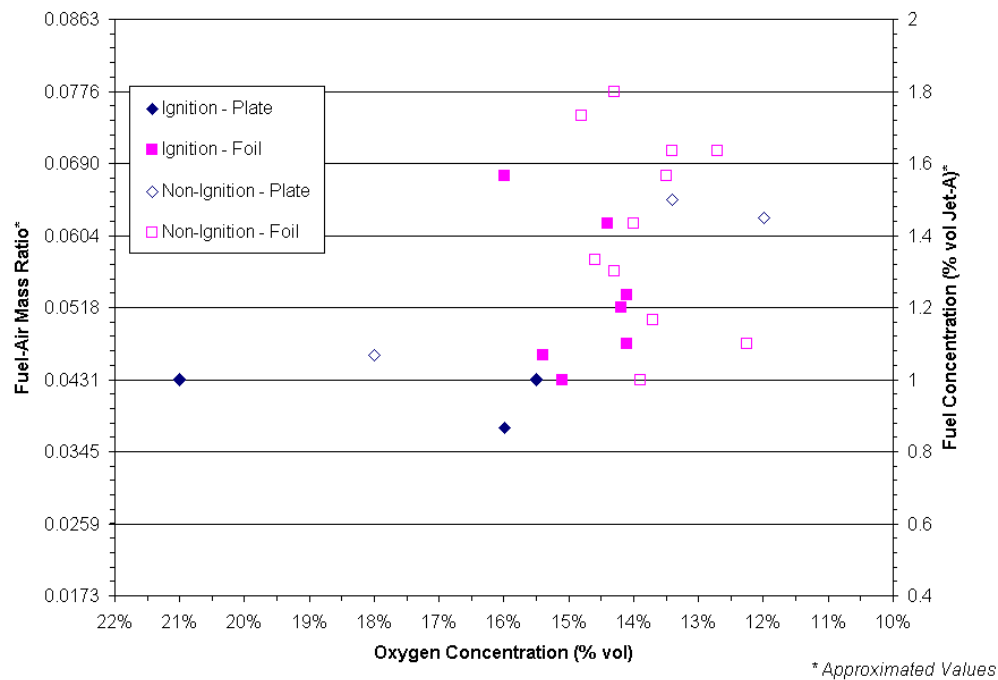
15

FIGURE 13. LIMITING OXYGEN CONCENTRATION DATA RESULTS—FUEL-AIR
RATIO AND FUEL VAPOR CONCENTRATION VS OXYGEN CONCENTRATION (20 kft)

FIGURE 14. LIMITING OXYGEN CONCENTRATION DATA RESULTS—FUEL-AIR
RATIO AND FUEL VAPOR CONCENTRATION VS OXYGEN CONCENTRATION (30 kft)
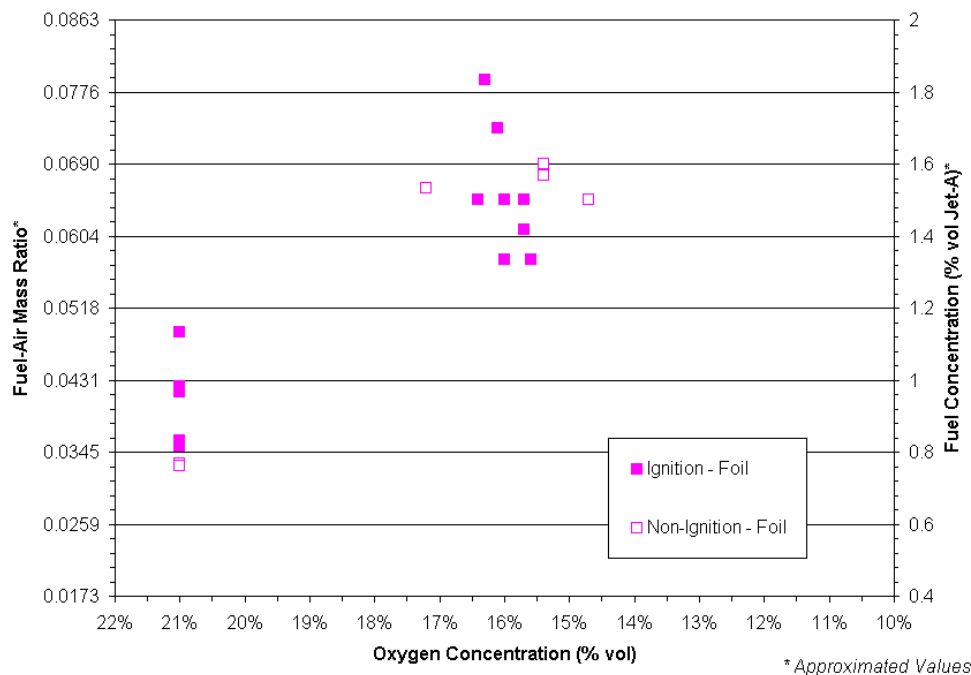
16

FIGURE 15. LIMITING OXYGEN CONCENTRATION DATA RESULTS—FUEL-AIR
RATIO AND FUEL VAPOR CONCENTRATION VS OXYGEN CONCENTRATION (38 kft)

Although excessive amounts of condensation at low altitudes precluded testing at a stoichiometric fuel-air mixture, later testing, as discussed in section 4.2.2, showed that the lowest values for LOC occurred at a near stoichiometric mixture for a fuel-12% O_2 air mixture.

Upon completion of these LOC tests, it was desired to measure the pressure rises caused by ignition, seen at low-oxygen concentrations, and examine the effect of increasing altitude. The two pressure transducers were used as described in section 2.2 of this report. Tests were conducted at altitudes from 0 to 30 kft, with the foil diaphragm acting as the pressure relief mechanism. Testing was limited to oxygen levels approximately 1% to 1.5% above the LOC values previously determined and shown in figure 10.

Both transducers recorded similar values, and the averaged results are shown in figures 16 and 17. Figure 16 depicts the peak pressure rise versus altitude. From this plot a decrease in the peak pressure is observed as altitude is increased from 0 to 30 kft. Figure 17 depicts the time duration to reach the peak pressure plotted versus altitude. The time duration increases as altitude is increased.

It should be noted, however, that with these particular tests, after the diaphragm ruptured, the transducers were reading the pressure of the entire chamber. It is for this reason that the peak pressures recorded in figure 16 seem relatively small, and similarly that the time durations in figure 17 are relatively long. Since the vessel volume is approximately 40 times the volume of the fuel tank, the peak pressures shown in figure 16 are approximately 1/40 of the potential pressure rise occurring in a closed, nonvented environment. This appears to be consistent with

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Shepherd, et al.'s [8] work, in which they recorded pressure rises near 50 psig, occurring at pressures equivalent to an altitude of approximately 15 kft.
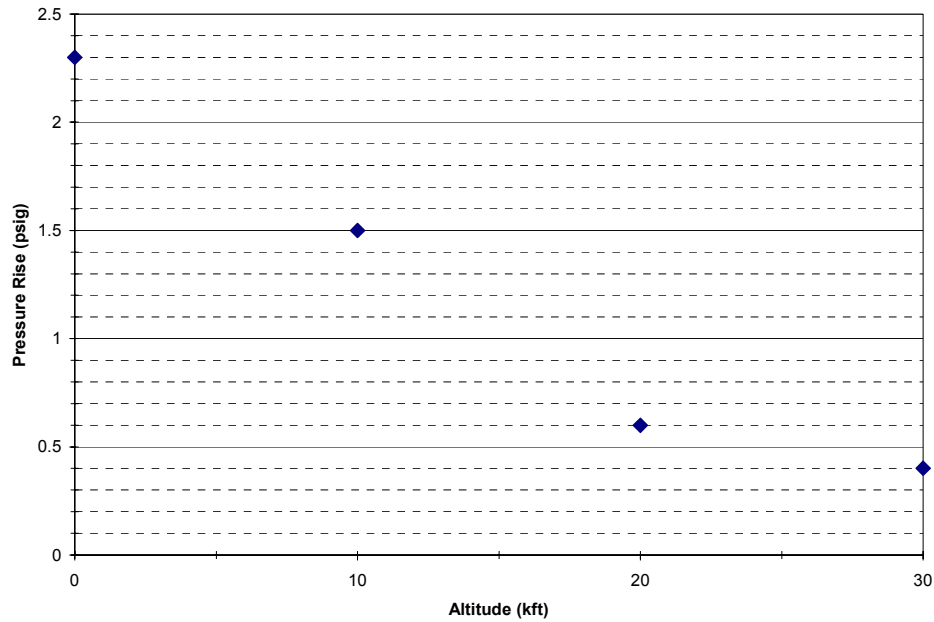

FIGURE 16. PEAK PRESSURE RISE VS ALTITUDE AT O_2 CONCENTRATIONS
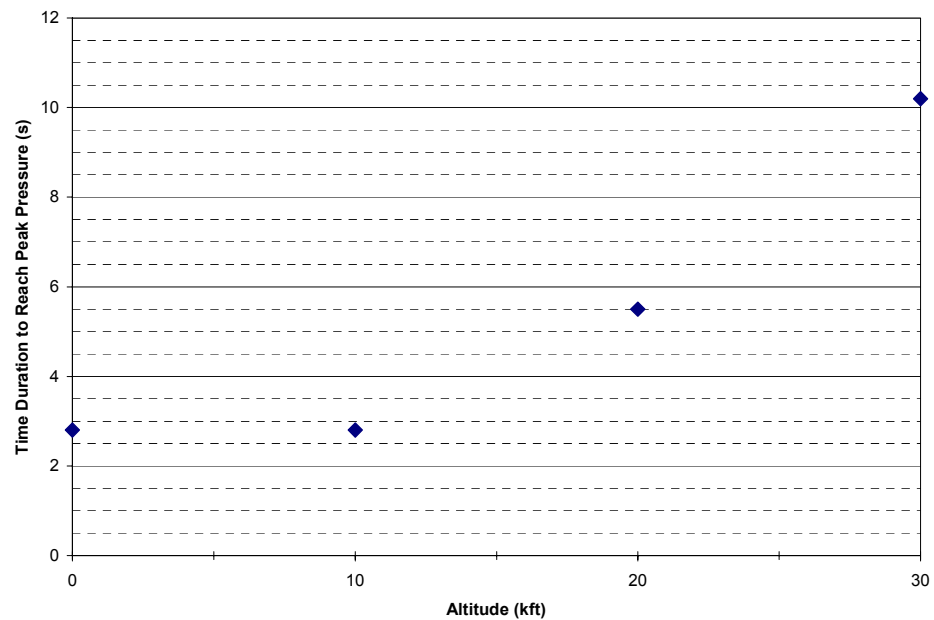1%-1.5% ABOVE THE LOC

FIGURE 17. IGNITION TIME DURATION VS ALTITUDE AT O_2 CONCENTRATION
1%-1.5% ABOVE THE LOC

The pressure rise data was further verified by a brief set of experiments that were conducted within the full-pressure vessel with no postignition pressure relief. In these tests, a 3- by 6-foot fuel pan was placed inside the vessel with the equivalent fuel loading as in previous tests. Heating of the fuel was achieved by three of the identical hot plates used in the 9-ft^3 tank attached to the bottom of the pan. Ignition was achieved using the same transformer, connected to two 1/8-in steel electrodes. Vessel pressure was recorded by a 0-200 psi sealed gauge, diaphragm-type transducer. Due to large condensation effects within this chamber, tests were only able to be conducted at altitudes above 20 kft. The results of these tests can be seen in table 3.

TABLE 3. NONVENTED, FULL VESSEL IGNITION PRESSURE RESULTS

Altitude (kft)	Oxygen Concentration	Initial Pressure (psia)	Final Pressure (psia)	Differential Pressure (psia)	Differential/Initial Pressure (psia)
20	21.0%	6.9	33.7	26.8	3.88
20	15.0%	6.8	30.5	23.7	3.49
38	21.0%	3.5	16.1	12.6	3.60
38	17.3%	3.8	16.5	12.7	3.34

Extrapolating the results in figure 16 to include a data point of approximately 0.3 psig at 38 kft, it can be seen that at both altitudes the nonvented data is approximately 42 times the vented pressure results. This data also shows that the ullage oxygen concentration has little or no effect on the resulting pressure rise from ignition, and that the ratio of differential to initial pressure does not vary much with either altitude or oxygen concentration.

4.2.2 Engine Spark Igniter Tests.

Results of tests conducted with the J-57 engine igniter can be seen in figure 18. In an attempt to verify that testing was being performed at the optimum hydrocarbon concentration, these tests were conducted within several fuel vapor concentration ranges. These consisted of those at levels near that of a stoichiometric 12% O_2 air mixture (i.e., 0.035 < FAR < 0.04), those at levels near that of a stoichiometric 21% O_2 air mixture (i.e., 0.065 < FAR < 0.07), and several that fell between these two ranges.

Due to the high amount of condensation occurring in the test tank, it was necessary to slightly modify the test fuel so as to be able to achieve those higher fuel vapor concentrations. Being that hexane has flammability properties that closely mimic that of jet fuel and has a rather low boiling point, it was decided to spike the test fuel with varying amounts of hexane as noted in the figure. To verify that this modification did not drastically affect the fuel, distillation curves and flash points were taken of the JP-8 and JP-8/Hexane mixtures. The results of these tests can be found in figure 19. From this figure, it is observed that the addition of hexane has affected the fuel only in increasing the quantity of low-boiling point components, thereby reducing the fuel's flashpoint. Above 20% distillation, however, little effect is seen.
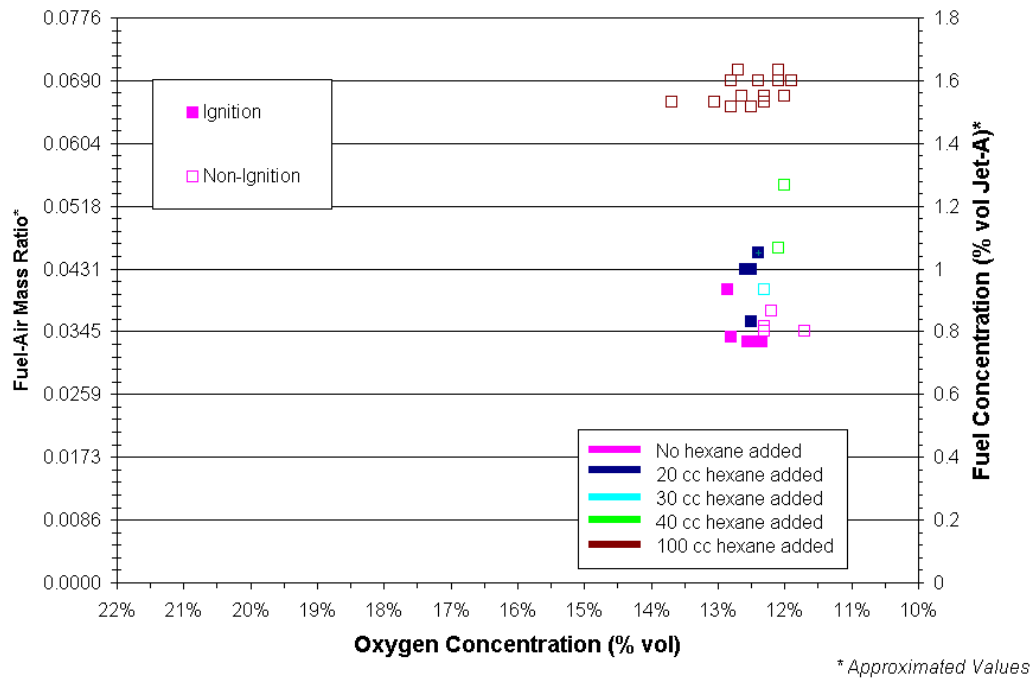
FIGURE 18. ENGINE IGNITER TEST RESULTS (SEA LEVEL)
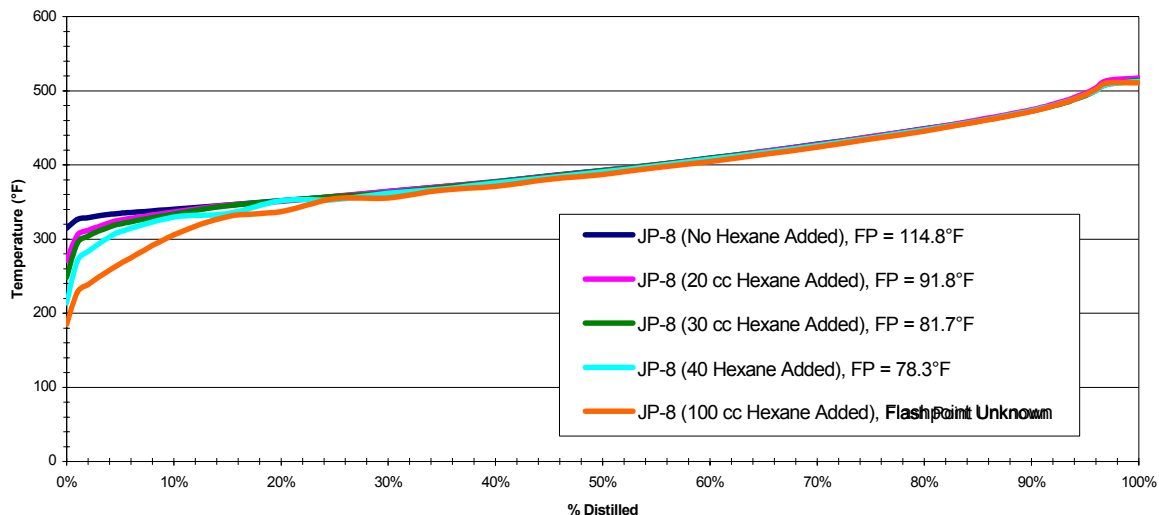
FIGURE 19. ASTM D 86 DISTILLATION CURVES AND FLASH POINT (FP) DATA OF
JP-8 AND HEXANE MIXTURES

There were 15 tests conducted at the stoichiometric 21% O_2 mixture, consisting of ullage O_2 concentrations from 11.9% to 13.7%. Of these 15 tests, not one resulted in ignition. Of the 18 tests conducted at FARs below this, the lowest ullage O_2 concentration resulting in ignition was 12.3%. Interestingly, this value of the LOC occurred at a near stoichiometric mixture for a fuel-12% O_2 air mixture as opposed to the initial thought that a stoichiometric mixture for 21% air

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would need to be used to obtain the lowest LOC value. It is believed that the inerting agent has effectively lowered the UFL, thereby resulting in a mixture that is too rich.

4.2.3 Short Duration Oil Burner Transformer Tests.

Table 4 summarizes results of six tests conducted using the oil burner transformer with a 0.1 second arc duration. The tests were performed near stoichiometric for a fuel-12% O_2 air mixture and at ullage O_2 concentrations ranging from 12.5%–14.3% at sea level conditions. Of these tests, three resulted in ignition, all at O_2 concentrations greater than 12.8%. Below this value, no ignition was achieved.

TABLE 4. SHORT DURATION OIL BURNER TRANSFORMER TEST RESULTS

O_2 Concentration	Total Hydrocarbons (ppm-C_3H_8)	% Volume of Jet-A	Fuel-Air Mass Ratio	Ignition?
12.5%	23000	0.7667	0.033	No
12.8%	22000	0.7333	0.032	No
12.8%	23500	0.7833	0.034	No
14.3%	24500	0.8167	0.035	Yes
13.2%	23000	0.7667	0.033	Yes
12.9%	24000	0.8000	0.034	Yes

4.2.4 Hot Surface Vapor Ignition Tests.

To ensure that the heated surface was a capable ignition source, the initial HSVI test was conducted in a noninerted atmosphere. The results of these tests are summarized in table 5. A violent ignition was observed during this test as the HST approached approximately 1350°F. Six subsequent tests were performed with ullage O_2 concentrations ranging from 11.3% to 14.0%, again with near stoichiometric concentrations for a fuel-12% O_2 air mixture. During these tests, as the HST approached approximately 1200°F, some slight puffs of smoke could be seen emanating from the vent of the fuel tank, however no ignition events were observed in any of the tests even as the surface was heated above 1400°F.

TABLE 5. HOT SURFACE VAPOR IGNITION TEST RESULTS

O_2 Concentration	Total Hydrocarbons (ppm-C_3H_8)	% Volume of Jet-A	Fuel-Air Mass Ratio	Maximum HST	Ignition?
21%	25500	0.8500	0.037	1300	Yes
14%	26000	0.8667	0.037	1430	No
13.1%	23000	0.7667	0.033	1420	No
12.7%	24000	0.8000	0.035	1440	No
11.5%	26000	0.8667	0.037	1430	No
11.3%	21500	0.7167	0.031	1420	No

5. CONCLUSIONS.

From these tests, it was determined that the limiting oxygen concentration (LOC) at sea level through 10 kft is approximately 12% O_2, with a linear increase from 12% at 10 kft to approximately 14.5% at 40 kft. Tests with various sparks and arcs as ignition sources under sea level conditions showed little variation in results, with the LOC ranging from 12.0% to 12.8%. Meanwhile, a heated surface capable of igniting a fuel-air mixture proved insufficient for ignition in a tank inerted to just 14% O_2. Pressure data showed that peak pressures resulting from ignition at oxygen concentrations 1% to 1.5% above LOC values decreased as the altitude was increased to 30 kft, while the time duration to reach the peak pressure increased.

6. REFERENCES.

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3.   Fuel Flammability Task Group, "A Review of the Flammability Hazard of Jet A Fuel Vapor in Civil Transport Aircraft Fuel Tanks," FAA Report DOT/FAA/AR-98/26, June 1998.

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7.   Shepherd, Krok, Lee, Brown, Lynch, Samaras, and Birky, "Results of 1/4 Scale Experiments, Vapor Simulant and Liquid Jet A Tests," NTSB Docket No. SA-516, Exhibit, No. 20O, 2000.

8.   Shepherd, J.E., Krok, J.C., and Lee, J.J., "Jet A Explosion Experiments: Laboratory Testing," NTSB Docket No. SA-516, Exhibit No. 20D, 1997.

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APPENDIX A—COMMERCIAL AND MILITARY AVIATION FUEL SPECIFICATIONS

ASTM D 1655 Detailed Specifications of Commercial Aviation Turbine Fuels

Property		Jet A or Jet A-1	Jet B
COMPOSITION			
Acidity, total mg KOH/g	Max	0.10	…
Aromatics, vol %	Max	25	25
Sulfur, mercaptan, weight %	Max	0.003	0.003
Sulfur, total weight %	Max	0.30	0.3
VOLATILITY			
Distillation temperature °C:			
10% recovered, temperature	Max	205	…
20% recovered, temperature	Max	…	145
50% recovered, temperature	Max	Report	190
90% recovered, temperature	Max	Report	245
Final boiling point, temperature	Max	300	…
Distillation residue, %	Max	1.5	1.5
Distillation loss, %	Max	1.5	1.5
Flash point, °C	Min	38	…
Density at 15°C, kg/m^3		775 to 840	751 to 802
Vapor pressure, 38°C, kPa	Max	…	21
FLUIDITY			
Frezing point, °C	Max	-40 Jet A -47 Jet A-1	-50
Viscosity -20°C, mm^2/s	Max	8.0	
COMBUSTION			
Net heat of combustion, MJ/kg	Min	42.8	42.8
One of the following requirements shall be met:			
Luminometer number, or			
(2) Smoke point, or	Min	45	45
(3) Smoke point, mm, and	Min	25	25
Naphthaleness, vol %	Min	18	18
	Max	3.0	3.0
CORROSION			
Copper strip, 2 h at 100°C	Max	No. 1	No. 1
THERMAL STABILITY			
JFTOT (2.5 h at control temperature of 260°C min)			
Filter pressure drop, mm Hg			
Tube deposits less than	Max	25 3	25 3
CONTAMINANTS			
Existent gum, mg/100 mL	Max	7	7
Water reaction:			
Interface rating	Max	1b	1b

Detailed U.S. Military Requirements of Aviation Turbine Fuels as Taken From Reference 4

Property		JP-4	JP-5	JP-8
COMPOSITION		0.015	0.015	0.015
Acidity, total mg KOH/g	Max	25.0	25.0	25.0
Aromatics, vol %	Max	5.0	5.0	5.0
Sulfur, mercaptan, weight %	Max	0.001	0.001	0.001
Sulfur, total weight %	Max	0.4	0.4	0.3
Color, Saybolt	Max	Report	Report	Report
VOLATILITY				
Distillation temperature °C:				
Initial boiling point, temperature	Max	Report	Report	Report
10% recovered, temperature	Max	Report	205	205
20% recovered, temperature	Max	145	Report	Report
50% recovered, temperature	Max	190	Report	Report
90% recovered, temperature	Max	245	Report	Report
Final boiling point, temperature	Max	270	290	300
Distillation residue, %	Max	1.5	…	1.5
Distillation loss, %	Max	1.5	…	1.5
Explosiveness, %	Max	…	50	
Flash point, °C	Min	…	60	38
Gravity, °API (15°C)	Max	45-57	36-48	37-51
Density at 15°C, kg/m^3	Max	751-802	788-845	775-840
Vapor pressure, 37.8°C, kPa (psi)		14-21	…	
FLUIDITY				
Frezing point, °C	Max	-58	-46	-50
Viscosity -20°C, mm^2/s	Max	…	8.5	8.0
COMBUSTION				
Aniline-Gravity product, or	Min	5250	4500	
Net heat of combustion, MJ/kg	Min	42.8	42.6	42.8
Smoke Point, or	Min	20.0	19.0	19.0
Hydrogen Content (wt %)	Min	13.6	13.5	13.5
CORROSION				
Copper strip, 2 h at 100°C	Max	1b	1b	1b
THERMAL STABILITY				
JFTOT ΔP (mm Hg)	Max	25	25	25
JFTOT Tube Color Code	Max	<3	<3	<3
CONTAMINANTS				
Existent gum, mg/100 mL	Max	7	7	7
Particulates (mg/liter)	Max	1	1	1
Water reaction interface	Max	1b	1b	1b
Water Separation Index Modified	Min	70	85	70
Filtration Time (minutes)	Max	15	…	...

Detailed U.S. Military Requirements of Aviation Turbine Fuels as Taken From Reference 4

Property	JP-4	JP-5	JP-8
ADDITIVES			
Anti-icing (vol %)	0.10-0.15	0.10-0.15	0.10-0.15
Antioxidant	Required	Required	Option
Corrosion Inhibitor	Required	Required	Required
Metal Deactivator	Option	Option	Option
Antistatic	Required	…	Required
OTHER			
Conductivity (pS/m	200-600	…	200-600
Service	All	Navy	USAF
NATO Code No.	F-40	F-44	F-34; F-35