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INERTED FUEL TANK OXYGEN CONCENTRATION REQUIRMENTS

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16. Abstract

A literature search was conducted to investigate the extent of experimental work and studies that were performed for determining and evaluating safety parameters of jet fuels in aircraft tanks when using nitrogen as an inerting agent. The search revealed that extensive laboratory studies have been made during the past 30 years and that safety zones can be predicted over a wide range of conditions and environments. Except for some very early full-scale tests using aircraft fuel tanks by the Royal Aircraft Establishment, all the studies were made using laboratory equipment.

As a conclusion from this search, it is considered that an oxygen content up to 9 percent in the effluent obtained by nitrogen inerting will produce an incombustible environment.

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INTRODUCTION

Purpose

The purpose of this report is to summarize the results of a literature search for establishing a safe oxygen limit in nitrogen inerting systems when used for the protection of aircraft fuel tanks against ignition and explosion.

Background

In the interest of reducing £ire hazards in aircraft fuel systems, the FAA sponsored a nitrogen fuel tank inerting system for installation in an FAA DC-9 aircraft, which is used £or air carrier inspection training at the Aeronautical Center in Oklahoma City. This system consists 0£ qualified components and has been demonstrated to comply with all applicable airworthiness standards 0£ the Federal Aviation Regulations £or transport category airplanes. Following supplemental type certification 0f the inerting system in the DC-9, the aircraft shall continue to be used in its normal missions with the inerting system in operation, in order to evaluate its functional characteristics and determine whether it is feasible for commercial air carrier service.
It was, therefore, considered desirable to investigate work performed on safe oxygen limit parameters jet fuels.

Jet fuels do not burn in the liquid phase. They must be vaporized and mixed with air in order to burn. In a tank containing fuel, the free space above the liquid (ullage) represents a potential fire or explosion hazard if the fuel vapors are in a flammable condition, Reference 1. Studies have been made which can accurately predict the flammable envelope of the ullage space when the fuel temperature, ullage pressure, dynamic or static conditions, and fuel specifications are given, Reference 2. A typical flammability envelope is shown in Figure 1. This indicates that when fuel and ullage are in temperature equilibrium, vapor below a certain temperature is too lean to burn and above a certain temperature too rich to burn. This flammable range is based on an ignitable fuel-air ratio by weight from .035 to .288. As the liquid fuel in the tanks becomes hotter, its vapor pressure becomes higher which in turn increases the fuel-air ratio. A relatively volatile jet fuel such as JP-4 would create an effluent flammable range at sea level between approximate temperature limits of –4°F and 63°F, while ales s volatile fuel, such as aviation kerosene, would fall between 100°F and 185°F, Reference 2.

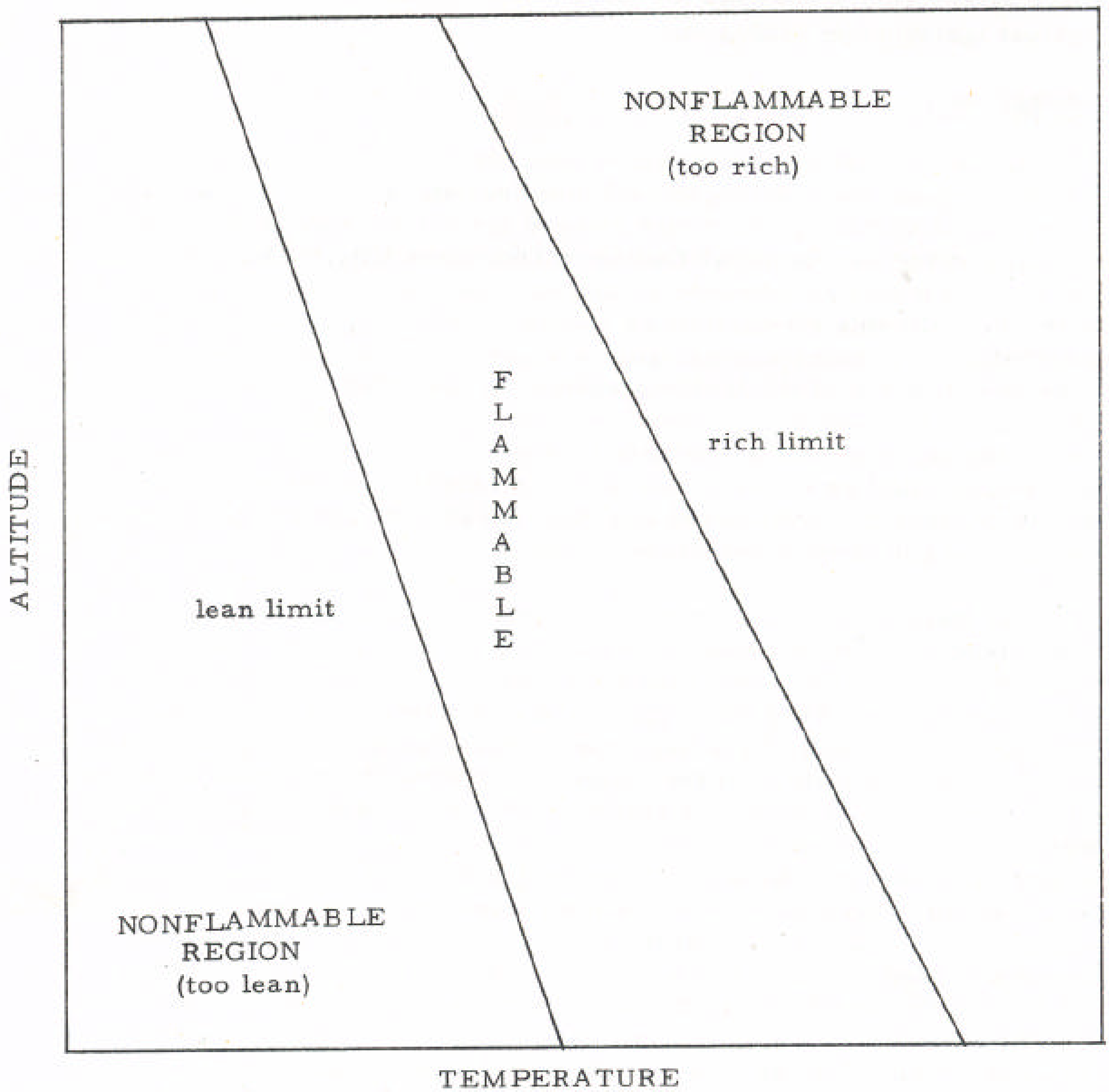

FIG. 1 TYPICAL FLAMMABILITY ENVELOPE OF AN AIRCRAFT TURBINE FUEL

Fuel-air ratio is the actual criteria which determines if a vapor is flammable. At sea level, the vplumetric composition of dry air is for ordinary purposes taken as N2 = 79 percent, 02 = 21 percent, Reference 3. If an external fire would transmit heat to a vented fuel tank, the effluent temperature would rise much more rapidly than the liquid. Tank pressure would remain the same since some of the expanded effluent would pass out of the vent system. In this case, equilibrium within the tank would be destroyed and ignition characteristics changed from the equilibrium curve of Figure I. The fuel-air ratio is still the controlling factor on the new flammability loop and a certain percentage of oxygen in the air is necessary for combustion; however, the oxygen requirement for combustion becomes less with an increase in effluent temperature and/or an increase in pressure, Reference 4.

The effluent temperature and pressure possibilities, of course, are a major criteria in the design of an inerting system. Inerting gases such as nitrogen and carbon dioxide not only displaces oxygen from the fuel-air mixture but reduces the resultant flame temperature. Since the volumetric heat capacity (Btu/ft3) of carbon dioxide is greater than that of nitrogen, the flame-quenching power of carbon dioxide is greater than that of nitrogen. On a volume basis, less carbon dioxide is required to produce a nonflammable mixture from an initially flammable hydrocarbon-air mixture. This is illustrated in Figure 2, References 4, 5 and 6. It should be noted, however, that CO2 is heavier than N2, requires a heavier container for compression, is more soluable in fuel, and has icing problems when released. Figure 2 also illustrates the significance of fuel-air ratio versus oxygen requirements in the flammable range. Minimum oxygen is required for flammability of stoichiometric mixture; however, this is a very small critical range and oxygen requirements increase rapidly along the rich and lean side of this point. Figure 3, Reference 4, illustrates the relationship of variables upon which flammability is contingent upon, and Figure 4, Reference 4, illustrates that as atmospheric pressure decreases nitrogen inerting requirement decreases. Again, it is emphasized that the point of stoichiometric mixture oil the curve is the point of minimum oxygen requirement and maximum nitrogen inerting needed. This is a very critical point and difficult to achieve. Probably because of the control of numerous variables in achieving minimum oxygen requirements and maximum nitrogen inerting for flammability, laboratory equipment and testing have been logically and extensively used in these studies over the many years.

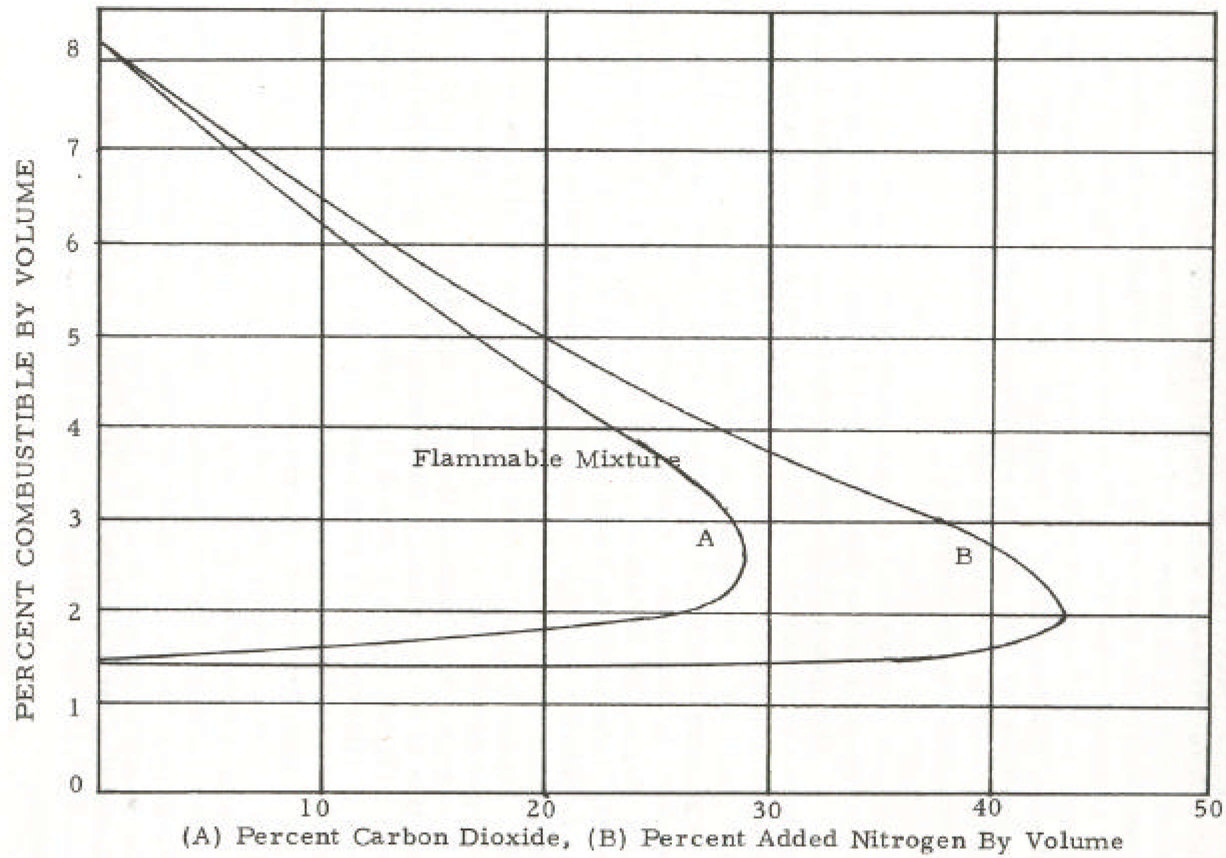

FIG. 2 CONCENTRATION LIMITS OF FLAMMABILITY FOR (A) AVIATION JET FUEL GRADE JP-4 VAPOR-AIR-CO_2 MIXTURES, AND (B) AVIATION JET FUEL GRADE JP-4 VAPOR-AIR-N_2 MIXTURES AT ATMOSPHERIC PRESSURE AND 75°F

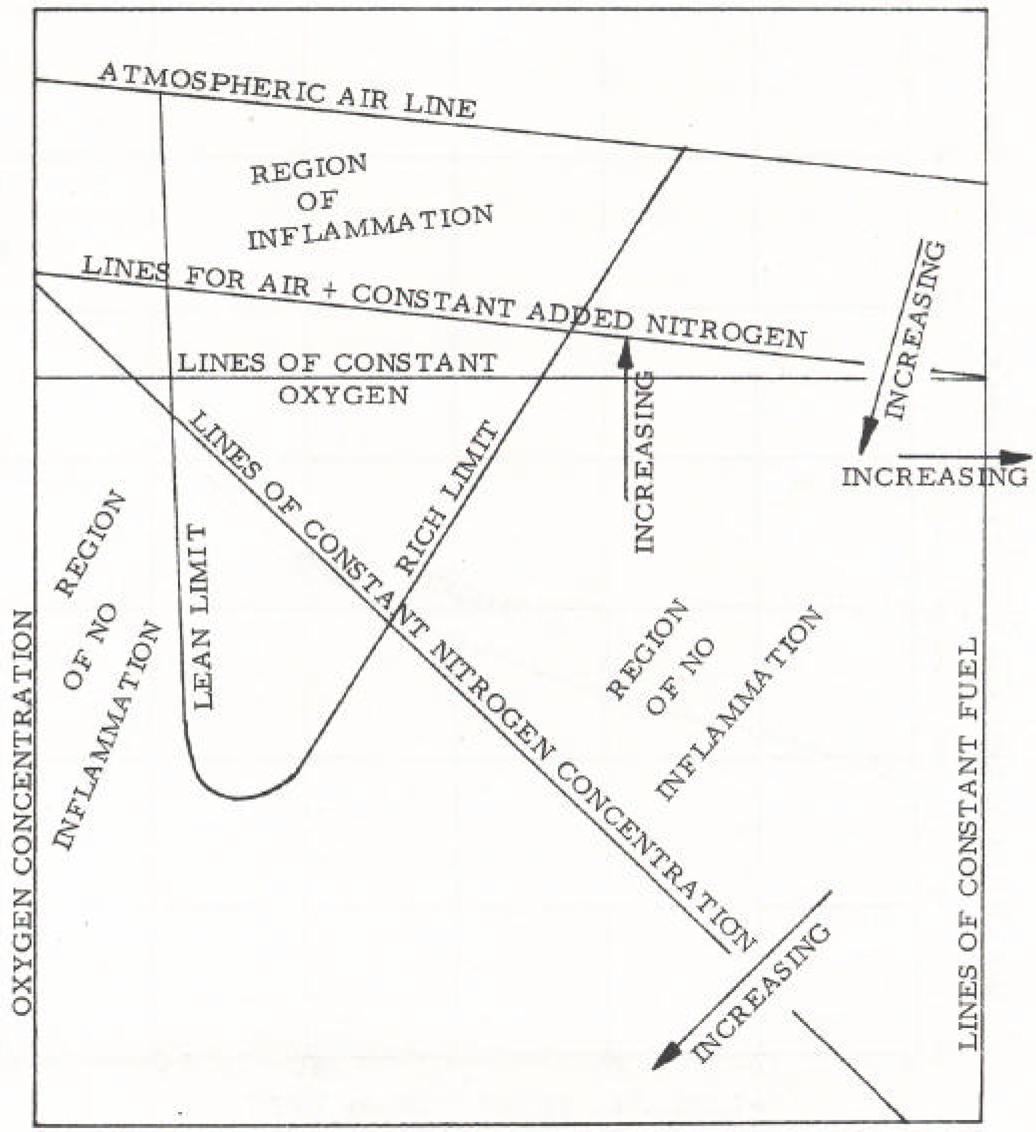

FIG. 3 MODEL FLAMMABILITY CURVE NITROGEN INERTING

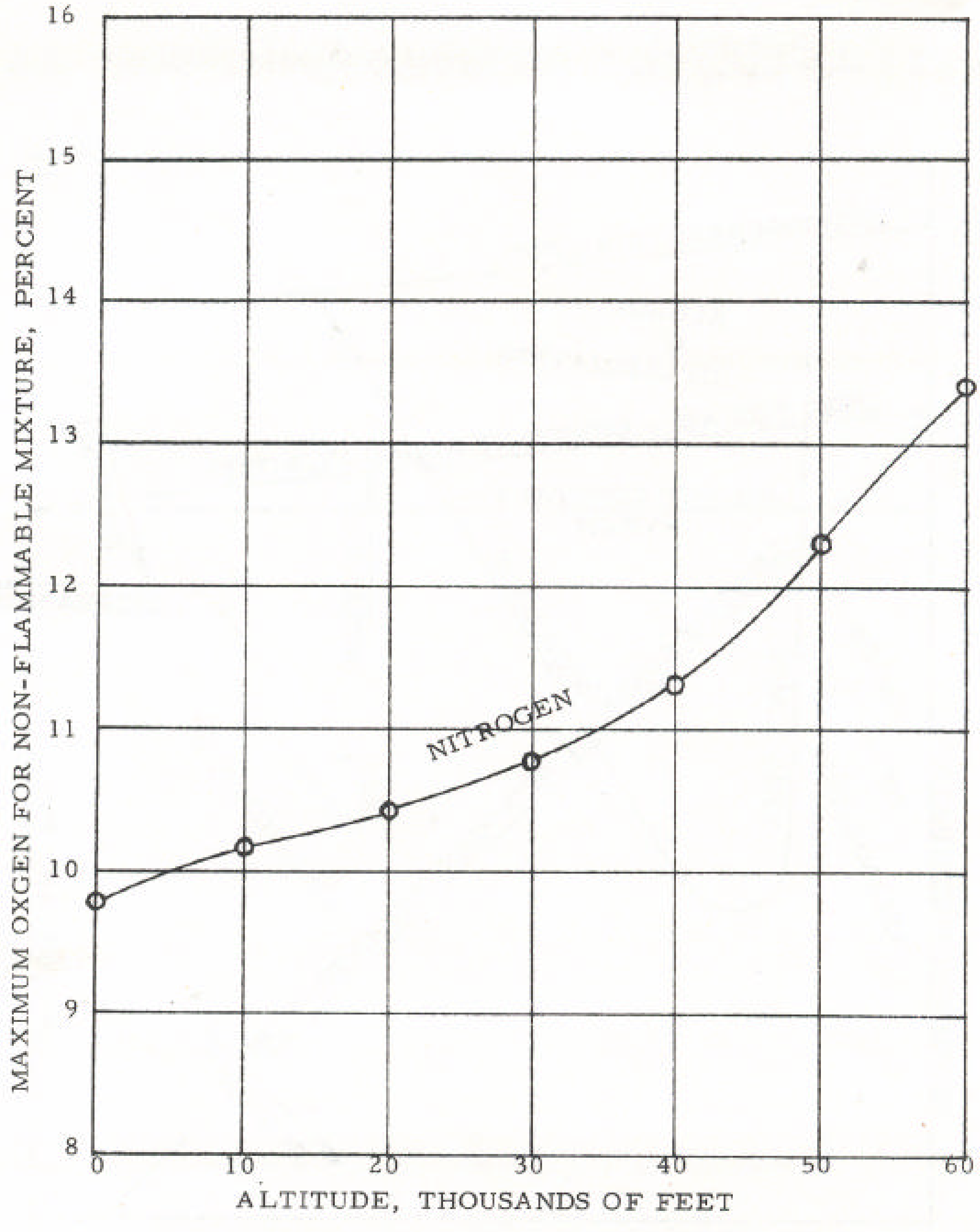

FIG. 4 PERMISSIBLE OXYGEN CONCENTRATION FOR N_2 INERTED FUEL-AIR MIXTURES AN-F-58 (JP-4) VAPOR

DISCUSSION

Testing Programs

Studies of nitrogen inerting requirements for safety of aircraft fuel tanks in the past 30 years have been performed by Boeing Aircraft Company, Bureau of Mines, University of California, Naval Research Laboratory, Wright Aeronautical Development Center, Royal Aircraft Establishment, and Convair Aircraft Company. The majority of the investigations found that an excess of 12 percent oxygen at laboratory conditions might support combustion. In accordance with Bureau of Mines data, Reference 7, the minimum amount of inert gas required to prevent the formation of flammable JP-4 vapor-air mixture at 80°F and one atmosphere is approximately 43 percent N2 and 11.5 percent by volume of 02 as illustrated in Figure 5, Reference 5. As can be seen in Figure 6, the minimum oxygen requirements for most hydrocarbons are within 1 percent of variation and are between 11 and 12 percent at one atmosphere and 80°F when inerted with N2.

The inerting requirements decrease with increasing pressure and decreasing temperature as illustrated in Figure 7, Reference 5. Table 1, Reference 5, from a Bureau of Mines report, summarizes differences in 02 requirements for various temperatures and altitudes and the effects on results when using different laboratory procedures. The lower minimum 02 values reported by Stewart and Starkman were obtained in a l2-l/2-cubic-foot tank using severa13-joule spark sources, as compared to a 2- or 4-inch-diameter vessel with a single spark source that was used in the Bureau work. In the latter work, the appearance of any flame was taken as evidence of a flammable mixture and pressure rises may have been only a few pounds per square inch. Thus, the reported limits are expected to be lower than normal flammability limits which define mixture concentration that can sustain flame propagation beyond the ignition source, Reference 5. Flammability limits also vary with ignition source energy. The minimum spark energy for the optimum fuel- vapor-air mixtures of most hydrocarbon fuels is about 0.25 millijoule at atmospheric pressure. Ignition energies ordinarily increase with decreasing ambient pressure and oxygen concentration, as shown in Figure 8, Reference 5. At constant pressure, flammability limits of hydrocarbon do not vary significantly with moderate changes in temperature, but over a wide temperature range, a correction for this variation must be made. Flammability limits of a hydrocarbon

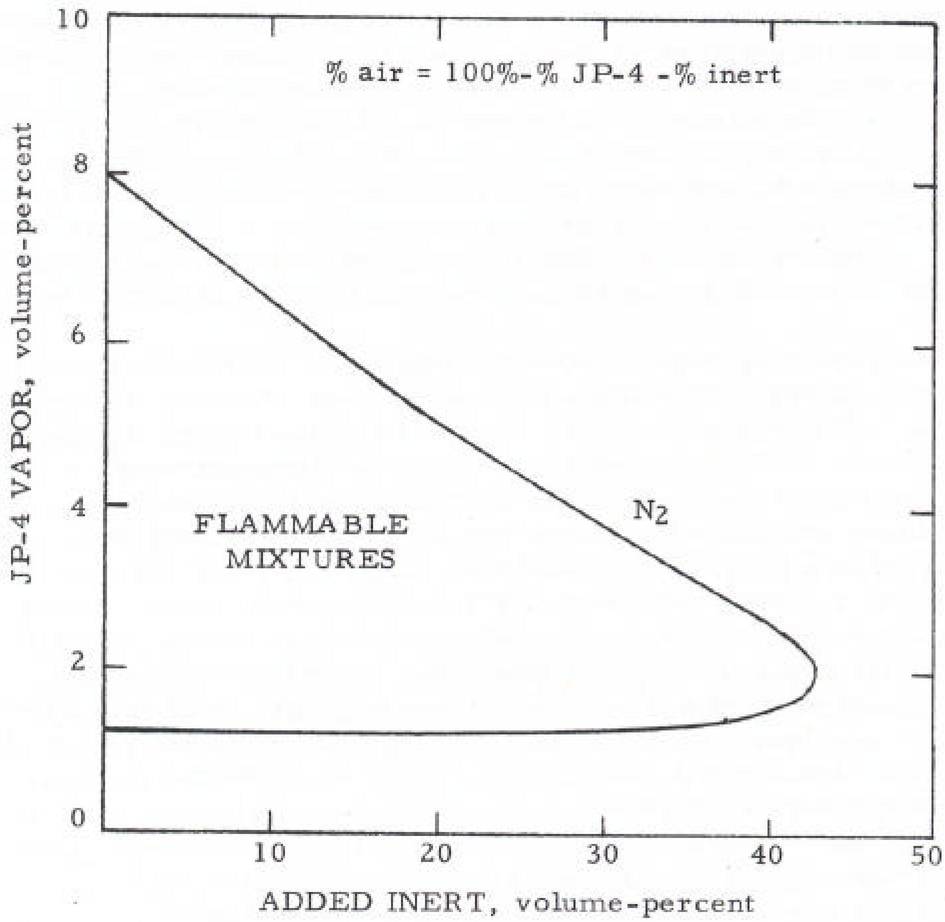

FIG. 5 LIMITS OF FLAMMABILITY OF JP-4 VAPOR-NITROGEN-AIR MIXTURES AT 80°F AND ATMOSPHERIC PRESSURE

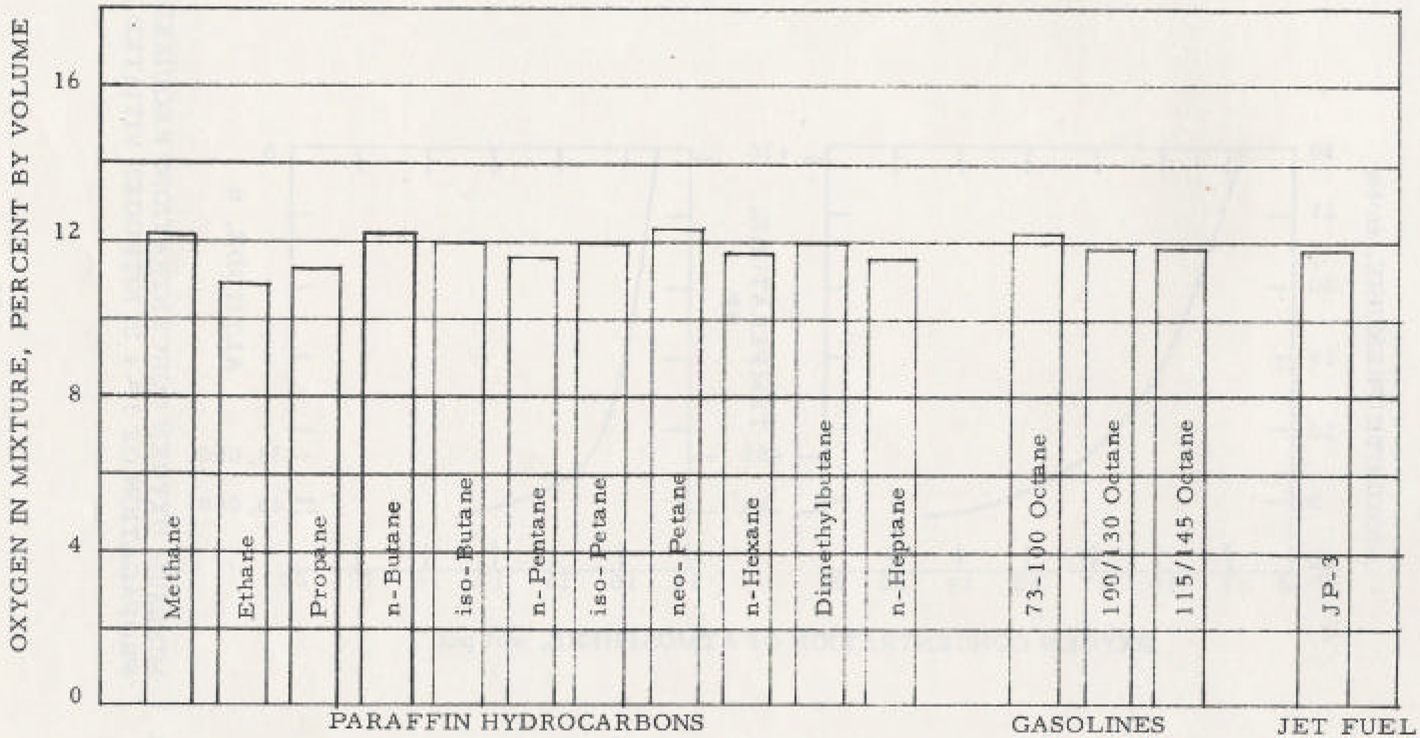

FIG. 6 A COMPARISON OF THE MINIMUM QUANTITIES OF OXYGEN REQUIRED FOR FLAME PROPAGATION IN VARIOUS COMBUSTIBLE VAPOR-AIR-ADDED INERT GAS MIXTURES AT LABORATORY TEMPERATURE AND PRESSURE (CONSTANT PRESSURE APPARATUS)

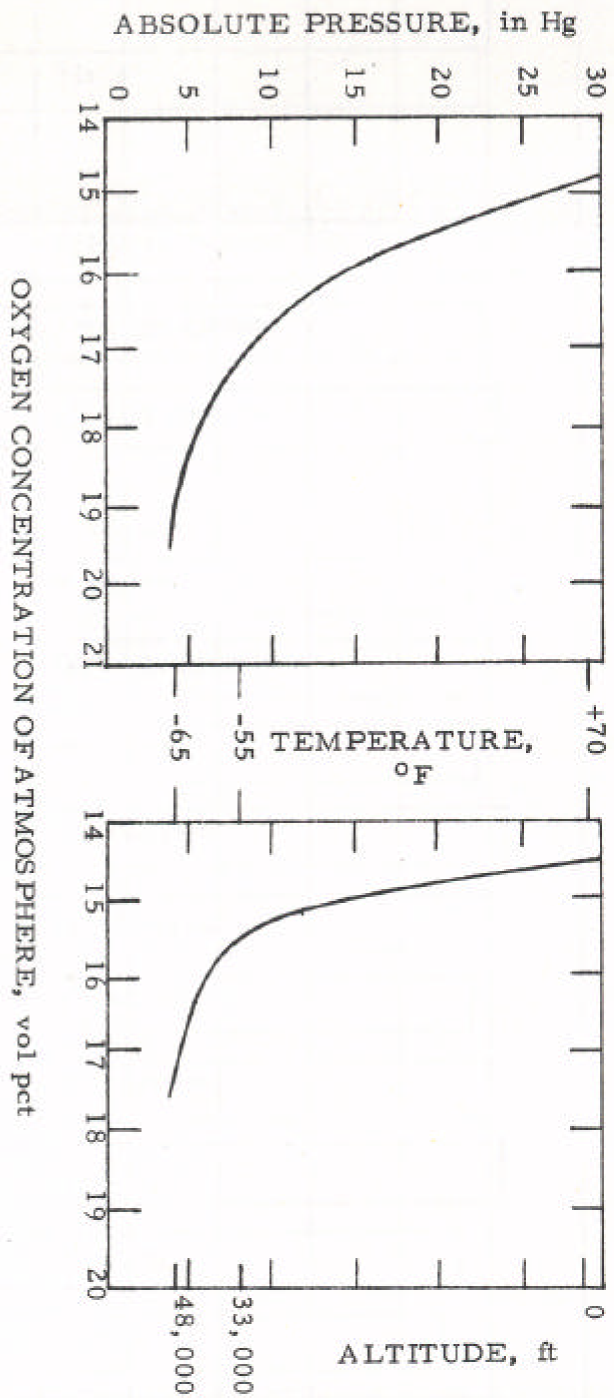

FIG. 7 MINIMUM OXYGEN CONCENTRATIONS REQUIRED FOR FLAME PROPAGATION OF JP-4 IN NITROGEN VITIATED ATMOSPHERES

TABLE 1. - MINIMUM OXYGEN REQUIREMENTS FOR FLAME PROPAGATION WITH VARIOUS FUELS IN AIR-N_2 ATMOSPHERES

Fuel	Press. in Hg	Press. Altitude	Temp.	Vol. Percent N_2 Inert
	(ft)	(ft)	(^oF)	
JP-1 1/	29.3	0	300	10.5
JP-1 2/	3.44	50,000	140	12.7
JP-3 1/	29.3	0	75	11.8
JP-4 1/	29.3	0	75	11.5
	15.0	18,000	75	11.4
	8.0	32,000	75	11.7
	4.0	47,000	75	12.4
JP-4 2/	29.3	0	70	9.8
	13.75	20,000	70	10.4
	5.54	40,000	70	11.3
	2.13	60,000	70	13.3
Av Gas 100/130 3/	29.3	0	80	11.9
Motor Gas 3/	29.3	0	80	11.5
Kerosene 3/	29.3	0	300	9.9
Benzene 3/	29.3	0	300	10.0

1/ Data from Reference 9, single spark source.
2/ Data from Reference 4, multiple spark source.
3/ BuMines unpublished data.

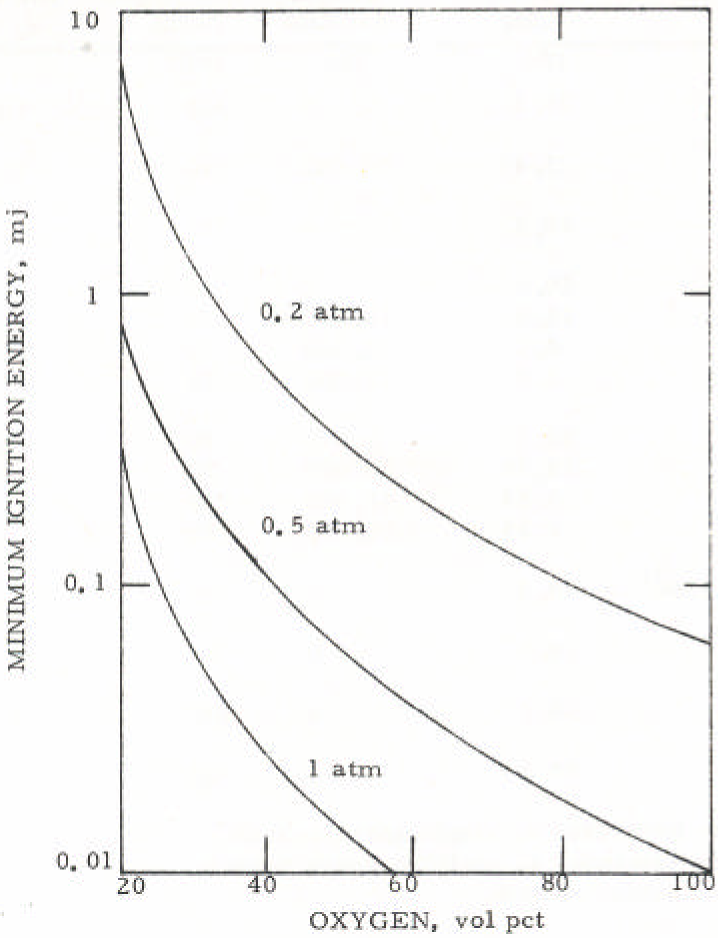

FIG. 8 VARIATION OF MINIMUM SPARK IGNITION ENERGIES WITH OXYGEN CONCENTRATION FOR PROPANE-OXYGEN-NITROGEN MIXTURES AT 0.2, 0.5, AND 1 ATMOSPHERE PRESSURES

vapor-air mixture decreases approximately linearly with increasing temperature. An expression given by Zabetakes can be used for determining flammability limits of minimum 02 values at various temperatures T {°F), References 5 and 8:

$$\frac{(\text{Min } 02)\ T}{(\text{Min } 02)\ 77^\circ} = 1 - 0.00040\ (T - 77)$$

This is a valuable tried and proven equation showing the relationship of minimum oxygen requirements as a function of temperature. The above equation was also combined with an expression by Le Chatelier to show that the flammability limits of a mixture vary with temperature in the same way as does a single component fuel-air mixture,
Reference 8.

SUMMARY OF RESULTS

A composite of data obtained from the literature search on maximum allowable oxygen concentration by nitrogen inerting is shown graphically in Figure 9. From Reference 10, it was found
that after a total of 68 ignition tests was conducted using 10 gallons
of 3P-8 in an 80-gallon capacity sealed combustion bomb, only one ignition occurred for an oxygen concentration below 13 percent. This unique ignition occurred at 12 percent oxygen and was a sloshing condition. It resulted in a pressure rise of only 1 psi. Several other ignition tests were conducted at or near this same fuel-vapor-oxygen condition for both the sloshing and the static cases. Therefore, the authors considered 12 percent oxygen as the maximum allowable percentage of oxygen for the total inerting with nitrogen of JP-8 fuel vapors.

Boeing Aircraft Company, Reference 11, used a 2-liter explosion bomb with liquid hexane in performing flammability studies. Hexane was used since published data showed its inflammable characteristics as very similar to the mixed hydrocarbon fuels, and for test purposes, it had the advantage of a constant boiling point. Oxygen concentrations for minimum explosions was considered at explosion pressure of 3 to 5 psi. Boeing Aircraft Company also arrived at 12 percent maximum oxygen requirements. Boeing Aircraft Company stipulated that for a safe limit, I percent 02 reduction should be made. other references, 7, 12 and 13, indicated that the ceiling of inertness at standard sea-level conditions was 11.5 percent 02 content. The

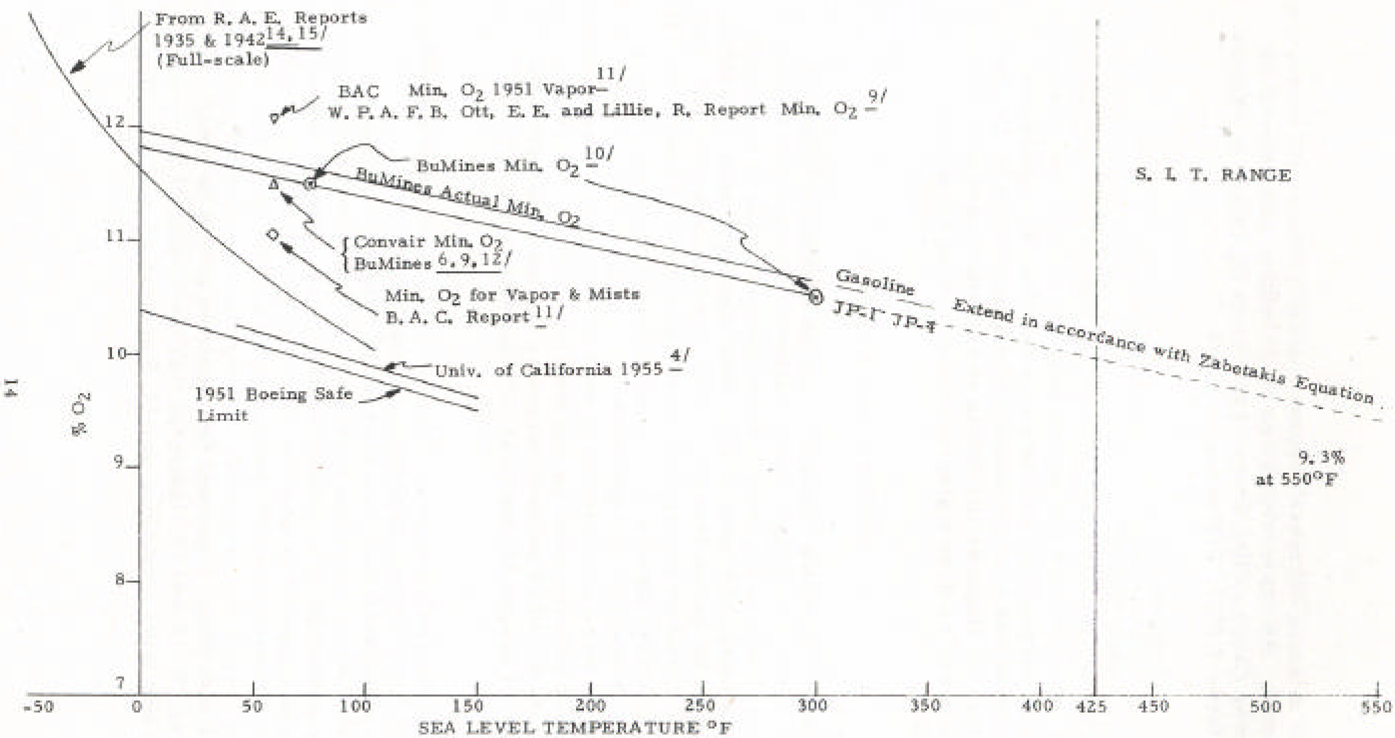

FIG. 9 COMPOSITE CHART OF INERTING REQUIREMENTS AS PLOTTED FROM LITERATURE SEARCH

Bureau of Mines suggested that in order to provide some margin of safety, the minimum 02 values should be reduced by a factor of 20 percent, Reference **5.**

CONCLUSIONS

Based on evaluation of a literature search on use of liquid nitrogen for inerting fuel tanks, it is concluded that:

I. The results from extensive studies made over the past 30 years by many activities are available.

2. The results of work performed by the United States Department of the Interior, Bureau of Mines, are applicable and valid for use in determining inerting requirements of jet fuels for aircraft use.

3. Because of the many variables encountered in arriving at the maximum allowable percentage of oxygen in an inerting system under varying conditions of temperature, pressure, and fuel-air ratio, laboratory controlled test methods are in general use.

4. Test results published by the many activities vary only by approximately 1 percent in the allowable percentage of oxygen. This is due to variation in test equipment used, definition of flammability considered, method of inerting, or consideration of the solubility factors of vapors in the liquid at various conditions.

5. In order to ascertain the safety of an actual fuel tank, vapor composition measurements could be made for obtaining conditions of stratification within the tank. By using the data from the flammability tests made in the past, a monitoring of the vapors from various locations within the effluent would determine the flammability hazards within the tank.

6. Maintaining an oxygen content below 9 percent in the effluent will produce an incombustible environment at mixture temperatures below the spontaneous ignition temperature of about 550oF at sea level pressure conditions.

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