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Investigation of Aircraft Fuel Tank Explosions and Nitrogen Inerting Requirements During Ground Fires.

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A PROJECT WAS CONDUCTED at the National Aviation Facilities Experimental Center (NAFEC) to determine the capability of nitrogen inerting in preventing fuel tank explosions during post-crash ground fires. The project was conducted in two distinct phases; Phase I being small-scale tests using a 50-gallon capacity test article and Phase II full-scale tests using outer wing panels from a C-133 aircraft (with a capacity of approximately 1,340 gallons).

OBJECTIVES

The main objectives of the program were as follows:

Phase I -

1. Determine the minimum nitrogen inerting (expressed in oxygen concentration) which will not support an internal tank reaction (explosion) due to hot-surface ignition, tank burn-through, or a high-energy spark in the tank.

2. Determine the effects of elevated skin and vapor temperature on the maximum oxygen concentration (minimum nitrogen inerting) needed to avoid any tank reaction.

Phase II -

1. Conduct large-scale testing to provide confidence in the extrapolation of the small-scale test results to full-size fuel tanks.

TEST EQUIPMENT

Phase I -

The test article used in Phase I was a 50-gallon aluminum tank (Fig. 1) with replaceable bottom and .003 aluminum blowout panel on the top. The blowout panel (12" by 18") was designed to relieve at approximately 4 psig.

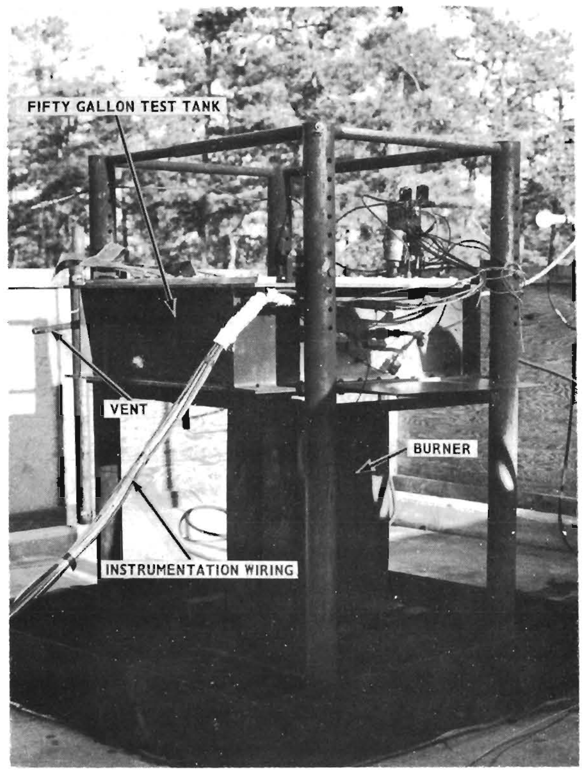

Fig. 1 - Small-Scale Test Article and Instrumentation

ABSTRACT

This paper describes the results of small-scale and full-scale tests conducted to determine the oxygen concentration (minimum nitrogen) limit in the fuel tank ullage that would prevent an explosion when the tank is exposed to an external ground fire. The results indicated that an oxygen concentration of nine percent or less would prevent any fuel tank explosion due to a post-crash fire. Full-scale tests confirmed the results of the small-scale tests.

The following parameters were measured during the program:

1. Temperature: Six number 30 chromel alumel thermocouples were located in the test article. The locations of the thermocouples varied according to the test configuration but usually included a bottom skin thermocouple, liquid fuel thermocouple, and vapor thermocouple. The thermocouple signals were recorded either on a Bristol Two-Pen Chart or on an Oscillograph, as was all other instrumentation.
2. Pressure: Two pressure transducers were mounted approximately 1 foot from the test article and were connected to probes in the test article by 1/4-inch copper lines. (minimum pressure rise detectable was 0.01 psi).
3. Fire Detection: Three Clairex photoconductive cells were located in the tank as was the reviewing lens of a Fenwal infrared detector.
4. Fuel Vapor Concentration: The concentration of fuel vapor in the test article was monitored by two Lira "300" infrared gas analyzers. The samples were drawn through heated lines (260°F) at 200 cubic centimeters per minute at 8 psia.
5. Oxygen Concentration: Two Beckman Model 715 units were used to monitor the oxygen concentration in the test article.

The test article was equipped with a nitrogen inerting line connected to a high-pressure nitrogen bottle through a regulator.

The flame source for all Phase I tests was a three-flue steel burner using atomized JP4 for fuel. Each flue had an exit of 6 by 9 inches. The temperature of the flame impinging on the test article could be adjusted by changing the fuel and air pressures or by changing the height of the test article from the burner. Flame temperatures used ranged from 1200°F (heat flux of .75 $Btu/ft^2/sec$) to 2000°F (heat flux of 2.25 $Btu/ft^2/sec$).

Phase II -

For the full-scale tests, four outboard fuel tanks from C-133 aircraft were used along with two DC-7 fuel tanks. The DC-7 tanks contained minimal instrumentation (one oxygen probe; one fuel vapor probe; one pressure sensor; and two thermocouples, one skin and one vapor), and were used primarily to determine any problems in the Phase II test procedures.

The same type of oxygen sensors, fuel vapor analyzers, optical detectors, pressure sensor, and thermocouples were used in Phase II as were used in Phase I. The following instrumentation was used in all four C-133 tank tests:

1. Twelve thermocouples (bottom skin fuel and vapor temperatures).
2. Four pressure transducers.
3. Two fuel vapor sensors.
4. Three oxygen sensors.
5. Five optical detectors.

All data were recorded on two ocillograph recorders. All tests were controlled from an instrumentation trailer 250 feet from the test article.

The test fire was supplied by six, six-flue burners using JP4 as fuel. The burners were situated under the wing in such a manner as to produce a 2000°F flame (heat flux of 2.25 $Btu/ft^2/sec$) on the wing.

DISCUSSION AND RESULTS

Phase I -

A variety of small-scale tests was run, under varying conditions, designed to first define the tank environment during a simulated post-crash fire and then define the maximum oxygen concentration that would prevent an explosion. Over 100 tests were conducted.

The small-scale tests showed that a reaction or explosion in the tank could be induced by hot surface (bottom skin) ignition or by a two-joule spark in the tank. A reaction is defined in this paper as a pressure rise caused by oxidizing fuel vapor, and an explosion is defined as a reaction of a magnitude large enough to rupture the tank or the relief panel. An explosion due to hot-surface ignition could only be obtained when the uninerted tank was rapidly heated with a 2000°F flame. A lower temperature flame (1600°F), having a heat flux of less than 1.75 Btu/ft^2/sec, would not cause an explosion. Therefore all tests were run using the 2000°F flame. Fig. 2 shows the rate of rise of the skin temperature during tests in which autoignition did and did not occur.

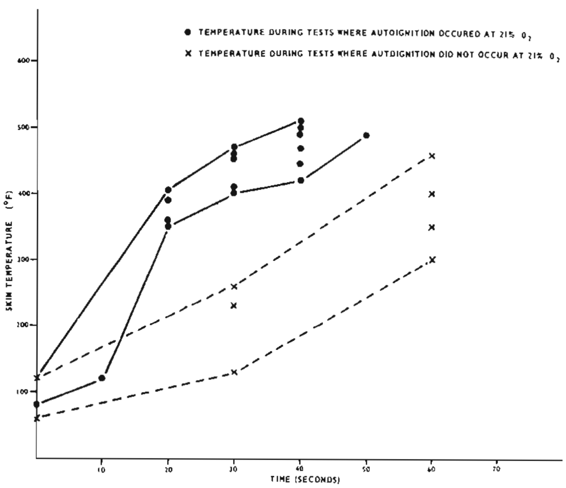

Fig. 2 - Autoignition as a Function of Rate of Rise of Skin Temperature

Fig. 3 represents a chemical identification of compounds in the fuel/air ullage mixture from tanks containing 21-percent oxygen and 2 ounces of Jet A fuel heated with a 2000°F flame (heat flux of 2.25 Btu/ft^2/sec) in one test and a 1600°F (heat flux of 1.5 Btu/ft^2/sec) flame of another. The samples were extracted just prior to the explosions during the 2000°F test and at a corresponding tank bottom skin temperature for the 1600°F test.

Strong concentration of methane and acetylene were in the exploding tank whereas these were replaced by carbonyl and alkene in the nonexploding tank. This seems to indicate that when the hydrocarbons combined with the oxygen in the tank thus preventing an explosion.

During the hot-surface ignition tests, all the explosions that occurred were with an oxygen concentration of 21 percent in the vapor space at the start of the test. When the initial concentration was lowered to 18 percent no "explosion" occurred; however, a reaction did occur in the tank causing a pressure rise.

This reaction continued to occur during the hot-surface ignition tests until O_2 concentration was lowered below 13.5 percent at which time no reaction occurred.

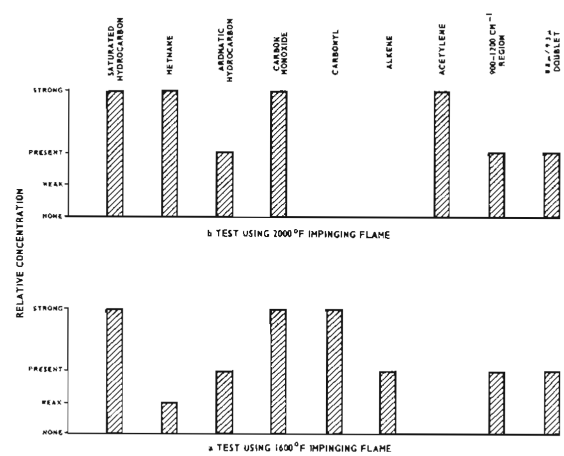

Fig. 3 - Infrared Spectro-Photometric Identification

Figure 4 represents the reaction due to autoignition at various oxygen concentrations for a Jet A type fuel. A 2000°F flame was used for these tests.

Tests using a spark ignition for an ignition source proved to be a more severe ignition source than either hot-surface ignition or burn-through. In such tests reactions in the tank were obtained with an oxygen concentration as low as 10 percent, and explosions were obtained as low as 10.5 percent.

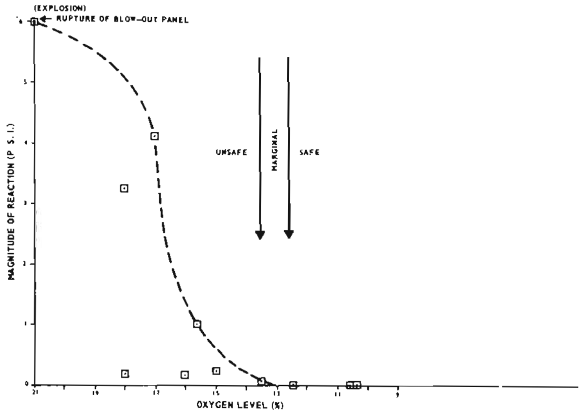

Fig. 4 - Effect of Oxygen Level on Reaction Due To Autoignition

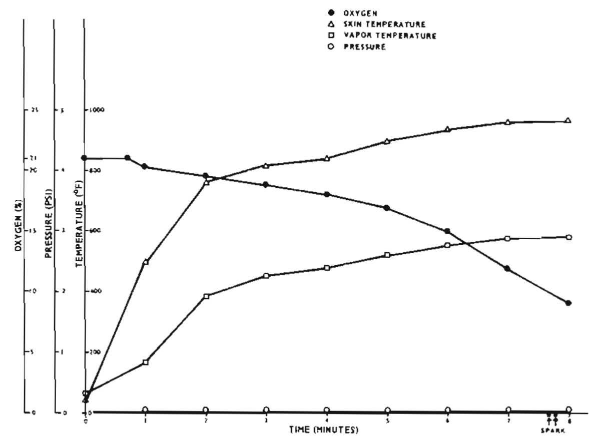

Fig. 6 - Typical Elevated Temperature Test

Fig. 5 shows the reaction due to an internal spark at various concentrations of oxygen. Although, as can be seen in the graph, the oxygen concentration at elevated temperatures has to be lower to suppress an explosion it should be noted that the O_2 concentration started at 21 percent for all the elevated temperature tests, and fell off, or self-inerted, as the test progressed. Fig. 6 shows a typical elevated temperature test and the self-inerting phenomenon.

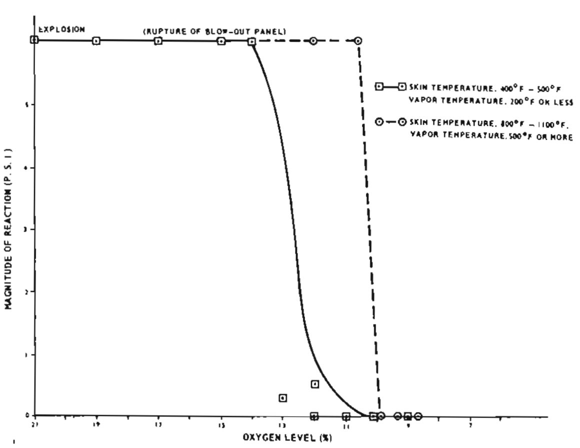

Fig. 5 - Effect of Oxygen Level on Reaction Due to Spark Ignition

A variety of tests was conducted in which tank burn-throughs occurred, but no reaction occurred in the tank as a result of that condition.

There was no noticeable difference between a burn-through into a tank having an O_2 concentration of 21 percent and a tank having zero percent O_2 concentration. A torching flame would exit the burn-through opening and no explosion occurred.

Phase II -

The first two preliminary tests using the DC-7 wings used three of six burners. One hundred gallons of Jet A fuel was used in the first test, and the tank was not inerted. About 13 minutes into the test, the flame penetrated the wing and continued to burn even after the test was terminated and the burners shut down. There was evidence of an internal fire throughout the wing (Fig. 7). Shortly after burn-through, the oxygen concentration in the wing fell to near zero.

The second DC-7 test was run with a lesser quantity of fuel (approximately 25 gallons). Two minutes into the test, a violent reaction (explosion) occurred in the tank. The entire top surface of the wing was destroyed by the reaction (Fig. 8), and a large fireball engulfed the wing. After examining the data and the wreckage of the wing, the probable cause of the reaction was determined to be hot-surface ignition. The reaction in this test was the same as in the small-scale tests when a small amount of fuel was heated very rapidly.

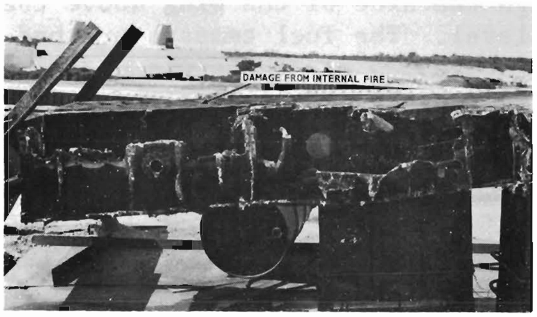

Fig. 7 - Post-Test Damage of First DC-7 Wing Test

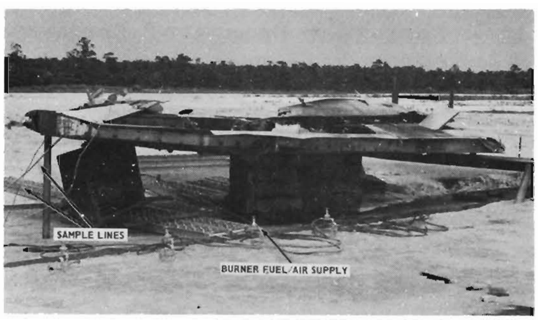

Fig. 8 - Post-Test Damage of Second DC-7 Wing Test

As a result of the two preliminary tests, various changes were made in the test setup such as break-away fitting being installed on all sampling lines so that a violent explosion would not destroy the instrumentation. The preliminary tests also showed that a wing would only last for one test even if there was no reaction in the tank; therefore, Phase II was limited to four tests; one on each of the four available C-133 wings.

The following test conditions were decided on to best demonstrate the results of Phase I.

Test 1. Demonstrate autoignition in a wing tank using a small quantity of Jet A fuel (50 gallons) and 21-percent O_2 in the ullage.

Test 2. Demonstrate the ability of a 9-percent oxygen concentration to prevent a reaction due to autoignition: Tank contained 50 gallons of Jet A fuel.

Test 3. Demonstrate the ability of a 9-percent oxygen concentration to prevent a reaction from an internal spark or burn-through of the wing. The tank contained 9-percent oxygen concentration and approximately a 20-percent fuel load (300 gallons) that covered the entire bottom of the tank.

Test 4. Demonstrate the result of an internal spark or burn-through of the wing containing a 15-percent O_2 concentration and 300 gallons of Jet A fuel.

The first full-scale C-133 tank test lasted 1 minute and 35 seconds at which time a violent explosion occurred. At the time of the explosion, the highest recorded skin temperature was approximately 500°F. The oxygen concentration fell rapidly near the top of the tank but remained at 21 percent near the bottom. The entire wing was engulfed in a large fireball, and pieces of the wing were thrown within a 100-yard radius. The wing summersaulted and came to rest upside down (Fig. 9). The entire top surface was blown from the wing.

Fig. 9 - Post-Test Damage of First C-133 Wing Test

The cause of the explosion was autoignition from the hot surface of the wing. (See Fig. 10.)

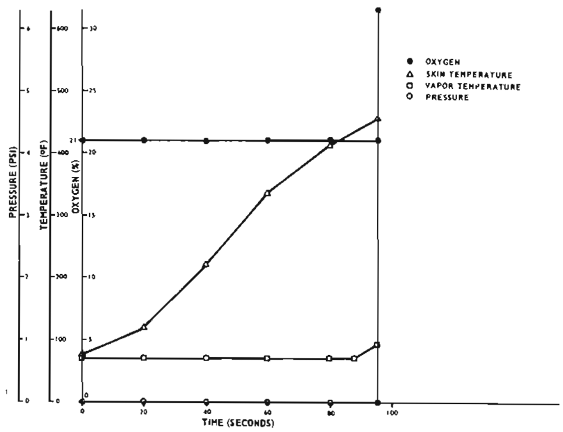

Fig. 10 - Uninerted C-133 Wing Explosion From Autoignition

It should be noted that the uninerted small tanks and the C-133 wing tanks incorporated unrestricted vents and in the inerted tests a 1.5 psig check valve was used in the vent exit.

Three minutes and 45 seconds into the second test, a burn-through occurred in the bottom skin of the wing. No reaction was noted in the wing. The oxygen concentration in the intact section of the wing dropped to zero. The burners remained on for 18 minutes. The wing itself was allowed to burn for another 6 minutes. All burning occurred in the open section of the wing (Fig. 11), but there was no evidence of burning inside the wing.

During the third test, the spark ignitor was activated at intervals throughout the test, and no reaction occurred in the tank. Approximately 5 minutes into the test, a burn-through occurred on the side of the wing above the fuel level. A slight torching could be seen eminating from the opening. After the burners were shut down, 15 minutes into the test, the torching continued from the wing. An examination of the wing (Fig. 12), after extinguishment, showed that a 2½-by 1-foot hole had been burned through the side of the wing above the fuel level. The fuel temperature had risen above 300°F. There was no evidence of any burning inside the wing.

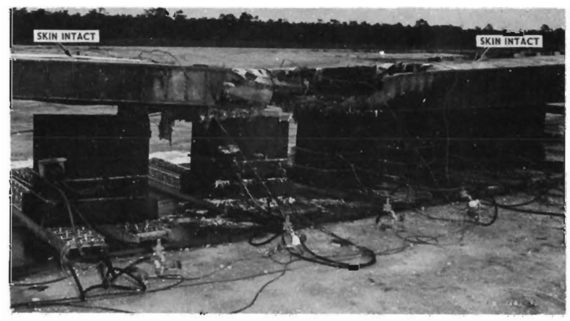

Fig. 11 - Post-Test Damage of Second C-133 Wing Test

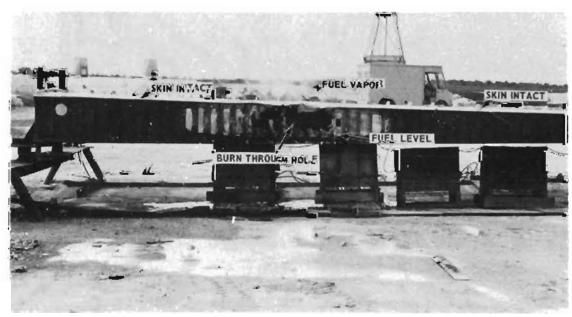

Fig. 12 - Post-Test Damage of Third C-133 Wing Test

The final test was a repeat of test 3 except for the 15-percent O_2 concentration. The result was a weak reaction "explosion" when the spark ignitor was activated. A flame occurred in the vicinity of the spark ignitor but did not propagate throughout the tank. A pressure buildup of about 15 psi caused a rupture of the tank (Fig. 13) in an area weakened by the ground fire.

The results of the large-scale tests confirmed those of the small-scale tests. Final Report No. FAA-RD-75-119, "Investigation of Aircraft Fuel Tank Explosions and Nitrogen Inerting Requirements During Ground Fires," details the test program.

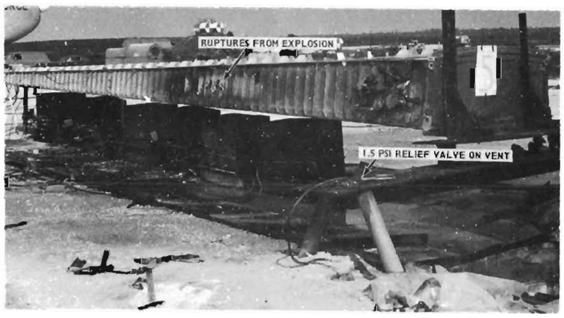

Fig. 13 - Post-Test Damage of Fourth C-133 Wing Test