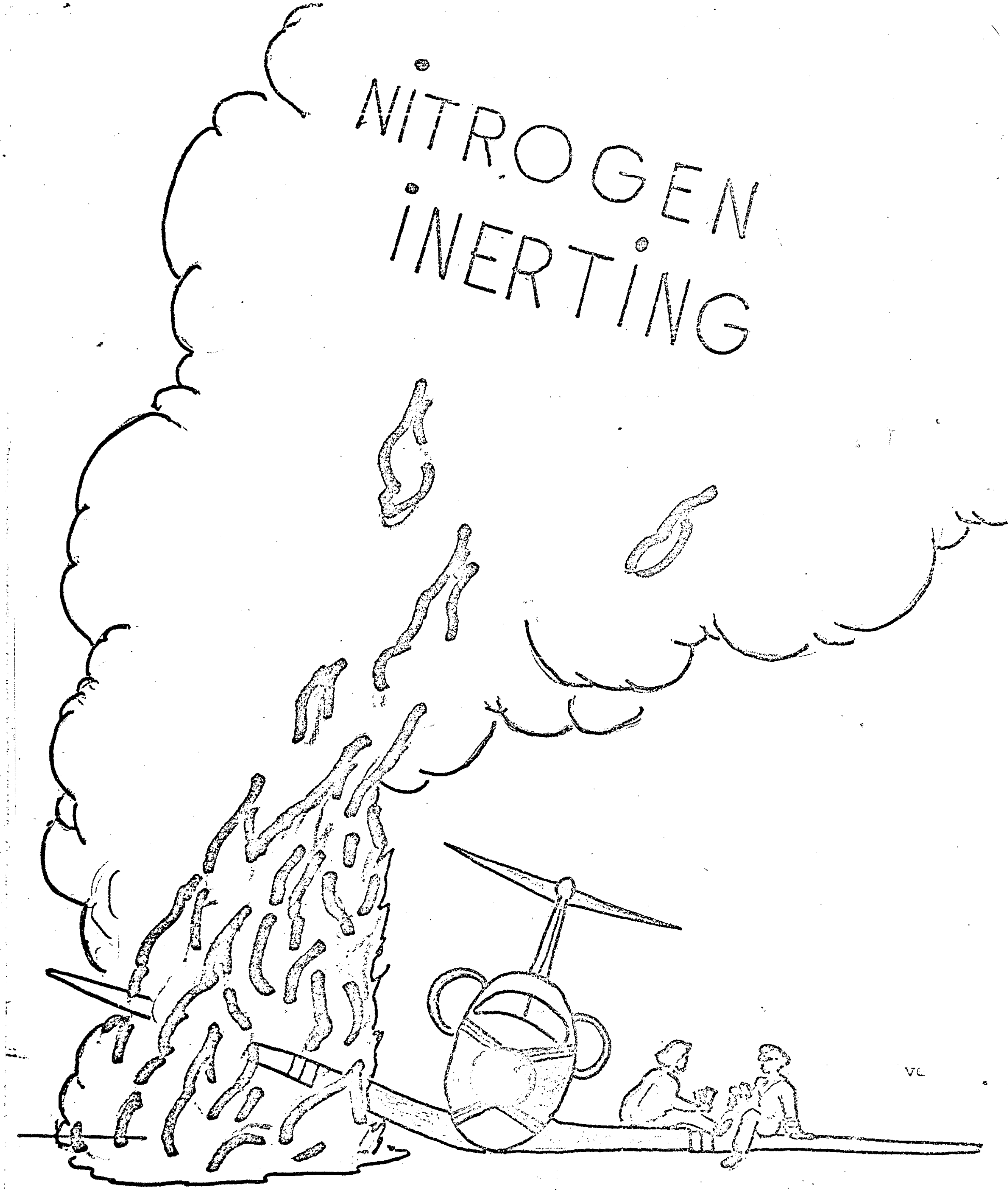
NITROGEN
INERTING

NITROGEN INERTING REQUIREMENTS FOR POST-CRASH FUEL TANK EXPLOSION PROTECTION

By

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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 tank and Phase II full-scale tests using outer wing panels from a C-133 aircraft (with a capacity of approximately 1,340 gallons).

The main objectives of the test program were as follows:

1. Phase I

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

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

2. Phase II

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

PHASE I TESTS

The test article used in Phase I was a 50-gallon aluminum tank 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. The test article was equipped with a nitrogen inerting line connected to a high-pressure nitrogen bottle through a regulator. The following parameters were measured during the program:

1. Temperature of the fuel, ullage, and bottom skin inside the test article.

2. Pressure inside the test article (minimum pressure rise detectable was 0.01 psi).

3. Visible flaming in the test article was monitored by three Clairex photoconductive cells and a Fenwal infrared detector.

4. Fuel vapor concentrations in the test article ullage.

5. Oxygen concentrations in the test article ullage.

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". 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 1,200°F (heat flux of .75 Btu/ft^2/sec) to 2,000°F (heat flux of 2.25 Btu/ft^2/sec).

A variety of small-scale tests was run, under varying conditions, designed to first define the fuel tank environment likely to cause an explosion during a post-crash fire and then define the amount of nitrogen inerting needed to reduce the oxygen level to the point where an explosion would not occur. Over 100 small-scale tests were conducted. The tests were divided into three series: Hot-surface ignition, spark ignition, and tank burn-through ignition. All tests utilized Jet A-type fuel in the tank.

A summation of the small-scale inerting requirements is shown in Table I.

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TABLE I. SMALL-SCALE TEST RESULTS

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

The inerting requirements in the small-scale tests were obtained from the following test results:

1. Explosions at fuel tank skin temperatures of less than 500°F and ullage temperatures of less than 300°F, from hot-surface ignition, did not occur when the O_2 concentration was lowered to 18 percent or below. Figure 1 represents the tank skin temperature, oxygen level, and pressure for three typical tests using various quantities of fuel. It should be noted that the time to auto-ignition increased as the fuel quantity increased. The skin temperature at auto-ignition remained in the same range (490-520°F), but the time to reach that temperature was increased by the greater amount of fuel.

2. Reactions at fuel tank skin temperatures of less than 500°F and ullage temperatures of less than 300°F, from hot-surface ignition, did not occur when the 0_2 was lowered to 12.5 percent or below. Figure 2 shows a comparison of two tests defining the auto-ignition level in terms of the absence of a recordable pressure rise. A slight pressure rise was noted at an oxygen concentration of 14 percent, but no rise was noted at a 12.5 oxygen level. Figure 3 shows the magnitude of reaction from auto-ignition for various oxygen concentrations. Since the absolute magnitude of a reaction is a faction of not only the intensity of the reaction, but also the vent system of the tank, therefore any reaction could produce an unsafe condition depending on the configuration and condition of the tank vent system.

3. Elevated temperature tests (skin temperatures above 500°F and ullage temperatures higher than 300°F) showed that tank explosions could occur at a 0_2 concentration of 17 percent, due to hot-surface ignitions. Because of a self-inerting phenomenon (slow oxidation) that occurred above a skin temperature of 500°F, hot-surface ignition tests at specific 0_2 concentrations and temperatures were impossible. Therefore, a number of tests were run, starting with an 0_2 concentration of 21 percent and using the 2,000°F flame, to determine if hot-surface ignition would occur at lower oxygen concentrations and elevated

temperatures. No hot-surface ignitions occurred below 17 percent O_2. Skin temperatures were allowed to reach the melting point of aluminum and O_2 concentrations dipped below 5 percent. The history of a typical elevated temperature test is shown in Figure 16. During that test, a spark ignition was activated at an O_2 concentration of 10.5 percent to show that an explosive mixture was present in the tank. At the time of the explosion, the skin temperature was 1,050°F and the ullage 800°F. Similar tests had been run in which no spark was used and no reactions occurred, with the test being terminated when the O_2 concentration dropped to near 5 percent. Figure 4 represents a typical elevated temperature auto-ignition test.

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

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

5. Elevated temperature tests using a spark ignitor showed that a 10.5 percent O_2 concentration supported an explosion and 10 percent O_2 was the lowest point at which a recorded reaction occurred. Figure 5 shows the magnitude of reaction for various oxygen concentrations from a high-energy spark. It can be seen from the graph that the difference in oxygen concentrations between an explosion and a reaction was far less than it was due to auto-ignition. Figure 6 represents an elevated temperature spark ignition test where slight reactions were noted due to the spark at oxygen levels above 10 percent but no reaction below 10 percent.

6. There were no recorded reactions during any of the burn-through tests. Figure 7 shows the reaction (or lack of it) for three burn-through tests at different oxygen levels (21 percent O_2, 14 percent O_2, and 0 percent O_2). No difference was noted between the tests.

PHASE II TESTS

Six full-scale tests were conducted using two DC-7 wing fuel tanks and four outboard wing fuel tanks from a C-133 aircraft. The same parameters were measured in the full-scale tests as were measured during Phase I. The test fire was supplied by six, six-flue burners using JP4 as fuel. The burners were situated under the wind in such a manner as to produce a 2,000°F flame (heat flux of 2.25 Btu/ft^2/sec) on the wing.

A summation of the inerting requirements for the full-scale tests is shown in Table II.

TABLE II. LARGE-SCALE TEST RESULTS

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

From the results of six full-scale tests, it was determined that:

1. A full-scale uninerted wing tank could explode from auto-ignition and that a 9 percent oxygen concentration in the ullage would prevent that occurrence. Figure 8 shows the wing configuration for the auto-ignition tests using 50 gallons of Jet A-type fuel and the wing sloped such that there were both wetted and dry zones on the bottom skin. Figure 9 shows a photographic display of the uninerted tank explosion. The results of that explosion are graphed in Figure 10, showing that the explosion occurred with a recorded skin temperature (T_{12}) of approximately 460°F, at 95 seconds into the test. When the tank was inerted to a 9 percent oxygen level, as shown in Figure 11, no reaction occurred. Note that the pressure buildup was a steady rise due to a 1.5 to 2.0 psi check valve which was installed in the vent line during all inerted tests.

2. A 9 percent O_2 concentration would prevent a reaction in a full-scale wing due to a high-energy spark.

3. A 15 percent O_2 concentration would allow an explosion due to a high-energy spark, but the magnitude of the explosion would be less than the uninerted wing explosion. Figure 12 shows the results of the 15 percent O_2 test. The reaction during this test produced a pressure buildup of a little over 9 psi and sent a torching flame from

three rupture holes in the rear spar edge of the wing. The flame self extinguished after a few seconds.

CONCLUSIONS

1. The results of the full-scale tests did not disagree with the results of the small-scale tests, thus giving confidence in the extrapolation of the small-scale test results to larger fuel tanks.
2. A 9 percent or lower O_2 concentration will provide undamaged tank explosion protection during a post-crash fire under all conditions tested.
3. Concentrations as high as 18 percent O_2 will provide limited protection under certain conditions during a post-crash fire.
4. Concentrations of oxygen lower than 12.5 percent will give protection against most conditions experienced during a ground fire.
5. Even though the elevated temperature environment provides the most severe explosive condition and a need for an O_2 concentration of 9 percent or lower, it is also the condition which produces a slow oxidation or self-inerting in the tank. This self-inerting would provide a margin of safety if a 9 percent O_2 concentration was used.

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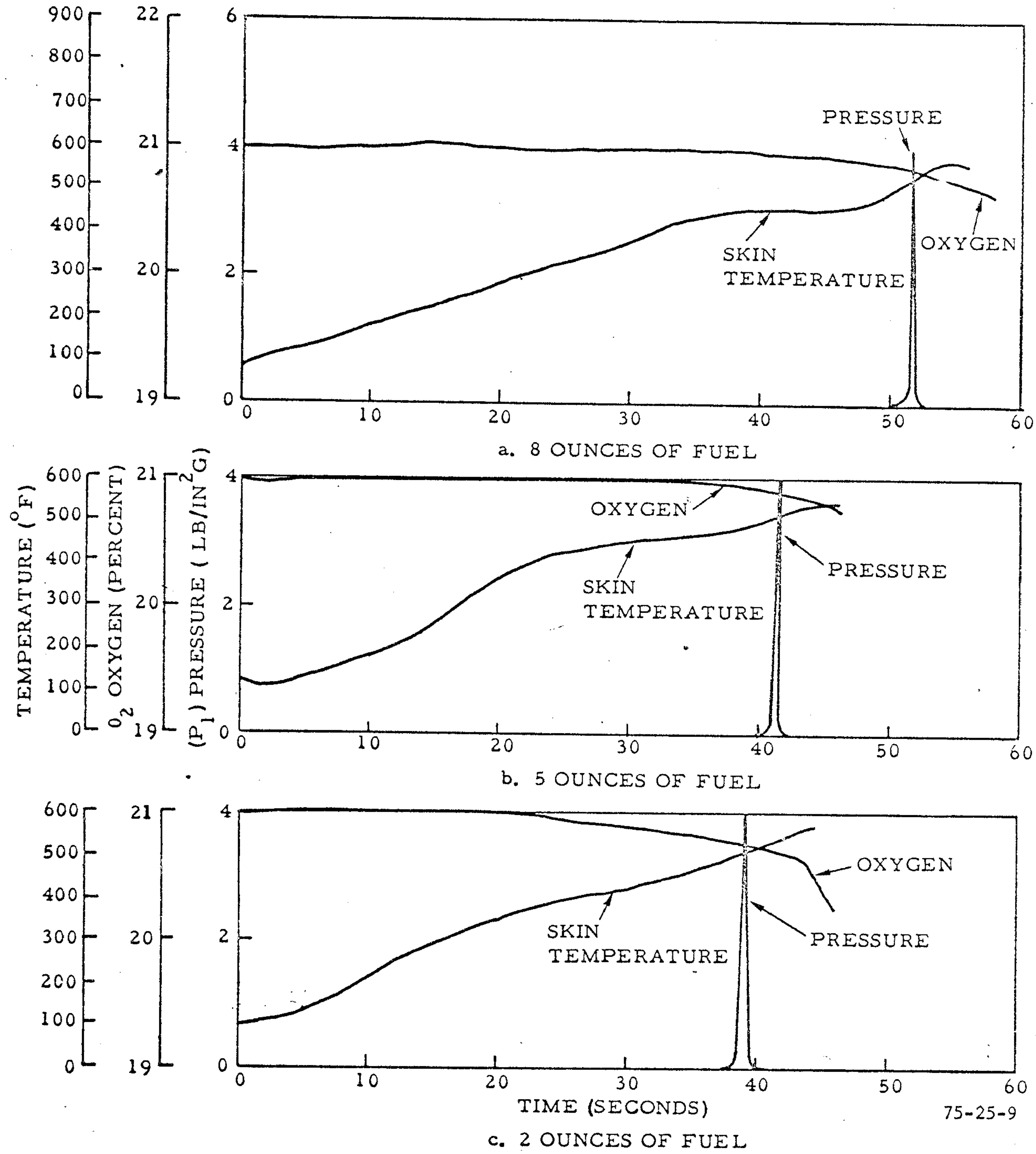
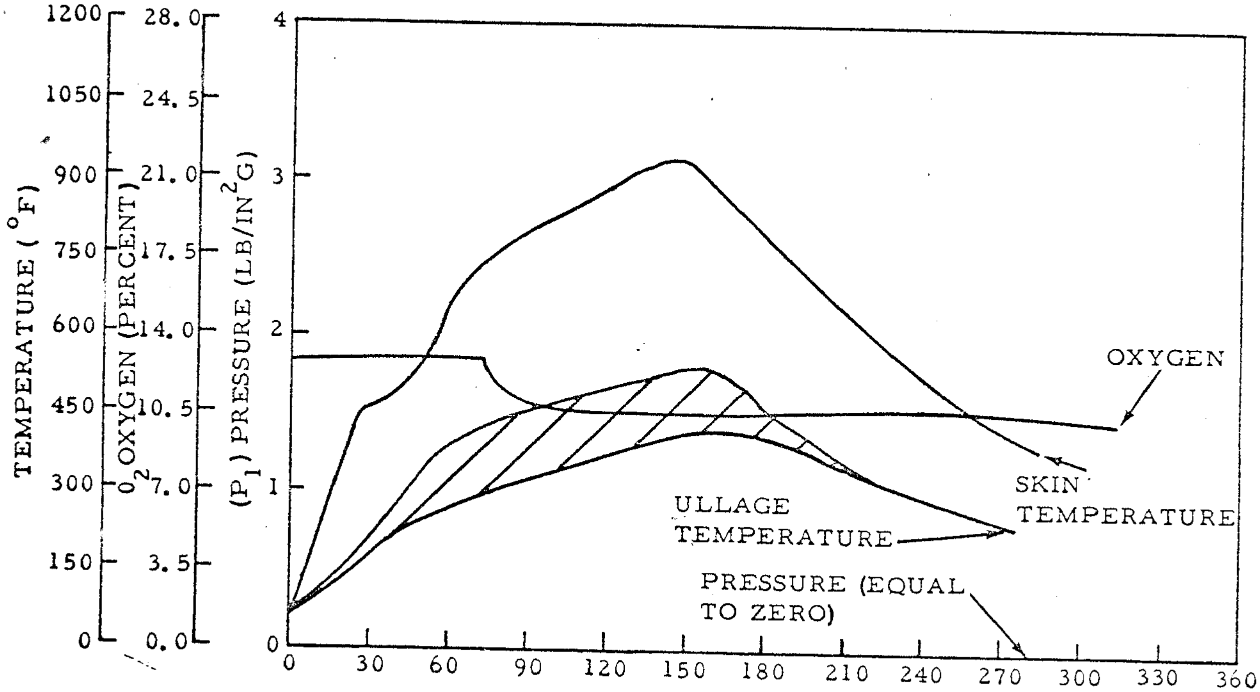
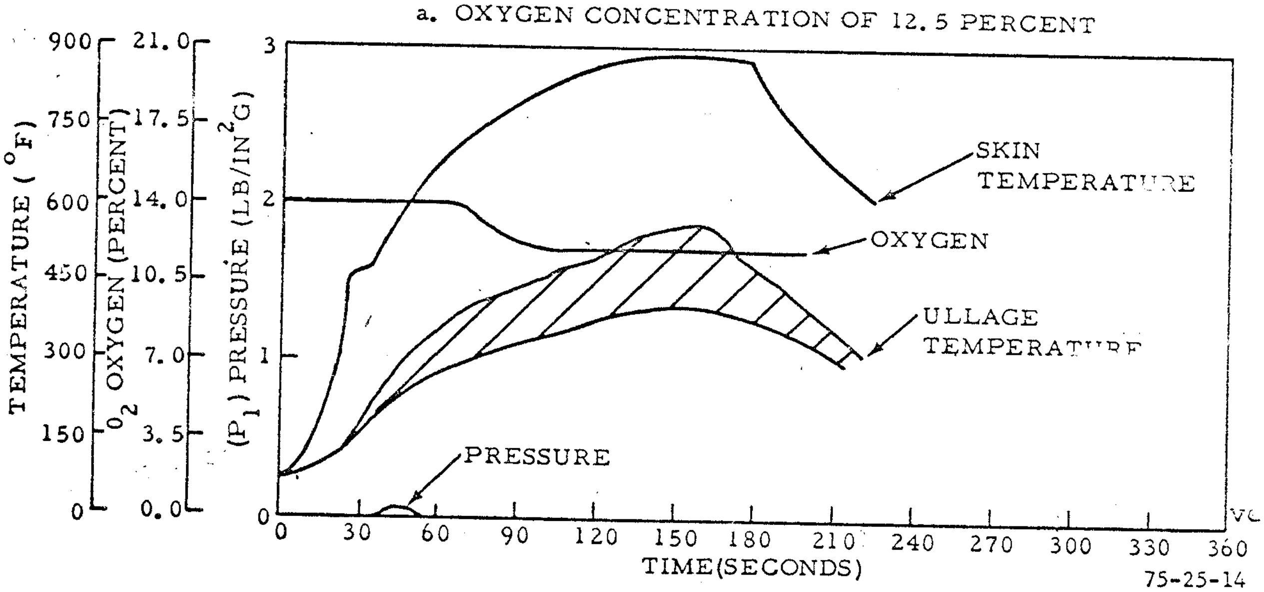


FIGURE 1. EFFECTS OF HEATING VARIOUS SMALL QUANTITIES OF JET "A" TYPE FUEL



a. OXYGEN CONCENTRATION OF 12.5 PERCENT



b. OXYGEN CONCENTRATION OF 14 PERCENT

FIGURE 14. OXYGEN CONCENTRATION LIMITS FOR HOT-SURFACE IGNITION

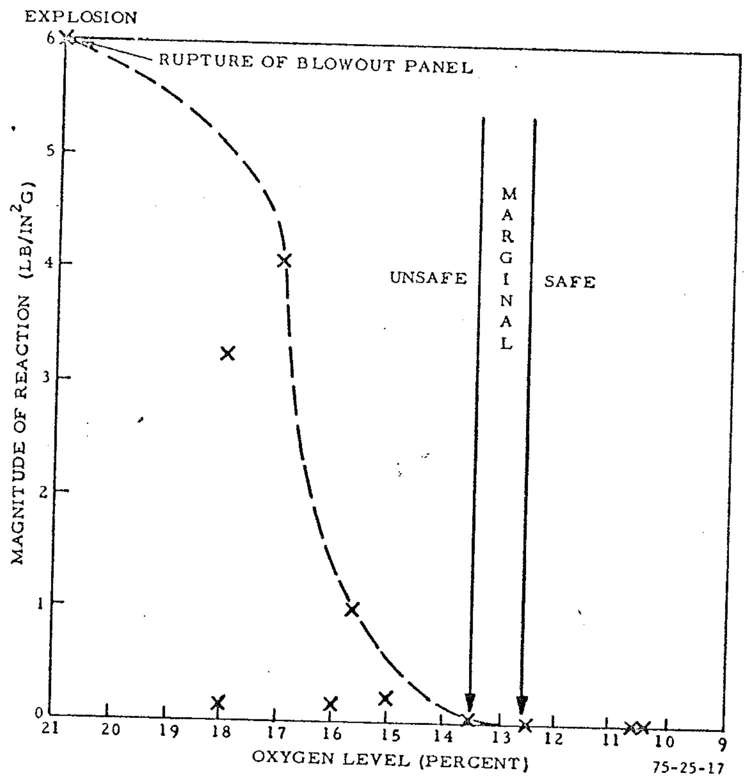


FIGURE ~~17~~ 3. THE EFFECT OF OXYGEN LEVEL ON MAGNITUDE OF REACTION FROM AUTOIGNITION

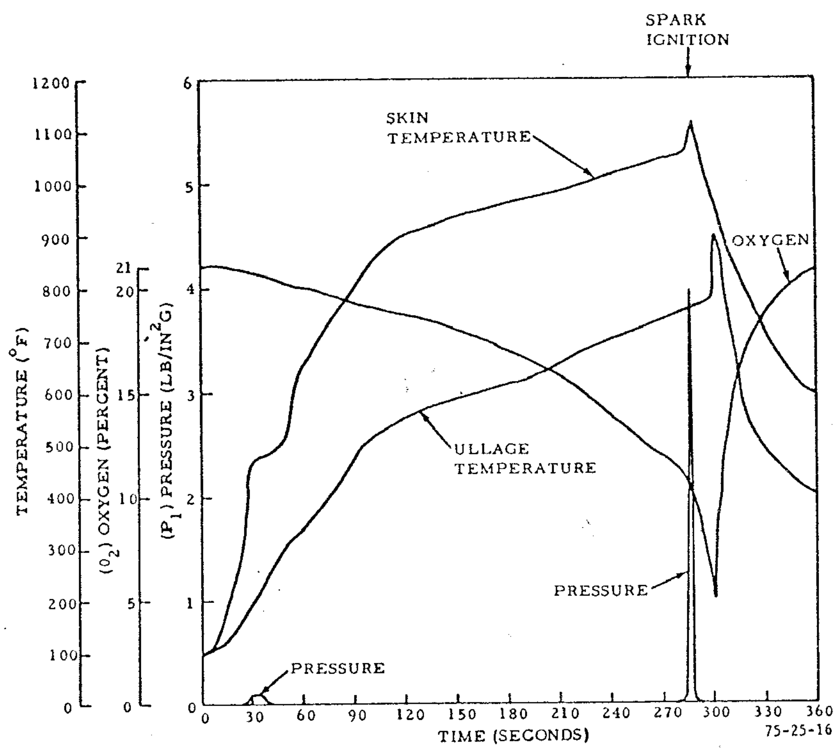


FIGURE ~~16~~ 4. ELEVATED TEMPERATURE TESTS WITH NO AUTOIGNITION

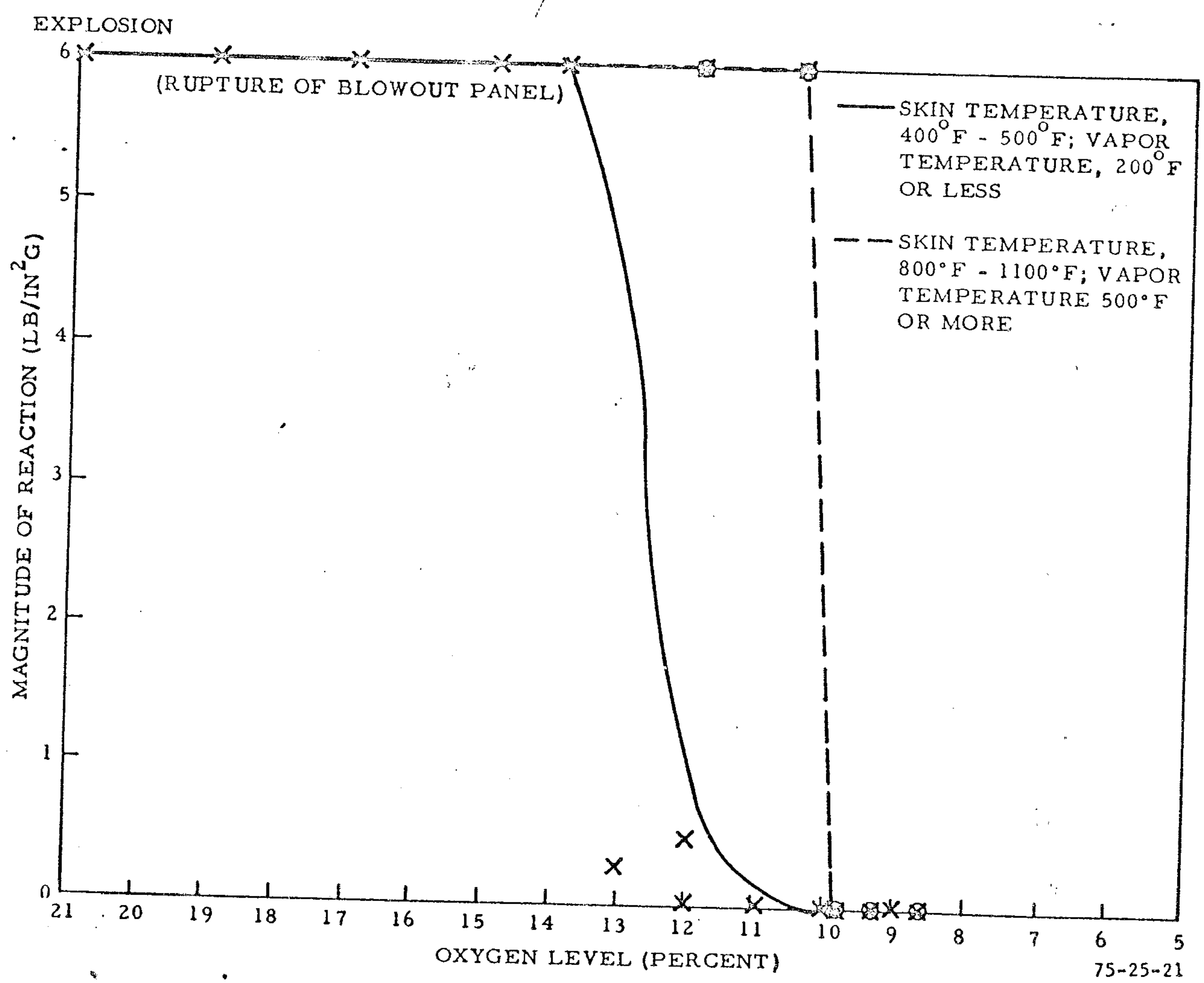


FIGURE 21.5 MAGNITUDE OF REACTION Vs. OXYGEN LEVEL DUE TO SPARK IGNITION

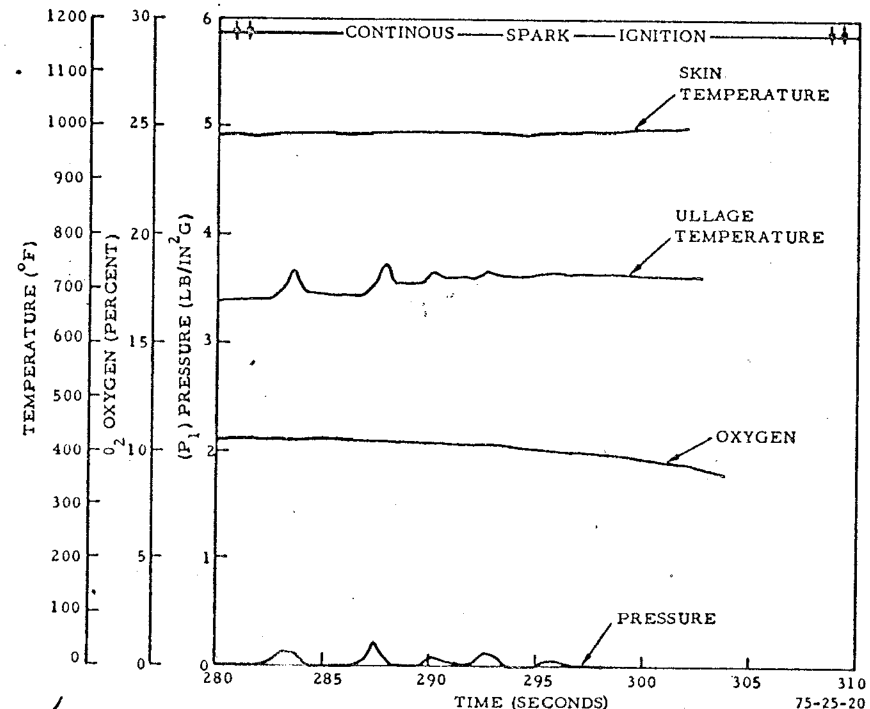


FIGURE ~~20~~ 6. SPARK IGNITION REACTION AT 10-PERCENT OXYGEN CONCENTRATION

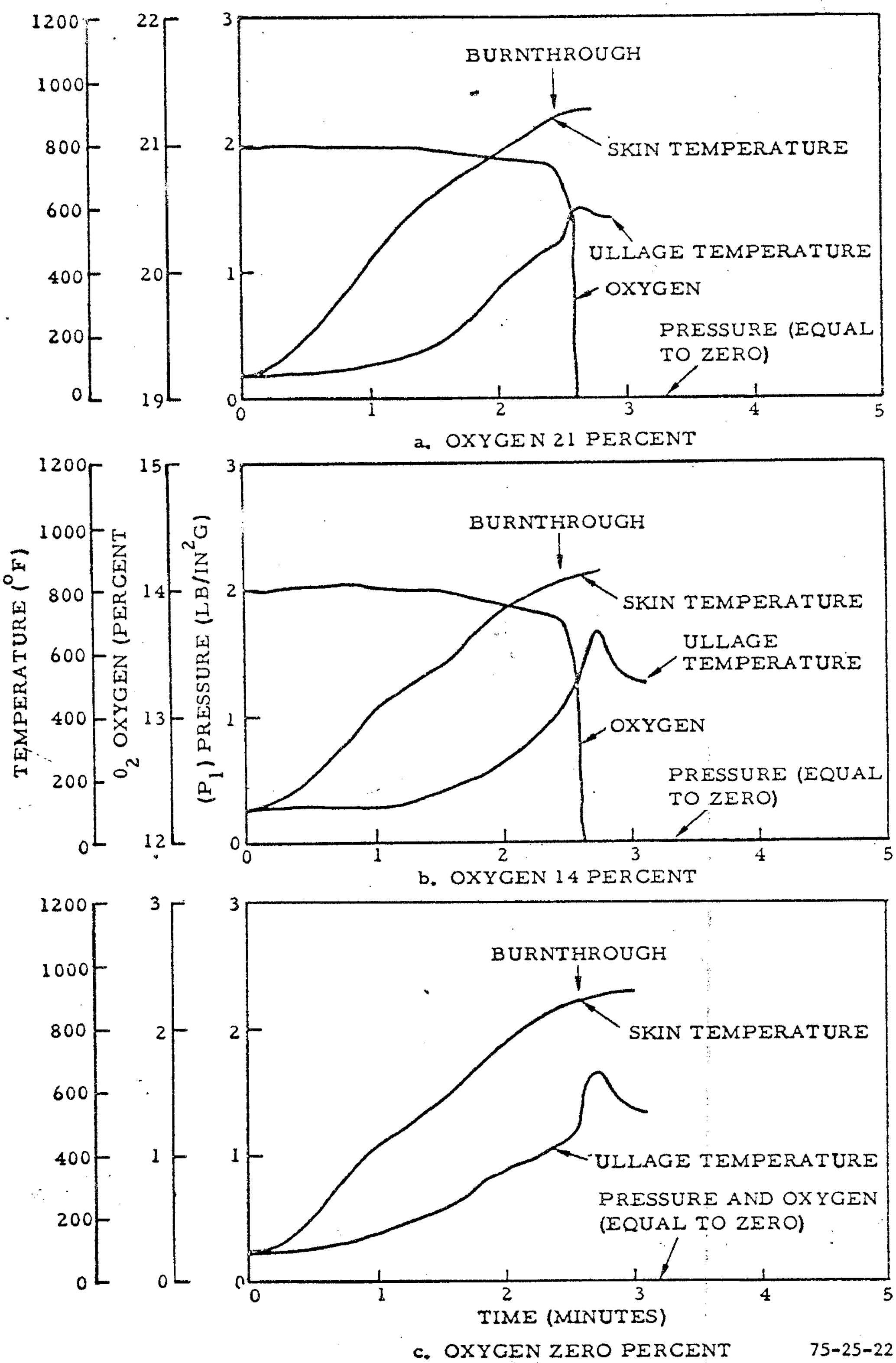


FIGURE 22. BURN-THROUGH REACTION FOR VARIOUS OXYGEN CONCENTRATION LEVELS