Stolen from J. HARDY TYSON

UNCLASSIFIED/LIMITED

DTIC

3383

TO: J. A. Tyson

DESTROY

Technical Report

distributed by

Defense Technical Information Center

DEFENSE LOGISTICS AGENCY

Cameron Station • Alexandria, Virginia 22314

UNCLASSIFIED/LIMITED

NOTICE

We are pleased to supply this document in response to your request.

The acquisition of technical reports, notes, memorandums, etc., is an active, ongoing program at the Defense Technical Information Center (DTIC) that depends, in part, on the efforts and interests of users and contributors.

Therefore, if you know of the existence of any significant reports, etc., that are not in the DTIC collection, we would appreciate receiving copies or information related to their sources and availability.

The appropriate regulations are Department of Defense Directive 5100.36, Defense Scientific and Technical Information Program; Department of Defense Directive 5200.20, Distribution Statements on Technical Documents; Military Standard (MIL-STD) 847-A, Format Requirements for Scientific and Technical Reports Prepared by or for the Department of Defense; Department of Defense Regulation 5200.1-R, Information Security Program Regulation.

Our Acquisition Section, DTIC-DDA-1, will assist in resolving any questions you may have. Telephone numbers of that office are: (202) 274-6847, 274-6874 or Autovon 284-6847, 284-6874

June 1982

WADC TECHNICAL REPORT 55-418

INERTING CONDITIONS FOR AIRCRAFT FUEL TANKS

PAUL B. STEWART
ERNEST S. STARKMAN

UNIVERSITY OF CALIFORNIA

SEPTEMBER 1955

WRIGHT AIR DEVELOPMENT CENTER

WADC TECHNICAL REPORT 55-418

INERTING CONDITIONS FOR AIRCRAFT FUEL TANKS

PAUL B. STEWART

ERNEST S. STARKMAN

UNIVERSITY OF CALIFORNIA

SEPTEMBER 1955

POWER PLANT LABORATORY

CONTRACT No. AF 33(600)-17877

PROJECT No. 3084

TASK No. 30257

WRIGHT AIR DEVELOPMENT CENTER

AIR RESEARCH AND DEVELOPMENT COMMAND

UNITED STATES AIR FORCE

WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Carpenter Litho & Prtg. Co., Springfield, O.

200 - June 1956

FOREWORD

This report was prepared by the University of California, under USAF Contract No. AF 33(600) - 17677. The contract was initiated under Project No. 3084, Task No. 30257 "Gas Flow Purging Sub-System," and was administered under the direction of the Power Plant Laboratory, Directorate of Laboratories Wright-Air Development Center, with Mr. John E. Branigan acting as Project Engineer.

ABSTRACT

Determination of the flammability limits of aircraft fuel as a function of pressure, type of fuel, temperature and ignition energy was the purpose of this investigation. The investigation was conducted in chambers ranging from 8 to 12.5 cubic feet to determine applicability of small scale Laboratory data to aircraft fuel tanks. The data obtained from a capacitor discharge spark ignition source was correlated with similar data obtained using incendiary ammunition as the ignition source. The latter data were obtained at sea level pressure.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

for

NORMAN C. APPOLD
Colonel, USAF
Chief, Power Plant Laboratory
Directorate of Laboratories

TABLE OF CONTENTS

		Page Number
I.	SUMMARY	1
II.	INTRODUCTION	4
III.	SPARK IGNITION TESTS	5
	A. Experimental Equipment	5
	B. Experimental Procedure	13
	C. Results and Discussion	16
	D. Conclusions	26
IV.	GUNFIRE TESTS	48
	A. Experimental Equipment	48
	B. Experimental Procedure	51
	C. Results and Discussion	53
	D. Conclusions	55
V.	SUPPORTING INVESTIGATIONS	65
	A. Design Correlations for Aluminum Foil Rupture Discs	65
	B. Vapor Pressure Measurements	67
	C. Surface Conductive Spark Plug Energy Release	68
VI.	REFERENCES	82
VII.	BIBLIOGRAPHY	83
VIII.	APPENDIX A	85
	I. Inspection Tests of Fuels	86
	II. Photographs of Installation.	88
	III. Engineering Drawings	95

LIST OF ILLUSTRATIONS

FIGURE No.	Title	Page
3-1	Schematic Diagram of Test Equipment	28
3-2	Model Flammability Curve-Nitrogen Inerting	29
3-3	Model Flammability Curve-Carbon Dioxide Inerting	30
3-4	Flammability Limits of AN-F-58 (JP-4) Vapor, Sea Level, Nitrogen Inerting	31
3-5	Effect of Incomplete Mixing on Flammability Limits of AN-F-58 (JP-4) Vapor with Nitrogen Inerting at 10,000 Feet	32
3-6	Flammability Limits for AN-F-58 (JP-4) Vapor with Nitrogen Inerting	33
3-7	Flammability Limits for AN-F-58 (JP-4) Vapor with Carbon Dioxide Inerting	34
3-8	Flammability Limits, AN-F-58 (JP-4) Vapor, CO_2-6 N_2 Inerting Gas	35
3-9	Permissable Oxygen Concentrations for CO_2 and N_2 Inerted Fuel-Air Mixtures, AN-F-58 (JP-4) Vapor	36
3-10	Quantities of Nitrogen and Carbon Dioxide Required for Inerting AN-F-58 (JP-4) Vapor	37
3-11	Ratio of Nitrogen to Carbon Dioxide Required for Inerting AN-F-58 (JP-4) Vapor	38
3-12	Flammability Limits, AN-F-58 (JP-4) Vapor, 35°F, Sea Level	39
3-13	Flammability Limits, AN-F-58 (JP-4) Vapor, 140°F, Sea Level	40
3-14	Effect of Temperature on Flammability Limits of AN-F-58 (JP-4) Vapor with Nitrogen Inerting Gas	41

LIST OF ILLUSTRATIONS (CONTINUED)

		Page No.
3-15	Flammability Limits, AN-F-48 Vapor, 35°F Sea Level	42
3-16	Flammability Limits of AN-F-48 Vapor, 140°F, Sea Level	43
3-17	Flammability Limits of Kerosene Vapor, 140°F, 50,000 ft	44
3-18	Flammability Limits, Isopentane Vapor with Nitrogen Inerting, 70°F, Sea Level	45
3-19	Flammability Limits, AN-F-58, 67% Liquid Filled, CO_2 Inerted, 35°F	46
3-20	Flammability Limits, AN-F-58, 67% Liquid Filled, N_2 Inerted, 35°F	47
4-1	Gunfire Tests; Fuel: AN-F-58 (JP-4); Ammunition: 50 cal API	57
4-2	Gunfire Tests; Fuel: AN-F-58; Ammunition: 20 mm HEI	58
4-3	Gunfire Tests: Fuel: AN-F-32 (Substitute); Ammunition: 50 cal API	59
4-4	Gunfire Tests Summary	57
5-1	Experimental Installation	70
5-2	6" Test Tank	71
5-3	Bursting Pressure vs. Disc Thickness for 250 Aluminum	72
5-4	Vapor Pressure Apparatus Assembly	73
5-5	Validation Experiments	74
5-6	Vapor Pressure of Fuel AN-F-58 (JP-4 Grade)	75
5-7	Vapor Pressure of Fuel AN-F-48 (100/130 Grade)	76

LIST OF ILLUSTRATIONS (CONTINUED)

		Page
5-8	Vapor Pressure of Fuel AN-F-32 Substitute	77
5-9	Spark Energy Calorimeter and Associated Equipment	78
5-10	View of Spark Plug Test Assembly	79
5-11	Energy Released by a Surface Discharge Spark Plug	80
5-12	Efficiency of Energy Transfer by a Surface Discharge Spark Plug	81

LIST OF TABLES

3-1	Spark Ignition Tests	17
4-1	Gunfire Tests, AN-F-58, 50 Calibre	61
4-2	Gunfire Tests, AN-F-58, 50 Calibre	62
4-3	Gunfire Tests, AN-F-32, 50 Calibre	63
4-4	Gunfire Tests, AN-F-58, 20 MM	64

I. SUMMARY

This report sumarizes an experimental investigation of inerting conditions for aircraft fuel tanks. The results herein presented were obtained in rectangular tanks of 8 and 12 1/2 cubic foot capacity with three different aviation fuels (AN-F-58 (JP-4 grade), AN-F-48 (100/130 grade), and AN-F-32 Substitute (kerosene)), three different inerting gases, two different ignition sources (high-energy electric sparks and incendiary ammunition), over a temperature range of 35°F to 110°F, and at pressures equivalent to altitudes from sea level to 60,000 feet in 10,000 foot increments. The more important results of this work are:

1. The present data show wider ignition limits than those hitherto reported using smaller equipment and lower energy ignition sources.
2. The presence of liquid fuel in a tank widens the range of combustible mixtures over that obtained with gas and vapor mixtures only.
3. Fuel tanks can be successfully inerted by maintaining the oxygen concentration in the vapor space below 9 percent, or the fuel vapor concentration greater than 11 percent.

4. Bay spaces should be inerted as well as fuel tanks.
5. Ordinary diffusional-convectional mixing is a very slow process. Stratification in the gas phase is thus quite likely. This makes it possible to have regions where inflammation can take place, even though the average composition is in the non-flammable region.
6. Nitrogen is the most efficient inerting gas tested on a weight basis, and carbon dioxide the most efficient on a volume basis.
7. The major effect of a change in temperature is to change the vapor pressure of the fuel.
8. The major effect of increasing altitudes or decreasing total pressure is to decrease the range of conditions for obtaining combustible mixtures. Combustion phenomena at pressures corresponding to 40,000 to 60,000 feet are usually of the cool flame type with little or no pressure rise accompanying the combustion, in contrast to explosive combustion at the lower altitudes.

In addition to describing the experimental equipment, experimental method and the results and conclusions to be drawn from the main program, three supporting investigations are summarized. These concern the design of aluminum foil rupture disks, the measurement of the vapor pressure of fuels over a wide temperature range and the relationship between the energy supplied and released from a surface conductive spark plug.

II. INTRODUCTION

The Fuel Ignition Studies Research Project had for its objective the determination of the ignition or combustion limits of mixtures of aircraft fuel vapor, oxygen, and inert gases. Both service experience and theoretical considerations led to the questioning of the validity of applying the then-existing information (obtained in small-scale equipment, and with low-energy ignition sources) on the combustion limits of hydrocarbon vapor-air mixtures to the problem of inerting aircraft fuel tanks. The present work was carried out in tanks of from 8 to 12.5 cubic feet capacity to answer the question raised by the use of glass laboratory equipment in the past, and high-energy electric sparks or service incendiary ammunition to increase the energy added to the fuel-gas mixture by the ignition source.

Supporting experimental investigations that were necessary for the successful accomplishment of the major program were:

1. The obtaining of engineering design data for the rupture disks.
2. The development of an apparatus for measuring the vapor pressure of hydrocarbon mixtures.
3. The measurement of the energy actually released to the gas mixture by the surface-discharge spark plugs.

All of the material contained in this report has been presented, as it became available, in earlier reports. These earlier reports (see Bibliography p. 79) usually contain greater detail than does this summary technical report, and should be consulted for more complete information.

From its inception this work has been performed under the direction of Faculty Investigators, Paul B. Stewart, Associate Professor of Process Engineering, and Ernest S. Starkman, Associate Professor of Mechanical Engineering. In the first year of the Research Project's operation significant contributions to its success were made by Frank Kreith, Acting Assistant Professor of Mechanical Engineering, and Charles H. Cohrs, Assistant Research Engineer, both of whom then left the University.

Other people who were employed on the project and also contributed to its success in subordinate rolls include Raymond E. Gott, Leo Lichtman, Robert T. Fox, Jr., George William Gurr, Burt L. Levin, James Dutzi, and William Nephew.

III. SPARK IGNITION TESTS

A. Experimental Equipment. The experimental equipment, separated into functional groups, was composed of:

(1) The test tank, (2) A vacuum pump system, (3) The gas and fuel supply system, (4) A temperature control system, (5) A pressure measuring system, (6) An ignition system, and (7) the program timer. A schematic arrangement diagram of the main units making up the equipment assembly is given in Figure 3-1 .

Drawings of the major units and assemblies are in the Appendix of this report.

1. Test Tank. The original test tank was a steel box 2 1/2 ft x 2 1/2 ft x 2 ft made of 1/4-inch steel plate, welded construction, reinforced with steel angle. This tank developed small leaks, presumably due to the severe flexing imposed on the walls and the welds by the more violent explosions. It was then replaced by a tank identical in all respects except of heavier construction, 3/8-inch plate, and heavier reinforcing angles. The tank was protected against overpressure by a rupture disk which burst at a nominal 20 psig. This limited the pressure rise due to combustion to values which could not damage the tank. A 1 1/2-inch pipe line to the atmosphere was provided for expulsion of gases remaining at the conclusion of each test, and the tank was connected by a 2-inch pipe to the vacuum system. A manifold which

could also be called part of the gas supply system was attached to the tank, as was the pressure measuring system.

For tests at other than ambient temperatures, the tank was wrapped with copper cooling or heating coils and covered with Foamglas insulation.

A 4-inch diameter Pyrex glass window in one side permitted visual observation or photography of flame phenomena.

A small stirring fan was installed inside the tank during the course of the tests when it was found that natural mixing was not sufficiently complete unless permitted to continue for impractically long period.

2. Vacuum Pump System. The vacuum pump system was built around 2 Kinney mechanical pumps, each capable of displacing 13 cubic feet per minute and of pumping down to an absolute pressure of 10 microns when blanked off. A cold trap, a steel tank packed with copper turnings and immersed in a bath of propylene dichloride (1, 3-dichloropropane) refrigerated with Dry Ice, kept large quantities of condensibles out of the vacuum pumps. All valves on the vacuum system were either Kinney bellows-sealed valves or Grinnel-Saunders diaphragm valves.

Even with the cold trap at a temperature of -70°F to -110°F troubles were experienced with the solubility of fuel vapor and of carbon dioxide in the vacuum pump oil. This solubility effectively raised the vapor pressure of the pump oil, and correspondingly decreased the vacuum attainable with the pumps. To overcome this problem the system was purged with air before pumping it down so that the vacuum pumps would no longer have to handle materials soluble in the pump oil. The air was supplied from the building compressed air supply, and the removal of the carbon dioxide and fuel vapor by a jet exhauster mounted on the roof above the tank. This jet exhauster, although designed for steam operation, operated effectively on compressed air.

The cold trap was isolated by valves from the system when it was not operating. It was drained periodically when not at reduced temperature.

3. Gas and Fuel Supply System. Gases and fuel vapor for the tests were admitted separately to the test tank from their respective tempering tanks through a manifold. The permanent gases (nitrogen, oxygen, and carbon dioxide) were kept under pressures of 25 to 50 psig in the tempering

tanks, being supplied thereto from high pressure gas bottles through pressure regulators. The other component, fuel vapor, was drawn from a fuel tempering tank when it evaporated from the liquid phase. All of these tanks were connected through valves to the vacuum system so they could be evacuated. They were constructed to withstand atmospheric pressure while evacuated and rated for 150 psig pressure. The tanks were wrapped with cooling or heating coils and insulated with Foamglas.

One difficulty encountered in the early tests resulted from liquid fuel being pulled through the vapor line from the tempering tank into the test tank. A liquid trap, therefore, was installed in the line at the tempering tank. This trap, a short piece of one-inch pipe filled with glass wool, capped at the top and with a drain valve at the bottom, was emptied each time the fuel was changed in the tempering tank.

The original fuel tempering tank was found to have too small a volume to provide sufficient vapor storage space for loading the test tank in a reasonable time interval when working with low-vapor pressure fuels, or all fuels at sub-zero temperatures. Accordingly, the original test tank was repaired and put into service as a fuel tempering tank of greatly increased volume.

4. Temperature Control System. As has been noted earlier, the external surfaces of the test tank and the tempering tanks had copper tubing soldered in place for heat transfer purposes. Heated or cooled liquids were pumped through these coils to bring the tanks and their contents to the desired temperature.

Water was used as the heat transfer fluid in the temperature range of 32°F to 140°F. Ice was used to chill the water when required, or an ordinary domestic gas-fired water heater to heat it.

For tests at temperatures less than 32°F methanol was the heat transfer fluid. The fluid originally used, propylene dichloride, proved to be too poor a lubricant which caused the pump seals to fail. The methanol was chilled to the desired temperature by pumping it through a helical coil of spined finned copper pipe immersed in a bath of propylene dichloride refrigerated with solid carbon dioxide (Dry Ice). The indirect cooling was necessary because of vapor lock problems in the pumps which were due to the solubility of carbon dioxide in the heat transfer fluid, and gas evolution in regions of reduced pressure.

Temperatures at various points throughout the installation were measured by copper-constantan thermocouples connected to a Brown Electronik strip chart temperature recorder.

5. Pressure Measuring System. The pressure in the test tank was observed during evacuation and loading by an absolute manometer and two Stokes McLeod gages covering different ranges. These instruments were connected to the test tank; or through valves they could be made to indicate pressures in other parts of the system, as, for example, the tempering tanks.

A Pirani gauge was connected to the vacuum system primarily for the detection of leaks. Points of suspected leakage, such as valves or joints, were squirted with methyl alcohol. Liquid alcohol which comes in contact with a leak is drawn into the system where it evaporates. This caused the Pirani gage to react, having the effect of indicating a sudden pressure rise. The calibration of this instrument has been found to vary excessively, so it is not used for absolute measurement. An Alphatron gage was added to the system later on for this same purpose because it was a less fragile instrument than the Pirani gauge.

A Statham pressure pickup was installed in the test tank. This instrument was, in turn, attached to a DuMont type 304A Oscillograph on which pressure-time curves were photographically recorded for each test. The single sweep required on the oscillograph was initiated by the program timer.

6. Ignition System. The ignition source was a row of 14 surface discharge spark plugs in the top of the test tank. Each spark plug was fired by discharging a sixteen microfarad capacitor through it. The fourteen capacitors, together with the power supply, control circuits, and program timer were housed in a cabinet with the required safety interlocks and cutouts. For reasons of safety, the power supply was energized by a push-button, so that it had to be manually actuated during the entire charging period. This button when released, in case of accident or danger, discharged all fourteen condensers through an internal shorting mechanism.

A high-voltage power supply with half-wave rectified output and continuously controllable voltage charged the capacitor banks. A Thyratron in each spark plug circuit acted as a switch, preventing the capacitors from discharging prematurely. The Thyratrons held as long as the grid bias was sufficiently negative. The operation of the program timer removed the grid bias from all Thyratrons simultaneously, causing all spark plugs to fire.

Ordinary automotive spark plugs were adapted for use in these tests by removing the ground-side spark electrode and filling the annular space between the center electrode and the plug body with Saureisen insulating cement. When this

[illegible] the surface was painted with Aquadag (a colloidal graphite [illegible]ion) and allowed to dry. The surface resistance of the spark [illegible] adjusted to approximately 10,000 ohms by application or [illegible] of Aquadag. In use, the plug resistance was found to [illegible] gradually because of the graphite film, leading eventually [illegible] of the plug to fire. It was found necessary to keep close
7. [illegible] the condition of the spark plugs in order to avoid collecting [illegible] data.

[illegible] Timer. The program timer consisted of a synchronous [illegible]ing a shaft on which were mounted six adjustable cams. [illegible] operated a microswitch to either open or close a circuit. [illegible] button on the front of the spark generator cabinet set the [illegible] operation, causing it to make one revolution in six seconds [illegible] The microswitches triggered the sweep on the oscillograph [illegible]sure measurement, fired the spark by removing the Thyratron [illegible] started and stopped a high speed movie camera which was [illegible]lly used to photograph phenomena inside the test tank. One
B. [illegible]tch turned off the timer motor at the end of one revolution [illegible] was a spare.

[illegible]ntal Procedure. The experimental procedure used in the [illegible]ition tests is outlined in the following paragraphs, separated [illegible] to the equipment units involved.

[illegible] Before operating the vacuum pumps, it was necessary [illegible] the temperature in the cold trap to $-70^{\circ}F$ or less. This [illegible] by adding pieces of Dry Ice to the propylene dichloride bath jacketing the cold chamber of the trap.

Tempering Tanks. The fuel in the tempering tank was changed frequently in order that only the light fractions of fuel, representative of the vapor in an aircraft fuel tank, be used in the ignition tests. Fuel to be discarded was expelled from the tempering tank by opening the bottom valve and applying nitrogen pressure. The tank was then dried by blowing nitrogen through it, after which the fuel transfer line was capped and the tank and line evacuated to approximately 100 microns absolute pressure. The capped end of the fuel transfer line was then submerged in fresh fuel and the cap removed. The loading valve was closed before the entire fuel supply was drawn in, so as not to admit air. Air in solution in the fuel was liberated when the fuel was subjected to the low pressure of the fuel tempering tank, and removed by opening the vacuum valve momentarily. The pressure gage on the fuel tempering tank was observed several times daily to make sure that no air had leaked into the vessel.

The gas tempering tanks were loaded at the beginning of the tests by being pumped to a pressure of 100 microns of mercury and then filled from their respective high pressure bottles. The pressure regulators on these bottles were adjusted so that the gas pressure in the tempering tanks was maintained at about 50 psig.

In tests at other than ambient temperature the tempering tanks were used to heat or cool the fuel and gases. This was accomplished by circulating a heat transfer fluid through the copper coils surrounding the tempering tanks.

Test Tank. The test tank was evacuated to less than 100 microns of mercury before loading. The components were then added in proportion to their final partial pressures in the resulting mixture. Since the vapor pressure was used as the driving force in loading the fuel, it was necessary to admit that component to the test tank first. Then the permanent gases were admitted to the test tank, the proportion being controlled by observation of pressure. For safety, oxygen was always the last component added.

The test tank loading procedure was modified when liquid fuel was used. The liquid fuel, at room temperature for tests at or above room temperature, at or below the test temperature for work below room temperature, was pumped into the test tank through the rupture disc port by a hand-operated transfer pump. The rupture disc was then replaced, and the pressure in the tank reduced to that of the vapor pressure of the fuel, thus minimizing the loss of the more volatile constituents by the pumping down procedure. The tank and its contents were then brought to the test temperature. During this partial evacuation of the tank dissolved gases in the fuel were apparently released from it with sufficient splashing of the liquid fuel to wet the spark plugs and make them inoperative.

Consequently it was necessary to replace the spark plugs with dryones and repeat the evacuation. The permanent gases were then loaded in the usual manner.

<u>Ignition.</u> The condenser bank was then charged up to the desired point, the program timer set in motion, and the spark plugs fired.

<u>Data.</u> The composition of the gas mixture in the tank was obtained by the pressure (partial pressure) readings taken during the loading procedure. A pressure-time history of the events taking place was obtained on the oscilloscope screen which was photographed.

The results of any one test, on a "go" or "no go" basis were assessed by the operator by visual observation. The room containing the test tank was darkened before the test. The phenomena taking place in the tank were observed, in a mirror forming a simple periscope system, through the glass port. Any flame at all, no matter what its characteristic, was recorded as a "go".

Some of the early tests were photographed, but this proved to be actually inferior in many ways to visual observation.

C. <u>Results and Discussion.</u> The results of the spark ignition test program are presented as a series of graphs showing regions where flammable and non-flammable mixtures exist. Table 3-1 following, summarizes the experimental conditions for each series of tests:

TABLE 3-1

SPARK IGNITION TESTS

EXPERIMENTAL CONDITIONS

Series No.	Fuel An-F-.	Alt. Press. Mft.	Temp. °F	Inert Gas	Plug Energy Joules	Liquid Phase Present
1	58	0-60	70	N_2	3	No
2	58	0-60	70	CO_2	3	No
3	58	0, 30, 50	70	N_2-CO_2	3	No
4	58	0	35	all	3	No
5	58	0	140	all	3	No
6	58	0	35	N_2;CO_2	6	No
7	58	0	140	all	6	No
8	48	0	35	all	3	No
9	48	0	140	N_2;CO_2	3	No
10	32	50	140	N_2;CO_2	3	No
11	i-C_5	0	70	N_2	3	No
12	58	0	35	N_2;CO_2	3	Yes

Coordinate System Used. All of the graphs showing the ignition limits for fuel vapor-oxygen-inert gas mixtures are plotted on Cartesian coordinates with the volume (or mole) percent of fuel vapor as the abscissa and the volume percent of oxygen as the ordinate. A straight line of negative slope labeled "Atmospheric Line" represents all mixtures of fuel vapor and atmospheric air. Lines parallel to this Atmospheric Line represent mixtures of fuel vapor, atmospheric air, and added inert gas. On the various graphs auxilliary scales are shown giving carbon dioxide and nitrogen concentrations.

The plotting system is explained in greater detail in the Model Flammability Curves, Figures 3-2, and 3-3.

All of these graphs in this report use a common coordinate system and scales to facilitate comparison.

Ignition Limits Curve. A curve, roughly U-shaped, with the ends of the U terminating on the Atmospheric Line is shown on each graph. This Ignition Limits Curve is the line of demarkation between a region containing flammable mixtures, and the region where mixtures are non-flammable. The left-hand branch of the curve is the lean limit (fuel lean limit) where the mixtures contain insufficient fuel to burn. The right-hand branch is the rich limit (fuel rich limit) where the mixtures contain too much fuel to burn. The bottom of the curve represents a region where there is too little oxygen for combustion. To summarize, points lying in the area bounded by the Atmospheric Line and the Ignition Limits Curve represent flammable compositions, making this area a Danger Zone; points outside this area are non-flammable, or safe.

Each ignition limits curve was determined by a series of "go" and "no go" experiments. At constant oxygen concentration a "go" and a "no go" were obtained differing by not more than 1/2 of 1 percent in fuel vapor concentration. This, then, established the curve within narrow limits. Extending the experimental conditions to other variables such as different total pressure produced a family of curves which were then smoothed, but still consistent with the data.

When the family of curves had been drawn, cross-plots were made to obtain lines of fuel vs. altitude for constant oxygen. By smoothing these latter curves and then replotting the original curves from the smoothed curves, a more consistent set was obtained which still agrees with the data. The curves at different altitudes tend to support each other, so that much of the original experimental uncertainty is eliminated with no additional experimental work.

The construction of a typical ignition curve is shown in Figure 3-4, after all smoothing operations, illustrating the results of this plotting procedure. This graph also shows the comparison of the results obtained in this investigation with those reported by Coward and Jones, U. S. Breau of Mines(1)*, for experiments with smaller equipment and lower energy ignition sources.

The effect of incomplete mixing or stratification is shown in Figure 3-5. The first experiments were conducted by loading the test tank as described earlier and allowing some 10 to 15 minutes for natural diffusional mixing to take place. Although consistent curves at any one total pressure were obtained, those at differing pressures did not correlate. An electric fan was then installed in the test tank to accelerate the mixing process with the results shown which were consistent.

The flammability (or ignitability) limits for AN-F-58 (JP-4) at 70°F ± 5° at pressures corresponding to altitudes of sea level to 60,000 feet in 10,000 foot increments with nitrogen and carbon dioxide inerting, and at pressures corresponding to sea level, 30,000 and 50,000 feet with an inerting gas mixture of 6 parts nitrogen and 1 part carbon dioxide are shown in Figures 3-6 , , and 3-8 . All of these graphs show the same effect as the altitude is increased, or the pressure reduced, of decreasing the area in which combustible mixtures occur. Not shown by the graphs, due to the method of assessing "go" and "no go" experiments is the difference in basic combustion phenomena. At the lowest altitudes, in general, combustion is violent, characterized by orange flames and a rapid pressure rise which

* Numbers in parentheses refer to References, p.52

results obtained in this investigation with those reported by Coward and Jones, U. S. Breau of Mines[(1)*], for experiments with smaller equipment and lower energy ignition sources.

The effect of incomplete mixing or stratification is shown in Figure 3-5. The first experiments were conducted by loading the test tank as described earlier and allowing some 10 to 15 minutes for natural diffusional mixing to take place. Although consistent curves at any one total pressure were obtained, those at differing pressures did not correlate. An electric fan was then installed in the test tank to accelerate the mixing process with the results shown which were consistent.

The flammability (or ignitability) limits for AN-F-58 (JP-4) at 70°F ± 5° at pressures corresponding to altitudes of sea level to 60,000 feet in 10,000 foot increments with nitrogen and carbon dioxide inerting, and at pressures corresponding to sea level, 30,000 and 50,000 feet with an inerting gas mixture of 6 parts nitrogen and 1 part carbon dioxide are shown in Figures 3-6, 3-7, and 3-8. All of these graphs show the same effect as the altitude is increased, or the pressure reduced, of decreasing the area in which combustible mixtures occur. Not shown by the graphs, due to the method of assessing "go" and "no go" experiments is the difference in basic combustion phenomena. At the lowest altitudes, in general, combustion is violent, characterized by orange flames and a rapid pressure rise which

*Numbers in parentheses refer to References, p. 82

invariably broke the rupture disk. At the highest altitudes, in general, the combustion takes place with little or no pressure rise and appears as a blue, green, or blue-green slowly moving flame front; this is in the so-called "cool flame" region.

A comparison of Figures 3-6, 3-7, and 3-8 brings out the effectiveness of the three inerting gases used. Carbon dioxide, on a volume percent basis, is the most effective inertant. There is little or no difference in the effect of changing the inertant on the fuel lean limit curve. However, the fuel rich limit is somewhat closer to the fuel lean limit for carbon dioxide inerting as compared to nitrogen inerting. The oxygen lean limit is affected the most, being approximately 10 percent for nitrogen inerting at sea level as compared to nearly 13 percent for carbon dioxide inerting under the same conditions. In all cases the gas mixture is intermediate in inerting effect between the two pure gases, and closely approximates nitrogen, the major component.

This comparison of the inerting efficiency is brought out more clearly in Figures 3-9 , 3-10 , and 3-11. These graphs are essentially plots of the minimum quantity of oxygen at which combustion takes place as functions of altitude. They bring out the superiority of carbon dioxide as an inertant on the volumetric basis, a fact in agreement with earlier, small-scale, investigations[2]. Due to the difference in molecular weight (44 vs. 28) nitrogen is superior on the weight basis. Although no measurements were made, carbon dioxide seemed to be more soluble in the fuel than was nitrogen, a fact that should be considered in choosing an inerting gas, due to the possibility of dissolved gases coming out of solution at reduced pressures.

Figures 3-12, 3-13, and 3-14 again show the effect of changing the inerting gas, and of changing the temperature. Results are given at the three temperatures of 35°F, 70°F ± 5°, and 140°F. Attempts were made to obtain data at -65°F as originally specified, but the vapor pressures of all the fuels were so low at this temperature that all mixtures were in the safe region, being outside the fuel lean limit. The same general relations existing among the three inerting gases at 70° hold true at the lower and higher temperatures.

The major effect of temperature is to change the vapor pressure of the fuel. In addition to making the taking of data at -65°F impossible, it made impossible obtaining a complete fuel rich limit curve at 35° Other effects of increasing the temperature, although relatively minor, are:

1. The fuel lean limit branches of the curve are essentially identical.
2. The oxygen lean limit (the bottom of the curve) is lowered to smaller values of total oxygen content by the 105° increase in temperature.

3. The fuel rich limit branch of the curve is moved to higher fuel concentrations by this same increase in temperature.

The results of using 6 joules stored energy on the condensers feeding the sparks plugs, as compared to the 3 joules used in the rest of this work were demonstrated in series 6 and 7 experiments. In general, the results obtained with the higher energy input check those obtained with 3 joules stored energy within experimental accuracy and therefore are not given as graphs. There is a slight, but reproducible, tendency for the curves at 140°F to show a widening of the rich limit as the composition approaches the atmospheric line. The conclusion from this work is that the quantity of energy delivered to the spark plugs is above the minimum ignition energy for both energy storage conditions.

Figures 3-15 and 3-16 show the effects of inerting fuel AN-F-48 with nitrogen, carbon dioxide, and the nitrogen-carbon dioxide mixture at 35°F and 140°F. The curves bounding the region of inflammation are very nearly identical to those obtained with fuel AN-F-58 (JP-4) under the same conditions except that they are displaced toward higher fuel concentrations by approximately 0.3 percent on the fuel axis. This shift may be due to a difference in the most volatile constituents of the two fuels, since it has been shown on a laboratory scale that the lightest hydrocarbons exhibit differences in combustion characteristics.

Inerting tests with kerosene (the authorized substitute for fuel AN-F-32 (JP-1) which was not obtainable) were conducted at 140°F with both nitrogen and carbon dioxide inerting at a pressure corresponding to an altitude of 50,000 ft. The data are shown in Figure 3-17.

The vapor pressure of the kerosene used (a typical commercial product) is so low that it is impossible to get a flammable mixture with it at sea level and 140°F, and only portions of the complete curve bounding the region of inflammation at pressures corresponding to altitudes of 10,000 ft to 40,000 ft inclusive. These two complete curves obtained with kerosene are exact duplicates of those for fuel AN-F-58 (JP-4) under the same experimental conditions. The conclusion to be drawn from this is that the most volatile constituents of these two fuels have the same inflammation characteristics, even though they differ in molecular weight and possibly in other ways from one fuel to the other.

Figure 3-18 gives the flammability limits of commercial isopentane (94 percent minimum purity), nitrogen inerted, at room temperature and sea level pressure, with three joules per spark plug stored electrical energy. Comparison of this curve with that obtained for fuel AN-F-58 (JP-4) shows that the two curves are identical within the limits of experimental accuracy. It seems to be standard practice in the petroleum industry to debutanize all aviation fuels, and to use isopentane, or a pentane mixture, in blending these fuels to vapor pressure specifications. These experimental data indicate that only the lightest fractions in a fuel are important in that fuel's behavior toward inflammation in the fuel tanks, or in storage, since they make the major contribution to the total vapor pressure at temperatures below 150°F.

The results of those tests made with liquid fuel (AN-F-58 (JP-4)) in the test tank are shown in Figures 3-19 and 3-20. These tests cover both nitrogen and carbon dioxide inerting, and were made at 35°F and at sea level pressure. Attempts were made to perform these tests at 140°F and at -65°F; all of these trials were "no go", presumably because in one case the fuel vapor pressure was so high that the fuel rich limit was exceeded, and at the other temperature the fuel vapor pressure was not sufficiently large to attain the fuel lean limit. Since these experiments involve liquid fuel at one temperature the fuel vapor concentration is a constant; the percentage of inertant (or oxygen) is the only free composition variable. The amount of liquid fuel, whether 67 or 87 percent of the tank volume, had no effect on the results.

In all cases the test results show inflammation outside of the curve previously determined without liquid fuel in the tank.

These test points show that combustible mixtures are moved approximately to a fuel composition one percent higher, and to an oxygen concentration one percent lower, both of these percentages being based on the total mixture rather than on the individual component. Thus, with liquid fuel in the tank, a greater amount of inerting is required than when liquid fuel is not present. A possible explanation for this shift in the fuel rich limit, is that the basic phenomenon is different: when liquid fuel is present there is the possibility of having not only fuel vapor in the freeboard space in the tank, but of also having in that space a fog of liquid droplets. The wetting of the spark plugs in these tests, mentioned earlier, indicates the likelihood of the presence of such a fog. Suspensions of small combustible particles, either liquid or solid, in air are well known to be highly flammable.

D. Conclusions. The conclusions from the test program conducted with high-energy electric sparks as ignition sources are:

1. The ignition or combustion limits determined in these experiments with a 12 1/2-cubic foot tank and a high-energy ignition source, at room temperature, are wider than those reported hitherto in the literature. This is presumably due to the difference in experimental conditions, and is true for both nitrogen and carbon dioxide inerting.

2. Component stratification or incomplete mixing in the gas phase can cause serious errors in experimental work of this type. The incomplete mixing could also lead to regions of local flammability even though the average composition of a mixture were in the non-flammable region.
3. Carbon dioxide is a more effective inertant than nitrogen on a volumetric basis, but less effective on a weight basis. Mixtures of the two gases are intermediate in effectiveness between the two pure gases.
4. The effect of increasing altitude, or decreasing the total pressure, is to narrow the ignition limits. Increasing the altitude to values of 40,000 feet or higher also causes a marked decrease in the violence of the combustion.
5. The major effect of changes in temperature is to change the vapor pressure of the fuel.
6. The inflammation characteristics of fuels AN-F-58 (JP-4), AN-F-32 substitute (commercial kerosene), and commercial isopentane are essentially identical, if vapor pressure differences are taken into account. Fuel AN-F-48 (100/130 grade) has the inflammation region shifted slightly toward higher fuel concentrations.
7. When liquid fuel is present in a fuel tank that tank must be more completely inerted than when only a gas phase is present to be in the non-flammable zone.

SCHEMATIC DIAGRAM OF TEST EQUIPMENT

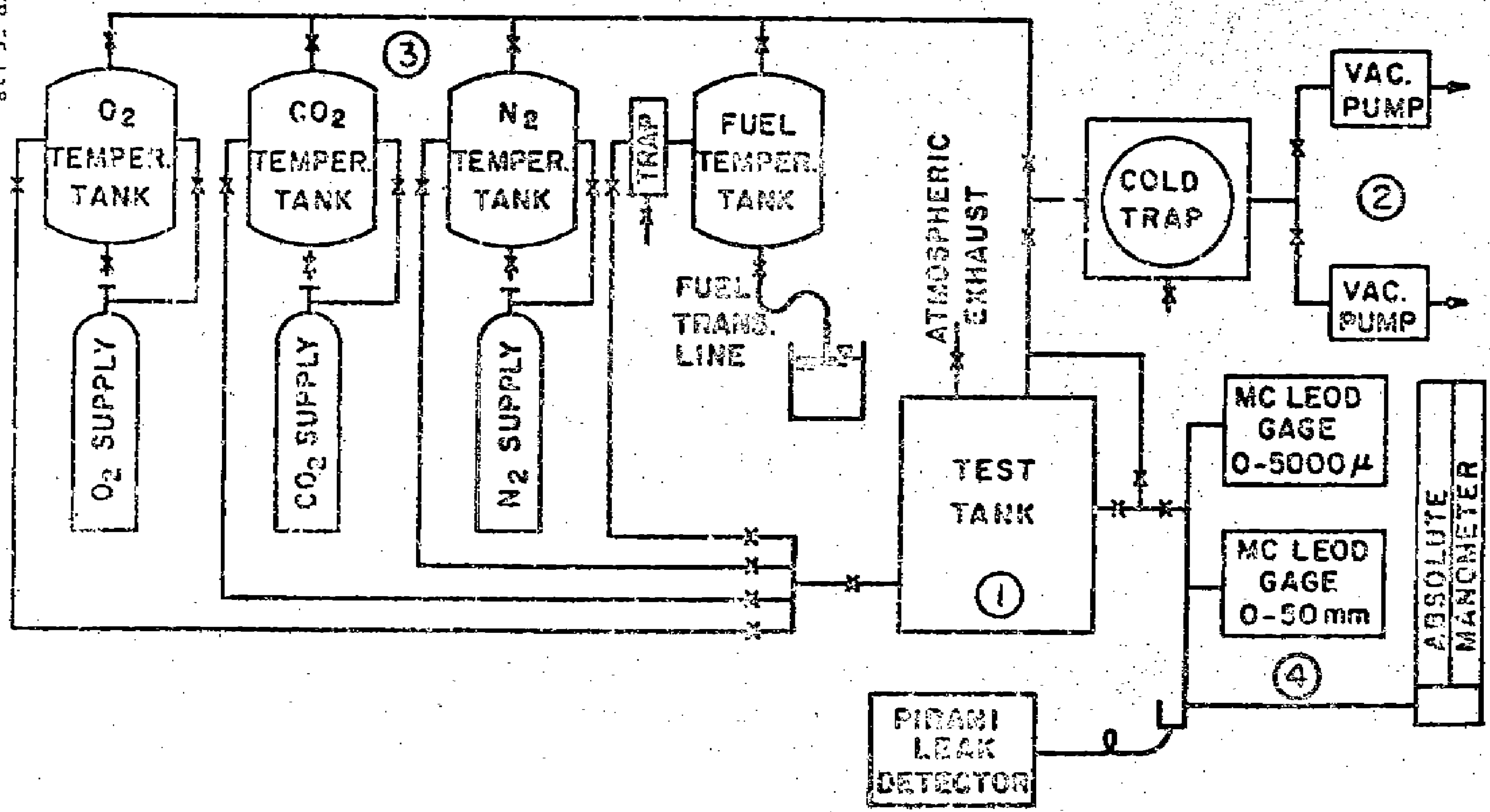


FIG. 3-1

MODEL FLAMMABILITY CURVE

NITROGEN INERTING

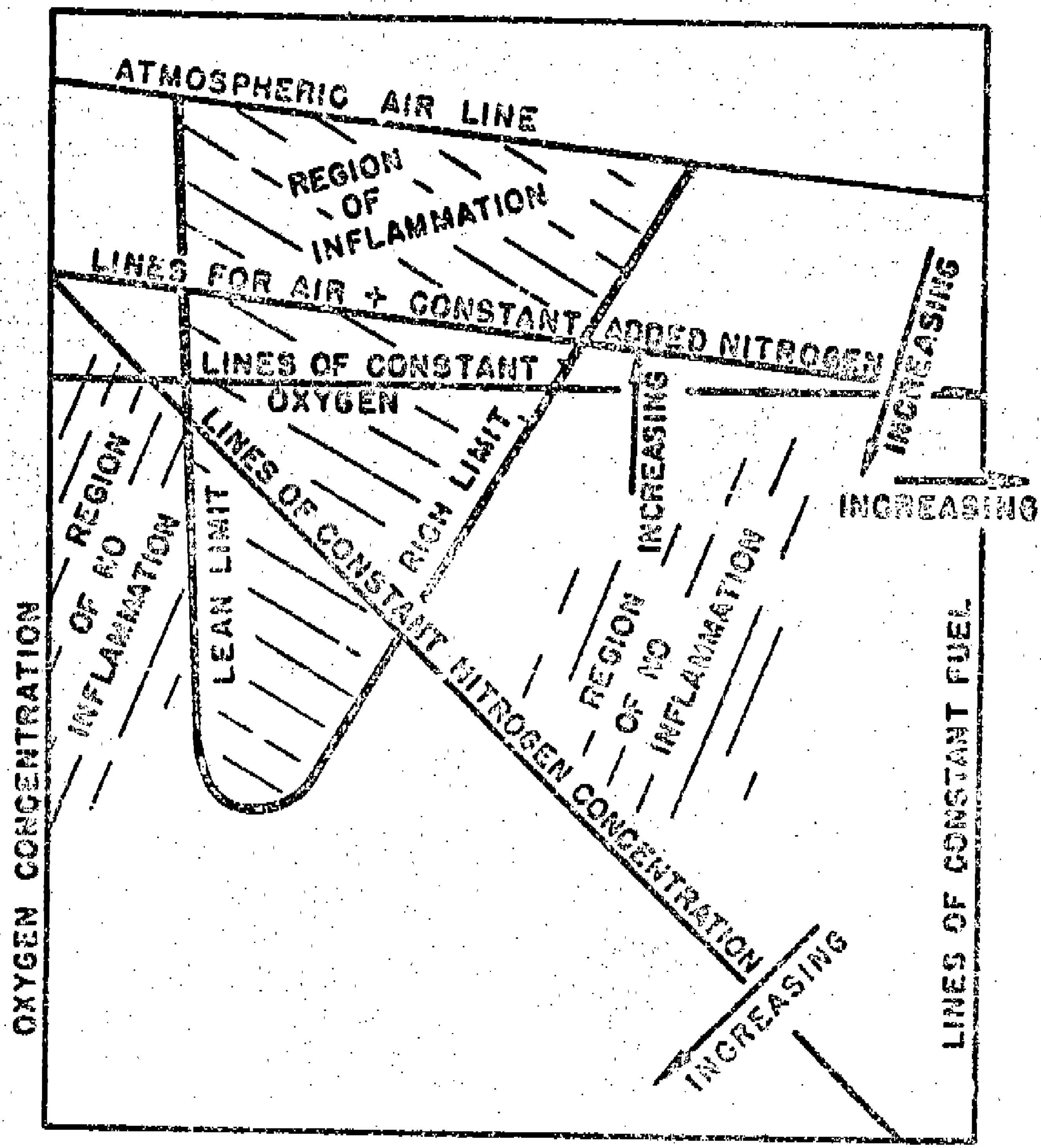


FIG. 3-2

MODEL FLAMMABILITY CURVE
CARBON DIOXIDE INERTING

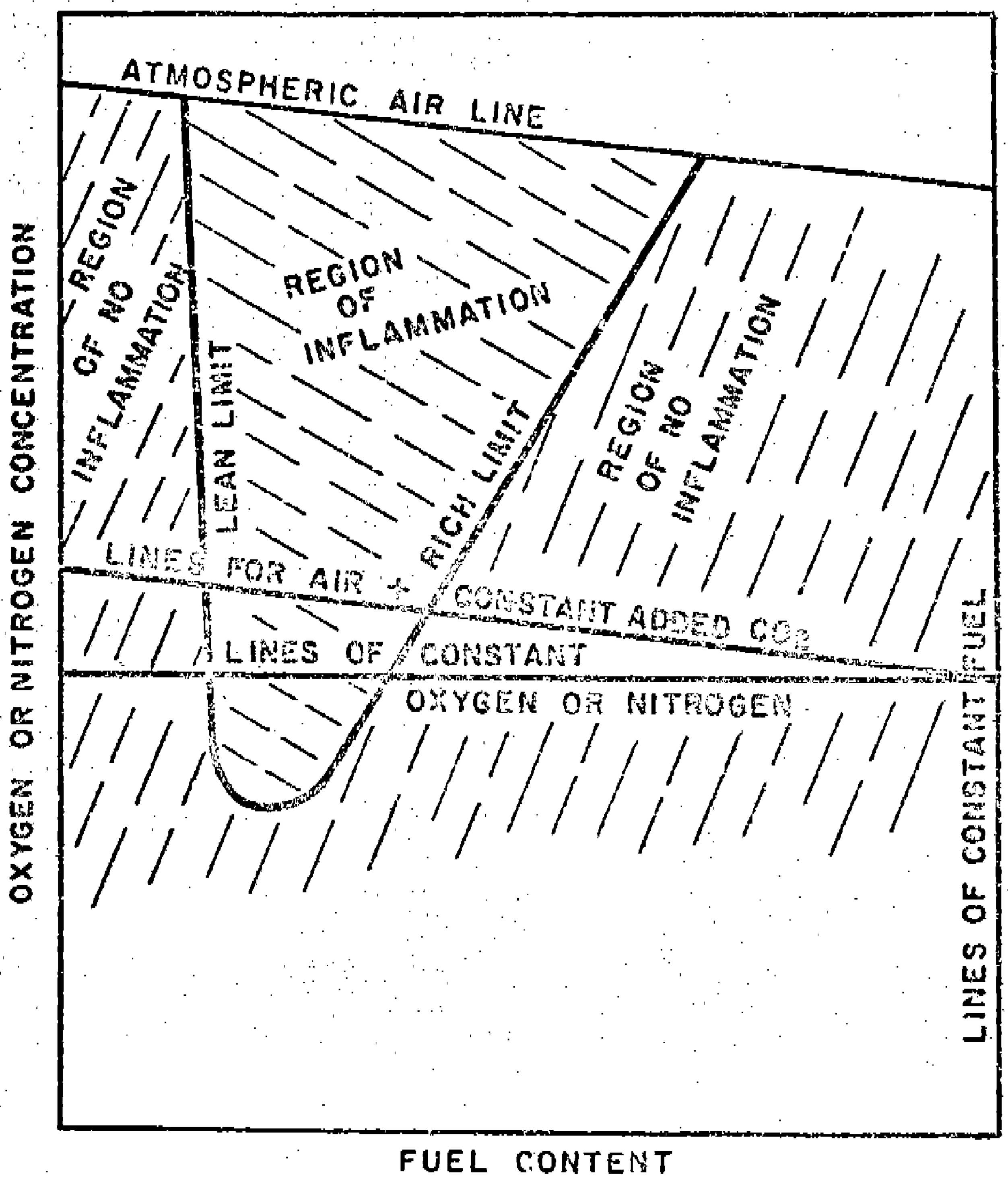


FIG. 3-3

FLAMMABILITY LIMITS
AN-F-58 (JP-4) VAPOR
SEA LEVEL
NITROGEN INERTING

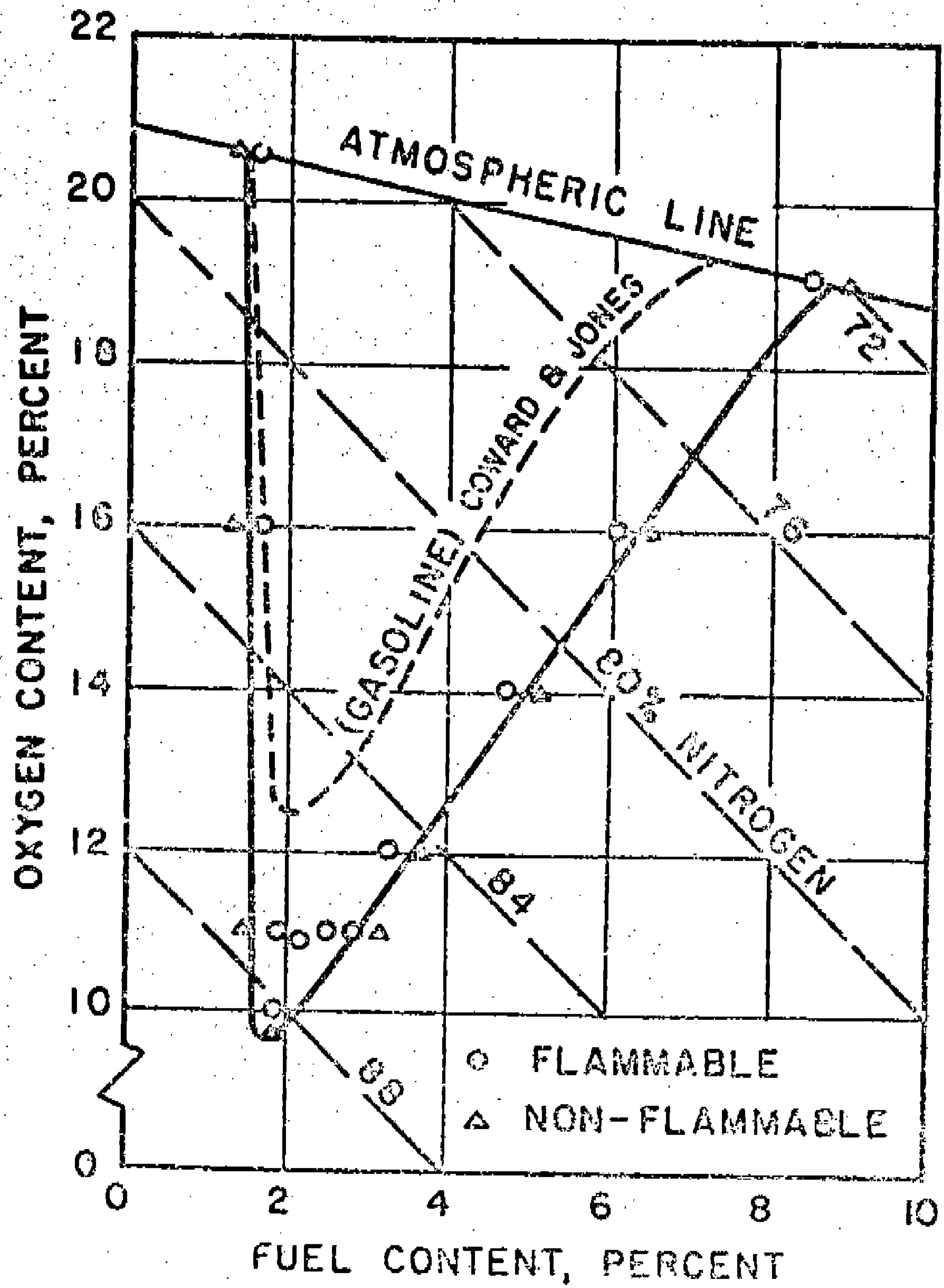


FIG. 3-4

LIMITS OF AN-F-58 (JP-4) VAPOR WITH NITROGEN INERTING AT 10,000 FEET

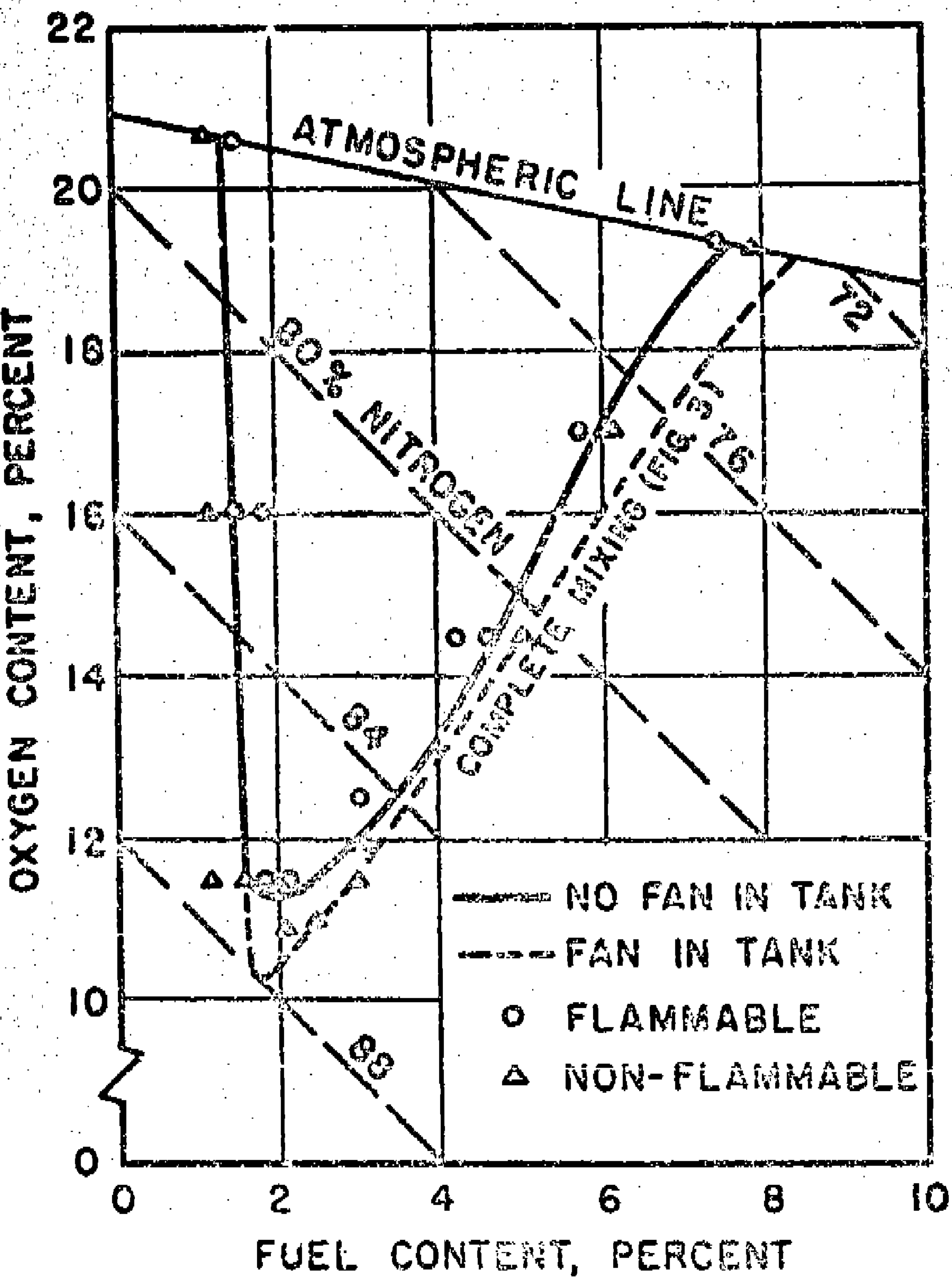


FIG. 3-5

FLAMMABILITY LIMITS FOR AN-F-58 (JP-4) VAPOR WITH NITROGEN INERTING

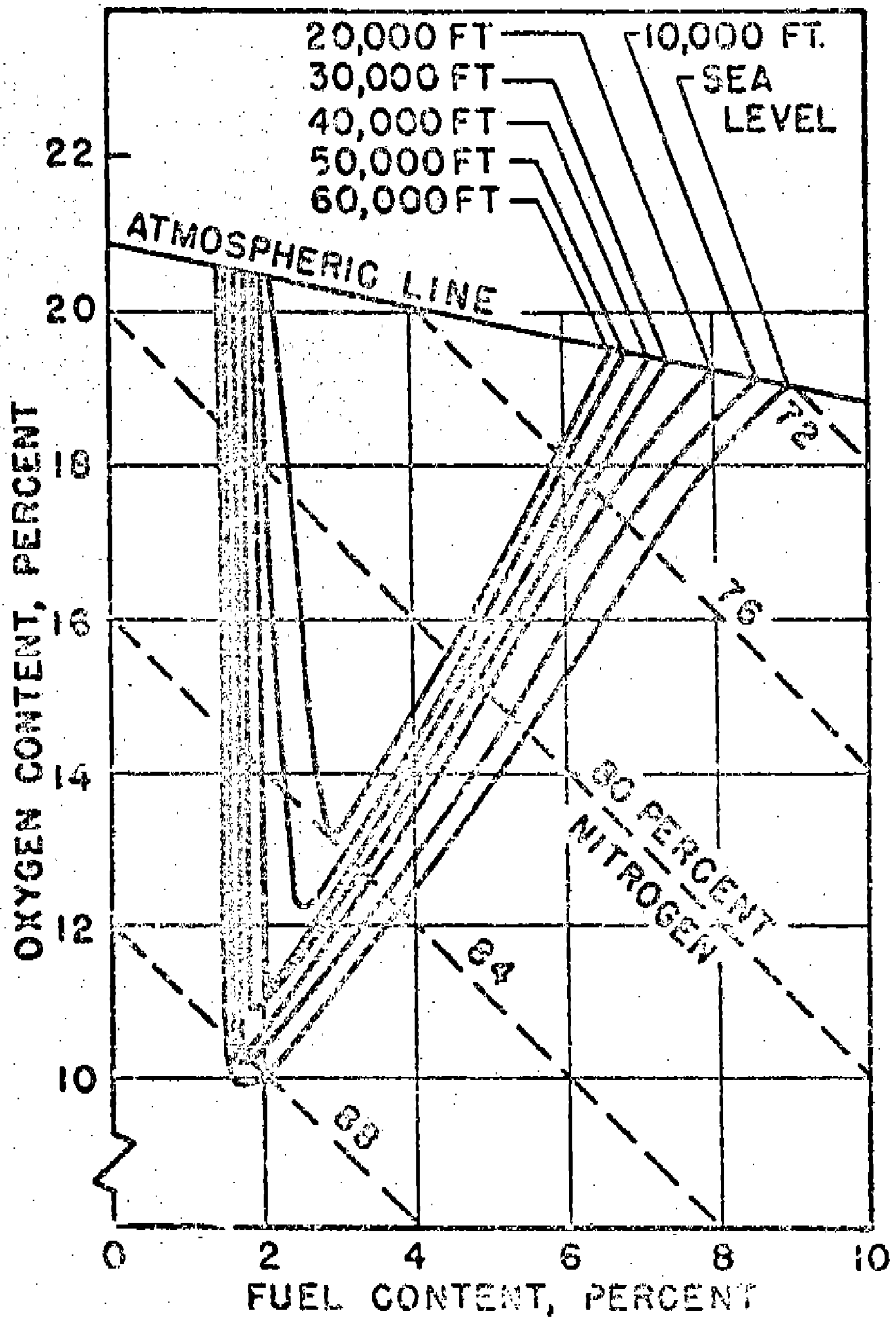


FIG. 3-6

FLAMMABILITY LIMITS FOR AN-F-58 (JP-4) VAPOR WITH CARBON DIOXIDE INERTING

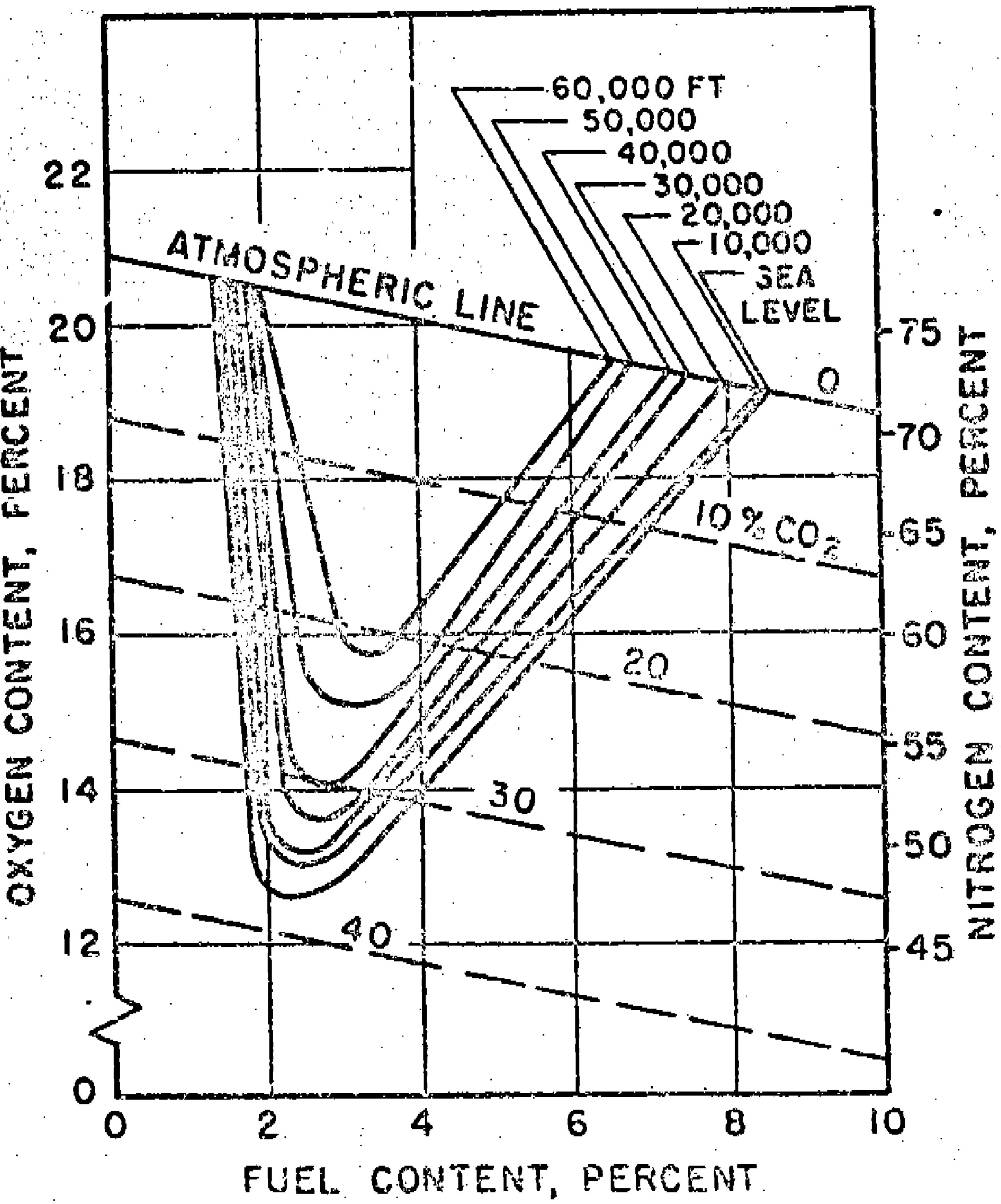


FIG. 3-7

FLAMMABILITY LIMITS
AN-F-58 (JP-4) VAPOR
CO_2-$6N_2$ INERTING GAS, 70°F

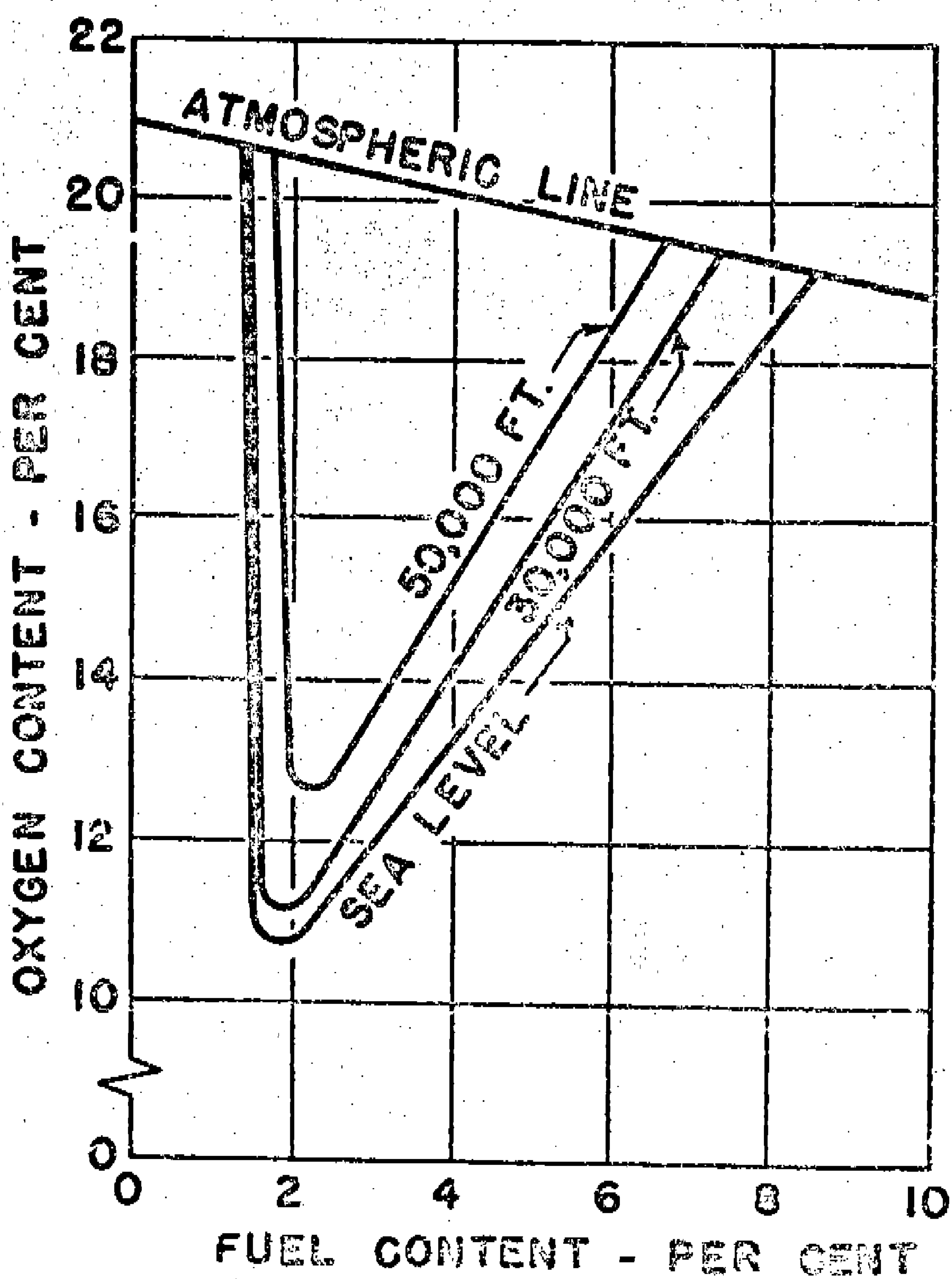


FIG. 3-8

PERMISSIBLE OXYGEN CONCENTRATION FOR CO_2 AND N_2 INERTED FUEL-AIR MIXTURES
AN-F-58 (JP-4) VAPOR

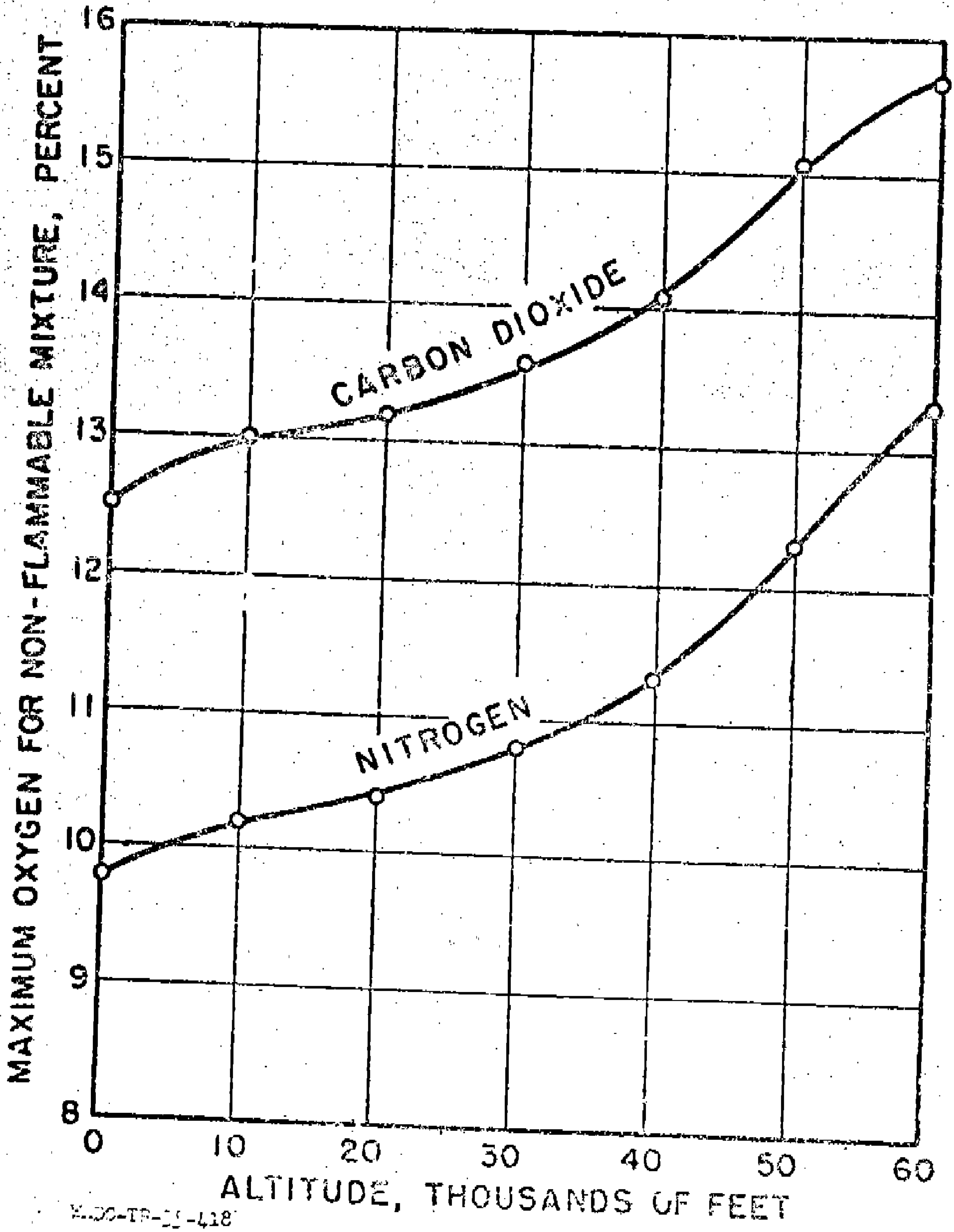


FIG. 3-9

QUANTITIES OF NITROGEN AND CARBON DIOXIDE REQUIRED FOR INERTING AN-F-58(JP-4)VAPOR

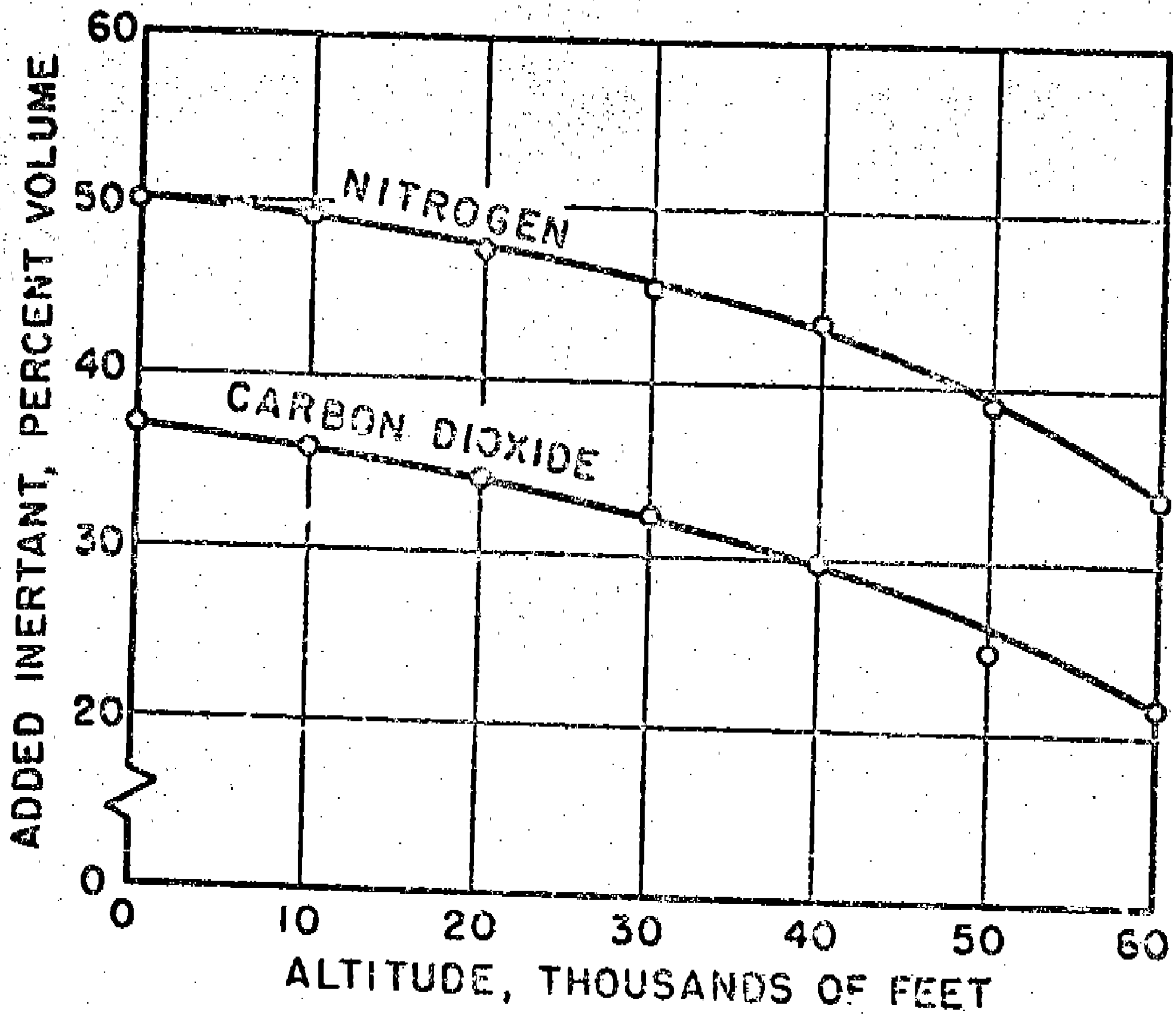


FIG. 3-10

RATIO OF NITROGEN TO CARBON DIOXIDE REQUIRED FOR INERTING AN-F-58 (JP-4) VAPOR

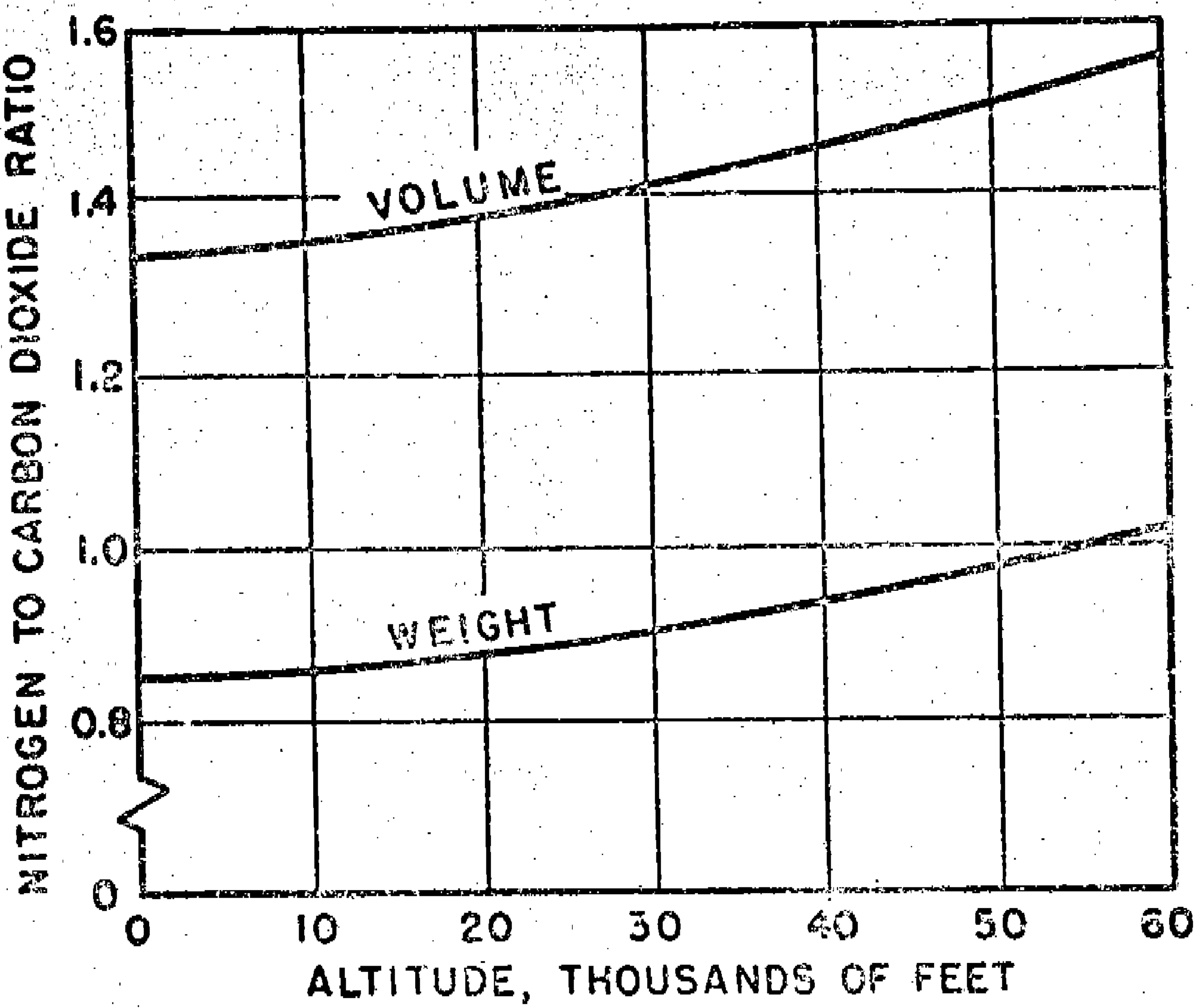


FIG. 3-11

FLAMMABILITY LIMITS AN-F-58 (JP-4) VAPOR 35°F, SEA LEVEL

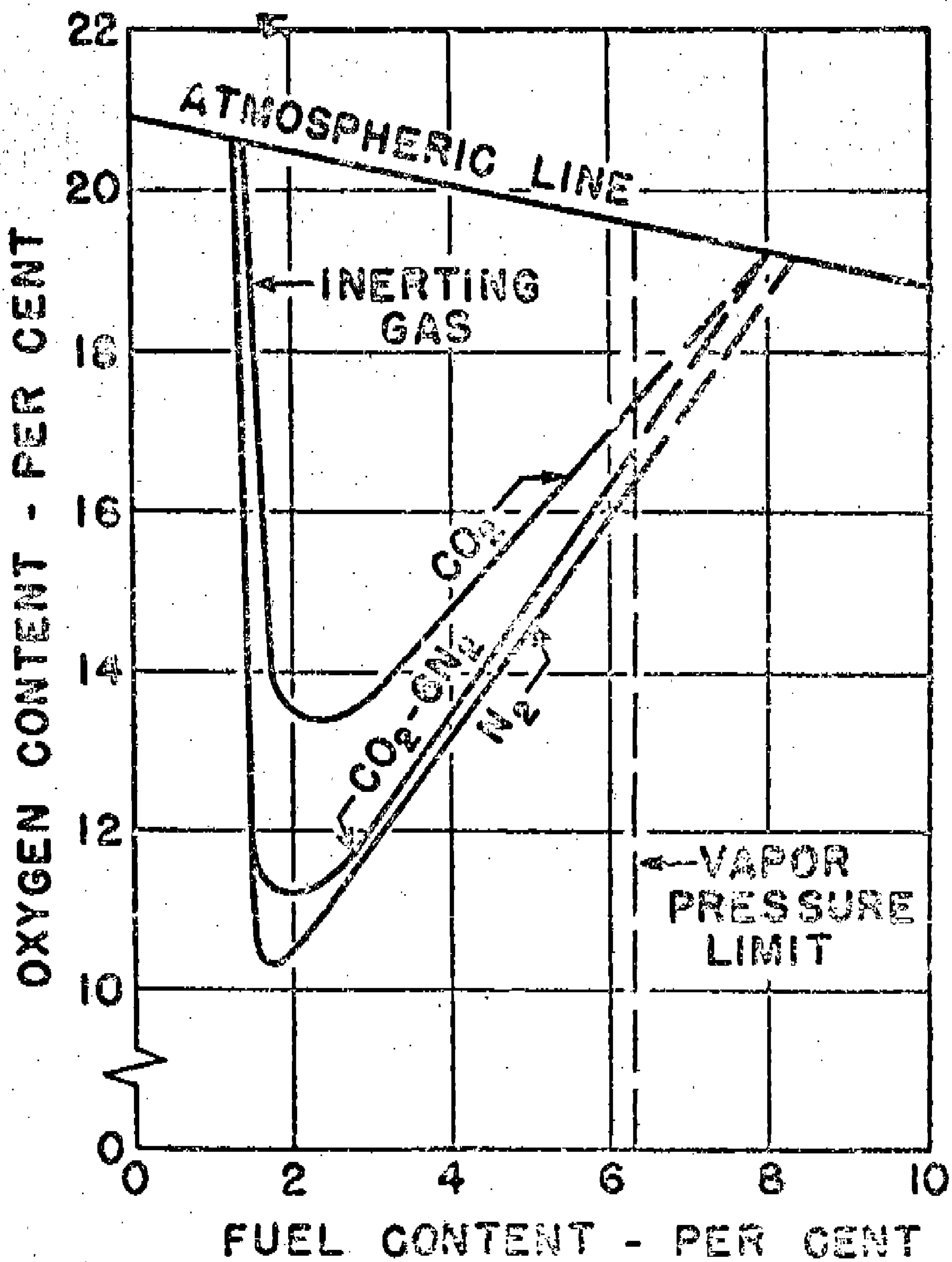


FIG. 3-12

FLAMMABILITY LIMITS AN-F-58 (JP-4) VAPOR 140°F, SEA LEVEL

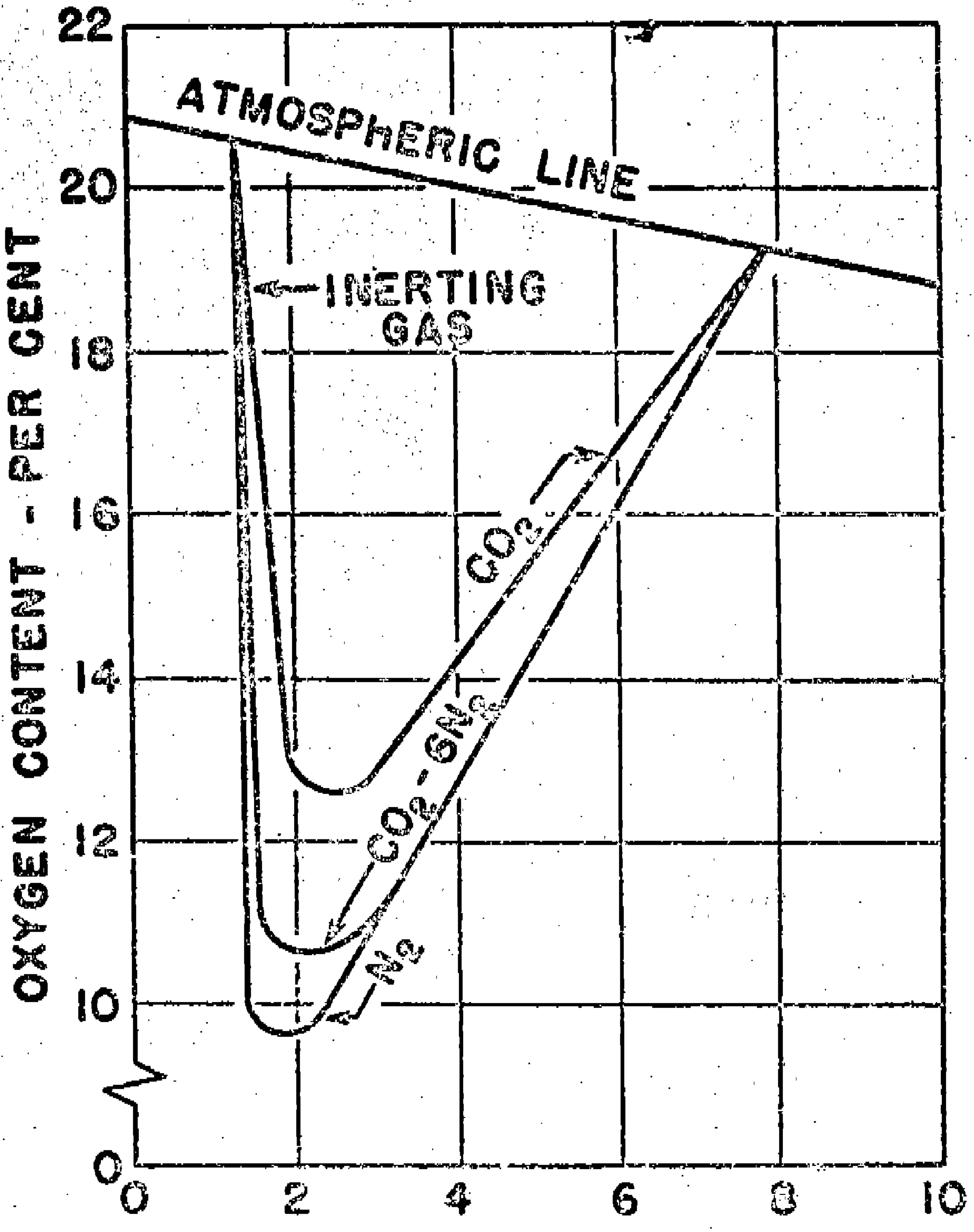


FIG. 3-13

FLAMMABILITY LIMITS AN-F-58 (JP-4) VAPOR N_2 INERTING GAS, SEA LEVEL

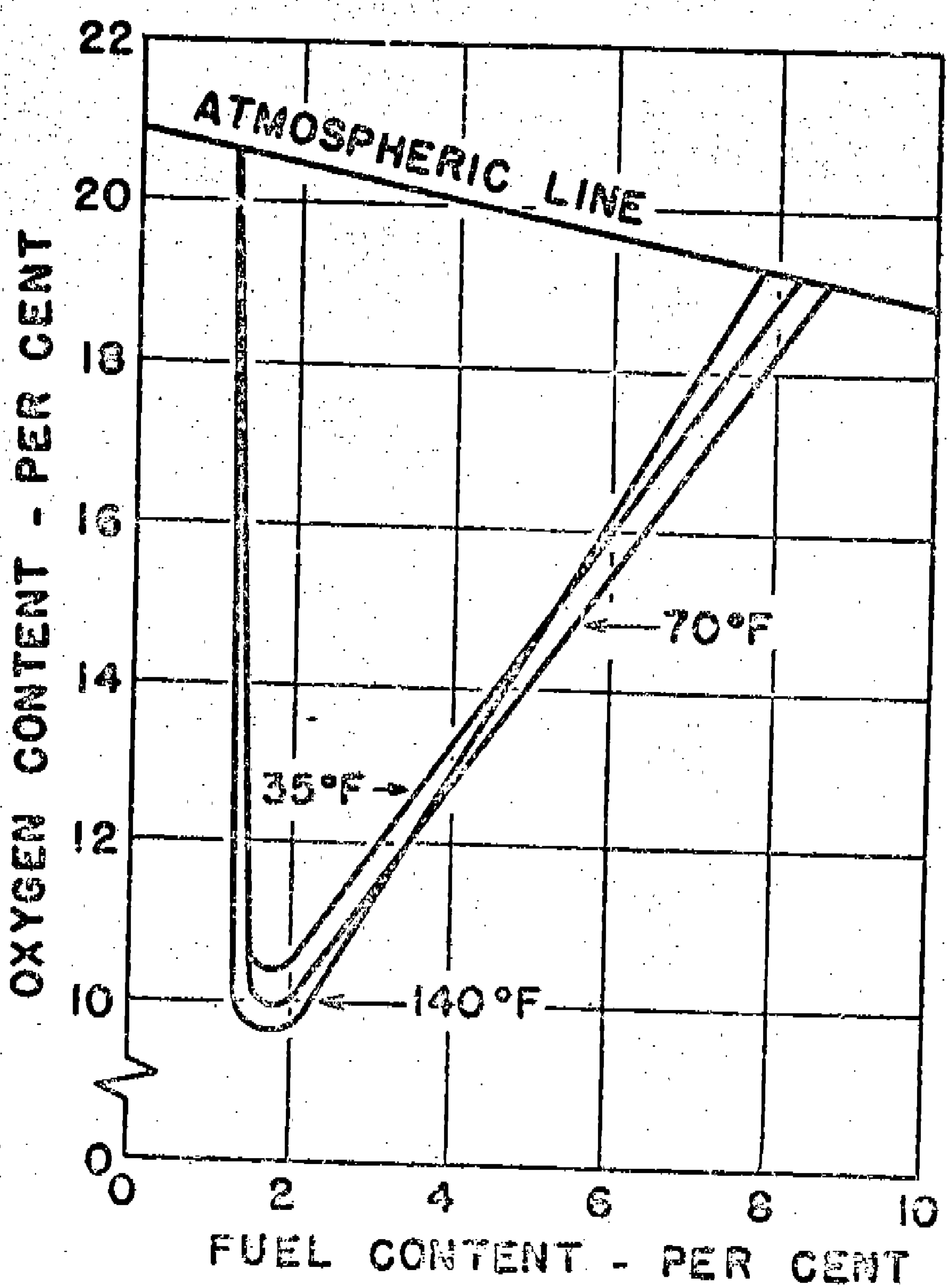
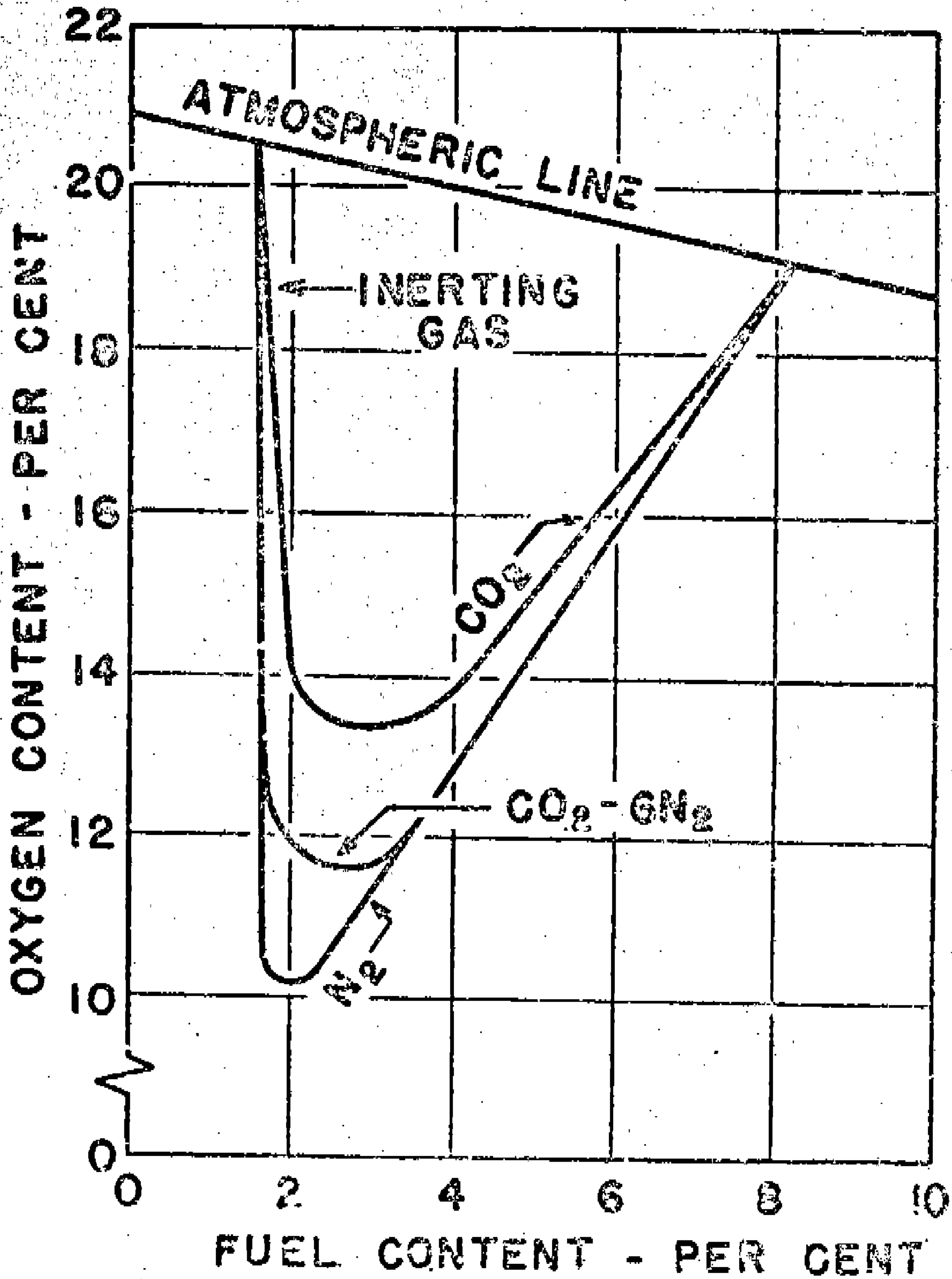


FIG 3-14

FLAMMABILITY LIMITS AN-F-48 VAPOR 35°F, SEA LEVEL



FLAMMABILITY LIMITS AN-F-48 VAPOR 140°F, SEA LEVEL

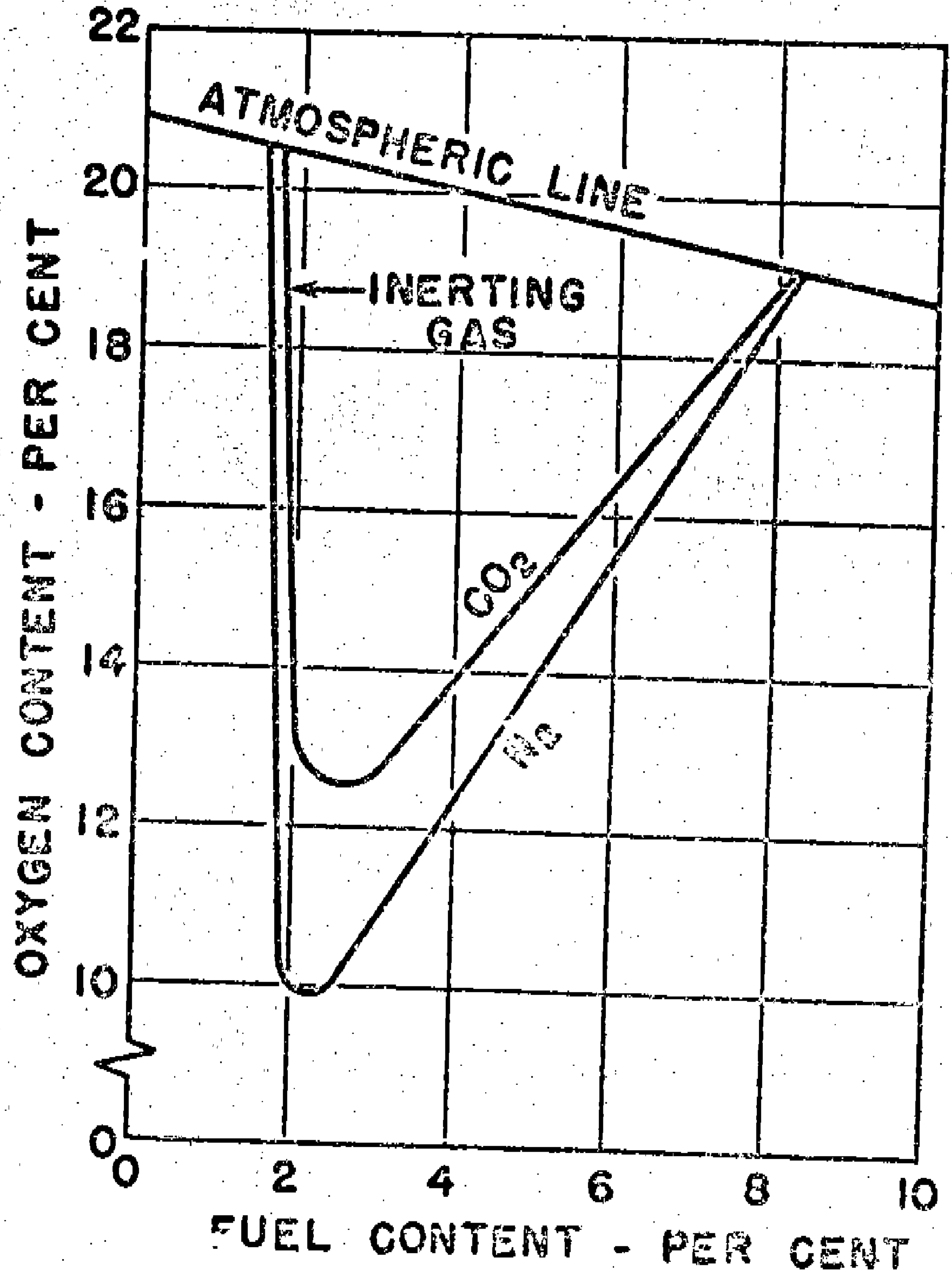


FIG. 3-16

FLAMMABILITY LIMITS
KEROSENE VAPOR
140°F, 50,000 FT.

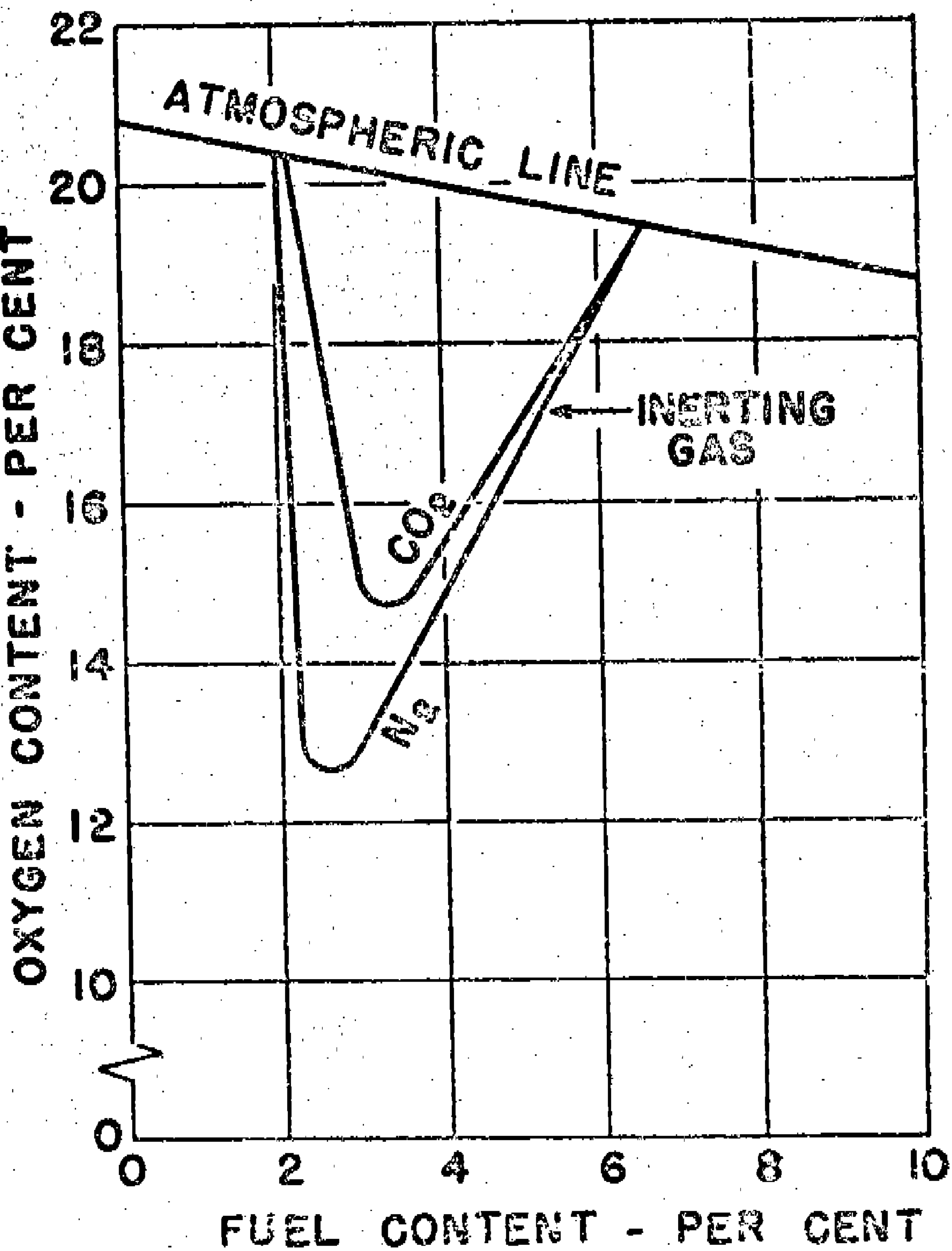


FIG. 3-17

ISO-PENTANE VAPOR
N_2 INERTING GAS
+70° F, SEA LEVEL

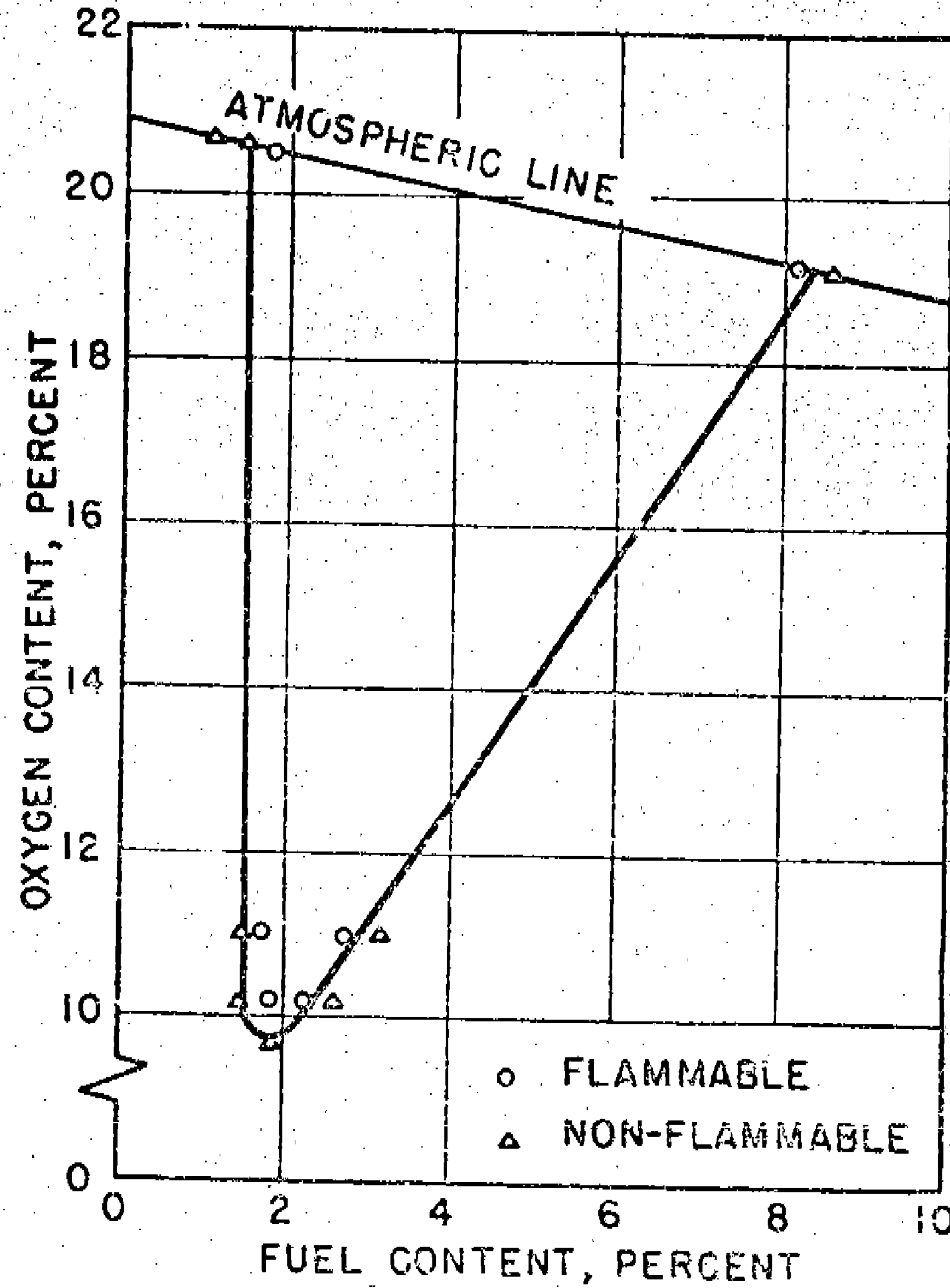


FIG. 3-18

FLAMMABILITY LIMITS
AN-F-58, 67% LIQUID
FILLED, CO_2 INERTED, 35° F

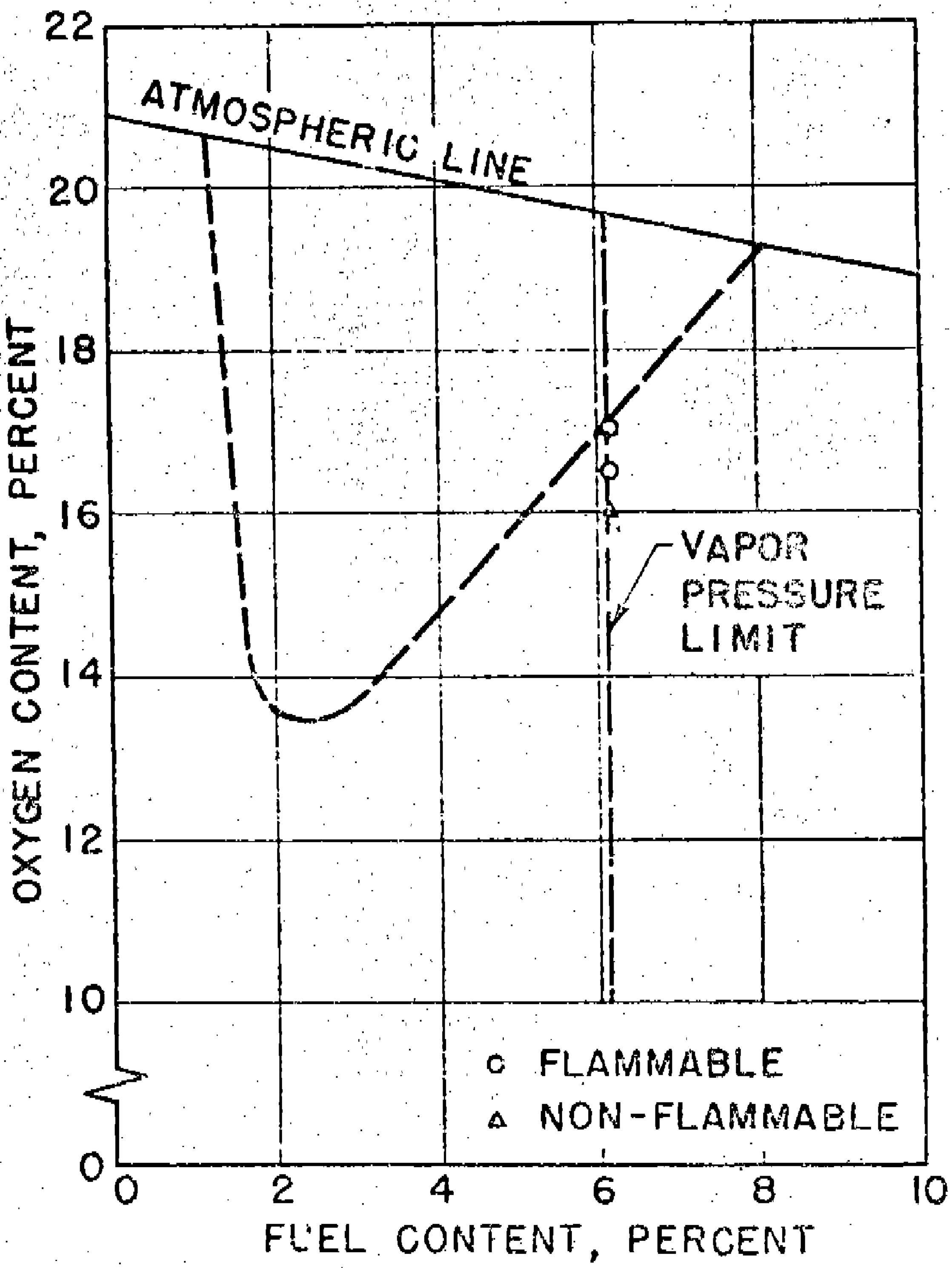


FIG. 3-19

FLAMMABILITY LIMITS
AN-F-58, 87% LIQUID
FILLED, N_2 INERTED, 35° F

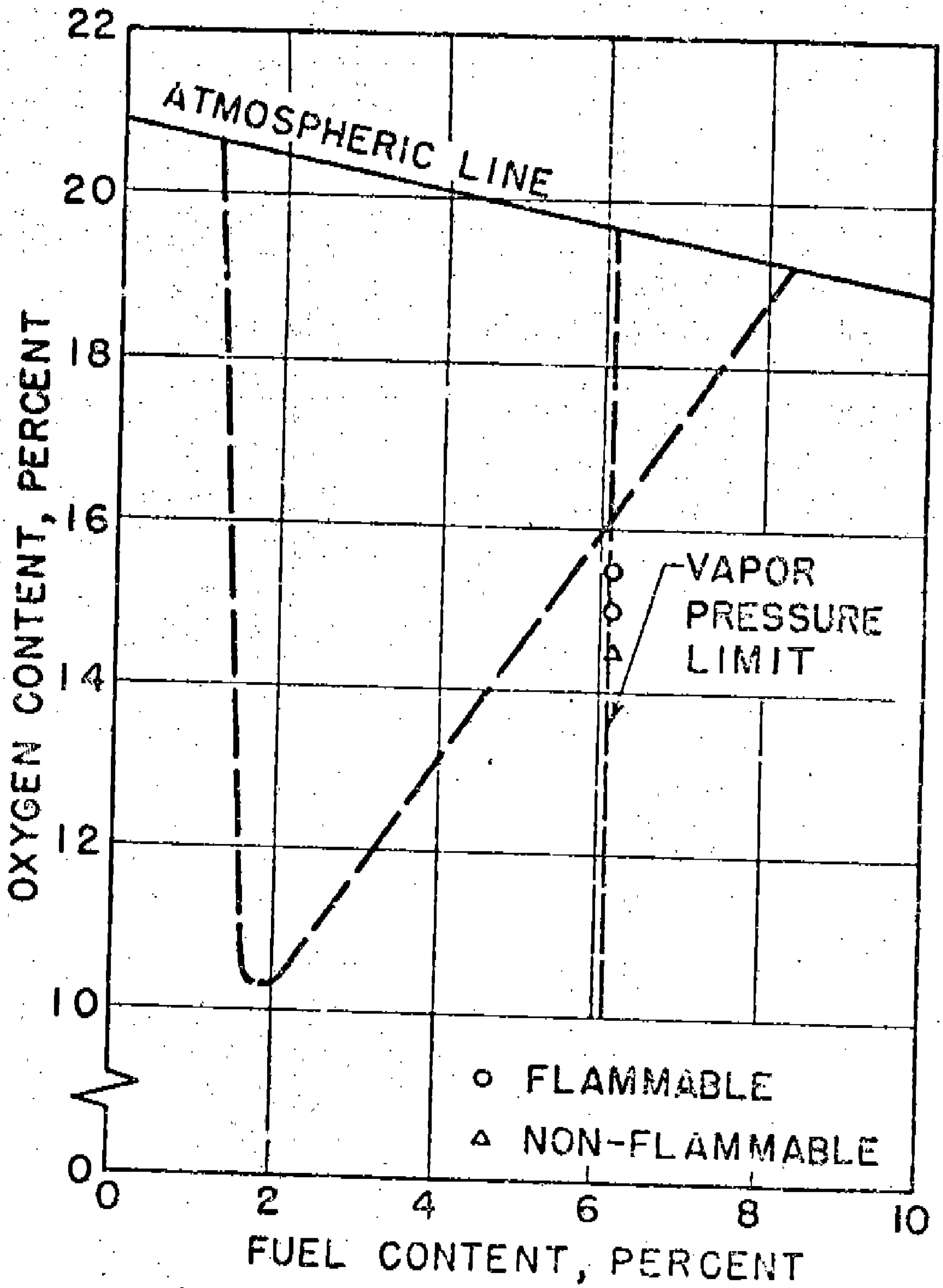


FIG. 3-20

IV. GUNFIRE TESTS

This section of the report describes the experimental equipment, the experimental method, and the results obtained with the test program using service incendiary ammunition as the ignition source.

A. Experimental Equipment. The experimental installation occupied a fenced-in area 35 feet by 135 feet, and was composed of the following units: (1) Target fuel cell, target fuel cell enclosure, and target area enclosure or barricade, (2) Gun installation, (3) Gases and fuel preparation equipment (4) Instrumentation, and (5) Fire fighting equipment. Engineering drawings of the main units and assemblies are in the Appendix of the report.

Target Fuel Cell and Related Equipment. A self-sealing, military specification, fuel cell 2 ft x 2 ft x 2 ft was the target tank in all tests. This fuel cell was enclosed in an aluminum alloy housing simulating an aircraft structure. Fiberglas-plastic anti-chafe boards were used between the fuel cell and the enclosing structure. The entire target assembly was mounted on a stand, on which also was mounted the 1/8 inch aluminum incendiary function plate, 1 foot ahead of the target tank and normal to the path of the projectile.

The top of the fuel cell enclosure was a steel cover plate with a well, fitting down into the opening in the top of the fuel cell. An acrylic plastic (Lucite or Plexiglas) window was installed in this opening to permit photographing the inside of the tank. A motor-driven stirrer, and service lines were installed through the window.

The entire target assembly was enclosed on three sides by a barricade designed to stop bullets and to contain fires. The barricade structure was composed of an inner wall of 6 inches of lumber followed by 3 feet of gravel followed by 6 inches of concrete. The roof was 6 inches of wood. The floor was a concrete pan of sufficient capacity to hold any possible liquid spill.

Gun Installation. The gun installation was housed in a sheet-metal shed on a concrete pad. The gun mount was designed to hold either of the two standard aircraft weapons used, 50 cal or 20 mm. The distance between gun and target was 100 feet. A 24-volt portable direct-current generator, and a bore-sighting kit were the main auxilliaries.

Gases and Fuel Preparation. Oxygen and nitrogen were obtained in standard commercial high-pressure cylinders. These two gases were mixed in the desired ratio in a gas mixing tank by first evacuating the tank, and then admitting them in turn, the total pressure (or partial pressure) being read on a precision gauge. Mixing of the gases in the gas mixing tank was accomplished by setting up convection currents in it by placing a block of solid carbon dioxide on top of the tank. The gas mixing tank was connected by suitable piping, valves, and regulators to both the commercial gas cylinders and the target tank.

Fuel preparation equipment consisted of a hand-operated transfer pump for loading the target tank from the 55-gallon drums in which the fuel was received, and a fuel cooling system. The cooling system was composed of a portable motor-driven pump which circulated the fuel from the target tank through a coil immersed in a steel drum containing propylene dichloride refrigerated with Dry Ice, and back to the target tank. In this manner the temperature of the fuel was adjusted so that it would have the desired vapor pressure and concentration in the gas phase.

Instrumentation. The instrumentation was composed of three units: (1) The photographic units, (2) The program timer, and (3) The bullet velocity assembly.

Two cameras were used. A Fastax high-speed motion picture camera was mounted on the roof of the barricade, and photographed the window in the top of the target tank, and the trailing edge. It was protected by a Pyrex brand glass port in the roof of the barricade. A standard 16 mm motion picture camera was tripod mounted about 25 feet in front of the target tank and well to one side; this unit operated at slow-motion speed, 64 frames per second.

The program timer, a duplicate of that used for the spark ignition tests, started and stopped the Fastax camera and fired the gun. Fire fighting controls were also incorporated in this unit.

The bullet velocity timer, used to make sure the ammunition was standard, consisted of two gates with photocells set 75 feet apart, and a Potter chronograph for measuring the time required for the bullet to pass between the gates.

Fire Fighting Equipment. A carbon dioxide system operated by a solenoid valve remotely controlled, was the main unit. This had dispersal nozzles in both rear corners of the barricade, and in the fuel cell itself. This unit proved adequate for all fires encountered, none of which were allowed to become large.

Other fire fighting equipment was portable carbon dioxide extinguishers, a Foamite unit, and fog nozzles on fire hoses.

B. Experimental Procedure. All of the gunfire tests were conducted under static conditions at sea level ambient pressure. The temperature of the liquid fuel was controlled to give the desired vapor pressure. All tests were made with liquid fuel in the bottom one-fourth of the tank, and a fuel vapor-oxygen-nitrogen mixture in the freeboard space above the liquid.

The projectile entered the vapor space in all cases, and was not intentionally tumbled. An incendiary function plate of 1/8-inch 75S-T aluminum alloy, 1 foot ahead of the tank leading edge and normal to the path of the bullet, was used with 50 cal bullets. The target tank enclosure was used as the function plate for 20 mm ammunition. All tests were single shot with standard service ammunition, 50 cal API-M8 or 20 mm HEI-M97.

The first step in a gunfire test was to assemble the target tank in its enclosure. After completely filling it with liquid fuel the cover holding the window was put on. Then the fuel was cooled, if necessary, to a temperature below that at which it would have the desired vapor pressure. At this point three-fourths of the liquid was syphoned out, and gas from the oxygen-nitrogen mixture in the gas mixing tank allowed to flow in as the liquid left. To mix the gas phase the fan was run for at least 30 minutes.

During this final mixing all instrumentation was checked, and other tasks performed. The gun was fired, data taken, and the fire put out if necessary.

Assessment of the results of any test had to await development of the Fastax film. Results, on a "fire" or "no fire" basis were determined by the time of illumination within the target tank. This time was evaluated by counting frames on the movie film, and the timing trace on the film edge. Times measured in thousandths of a second were considered to be due to incendiary flash, and not to combustion. Longer times, usually hundredths, tenths, or even seconds were considered to be "go" experiments.

The composition of the gas-vapor mixture in the fuel cell was computed from the known oxygen-nitrogen ratio, and the fuel temperature and vapor pressure. In some of the early tests the fuel temperature was estimated from weather records; these data are designated "approximate" and should be in error by less than 20 per cent

C. Results and Discussion. The results of the gunfire tests are given in Figures 4-1, 4-2, 4-3 and 4-4, and Tables 4-1, 4-2, 4-3 and 4-4.

Shot No. 56 (50 cal, AN-F-58) is quite typical of many of the experiments, and illustrates the necessity for use of the Fastax camera to portray what happened in the fuel cell. On this shot there was a fairly violent fire, and the CO_2 system had to be used to extinguish it. Examination of the Fastax film showed no fire in the tank; all of the fire was in the bay space and outside of it. Apparently the bullet, on leaving the tank, drags with it sufficient fuel vapor from the tank. Thus, inerting the tank is not enough; the bay space should be inerted, too.

All of the gunfire test data, with fuels AN-F-58 and AN-F-32 substitute (commercial kerosene), and with both 50 cal and 20 mm ammunition indicate that the combustion or ignition limits are considerably wider than those determined for the gas phase only with electric sparks as ignition sources. The spark data are shown as curves on all the four graphs in this section.

Due to the low vapor pressure of the kerosene all of the data taken with it fall outside the fuel lean limit determined with sparks for the gas phase.

With the 20 mm ammunition, shots 41, 42, and 43 are worthy of mention. These are all in the middle of the combustible zone, and yet no fires occurred. This is probably an example of flame suppression by the explosive charge in the projectile.

Figure 4-4 summarizes the gunfire tests with compositions outside the inflammation area determined with electric sparks for the gas phase only. The "fire" and "no fire" points determined by spark ignition with liquid fuel present in the tank are also shown on this graph.

The cross-hatched area on this graph is the enlargement of the danger zone indicated by the gunfire tests as compared to that determined by spark ignition for the gas phase. Since the gunfire tests and the spark tests with liquid fuel present correlate, this enlargment of the danger zone is attributed to the presence of the liquid fuel, rather than to the ignition source. An explanation, as noted in the proceeding section of this report, is the possible presence of a fog of liquid droplets.

For these sea level experiments it is noticed that both the fuel lean limit and the fuel rich limit are extended outward. The extension of both limits becomes greater at higher oxygen concentrations. The oxygen lean limit is apparently affected but little, if at all.

In many tests it was observed that the Fiberglas-plastic anti-chafe boards were potential (or actual) ignition sources. Even after the complete extinguishing of a fire in the bay space, the plastic, and possibly some incendiary, continued to smoulder and glow brightly. In at least one case this reignited a bay space fire after it was apparently out.

D. Conclusions. The conclusions from the gunfire test program are:

1. The presence of liquid fuel in an aircraft fuel tank at sea level markedly extends the zone in which inflammation can take place, as compared to the case in which only a gas phase is present.
2. If the fuel vapor concentration is greater than 11 percent the tank is inerted, or non-flammable.
3. If the oxygen concentration is less than 9 percent the tank is inerted, or non-flammable.
4. Even though the fuel tank is completely inerted, bay spaces surrounding the tank are hazardous when not inerted.
5. Explosive ammunition may, in some cases, extinguish a fire it starts.

GUN FIRE TESTS
FUEL : AN-F-58 (JP-4)
AMMUNITION : 50 CAL. API

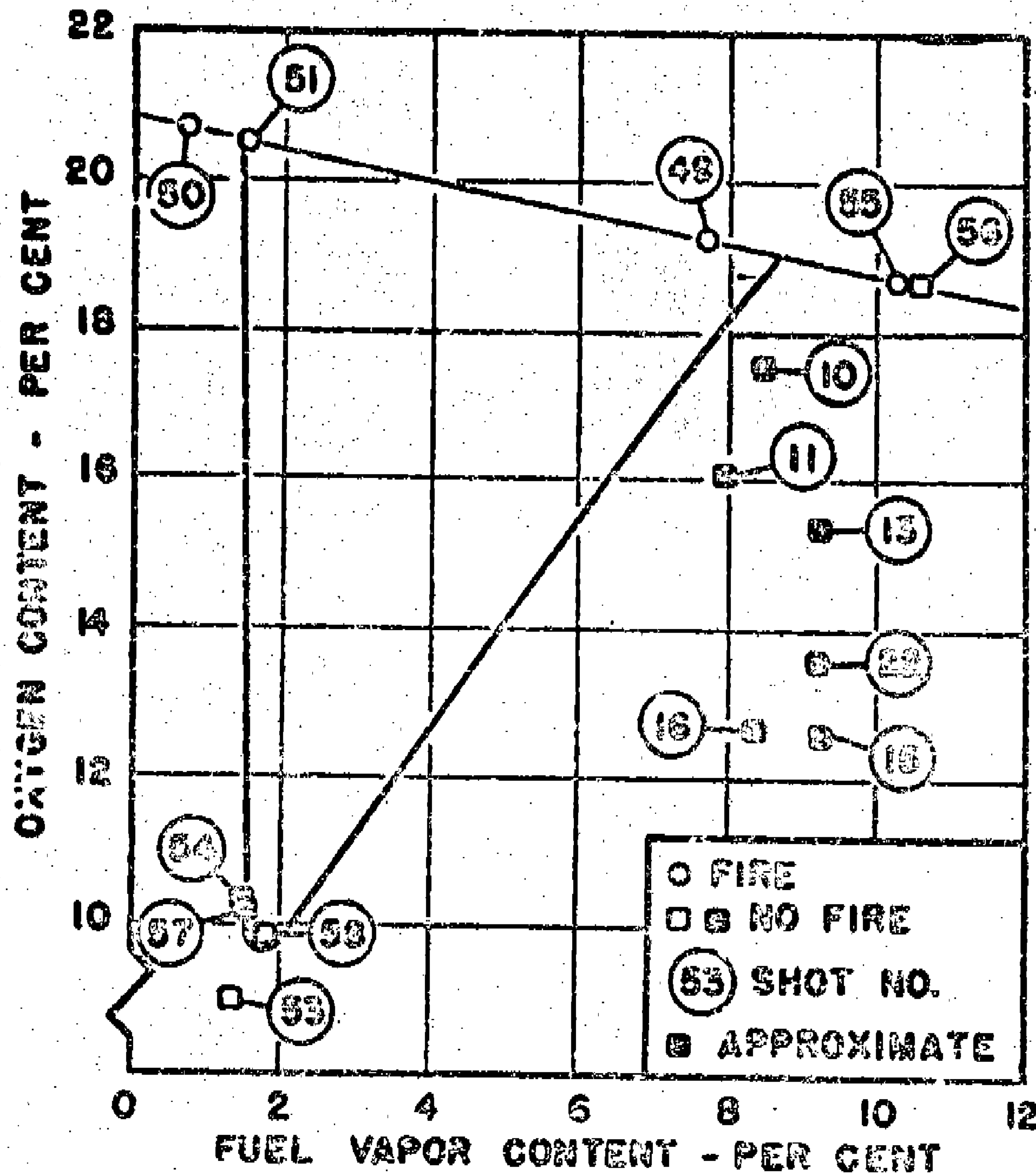


FIG. 4-1

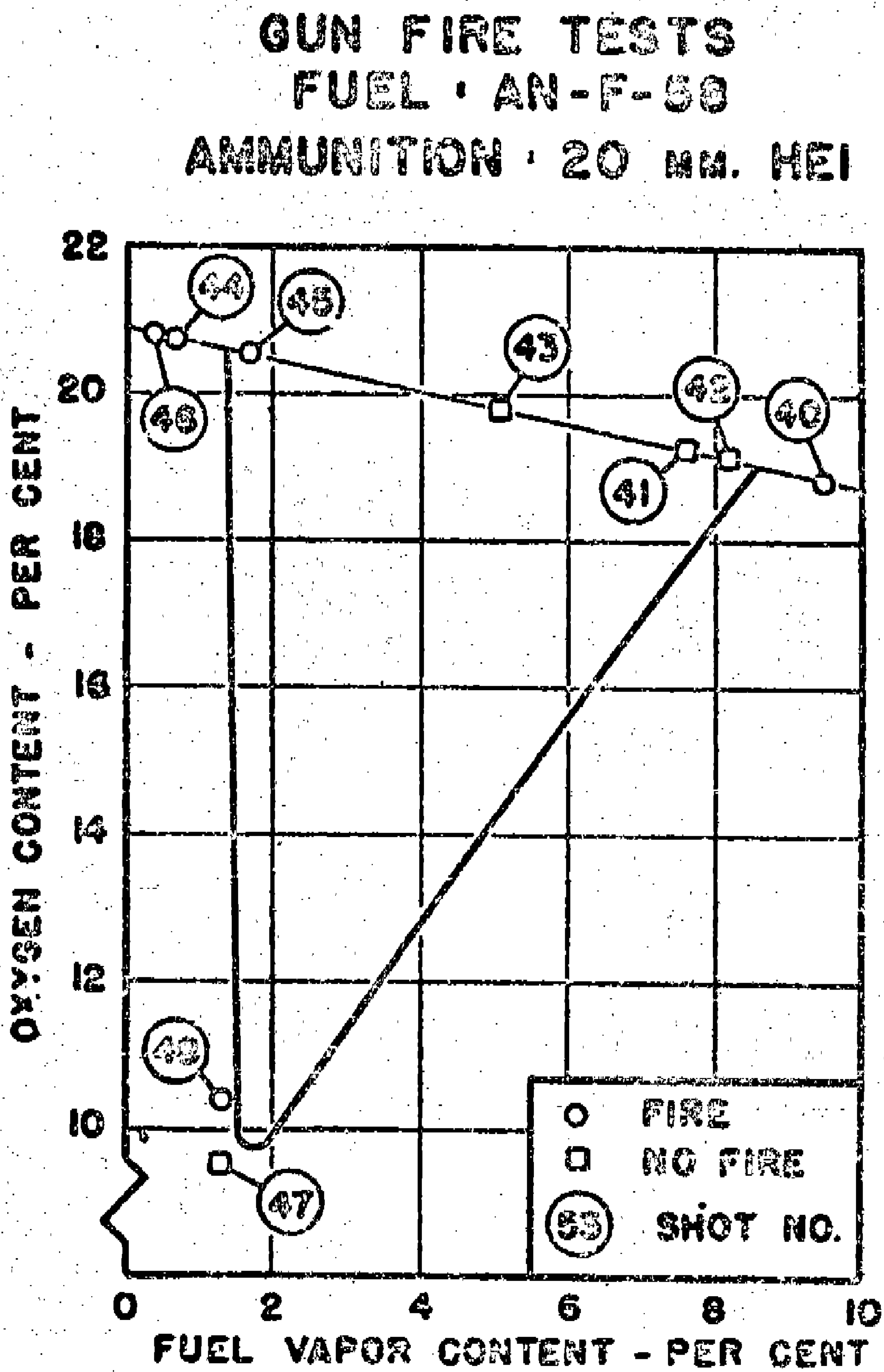

GUN FIRE TESTS
FUEL · AN-F-58
AMMUNITION · 20 MM. HEI
OXYGEN CONTENT - PER CENT
FUEL VAPOR CONTENT - PER CENT
22
20
18
16
14
12
10
0
2
4
6
8
10
44
45
43
42
40
46
41
48
47
FIRE
NO FIRE
55
SHOT NO.

FIG. 4-2

GUN FIRE TESTS
FUEL : AN-F-32 (SUBSTITUTE)
AMMUNITION : 50 CAL. API

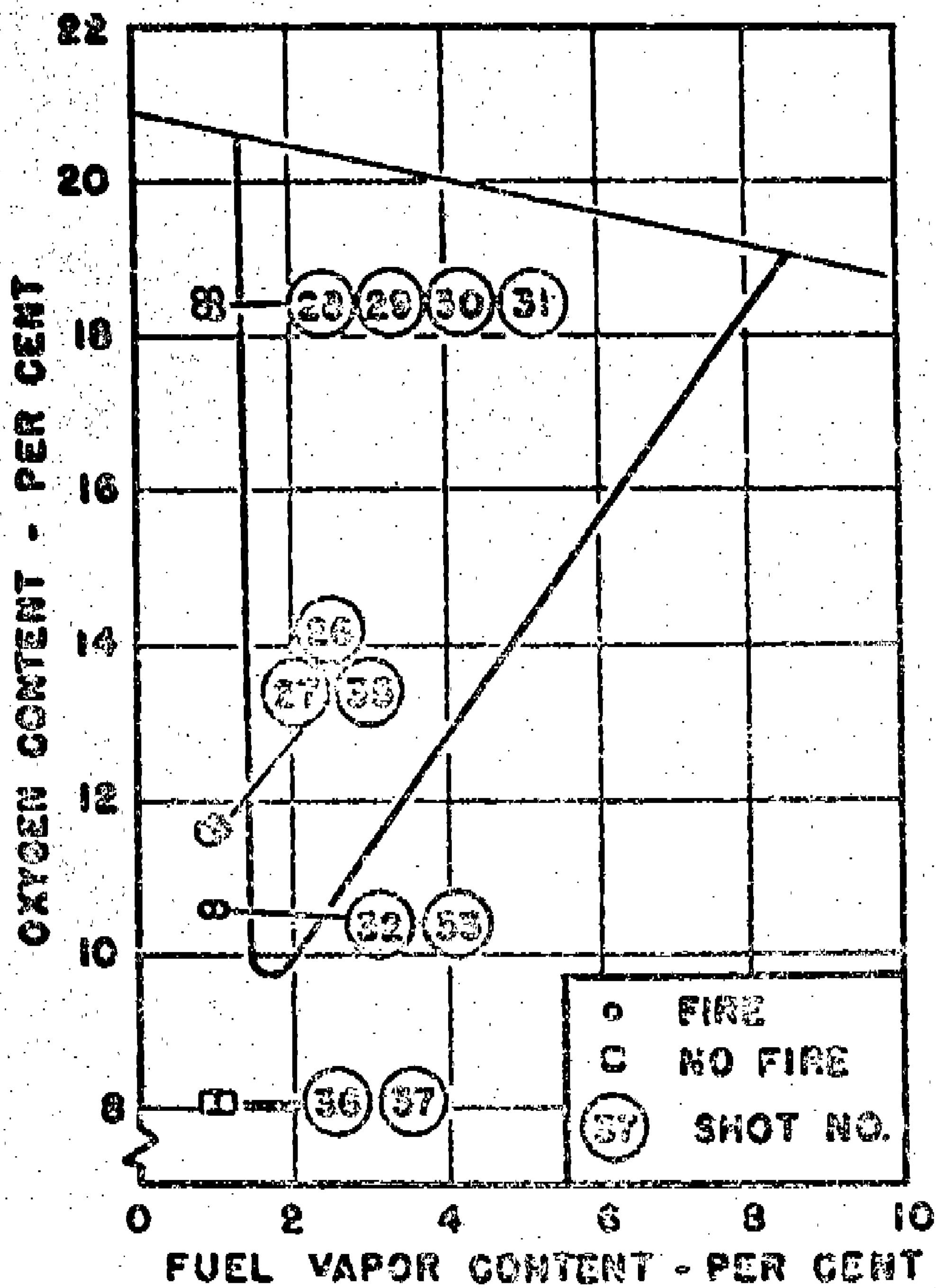


FIG. 4-3

GUN FIRE TESTS SUMMARY

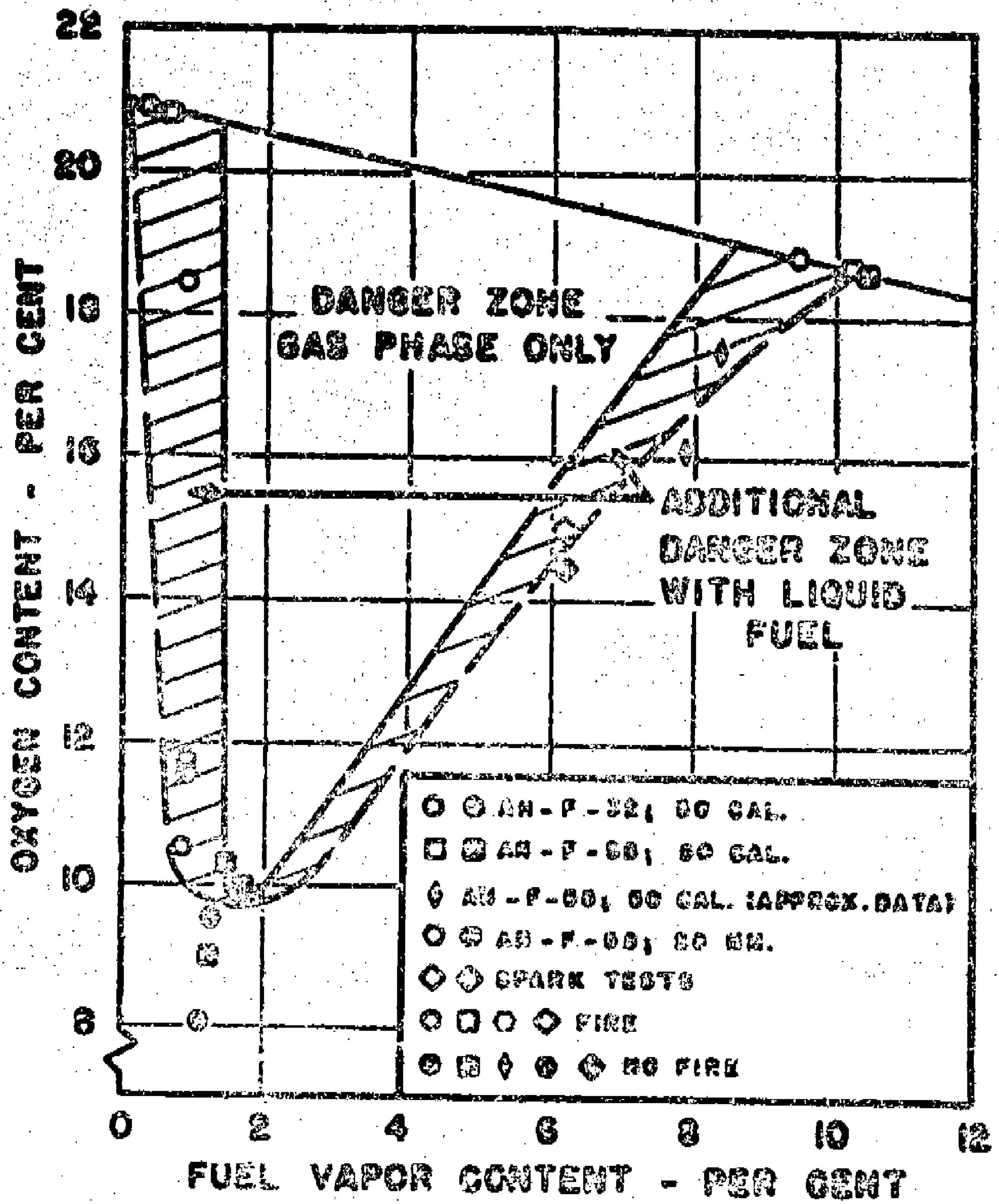


FIG. 4-4

TABLE 4-1

GUNFIRE TESTS

FUEL: AN-F-58 (JP-4 GRADE)

AMMUNITION: 50 Cal.; API-M8

Shot	Gas Mix. Tank % O_2	% N_2	Fuel Temp. °F	Fuel V.P. mm	Fuel Cell Comp. % Fuel	% O_2	% N_2	Flame Time Inside Sec	Outside Sec	Go	No Go	Comments
49	21	79	+43	58	7.65	19.4	73.0	0.6*	0.04*	X		Sound of escaping gas, much smoke.
50	21	79	-61	5.8	0.76	20.8	78.4	0.45	0.017	X		Sound of escaping gas. Black smoke. Incend. functioned after entrance.
51	21	79	-26	11	1.45	20.7	77.8	0.6*	0.04*	X		Sound of escaping gas smoke. Tumbled bullet.
53	9.1	90.9	-32	9.5	1.25	9.0	89.8	--	--		X	No visible phenomena except for incendiary flash.
54	10.4	89.6	-26	11	1.45	10.3	88.2	0.025	0.008		X	Incend. functioned inside tank.
55	21	79	+58	78	10.3	18.8	70.8	0.483	0.075	X		Same as Shot No. 50.
56	21	79	+60	80	10.5	18.8	70.7	0.033	1.63-		X	--
57	10.4	89.6	-23	11	1.45	10.25	88.3	0.015	0.002		X	Incend. functioned inside tank.
58	10	90	-22	12	1.6	9.85	88.5	--	--		X	--

* = Approximate

TABLE 4-2

GUNFIRE TESTS

FUEL: AN-F-58

AMMUNITION: 50 Cal.; API-M8

Shot	Gas Mix. % O_2	Tank % N_2	Temp. °F Max.	Temp. °F Min.	Vap. Press - mm Max.	Vap. Press - mm Min.	Vap. Press - mm Avg.	Fuel Cell Comp. % Fuel	Fuel Cell Comp. % O_2	Fuel Cell Comp. % N_2	Flame Time Inside Sec	Flame Time Outside Sec	Go	No Go
10	19.1	80.9	60	37	60	48	64	0.4	17.5	74.0	0.036	0.003		X
11	17.5	82.5	55	35	72	47	60	7.9	16.1	76.0	0.006	0.006		X
12	17.5	82.5	55	35	72	47	60	7.9	16.1	76.0	0.021	0.002		X
13	16.9	83.1	65	40	88	52	70	9.2	15.4	75.3	0.010	0.032		X
14	16.9	83.1	65	40	88	52	70	9.2	15.4	75.3	0.016	0.002		X
15	13.8	86.2	60	39	80	52	66	6.7	12.6	78.7	0.023	1.20		X
16	13.8	86.2	61	34	80	46	63	8.3	12.7	79.0	0.017	1.05		X
17	0	100	61	34	80	46	63	8.3	0	91.7	0.005	0.56		X
18	0	100	50	32	65	43	54	7.1	0	92.9	0.006	0.067		X
19	0	100	50	32	65	43	54	7.1	0	92.9	0.006	0.014		X
21 - OUT											--	--	--	--
22	15	85	59	49	70	63	70	9.2	13.6	77.2	0.026	0.016		X
23	15	85	59	49	78	63	70	9.2	13.6	77.2	0.011	1.125		X
24	15	85	57	48	75	62	69	9.1	13.6	77.2	0.025	1.667		X
25	15	85	57	48	75	62	69	9.1	13.6	77.2	0.017	1.425		X

TABLE 4-3

GUNFIRE TESTS

FUEL: AN-F-38 (SUBSTITUTE)

AMMUNITION: 50 Cal.; API-M8

Shot	Gas Mix. % O_2	Tank % N_2	Fuel Temp. °F	Fuel V.P. mm	Fuel Cell Comp. % Fuel	% O_2	% N_2	Flame Time Inside Sec	Outside Sec	Go	No Go	Comments
26	11.7	88.3	54	7.3	0.96	11.6	87.4	0.025	0.081		X	Orange flash only visible phenomenon.
27	11.7	88.3	61	8	1.05	11.6	87.4	0.149	0	X		Same as No. 26.
28	10.7	81.3	52	7	0.92	18.5	80.5	0.165	0.165	X		Same as No. 26.
29	10.7	81.3	62	8	1.05	18.5	80.5	0.778	0.003	X		Orange flame out back of tank.
30	18.6	61.4	49	7	0.92	18.4	80.6	0.159	0.033	X		Much smoke. Flames.
31	18.6	81.4	60	8	1.05	18.4	80.6	0.550	0.043	X		Flames. Smoke. Gas emerges under pressure as in No. 25, No. 30.
32	10.7	89.3	51	7	0.92	10.6	88.3	0.125	0.006	X		No external phenomenon.
33	10.7	89.3	61	8	1.05	10.6	88.3	0.108	0.001	X		No external phenomenon.
35	11.8	88.2	56	7.7	1.91	11.7	87.3	0.800	0.066	X		Orange flames.
36	8.2	91.8	51	7	0.92	8.1	90.8	0.005	0.438		X	No visible phenomenon.
37	8.2	91.8	58	7.7	1.01	8.1	90.8	0.033	0.018		X	No visible phenomenon.

TABLE 4-4

GUNFIRE TESTS

FUEL: AN-F-58 (JP-4 GRADE)

AMMUNITION: 20 mm HEI-M97

Shot	Gas Mix, % O_2	Tank % N_2	Fuel Temp. °F	Fuel V. P. mm	Fuel Cell Comp. % Fuel	Fuel Cell Comp. % O_2	Fuel Cell Comp. % N_2	Flame Time Inside Sec	Flame Time Outside Se.	Go	No Go	Comments
39	0	100	55	72	9.5	0	90.5	0.007*	0.1*		X	3" hole in tank front. Flames shot out abt. 4'. Fire in bay space.
40	21	79	55	72	9.5	19.0	71.5	0.04*	--	X		Liquid fuel expelled from 3" front hole. External fire.
41	21	79	42	55	7.2	19.5	73.3	0.009	--		X	Flames shot out 6' from front panel. Otherwise same as No. 39, No. 40.
42	21	79	48	63	8.3	19.2	72.5	0.014	0.012		X	Same as before. More explosive damage to installation.
43	21	79	27	39	5.1	19.9	75.0	0.025*	0.007*		X	Initial flash followed by large flame out of front.
44	21	79	-55	5.5	0.72	20.8	78.4	0.03*	0.004*	X		Flames abt. 25' from front of tank.
45	21	79	-77	3	0.4	20.9	78.6	0.05*	0.006*	X		Same as No. 44.
45	21	79	-20	13	1.7	20.7	77.7	--	--	X		Same as No. 44.
47	9.6	90.4	-31	10	1.3	9.5	89.2	0.03*	0.004*		X	No flames out front of tank.
48	10.5	89.5	-30	10	1.3	10.4	88.3	0.03*	0.008*	X		Weak flame from front of tank.

* Approximat

V. SUPPORTING INVESTIGATIONS

Three minor experimental programs fall in this category. The first of these was concerned with determining the bursting pressures of rupture disks made of aluminum foil, so that these inexpensive devices could be used in the spark ignition work instead of more expensive, commercial units. The second program was the development of an apparatus for measuring the vapor pressure of hydrocarbon mixtures over a wide temperature range, and then determining the vapor pressures of the fuels used in all of the experimental work, needed for computing the gas phase composition in the gunfire test program. Lastly, the relationship was determined between the electric energy supplied and that released at the surface of the surface conductive spark plugs which were used in the investigation.

A. Design Correlations for Aluminum Foil Rupture Discs. The safe relieving of excessive pressures caused by combustion in the steel test tank used for the spark ignition tests was one of the problems encountered in its design. The requirements of a satisfactory pressure relief device were: (1) That it be reliable, (2) That it be extremely fast acting, (3) That it offer but little flow restriction, and (4) That it be suitable for holding a high vacuum prior to the imposition of pressure. These requirements dictated the use of rupture discs rather than mechanical valves.

Commercial rupture discs, at a cost of approximately 15 dollars each for disc and vacuum support, were available and suitable. Due to the number of disc failures expected, it was estimated that these units would cost at least 1500 dollars. Therefore, it was considered a good investment to spend several hundred dollars for an experimental investigation to enable the use of discs that cost but a few cents each.

After the necessary design data had been obtained, they were extended by Robert T. Fox, Jr., as a Master of Science Thesis project.

Experimental Equipment. A diagram of the experimental assembly is shown in Figure 5-1. Three test tanks were used, of 2-inch, 4-inch, and 6-inch nominal diameters respectively. The flanges gripping the aluminum foil were standard pipe welding flanges. A circle of 4 mesh 18 gauge woven wire screen was used as a vacuum support, to prevent reverse flexure, in this program. This support was later found to offer too much flow resistance, and was discarded; thus in use the rupture discs were in the "reverse shape" when excess pressure was applied.

Experimental Procedure. Foil tested ranged in thickness from 0.001 inches to 0.010 inches, and was available in two tempers, 2S-0 and 2S-H18. Four test procedures were used: (1) Initial pressure atmospheric, pressure applied gradually, (2) Initial pressure atmospheric, pressure applied suddenly, (3) Initial vacuum, pressure applied gradually, and (4) Initial vacuum, pressure applied suddenly.

Tests were limited by the air pressure available to discs that would burst at less than 100 psig. The minimum bursting pressure for each disc, diameter, thickness, and material was determined.

Results and Conclusions. Figure 5-3 shows the results obtained with initial atmospheric pressure, and gradual pressure rise, and requires no comments. Other results were: (1) Vacuum preloading of the discs had little or no effect, (2) Sudden application of the load had little or no effect, and (3) Too few specimens of temper H18 were available to determine the effect of temper.

B. Vapor Pressure Measurements.

Experimental Equipment. The experimental equipment developed for the measurement of the equilibrium total pressure, or vapor pressure, of hydrocarbon mixtures is shown in Figure 5-4. It consists of a sample bulb of vapor-to-liquid ratio of 5, immersed in a Dewar flask as a constant temperature bath.

The sample bulb was connected to a mercury manometer as the pressure measuring instrument, and had other openings for joining it to a vacuum pump, and carrying the thermocouple leads.

Experimental Method and Results. To demonstrate that the equipment was capable of yielding reliable results, validation experiments were run with isopentane and isooctane; these are shown in Figure 5-5.

Vapor pressure curves on all the fuels used were run on both the "as received" basis, and on desiccated fuel, dried over phosphorus pentoxide. The general experimental method was to first remove dissolved gases by applying a vacuum after first cooling the fuel to a temperature at which its vapor pressure was negligible, and then to take simultaneous pressure and temperature readings over the temperature range of interest. The results of these determinations are shown in Figures 5-6, 5-7, and 5-8.

C. Surface Conductive Spark Plug Energy Release. A lack of information in the literature relating to the efficiency with which surface conductive spark plugs operate (See section 3 of this report) made it necessary to conduct such an investigation. The converted 14 millimeter automotive spark plugs adapted for use in the investigation were placed in a double wall Dewar flask for this purpose and the energy released from single discharges measured as a pressure rise by Rutishauser indicating equipment and oscilloscope.

This study was used as a Master of Science Thesis by Leo Lichtman.

<u>Experimental Equipment and Results.</u> A diagram of the circuitry used is shown in Figure 5-9 and a general view of the equipment in Figure 5-10.

Plotted in Figures 5-11 and 5-12 are the important results of the study. Figure 5-11 indicates the amount of energy released at the plug and Figure 5-12 the efficiency of the discharge as a function of supply condenser voltage. It was concluded that;

1. The thermal energy released to a gas by a surface discharge spark plug of the type used in Fuel Ignition Studies is dependent on the capacitance supplying the energy, the voltage to which it is charged and the circuit resistance.
2. The spark energy is independent of spark plug film resistance.

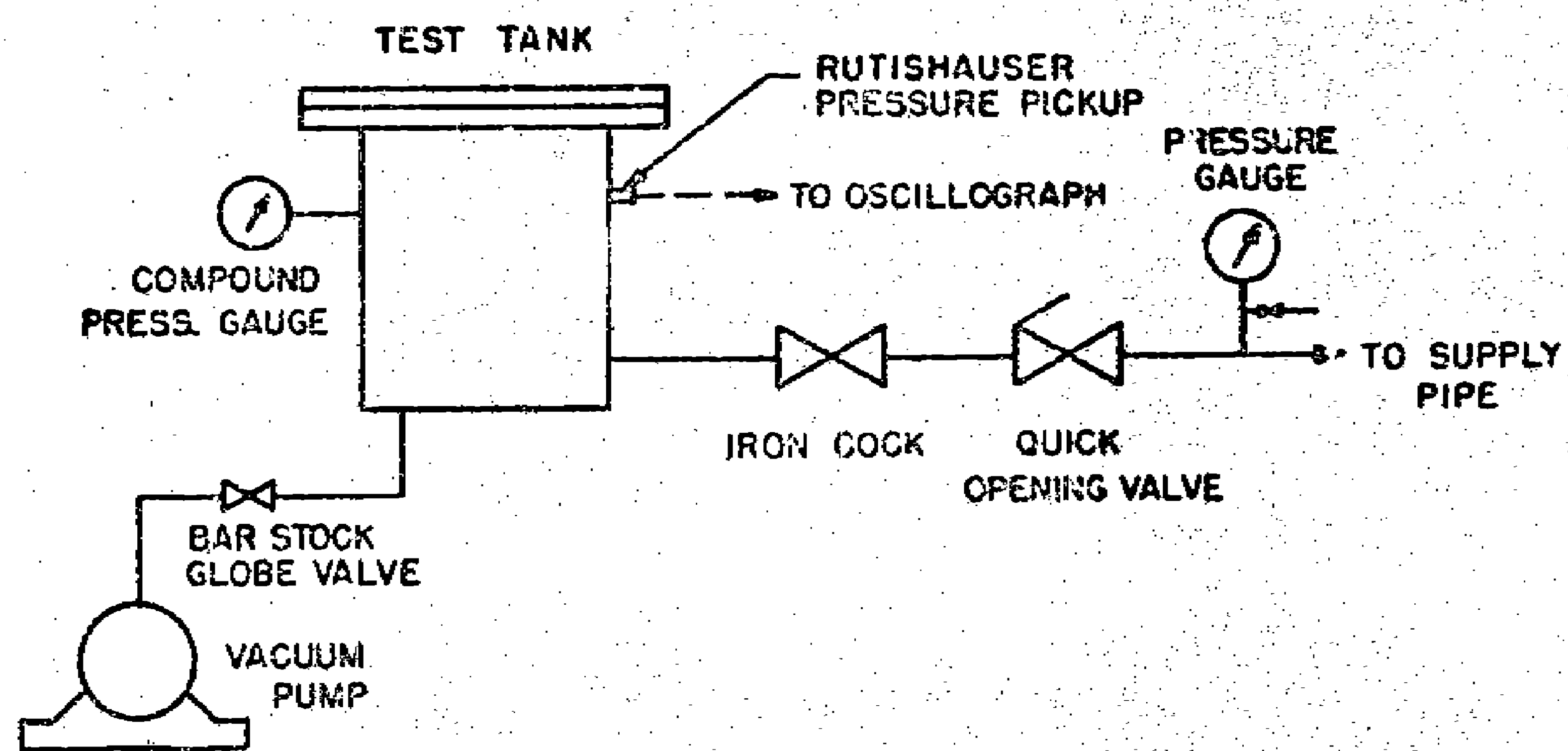


FIG. 5-1 EXPERIMENTAL INSTALLATION

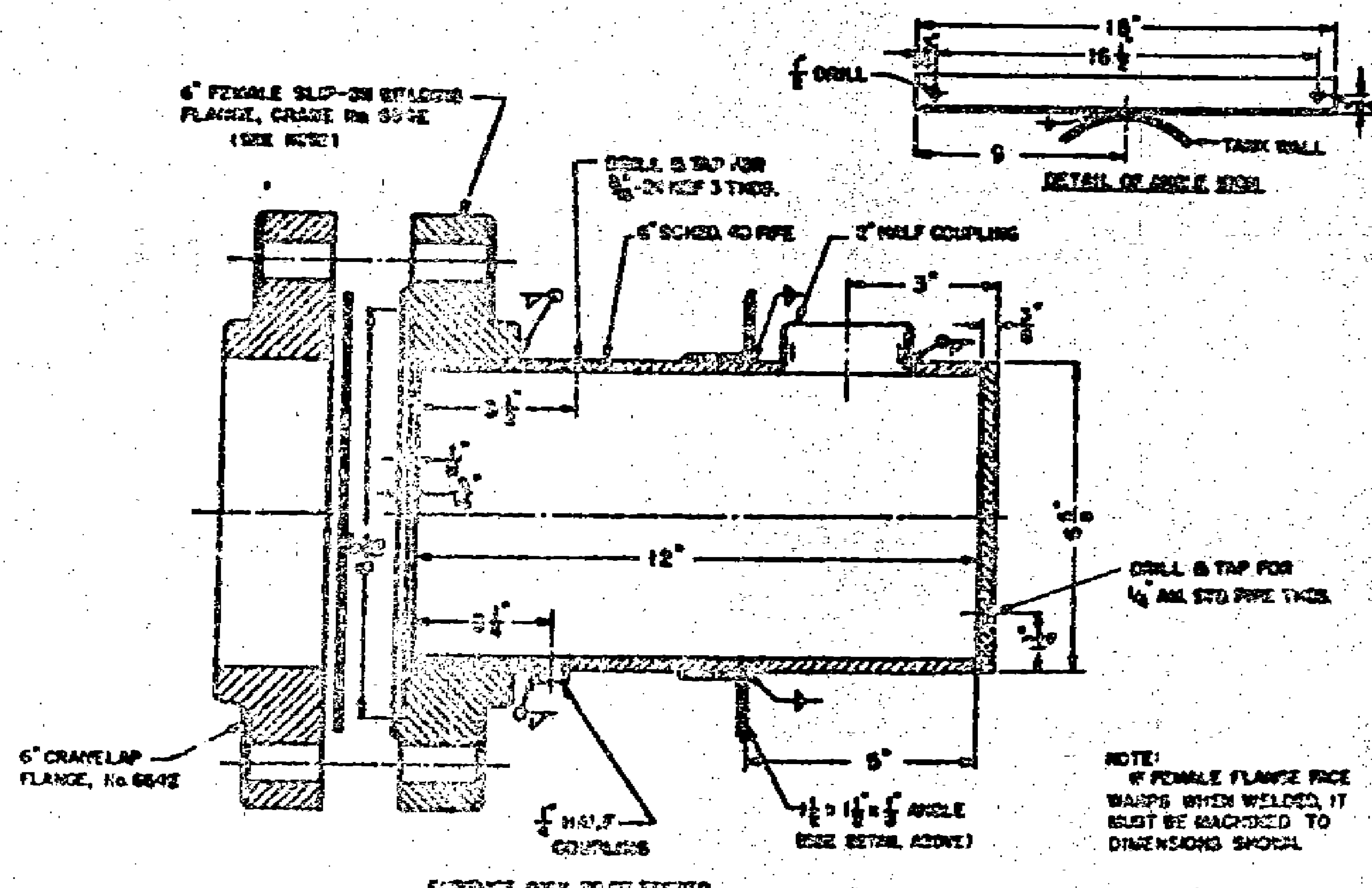


FIG 5-2 6" TEST TANK

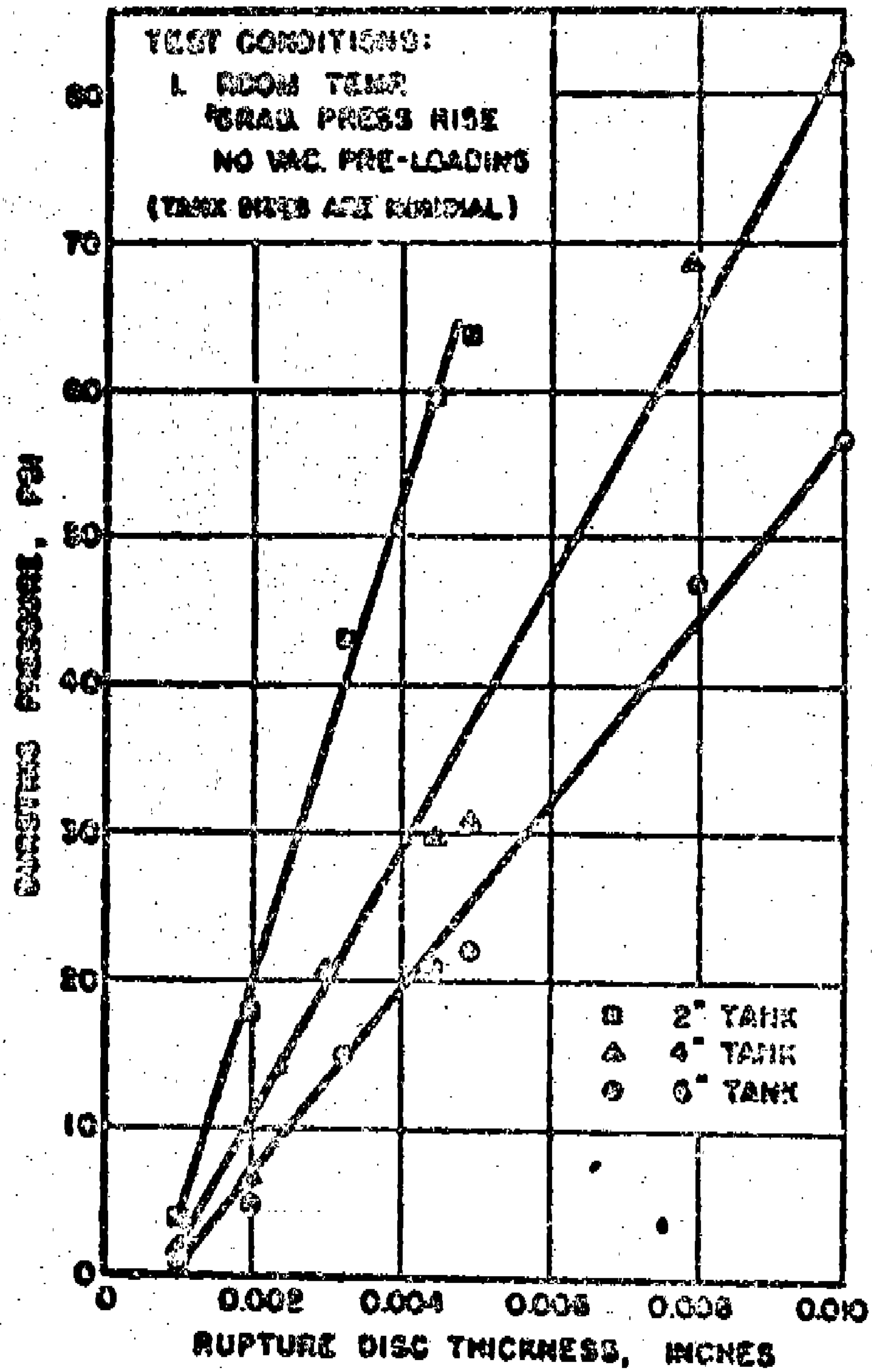


FIG. 5-3 BURSTING PRESSURE vs DISC THICKNESS FOR 2SO ALUMINUM

VAPOR PRESSURE APPARATUS ASSEMBLY

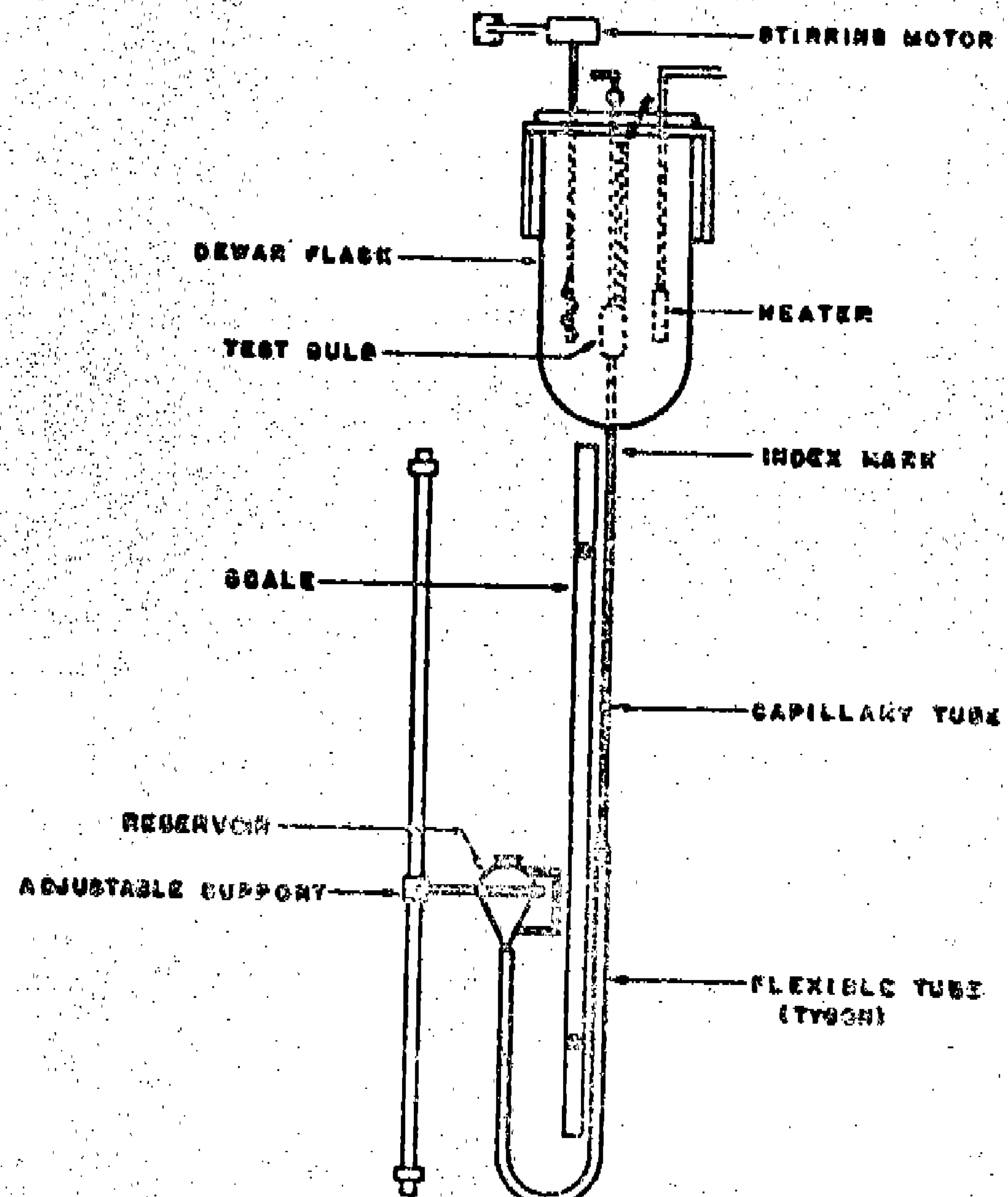


FIG. 5-4

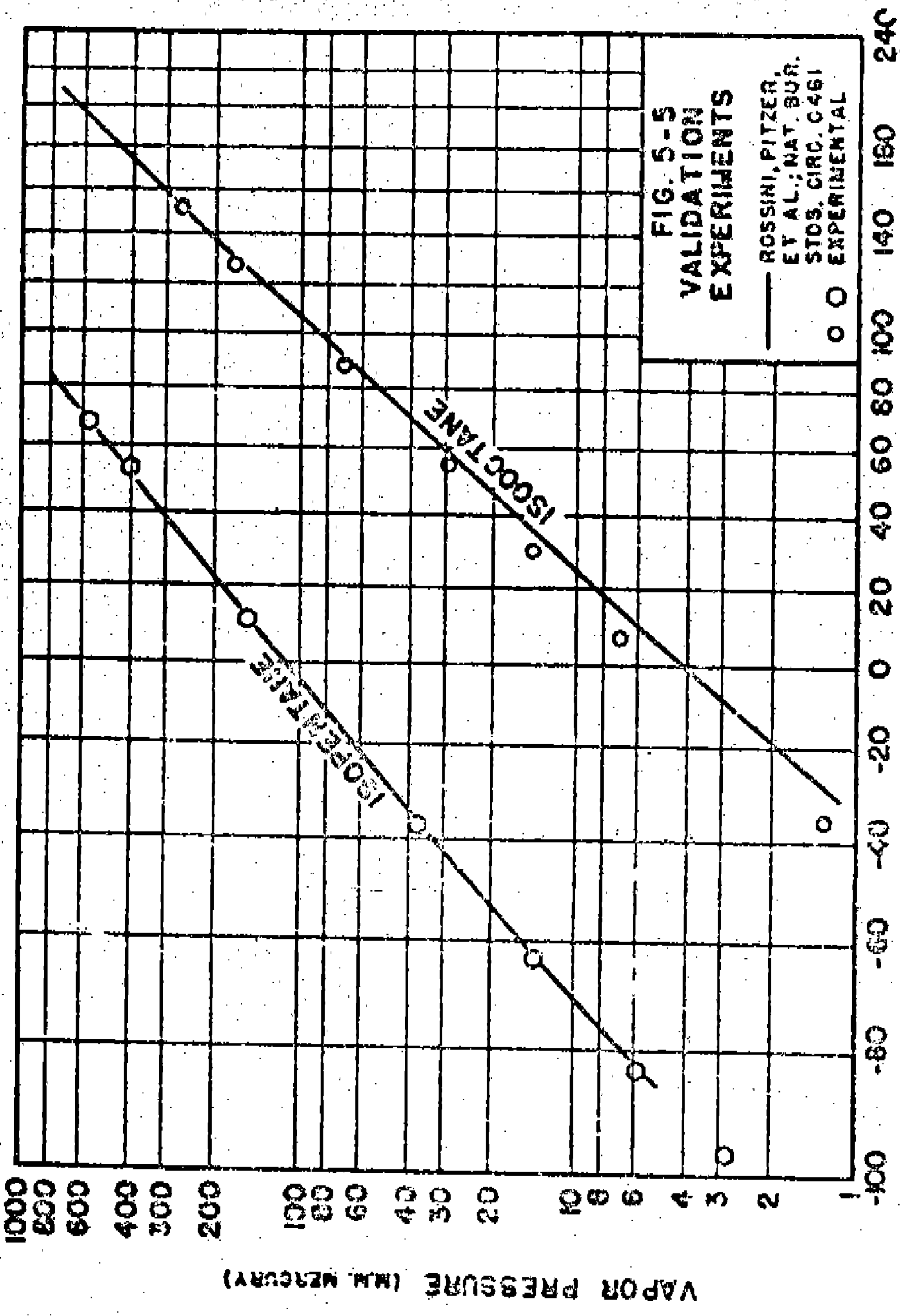


FIG. 5-5
VALIDATION
EXPERIMENTS
ROSSINI, PITZER, ET AL.; NAT. BUR. STDS. CIRC. C461
EXPERIMENTAL
ISOOCTANE
ISOPENTANE
TEMPERATURE - °F
VAPOR PRESSURE (MM. MERCURY)
-100
-80
-60
-40
-20
0
20
40
60
80
100
140
180
240
1000
800
600
400
300
200
100
80
60
40
30
20
10
8
6
4
3
2
1

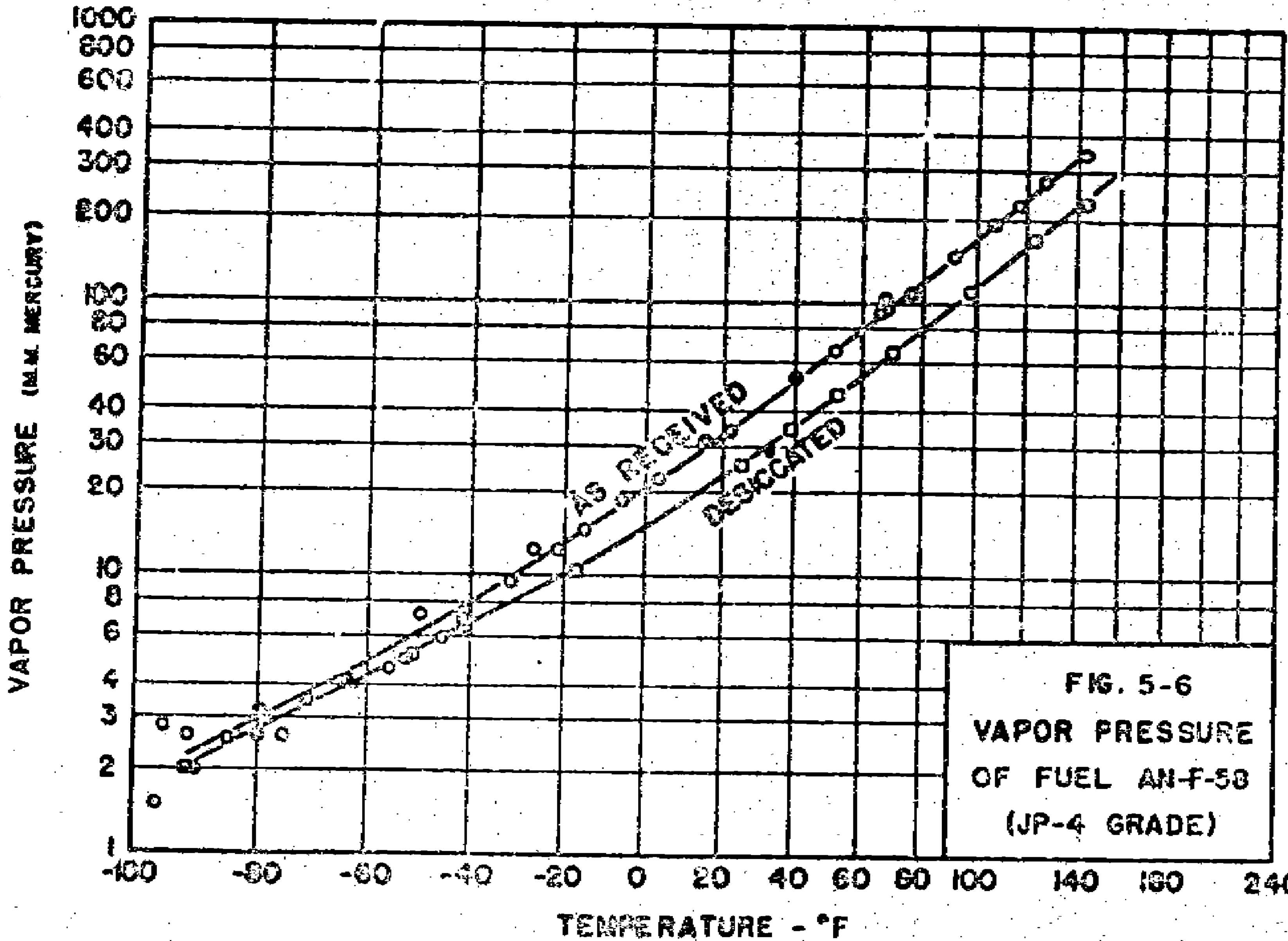


FIG. 5-6
VAPOR PRESSURE
OF FUEL AN-F-58
(JP-4 GRADE)

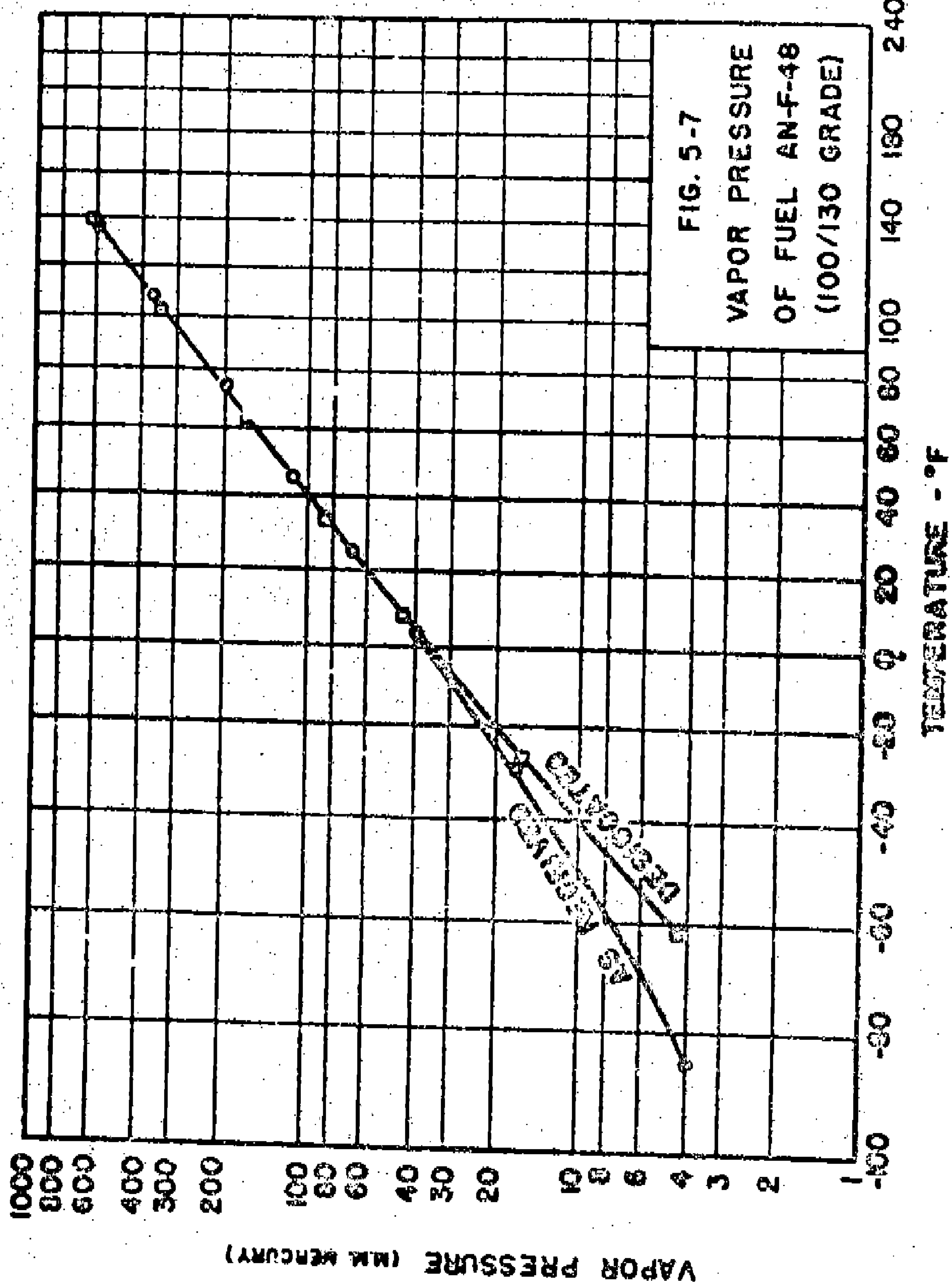


FIG. 5-7
VAPOR PRESSURE
OF FUEL AN-F-48
(100/130 GRADE)

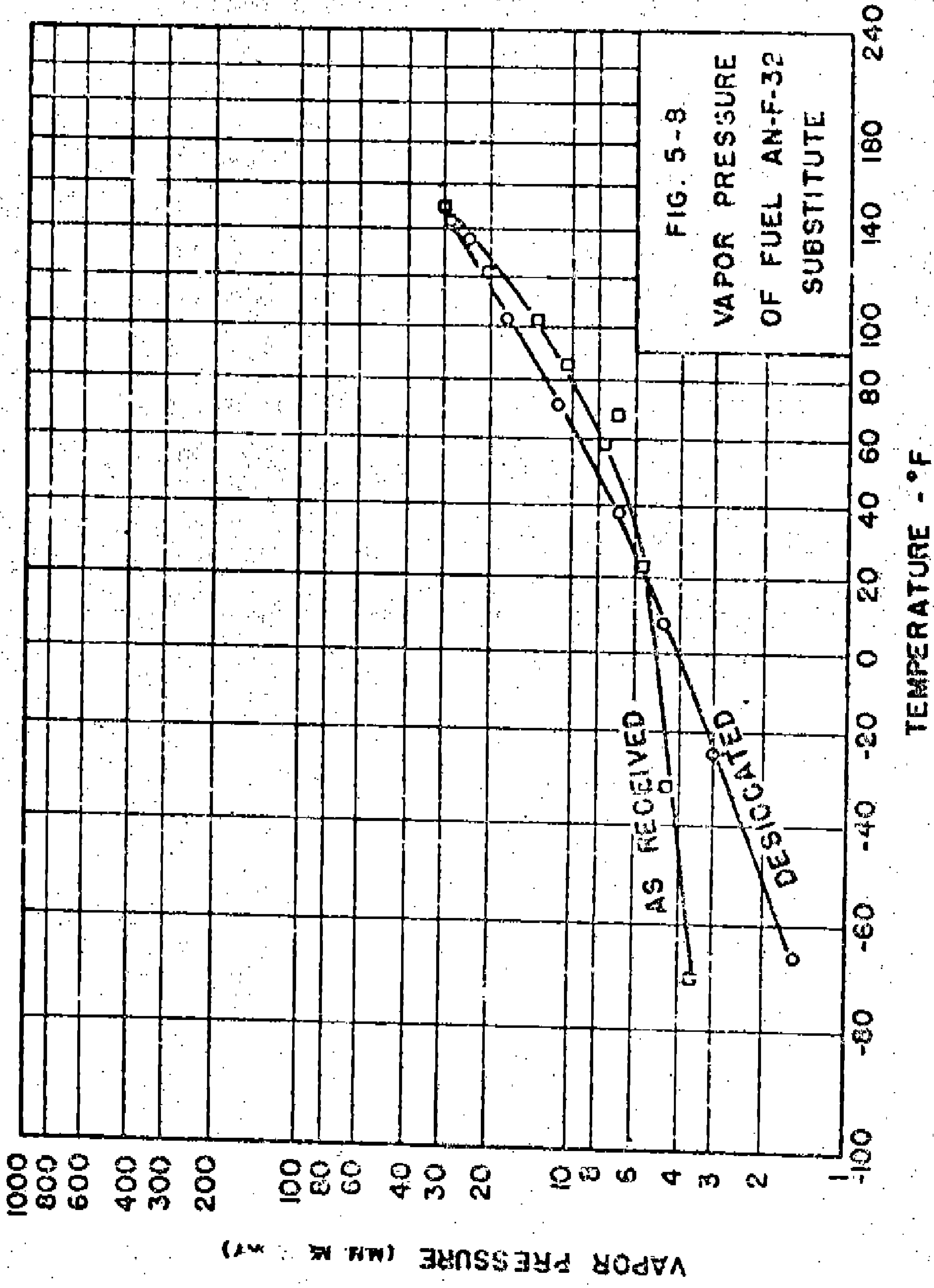
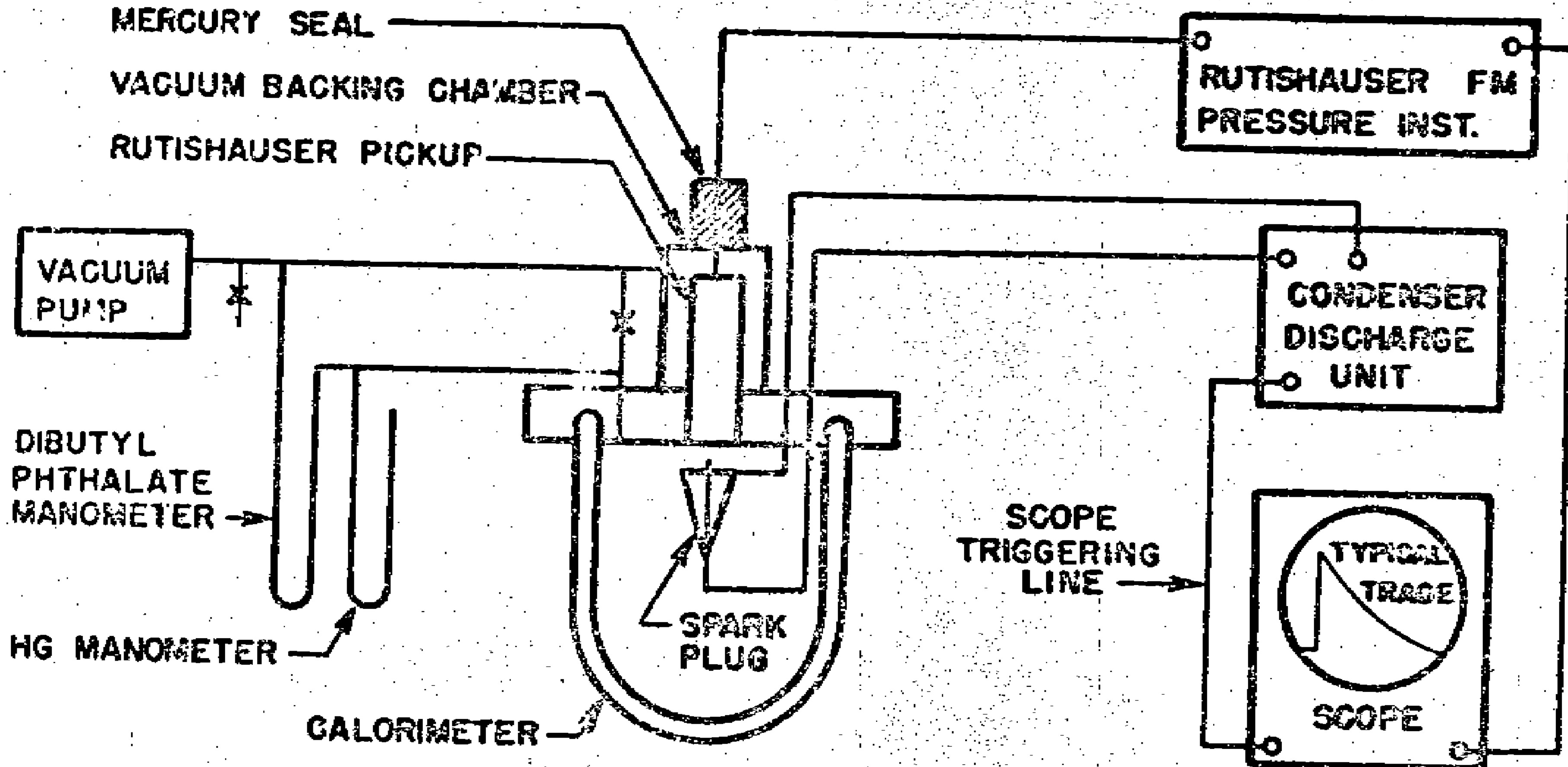
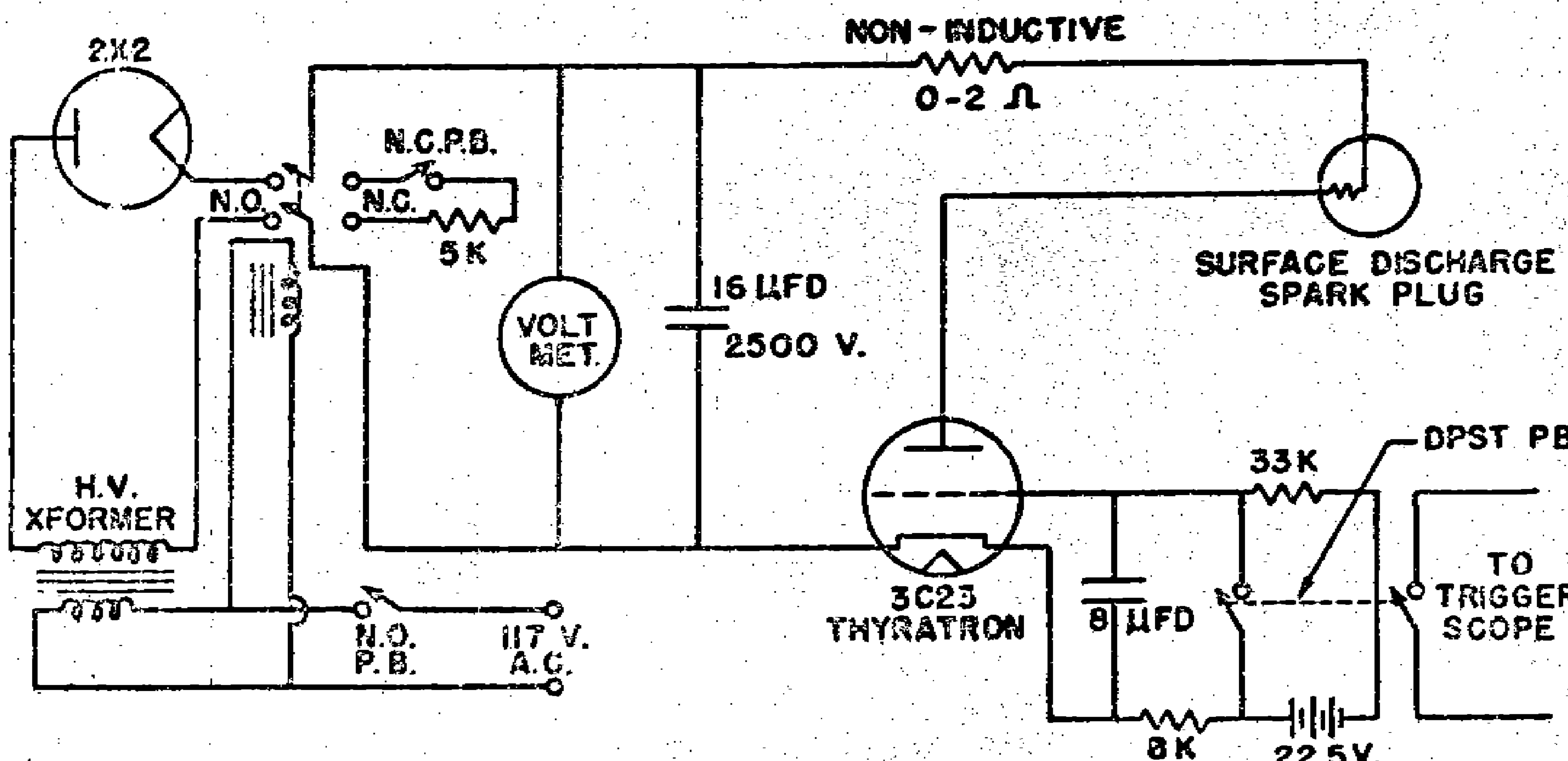


FIG. 5-8 VAPOR PRESSURE OF FUEL AN-F-32 SUBSTITUTE



SPARK ENERGY CALORIMETER AND ASSOCIATED EQUIPMENT

FIG. 5-9



CONDENSER DISCHARGE UNIT

FIG. 5-10

ENERGY RELEASE BY A SURFACE DISCHARGE SPARK PLUG

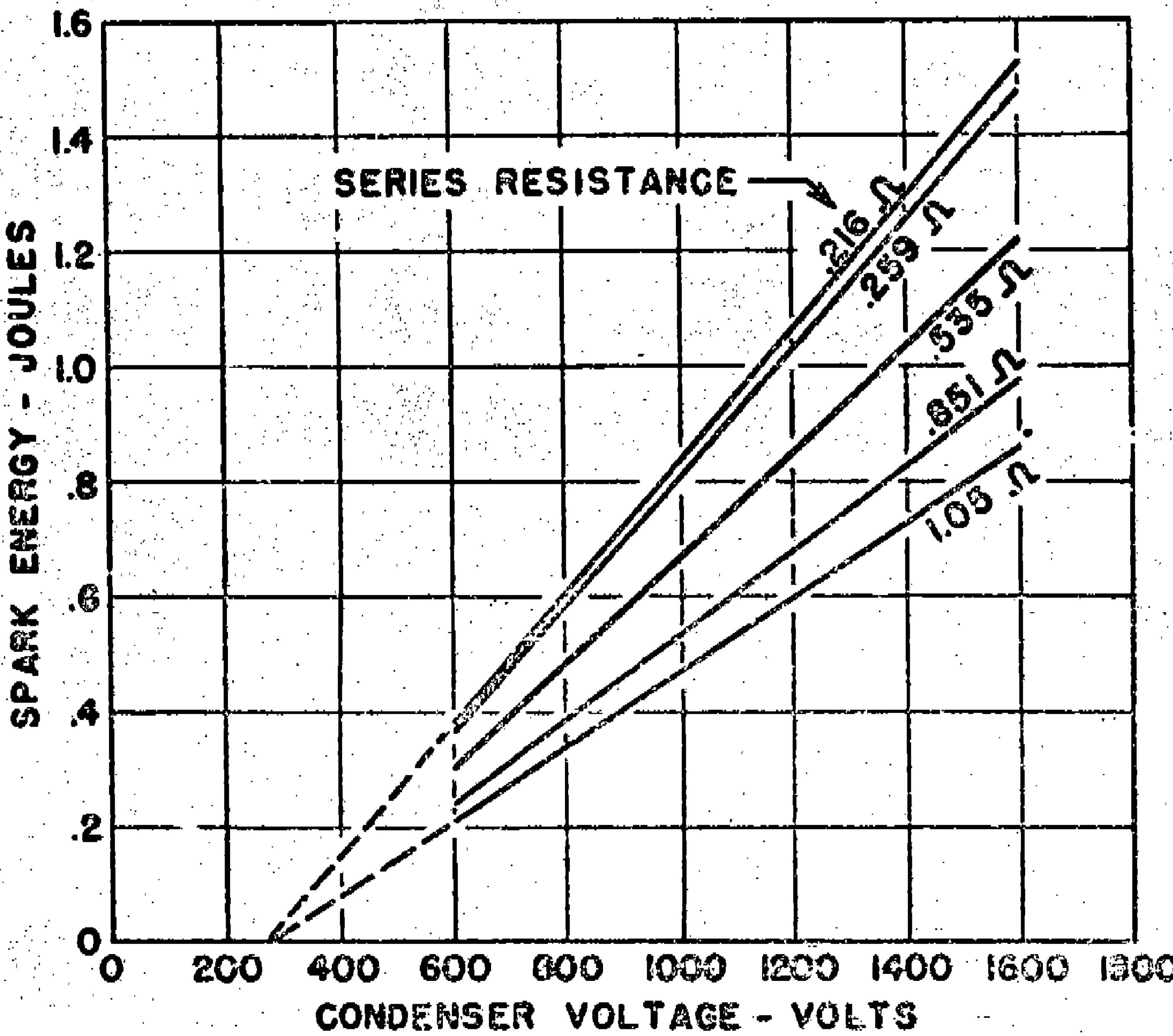


FIG. 5-11

EFFICIENCY OF ENERGY TRANSFER BY A SURFACE DISCHARGE SPARK PLUG

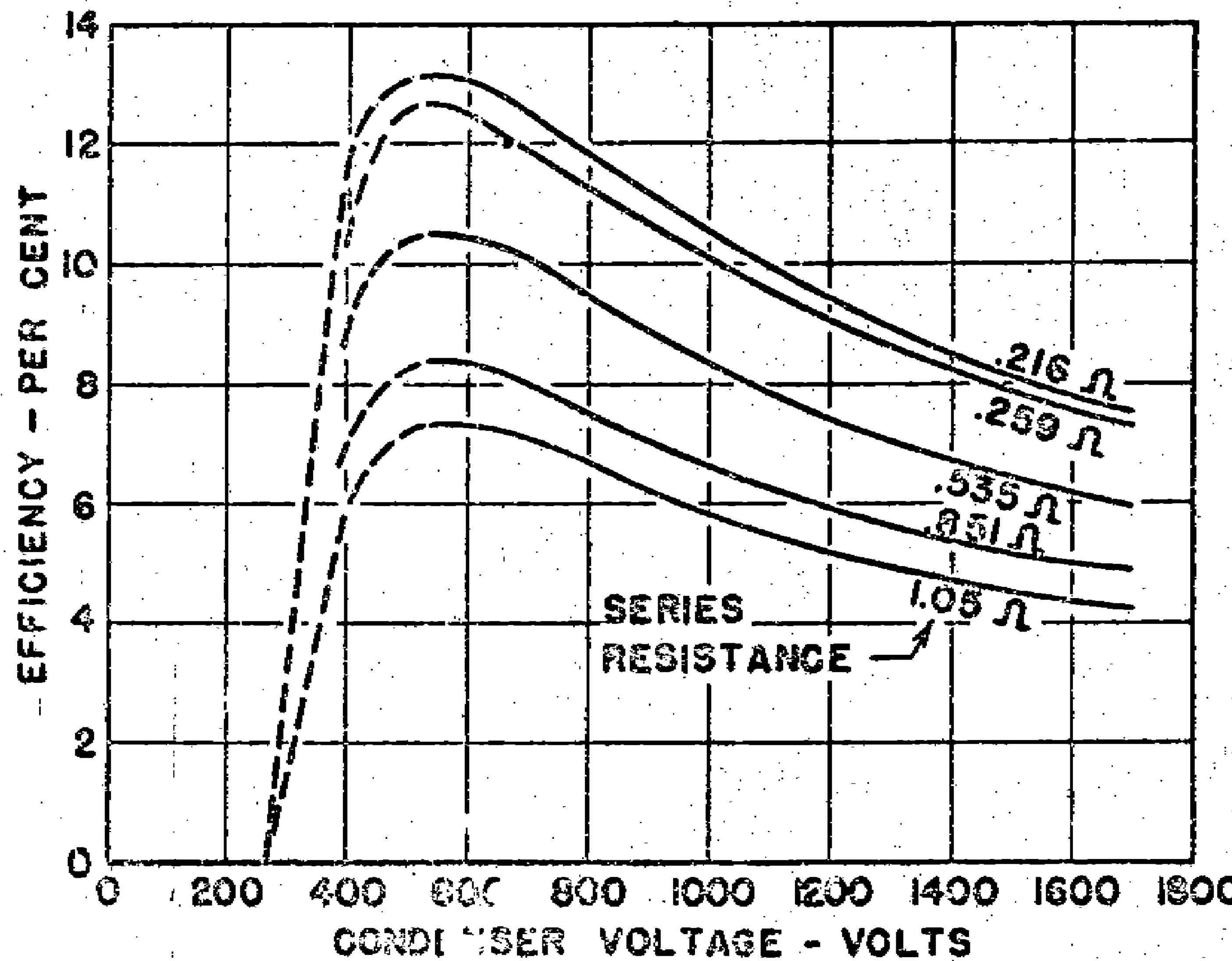


FIG. 5-12

VI. REFERENCES

1. Coward, H. F., and G. W. Jones.
   "Limits of Flammability of Gases and Vapors".
   U. S. Bureau of Mines Bulletin 503 (1952).

2. Jones, G. W., and W. R. Gilliland.
   "Extinction of Gasoline Flames by Inert Gases".
   U. S. Bureau of Mines Report of Inv. 3871 (1946).

VII. BIBLIOGRAPHY

Other reports issued by this Research Project.

All reports are University of California, Berkeley, Institute of Engineering Research Reports, Series 49.

1. Stewart, Paul B., Ernest S. Starkman, and F. Kreith, "Fuel Ignition Studies, Design Study Report", No. 1, (Sept. 1952).
2. Stewart, Paul B., Ernest S. Starkman, and Chas. H. Cehes, "Progress Report, Phase 2", (Construction of Facilities), No. 2, (July 1953).
3. Starkman, E. S., P. B. Stewart, R. E. Gott, and L. Lichtman, "Flammability of AN-F-58 (JP-4) Vapor with Nitrogen Inerting", No. 3, (November 1953).
4. Starkman, E. S., P. B. Stewart, R. E. Gott, and L. Lichtman, "Flammability of AN-F-58 (JP-4) Vapor with Carbon Dioxide Inerting", No. 4, (Jan. 1954).
5. Stewart, Paul B., and R. T. Fox, Jr., "Design Correlations for Aluminum Foil Rupture Discs", No. 5, (July 1954).
6. Stewart, Paul B., E. S. Starkman, R. E. Gott, and L. Lichtman, "Flammability of Aircraft Fuels in Inerted Tanks", No. 6, (Aug. 1954).

VII. BIBLIOGRAPHY (CONTINUED)

7. Stewart, Paul B., and Donald K. Miller, "Preliminary Design Study Report for Stratification Studies Work", No. 7, (May 1955).

8. Stewart, Paul B., and Ernest S. Starkman, "Properties of Fuels Used", No. 8, (Aug. 1955).

9. Stewart, Paul B., and Ernest S. Starkman, "Gunfire Tests", No. 9, (Sept. 1955).

10. Starkman, Ernest S., and L. Lichtman, "Energy Released from Spark Plugs", No. 10.

VIII. APPENDIX A

I. TABLES ON INSPECTION TESTS OF FUELS

II. PHOTOGRAPHS OF INSTALLATION

III. ENGINEERING DRAWINGS

TABLE 8-1

ASTM DISTILLATION OF FUELS

Fuel Test	Isopentane 1	Isopentane 2	Isopentane 3	AN-F-48 1	AN-F-48 2	AN-F-58 1	AN-F-58 2	AN-F-32 Substitute 1	AN-F-32 Substitute 2
I. B. P.	78°F	82°F	78°F	114°F	114°F	122°F	124°F	329°F	325°F
10%	82.5	85.5	82.0	149	152	207	208	379	379
20%	82.5	87.0	82.5	163	166	268	268	392	394
30%	82.5	87.5	83.0	178	182	302	307	405	405
40%	83.0	88.0	84.0	193	197	331	333	414	414
50%	83.5	88.5	84.5	208	207	354	356	424	424
60%	84.0	89.0	85.0	215	216	377	376	435	437
70%	84.5	90.0	86.0	222	224	395	395	446	450
80%	86.0	91.5	87.0	235	234	414	412	462	464
90%	89.0	93.0	97.0	249	249	443	440	486	488
E. P.	97.0	103	103	283	283	496	493	527	527
Recovery	93%	95%	95%	97%	97%	98%	98%	98.5%	98%
Residue	0	0	0	1%	1%	1.5%	1.5%	1%	1.5%
Loss	7%	5%	5%	2%	2%	0.5%	0.5%	0.5%	0.5%

TABLE 8-2

REID VAPOR PRESSURE OF FUELS

Isopentane	19.5 lb/in^2
AN-F-58	1.85
AN-F-48	5.95
AN-F-32 Subst.	0

SPECIFIC GRAVITY OF FUELS

TABLE 8-3

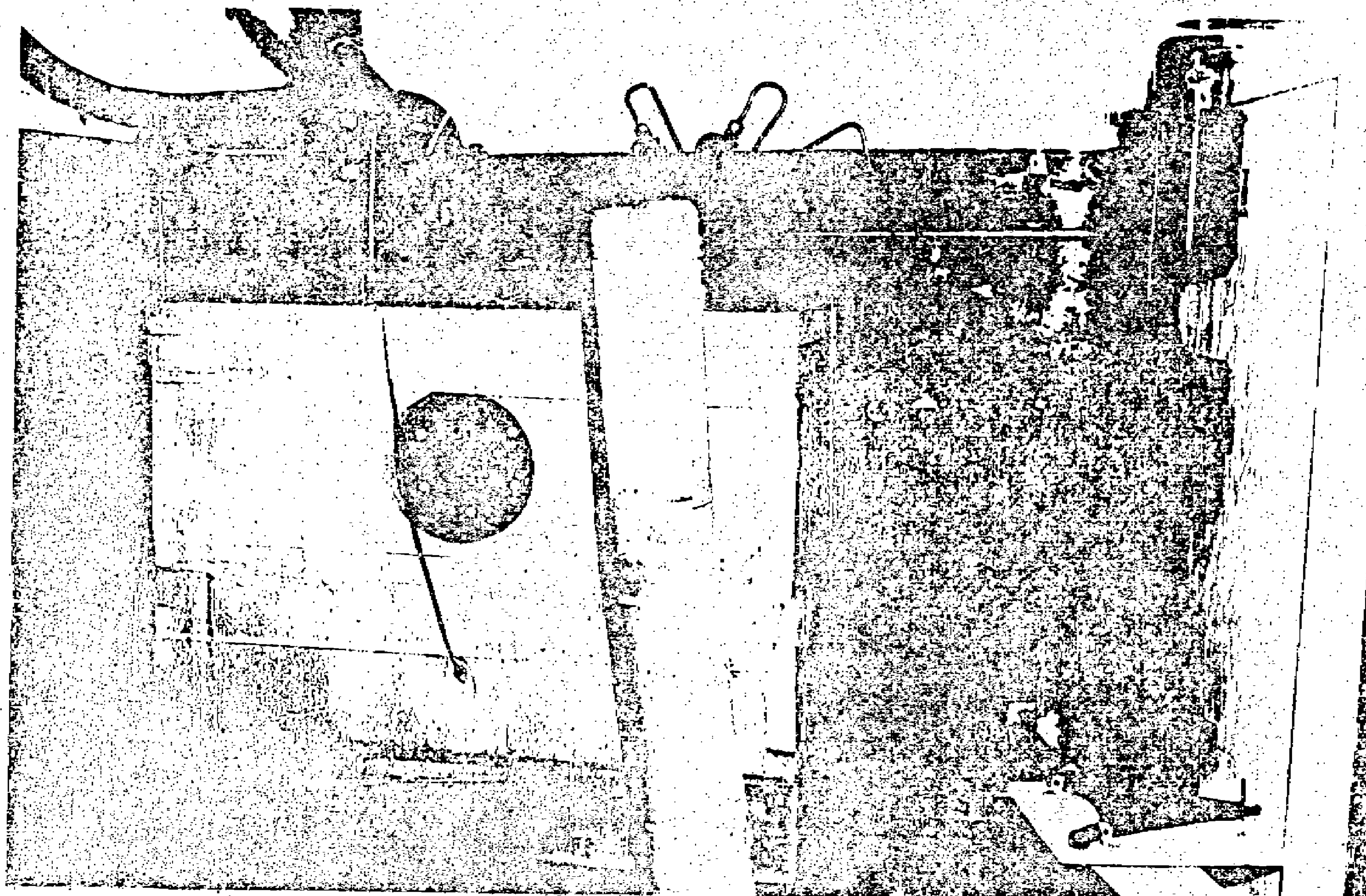
	Temp.	Sp. Gr.
Isopentane	74°F	0.6230
AN-F-58	70°F	0.7865
AN-F-48	74°F	0.7136
AN-F-32 Subst.	70°F	0.7977

Method: Westphal Balance

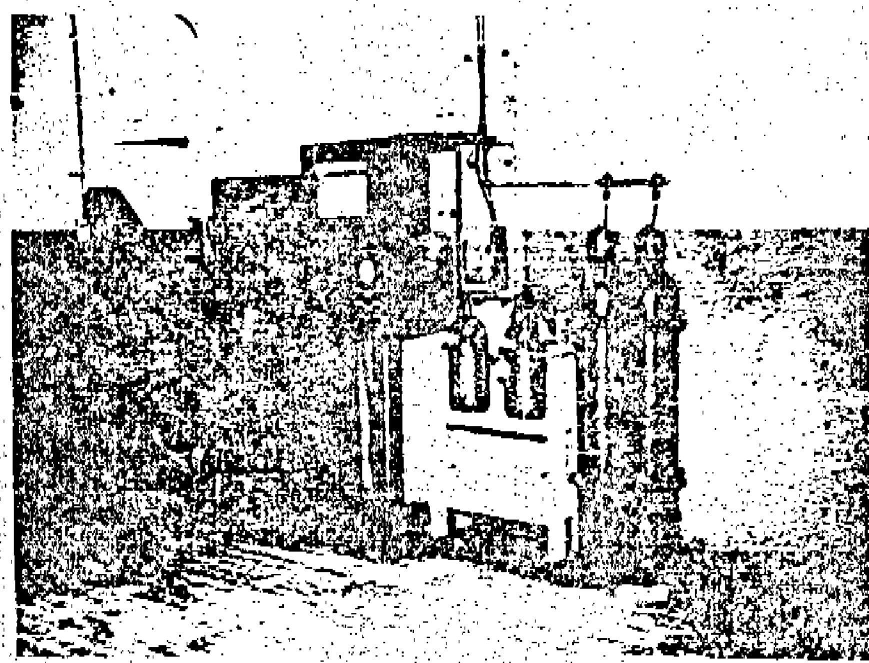
LIST OF PHOTOGRAPHS

1. Test Tank Installation
2. Test Tank after Insulation
3. Test Tank Instrumentation
4. Tempering Tanks
5. Tempering Tanks Installation
6. Vacuum System
7. Heat Transfer System
8. Gun Mount
9. Target Installation
10. Gun Range - Target and Instrumentation

No. I TEST TANK INSTALLATION

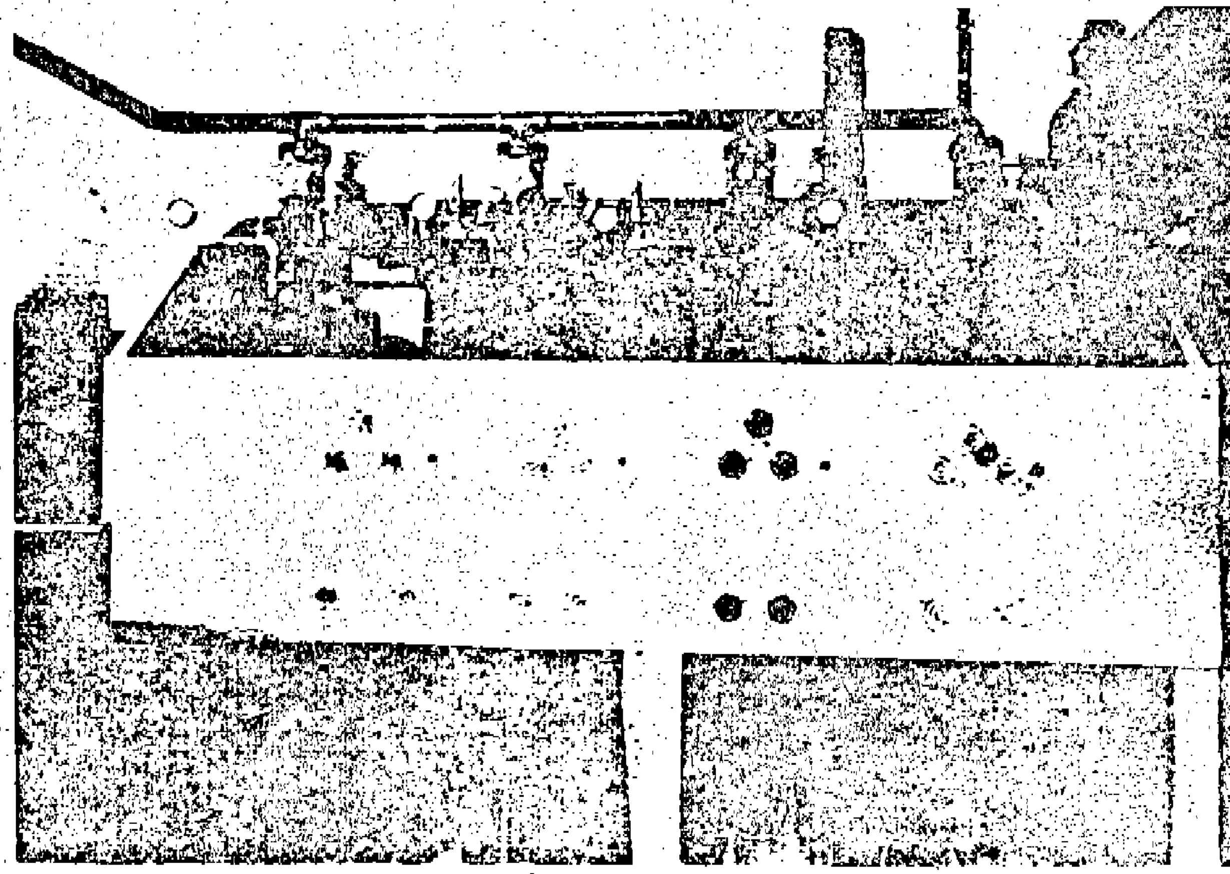


No. 2 TEST TANK AFTER IN[illegible]ON

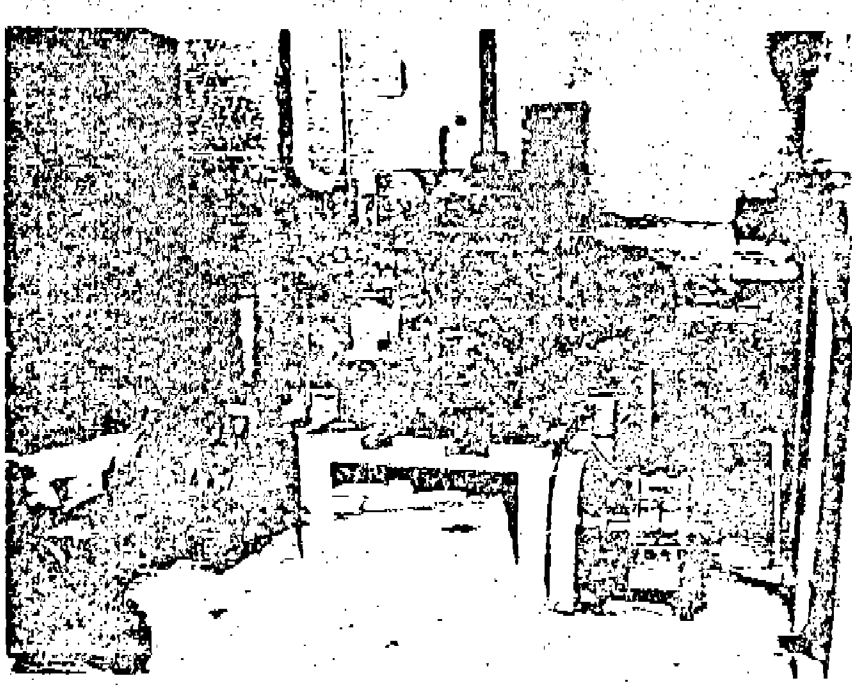


No. 3 TEST TANK INSTRUMENTATION

No. 4 TEMPERING TANKS

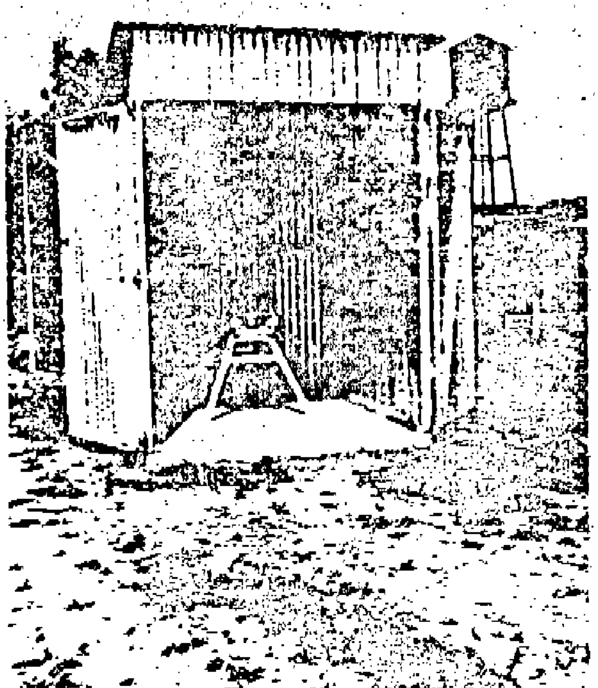


No. 5 TEMPERING TANKS INSTALLATION

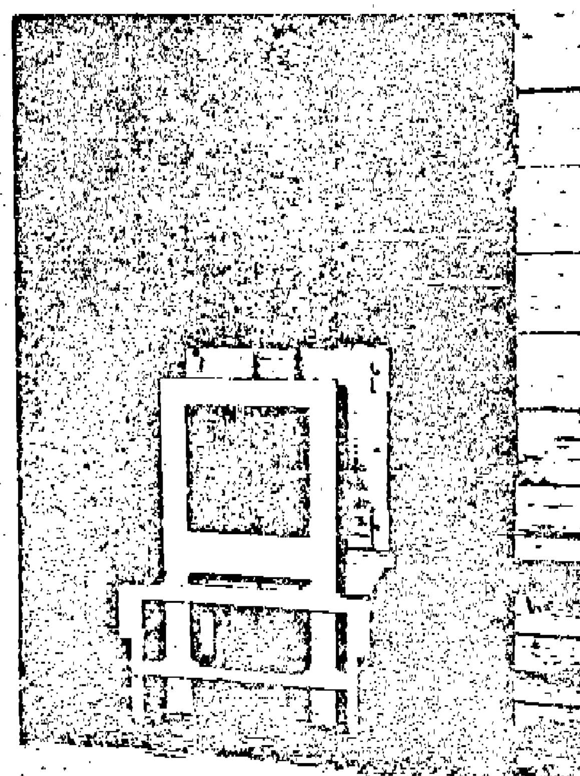


No. 6 VACUUM SYSTEM

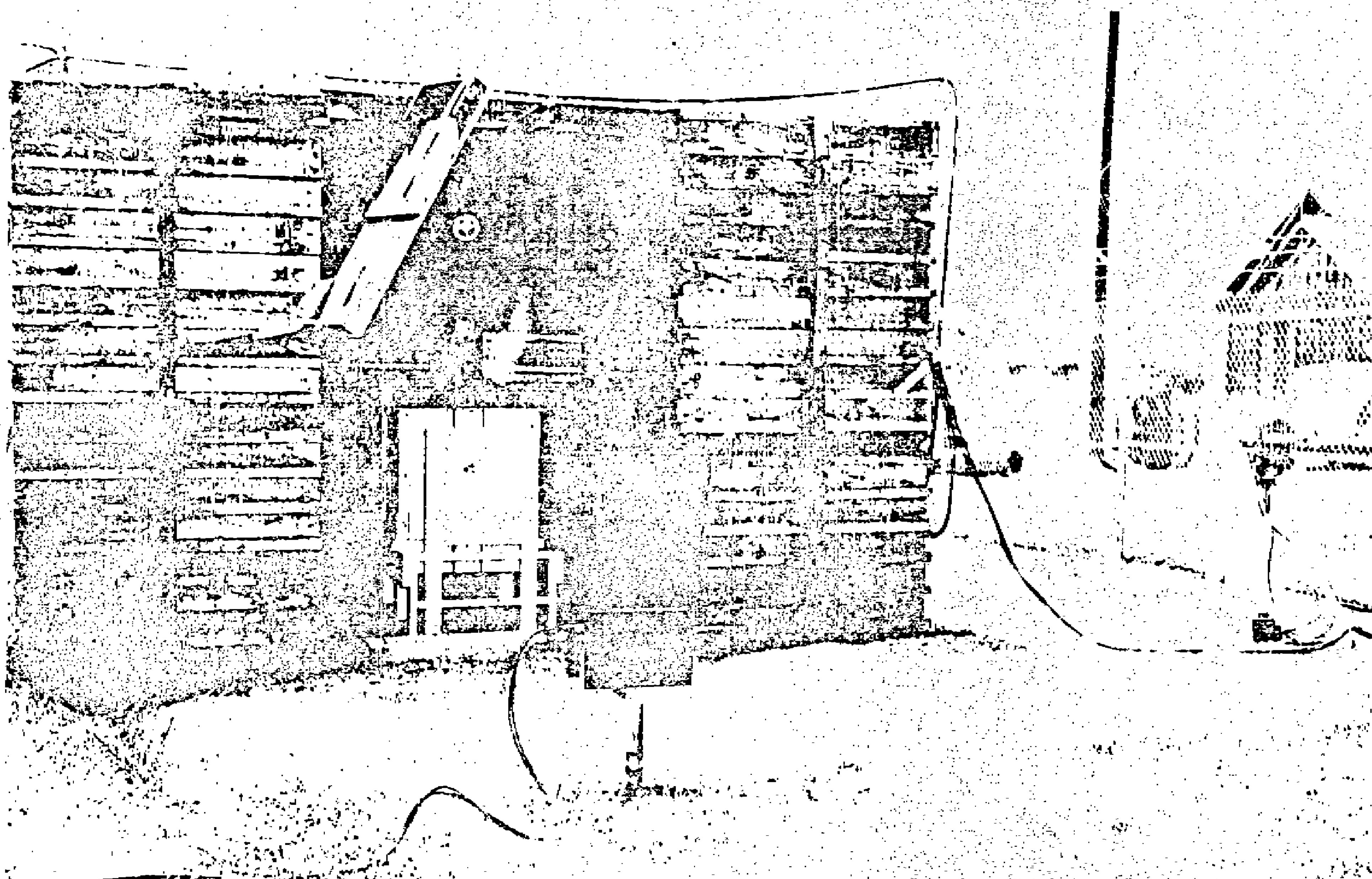
No. 7 HEAT TRANSFER SYSTEM



No. 8 GUN MOUNT



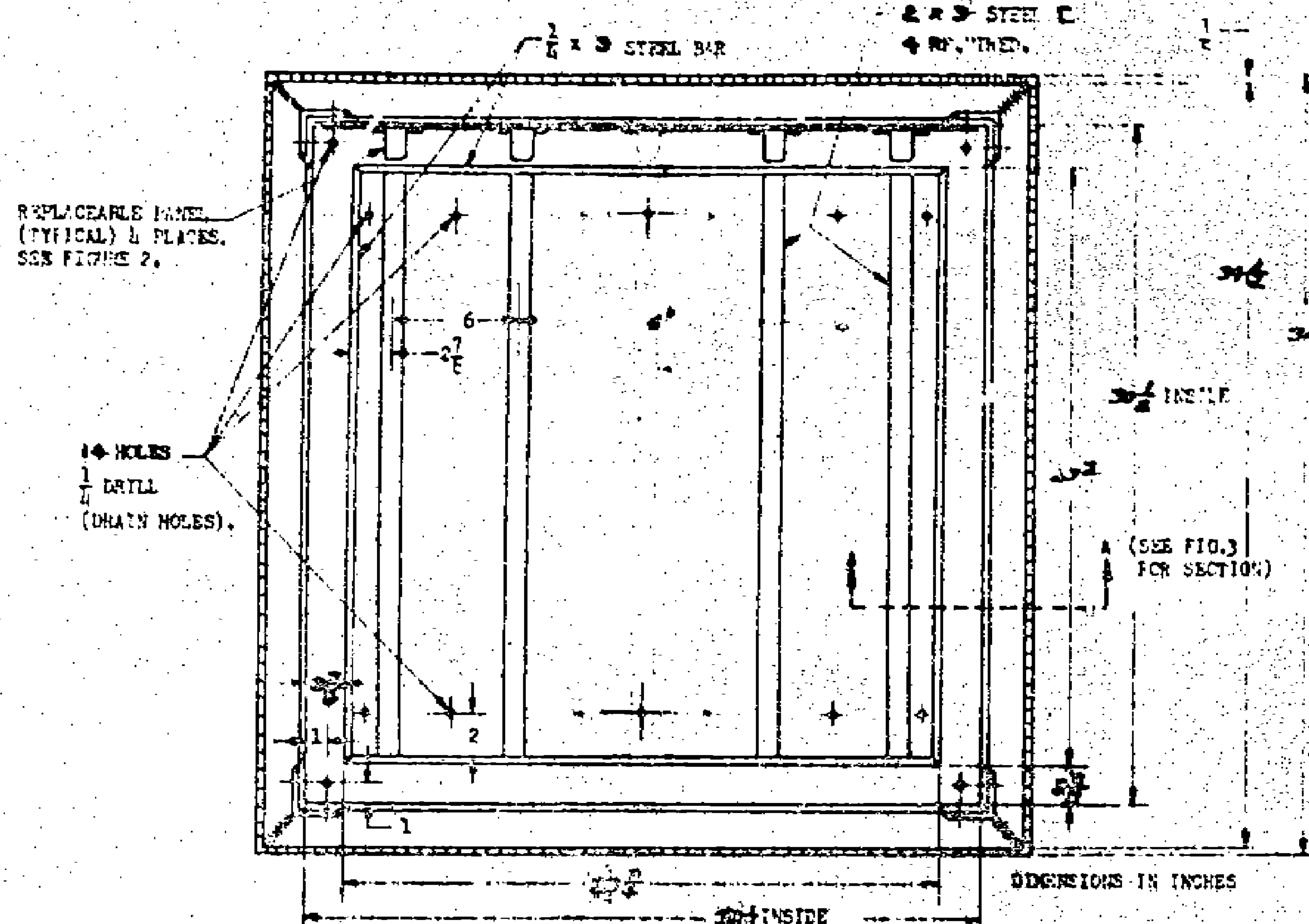
No. 9 TARGET INSTALLATION



No. 10 GUN RANGE - TARGET AND INSTRUMENTATION

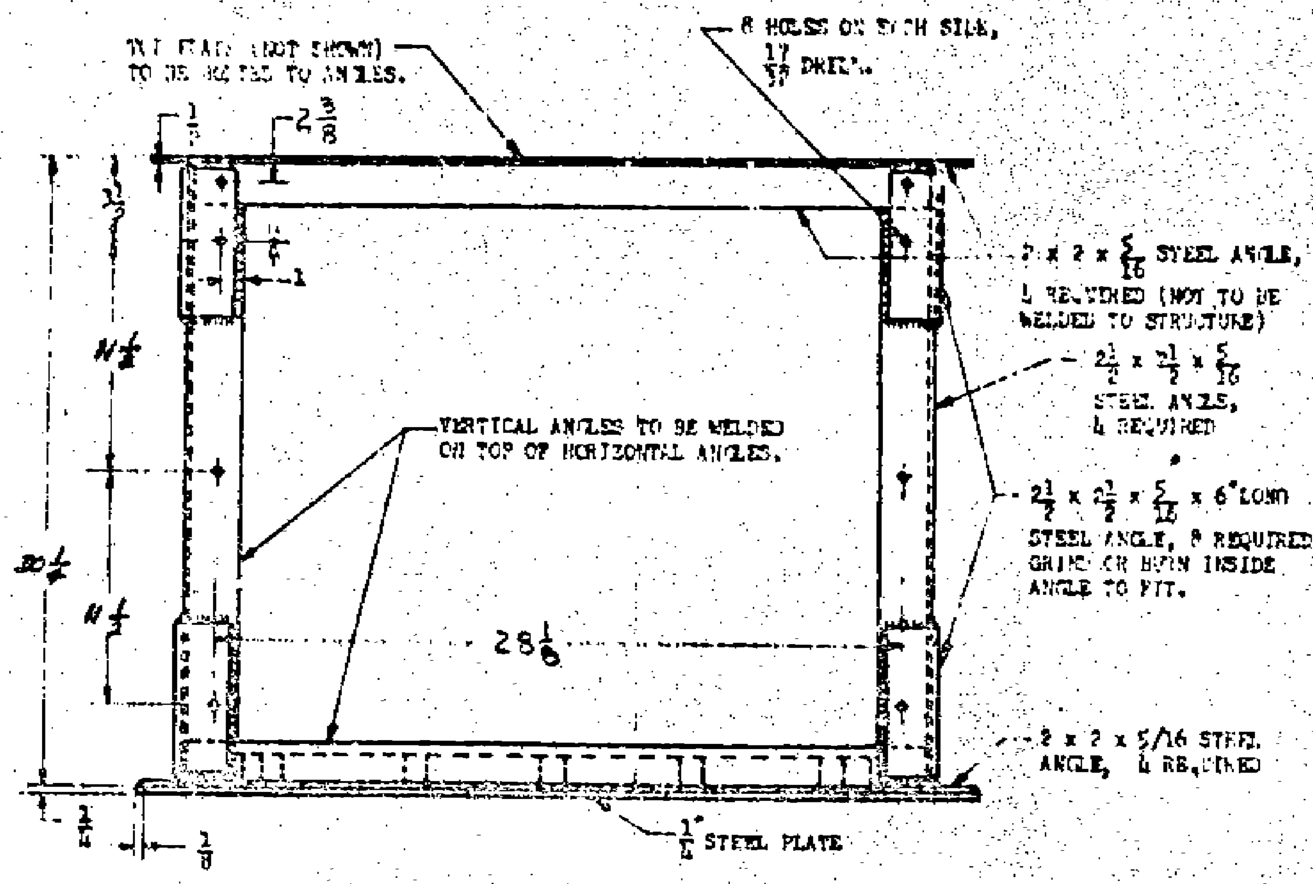
LIST OF DRAWINGS

A-29	Gunfire Test Structure
A-30	Gunfire Test Structure
A-32	Gunfire Test Structure Details
B-4	Test Tank
B-8	Piping Diagram
B-16	Spark Circuit
B-20	Gas Mixing and Tempering Tanks
B-41	Gunfire Barricade
B-55	Test Tank No. 2



PLAN VIEW
(TOP PLATE AND ANGLES NOT SHOWN)
SEE FIGURE 2 FOR DETAIL OF TOP

FIGURE 1. (Sheet 1) - Gunfire Test Structure



SIDE ELEVATION

DIMENSIONS IN INCHES

FIGURE .. (Sheet 2) - [illegible]

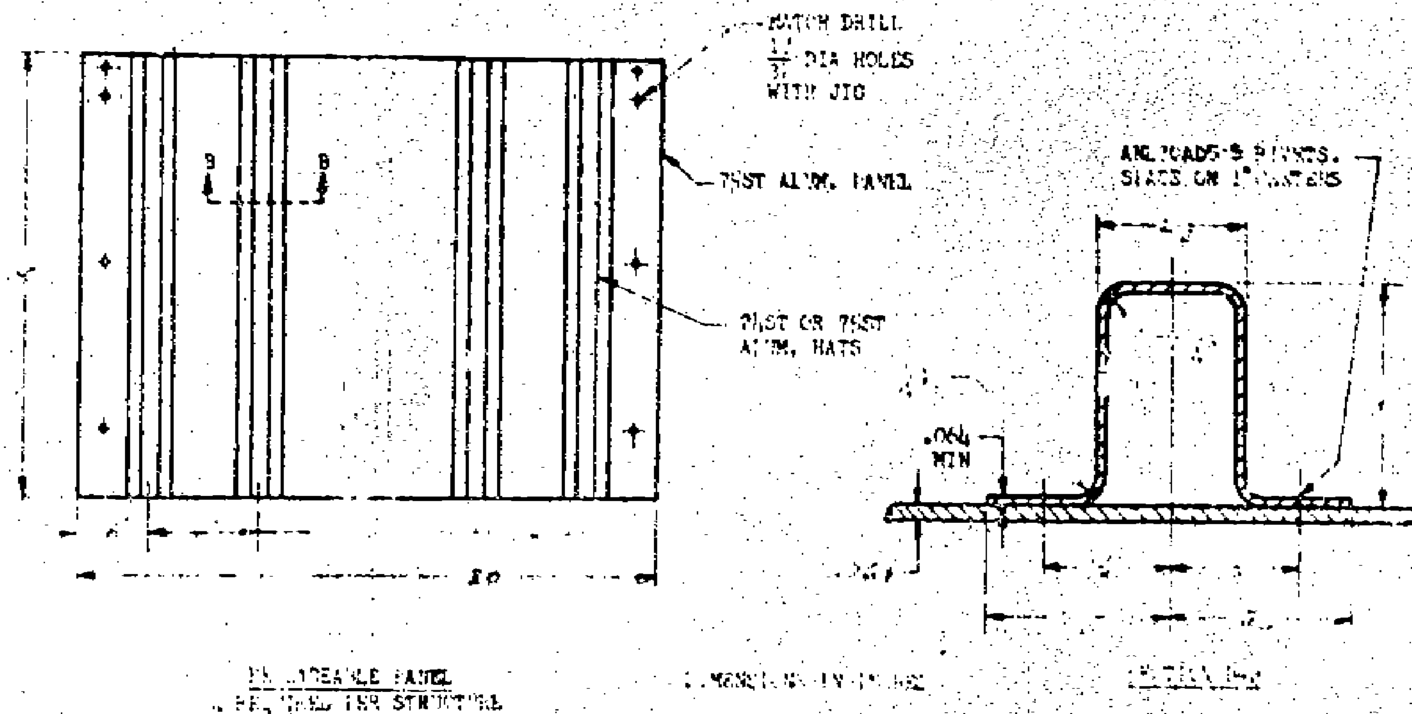
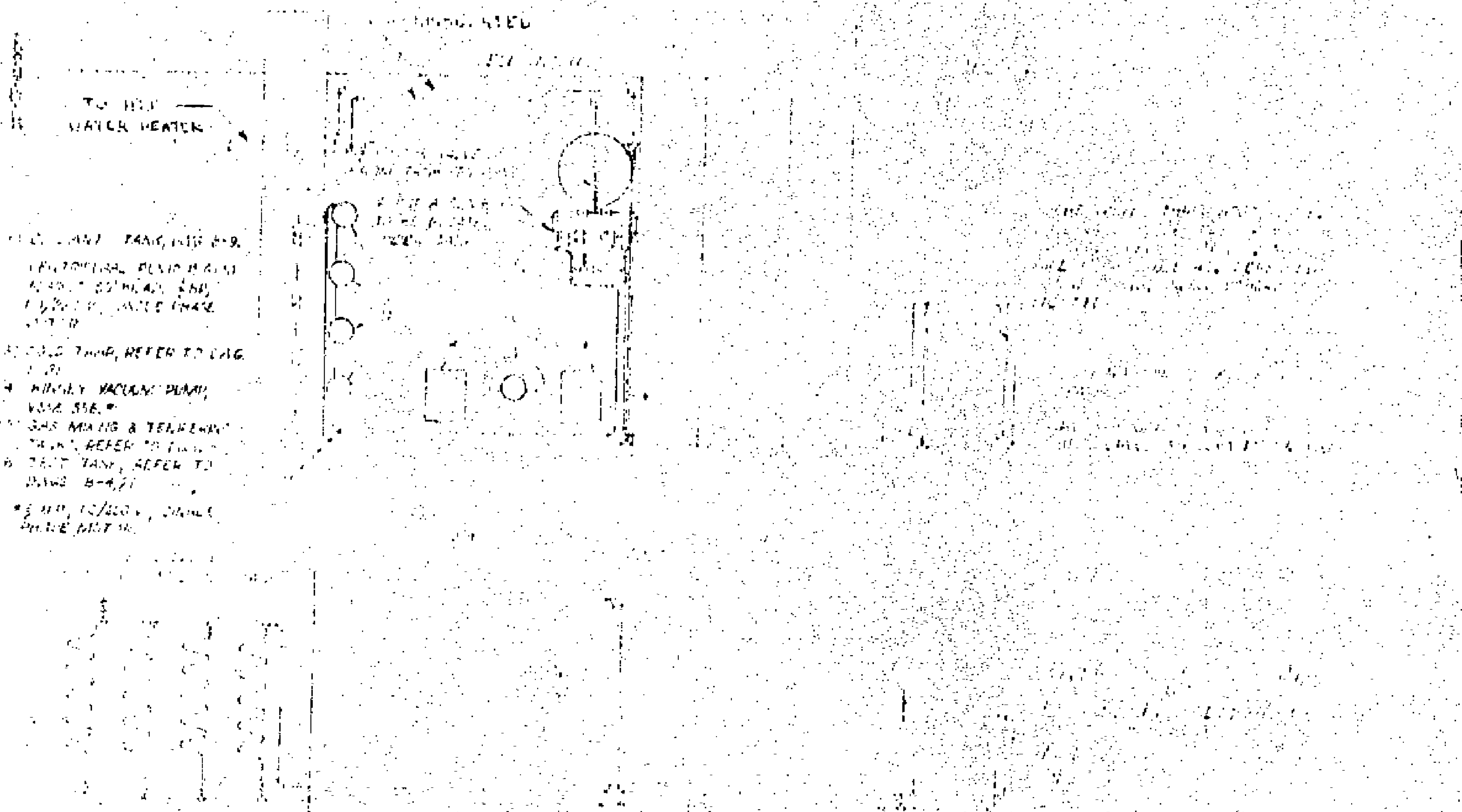


FIGURE [illegible] (Cont'd) - [illegible] Test Structure Details


TO HOT WATER HEATER
KINNEY VACUUM PUMP,
GAS MIXING & TEMPERING TANK, REFER TO
PHASE MOTOR