NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

June 1945 as
Memorandum Report E5F26

NITROUS OXIDE SUPERCHARGING OF AN AIRCRAFT-ENGINE CYLINDER

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WASHINGTON

NACA MR No. E5F26

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

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SUMMARY

An investigation was made to determine the performance of an aircraft-engine cylinder using nitrous oxide to provide additional supercharging. Single-cylinder tests were conducted at constant manifold pressure in which nitrous oxide was added as a gas to the inlet air to provide extra supercharging. Determinations were made of the effects of this method of supercharging on power output, cylinder-head temperature, and fuel consumption; and an evaluation was made of methods of cooling the cylinder when using nitrous oxide. Additional tests were conducted to find the effects of nitrous oxide supercharging on the knock limits when using 28-R and 33-R fuels. Calculations were made using these data to estimate the effect on engine performance of injecting the nitrous oxide into the induction system as a liquid.

The results of the tests and calculations are summarized as follows:

Injection as a gas (test results):

1. With constant manifold pressure, the nitrous oxide increased the power output about 14 percent on an indicated basis at a nitrous oxide-air ratio of 0.1; this increase amounted to about 25 percent at a ratio of 0.2.

2. The knock-limited power output was increased about 9 percent on an indicated basis with a nitrous oxide-air ratio of 0.1 and about 17 percent with a nitrous oxide-air ratio of 0.2. The knock-limited manifold pressure was decreased about 2 percent and 4 percent, respectively, for these ratios.

3. Increasing the oxygen concentration in the charge by the addition of nitrous oxide increased the flame speed, resulting in decreased values of optimum spark timing. This effect was especially notable at extremely rich fuel-oxygen ratios.

4. The use of nitrous oxide resulted in abnormally high cylinder-head temperatures. When knock is not a limitation, these temperatures can be controlled to best advantage by the use of mixture enrichment. When knock is a limitation, the use of water or water-alcohol injection may be preferable.

Injection as a liquid at -128° F (calculated results):

1. The nitrous oxide would lower the inlet-mixture temperature to such an extent when injected as a liquid that poor mixture distribution may result unless special means are provided to prevent this difficulty. When mixture distribution is not a problem, calculations indicate that the liquid nitrous oxide would increase the indicated power output about twice as much as with gaseous injection for a given manifold pressure.

2. Calculations and test data show that the lowered mixture temperatures brought about by injection of nitrous oxide as a liquid should cause the knock-limited indicated power output to be somewhat lower than that obtained with gaseous injection at a fuel-oxygen ratio of 0.410. At richer fuel-oxygen ratios, however, the knock-limited power was increased as the mixture temperature was lowered.

INTRODUCTION

A number of investigations have been conducted to determine the effectiveness of oxygen supercharging of military aircraft engines, particularly for momentary bursts of power at high altitudes. (See references 1 and 2.) The tests of reference 1 showed that, although the addition of oxygen supplied considerable extra power, the effect on the knock limit and on engine temperatures was detrimental unless large quantities of internal coolants were injected.

Recently the Air Technical Service Command, Army Air Forces, requested the NACA to conduct tests using nitrous oxide to provide additional oxygen for supercharging. Data obtained from the Army Air Forces indicated that this compound was selected in an attempt to obtain the benefits of oxygen supercharging without incurring any reduction of the knock limit. It was understood that the tests should be applicable insofar as possible to the in-line liquid-cooled engine with a 1650-cubic-inch displacement installed in a pursuit airplane. Inasmuch as no single-cylinder setup of the 1650-cubic-inch displacement engine was available, the tests were conducted on a single-cylinder setup of an in-line liquid-cooled engine with a 1710-cubic-inch displacement. The compression ratio of the 1710 cylinder was adjusted to that of the 1650 cylinder; other operating conditions were selected to correspond as nearly as possible to those of the 1650 engine.

The tests were conducted at the Cleveland Laboratory of the NACA during the early part of 1945.

FUELS AND MATERIALS

Two fuels, 28-R (grade 100/130) and 33-R (grade 115/145), were used in the tests. The A.S.T.M. distillation curves for these fuels are shown in figure 1.

The nitrous oxide used in the tests was obtained commercially and was indicated to be at least 98 percent pure; the impurities in the nitrous oxide were mostly free nitrogen. The normal boiling point of nitrous oxide is -128° F and the vapor pressure at 70° F is about 760 pounds per square inch absolute. Complete data on the variation of vapor pressure with temperature are shown in figure 2, which was plotted from data given in reference 3, page 48. Other pertinent thermodynamic data for nitrous oxide, obtained from references 3, 4, 5, and 6, are presented in table I.

Extrapolation of the vapor-pressure curve (fig. 2) to the fusion temperature of -152.3° F for nitrous oxide (table I) indicates that the fusion temperature will equal the saturation temperature at a pressure of about 7 pounds per square inch absolute. Nitrous oxide cannot therefore be kept as a liquid unless it is under a pressure greater than 7 pounds per square inch absolute; if the nitrous oxide is kept as a liquid by self-refrigeration some precautions are necessary to prevent freezing.

Some of the tests were conducted using two internal coolants, water and a mixture of 50-percent water and 50-percent ethyl alcohol by volume. The ethyl alcohol was denatured with 5-percent methyl alcohol. The engine was cooled with a mixture of 30-percent ethylene glycol and 70-percent water by weight and was lubricated with Navy 1120 oil.

APPARATUS

Engine. - The tests were conducted on a single-cylinder setup of a multicylinder block mounted on a CUE crankcase. Cylinders 4, 5, and 6 were used to obtain the data for this report. A description of this engine is given in reference 7.

A piston providing a compression ratio of 6.0 and equipped with a chrome-plated keystone top ring was installed in the engine. Because of the high temperatures encountered during the tests, Nichrome-coated exhaust valves and cold-operating spark plugs were used to avoid preignition.

Nitrous oxide metering apparatus. - A diagrammatic sketch of the nitrous oxide system used with the test engine is shown in figure 3. The nitrous oxide tanks were inverted in order that the liquid would drain from them first. The nitrous oxide passed from the tanks through an expansion valve, which also regulated the flow rate, and into an evaporator where any remaining liquid was vaporized. The gas was then piped through a metering orifice and into the combustion-air surge tank.

Induction system. - The combustion air was taken from the central laboratory system and passed through a pressure-regulating valve; a measuring orifice, and an electric heater before entering the surge tank. In this tank, which had a capacity of about 18 cubic feet, the nitrous oxide and the combustion air were mixed. At the exit of the surge tank the fuel and the internal coolants (when used) were admitted to the mixture. The mixture then passed through the vaporization tank and to the engine-inlet port. The vaporization tank was equipped with several inclined baffles to aid in providing a homogeneous mixture of fuel, internal coolant, nitrous oxide, and air.

Instrumentation. - Thin-plate orifices, installed in accordance with A.S.M.E. standards, were used to measure the flow rates of the nitrous oxide and the combustion air. The differential pressures across these orifices were measured with water manometers. A Bourdon gage measured the pressure before the nitrous oxide orifice and a mercury manometer measured the pressure before the combustion-air orifice. The fuel-flow rate and the internal-coolant flow rate were measured with calibrated rotameters.

All temperatures were measured with iron-constantan thermocouples connected to a self-balancing potentiometer. The cylinder-head thermocouple was located between the exhaust-valve seats in the position indicated in figure 4.

DEFINITION OF TERMS

Nitrous oxide-air ratio. - Because the nitrous oxide was used to supplement the air in supporting conbustion, it was decided that the nitrous oxide flow should be expressed as a function of the air flow. For this reason the term "nitrous oxide-air ratio" (ratio of mass rate of flow of nitrous oxide to mass rate of flow of air) was selected to describe the nitrous oxide flow. The use of this dimensionless ratio facilitates the comparison of data obtained at different engine conditions.

Fuel-oxygen ratio.- The commonly used term "fuel-air ratio" cannot be used to describe adequately mixture strength when there is introduced some material that also supports combustion. The term "fuel-oxygen ratio" (ratio of mass rate of fuel flow to mass rate of oxygen flow with the oxygen in both the air and the nitrous oxide considered) has therefore been used throughout the report to describe mixture strength. Four values of fuel-oxygen ratio have been used in this investigation. With no nitrous oxide flow the fuel-air ratios equivalent to these fuel-oxygen ratios are:

Fuel-oxygen ratio	Fuel-air ratio
0.410	0.095
.453	.105
.495	.115
.539	.125

Optimum spark timing. - As used in this report the term "optimum spark timing" refers to the spark timing giving maximum power at constant manifold pressure for a given set of operating conditions.

Internal coolant-nitrous oxide ratio. - In the course of the investigation it was found that the use of nitrous oxide caused abnormally high cylinder temperatures. Because the amount of extra cooling required to limit these cylinder temperatures depends on the nitrous oxide flow, this extra cooling should be expressed as a function of nitrous oxide flow. When internal coolants were used to provide this extra cooling, the term "internal coolant-nitrous oxide ratio" (ratio of mass rate of internal-coolant flow to mass rate of nitrous oxide flow) was used as a measure of the amount of internal coolant supplied to the charge.

Ratio of supplemental fuel to nitrous oxide. - During a part of the investigation some data were obtained at rich mixtures to find the effect of mixture enrichment on cylinder cooling. In order to make these results comparable with the results of tests using internal coolants, the amount of mixture enrichment was expressed by the term "ratio of supplemental fuel to nitrous oxide." The supplemental fuel refers to the mass rate of fuel flow greater than that required for the basic fuel-oxygen ratio of 0.410.

TEST PROCEDURE

Throughout all tests the follwoing operating conditions were maintained:

Engine speed, rpm	3000
Compression ratio	6.0
Inlet-oil temperature, °F	185
Outlet-coolant temperature, °F	250
Coolant flow, gallons per minute	120

The nitrous oxide was injected as a gas for all tests. For each test the temperature of the inlet air upstream of the fuel and internal-coolant nozzles was adjusted in order to obtain the desired inlet-mixture temperature at the cylinder port without nitrous oxide. When the nitrous oxide was injected the mixture of nitrous oxide and air was heated to the temperature required for air alone. Because additional fuel was required to maintain a constant fuel-oxygen ratio with nitrous oxide supercharging, the mixture temperature at the cylinder port decreased slightly as the nitrous oxide flow was increased.

Test with constant manifold pressure. - The tests with constant manifold pressure were run with a certain basic operating condition from which each basic variable (except mixture temperature) was separately changed to determine the effects of nitrous oxide supercharging on engine performance at various operating conditions. The following table shows the basic variables and the values used when conditions other than the basic were tested.

Variable	Basic value	Values used
Manifold pressure, in Hg absolute	50	30, 50, 70
Fuel-oxygen ratio	0.410	[a]0.410 (0.095), 0.453 (0.105) 0.495 (0.115), 0.539 (0.125)
Spark timing, deg B.T.C.		
Inlet	28	14-52
Exhaust	34	20-58
Mixture temperature, °F (with no nitrous oxide flow)	150	150
Internal coolant-nitrous oxide ratio	0	0, 0.25, 0.50

[a]Values in parentheses indicate the corresponding fuel-air ratio with no nitrous oxide flow.

For all except the spark-timing tests, the nitrous oxide flow was the independent variable. For the spark-timing tests the nitrous oxide-air ratio was held constant while the spark timing was varied through the desired range.

The fuel used for all the tests with constant manifold pressure was 33-R.

Knock-limit tests. - Tests were run to determine the effect of nitrous oxide flow on the knock limit with 28-R and 33-R fuels. Both fuels were tested at the basic operating conditions (except manifold pressure) noted in the table for the constant manifold-pressure tests. In addition, knock tests were run with 33-R fuel with an enriched mixture (0.495 fuel-oxygen ratio) and with a lowered mixture temperature (approx. 60°F). Nitrous oxide flow was the independent variable for the knock tests.

RESULTS AND DISCUSSION

Results of Tests with Nitrous Oxide Injected as a Gas

Effect of nitrous oxide supercharging at constant manifold pressure. - Figure 5 shows the variation of indicated mean effective pressure with nitrous oxide-air ratio for constant manifold pressures of 30, 50, and 70 inches of mercury absolute. The percentage increases in indicated mean effective pressure for various nitrous oxide-air ratios are presented in table II for a manifold pressure of 50 inches of mercury absolute. These data show that the power output increased almost linearly with the nitrous oxide-air ratio. A nitrous oxide-air ratio of 0.1 resulted in an increase of about 14 percent in power output and a ratio of 0.2 resulted in an increase of about 25 percent. The percentage values varied only a small amount with manifold pressure, becoming slightly less as the manifold pressure was increased.

In figure 6 the cylinder-head temperature is plotted as a function of indicated mean effective pressure for these same tests. The increase in the cylinder-head temperature was considerably greater for a given increase in power output with nitrous oxide supercharging than with air supercharging. This effect caused considerable trouble with preignition at the higher outputs until colder-operating spark plugs were installed. This rapidly rising cylinder-head temperature is probably caused by higher equilibrium flame temperatures associated with the increased oxygen concentration in the charge.

Effect of nitrous oxide supercharging on the knock limit. - The knock-limited performance of 28-R and 33-R fuels with nitrous oxide supercharging is shown in figure 7. With both fuels the knock-limited power output was increased when nitrous oxide was injected whereas the knock-limited manifold pressure was decreased. With a nitrous oxide-air ratio of 0.1 the knock-limited indicated mean effective pressure was increased about 9 percent for both fuels with a decrease in knock-limited manifold pressure of about 2 percent; with a nitrous oxide-air ratio of 0.2 the increase in knock-limited indicated mean effective pressure was about 17 percent with a decrease in knock-limited manifold pressure of about 4 percent.

Data similar to those shown in figure 7 were obtained at a richer mixture (0.495 fuel-oxygen ratio) and at a lower inlet-mixture temperature and are plotted as a function of inlet-mixture temperature in figure 8. Straight lines were drawn between the points because only two mixture temperatures were tested for each fuel-oxygen ratio. Here again the knock-limited indicated mean effective pressure was raised and the knock-limited manifold pressure was lowered as the nitrous oxide-air ratio was increased for all engine conditions tested. As the mixture temperature was lowered with the leaner fuel-oxygen ratio, the presence of nitrous oxide caused the knock-limited power output to be also lowered; with the richer fuel-oxygen ratio the injection of nitrous oxide caused the knock-limited power output to increase as the mixture temperature was lowered. These facts are important in estimating the effect on engine performance of injecting nitrous oxide as a liquid.

Spark-timing requirements with nitrous oxide supercharging. - The results of tests to determine optimum spark timing with varying percentages of nitrous oxide at two fuel-oxygen ratios are presented in figure 9; figure 10 shows optimum spark timing as a function of the nitrous oxide-air ratio. It will be noted that in all cases the optimum spark timing was retarded as the percentage of nitrous oxide in the charge was increased; this effect became more pronounced as the mixture was enriched. The richer fuel-oxygen ratio tested (0.495) is near the limit of inflammability for fuel-air mixtures and consequently required a large ignition advance to compensate for the resultant low flame speed. Increasing the oxygen concentration in the charge by the addition of nitrous oxide increases the flame speed and permits optimum operation at a much more retarded spark timing.

The fuel consumption was reduced appreciably with the addition of nitrous oxide. (See fig. 9.) This decrease is probably caused by two effects: (1) Nitrous oxide has a positive heat of formation (table I) and therefore liberates energy as it dissociates in the combustion chamber, and (2) the increased concentration of oxygen in the charge causes higher equilibrium flame temperatures, which increase the engine efficiency.

Effect of internal cooling in conjunction with nitrous oxide supercharging. - From the results of the tests at constant manifold pressure and from the knock tests, it appears that the main problem associated with the use of nitrous oxide for extra supercharging is cylinder cooling. For this reason tests were run to determine the effects of mixture enrichment (internal cooling with supplemental fuel) and of internal cooling with water and water-alcohol on the cylinder-head temperature. The results of tests at constant manifold pressure to determine the effects of supplemental fuel as a means of cooling are presented in figure 11. These data show that as the nitrous oxide-air ratio was increased the loss in power caused by enriching the mixture became less until at a high nitrous oxide-air ratio the mixture could be greatly enriched with no loss in power. At the same time the cylinder-head temperature was considerably lowered by mixture enrichment.

Some of these data were replotted in figure 12 with cylinder-head temperature as a function of indicated mean effective pressure; the curves for supplemental fuel were obtained from the data of figure 11 by interpolation. The dashed line represents the cylinder-head temperatures encountered with air supercharging at a fuel-oxygen ratio of 0.410. If the cylinder-head temperature encountered with air supercharging can be tolerated for the desired increase in power output, then the amount of supplemental fuel required to limit this temperature to the air-supercharging value when using nitrous oxide supercharging will be about 10 percent of the nitrous oxide flow. If the cylinder-head temperature cannot be allowed to exceed the original value at the power level at which nitrous oxide injection was begun, the amount of supplemental fuel required will be about 20 percent of the nitrous oxide flow.

Data are shown in figure 13 for internal cooling with water and water-alcohol. For the intermediate internal coolant-nitrous oxide ratio (0.25) both of these internal coolants resulted in a very slight increase in power as compared with the slight decrease noted for cooling with supplemental fuel. The leveling of the mixture-temperature curves in figure 13 indicates saturation of the mixture with the internal coolants. Data from figure 13 were replotted in figure 14 with cylinder-head temperature as a function of indicated mean effective pressure. With both of the coolants (water and water-alcohol) the rate of flow required to limit the temperature to that obtained with air supercharging was about 25 percent of the nitrous oxide flow as compared with the 10 percent previously mentioned for cooling with supplemental fuel. In order to limit the cylinder-head temperature to the original value at the power level where nitrous oxide injection was begun, it appears that the flow of either water or water-alcohol would have to be about 40 percent of the nitrous oxide flow. The corresponding flow rate for supplemental fuel in this case was 20 percent.

The results just mentioned show that the amount of supplemental fuel required for cooling the cylinder with nitrous oxide supercharging was less than half the required amount of either water or water-alcohol. It has also been shown that the effect on power output was small for any of these methods of internal cooling. When knock is not a limitation the use of mixture enrichment is preferable to water or water-alcohol injection if the nitrous oxide flow rate is such that extra cooling is required. When knock is a limitation, however, it may be necessary to resort to water or water-alcohol injection because mixture enrichment decreased the knock limit at these low mixture temperatures. (See fig. 8.)

Estimation of Results with Nitrous Oxide Injected as a Liquid

<u>Power output at constant manifold pressure.</u> - In a multicylinder engine the nitrous oxide would probably be injected into the induction system as a liquid rather than as a gas because of the comparative simplicity of the liquid system and because of the charge cooling obtained by the evaporation of the liquid. For this reason calculations were made to estimate the power output that would be

obtained at constant manifold pressure with nitrous oxide injected as a liquid at its normal boiling point (-128°F). The methods used in making these calculations appear in the appendix.

Figure 15 and table III show the power output that could be obtained with liquid nitrous oxide injection as compared with the power output obtained with gaseous injection at constant manifold pressure. It appears from figure 15 that the increase in power output obtained by liquid injection would be about double the increase obtained by gaseous injection at all valves of nitrous oxide-air ratio. The nitrous oxide, however, lowers the inlet-mixture temperature so much when injected in this manner that little of the fuel would be vaporized at the time of induction into the cylinder, which would probably lead to mixture-distribution difficulties with the multicylinder engine. If extremely high nitrous oxide-air ratios were used (above 0.2) the mixture temperature might even be lowered so much that the use of water injection for cylinder cooling would cause icing in the induction system. The best solution for these difficulties would be to inject the nitrous oxide into the intake manifolds as near as possible to the individual cylinder ports. The desirable feature of higher charge-air density (due to lower mixture temperature) would be partly lost because of lack of time for complete vaporization and mixing before induction into the cylinder; this loss would be compensated for in some measure, however, by the high density of the liquid nitrous oxide entering the cylinder.

Knock-limited power output. - The lowered inlet-mixture temperatures brought about by injection of the nitrous oxide as a liquid would be of doubtful value where the knock limit is concerned. Figure 8 shows that at the basic fuel-oxygen ratio of 0.410 the presence of nitrous oxide caused the knock-limited indicated mean effective pressure to be lowered as the mixture temperature was lowered. These curves have been used for determining the values of knock-limited indicated mean effective pressure with liquid nitrous oxide injection given in table III. (See the appendix for methods used in making these determinations.) On the basis of these curves and the information in table III it is seen that the nitrous oxide would increase the knock-limited power only about half as much with liquid injection as with gaseous injection. If mixture enrichment is used to limit the cylinder temperatures when using nitrous oxide, this situation may be changed to some extent because figure 8(b) shows the knock-limited power at a richer mixture (fuel-oxygen ratio of 0.495) to be increased as the mixture temperature is lowered.

SUMMARY OF RESULTS

The results of the tests and calculations to investigate the possibilities of using nitrous oxide for extra supercharging at high altitudes are summarized as follows:

Injection as a gas (test results):

1. With constant manifold pressure, the nitrous oxide increased the power output about 14 percent on an indicated basis at a nitrous oxide-air ratio of 0.1; this increase amounted to about 25 percent at a ratio of 0.2.

2. The knock-limited power output was increased about 9 percent on an indicated basis with a nitrous oxide-air ratio of 0.1 and about 17 percent with a nitrous oxide-air ratio of 0.2. The knock-limited manifold pressure was decreased about 2 percent and 4 percent, respectively, for these ratios.

3. Increasing the oxygen concentration in the charge by the addition of nitrous oxide increased the flame speed, resulting in decreased values of optimum spark timing. This effect was especially notable at extremely rich fuel-oxygen ratios.

4. The use of nitrous oxide resulted in abnormally high cylinder-head temperatures. When knock is not a limitation, these temperatures can be controlled to best advantage by the use of mixture enrichment. When knock is a limitation, the use of water or water-alcohol injection may be preferable.

Injection as a liquid at -128°F (calculated results):

1. The nitrous oxide would lower the inlet-mixture temperature to such an extent when injected as a liquid that poor mixture distribution may result unless special means are provided to prevent this difficulty. When mixture distribution is not a problem, calculations indicate that the liquid nitrous oxide would increase the indicated power output about twice as much as with gaseous injection for a given manifold pressure.

2. Calculations and test data show that the lowered mixture temperatures brought about by injection of nitrous oxide as a liquid should cause the knock-limited indicated power output to be somewhat lower than that obtained with gaseous injection of a fuel-oxygen ratio of 0.410. At richer fuel-oxygen ratios, however, the knock-limited power was increased as the mixture temperature was lowered.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, June 26, 1945.

APPENDIX - ESTIMATION OF ENGINE PERFORMANCE WITH INJECTION OF LIQUID NITROUS OXIDE

During the investigation made at the NACA on supercharging with nitrous oxide, the tests were all conducted with nitrous oxide injected as a gas and then heated to the temperature of the inlet air. The use of liquid nitrous oxide at a low temperature, however, would bring about a pronounced drop in the inlet-mixture temperature at the cylinder port and would therefore have an effect on engine performance.

Evaluation of the cooling effect of the nitrous oxide was first necessary. The evaporation of the fuel would probably not be complete at the resulting low inlet-mixture temperatures; data were obtained to show the variation of mixture temperature with inlet-air temperature in this low-temperature range. The curve plotted from these data were used in the calculations.

The cooling effect of the nitrous oxide was determined from the equation

$$W_a \, c_{p_a} \, (t_a - t_m) = W_{N_2O}\left[c_{p_{N_2O}}\left(t_m - t_{N_2O}\right) + H_{v_{N_2O}}\right] \qquad (1)$$

where

W_a mass rate of flow of air, lb/hr

W_{N_2O} mass rate of flow of nitrous oxide, lb/hr

c_{p_a} specific heat of air at constant pressure, Btu/(lb)(°F)

$c_{p_{N_2O}}$ specific heat of nitrous oxide gas at constant pressure, Btu/(lb)(°F)

t_a initial temperature of the air, °F

t_{N_2O} initial temperature of the nitrous oxide, °F

t_m temperature of the resulting mixture, °F

$H_{v_{N_2O}}$ latent heat of vaporization of nitrous oxide at temperature t_{N_2O}, Btu/lb

When values of 0.24 for c_{p_a}, 0.212 for $c_{p_{N_2O}}$, 171.5 for $H_{v_{N_2O}}$, 210 for t_a, and -128 for t_{N_2O} are substituted into equation (1) and it is solved for t_m, the equation becomes

$$t_m = \frac{50.4 - 198.6\ (W_{N_2O}/W_a)}{0.24 + 0.212\ (W_{N_2O}/W_a)} \tag{2}$$

where $W_{N_2O}\ W_a$ is the nitrous oxide-air ratio. The inlet-air temperature of 210° F was taken from the curve to correspond to an inlet-mixture temperature at 150° F.

Equation (2) was used to calculate the resultant temperature for various mixtures of nitrous oxide and air. The mixture temperature corresponding to the calculated inlet-air temperature was determined by means of the curve previously mentioned.

The increase in indicated engine output caused by charge cooling is dependent upon the increase in charge density and is given by the reciprocal of the ratio of the absolute temperatures. Accordingly, the increase in indicated mean effective pressure with the use of liquid nitrous oxide is given by

$$(imep)_l = (imep)_g\ (T_g/T_l) \tag{3}$$

where

$(imep)_l$ indicated mean effective pressure with liquid nitrous oxide, lb/sq in.

$(imep)_g$ indicated mean effective pressure with gaseous nitrous oxide, lb/sq in.

T_l mixture temperature at the cylinder port with liquid nitrous oxide, °R

T_g mixture temperature at the cylinder port with gaseous nitrous oxide, °R

Values of $(imep)_g$ were taken from figure 5, and a mixture temperature of 610° R was used for T_g. Equation (3) was then used to determine the indicated mean effective pressures for liquid nitrous oxide injection at constant manifold pressure.

The knock-limited performance estimates were made by interpolation of figure 8 at the calculated mixture temperature.

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TABLE I - THERMODYNAMIC PROPERTIES OF NITROUS OXIDE

Property	Value	Conditions	Reference
Heat of formation, Btu/lb	691	Gas at 64.4° F and 14.7 lb/sq in. absolute	4 (p. 162)
Latent heat of vaporization, Btu/lb	172.3	-130° F	3 (p. 48)
	139.1	-40° F	3 (p. 48)
	121.4	5° F	3 (p. 48)
	95.8	50° F	3 (p. 48)
Specific heat of liquid, Btu/(lb)(°F)	0.422	-125° F	5 (pp. 107-109)
Specific heat of gas at constant pressure, Btu/(lb)(°F)	0.212	5°-86° F	5 (pp. 107-109)
Ratio of specific heats of gas	1.280	5°-86° F	5 (pp. 107-109)
Density of liquid, lb/cu ft	81.2	-130° F	3 (p. 48)
	39.1	86° F	3 (p. 48)
Fusion temperature, °F	-152.3	------------------	6 (pp. 454-455)

TABLE II - INCREASES IN ENGINE POWER WITH NITROUS OXIDE INJECTION AT CONSTANT MANIFOLD PRESSURE

Nitrous oxide-air ratio	Nitrous oxide injected as gas at 210° F		Nitrous oxide injected as liquid at -128°F (a)	
	Indicated mean effective pressure	Percentage increase	Indicated mean effective pressure	Percentage increase
0.00	237	---------	237	---------
.05	255	8	275	16
.10	271	14	311	31
.15	285	20	338	43
.20	297	25	369	56
.25	307	30	406	71

[a]Calculated values.

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TABLE III - KNOCK-LIMITED PERFORMANCE WITH NITROUS OXIDE INJECTION

[Fuel, 33-R; fuel-oxygen ratio, 0.410]

Nitrous oxide-air ratio	Nitrous oxide injected as gas at 210° F			Nitrous oxide injected as liquid at -128° F (a)		
	Knock-limited manifold pressure (in. Hg absolute)	Knock-limited indicated mean effective pressure (lb/sq in.)	Percentage increase in indicated mean effective pressure	Knock-limited manifold pressure (in. Hg absolute)	Knock-limited indicated mean effective pressure (lb/sq in.)	Percentage increase in indicated mean effective pressure
0.00	80.5	385	----------	80.5	385	----------
.05	79.6	405	5	75.0	404	5
.10	78.8	420	9	69.1	415	8
.15	78.0	436	13	[b]64.5	[b]422	10
.20	[b]77.0	[b]452	17	----------	----------	----------

[a]Calculated values.
[b]Extrapolated.

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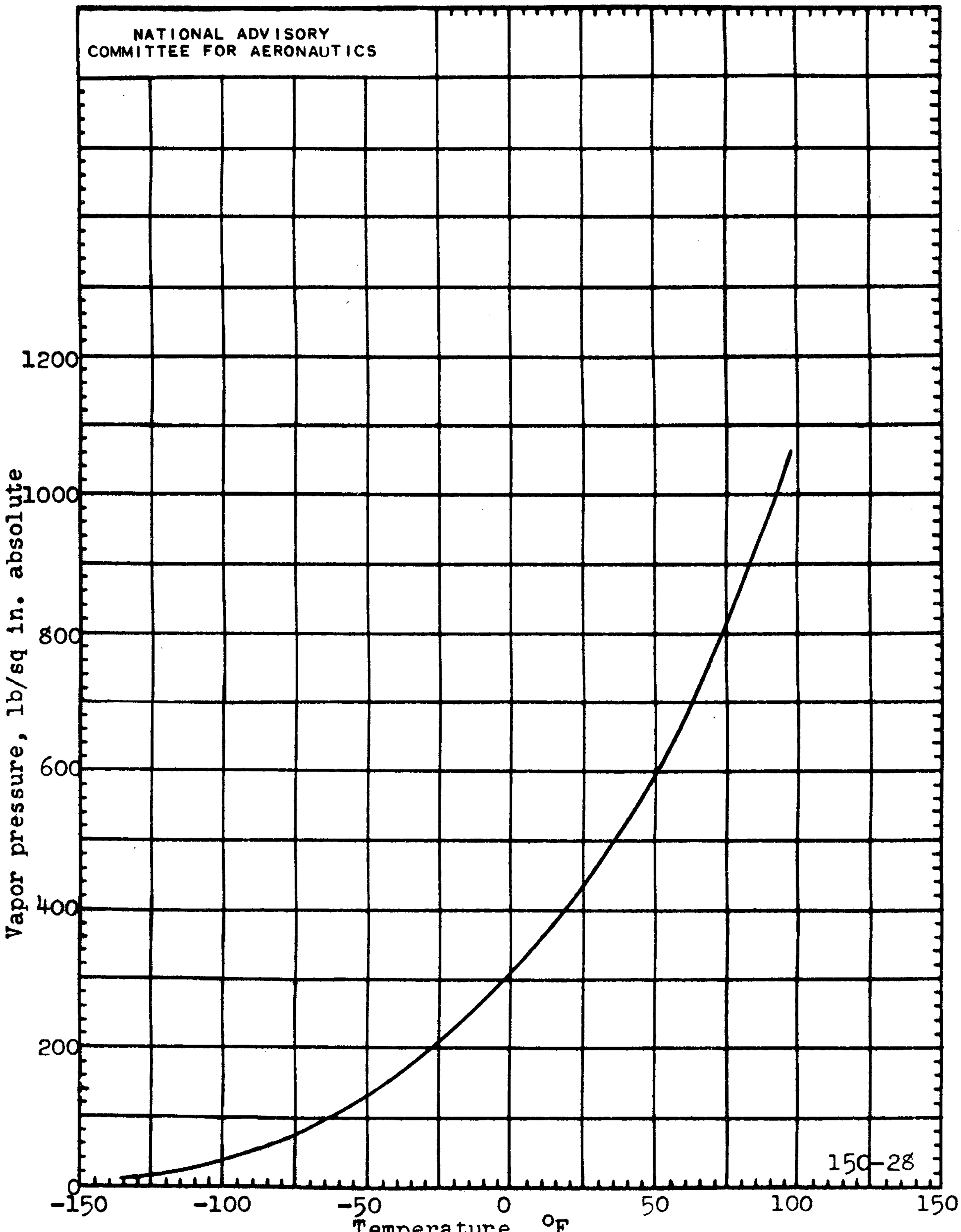

Figure 2. - Variation of vapor pressure of nitrous oxide with temperature. Data from reference 3, page 48.

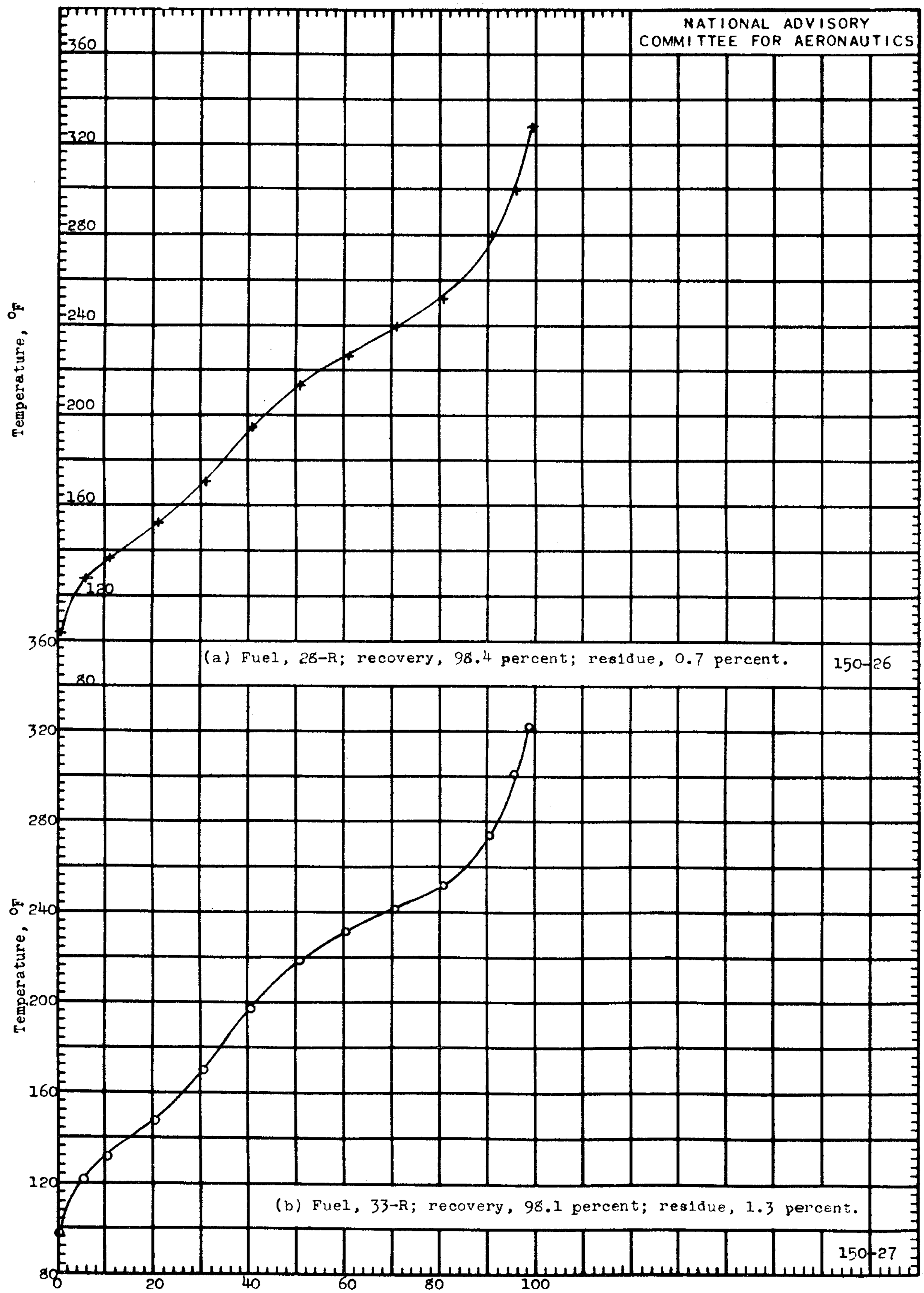

Figure 1. - A.S.T.M. distillation curves for the fuels used in tests.

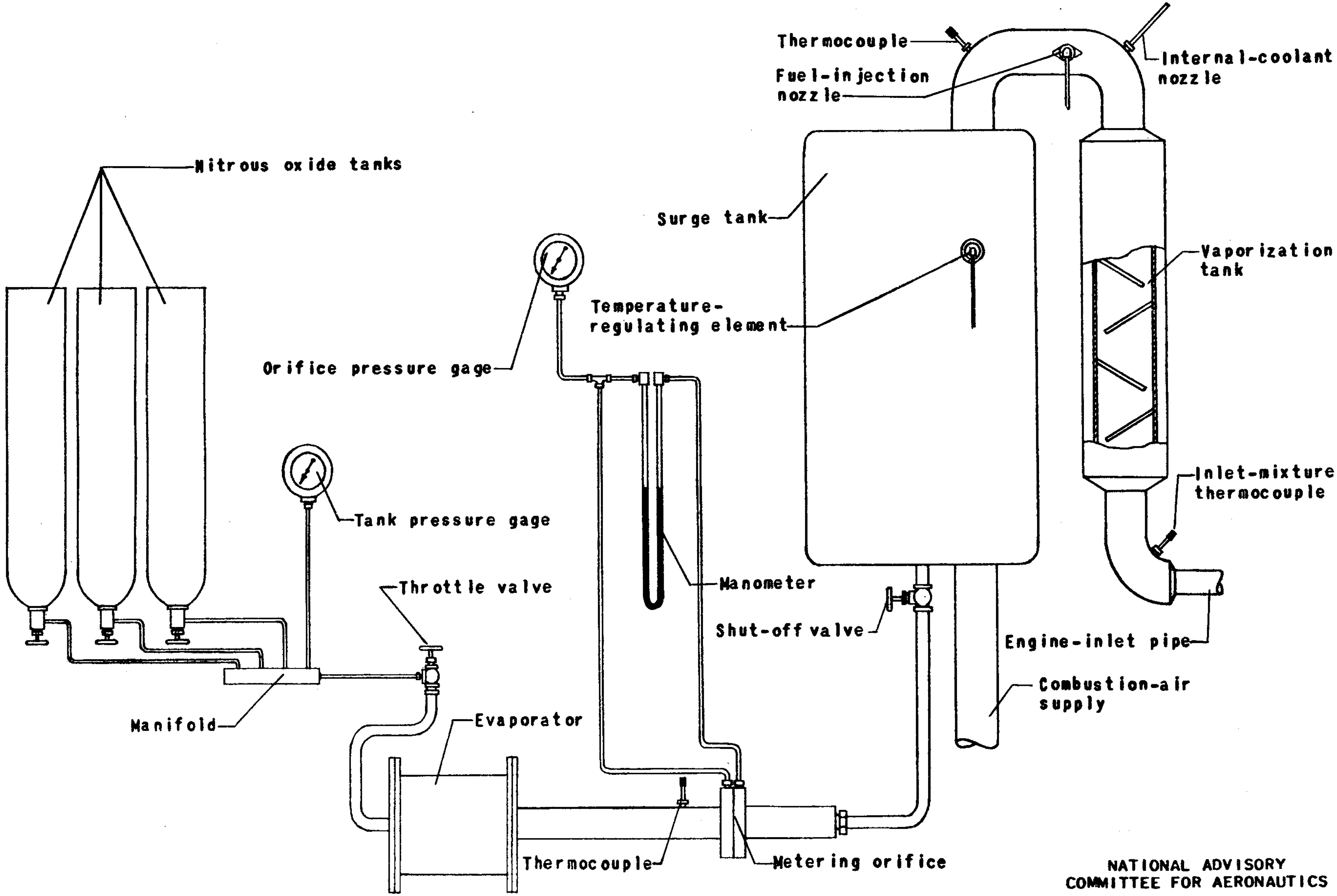

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Figure 3. - Nitrous oxide supply system used with the test engine.

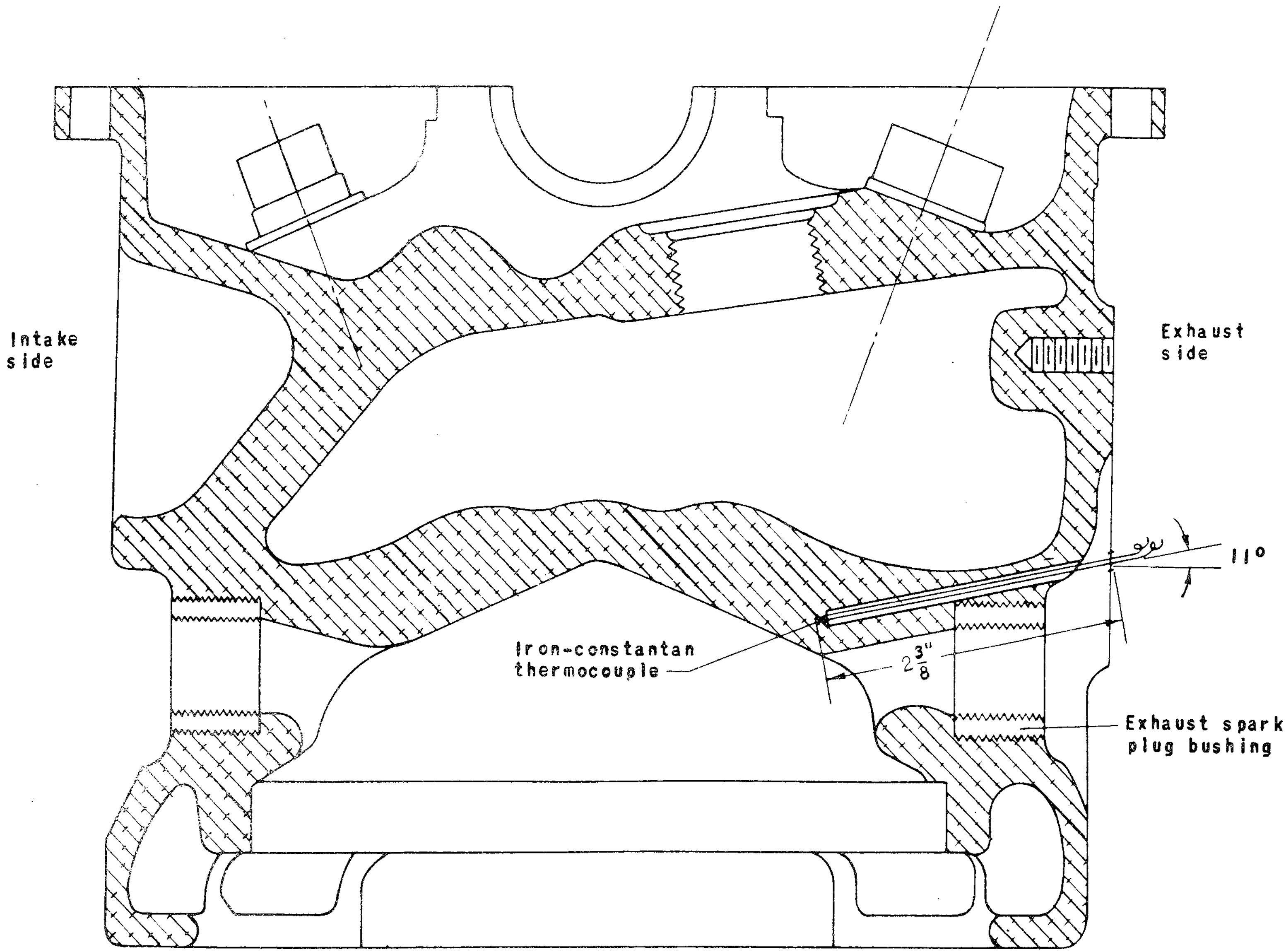

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Figure 4. - Location of thermocouple in cylinder head.

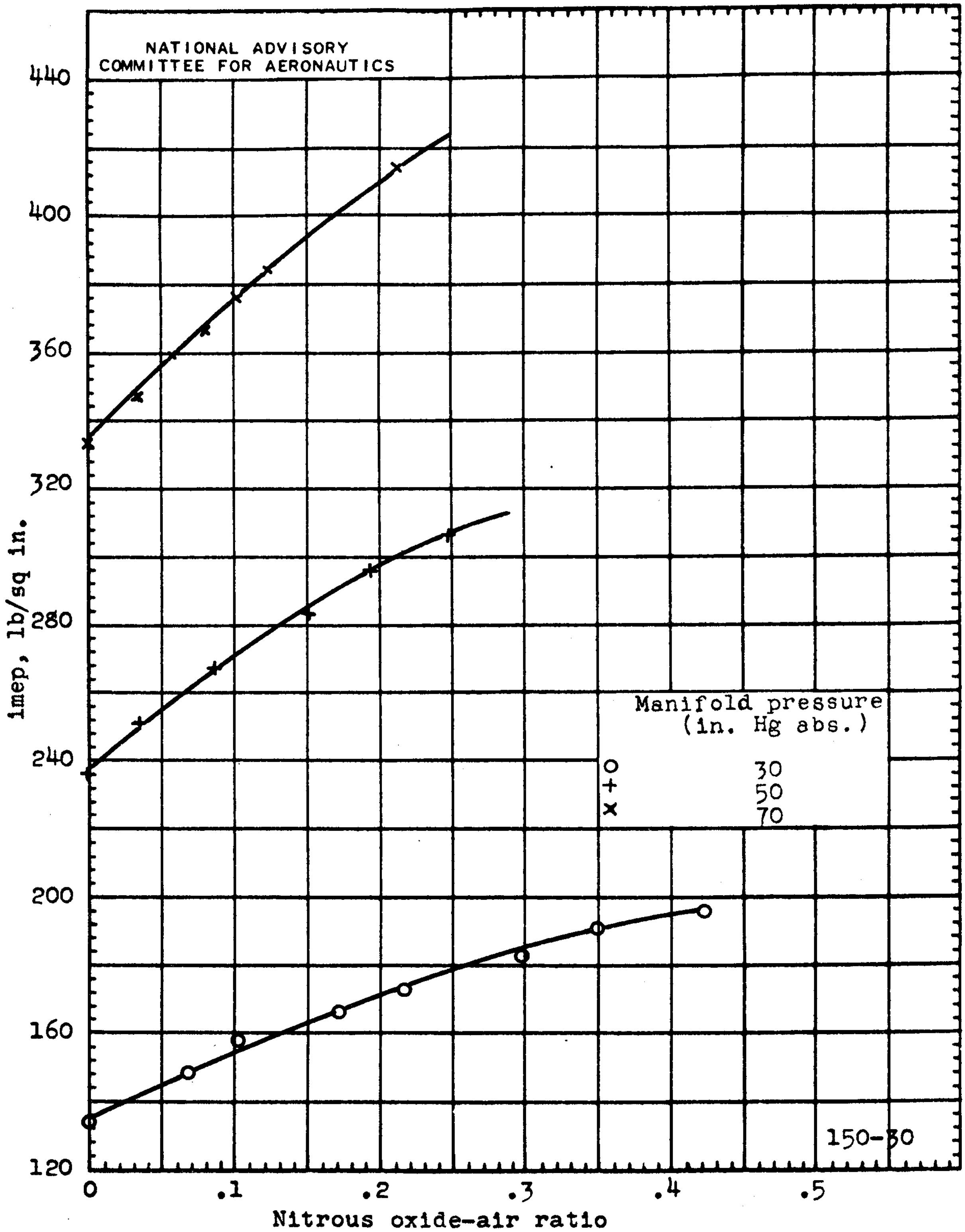

Figure 5. - Variation of indicated mean effective pressure with nitrous oxide-air ratio at three constant manifold pressures. Engine speed, 3000 rpm; initial inlet-mixture temperature, 150° F; compression ratio, 6.0; fuel-oxygen ratio, 0.410; inlet-oil temperature, 185° F; outlet-coolant temperature, 250° F; fuel, 33-R.

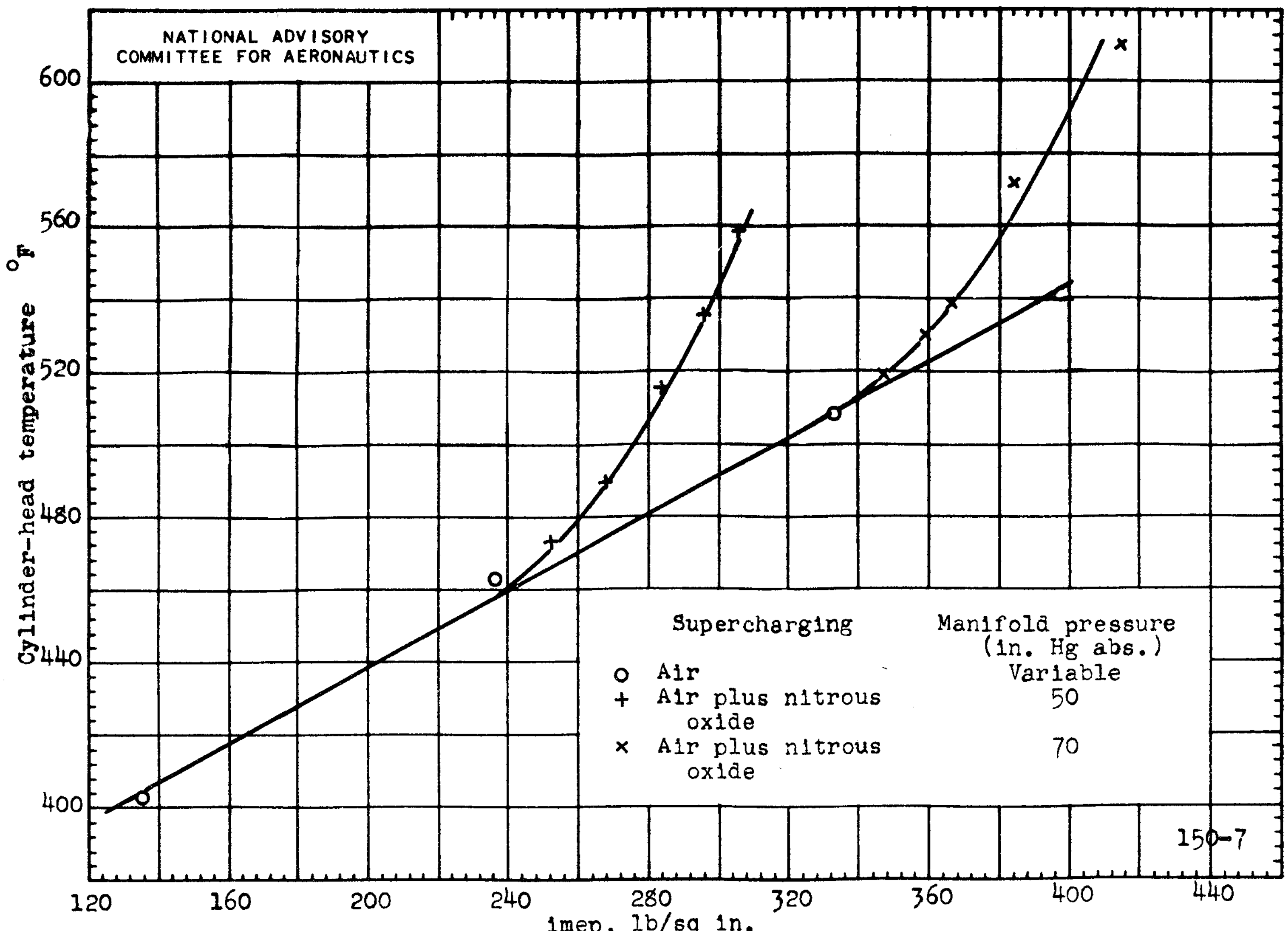

Figure 6. - Variation of cylinder-head temperature with indicated mean effective pressure for air and for nitrous oxide supercharging. Engine speed, 3000 rpm; initial inlet-mixture temperature, 150° F; compression ratio, 6.0; fuel-oxygen ratio, 0.410; inlet-oil temperature, 185° F; outlet-coolant temperature, 250° F; fuel, 33-R.

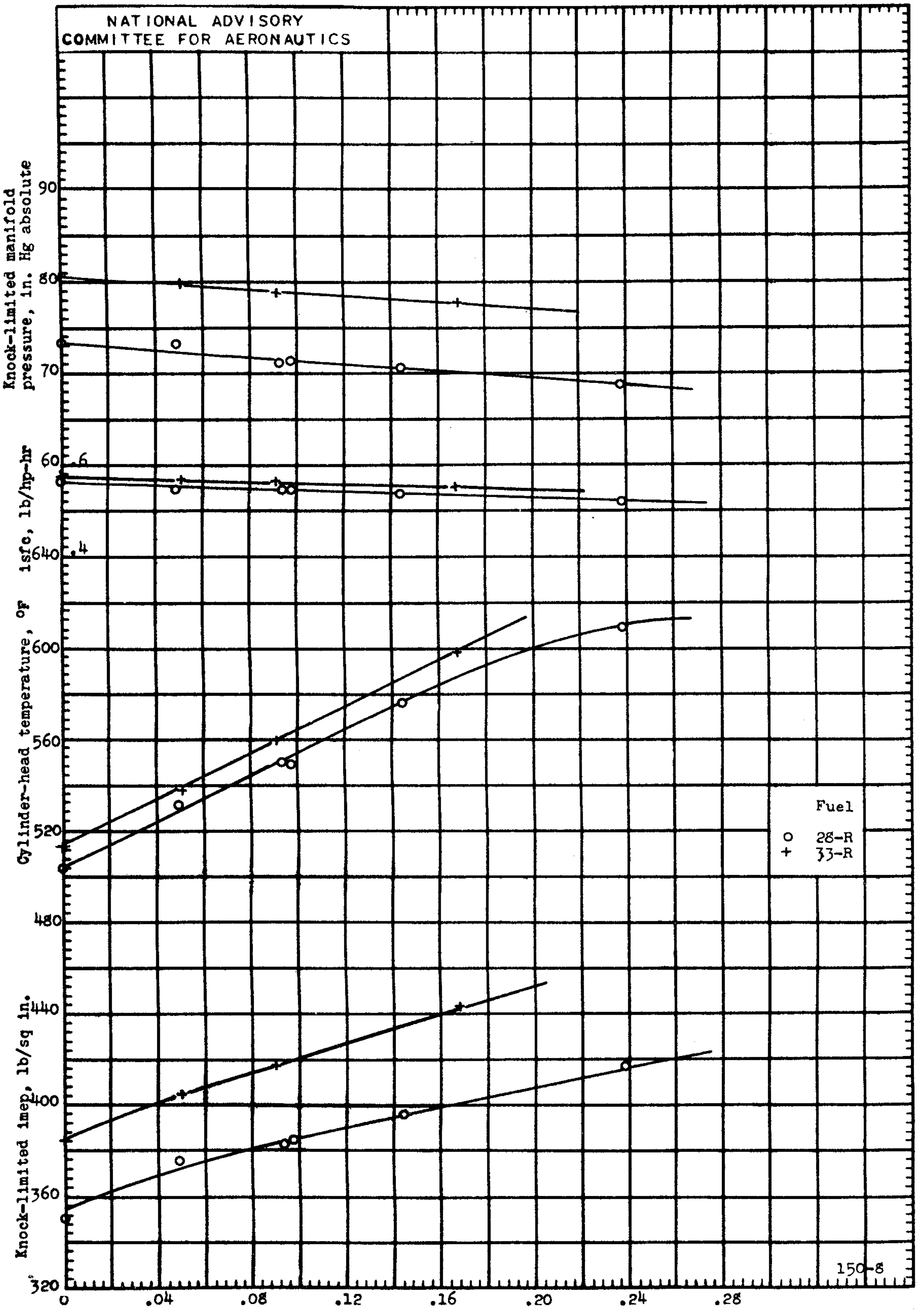

Figure 7. - Knock-limited performance of 28-R and 33-R fuels in single-cylinder engine with nitrous oxide supercharging. Engine speed, 3000 rpm; initial inlet-mixture temperature, 150° F; compression ratio, 6.0; fuel-oxygen ratio, 0.410; inlet-oil temperature, 185° F; outlet-coolant temperature, 250° F.

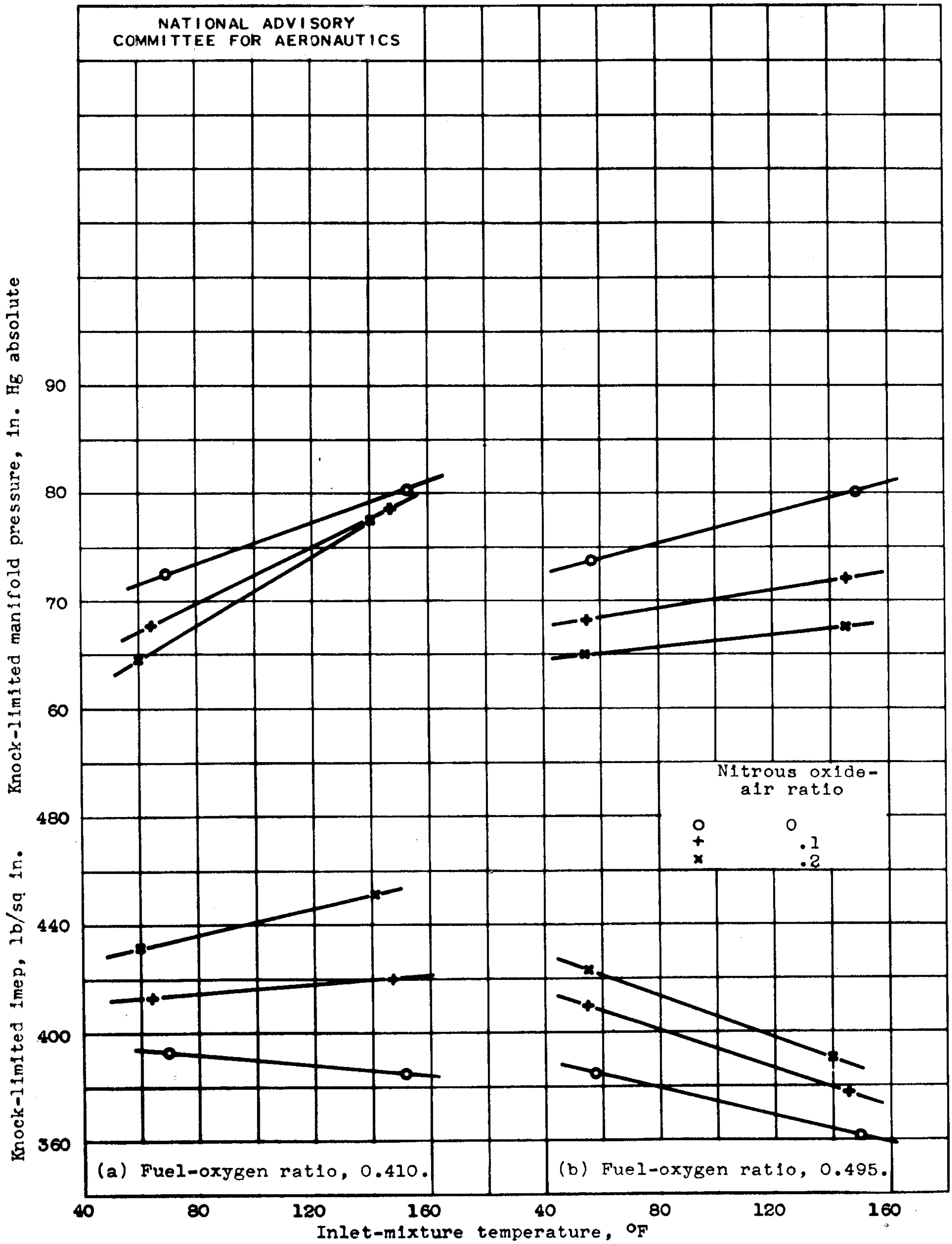

Figure 8. - Effect of inlet-mixture temperature and fuel-oxygen ratio on knock-limited performance of single-cylinder engine with nitrous oxide supercharging. Engine speed, 3000 rpm; compression ratio, 6.0; inlet-oil temperature, 185° F; outlet-coolant temperature, 250° F; fuel, 33-R.

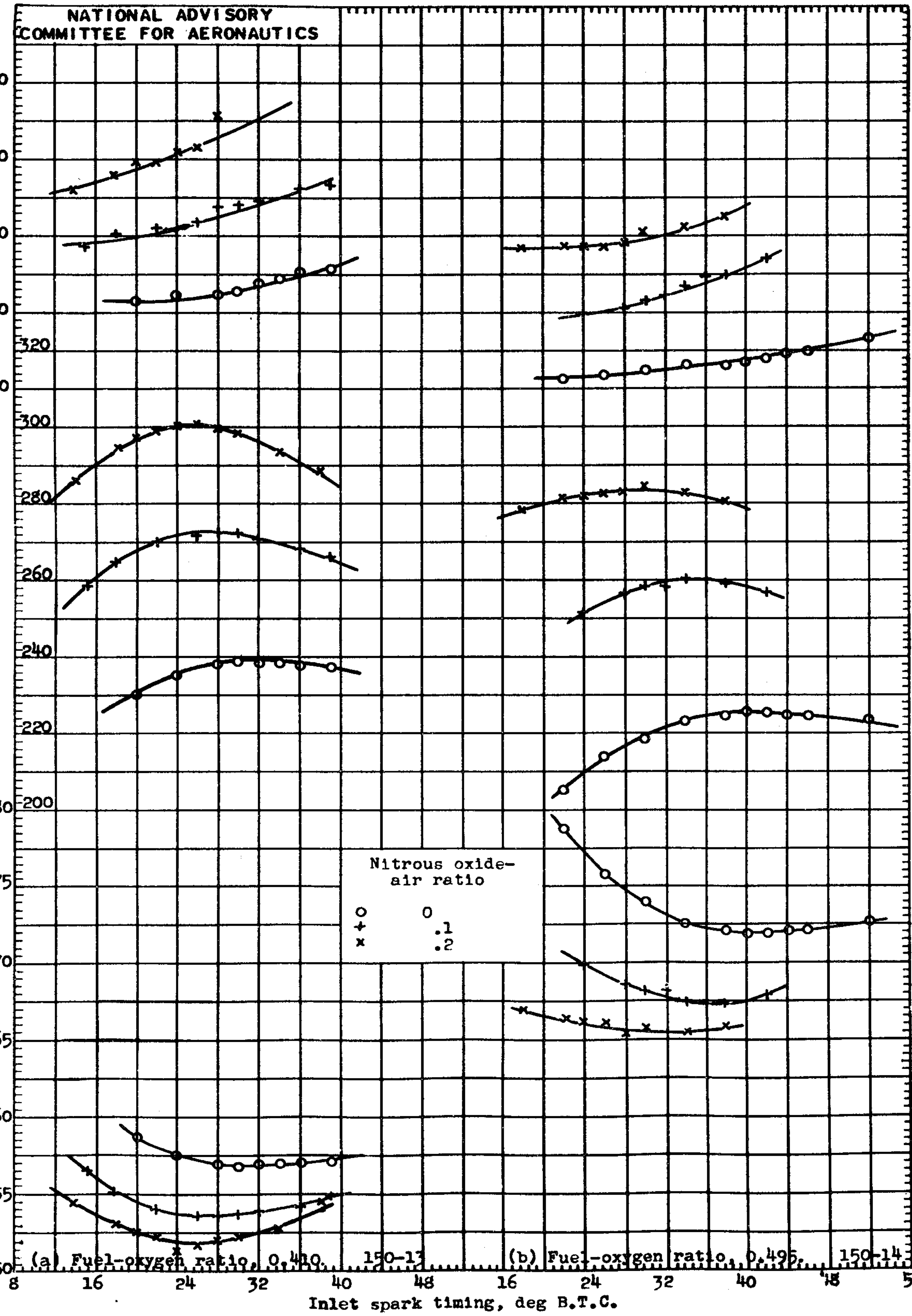

Figure 9. - Effect of spark timing on performance of single-cylinder engine with nitrous oxide supercharging. Exhaust spark timing advanced 6° beyond inlet spark timing. Engine speed, 3000 rpm; manifold pressure, 50 inches mercury absolute; initial inlet-mixture temperature, 150° F; compression ratio, 6.0; inlet-oil temperature, 185° F; outlet-coolant temperature, 250° F; fuel, 33-R.

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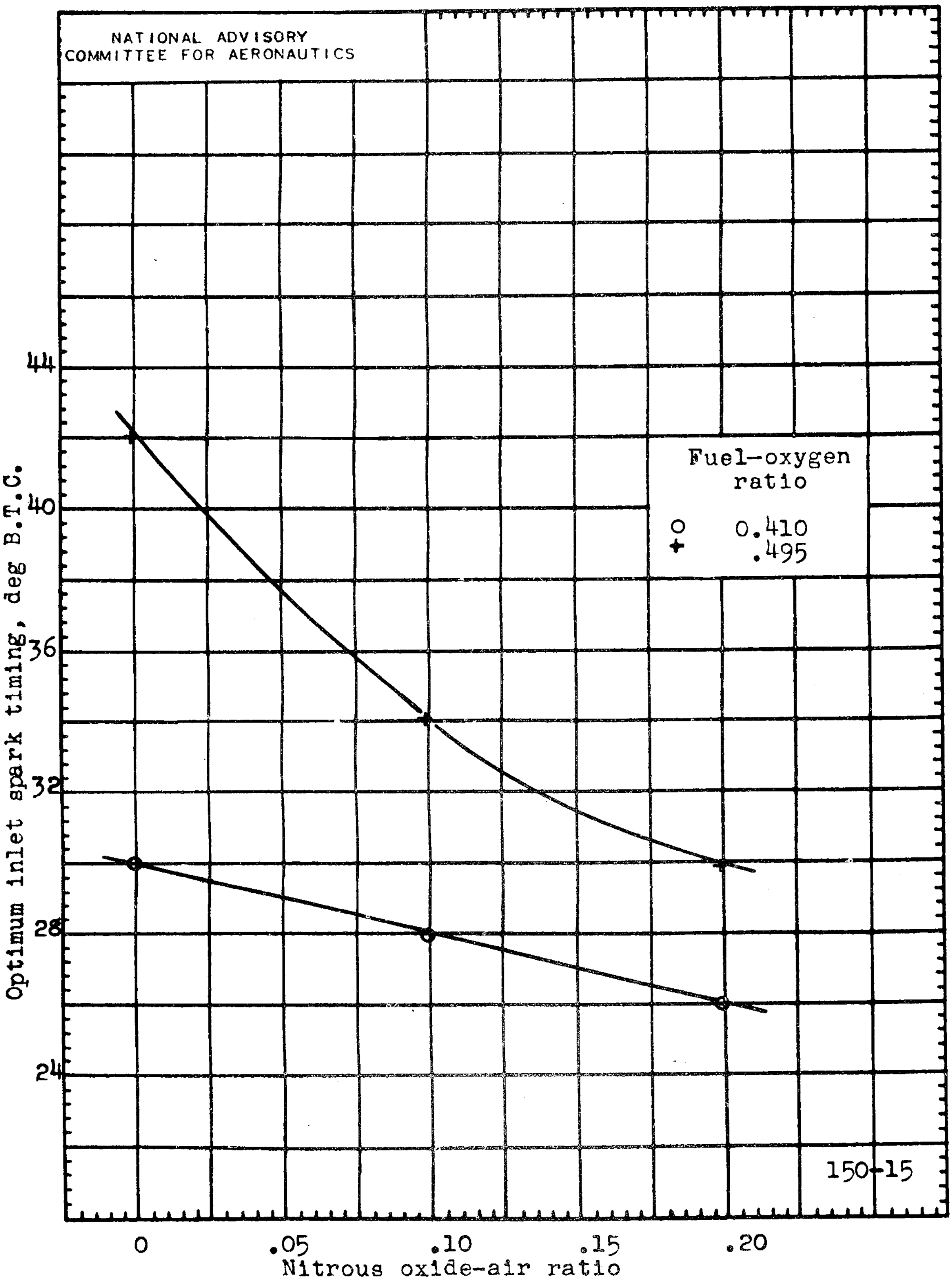

Figure 10. - Variation of optimum inlet spark timing with nitrous oxide-air ratio. Cross plot of figure 9.

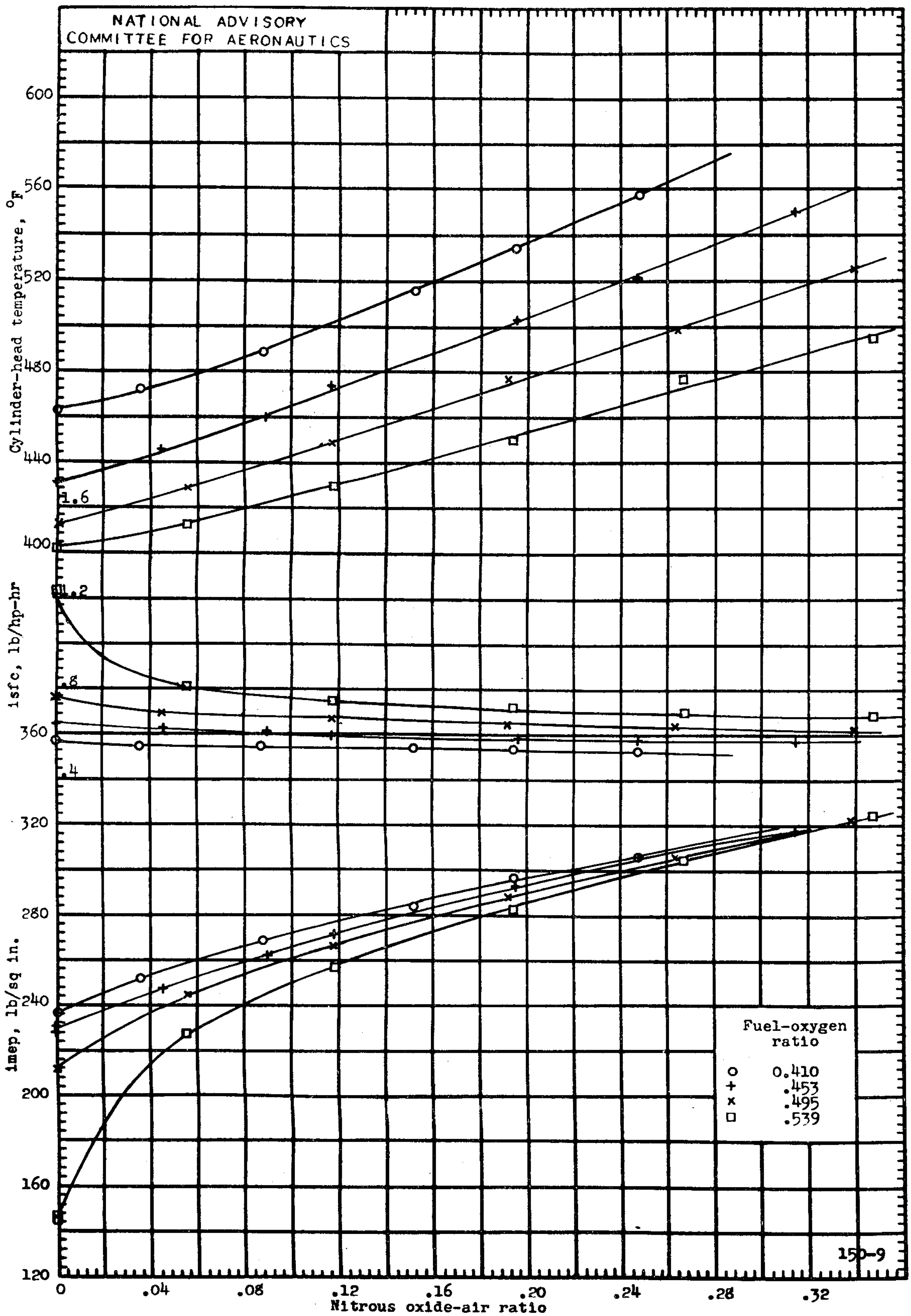

Figure 11. - Effect of nitrous oxide-air ratio on performance of single-cylinder engine at four fuel-oxygen ratios. Engine speed, 3000 rpm; manifold pressure, 50 inches mercury absolute; initial inlet-mixture temperature, 150° F; compression ratio, 6.0; inlet-oil temperature, 185° F; outlet-coolant temperature, 250° F; fuel, 33-R.

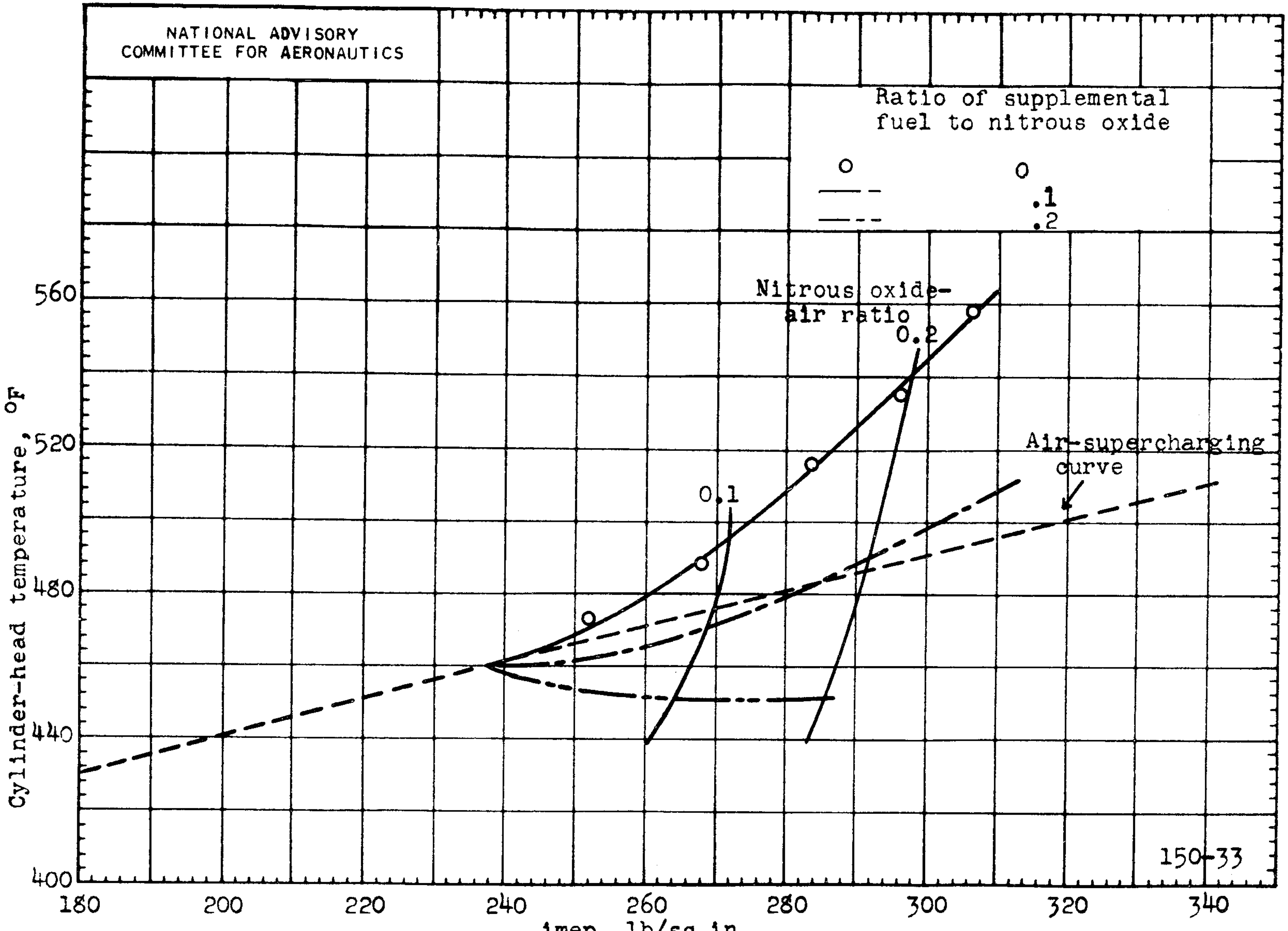

Figure 12. - Variation of cylinder-head temperature with indicated mean effective pressure using supplemental fuel for internal cooling. Plotted by interpolation of figure 11.

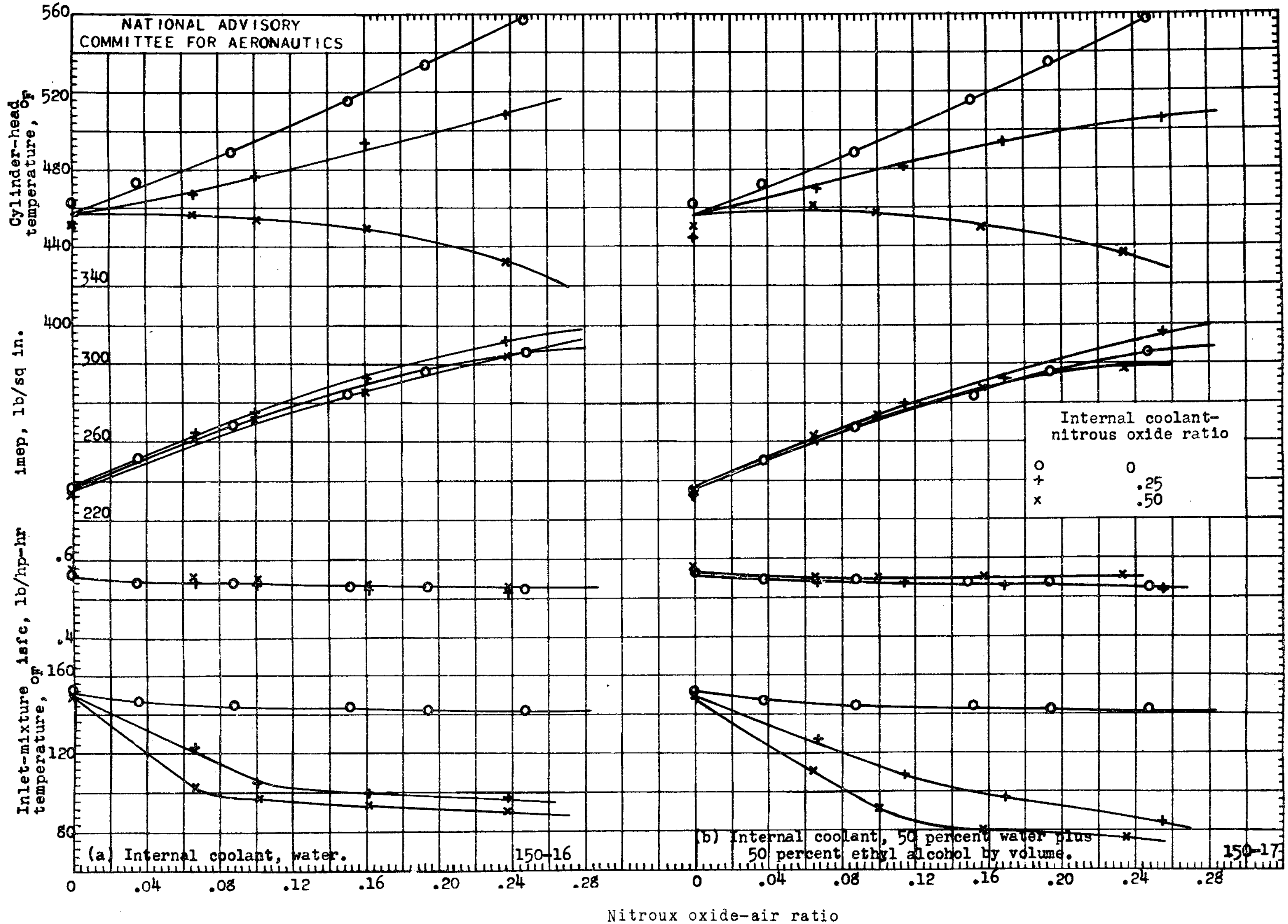

Figure 13. - Effect of nitrous oxide-air ratio on performance of single-cylinder engine with internal cooling. Engine speed, 3000 rpm; manifold pressure, 50 inches mercury absolute; compression ratio, 6.0; fuel-oxygen ratio, 0.410; inlet-oil temperature, 185° F; outlet-coolant temperature, 250° F; fuel, 33-R.

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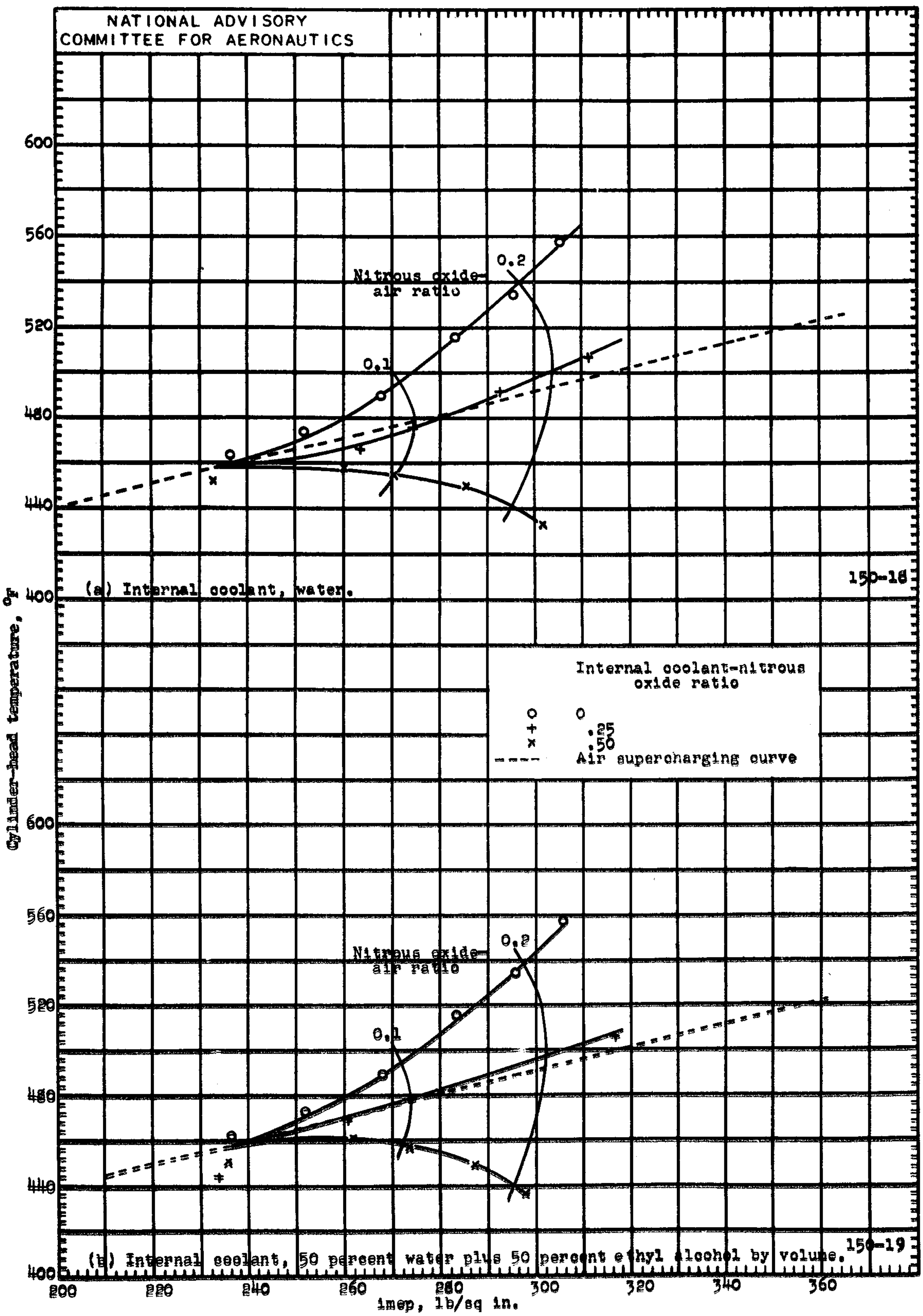

Figure 14. - Variation in cylinder-head temperature with indicated mean effective pressure with nitrous oxide supercharging and internal cooling. Engine speed, 3000 rpm; manifold pressure, 50 inches mercury absolute; initial inlet-mixture temperature, 150° F; compression ratio, 6.0; fuel-oxygen ratio, 0.410; inlet-oil temperature, 185° F; outlet-coolant temperature, 250° F; fuel, 33-R.

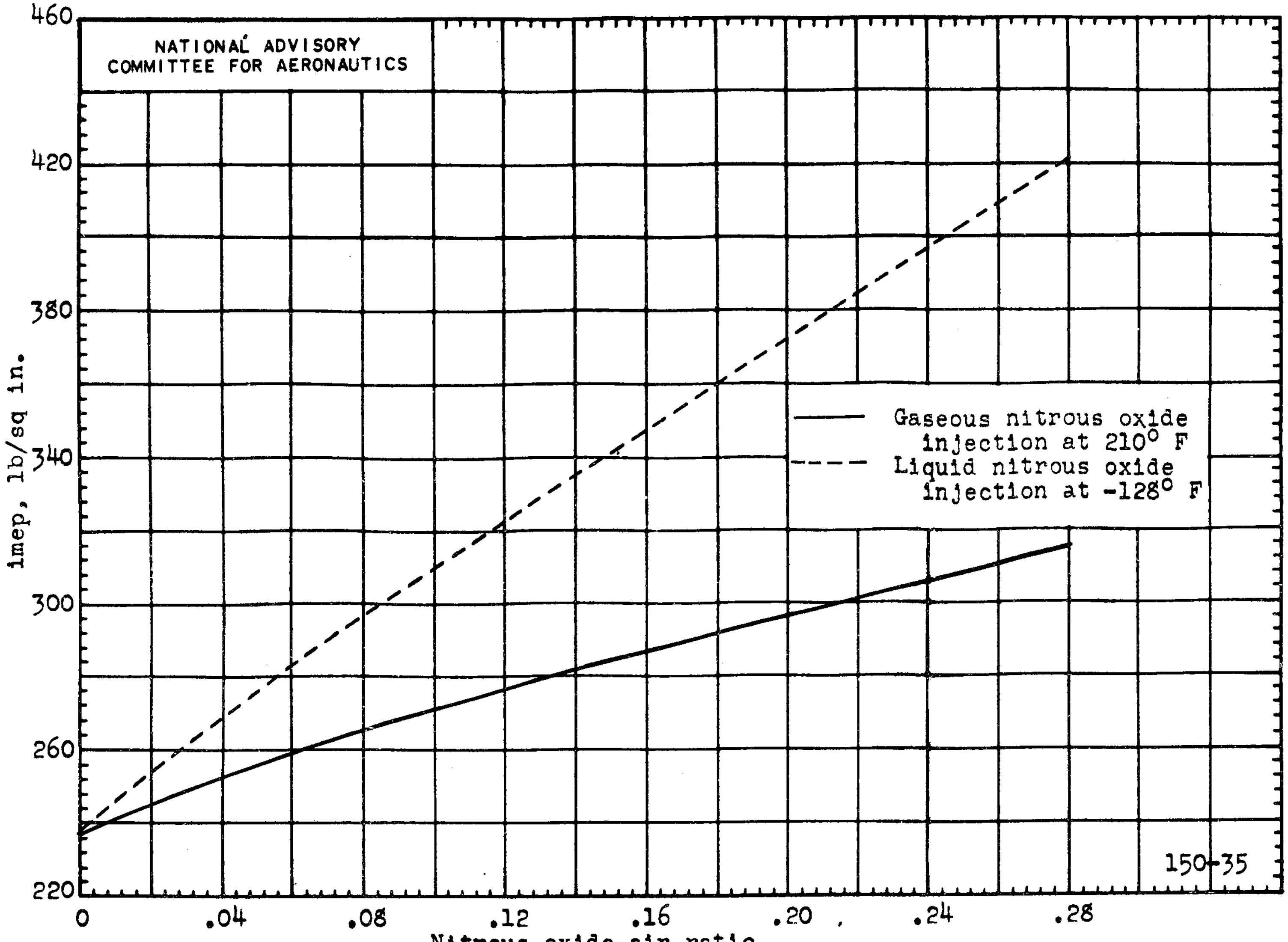

Figure 15. - Effect of nitrous oxide-air ratio on indicated mean effective pressure with liquid and with gaseous nitrous oxide injection. Calculated by methods described in appendix with data from figure 5. Fuel-oxygen-ratio, 0.410; manifold pressure, 50 inches mercury absolute.