

AN ABSTRACT OF THE THESIS OF

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Title PARTIAL RECIRCULATION OF DIESEL EXHAUST FOR THE
REDUCTION OF OXIDES OF NITROGEN

Abstract approved


(Major professor)

Oxides of nitrogen are a concern as effluents to atmospheres because they participate in photochemical reactions which produce smog, because they attenuate sunlight which gives the atmosphere a reddish brown cast, and because of their toxic properties and the health hazards associated with the photochemical products they produce.

Oxides of nitrogen are formed during the heterogeneous combustion of the diesel engine. When the locally overlean regions are subjected to high temperatures, nitric oxide (NO) is formed from the nitrogen and oxygen in the air. Nitrogen dioxide (NO₂) is formed slowly from the nitric oxide. The concentration of oxides of nitrogen formed is a function of the fuel-air ratio; the concentration magnitude is limited at low fuel-air ratios by the peak-cycle temperature of

combustion and at high fuel-air ratios by the amount of excess air available.

Oxides of nitrogen were measured by the spectrophotometric method, which was originally conceived by California Research Corporation. An instrument based on this method was built at this institution by Douglas E. Johnson and was modified and developed as a part of this thesis.

The tests were conducted by setting the engine to initial conditions of speed and load close to peak power but below the exhaust smoke point. This initial run was made without any recirculation. The subsequent runs allowed increasing amounts of recirculated gas to flow to the engine intake; the engine speed was maintained constant by varying the load on the engine. The quantity of recirculation was independently varied and the temperature, which was dependent on the quantity of recirculation, was allowed to vary simultaneously.

The results of these recirculation tests, which allowed both recirculation variables to increase simultaneously, show that the concentration of oxides of nitrogen in the exhaust gas remained essentially constant, at 300 parts per million (ppm), up to eight percent of exhaust gas recirculation from which the concentration increased rapidly to 700 ppm at 11 percent of exhaust gas recirculation. Increasing the percent of exhaust recirculation from zero to 11 percent caused the fuel-air ratio to increase from 0.050 to 0.065.

The engine performance parameters were also affected by the exhaust recirculation. The horsepower (hp) output decreased from 32 hp at zero percent recirculation to 27.7 hp at 11 percent recirculation, a decrease of 12.5 percent. The exhaust smoke intensity decreased slightly between zero and about four or five percent recirculation but then increased rapidly becoming objectionable before reaching 11 percent recirculation. The temperature of the exhaust gas in the exhaust stack remained essentially constant at 1,000° F from zero to seven percent recirculation and then increased to 1,100° F at 11 percent recirculation. Concentrations of carbon monoxide, 0.1 percent, and unburned hydrocarbons, 20 ppm, were not substantially affected by the recirculated exhaust; carbon dioxide concentrations increased from 9.6 percent at zero percent recirculation to 11.6 percent at 11 percent exhaust recirculation.

These tests show that there are no reductions in concentration of oxides of nitrogen to be gained by recirculation of exhaust gas, as conducted in the manner of these tests. In addition, the engine parameters of horsepower and smoke intensity were not benefited; the concentration of carbon monoxide and hydrocarbons was virtually unaffected, and the concentration of carbon dioxide increased by two percent.

It is recommended that further studies of diesel exhaust recirculation be conducted under conditions where the recirculation

temperature is held to a low constant value, because theory and earlier work, under unknown operating conditions, indicate that oxides of nitrogen can be reduced by exhaust gas recirculation.

PARTIAL RECIRCULATION OF DIESEL ENGINE EXHAUST
FOR THE REDUCTION OF OXIDES OF NITROGEN

by

DONALD JAMES ADDICOTT

A THESIS

submitted to

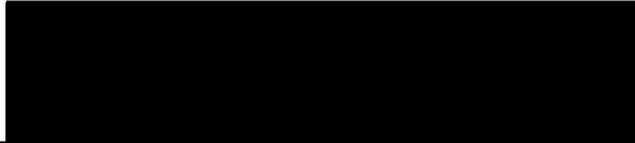
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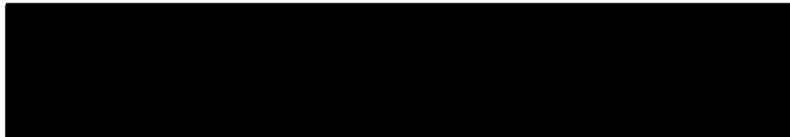


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PARTIAL RECIRCULATION OF DIESEL ENGINE EXHAUST FOR THE REDUCTION OF OXIDES OF NITROGEN

I. INTRODUCTION

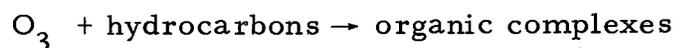
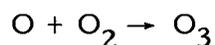
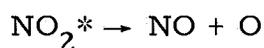
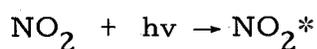
There are several reasons for concern over the presence of oxides of nitrogen in our atmospheres. Oxides of nitrogen participate in photochemical reactions producing smog; oxides of nitrogen attenuate sunlight, giving the atmosphere a reddish brown color; oxides of nitrogen are health hazards in themselves and through the photochemical products they produce (17, p. 1). "Diesels emit about the same amount of oxides of nitrogen as gasoline-powered vehicles" (18, p. 2). However, there are significantly fewer diesel-powered vehicles than there are gasoline-powered vehicles. In California in 1960 only one-third of one percent of the registered vehicles were diesel powered and these vehicles used only five percent of motor vehicle fuel in California (18, p. 2).

Of the many oxides of nitrogen, nitric oxide (NO) and nitrogen dioxide (NO₂) are the only ones considered toxic (8, p. 16). Threshold limit value, the concentration which a normal, healthy man can withstand eight hours a day, five days a week without any ill effects, is five parts per million (ppm) for nitrogen dioxide (19, p. 327). The toxicity of an oxide of nitrogen atmosphere is dependent upon the relative proportion of nitrogen dioxide present in the gas (8, p. 19). No

cases of nitric-oxide poisoning have been reported in the literature (8, p. 16). However, in atmospheres containing an ample supply of air, nitric oxide is readily converted to nitrogen dioxide by reacting with the oxygen.

Both nitric oxide and nitrogen dioxide derive their toxic properties from combining with lung moisture to form nitric acid which in any concentration will destroy lung tissue. The lung tissue has a limited ability to neutralize the acidic gases by forming nitrate salts from the body tissue and to heal slight burns on the alveoli caused by the acidic gases. Respiratory reflexes are not given as a warning to the damage occurring in the lungs, except at higher concentrations of oxides of nitrogen (23, p. 625).

Oxides of nitrogen are considered to be one of the principal participants in the photochemical reactions occurring in the atmosphere to produce Los Angeles type smog. The basic reactions occurring in smog formation are shown below (7, p. 342).



$h\nu$ = quantum of light

* = excited state

At nighttime the nitric oxide formed during the day is converted back to nitrogen dioxide by reacting with the oxygen present in the air.

This constitutes the smog cycle which, under atmospheric inversion conditions, will act for several days to build up the concentration of photochemical products.

The primary and almost sole source of nitric oxide and nitrogen dioxide in the atmosphere is the combustion of fuels The amount depends mostly on the temperature level reached during burning, and the rapidity with which the combustion effluents are quenched (7, p. 342).

On the basis of vehicles of equivalent engine size, diesel engines have been shown to be less of an air pollution nuisance in most respects than are gasoline-powered vehicles.

The amounts of diesel exhaust hydrocarbons appear less than emitted from equivalent size gasoline-powered vehicles. . . . Diesel-powered vehicles meet the present exhaust carbon monoxide and the crankcase hydrocarbon standards which have been established by the Department (California Department of Public Health). . . . Diesels do not emit smoke in objectionable amounts if they were properly operated and maintained The odor and irritation causing compounds of diesel exhaust have not been thoroughly defined and will not be eliminated merely by improved operation and maintenance. . . . It is hoped that work now under way will lead to a standard on odors in the near future. . . . Diesels emit about the same amount of oxides of nitrogen as gasoline-powered vehicles. The emissions of diesels as well as of gasoline vehicles will need consideration in any subsequent motor vehicle emission standards for oxides of nitrogen (18, p. 2-3).

The effluents of diesel engines in relatively closed locations, such as mines, warehouses, and holds of ships, must be considered for the safety of persons in these locations. Ventilation is usually required in such locations to dilute and remove harmful or objectionable constituents of the diesel exhaust. In these situations the engine is usually not operating with fresh air even though ventilation is supplied. Significant changes in the composition of the diesel exhaust may result when the engine uses a contaminated atmosphere instead of fresh air. Such possibilities of increased concentrations of harmful or objectionable constituents must be considered when the required ventilation in such locations is being determined (3, p. 2; 6, p. 330).

Three methods have been suggested for alleviating the oxides of nitrogen emitted from diesel engines. In the first method it was suggested that a suitable chemical, which would absorb the oxides of nitrogen, could be added to the conditioner for an enclosed location (20, p. 13.1). However it has been shown that no substantial improvement in the absorption of the oxides of nitrogen in the exhaust gases can be obtained by the use of a wide range of chemicals added to the water in the conditioner box for an enclosed location (20, p. 13.1). In the second method it was suggested that a chemical be added to the fuel which would "combine with the oxides of nitrogen and render them readily soluble in the conditioner fluid [for an enclosed location] . . ." (20, p. 13.1). None of the fuel additives presently

available are specifically designed to combine readily with oxides of nitrogen and none have done so. This is still an open field (20, p. 13.2). The third method is to "i) reduce the maximum gas temperature attained during combustion, ii) weaken the fuel/air ratio, iii) reduce the delay period" (20, p. 13.1).

This project was based upon the third method. It is theorized (in the next section) that the partial recirculation of diesel engine exhaust to the intake of the diesel engine would have such an effect on the peak-cycle temperature of combustion and on the fuel-air ratio as to cause the concentration of oxides of nitrogen in the exhaust gas to be reduced.

II. THEORY

Oxides of nitrogen are formed when oxygen and nitrogen are subjected to high temperatures. If atmospheric oxygen and nitrogen are subjected to high temperatures 1,000 ppm would be formed at 2,246^o F and 44,000 ppm would be formed at 5,126^o F (23, p. 626).

During the combustion process the presence of calcine oxides of cobalt, chromium, nickel, barium, magnesium, and lead act to lower the temperature at which an equal concentration of nitric oxides is formed. The calcine oxides act as catalytic agents which allow the oxides of nitrogen to be formed at much lower temperatures (23, p. 626). In addition, "the products of combustion, carbon dioxide and water, not only use up a substantial part of the original oxygen but they also dilute the remaining free oxygen and nitrogen to a point where only around 1,000 ppm or 0.10% of nitric oxide forms in a temperature that is otherwise capable of combining around 4%" (23, p. 626).

"Broadly speaking, the combustion process in the diesel engine can be divided into two periods: (1) an ignition delay period during which preflame oxidation reactions occur at an accelerating rate finally leading to ignition; and (2) an inflammation period during which combustion is completed either by rapid oxidation of mixtures of fuel and air or by the oxidation of mixtures of the products of

thermal decomposition of the fuel with air" (6, p. 331). Diesel combustion occurs under extremely heterogeneous conditions during both the delay and inflammation periods. ". . . The concentration of fuel in local regions in the combustion chamber may range from 0 to 100%" (6, p. 331).

During the delay period, the fuel/air mixture may be locally overlean, locally overrich, or correct for combustion. . . . As used in this sense, 'correct mixture' means one in which flame propagates and which contains oxygen sufficient to burn the fuel completely. During the inflammation period products of incomplete combustion originate in locally overrich fuel/air mixtures, in regions where fuel is thermally decomposed and the products are not properly mixed with air or when correct mixtures of fuel and air are chilled (6, p. 332).

When the local regions containing air with a small amount of fuel are subjected to high temperatures, the reaction $N_2 + O_2 \rightleftharpoons 2NO$ will occur. At temperatures encountered in combustion the reaction-equilibrium constant is a large positive quantity; thus, the forward reaction occurs at a much faster rate than does the reverse reaction (6, p. 332; 24, p. 423). During the expansion and exhaust strokes the temperature of the exhaust gas drops; the reverse reaction takes place at an increasing rate, but not fast enough to establish equilibrium (4, p. 510-511). The formation of nitrogen dioxide from nitric oxide occurs slowly because of the very low reaction equilibrium constant; the reaction will occur only under conditions of excess air.

Therefore, depending upon the temperature and the oxygen concentration, oxides of nitrogen may be in the form of nitric oxide or nitric oxide plus nitrogen dioxide (4, p. 511; 24, p. 423). Any oxide of nitrogen atmosphere, irrespective of its composition, may be referred to as NO_x , meaning the total oxides of nitrogen in the atmosphere.

The quantity of oxides of nitrogen formed in the combustion process increases with increasing temperature and with increasing oxygen concentration. Because temperature increases and oxygen concentration decreases with increasing fuel-air ratio, an optimum fuel-air ratio will exist for the formation of NO_x . At low fuel-air ratios, where there is an excess of oxygen, the temperature dominates in controlling the formation of oxides of nitrogen. At intermediate and high fuel-air ratios, where a limited supply of air exists, the concentration of the oxygen dominates in controlling the formation of oxides of nitrogen (4, p. 511).

At fuel-air ratios where the temperature dominates in the formation of NO_x , the concentration of NO_x decreases with increasing engine speed. Increased turbulence resulting from increased speed brings about a better distribution of the fuel-air mixture and lower average temperatures in regions of intense combustion. Where oxygen concentration dominates, oxides of nitrogen increase with increasing engine speed. The turbulence and better fuel-air distribution result in higher partial pressures of oxygen in regions of intense

combustion (4, p. 511).

The formation of oxides of nitrogen then depends upon the peak-cycle temperature and the amount of excess oxygen present in the combustion chamber. Any engine parameter which affects either of these two variables will have an influence on the formation of oxides of nitrogen. These engine parameters include: fuel-air ratio, duration of fuel injection, timing of fuel injection, inlet air temperature, engine speed, density of inlet air, temperature of recirculated exhaust gas, combustion chamber design, injector design, compression ratio, and engine load.

The parameters involved with recirculation of exhaust gas, which would affect peak-cycle temperature of the combustion gas or the amount of excess oxygen, would be either the temperature or the quantity of recirculation gas. All other engine parameters affecting formation of oxides of nitrogen would be held constant. If the temperature of recirculated gas were held constant, the affect of the amount of recirculation would be to increase the fuel-air ratio as the amount of recirculation increased. This would reduce the amount of oxygen available for formation of nitric oxide and for oxidation of nitric oxide to nitrogen dioxide. If the amount of recirculation were held constant as the temperature of the recirculated gas were varied, the peak-cycle temperature would increase as the temperature of the recirculated gas increased; consequently, the amounts of oxides of nitrogen would

increase with the rising recirculated gas temperature.

Several engine performance parameters would be affected by the recirculation of exhaust gas. With increasing quantity of recirculation, the power would be expected to decrease; the brake specific fuel consumption would tend to increase; and the fuel to air ratio would increase.

Oxides of nitrogen were measured as equivalent nitrogen dioxide by the spectrophotometric method. The same amount of nitric or nitrous acid will be formed in the lungs regardless of the form in which the oxides of nitrogen may exist (23, p. 625). Therefore, expression of the analytical findings in terms of equivalent nitrogen dioxide gives satisfactory evaluation of the toxic oxides of nitrogen in the exhaust (10, p. 9). The spectrophotometric method is based upon absorption of ultraviolet light by nitrogen dioxide, which absorbs a maximum amount of energy at a wavelength of 390 millimicrons. The combination of Beer's and Lambert's Laws, commonly called Beer's Law, states that the monochromatic light energy absorbed by the gas is directly proportional to the concentration of the gas. The instrument for measuring NO_x concentrations, which was built at this institution, was based upon the above principles.

III. APPARATUS

The principal apparatus required for conducting tests involved with recirculation of diesel exhaust gas is shown in Figures 1, 2, 4 and 5. All equipment involved with the testing is described below.

The engine used for these tests, a Caterpillar D3400, is shown in Figure 1. The four-stroke engine of 221-cubic-inch displacement was normally aspirated and was of the precombustion cylinder head type. The four cylinders were three and three-quarter-inch bore by five-inch stroke. Individual fuel injection pumps supplied fuel at 1,500 pounds per square inch (psi) to single fuel injector valves. The pumps used during the tests were large experimental models previously obtained from the Caterpillar Tractor Company. They supplied more fuel than the normal pumps; and, thus, they increased both the power output and combustion temperatures of the engine. The load was applied to the engine with a water-cooled, eddy current dynamometer. A beam balance attached to the dynamometer measured the engine load. The control panel in front of the engine is shown in Figures 1 and 2. The panel contained temperature indicators for the cylinder jacket water into and out of the engine, for the oil temperature, and for the exhaust temperatures in the manifold, as measured near cylinders one, four, and the common point to cylinders two and three, and in the exhaust stack. A fifth thermocouple was located in

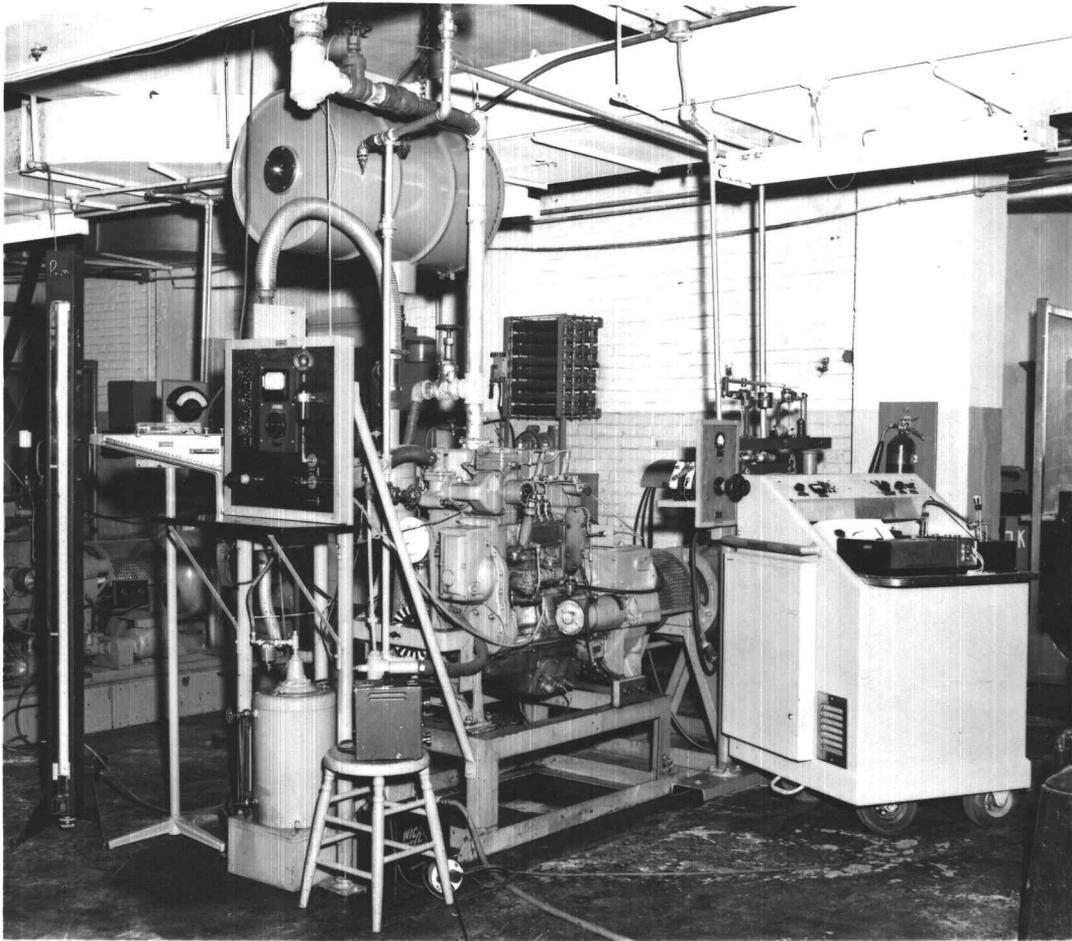


FIGURE 1. Diesel Test Engine with NO_x Analyzer and Associated Apparatus

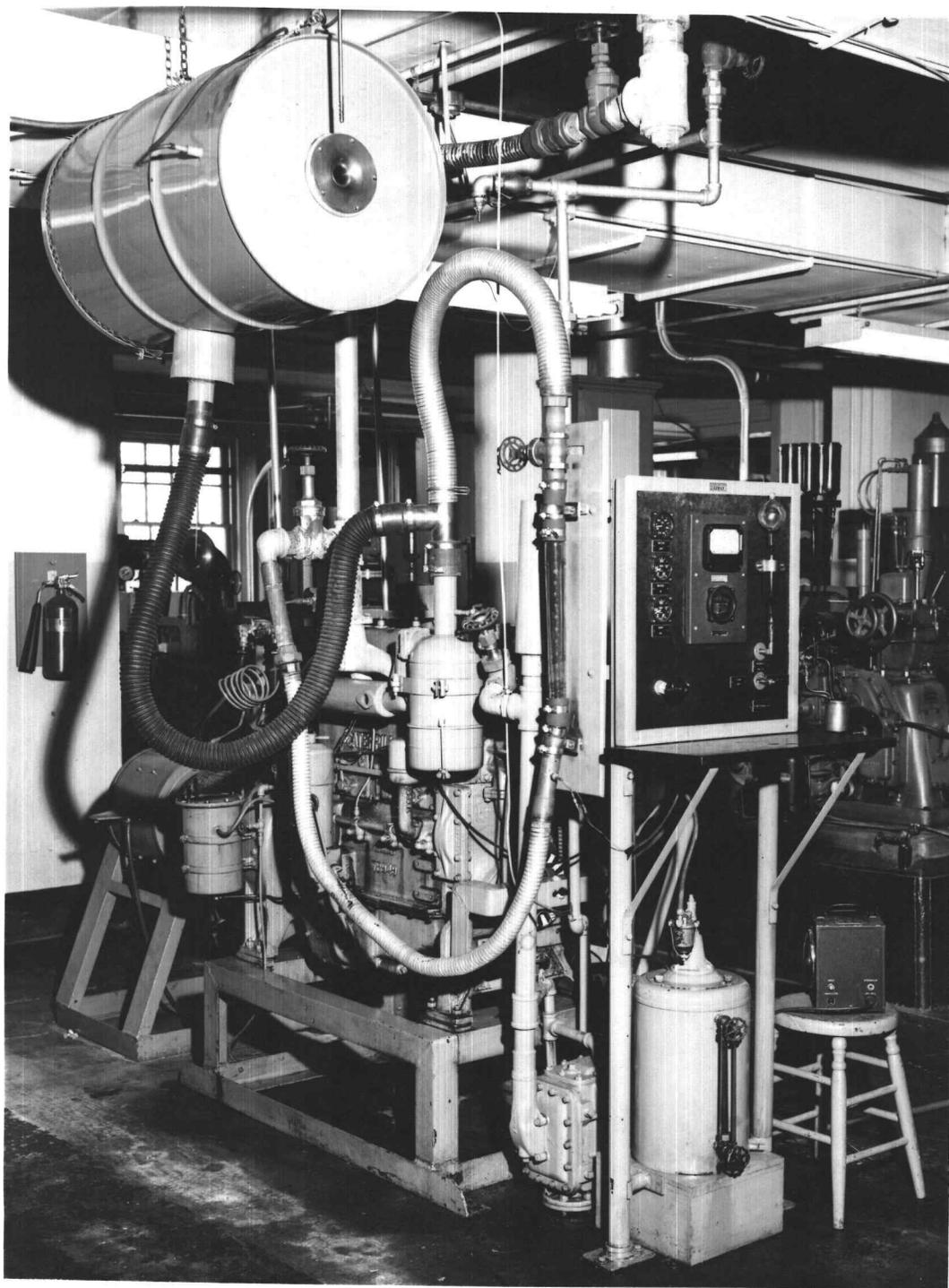


FIGURE 2. Exhaust Recirculation Line with Rotameter and Fresh Air Metering System

the exhaust gas recirculation line immediately below the inlet to the rotameter, shown in Figure 2. In addition to the temperature gauges, the control panel housed the injection pump rack control at the lower left and on the right a pipette with a control valve for measuring fuel flow to the engine. The speed of the engine was measured with a calibrated strobotach, shown in Figures 1 and 2.

Figure 1 also shows the pressure gauges used in testing. The manometer on the left measured the exhaust back pressure, in inches of water, at a point several inches above the exhaust manifold. Next to it, an inclined manometer measured the pressure drop, in inches of water, across the flow nozzle mounted in one end of the 55-gallon steel drum. This drum, fitted with a rubber head at the other end, was used to eliminate pulsations in the intake air flow, thus allowing easier measurement of the fresh air flow to the engine. (The drum, seen in Figure 2, will be referred to as the air drum from hereon.) A thermometer and an atmospheric barometer near the air drum nozzle gave information necessary for determination of the intake air density.

Figure 2 shows the left side of the engine with the loop to provide the partial recirculation of exhaust gas to the engine intake. The recirculated gas was extracted from the exhaust stack several inches above the exhaust manifold and was passed through a valve into the recirculation piping to the rotameter, shown on the right. The gas

passed through the rotameter and then combined with the fresh air from the air drum; the mixture flowed into the engine. The Fischer and Porter Company rotameter (series 10A1027A, meter size number six) provided flow measurements to 36 cubic feet per minute at 70° F and standard atmospheric pressure. The meter scale was calibrated in percent with 100 percent equaling 36 cubic feet per minute.

The exhaust gas was sampled from the top of the exhaust stack with a one-quarter-inch stainless steel probe which was inserted into the exhaust pipe along its center line. The end of the probe was plugged and one-sixteenth-inch holes were drilled on one side of the probe, one inch apart. The probe was rotated 90 degrees, longitudinally shifted one-quarter inch, and another set of evenly-spaced holes was drilled. This was repeated twice again, giving a helical effect of holes in the probe. A total length of nine inches was drilled as just described. The sampling line may be seen extending through the exhaust stack, in Figure 1, to the bottom of the control panel, in Figure 2. The sampling line was connected to three pieces of apparatus separately during each steady-state run. An evacuated two-liter flask was used to collect exhaust gas samples for determination of NO_x concentrations. A smoke meter was connected for qualitative smoke determinations and an instrument for carbon monoxide, carbon dioxide, and hydrocarbon concentrations was connected.

The Von Brandt smoke meter, obtained from the California

Research Corporation, contained a vacuum pump which drew the exhaust gas through two test tubes which served as condensate traps. The gas was then drawn through a moving strip of white paper on which the smoke was deposited. The remaining gas was pumped through the vacuum pump and exhausted to the atmosphere. The strip of paper collected the smoke particles from the exhaust gas and provided a permanent record of the relative smoke intensity. The paper strip was fed through an American Iron and Steel Institute paper tape reader, which was obtained from the Oregon State Board of Health; the instrument measured the amount of light transmitted through the paper. This gave a measure of the relative smoke intensity of the exhaust. Measurements of carbon monoxide, carbon dioxide, and hydrocarbon concentrations in the exhaust gas were made with infrared analyzing units which were built and developed at this institution as part of a joint thesis by Neill R. Parkin and Gary D. Jaros. (These last three pieces of apparatus are not shown in the photographs.)

The scheme of the spectrophotometric instrument used for measuring oxides of nitrogen concentrations was originally conceived by California Research Corporation (21, p. 985-988) and an instrument using this scheme was built by Douglas E. Johnson as partial fulfillment for the degree of Master of Science (11, p. 1-48). The schematic drawing of the present instrument, including all the modifications, is shown in Figure 3. The photographed instrument is

shown in Figures 4 and 5. The black box in the right of Figure 4 contained the heart of the instrument. The tubing emerging from the front and back of the box were the inlet and outlets, respectively, to the test cell. The test cell was a 12-inch length of one-inch diameter stainless steel tubing. The tube ends were sealed with neoprene rubber O rings and quartz windows, which transmitted over 99 percent of the incident light. At the front of the test cell was situated a tungsten filament light bulb which provided the ultraviolet energy, and a monochromatic filter which allowed a peak transmittancy of 41 percent at 390 millimicrons. At the other end of the test cell was the photocell which received the light transmitted through the test cell. The light bulb was powered by a transistorized power supply which provided a very low-ripple, constant-current power source for the light bulb. A constant-current power source was extremely important for this apparatus, because any slight change in the current produced a change in light intensity and thus a change in the output of the photocell. The power supply, Power Designs model 2050, is shown in the side view of the NO_x instrument, Figure 5, which also shows the oxygen supply cylinder used for purging the test cell and for oxidizing NO to NO_2 . The oxygen was supplied to the test cell from the cylinder with Tygon tubing via the three-way stopcock at the front of the test cell box. A serum stopper, mounted on the third leg of this stopcock, allowed injection of the exhaust gas sample with a 100

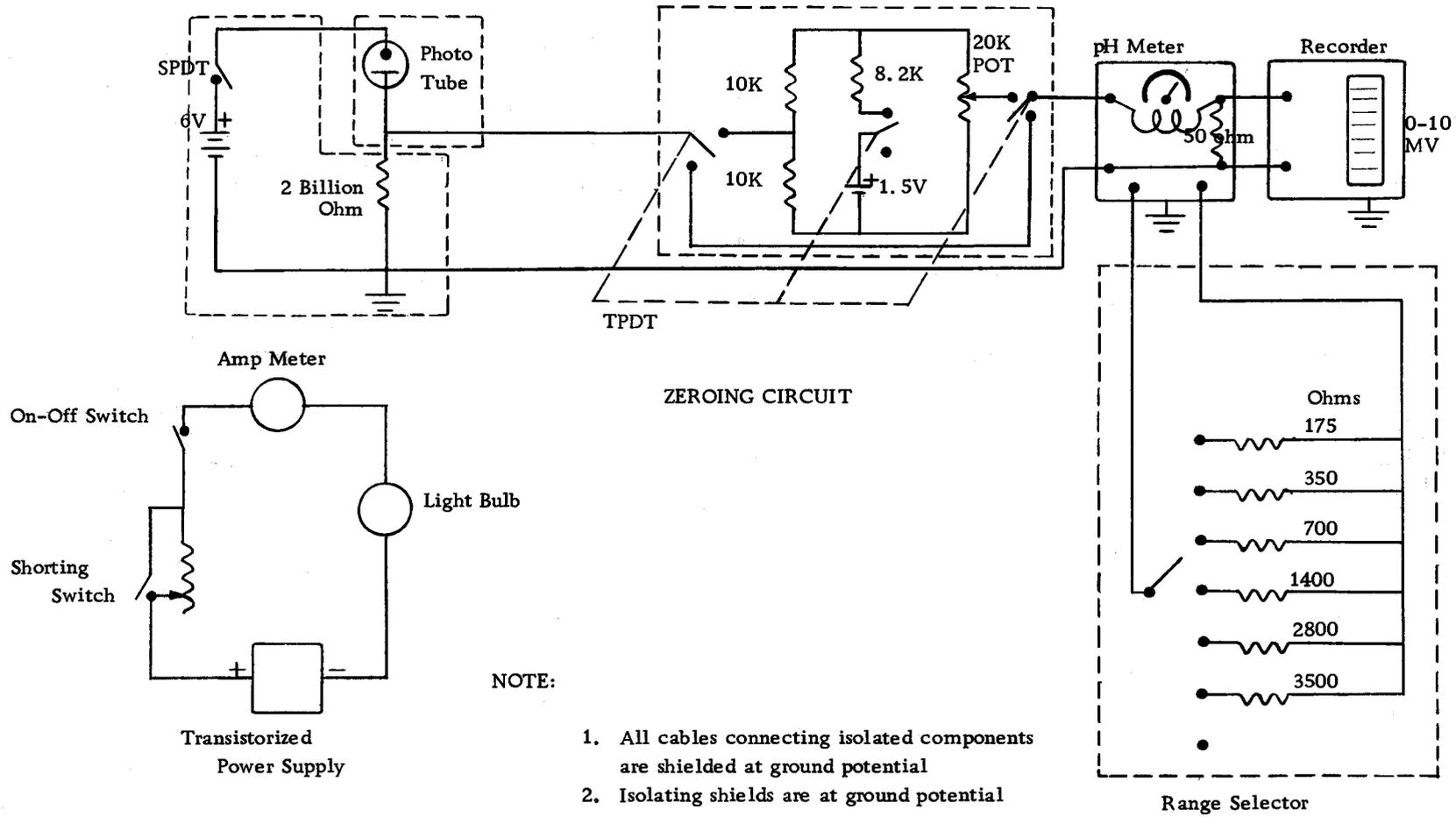


FIGURE 3. Schematic of the NO_x Spectrophotometric Analyzer

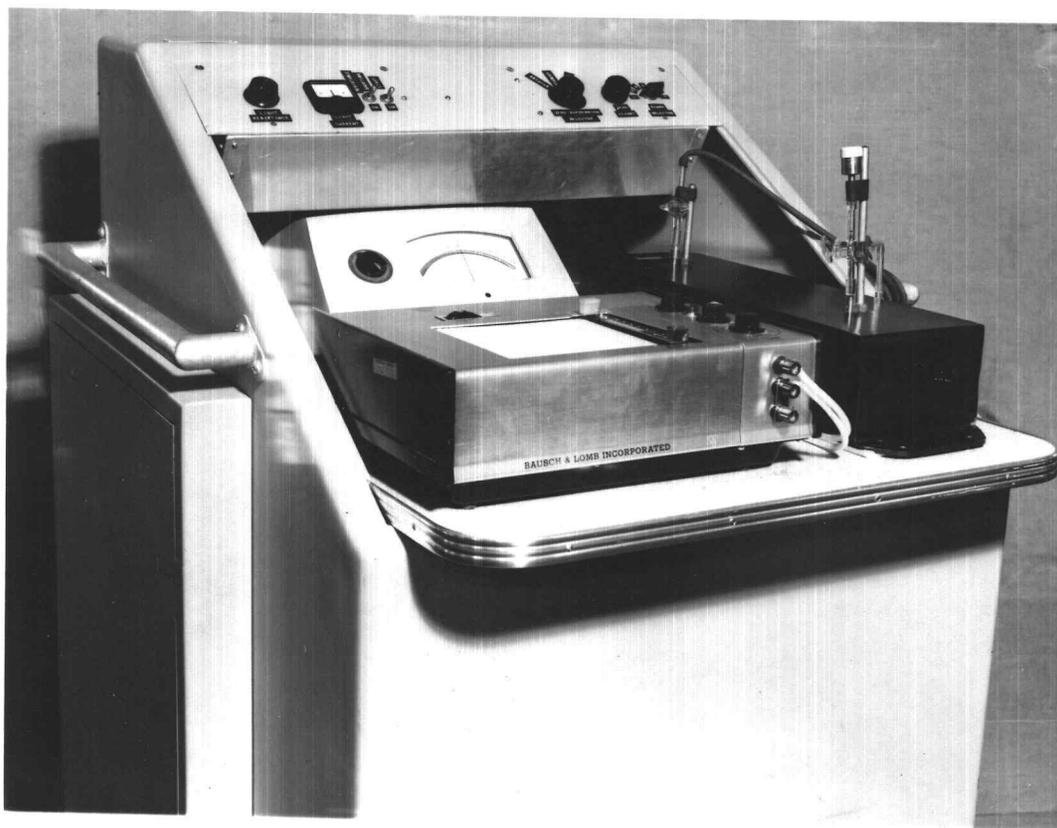


FIGURE 4. NO_x Spectrophotometric Analyzer Console Top

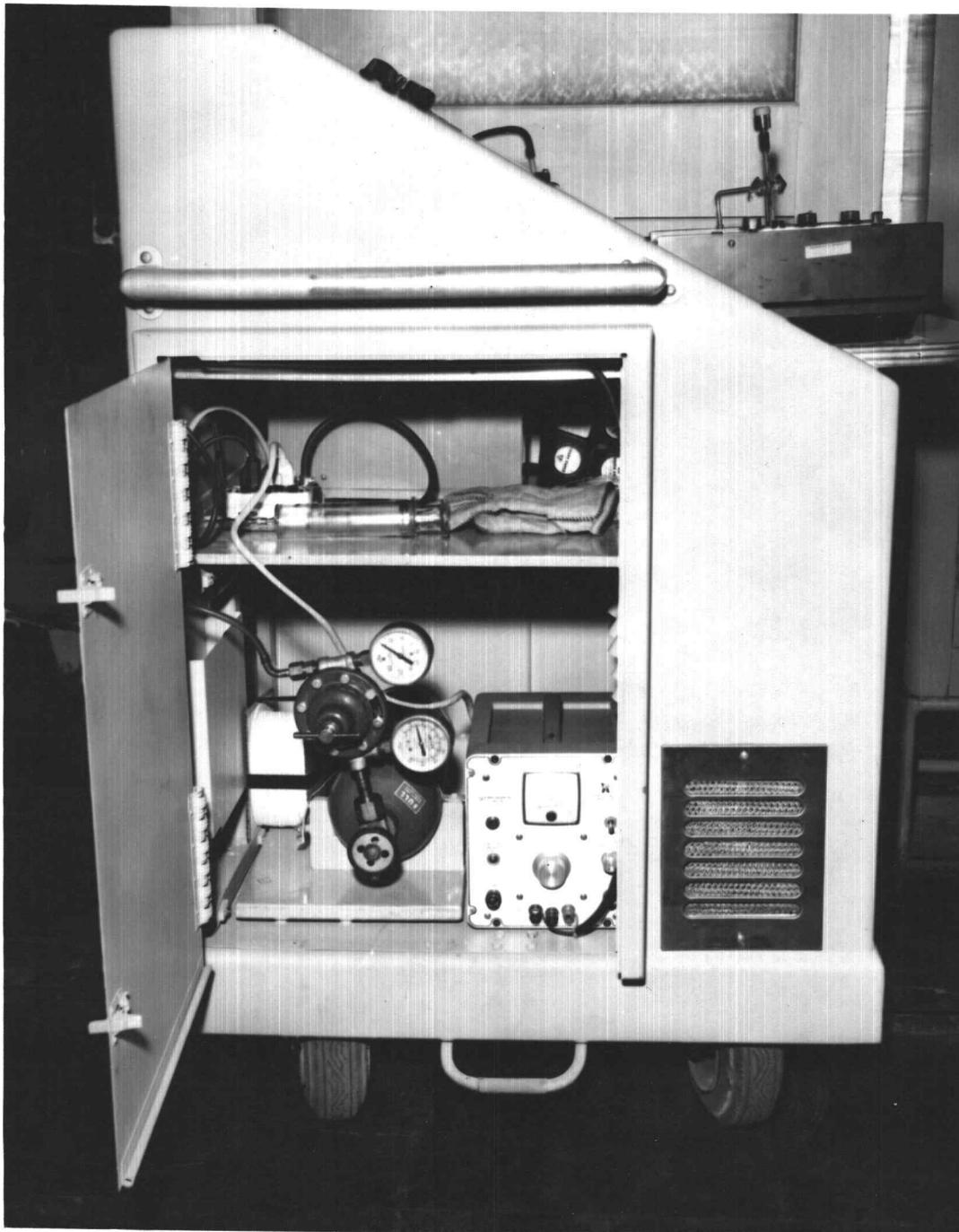


FIGURE 5. Side View of NO_x Analyzer Console

cubic centimeter (cc) syringe.

The photocell was connected with shielded cables to the circuit contained in the bread pans, just visible in Figure 4, immediately behind the test cell box. In the bread pans, wired in series with the photocell, were a six-volt battery, a two-billion ohm resistor, and a switch for closing the circuit. Current flowing in this circuit produced a voltage drop across the resistor, and any change in the current, caused by variation of the photocell output, caused a change in voltage across the resistor. The voltage across the resistor was fed to the input of the pH meter, which amplified the signal and provided an input signal to the recorder where all measurements were determined. The pH meter is a Beckman Zeromatic and the recorder is a Bausch and Lomb V. O. M. -5 laboratory recorder.

Johnson's original NO_x instrument was modified and developed as a part of this thesis. A major modification was to mount the entire instrument in a new console, shown in Figures 4 and 5. Figure 5 shows the equipment mounted inside the console. An isolation power transformer was mounted on the shelf in back and the oxygen cylinder and transistorized power supply for the light bulb were placed on the bottom of the console. A control panel, which was built and mounted on the console (above the pH meter), contained the circuitry for the light bulb controls, and the newly-incorporated zeroing and range controls. All parts of the NO_x instrument were carefully

isolated and shielded from stray signals as discussed by Bair (1, p. 263-271) and as shown in Figure 3.

The range switch was built for measuring lower concentrations of NO_x and a zeroing circuit was included to provide zeroing on the low ranges, which was not possible with the pH meter alone. The modifications are included in the schematic drawing of Figure 3. The grounded side of the resistor passed directly to the grounded side of the pH meter input. The high side of the resistor output went through the zeroing circuit. The zeroing circuit described by Keegan and Matsuyama (12, p. 1293) was used for zeroing on the most sensitive scales and was not necessary on the less sensitive scales. In the latter case, zeroing was accomplished by the asymmetry control on the pH meter. Keegan and Matsuyama (12, p. 1292-1293) also discussed a method of increasing the sensitivity on the Beckman pH meter. The range switch, providing the increased sensitivity, may be seen in Figure 4. When the pH meter was operated on the automatic temperature compensating position, any external resistor connected to the automatic temperature compensating jacks became the feedback resistor in the amplifier circuit; thus, a smaller resistance caused full-scale deflection of the meter for a lower input voltage. Matching of the recorded input resistance and pH meter output resistance was accomplished inside the pH meter as outlined in the Beckman pH meter manual (2, p. 16).

The concentrations of oxides of nitrogen were shown as changes in the output of the recorder. Because the photocell would produce a current without any NO_2 in the test cell, a zero line was established on the recorder by use of the zeroing circuit. When the NO_2 gas was present in the test cell the photocell changed its current output, which resulted in a different output on the recorder. The change of output on the recorder was a measure of the concentration of NO_2 in the test cell.

The instrument was operated as follows. The test cell was purged with oxygen from the oxygen supply to provide the means of converting nitric oxide to nitrogen dioxide. The oxygen cylinder was closed, and the test cell stopcocks were closed to seal in the oxygen. When the 100 cc exhaust gas sample was obtained, the syringe needle was placed in the test cell serum stopper, and the three-way stopcock and syringe stopcock were opened. In quick sequence the test cell outlet stopcock was opened, the exhaust sample was injected into the test cell, and the outlet stopcock was closed. Opening of the outlet stopcock was necessary because the volume of the test cell was only 154 cc and because the test cell should have been at atmospheric pressure. Even though there was a chance for partial loss of the sample out of the stopcock, calibration and experimental results were found to be repeatable. The sample was allowed to remain in the test cell until the output of the recorder showed a peak reading

which indicated that oxidation was completed. At that point the glass stopcocks were opened and the test cell was again purged with oxygen to exhaust the NO_2 gas and also to check the zero reading in case drift had occurred.

IV. PROCEDURE

The engine tests were begun with a series of runs which did not include recirculation of the exhaust gas. The purpose of these runs was to determine the characteristics of the engine versus fuel-air ratio at constant speed and to provide a basis from which to pick an initial point from which to begin the recirculation runs. The recirculation runs commenced from the chosen initial rack control and engine load conditions by increasing the exhaust recirculation while simultaneously decreasing the engine load to maintain a constant engine speed.

The engine tests without recirculation were run at 1,600 revolutions per minute (rpm) commencing at no load and increasing to full load. The exhaust pressure was maintained at 30 inches of water and the cylinder jacket water temperature was held to 160° F. After equilibrium was attained data were recorded, as shown in Appendix A, for each run. The data recorded are discussed fully in relation to the recirculation runs.

The engine recirculation tests were conducted by setting the engine, initially without recirculation, to the specific conditions of speed and load: 32 horsepower, 1,600 rpm, and slightly below the incipient smoke point. For this initial condition the rack control was adjusted so that the engine was running under an 80-pound dynamometer beam

load, which corresponded to 32 horsepower at 1,600 rpm. Once the initial condition was set up, the position of the rack control was not changed for the remainder of the runs that day. The exhaust back pressure, controlled with the exhaust valve leading to the laboratory exhaust main, was set to 30 inches of water; the cylinder jacket water temperature out of the engine was set up and maintained at 160° F for all runs. When the engine was properly warmed and all temperatures were stabilized, data were recorded for the initial run.

All of the remaining runs involved recirculation. Each run was begun by opening the recirculation valves to obtain the desired flow rate; the load was adjusted to maintain the speed at 1,600 rpm. The back-pressure valve was adjusted to maintain 30 inches of water back pressure, and the jacket water outlet temperature was adjusted to maintain 160° F. When the engine reached equilibrium, as indicated by the stability of the engine's temperatures, data were recorded for the run. Measurements were made of the fuel flow and of the pressure drop across the air drum nozzle for the determination of the fuel-air ratio. The fuel flow rate was measured as the time required for fuel to flow from a 100 cc pipette into the engine. With knowledge of the API gravity, and thus the specific gravity of the fuel, the mass flow rate of the fuel to the engine was calculated. From this gross fuel flow rate was subtracted the flow rate of excess fuel returning from the fuel injectors, because not all of the fuel

which flowed to the engine was injected into the engine. The excess was normally returned to the fuel tank. The return fuel flow rate was determined by measuring the time required for the returning fuel to fill a ten-cubic-inch graduated cylinder. The barometric pressure for the day and the air temperature at the air drum were measured and recorded. The engine load at 1,600 rpm was measured with the dynamometer and then recorded. The engine temperatures in the exhaust manifold, exhaust stack, oil pan, and jacket water, into and out of the engine, were recorded. An exhaust gas sample was collected in an evacuated two-liter flask for measuring the concentration of oxides of nitrogen. Exhaust gas was allowed to flow through the infrared analyzing equipment and concentrations of carbon monoxide, carbon dioxide, and hydrocarbons were recorded. Exhaust gas was also allowed to pass through the smoke meter which collected smoke particles on a continuously moving, white paper tape. Measurement of the relative smoke intensity was later obtained from a paper tape reader which measured the light transmitted through the tape. One hundred percent represented no smoke and complete transmission of light through the paper. The recorded data are included in the Appendix. Sample calculations for the fuel flow rate, the fresh air flow rate, the recirculation flow rate, the percent of exhaust gas, recirculation, and the true fuel-air ratio are also included in the Appendix.

The NO_x instrument was calibrated by injecting a known

concentration of a NO_x gas into the instrument's test cell. Nitric oxide was used as the calibration gas. Just as with an exhaust gas sample, the nitric oxide was allowed to oxidize in the test cell with oxygen. Four or five known concentrations were injected into the instrument for calibration of each range. The known concentrations were mixed in a two-liter flask, the exact volume of which was accurately measured. The two-liter flask was evacuated to a gauge vacuum of 29.5 inches of mercury and then filled with nitrogen; the process was repeated. The flask was evacuated a third time to 29.5 inches of mercury and was purged with nitrogen to exactly atmospheric pressure. The sample of nitric oxide was obtained with a small glass syringe from a supply cylinder. The glass syringe was equipped with a metal stopcock between the needle and the syringe body. The nitric oxide gas was injected into the flask with the glass syringe, through the serum stopper on one end of the flask. After closing the syringe stopcock, the glass syringe body was removed from the stopcock, leaving the needle and stopcock in the serum stopper. A supply line from the nitrogen cylinder was then attached to the syringe stopcock and the two-liter flask was pressurized to approximately two inches of mercury. This last procedure was necessary for two reasons: first, the nitrogen was pumped into the flask immediately behind the nitric oxide sample because the sample was so small (compared to the two liters) that adequate mixing of the nitric

oxide and the nitrogen would not otherwise occur; secondly, it was necessary to pressurize the flask to approximately two inches of mercury, so that when a 100 cc sample was removed from the flask for injection into the NO_x instrument, the pressure in the combined volumes of the two-liter flask and the 100 cc syringe would be at atmospheric pressure. The exact pressure to which the flask was raised was calculated by a consideration of the atmospheric pressure, the volume of the flask, and the volume of the syringe. This calculation is included in the Appendix. The known sample was then ready for injection into the NO_x instrument. The sample was withdrawn into a 100 cc syringe from the two-liter flask through the serum stopper on the end of the flask. This syringe was also equipped with a metal stopcock between the syringe and the needle. The 100 cc sample was injected into the NO_x instrument where oxidation of the nitric oxide occurred, forming nitrogen dioxide. The time required for oxidation of nitric oxide varied from 10 to 25 minutes depending upon the instrument scale used and upon the relative proportion of nitric oxide in the exhaust sample. The output on the recorder resulting from the injection of the sample was then used with the known concentration of the sample as one point on the calibration curve.

Exhaust gas samples were obtained from the exhaust sampling line with an evacuated two-liter flask. The flask was prepared by its evacuation to 29.5 inches of mercury and by subsequent purging with

nitrogen. This was repeated twice and the flask was finally evacuated to 29.5 inches of mercury. The exhaust sample was collected in the evacuated flask; the 30 inches of water back pressure in the exhaust system left the pressure in the sampling flask slightly above atmospheric pressure. The positive pressure in the flask was approximately equal to the positive pressure used in the calibration procedure. Thus, withdrawal of the 100 cc sample from the flask allowed the pressure in the combined volumes of the flask and the syringe to be near atmospheric pressure. Opening the syringe stopcock momentarily assured that the sample was at atmospheric pressure. The exhaust sample was injected into the NO_x instrument and the concentration of the sample was determined from the output of the recorder and the previously determined calibration curve.

V. RESULTS

The tests for this project were conducted as outlined in the previous section. The data for these tests are included in Appendix A. Parts of these data were used for calculating other quantities to be utilized as basic parameters, as shown in the sample calculations. The results of these data and calculations are shown in Figures 6-11.

Figure 6 shows the results of the tests conducted without recirculation. The engine parameters of brake horsepower, NO_x concentration, smoke intensity and exhaust stack temperature are plotted versus fuel-air ratio.

Figure 7 is a plot of the concentrations of oxides of nitrogen, measured as nitrogen dioxide, in parts per million, versus the percent of recirculated exhaust gas. These results show that the concentration of oxides of nitrogen remained essentially constant for low amounts of recirculation and increased rapidly at higher recirculations. Percent of recirculated gas was calculated, as shown in Appendix B, as the ratio of recirculated exhaust gas to the total amount of gas flowing into the engine. The total gas is the sum of the mass flow rate of fresh air and the mass flow rate of recirculated exhaust gas. The mass flow rate of recirculated exhaust gas was calculated as shown in Appendix B. The Fischer-Porter rotameter was factory calibrated to read percent of 36 cubic feet per minute when the gas

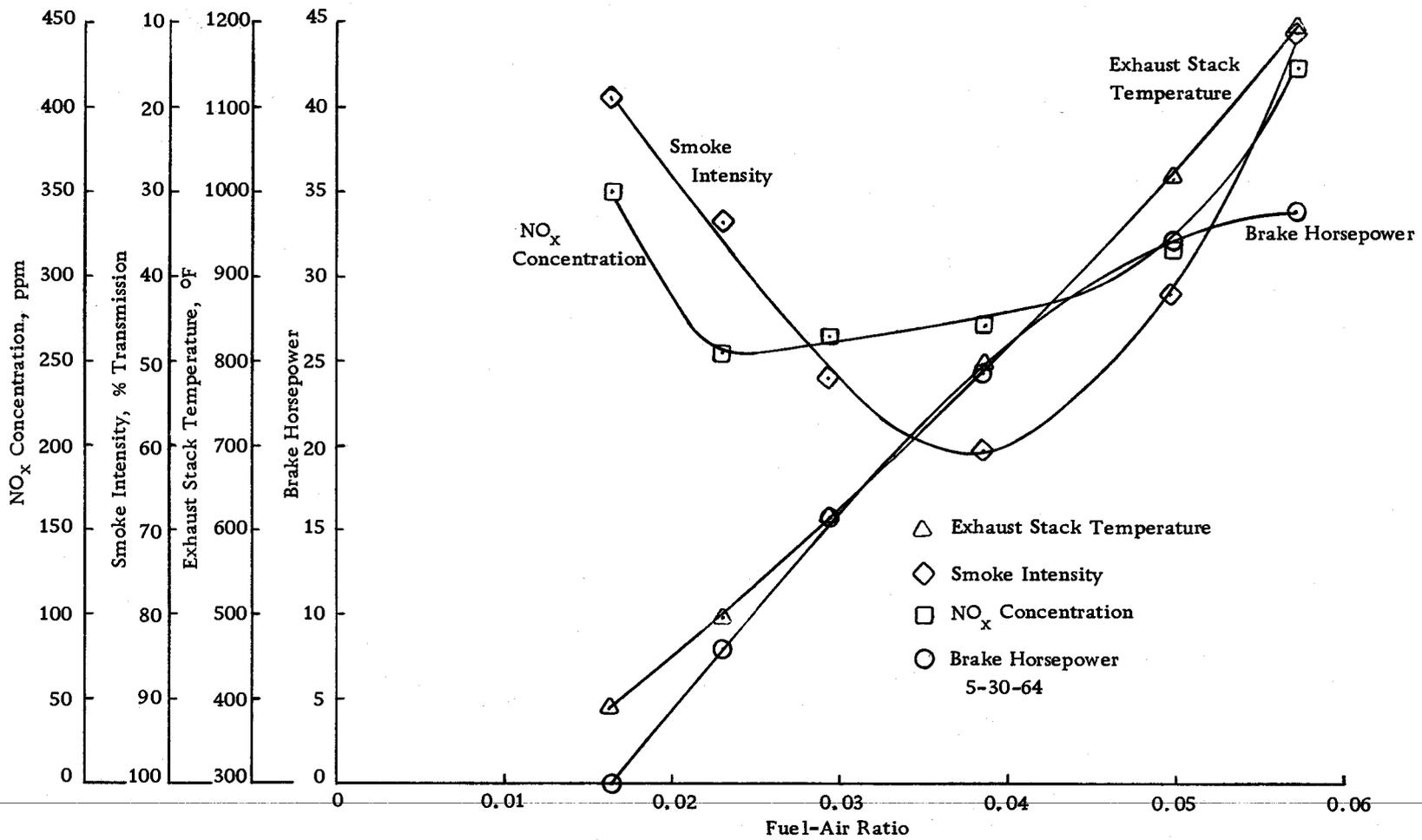


FIGURE 6. Engine Parameters without Recirculation versus Fuel-Air Ratio

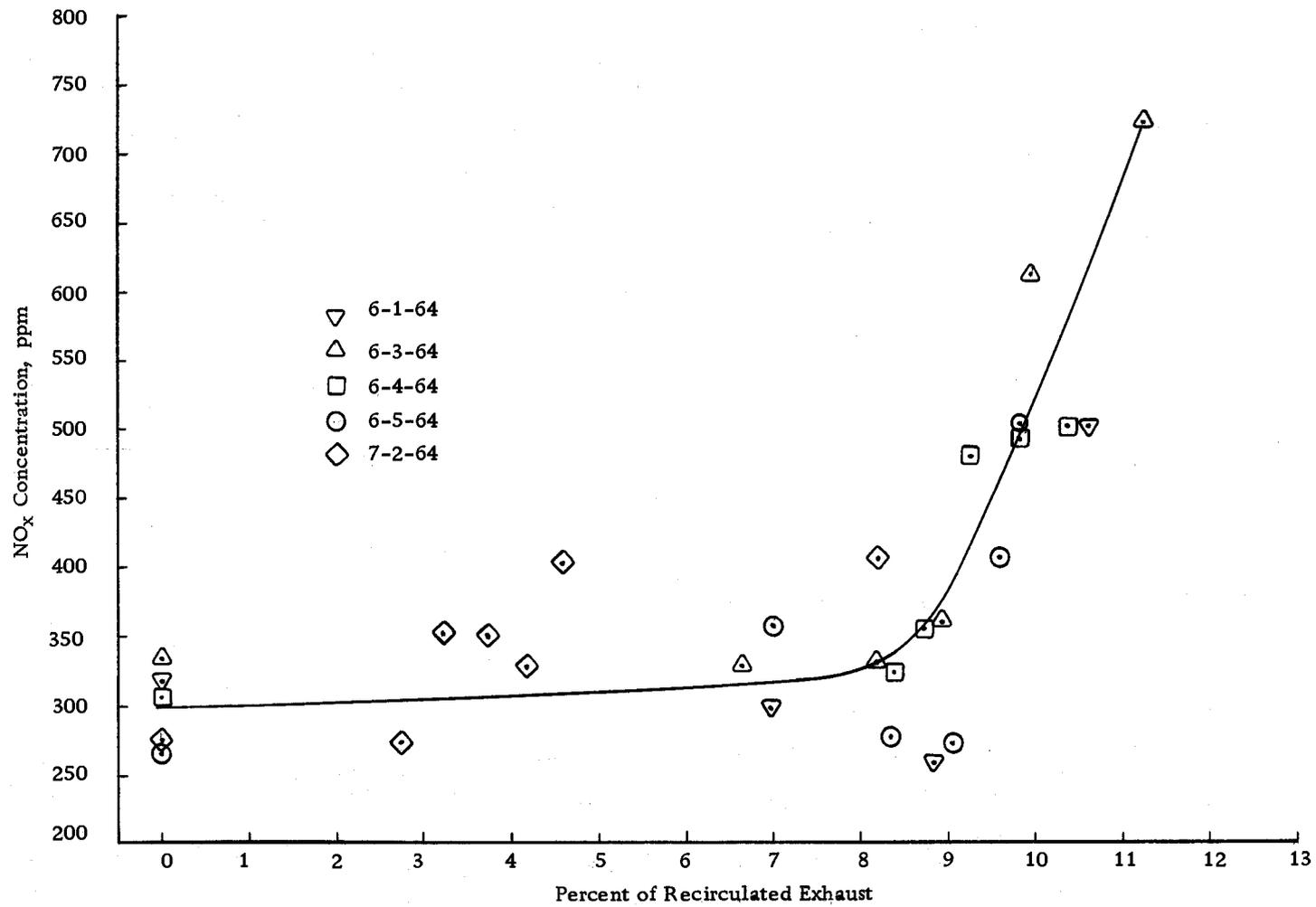


FIGURE 7. NO_x Concentration versus Percent of Recirculated Exhaust

flowing through the rotameter was at 70° F and 14.7 psi. As shown in the sample calculations the volume flow rate through a rotameter is inversely proportional to the square root of the density of gas flowing through it. Because the recirculated exhaust gas flowing through the rotameter was not at 70° F or 14.7 psi, a correction factor was applied to the indicated rotameter reading to correct the density from the temperature and pressure conditions in the recirculated exhaust gas to that which the meter was calibrated. This calculation gave the corrected volume flow rate. The mass flow rate was then calculated by multiplying the volume flow rate times the density of the exhaust gas flowing through the rotameter. A sample calculation for the mass flow rate of fresh air to the engine is also included in the sample calculations. The mass flow of fresh air was obtained from a consideration of the conservation of energy across the air flow nozzle as shown in the sample calculations. The percent of recirculated exhaust gas was then calculated as outlined above.

Figure 8 is a plot of the concentration of oxides of nitrogen versus the true fuel-air ratio. These results show that increased recirculation caused the fuel-air ratio to increase while simultaneously increasing the oxides of nitrogen. The true fuel-air ratio takes into account the amount of oxygen recirculated with the exhaust gas to the intake of the engine, and bases the fuel-air ratio on the amount of fresh air plus the amount of recirculated air flowing to the engine.

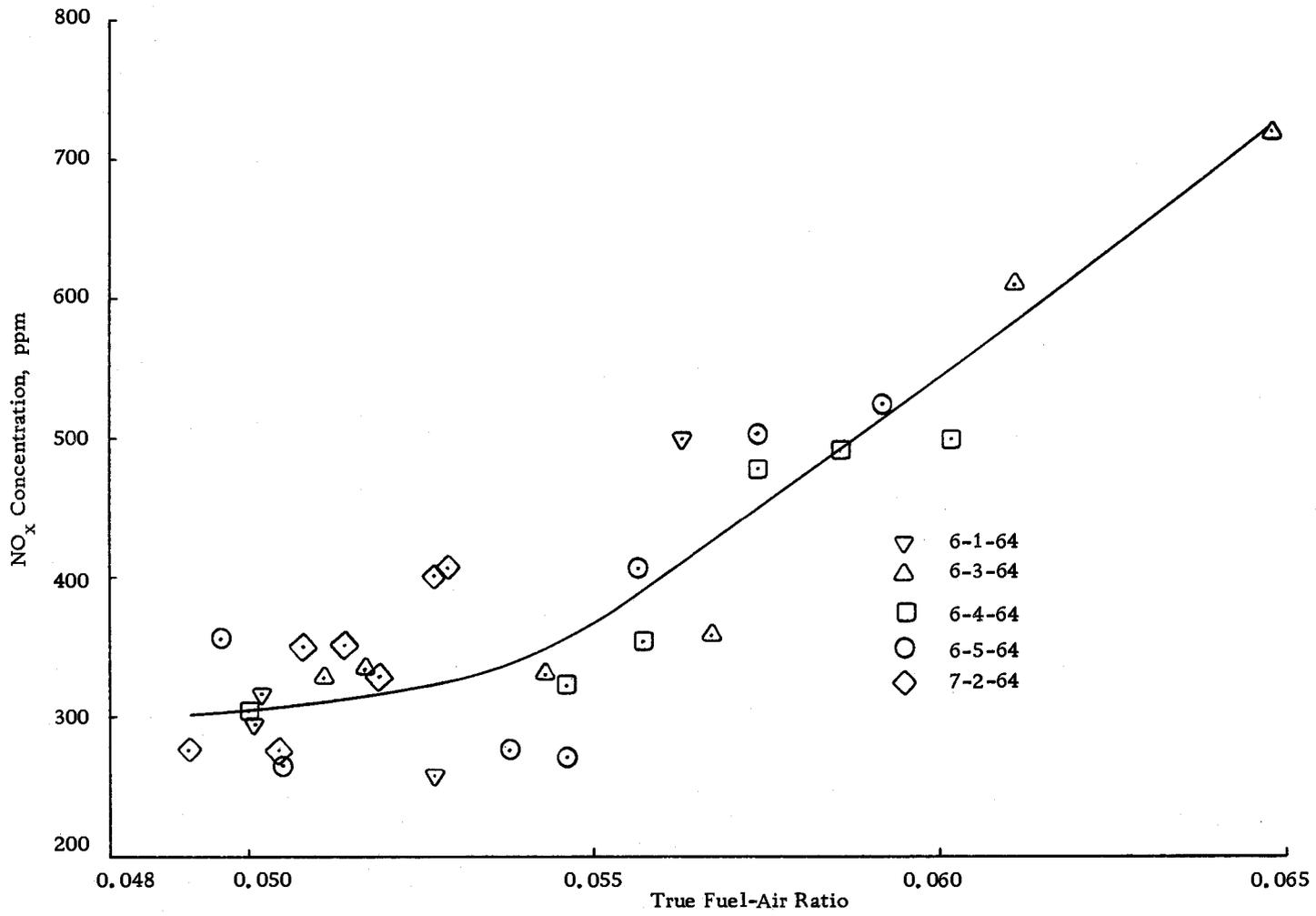


FIGURE 8. NO_x Concentration versus True Fuel-Air Ratio

Because diesel engines are run on the lean side of the stoichiometric mixture, an excess amount of oxygen is always to be found in diesel exhaust. Because a portion of the exhaust was recirculated and because this exhaust contained some oxygen, it was necessary to take into account the oxygen fed into the intake of the engine with the recirculated gas in addition to the fresh air fed to the engine. From the knowledge of the oxygen and carbon dioxide concentrations in the diesel exhaust gas, as determined with an Orsat gas analyzing apparatus and checked with the infrared analyzing apparatus, the weight of air returned with the recirculated exhaust gas per pound of fuel was calculated as shown in Appendix B. When this amount of air recirculated per pound of fuel was multiplied times the percent of exhaust recirculated and the fuel flow rate, the total amount of air per second returned with the recirculated exhaust gas was calculated. The true fuel-air ratio was then calculated as the net fuel flow to the engine divided by the fresh air flow rate to the engine plus the flow rate of the air supplied to the intake with the recirculated exhaust gas.

Figure 9 is a plot of the brake horsepower of the engine and of the relative smoke intensity versus the percent of recirculated exhaust gas. The figure shows that as the amount of recirculated exhaust gas was increased, the brake horsepower decreased and the smoke intensity increased significantly.

Figure 10 is a plot of the exhaust gas temperatures in the

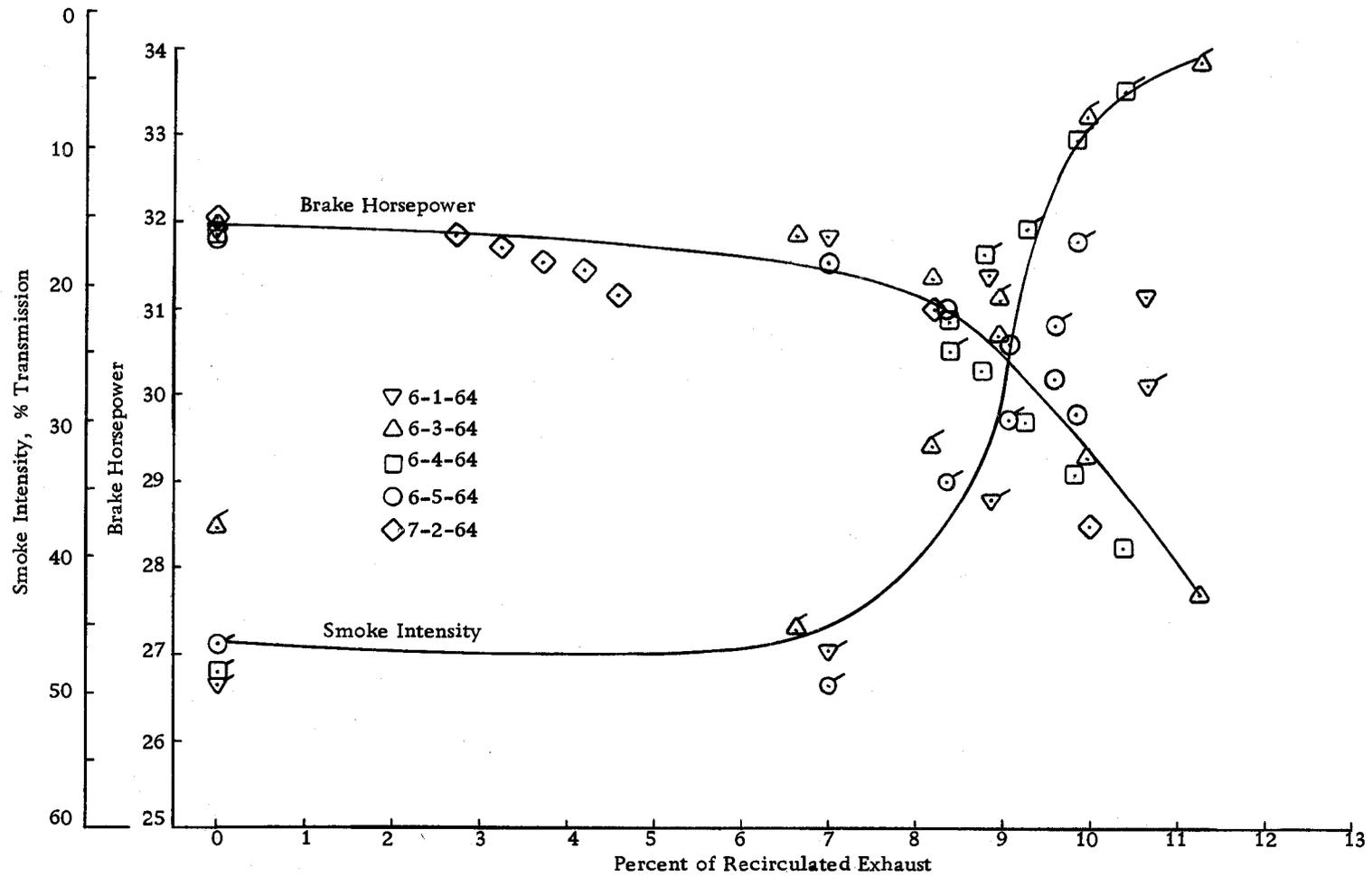


FIGURE 9. Smoke Intensity and Brake Horsepower versus Percent of Recirculated Exhaust

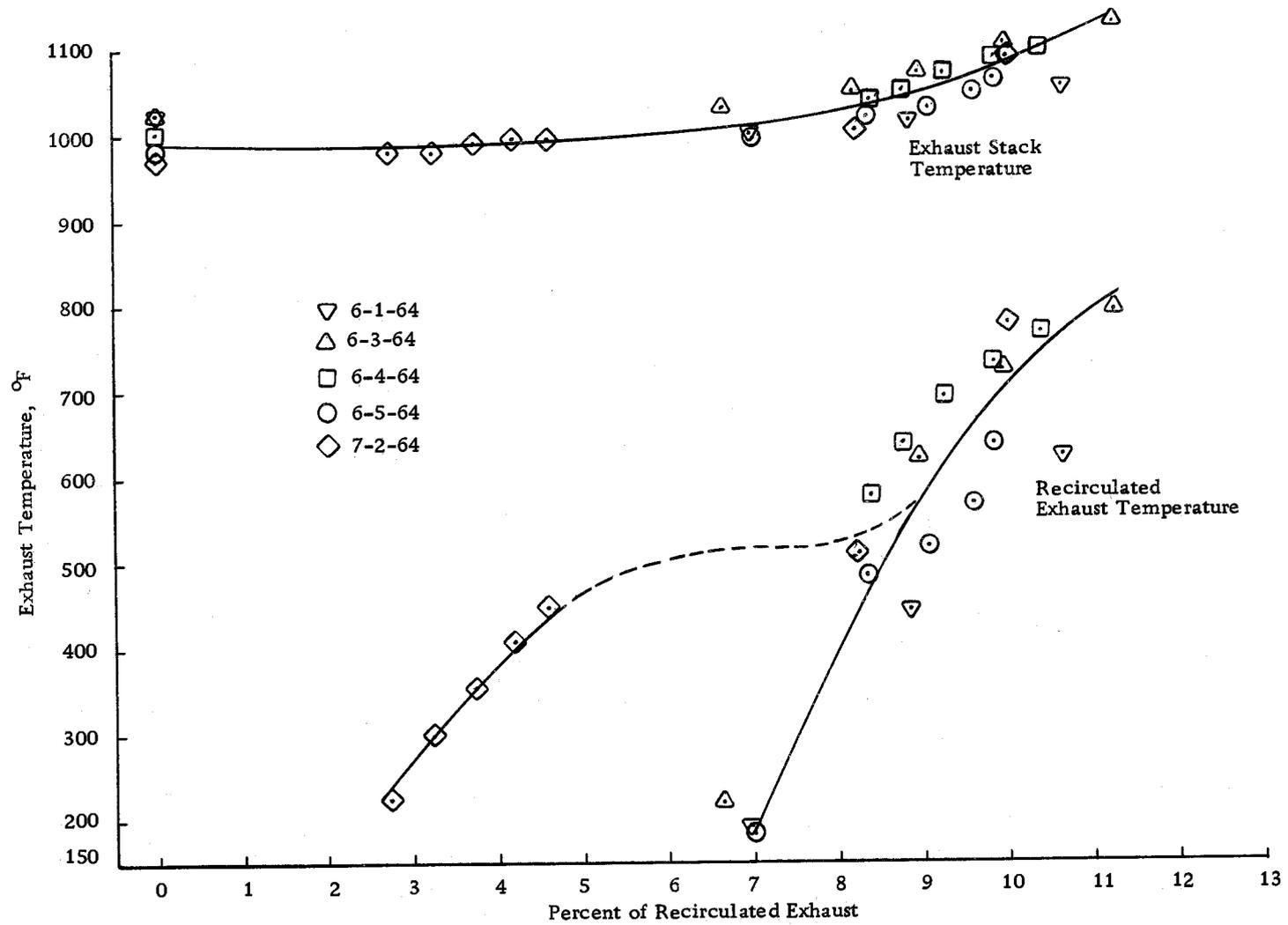


FIGURE 10. Exhaust Temperatures versus Percent of Recirculated Exhaust

exhaust stack and in the exhaust recirculation line versus the percent of exhaust gas recirculation. The figure shows that the exhaust gas stack temperature increased slightly and that the exhaust gas recirculation temperature increased considerably as the recirculation of exhaust gas increased.

Figure 11 shows the concentrations of carbon monoxide, carbon dioxide, and hydrocarbons versus the percent of recirculated exhaust gas. The figure shows that the parts per million concentration of hydrocarbons changed slightly, that the concentration of carbon monoxide remained essentially constant, and that the concentration of carbon dioxide increased slightly with the increase of recirculated exhaust gas.

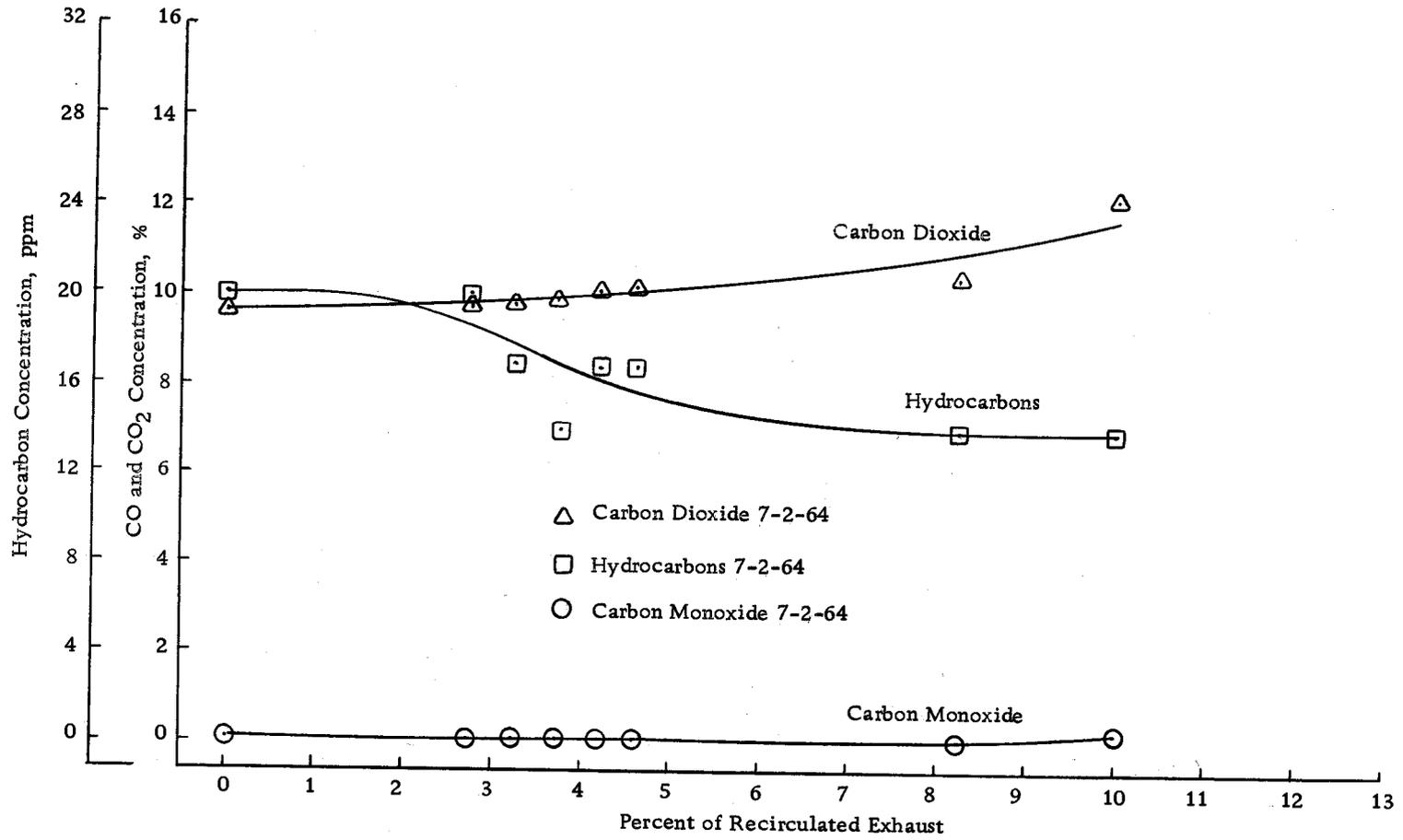


FIGURE 11. Concentration of CO₂, CO, and Hydrocarbons versus Percent of Recirculated Exhaust

VI. DISCUSSION

Figure 7 shows that as the amount of recirculated exhaust gas was increased, the concentration of NO_x remained essentially constant up to eight percent of recirculated exhaust gas and then increased by 400 ppm to 700 ppm at 11 percent. Figure 8 shows that as the exhaust gas recirculation was increased from zero to 11 percent of exhaust recirculation the fuel-air ratio increased from about 0.050 to 0.065 due to the decreasing amount of air available for combustion with the essentially constant fuel flow. Figures 9 and 10 show that the engine parameters of horsepower, exhaust temperature, and smoke intensity were not benefited by the recirculation of exhaust gas. Although the concentration of oxides of nitrogen in these tests increased with increased exhaust recirculation, the recirculation variables of temperature and quantity were allowed to vary simultaneously. Under conditions in which one variable is controlled and the other is allowed to vary, the concentration of oxides of nitrogen may decrease.

The recirculation tests of this project were conducted without regard for controlling both the recirculation variables, i. e., temperature and quantity. The quantity of recirculation was controlled independently of the temperature. The recirculation temperature was dependent upon the amount of recirculation, because a greater amount

of the hot exhaust gas was allowed to flow through the recirculation line and because the heat transfer from the recirculation line to the surrounding air was very low. Only the quantity of recirculation was purposely controlled; installation of a device on a diesel-powered vehicle which could simply meter recirculated exhaust gas would be more practical from the standpoint of economy and space, than to include additional heat exchange equipment for controlling the temperature of the recirculated exhaust gas. It was for this reason that each variable was not studied independently to determine its individual effect upon the formation of oxides of nitrogen.

Comparison of Figure 6 with Figure 7 shows that the NO_x concentrations on an equivalent fuel-air ratio basis were substantially higher when exhaust gas was recirculated than when the engine was run entirely on fresh air. Some may claim that the concentration of oxides of nitrogen should be expected to increase with recirculation because the fuel-air ratio increases and because Figure 6 has already shown NO_x to be proportional to fuel-air ratio. However, this argument is not well-founded; because with recirculation, the increase in fuel-air ratio is due entirely to a decrease in volumetric efficiency of the air flow and does not relate to the fuel-air ratio parameters of increasing load and fuel flow which act to increase the peak-cycle temperature and thus the concentration of oxides of nitrogen. The cause of the increased NO_x concentrations may then be laid entirely to the

recirculation variables. Because both NO_x and temperature increase with greater quantity of recirculation, as shown in Figures 7 and 8, it may be presumed that either one or both of the recirculation variables were responsible for increasing the concentration of oxides of nitrogen. The magnitude of NO_x concentrations are in general agreement with results obtained by others (3, p. 7; 9, p. 34-38; 27, p. 34-41; 15, p. 4-10; 16, p. 511; 22, p. 617). Differences in NO_x concentrations from these references are attributed to differences in engine characteristics and to the problems attributed to wet chemical methods of measuring NO_x concentrations (13, p. 5-7).

Thus, the results indicate that there are no advantages to be gained with NO_x concentrations by allowing both the recirculation variables, temperature and quantity, to increase simultaneously. As discussed in the theory section, the effect of decreasing the amount of air flowing to the combustion chamber is to decrease the oxygen and nitrogen available for fixation to oxides of nitrogen. The effect of an increase in peak-cycle temperature during combustion is to increase the concentration of oxides of nitrogen, because the formation of oxides of nitrogen is directly proportional to temperature. Because the recirculation temperature in these tests increased and the air available for combustion simultaneously decreased and because the oxides of nitrogen in the exhaust gas increased, it may be concluded that any benefit to be derived from the increased quantity of recirculation was

overshadowed by the increased recirculation temperature. That the recirculation temperature increase of 600° F significantly affected the peak-cycle temperature, causing increased NO_x concentration, may be seen by comparing the exhaust temperatures of Figures 6 and 10. The temperatures measured in the exhaust stack were not the temperatures in the combustion chambers, but they were directly proportional to the peak-cycle temperature. The recirculation of exhaust gas caused an increase in fuel-air ratio of about 0.015. Over a change in fuel-air ratio of 0.015 without recirculation (Figure 6), the exhaust stack temperature increased by 340° F; whereas, the exhaust stack temperature with recirculation (Figure 10) increased by only 100° F over the same increment of fuel-air ratio. Therefore, the increase in exhaust stack temperature with recirculation was probably caused by the increased recirculation temperature and not the quantity of recirculated gas which acted to increase the fuel-air ratio. In summary, there appears to be no possible way in which recirculation of increasingly hotter exhaust gas could help reduce oxides of nitrogen; its only effect appears to be detrimental.

In order for recirculation of exhaust gas to be a practical means of reducing concentrations of oxides of nitrogen in diesel exhaust gas, the factor of recirculation temperature, which acts to increase the peak-cycle temperature and thus the concentration of oxides of nitrogen, should be held at a constant low temperature while

the recirculation quantity is allowed to vary. Of the two variables, only increased quantity of recirculation would act to decrease oxides of nitrogen; so, it seems apparent that this variable should be investigated while holding the temperature variable constant. The 1940 work on recirculation of exhaust gas, in a slightly different form than conducted for this project, as reported by the Bureau of Mines (3, p. 4), showed that concentrations of oxides of nitrogen were reduced by increased recirculation. However, since publication of that work did not include information on temperatures of the recirculated exhaust gas or detailed information on their method of calculating the amount or percent of recirculation flow, comparison of their work with the work done on this project is not meaningful.

In addition to the disadvantage of the increased concentration of oxides of nitrogen, the results indicate that there are no other benefits to be gained from allowing both recirculation temperature and quantity to increase simultaneously. At 11 percent exhaust recirculation the horsepower output of the engine has decreased by 12.5 percent, from 32 to 27.7 horsepower, and the smoke intensity has increased to the point of being an objectionable nuisance, as shown in Figure 9. Both of these results are readily explained because the amount of air available for combustion decreased while the fuel flow remained constant, so that combustion was not as complete. Thus, the developed power decreased and the smoke increased. The 0.1

percent concentration of carbon monoxide and the 20 ppm concentration of unburned hydrocarbons were not substantially affected by the recirculation of exhaust gas, as shown in Figure 11. However, carbon dioxide was affected to some degree; the concentration of carbon dioxide increased from 9.6 to 11.6 percent, a two percent increase. None of these latter three effects are especially significant as far as emissions to the atmosphere are concerned, with the exception of the increased emission of carbon dioxide in an enclosed location.

VII. CONCLUSIONS

It was concluded from the foregoing material in the theory and discussion sections that:

1. The use of recirculating exhaust gas to the intake of the diesel engine was not successful in reducing the concentration of oxides of nitrogen in diesel exhaust under conditions allowing recirculation temperature and quantity to increase simultaneously. The concentration of NO_x increased by 400 ppm to 700 ppm at 11 percent of exhaust gas recirculation.

2. Recirculation affected other engine parameters, such as horsepower, which dropped off by 12.5 percent, and smoke intensity of the exhaust, which increased to the point of being objectionable at 11 percent of exhaust gas recirculation.

3. Recirculation of 11 percent of exhaust gas caused the fuel-air ratio of combustion to increase from about 0.050 to 0.065; this was accompanied by an increase of about 100°F in the exhaust gas temperatures.

4. Concentrations of other common effluents, such as carbon dioxide and hydrocarbons, were not significantly affected by the recirculation of exhaust gas. However, the concentration of carbon dioxide increased by two percent at ten percent of exhaust gas recirculation.

5. Because oxides of nitrogen were shown by earlier work to be reduced under some unknown operating conditions and because of the arguments presented in the discussion section, it would seem that recirculation studies under conditions different than used in these tests should be investigated.

VIII. RECOMMENDATIONS

Since there is evidence which indicates that diesel exhaust recirculation tests, run in a different manner than conducted in this project, would be beneficial in reducing concentrations of oxides of nitrogen, the following recommendations are included for future work on this project.

1. Recirculation tests, in which the temperature of recirculation is held constant and to a low value, preferably around 100° F, should be undertaken. The quantity of recirculation should be allowed to increase to determine if its affect truly decreases the concentration of oxides of nitrogen, as the theory indicates. To be certain of the role each recirculation variable plays, tests could also be conducted in which the quantity is held constant and the temperature is allowed to vary. To maintain a constant recirculation mass flow rate, the volume flow rate, read with the rotameter, would have to be changed slightly to account for changes in exhaust density due to changes in the exhaust temperature.

2. The fuel pump rack control was found to have a small amount of slack, which may have been causing a slight degree of surging in the running of the engine. It is suggested that the control be spring loaded near the fuel pump rack so that positive control of the rack is assured.

3. It is suggested that the NO_x instrument be operated with a vacuum system for injection to and purging of the test cell. This simply involves injection of the exhaust gas sample into the test cell when it is at a high vacuum; and then filling the test cell with oxygen to atmospheric pressure for the oxidation of nitric oxide. Samples would be removed from the test cell with the vacuum pump which would insure complete removal of the old sample; this is not completely guaranteed when the cell is purged with oxygen at atmospheric pressure. This procedure would also eliminate the possibility of losing a part of the sample through the outlet stopcock of the test cell when the sample was injected.

4. It may be an advantage to obtain exhaust gas samples directly with the 100 cc syringe instead of the two-liter flask, simply for a matter of convenience. If this method is used, care must be taken that the gas in the syringe is at atmospheric pressure before it is injected into the test cell, since calibrations are made with the sample at atmospheric pressure.

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A. TEST DATA

General Notes for all Test Data:

1. Pressure drop between exhaust manifold and rotameter was constant, for all rotameter readings, at one-inch water.
2. Return fuel flow for recirculation runs was constant at 4.1×10^{-4} lb/sec.
3. The exhaust temperatures indicated in the data correspond to the following engine locations:
 - a. Number 1, cylinder number one.
 - b. Number 2, cylinder number four.
 - c. Number 3, exhaust stack.
 - d. Number 4, common point to cylinders number two and three.
 - e. Number 5, recirculation line, below rotameter.

TABLE 1. Test Data without Recirculation (5-30-64)

Run	Load, lb	Brake horsepower	Fuel flow, sec/100 cc	Jacket out, °F	Jacket in, °F	Oil temperature, °F	Exhaust Temperature, °F				ΔP Nozzle, in H ₂ O	Air temperature, °F	NO _x concentration, ppm	Smoke meter, % transmission
							1	2	3	4				
1	84.8	33.9	31.67	160	153	184	1090	1080	1195	1115	3.35	93.0	424	11
2	80.2	32.1	35.31	160	155	184	965	960	1015	1000	5.55	94.0	317	42
3	60.6	24.25	43.83	161	158	183	775	770	795	790	5.775	90.0	272	60.5
4	39.4	15.75	55.10	160	160	182	610	610	615	610	5.925	89.0	266	52
5	19.9	7.96	68.14	159	159	182	495	500	495	500	5.975	90.5	255	34
6	0	0	89.42	159	161	180	395	400	390	395	6.05	90.5	350	19

NOTES:

1. Barometric pressure = 29.78 @ 80°F
2. Engine speed = 1,600 rpm
3. Exhaust back pressure = 30 in. H₂O
4. Fuel specific gravity = 0.851

TABLE 2. Test Data with Recirculation (6-1-64)

Run	Recirculation, % of gauge	Load, lb	Brake horsepower	Fuel flow, sec/100 cc	Jacket out, °F	Jacket in, °F	Oil temperature, °F	Exhaust Temperature, °F					ΔP Nozzle, in H ₂ O	Air temperature, °F	NO _x concentration, ppm	Smoke, % transmission
								1	2	3	4	5				
1	0	79.8	31.9	35.26	160	152	179	950	960	1025	995	---	5.55	92.0	317	49.5
2	20	79.6	31.85	35.27	160	153	180	920	930	1000	965	190	5.325	93.0	295	47.0
3	40	78.5	31.4	35.29	160	153	180	935	935	1015	975	445	4.70	93.5	258	36.0
4	60	75.4	30.15	35.33	160	153	181	970	960	1055	1015	625	4.025	97.0	500	27.5

NOTES:

1. Barometric pressure = 29.69 in. Hg. @ 80° F
2. Engine speed = 1,600 rpm
3. Exhaust back pressure = 30 in. H₂O
4. Fuel specific gravity = 0.851

TABLE 3. Test Data with Recirculation (6-3-64)

Run	Recirculation, % of gauge	Load, lb	Brake horsepower	Fuel flow, sec/100 cc	Jacket out, °F	Jacket in, °F	Oil temperature, °F	Exhaust Temperature, °F					ΔP Nozzle, in H ₂ O	Air temperature, °F	NO _x concentration, ppm	Smoke, % transmission
								1	2	3	4	5				
1	0	79.9	31.95	34.78	161	154	182	945	955	1025	995	---	5.40	94.0	334	38
2	20	79.6	31.85	34.71	160	153	182	945	950	1030	1000	220	5.325	92.5	328	45.5
3	40	78.4	31.35	34.70	161	154	184	965	960	1050	1010	505	4.625	94.5	331	32
4	50	76.7	30.7	34.68	161	154	185	985	970	1070	1030	620	4.225	95.0	359	21.5
5	60	73.3	29.3	34.56	161	154	185	1015	990	1105	1060	725	3.625	95.0	610	8
6	70	69.2	27.7	34.47	161	155	187	1040	1005	1130	1080	795	3.175	99.0	720	4

NOTES:

1. Barometric pressure = 29.62 @ 80° F
2. Engine speed = 1,600 rpm
3. Exhaust back pressure = 30 in. H₂O
4. Fuel specific gravity = 0.851

TABLE 4. Test Data with Recirculation (6-4-64)

Run	Recirculation, % of gauge	Load, lb	Brake horsepower	Fuel flow, sec/100 cc	Jacket out, °F	Jacket in, °F	Oil temperature, °F	Exhaust Temperature, °F					ΔP Nozzle, in H ₂ O	Air temperature, °F	NO _x concentration, ppm	Smoke, % transmission
								1	2	3	4	5				
1	0	79.6	31.85	35.36	160	153	181	935	935	1000	975	---	5.575	93.5	305	48.5
2	45	77.1	30.85	35.23	159	153	183	965	955	1040	1000	580	4.425	95.0	323	25
3	50	75.8	30.3	35.41	160	153	183	975	955	1050	1015	640	4.175	93.0	354	18.0
4	55	74.3	29.7	35.35	159	153	183	990	970	1070	1030	695	3.875	95.0	479	16.0
5	60	72.7	29.1	35.74	160	154	183	1010	980	1090	1045	735	3.625	95.0	492	9.5
6	65	70.6	28.25	35.26	159	153	185	1020	1000	1100	1055	770	3.400	95.5	500	6.0

NOTES:

1. Barometric pressure = 20.66 @ 80°F
2. Engine speed = 1,600 rpm
3. Exhaust back pressure = 30 in. H₂O
4. Fuel specific gravity = 0.851

TABLE 5. Test Data with Recirculation (6-5-64)

Run	Recirculation, % of gauge	Load, lb	Brake horsepower	Fuel flow, sec/100 cc	Jacket out, °F	Jacket in, °F	Oil temperature, °F	Exhaust Temperature, °F					ΔP Nozzle, in H ₂ O	Air temperature, °F	NO _x concentration, ppm	Smoke, % transmission
								1	2	3	4	5				
1	0	79.5	31.8	35.81	160	154	180	920	930	990	960	---	5.625	89.0	266	46.5
2	20	78.9	31.55	35.91	160	153	181	925	930	995	960	185	5.375	88.0	357	49.5
3	40	77.5	31.0	35.95	160	154	181	945	940	1020	975	485	4.675	90.0	277	34.5
4	45	76.5	30.6	35.80	160	153	182	955	950	1030	990	520	4.40	90.0	272	30.0
5	50	75.5	30.2	35.94	160	154	182	970	960	1050	1005	570	4.15	91.0	407	23.0
6	55	74.5	29.8	35.84	160	153	182	980	970	1065	1020	640	3.90	89.5	503	17.0
7	60	72.6	29.05	35.86	160	153	182	1000	975	1080	1035	730	3.675	92.0	525	13.0

NOTES:

1. Barometric pressure = 29.67 @ 78.5°F
2. Engine speed = 1,600 rpm
3. Exhaust back pressure = 30 in. H₂O
4. Fuel specific gravity = 0.851

TABLE 6. Test Data with Recirculation (7-2-64)

Run	Recirculation, % of gauge	Load, lb	Brake horsepower	Fuel flow, sec/100 cc	Jacket out, °F	Jacket in, °F	Oil temperature, °F	Exhaust Temperature, °F					ΔP Nozzle, in H ₂ O	Air temperature, °F	NO _x concentration, ppm	Hydrocarbons, ppm	Carbon monoxide, %	Carbon dioxide, %
								1	2	3	4	5						
1	0	80.1	32.05	36.02	161	155	184	910	925	975	945	---	5.55	87	277	20	0.1	9.65
2	8	79.6	31.85	35.76	161	156	184	920	925	980	950	225	5.175	89	277	20	0.1	9.75
3	11	79.3	31.70	36.05	160	155	184	910	925	980	950	300	5.100	90	351	15	0.1	9.80
4	14	78.9	31.55	36.07	160	154	184	920	930	990	955	355	4.95	90	351	10	0.1	9.9
5	17	78.6	31.45	36.10	160	155	184	925	930	995	965	410	4.825	91	328	15	0.1	10.1
6	20	77.9	31.15	36.05	160	154	184	925	930	995	960	450	4.675	90	402	15	0.1	10.2
7	40	77.5	31.00	36.07	161	155	184	930	935	1005	965	510	4.500	91.5	407	10	0.1	10.4
8	60	71.3	28.50	35.66	161	155	184	1005	995	1090	1050	780	3.15	94	1110	10	0.3	12.2

NOTES:

1. Barometric pressure = 29.89 @ 80°F
2. Engine speed = 1,600 rpm
3. Exhaust back pressure = 30 in. H₂O
4. Fuel specific gravity = 0.851

B. Sample Calculations for Run 2, (6-5-64)

1. Fresh Air Flow Rate

The flow through the air barrel nozzle is given by,

$$M_A = CA\rho_A \sqrt{\frac{2g \Delta P \rho_W}{12 \rho_A}}$$

M_A = Mass air flow, lb/sec.

C = Nozzle constant = 99%

ρ_A = Density of air, lb/ft³

g = Gravitational acceleration, ft/sec.²

ΔP = Pressure drop across nozzle, in. H₂O

ρ_W = Density of water, lb/ft³

$$\begin{aligned} M_A &= 0.99\pi \left(\frac{1.259}{4}\right)^2 \rho_A \sqrt{\frac{64.4 \Delta P 62.4}{12 \rho_A}} \\ &= 0.1564 \sqrt{\rho_A \Delta P} \end{aligned}$$

$$\rho_A = \frac{P_B}{RT_A}$$

P_B = Corrected barometric pressure, in.Hg

R = Gas constant = 1545 $\frac{\text{ft}\cdot\text{lb}}{\text{Mole}\cdot\text{R}}$

T_A = Air temperature, °R

$$\begin{aligned} \rho_A &= \frac{\text{Mole } \text{R} \cdot 29 \text{ lb} \cdot 29.53 \text{ in. Hg} \cdot 70.73 \text{ lb}}{1545 \text{ ft lb Mole} \cdot 548 \text{ R} \cdot \text{ft}^2 \text{ in.Hg}} \\ &= 0.0716 \text{ lb/ft}^3 \end{aligned}$$

$$\begin{aligned} M_A &= 0.1564 \sqrt{(0.0716)(5.375)} \\ &= \underline{0.0967 \text{ lb/sec}} \end{aligned}$$

2. Recirculation Flow Rate

The volume flow rate through a rotameter is given by,

$$Q = 60A_E C \left[\frac{2g V_F (\rho_F - \rho_E)}{A_F \rho_E} \right]^{1/2}$$

Because the density of the float is much greater than the density of the exhaust gas, $\rho_F \gg \rho_E$, this equation may be reduced to a constant times a function of the exhaust density.

$$Q = K \left(\frac{1}{\rho_E} \right)^{1/2}$$

Because the Fischer-Porter rotameter was calibrated to read percent of 36 cubic feet per minute (cfm) when the gas flowing through it was at 70°F and 14.7 psi, it was necessary to apply a correction factor, based on the above relationship, to correct the indicated rotameter reading from the existing exhaust density to the calibration density.

$$Q_{\text{corrected}} = (\text{Indicated gauge \%}) \frac{(36 \text{ cfm})}{60} \left(\frac{1}{\frac{30.00 P_R}{530 T_R}} \right)^{1/2}, \frac{\text{ft}^3}{\text{sec}}$$

P_R = Recirculation pressure, in. Hg
 T_R = Recirculation temperature, °R

The recirculation mass flow rate is then the corrected volume flow rate times the exhaust gas density,

$$M_R = (Q_{\text{corrected}}) (\rho_E), \text{ lb/sec}$$

$$\begin{aligned} M_R &= 20\% \frac{36}{60} \left[\frac{(29.53)(530)}{30.00 \ 645} \right]^{1/2} (0.0652) \\ &= \underline{0.00729 \text{ lb/sec}} \end{aligned}$$

3. Percent of exhaust gas recirculation

Percent of exhaust gas recirculation is the mass flow rate of recirculated exhaust gas divided by the total amount of gas flowing into the engine, fresh air flow rate plus recirculated flow rate.

$$\begin{aligned}
 \% \text{ of Recirculated Exhaust} &= \frac{M_R}{M_R + M_A} \times 100\% \\
 &= \frac{0.00729}{0.00729 + 0.0967} \times 100\% \\
 &= \underline{7.01\%}
 \end{aligned}$$

4. Net fuel flow

The net fuel flow is the gross fuel flow minus the flow of fuel returned from the fuel injectors.

$$\begin{aligned}
 \text{Gross fuel flow} &= (100 \text{ cc}) \left(\frac{1 \text{ gm}}{\text{cc}} \right) (\text{sp. gr.}) \left(\frac{\text{lb}}{453 \text{ gm}} \right) \left(\frac{1}{\text{time}} \right) \text{lb/sec} \\
 &= \frac{(100)(0.853)}{(453)(35.91)} \\
 &= 0.00533 \text{ lb/sec}
 \end{aligned}$$

$$\text{Return fuel flow} = \frac{(10 \text{ cc})(0.86)}{(453)(46.80)} = 0.00041 \text{ lb/sec}$$

$$\begin{aligned}
 \text{Net fuel flow} &= M_F = 0.00533 - 0.00041 \\
 &= \underline{0.00492 \text{ lb/sec}}
 \end{aligned}$$

5. Excess air in recirculated exhaust

The calculation of excess air present in the exhaust is based on an average fuel molecule of $C_{16}H_{34}$ and on the concentration of oxygen and carbon dioxide present in the exhaust,

$$O_2 = 6.975\%$$

$$CO_2 = 9.5\%$$

$$\begin{aligned} \text{Excess air} &= \frac{\text{lb mol } CO_2}{\text{mol fuel}} \times \frac{100 \text{ mol d. g.}}{9.5 \text{ mol } CO_2} \times \frac{6.975 \text{ mol } O_2}{100 \text{ mol d. g.}} \times \frac{100 \text{ mol air}}{21 \text{ mol } O_2} \\ &= \underline{7.18 \text{ lb air/lb fuel}} \end{aligned}$$

6. True fuel - air ratio

The true fuel-air ratio is the net fuel flow divided by the sum of the fresh air flow plus the amount of air in the recirculated exhaust gas.

$$\begin{aligned} \text{True fuel-air} &= \frac{M_F}{M_A + (\% \text{ Recirculation})(\text{Excess air})(M_F)} \\ &= \frac{0.00492 \text{ lb/sec}}{0.0967 \text{ lb/sec} + 7.01\% \times 7.18 \frac{\text{lb air}}{\text{lb fuel}} \times 0.00492 \frac{\text{lb fuel}}{\text{sec}}} \\ &= \frac{0.00492}{0.0992} = \underline{0.0496} \end{aligned}$$

7. Gas flask pressurization during calibration

When preparing known concentrations of NO in the gas flask it was necessary to pressurize the flask so that, when a 100 cc sample was withdrawn, the combined volumes of the flask and syringe would be at atmospheric pressure. The sample, then at atmospheric pressure, was injected into the NO_x instrument.

Vol. of flask = 2,063.5 ml.
Vol. of syringe = 100 ml.
Barometric
pressure = 29.53 in. Hg.

The pressure times the volume of the flask must equal the barometric pressure times the volume of the flask and syringe.

$$P_f V_f = P_B V_{f+s}$$

$$P_f 2063.5 = (29.53) 2163.5$$

$$P_f = 31.00 \text{ in. Hg or } 1 \text{ in. Hg above atm. press.}$$