

AN ABSTRACT OF THE THESIS OF

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Title THE FATE OF OXIDES OF NITROGEN THROUGH A DIRECT  
FLAME AFTERBURNER IN THE EXHAUST OF A GASOLINE ENGINE

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Compounds, such as oxides of nitrogen and unburned hydrocarbons, found in automotive exhaust have been definitely linked with the formation of photochemical smog.

The state of California has the greatest problem with photochemical smog. To cope with this problem the California Motor Vehicle Pollution Control Board was formed and adopted the maximum allowable emission standard of 275 parts per million of hydrocarbons and 1.5 percent carbon monoxide by volume in the exhaust of an automobile when averaged over a specified driving cycle. There is no specification for nitrogen oxides at the present time but a definite possibility exists that a nitrogen oxide standard will be established due to the participation of such compounds in photochemical smog formation.

Direct flame afterburners have been developed and tested extensively as a means of meeting the California standards. The direct flame afterburner operates on the basic principle of introducing secondary air into a combustion chamber through which the exhaust gases pass. The unburned portion of the exhaust gases, namely carbon monoxide and hydrocarbons, mixes with the air and these gases are ignited by a spark plug in the afterburner combustion chamber. Exhaust gas temperature may reach as high as 2,000 degrees Fahrenheit in the afterburner combustion chamber which brings up the question: do oxides of nitrogen form in the afterburner? The answer to this question could have a very significant effect in afterburner development and in the possible establishment of a nitrogen oxide standard. It is the purpose of this work to determine if nitrogen oxides are formed in a direct flame afterburner.

The experimental work was carried out in an engine laboratory by simulating road load conditions and programming the engine to follow the California seven-mode test cycle. The nitrogen oxide concentrations at the afterburner inlet and outlet were determined throughout the 129 second seven-mode cycle using a 2.5 second interval progressive grab sampling method. The concentrations were measured as nitrogen dioxide by an absorption spectrophotometric analyzer which was developed at Oregon State University. Hydrocarbon, carbon monoxide and carbon dioxide concentrations were also monitored by commercial

non-dispersive infrared analyzers for the purpose of correlating this work with that being done by others in this field.

The results of investigating the fate of oxides of nitrogen through a direct flame afterburner can be summarized as follows:

1. The total oxides of nitrogen concentrations were essentially unchanged across the afterburner.
2. The progressive grab sampling technique that was used for oxides of nitrogen proved successful. Consistent results over the entire California Seven-mode cycle were obtained. The spectrophotometric oxides of nitrogen analyzer operated satisfactorily and gave consistent results.
3. A n-hexane sensitized infrared hydrocarbon analyzer does not measure total unburned hydrocarbon concentrations adequately to compute a carbon balance across the afterburner.
4. The engine-afterburner combination tested did not meet the California requirements pertaining to maximum allowable unburned hydrocarbons and carbon monoxide, but this may be due to the overly rich carburetor. The afterburner operated satisfactorily during all testing.

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THROUGH A DIRECT FLAME AFTERBURNER  
IN THE EXHAUST OF A GASOLINE ENGINE

by

GARY DEAN JAROS

and

NEILL RICHARD PARKIN

A THESIS

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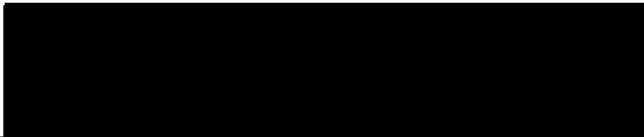
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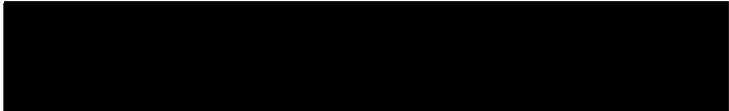
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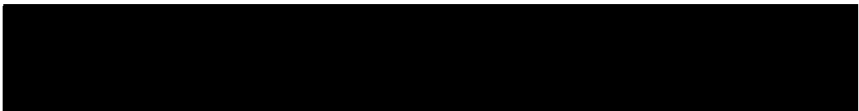
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## NOMENCLATURE AND ABBREVIATIONS

<u>ABBREVIATION</u>	<u>DEFINITION OR TERM</u>
$\text{lb}_m\text{-ft}^2$	pounds mass-square feet
ppm	parts per million
a. c.	alternating current
$\text{O}_2$	oxygen
CO	carbon monoxide
$\text{CO}_2$	carbon dioxide
NO	nitric oxide
$\text{NO}_2$	nitrogen dioxide
$\text{NO}_x$	nitric oxide and nitrogen dioxide, usually referred to as "total oxides of nitrogen"
accel	acceleration
decel	deceleration
$\pm$	plus or minus
mv	millivolt
Hg	mercury
HC	hydrocarbon
MVPCB	Motor Vehicle Pollution Control Board
NDIR	non-dispersive infrared
rpm	revolutions per minute
mph	miles per hour

# THE FATE OF OXIDES OF NITROGEN THROUGH A DIRECT FLAME AFTERBURNER IN THE EXHAUST OF A GASOLINE ENGINE

## I. INTRODUCTION

### The Problem

During the past decade compounds contained in automobile exhaust have been definitely linked with the formation of photochemical smog. Air pollution is not new to most urban areas but the importance of the automobile in its formation is increasing.

The increasing concern about automobile exhaust and its relation to urban air pollution is due to the tremendous growth and concentration of the motor vehicle population. For example in Los Angeles County alone, the most widely publicized smog area in the world, there are some 3.5 million vehicles which use about seven million gallons of gasoline per day (13, p. 80). Similar conditions of varying degree exist in many other large metropolitan areas such as New York, San Francisco, Detroit, Tokyo and others.

Photochemical smog is not a combination of smoke and fog, which the name implies, but is the product of low temperature chemical reactions which take place at atmospheric temperature and pressure (5, p. 157). The essential constituents of photochemical smog are: (1) sunlight, (2) oxides of nitrogen, and (3) hydrocarbons such as those

found in automobile exhaust. Only the ultraviolet portion of the sun's energy spectrum is utilized to promote the smog reaction. The visible portion of the sun's spectrum has no appreciable effect on smog production. Nitrogen dioxide ( $\text{NO}_2$ ) acts as a primary absorber of the sunlight's ultraviolet energy and dissociates into nitric oxide (NO) and highly energetic oxygen atoms. The nitrogen dioxide is replenished by reoxidation of nitric oxide which does not require solar energy (15, p. 89). The oxygen atoms, and the ozone which is formed by the oxidation of oxygen atoms, react with the hydrocarbons (unsaturated ones more readily) to form the smog irritants. The above discussion is only a brief description of the photochemical smog cycle but it does introduce the basic constituents and steps in which photochemical smog is formed.

The by-products of combustion of gasoline and oil give off substantial proportions of hydrocarbons and oxides of nitrogen. Because of the seriousness of contaminated air in many urban areas air pollution control legislation of varying scope has been enacted in almost every state. Cities also have enacted their own local laws. The Los Angeles area has the most extensive set of air pollution control statutes. The Los Angeles County Air Pollution Control District, formed in 1948, has brought stationary sources of pollutants such as refineries and power plants well under control (13, p. 80). It should be pointed out that oxides of nitrogen are not now one of the pollutants

controlled by the district. After considerable reduction in emissions from stationary sources there was no significant reduction in the intensity of smog in the Los Angeles basin. It was believed this was due to the tremendous growth of the motor vehicle population. In California the motor vehicle registration increased from approximately 3,800,000 in 1948 to 8,900,000 in 1963. The exhaust of an average maintained automobile contains high concentrations of unburned hydrocarbons, carbon monoxide, oxides of nitrogen and many other products which are known to play a role in the formation of photochemical smog.

To cope with the motor vehicle exhaust gas problem California formed the Motor Vehicle Pollution Control Board (MVPCB) in 1960. The seriousness of the problem is well shown by some January 1963 figures on emissions in Los Angeles County (13, p. 80).

Hydrocarbons - 2235 tons per day, 73 percent of this from gasoline powered motor vehicles.

Carbon monoxide - 8,580 tons per day, 96 percent from motor vehicles.

Nitrogen oxides - 850 tons per day, 57 percent from motor vehicles.

The MVPCB adopted the standards set by the California Department of Public Health. These specified a maximum of 275 ppm hydrocarbons and 1.5 percent carbon monoxide by volume in the exhaust of an automobile when averaged over a specific driving cycle.

An average emission for a number of cars that do not have smog control devices is about 950 ppm hydrocarbons and 3.5 percent carbon monoxide. There is no specification for nitrogen oxides. There is some doubt but a definite possibility that a nitrogen oxide standard will be established. The MVPCB have reported (5, p. 3) that:

An ambient air standard for oxides of nitrogen may be found necessary on the basis of the direct toxic effects of nitrogen dioxide on man, and, in this case, control of motor vehicle emissions of oxides of nitrogen may be required. A standard for oxides of nitrogen might also be found necessary because of their participation in the photochemical air pollution complex. It has been established that oxides of nitrogen are an essential component along with organic compounds and sunlight for the production of ozone (10). Recent studies have postulated that because of varying relationships between the levels of hydrocarbon and nitrogen dioxide in the formation of ozone, control over nitrogen oxides may be found necessary to effect a greater reduction in atmospheric ozone levels and in photochemical air pollution than is possible with a control program to meet only the hydrocarbon standard (14).

The following statement by A. J. Haagen-Smit (6, p. 444) supports the above excerpt:

There is no reasonable doubt that control of olefins and other reactive organic pollutants as well as oxides of nitrogen is the most practical way for returning air of acceptable quality to our cities.

Motor vehicle pollutants come from three sources: exhaust, crankcase ventilation and fuel evaporation. The crankcase ventilation emissions are well under control by recirculation devices which are

required by law in California and are now almost universally installed as factory equipment on new cars. The methods of controlling automotive exhaust emissions can be broken down into four basic groups: (1) fuel modification, (2) oxidation of the exhaust, (3) modification of engine operating variables and (4) change of engine combustion process or engine type (14, p. 323). All of the above possible control methods have received attention and study but the exhaust oxidation devices, specifically the direct flame and catalytic afterburners, have been developed and tested extensively as a means of meeting the California standards. The direct flame type might appear to be the more practical of the two in that it does not require the frequent renewal of a catalyst as does the catalytic afterburner. The direct flame afterburner works on the basic principle of introducing secondary air into a combustion chamber through which the exhaust gases pass. The unburned portion of the exhaust gases, namely carbon monoxide and hydrocarbons, mix with the air and are ignited by a spark plug. The completely oxidized exhaust gas then passes on into the atmosphere. Since temperatures as high as 2,000 degrees Fahrenheit can be attained in the afterburner a question arises: do oxides of nitrogen form in the afterburner? The answer to this question could have a very significant effect in afterburner development and in the possible establishment of nitrogen oxide standards. It is the purpose of this work to determine the fate of oxides of nitrogen in a direct flame



afterburner.

### Scope of Study

It was the intention of this investigation to determine what effect a direct flame afterburner has on the nitrogen oxide concentration in automobile exhaust. The work was carried out in an engine laboratory by simulating road load conditions and programming an engine to follow the California seven-mode test cycle.

The nitrogen oxide concentrations at the afterburner inlet and outlet were determined throughout the seven-mode cycle. A progressive grab sampling method was used and the concentrations were measured by an absorption spectrophotometric analyzer which was developed at Oregon State University. Hydrocarbon, carbon monoxide and carbon dioxide concentrations were also monitored by commercial non-dispersive infrared analyzers for the purpose of correlating this work with that being done by others in this field.

The afterburner under test was borrowed from the American Machine and Foundry Company and all work was carried out by two graduate students under the supervision of their respective major professors. The entire investigation was supported by the U. S. Public Health Service, Division of Air Pollution.

Following is a detailed discussion of the apparatus, test procedure used, and the findings that resulted from this investigation.

## II. APPARATUS

The experimental work carried out in this investigation was performed in the Engineering Laboratory Building at Oregon State University. Road load conditions were simulated by use of an electric dynamometer equipped with inertia flywheels. A photograph of the engine, dynamometer and some of the instrumentation, Figure 1, shows the overall test layout. All equipment used was in excellent operating condition. Numerous items, such as the engine, inertia flywheels and gas analyzers, were purchased to provide the latest in equipment. Considerable time and effort was expended to assemble this equipment for the work to be undertaken.

### Engine

The engine used was a 1963 6-cylinder overhead camshaft Kaiser-Jeep Tornado model. It has a piston displacement of 230 cubic inches, a compression ratio of 8.5:1, and a power rating of 140 horsepower at 4,000 revolutions per minute. Engines of this type are commonly used in Jeep station wagons and pickups. The engine was received in used condition and completely rebuilt prior to its use in this project. All carburetion was as specified by the manufacturer. The Holly Model 2300 two-throat carburetor is standard equipment.

During all testing the engine was controlled to operate on the

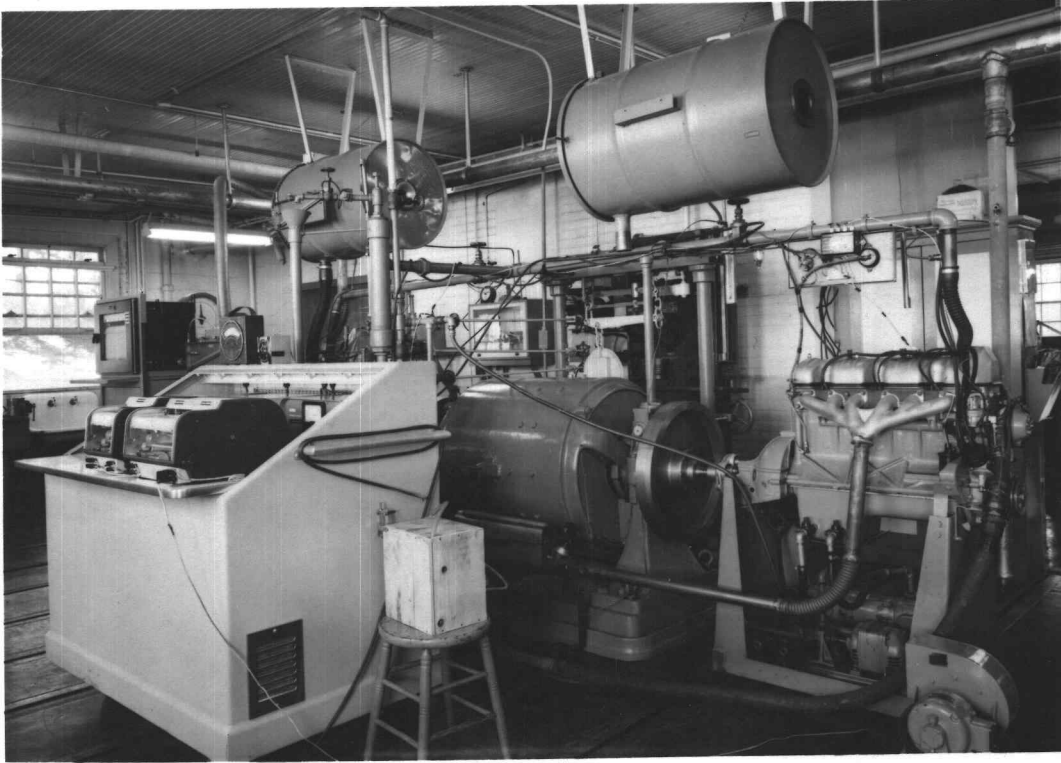


Figure 1. Overall view of test layout

California seven-mode cycle (3, pt. 1, p. 3) which consists of the various modes, idle, cruise, accelerations, and decelerations. The engine control used was suggested by Ray Ulyate of the American Machine and Foundry Company, who had built a similar control and successfully used it in afterburner development work. A schematic diagram of this control is shown in Figure 2. Photographs of the control turntable and throttle control mechanism are pictured in Figures 3 and 4. A microswitch was used on the control turntable to put reference pips on recorder charts at the start of each cycle.

### Dynamometer

The dynamometer used was a General Electric direct current generator. Its capacity is 100 horsepower in the 1050-3500 rpm speed range. Prior to testing, the moment of inertia of the armature was found to be  $176 \text{ lb}_m\text{-ft}^2$ .

The equivalent moment of inertia of a 4000 pound automobile with a similar 6-cylinder engine, 7.50 x 14 tires and 3.45:1 rear axle ratio was calculated to be  $415 \text{ lb}_m\text{-ft}^2$ .

To make the dynamometer equivalent to the above hypothetical 4000 pound automobile, two inertia flywheels were designed, and constructed. Calculations of moments of inertia and flywheel design are included in Appendix A.

The road load of the 4000 pound hypothetical automobile was

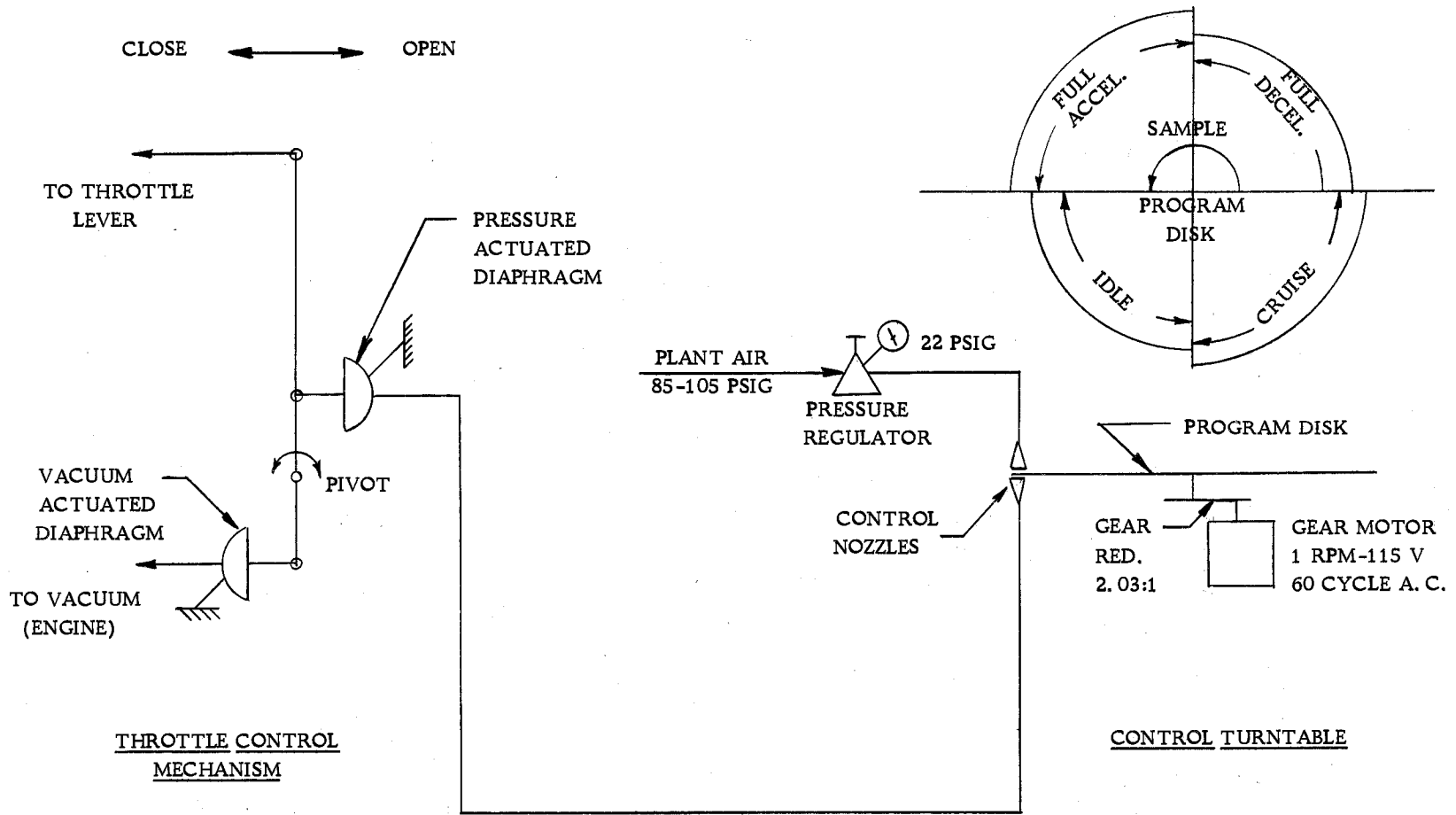


Figure 2. Schematic of engine pneumatic speed control

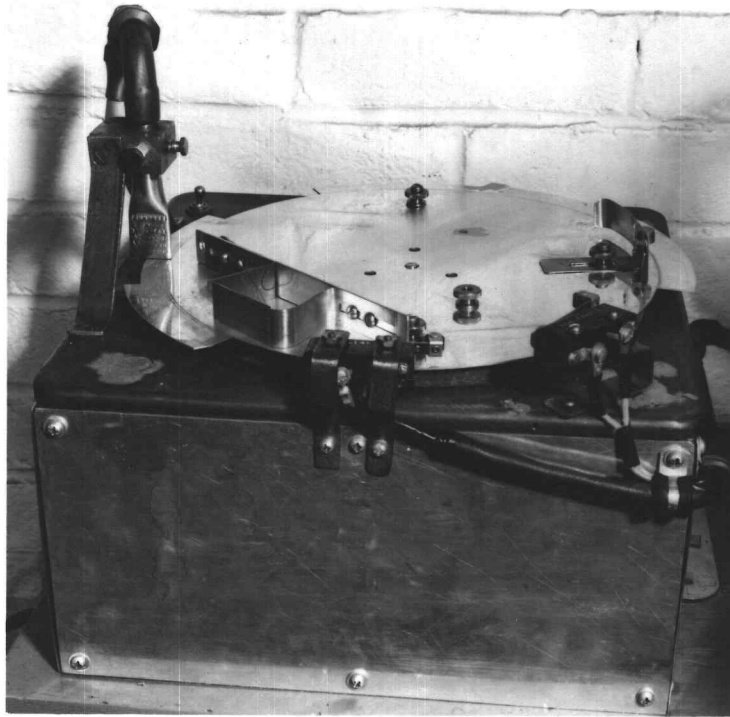


Figure 3. Pneumatic throttle control turntable

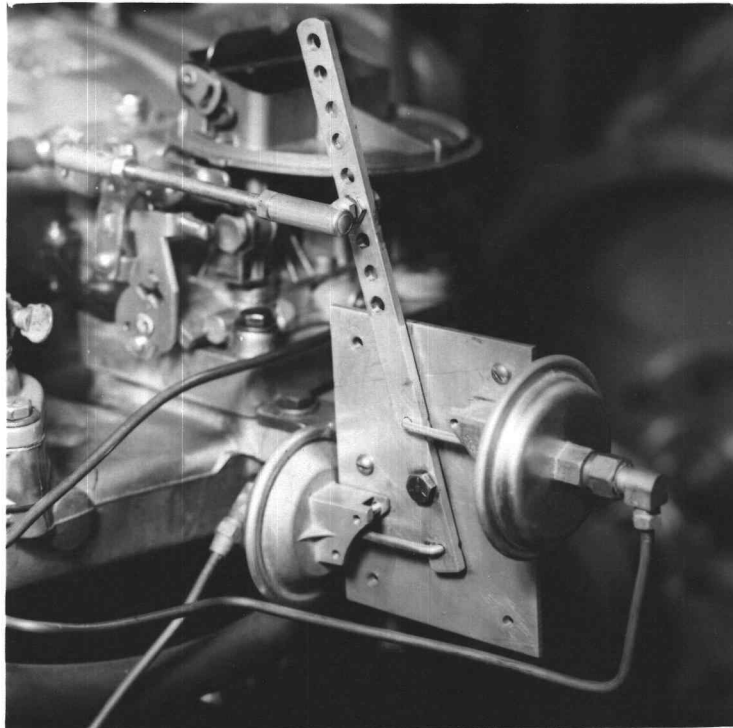


Figure 4. Pneumatic throttle control mechanism

calculated using the General Motors design equation (11, p. 726) for axle power to overcome wind and rolling resistance. Calculations are included in Appendix B. The road load requirements for the hypothetical 4000 pound automobile are shown in Figure B-1.

The road load was applied electrically to the engine as a function of engine speed by separately exciting the field of the dynamometer. Actual loads are shown as the circled data points of Figure B-1.

Extra load was required during decelerations to meet the rates prescribed in the California seven-mode cycle. This extra loading was accomplished by momentarily reducing the field resistance (shorting out part of the field rheostat) with a microswitch on the engine control turntable. A schematic of this electrical loading system can be seen in Figure 5.

### Afterburner

The direct flame afterburner was obtained on consignment from the American Machine and Foundry Company Development Laboratories, Hawthorne, California. The model tested in this work was the Mark IX, a slightly earlier model than that which recently passed the California test program successfully. A photograph of the afterburner can be seen in Figure 6.

The afterburner was located in approximately the same position with respect to the engine as it would normally be installed in an

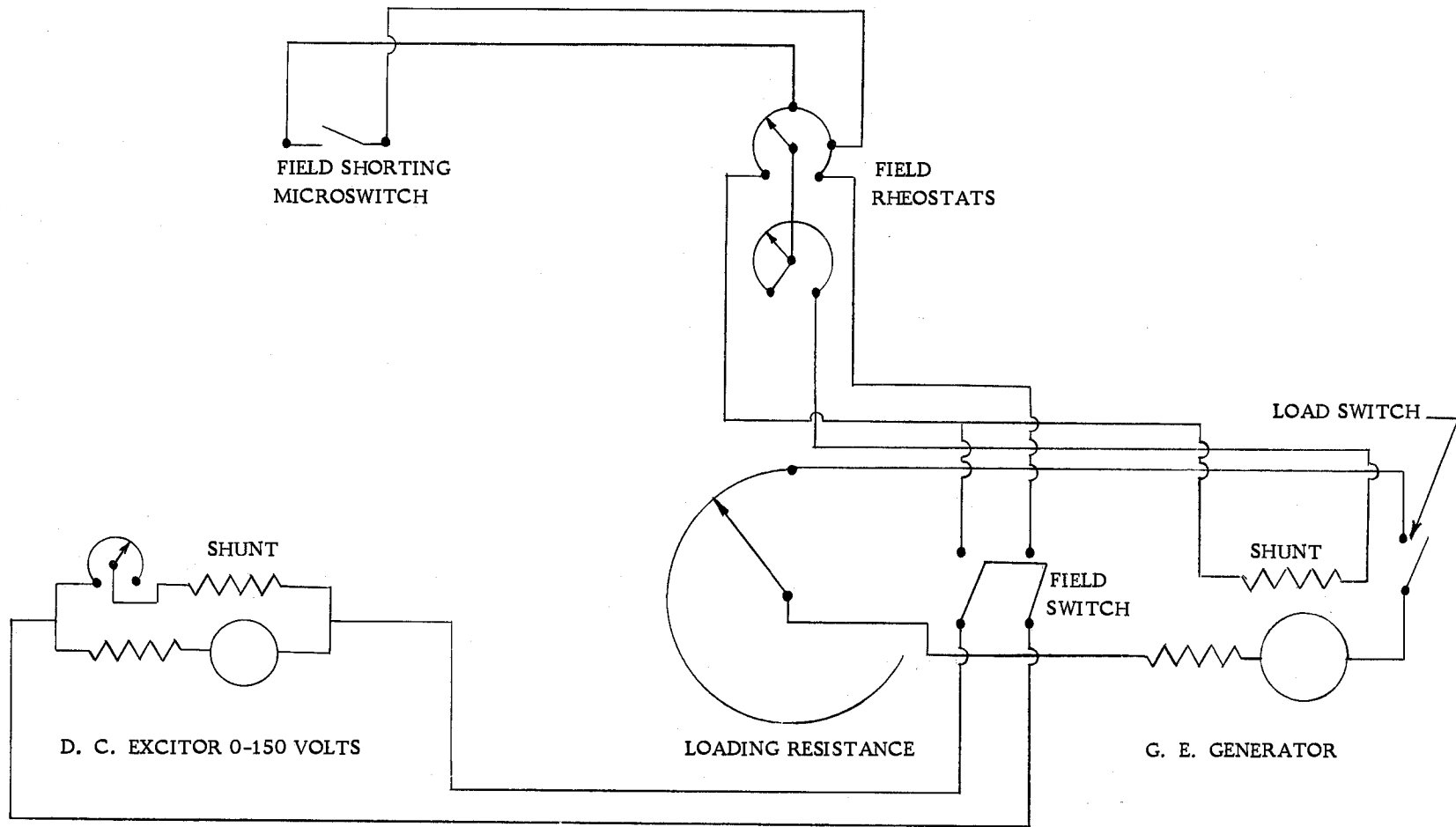


Figure 5. Dynamometer electrical loading schematic diagram



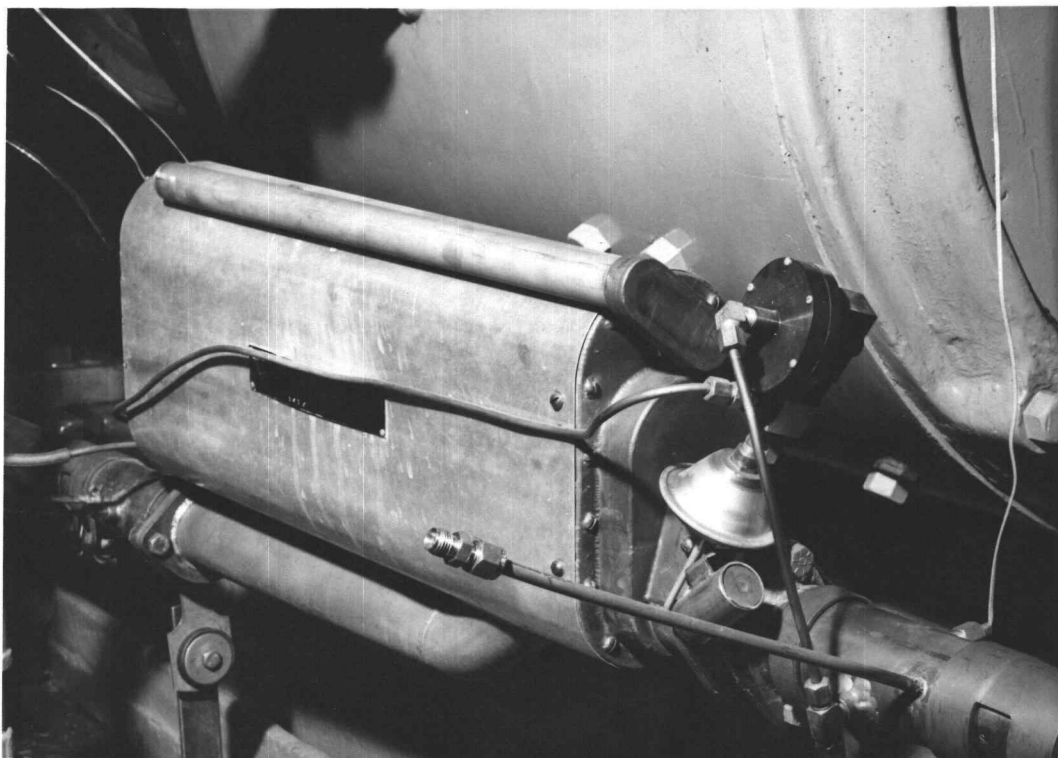


Figure 6. American Machine and Foundry Company Mark IX Afterburner

automobile. It was positioned horizontally about five feet after the engine manifold. A three foot straight section preceded and followed the afterburner. In these three foot straight sections exhaust gas sample probes were located. Static pressure taps and thermocouple locations were also placed ahead and behind the afterburner. The three foot section exhaust pipe at the exit of the afterburner emptied into a section of three inch diameter flexible piping which connected to an exhaust stack. A schematic diagram of the exhaust system is shown in Figure 7.

A 12-inch mercury manometer was used to monitor exhaust back pressure before the afterburner and a four-inch water manometer was used to measure exhaust pressure after the afterburner.

Exhaust gas temperatures were measured with chromel-alumel thermocouples in three locations. They were just before entrance to the afterburner, in afterburner combustion chamber, and immediately after the exhaust gas left the afterburner. The outputs of the thermocouples were recorded on a Brown Electronik Millivolt Recorder.

#### Gas Analysis Equipment

Exhaust gas analysis equipment used during this test consisted of three Beckman Model IR-15A Non-dispersive Infrared Analyzers. The analyzers consist of two basic units, an analyzer and an amplifier which are contained in separate housings. The infrared energy

INSTRUMENTATION DESCRIPTION

- (T<sub>1</sub>) TEMPERATURE OF EXHAUST GAS INTO AFTERBURNER - °F
- (T<sub>2</sub>) TEMPERATURE OF EXHAUST GAS IN COMBUSTION CHAMBER - °F
- (T<sub>3</sub>) TEMPERATURE OF EXHAUST GAS LEAVING AFTERBURNER - °F
- (P<sub>1</sub>) STATIC EXHAUST PRESSURE BEFORE AFTERBURNER - IN. HG.
- (P<sub>2</sub>) STATIC EXHAUST PRESSURE LEAVING AFTERBURNER - IN. H<sub>2</sub>O.
- (S<sub>1</sub>) EXHAUST GAS SAMPLE TO NDIR INSTRUMENTS
- (S<sub>2</sub>) EXHAUST GAS SAMPLE TO NO<sub>x</sub> SAMPLING TRAIN.
- (S<sub>3</sub>) EXHAUST GAS SAMPLE TO NO<sub>x</sub> SAMPLING TRAIN.
- (S<sub>4</sub>) EXHAUST GAS SAMPLE TO NDIR INSTRUMENTS

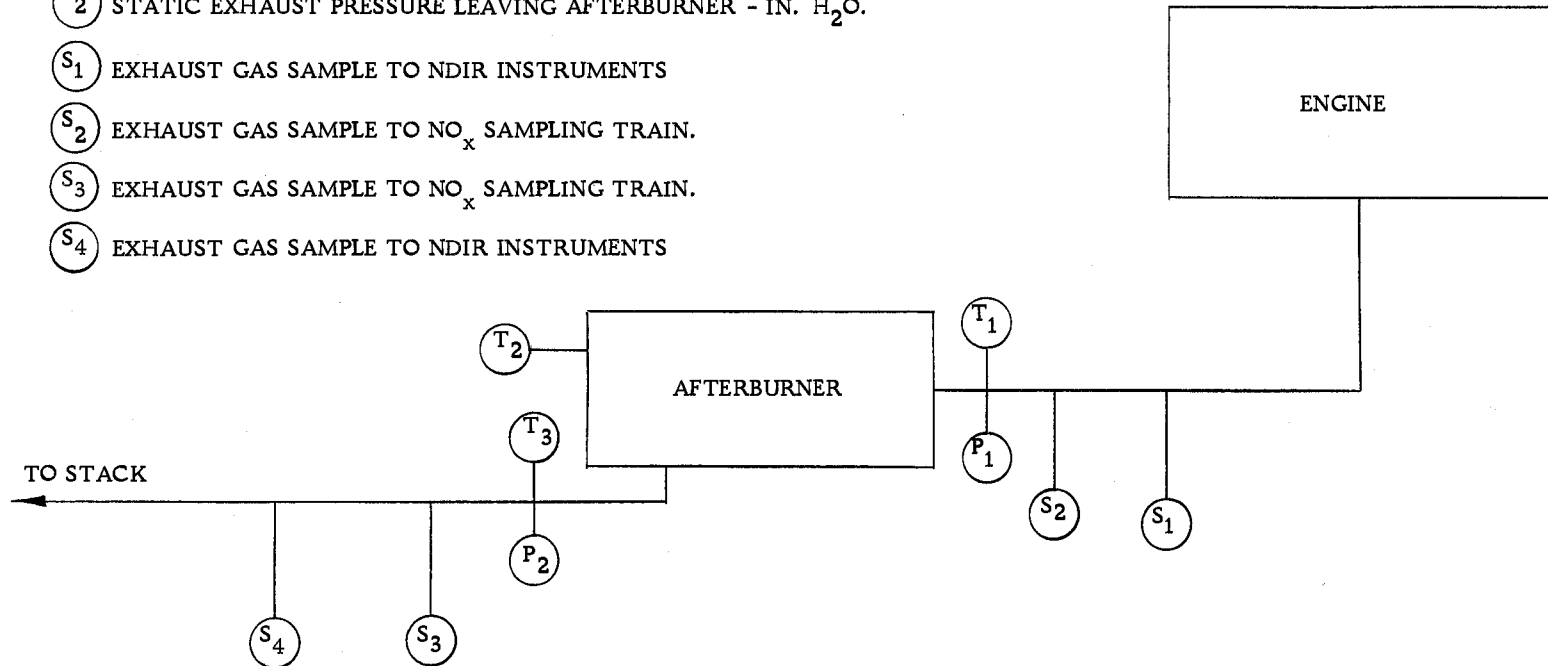


Figure 7. Schematic of exhaust system

sources, energy beam chopper, sample and reference cells, and detector are located in the analyzer. The amplifier unit contains the operating controls, a stable drift free a. c. amplifier and a power supply.

During operation, the instrument detects the presence of material in the sample cell to be monitored, and responds to its absence with a reading of zero. Infrared radiation, chopped ten times per second, is passed simultaneously through the reference cell containing some non-absorbing gas. Because of the difference in spectral absorption between the sample and reference materials, the beams emerge from the cells into the two compartments of the detector at unequal energy levels, which produces a differential pressure in the two detector compartments. This pressure differential moves the sensitive diaphragm-condenser separating the detector compartments. The result is a ten-cycle signal, proportional to the unbalance between the two beams. This voltage is demodulated, amplified, rectified and then read on a meter as a function of sample concentration and may be used to drive a recorder. The three analyzers continuously monitored concentrations of carbon monoxide, carbon dioxide, and unburned hydrocarbons.

The hydrocarbon analyzer had a n-hexane sensitized detector. It was equipped with a one and one half inch  $\text{CO}_2$  filter cell, a 13.5 inch sample cell which was calibrated for 2000 ppm hexane full scale, and a 5.25 inch sample cell which was calibrated for 10,000 ppm full

scale deflection of the recorder.

The carbon monoxide analyzer had a 1/8 inch sample cell. The analyzer was calibrated to 10 percent CO for 90 percent full scale deflection of the recorder.

The carbon dioxide analyzer had a 1/8 inch sample cell. The analyzer was calibrated to 15 percent CO<sub>2</sub> for 90 percent full scale deflection of the recorder.

Texas Instrument Recti-riter Recorders continuously recorded output of the three analyzers during test cycles. A schematic drawing of the Beckman Analyzers, Texas Instrument Recorders and complete sampling train is shown in Figure 8. Photographs showing the analyzer arrangement and parts of the sampling train are shown in Figures 9 and 10. All infrared analyzers, amplifiers, recorders and sampling train were located as shown in one portable instrument console.

The apparatus for determination of oxides of nitrogen in the exhaust gas was a spectrophotometric analyzer. The spectrophotometric method used was developed, and an instrument built, by Nicksic and Harkins of California Research Corporation (12, p. 1-21). A similar piece of equipment was constructed and tested at Oregon State University in 1962 by Douglas E. Johnson (10, p. 6-42), now also of California Research Corporation. This original oxides of nitrogen (usually expressed as "total oxides of nitrogen" or NO<sub>x</sub>)

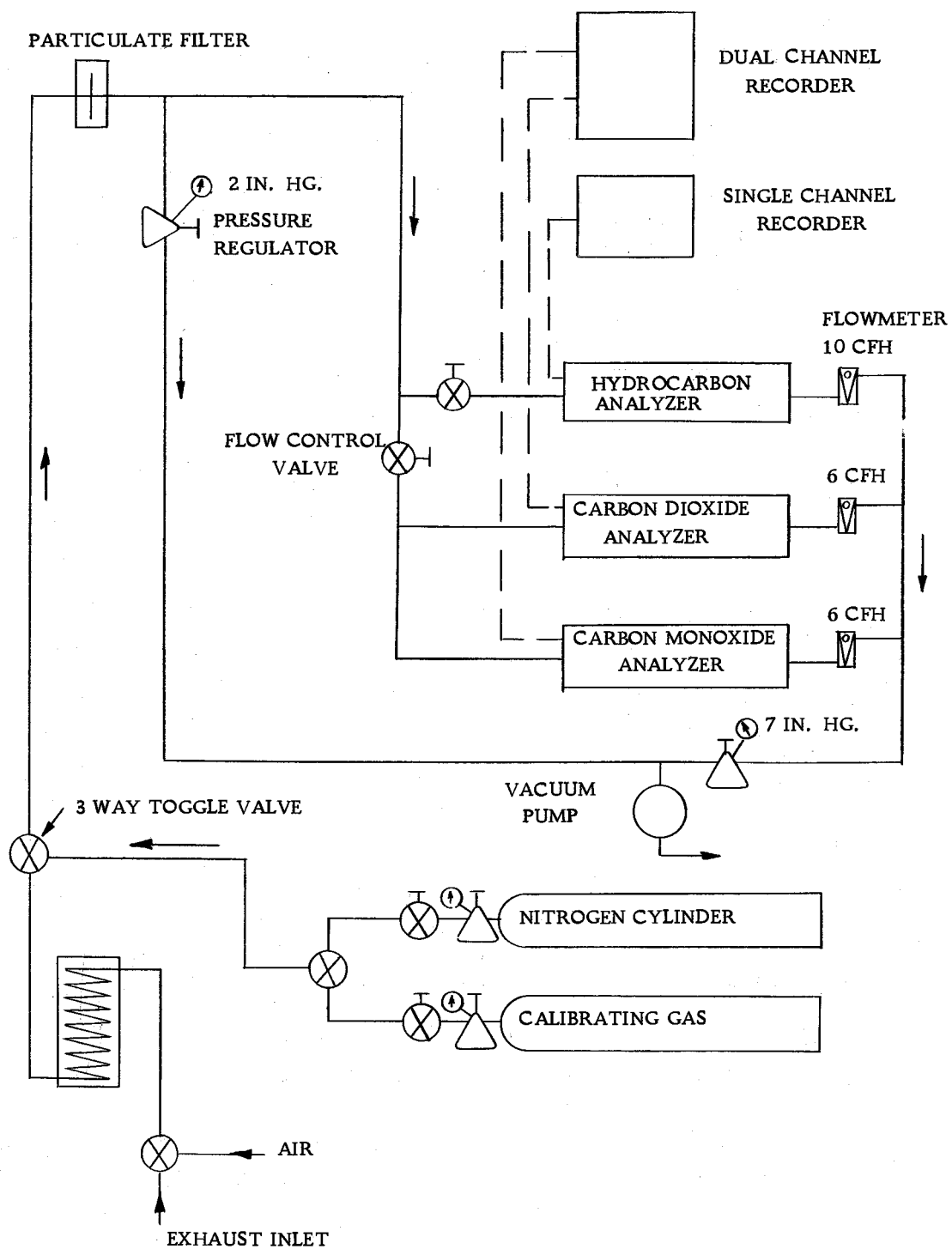


Figure 8. Schematic of sampling system used for infrared analyzers

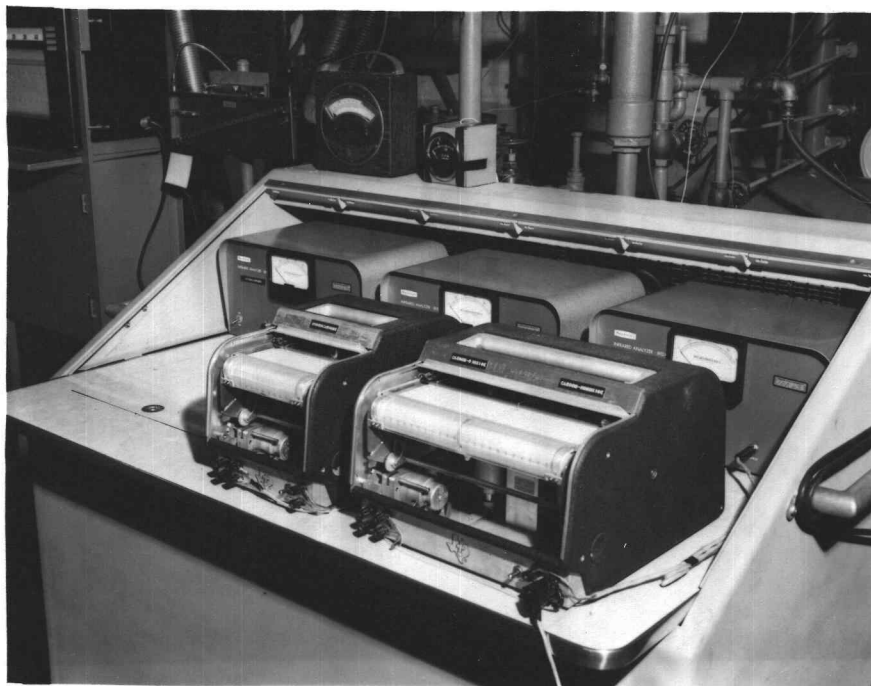


Figure 9. Amplifiers and recorders for infrared analyzers

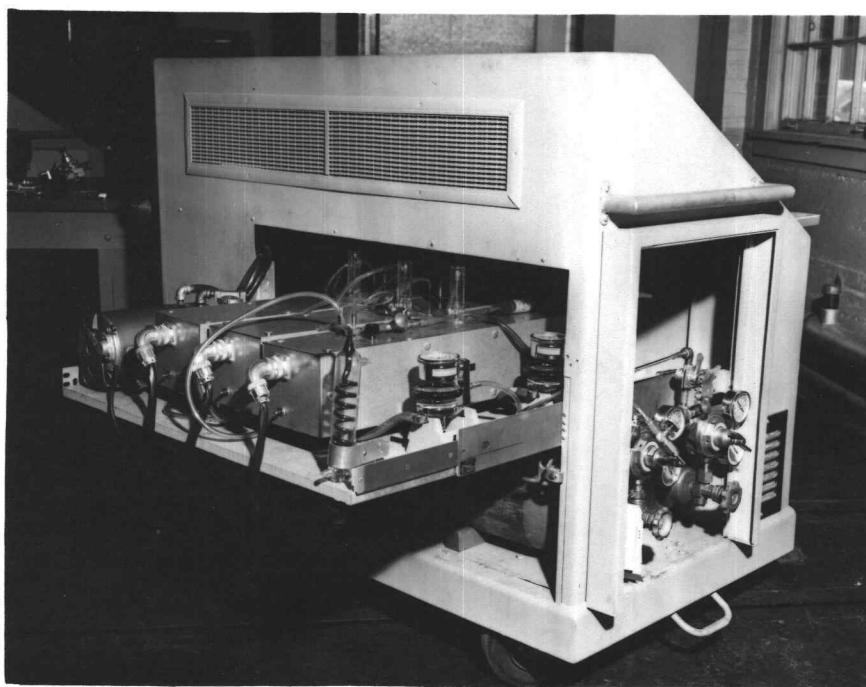


Figure 10. Infrared analyzers and sampling system in portable console

analyzing equipment has since received considerable upgrading and refinement by Donald J. Addicott (1, p. 7-17).

The  $\text{NO}_x$  instrument employs spectrophotometric principles to selectively examine exhaust gas for nitrogen dioxide. A limited amount of light of 3900 Angstroms wave length is passed through a sample cell to a phototube. The intensity of light striking the phototube is reduced by absorption of the light by nitrogen dioxide. The phototube current, which is a function of the amount of light striking the tube, is passed through a resistor. The voltage drop across the resistor is therefore proportional to gas concentration. This voltage is amplified by a pH meter and recorded with a millivolt recorder.

Prior to introduction of the exhaust gas sample to the oxides of nitrogen analyzer it was passed through a copper coil in an ice bath to remove water vapor and a U tube filled with drierite to further dry the sample. A vacuum pump and flowmeter were used in the system to keep the exhaust flow constant. A schematic diagram of this drying and sampling system is shown in Figure 11. A 100 cubic centimeter syringe was used to draw a dry exhaust gas sample, just prior to the flowmeter, by inserting a large hypodermic needle into the rubber tubing.

The output of the spectrophotometric  $\text{NO}_x$  analyzer was continuously recorded with a Bausch and Lomb Model VOM-5 Recorder.



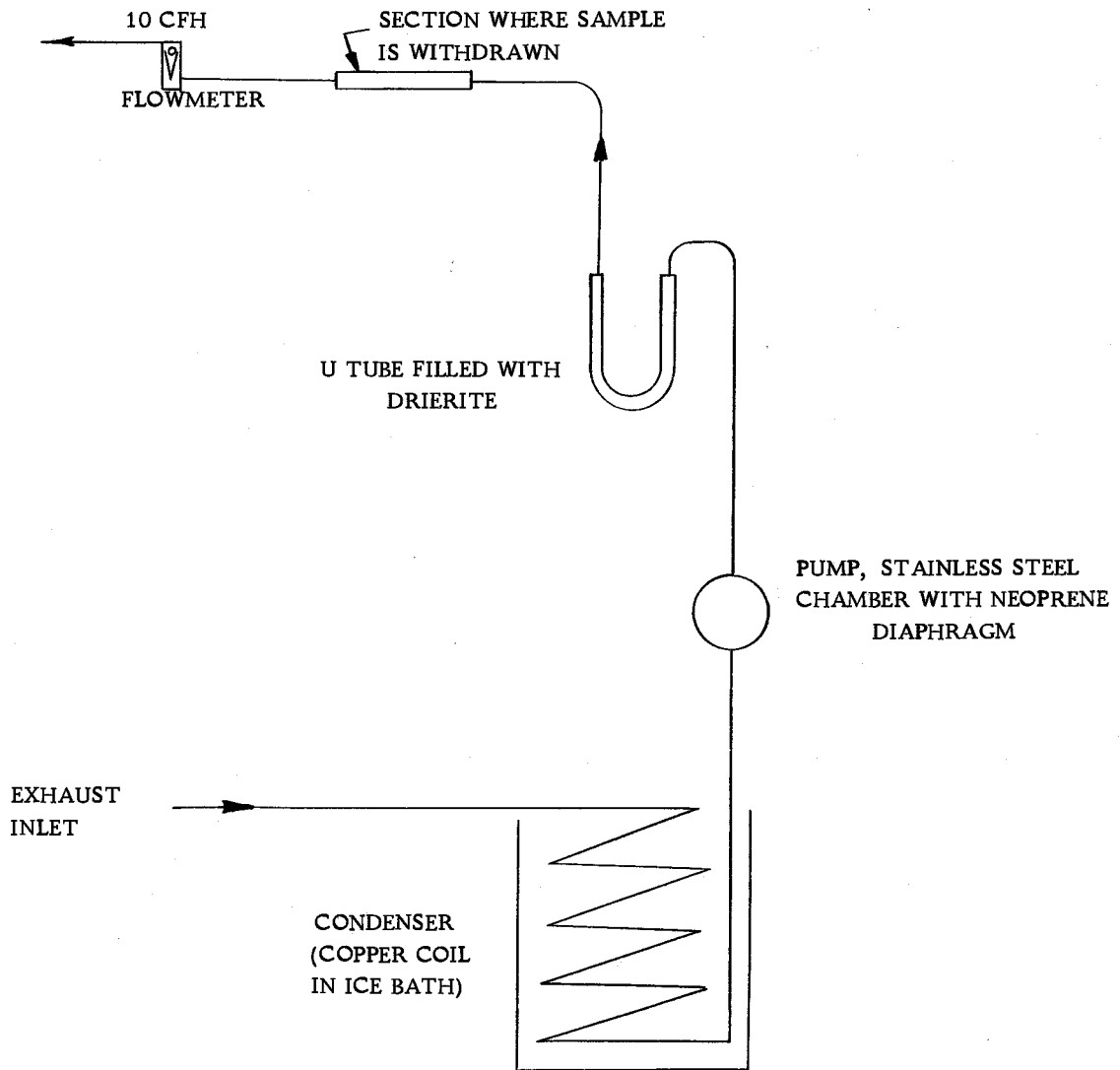


Figure 11. Nitrogen oxide sampling system

A bottle of high purity nitric oxide, a 2-liter flask, and calibrated syringes were used to calibrate the oxides of nitrogen analyzing instrument.

A Beckman GC-2A Gas Chromatograph with a thermal conductivity detector was used to determine calibration gas concentrations for the non-dispersive infrared analyzers.

### III. TESTING PROCEDURE

#### Preparatory Operations

Prior to testing, numerous tasks had to be accomplished. The engine throttle controller was constructed and programmed to produce the California seven-mode cycle (3, pt. 1, p. 3). This cycle is shown in Table I.

TABLE I. SEVEN-MODE CALIFORNIA CYCLE

Sequence No.	Mode	Mode Time, Seconds	Cumulative Time, Seconds
1	Idle	20	20
2	0-30 mph accel	14	34
3	30 mph cruise	15	49
4	30-15 mph decel	11	60
5	15 mph cruise	15	75
6	15-50 mph accel	29	104
7	50-20 mph decel	25	129

The above cycle was strictly adhered to with the following exceptions:

(1) All modes were carried out in direct drive as no transmission was used.

(2) The idle modes were performed with the road load on the

engine.

Following completion of the programming of the engine to operate on the California cycle the sequence was checked for repeatability. The following accuracy was achieved. The engine would consistently run to within ± one mile per hour of the desired speeds and the timing of sequences was within one second of the time durations in Table I.

### Instrument Calibration

The model IR-15A infrared analyzers were calibrated with gases having known concentrations of n-hexane, CO, and CO<sub>2</sub>. Detailed information on the concentrations of these calibration gases as determined with a Beckman GC-2A Gas Chromatograph and calibration is explained in Appendix C.

The hydrocarbon analyzer was calibrated with its 5.25 inch sample cell to have full scale deflection of the recorder with a known concentration of 10,000 ppm as n-hexane.

The carbon monoxide analyzer was calibrated to have 90 percent full scale deflection of the recorder with a known concentration of 10 percent CO.

The carbon dioxide analyzer was calibrated to have 90 percent full scale deflection of the recorder with a known concentration at 15 percent CO<sub>2</sub>.

The spectrophotometric analyzer for determination of

concentrations of oxides of nitrogen was calibrated by introducing known concentrations of nitric oxide (NO) into the sample cell. Nitric oxide is the only oxide of nitrogen that is formed in any significant quantity in the combustion process. As Wimmer and McReynolds have stated (16, p. 1) concerning the oxides of nitrogen,  $N_2O$ , NO,  $N_2O_3$ ,  $NO_2$ ,  $N_2O_4$ , and  $N_2O_5$ ,

Nitric oxide (NO) alone possesses an equilibrium constant of formation sufficiently large at combustion temperatures that any measureable quantity of the compound would be formed.

The peroxides of nitrogen are unstable at atmospheric conditions and therefore do not appear in the products of engine combustion.

Wimmer and McReynolds (16, p. 1) refer to peroxides in the following manner.

The peroxides such as  $NO_3$ ,  $N_2O_6$ ,  $N_3O_4$ ,  $N_2O_7$  decompose spontaneously at ambient conditions to  $NO_2$  and oxygen and can be eliminated as significant combustion products since the equilibrium constants of formation would be less than that for  $NO_2$ .

The reaction of nitric oxide with oxygen does not develop significantly because the speed of the nitric oxide oxidation reaction is extremely slow at the temperatures and concentrations involved.

Wimmer and McReynolds sum up the formations of oxides of nitrogen in the following manner. "Thus, nitric oxide is left as the only nitrogen oxide of appreciable importance with respect to engine combustion" (16, p. 2).

Nitric oxide was injected into the sample cell of the instrument which had been evacuated to 29 inches of Hg and then filled with  $O_2$  to a pressure of 4.5 inches of Hg absolute. After injection of 100 cubic centimeters of a known concentration of NO in nitrogen at atmospheric pressure into the cell the pressure in the cell was brought up to atmospheric pressure with  $O_2$ . The NO in the excess  $O_2$  readily oxidized to  $NO_2$  to which the analyzer is sensitive. The output of the spectrophotometric analyzer was monitored with a Bausch and Lomb VOM-5 Recorder.

After approximately 15 minutes at which time the NO had completely oxidized to  $NO_2$ , and the recorder peak had become stable, the sample cell was purged with  $O_2$  to bring the analyzer back to zero deflection. The cell was evacuated to 29 inches of Hg and refilled with  $O_2$  to atmospheric pressure to make certain that no hang up of  $NO_2$  was present. The deflection of the recorder versus different concentrations of NO provided a calibration curve. The  $NO_x$  instrument was calibrated over three ranges: range 1 (0-500 ppm), range 2 (0-1000 ppm), and range 3 (0-2000 ppm). Calibration curves for the three ranges used and sample calculations for concentration determinations are included in Appendix C.

The Brown Elektronik chart recorder used for temperature measurement was calibrated by imposing a known millivolt input and reading the recorder output off the chart. The chart deflections were

plotted versus the temperatures corresponding to the known millivolt input to provide a calibration curve.

### Test Operations

The amplifiers for the infrared analyzers and power supply for the oxides of nitrogen analyzer were left on continuously during all testing. This was to eliminate any drift caused by warmup. One hour prior to using the infrared gas analyzers, the choppers were turned on and the sample cells purged with air. The oxides of nitrogen zero circuit and lamp were turned on for warmup.

The engine was checked for proper oil level, the fuel tank filled, and all cooling water control valves were set prior to starting. The engine was then started and allowed to warm up at 1500 rpm for one hour under road load condition. This allowed engine temperatures to attain operating levels and dynamometer windings and electrical resistance grids to come to an equilibrium close to actual cycle temperatures.

During engine warmup, calibration checks of the infrared analyzers were made by checking the zero setting with nitrogen purge and full scale deflection with the upscale calibration gas. Care was taken that flow rates through the sample cells were constant during calibrations and actual exhaust gas analysis. These rates were six cubic feet per hour through the carbon monoxide and carbon dioxide sample

cells, and ten cubic feet per hour through the hydrocarbon sample cells.

The oxides of nitrogen sample system was purged with dry compressed air to rid the apparatus of any condensation in the condenser or tubing connections. The container surrounding the condenser coil was filled with a mixture of ice and water. The U tube dehydrator was filled with Drierite (refer to Figure 11).

Prior to any actual testing, the time delay for the gas to leave the engine and reach the infrared analyzer was determined by timing the interval between actual throttle closure and the instant when a sharp change in hydrocarbon concentration appeared on the strip chart. The delay time in the oxides of nitrogen sampling system was determined similarly by passing the exhaust gas directly into the hydrocarbon analyzer upon leaving the  $\text{NO}_x$  sampling system. The two sampling systems were time correlated in this manner. Flow rates through the two sampling systems were maintained as specified during time correlations as well as during all actual testing.

It was determined from actual drawing of grab samples with the 100 cubic centimeter syringe (for  $\text{NO}_x$  determination) that approximately three seconds were required to draw the sample through the large hypodermic needle.

The first series of sampling was done at the afterburner inlet.

After an engine warm up of approximately one hour and checking



all instrumentation, testing was started. The engine was allowed to run at a slow cruise, under road load and approximately 1,000 rpm, between repetitive seven-mode cycles. This was done to keep the engine and dynamometer at operating temperatures. Just prior to taking any gas samples the engine was decelerated to idle and the infrared sampling train switched from air to exhaust gas sampling by means of a three-way valve in the line. Recorders were started. A cap was removed from the oxides of nitrogen sampling system exhaust probe allowing the exhaust gas to flow through the system. The vacuum pump in this sampling system served to keep the flow constant.

The oxides of nitrogen analyzer sample cell was evacuated to 29 inches of Hg and refilled to a pressure of 4.5 inches of Hg absolute with oxygen.

The engine, idling with road load, was started into its seven-mode cycle by starting the engine control turntable. At the start of the first acceleration the control turntable actuated a microswitch which closed a circuit with a 6-volt battery as a power source to put a marking pip on all recorder charts.

The first oxides of nitrogen exhaust gas grab sample was taken during idle, before starting the control cyler. Slightly more than 100 cubic centimeters was drawn into the syringe. Before injection into the oxides of nitrogen gas analyzer sample cell the syringe stop cock was opened and any excess over 100 cubic centimeters was

ejected slowly. This was done to get exactly 100 cubic centimeters of exhaust gas at atmospheric pressure. Then the hypodermic needle was inserted into the serum stopper top and the sample was injected into the  $\text{NO}_x$  analyzer sample cell. Immediately following injection, the sample cell was brought up to atmospheric pressure by introducing more oxygen into the cell. Care was taken not to allow any of the exhaust sample to escape but to keep the oxygen flowing steadily into the cell. This was done by putting enough excess, above atmospheric, pressure in the external piping of the sample cell so that when the stopcock was rotated one turn slowly the pressures would equalize at atmospheric pressure.

After allowing approximately 15-20 minutes for the sample to completely oxidize to  $\text{NO}_2$  and the recorder output to stabilize, the cell was purged with oxygen. This brings the recorder deflection rapidly to zero. After purging, the cell was evacuated to 29 inches of Hg then refilled with oxygen to a pressure of 4.5 inches of Hg absolute at which time it is ready for another exhaust gas sample.

The next grab sample was taken at the start of the pip on the recorder chart paper which is at the start of the first acceleration. Each successive grab sample was taken at a time five seconds later than the previous sample in another seven-mode cycle. This sequence of sampling produced 23 samples along the complete seven-mode cycle. Between each grab sample there was a period of 20-25 minutes which

was needed to allow the NO in the exhaust gas sample to completely oxidize to NO<sub>2</sub>, to purge the cell, evacuating it, and prepare for another determination.

A complete seven-mode cycle was conducted for each grab sample and concurrently the concentrations of CO, CO<sub>2</sub>, and unburned hydrocarbons were recorded as well as one of the exhaust gas temperatures. The latter was done to insure that each run was a repetition of the preceding one and that the NO<sub>x</sub> sample was valid. Only one temperature was recorded each time as but one recorder was available.

After completion of taking grab samples every five seconds along the seven-mode cycles, the NO<sub>x</sub> concentrations from all runs were observed from the charts, quantities tabulated, plotted and checked for consistency. The entire test was repeated by obtaining a series of grab samples displaced by 2.5 seconds with respect to the first series along the seven-mode cycle. This was to check repeatability, credibility, and give more data on intermediate points. This was completed with a procedure similar to the first series and the data again tabulated, plotted and checked for consistency.

The infrared instruments were again completely calibrated and checked against original calibrations. No significant change had taken place in their calibration.

The hydrocarbon instrument was now disassembled and the 5.25 inch sample cell removed. The 13.5 inch sample cell was installed

and calibrated to read 2,000 ppm full scale deflection of the recorder chart.

Because the instruments were connected for sampling at the afterburner outlet, the new delay time of the two systems was again determined in a manner similar to that which was done when sampling at the afterburner inlet.

Two series of test were conducted at the afterburner outlet. Data were tabulated, plotted, and checked after each series of tests.

After completion of the transient sample tests, data were taken at the inlet and outlet of the afterburner under the following steady state conditions:

<u>Vehicle Speed, mph</u>	<u>Engine Speed, rpm</u>	<u>Load</u>
Idle	600	None
15	675	road load
30	1350	road load
50	2250	road load

The following observation were made: percent CO and CO<sub>2</sub>, ppm of hydrocarbons as n-hexane and total oxides of nitrogen.

The infrared instruments were again calibrated over their complete range. Calibration curves and calibration gas concentrations are shown in Appendix C.

This completed the experimental work that was carried out. The findings are presented in the Results section which follows.

## IV. RESULTS

The summarized results of this research project are as follows:

1. Oxides of nitrogen concentration at afterburner inlet and outlet as a function of time during the California seven mode cycle are shown in Figures 12 and 13. Figure 14 shows a comparison of the inlet and outlet concentrations during a cycle with the outlet concentration corrected for dilution by the aspirated burner air.
2. Oxides of nitrogen, hydrocarbon, carbon dioxide, and carbon monoxide concentrations at afterburner inlet and outlet during steady state conditions are shown in Table II.
3. Weighted average concentrations of hydrocarbon, carbon monoxide, and carbon dioxide at afterburner inlet and outlet during California seven mode cycle are shown in Table III.
4. Exhaust temperatures at afterburner inlet, outlet and afterburner combustion chamber are shown in Figure 15.

The concentration of oxides of nitrogen taken during the California seven-mode cycle were plotted at the median time of the three seconds required to fill the 100 cubic centimeter syringe. All steady state afterburner outlet concentrations (Table II) were corrected for dilution by a carbon balance (refer to appendix C for details).

During the start of the high speed deceleration in the California cycle the hydrocarbon concentration exceeded 10,000 parts per

million therefore the concentrations were estimated from the hydrocarbon tapes by extrapolation.

Appendix A contains the design and calculations of the inertia flywheels for the simulation of an hypothetical 4,000 pound automobile. The calculation of road load from an empirical equation and the actual dynamometer road load results are shown in Appendix B. Appendix C describes: (1) the calibration procedure for the gas analyzing equipment and (2) sample concentration calculations.

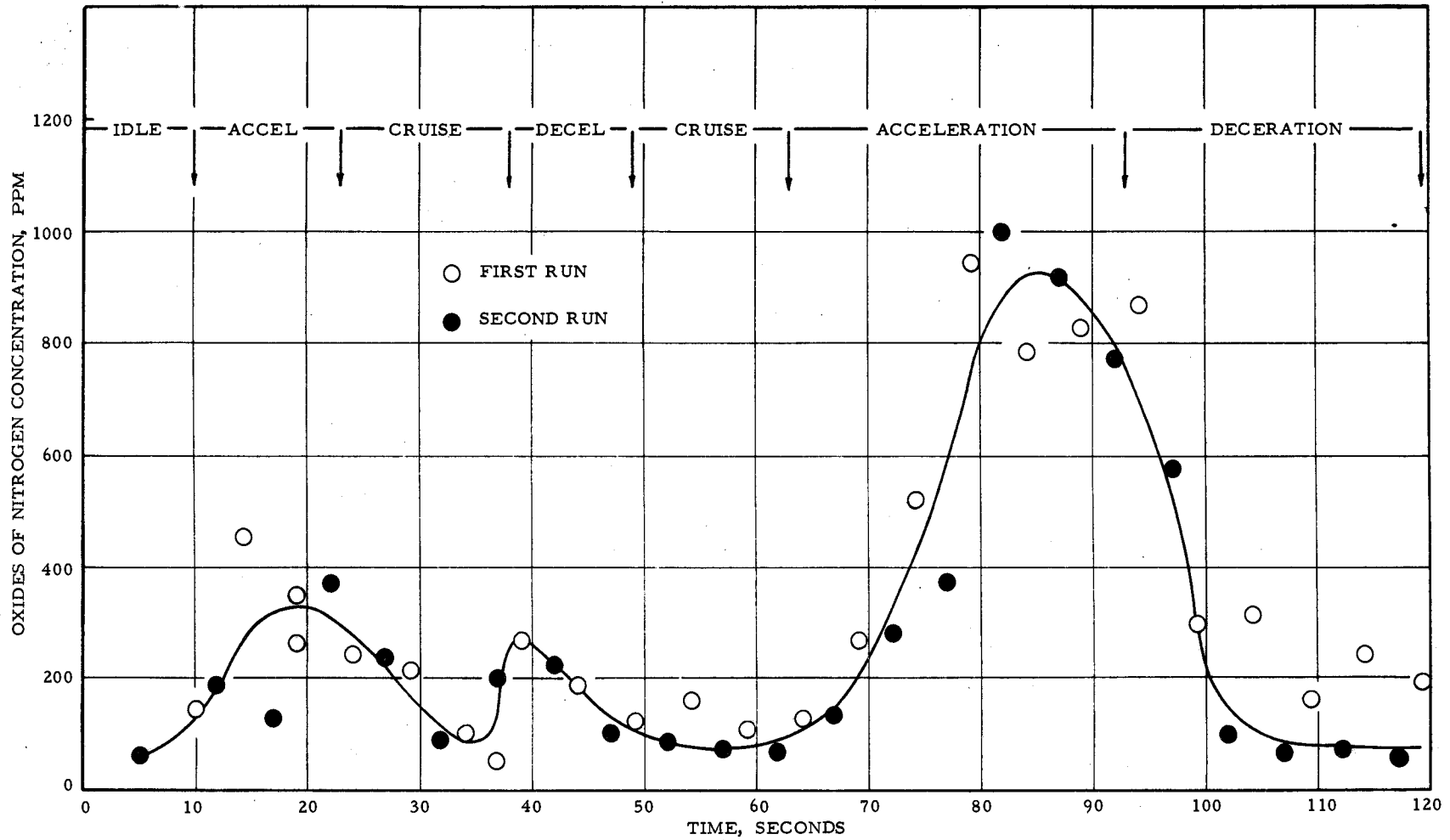


FIGURE 12. OXIDES OF NITROGEN CONCENTRATION AT AFTERBURNER INLET AS FUNCTION OF TIME DURING CALIFORNIA SEVEN-MODE CYCLE

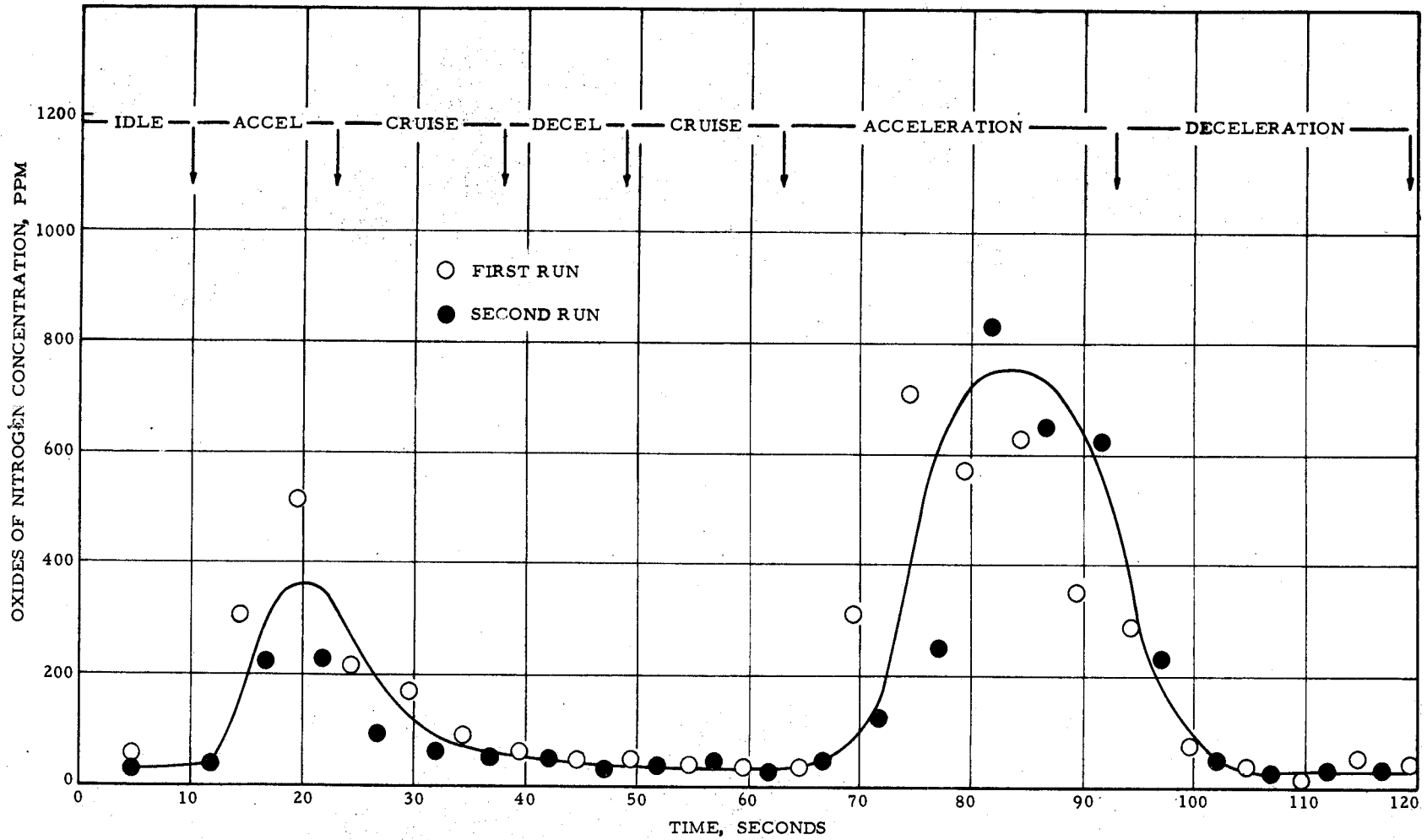


FIGURE 13. OXIDES OF NITROGEN CONCENTRATION AT AFTER-BURNER OUTLET AS FUNCTION OF TIME DURING CALIFORNIA SEVEN-MODE CYCLE



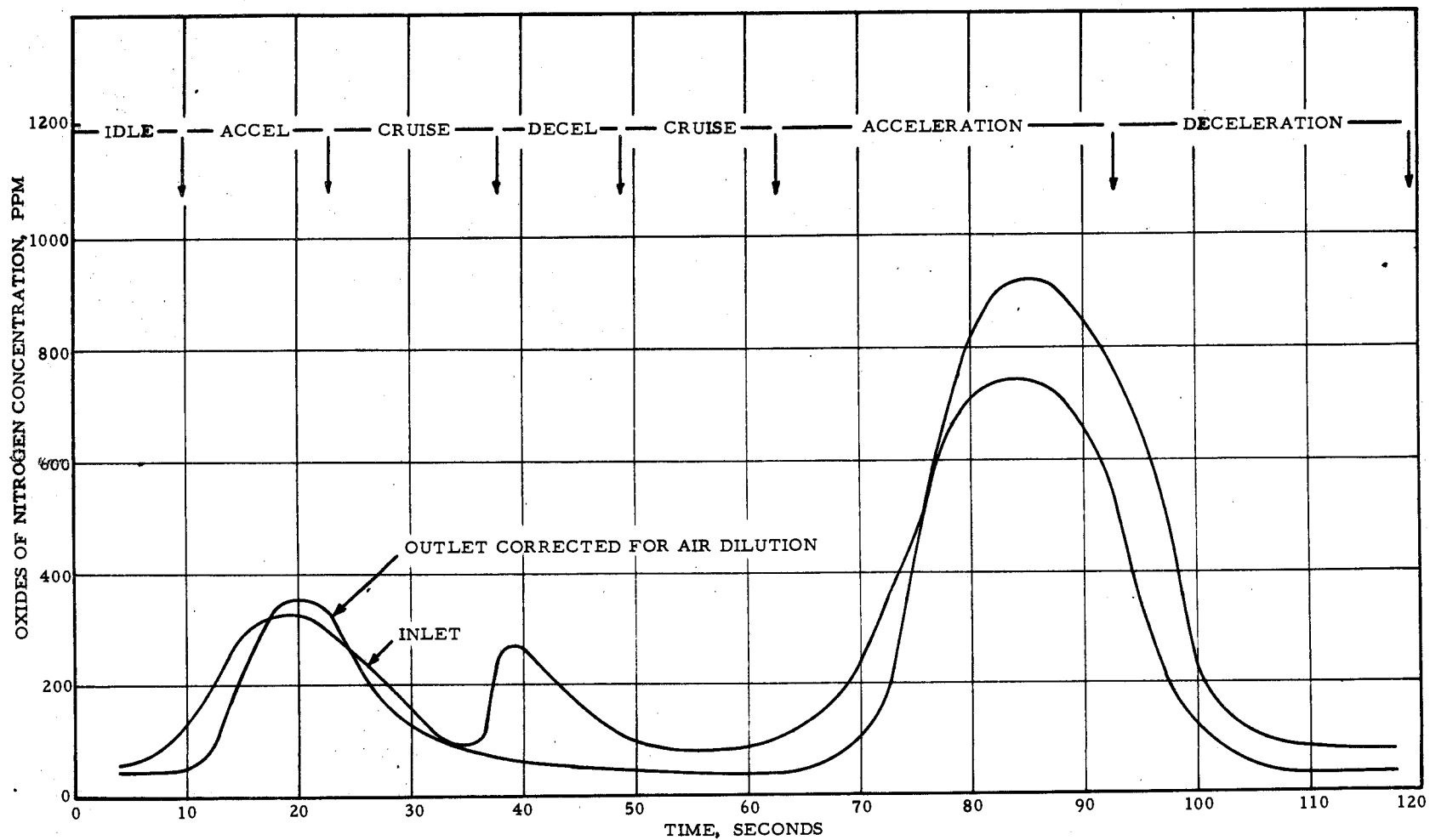


FIGURE 14. A COMPARISON OF THE OXIDES OF NITROGEN CONCENTRATION AT THE AFTERBURNER INLET WITH OUTLET CONCENTRATION AS A FUNCTION OF TIME DURING THE CALIFORNIA SEVEN-MODE CYCLE

TABLE II. ANALYSIS OF EXHAUST GAS AT AFTERBURNER INLET AND OUTLET DURING STEADY STATE OPERATION

Hydrocarbons as ppm n-hexane  
 Nitrogen Oxides (NO<sub>x</sub>) as ppm  
 CO and CO<sub>2</sub> as percent by volume

Speed	INLET					OUTLET						
	HC	CO	CO <sub>2</sub>	NO <sub>x</sub>	A/F	HC	CO	CO <sub>2</sub>	NO <sub>x</sub>	Corrected for Dilution		
										HC	CO	NO <sub>x</sub>
Idle*	5750	7.7	6.7	68	10.8	70	3.5	13.9	58	86	4.2	71
Cruise:												
15 mph	1130	9.1	9.2	40	11.3	760	6.6	6.5	32	1058	9.2	44
30 mph	430	6.8	11.6	60	12.4	380	6.5	9.8	54	430	7.3	61
50 mph	300	5.2	12.3	345	12.7	280	5.4	12.2	327	280	5.4	327

\* Total inertia rotating during 600 rpm idle.

TABLE III. EXHAUST GAS ANALYSIS AT AFTERBURNER INLET AND OUTLET DURING CALIFORNIA SEVEN-MODE CYCLE OPERATION (All concentrations determined in accordance with California Code. All data corrected to 15% carbon in exhaust)

Mode	INLET			OUTLET		
	HC ppm	CO%	CO <sub>2</sub> %	HC ppm	CO%	CO <sub>2</sub> %
Idle*	3,240	6.56	6.48	283	3.21	11.80
0-30 mph	874	2.72	11.85	358	2.90	12.10
30 mph	591	6.29	8.45	469	6.56	8.45
30-15 mph	7,970	6.00	4.30	571	6.00	9.56
15 mph	2,590	6.86	6.59	561	3.58	11.30
15-50 mph	1,165	2.65	11.65	426	3.02	12.00
50-20 mph	<u>11,590</u>	<u>4.58</u>	<u>3.48</u>	<u>376</u>	<u>5.71</u>	<u>9.29</u>
Weighted Average	1,908	3.74		423	3.71	

\* Road load and total inertia was engaged during 500 rpm idle.

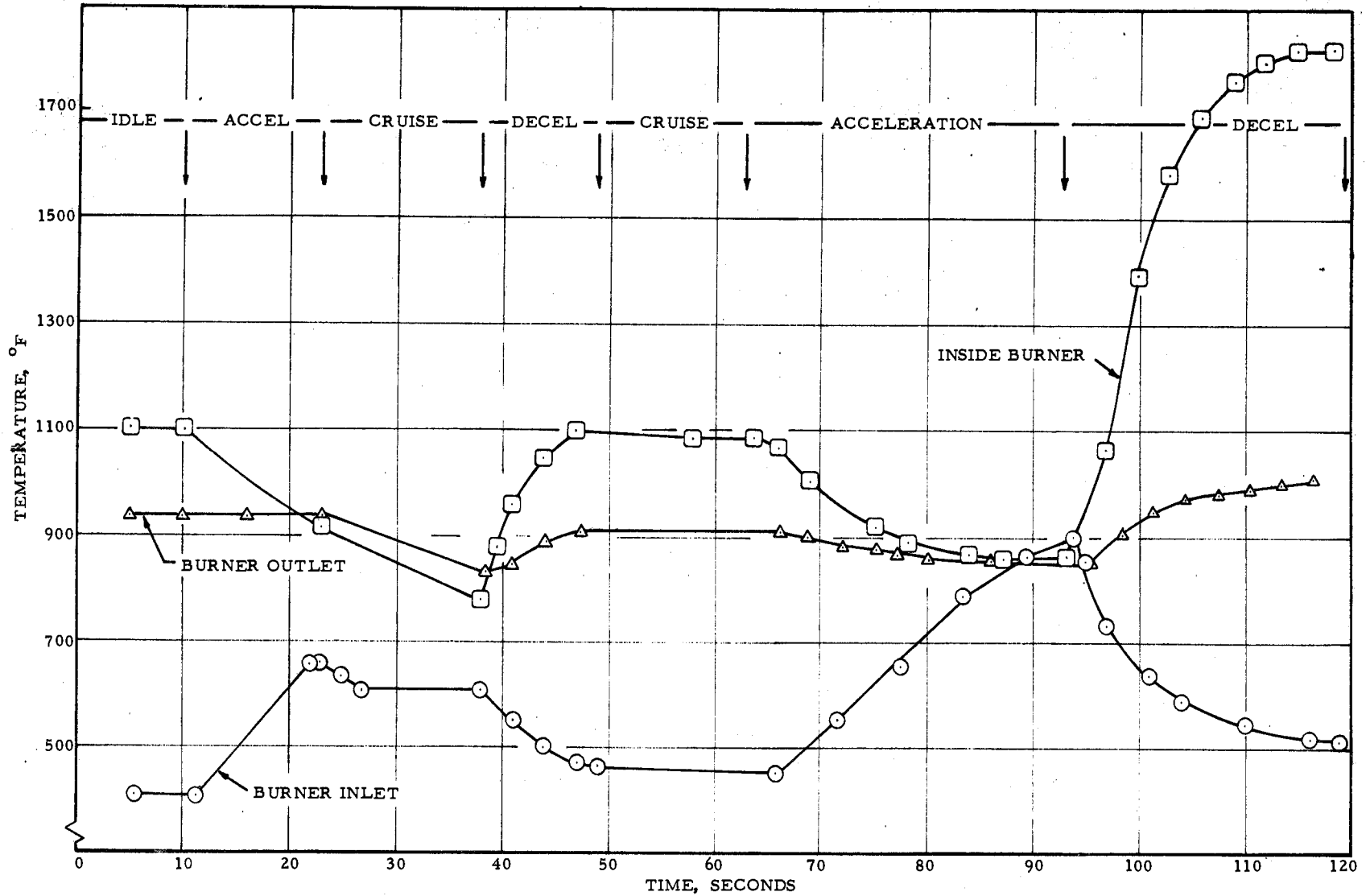


FIGURE 15. TEMPERATURE OF EXHAUST GAS AS FUNCTION OF TIME DURING CALIFORNIA SEVEN-MODE CYCLE

## V. DISCUSSION OF RESULTS

### Cycle Repeatability

The reliability of the oxides of nitrogen concentrations shown in Figures 12 and 13 depends largely on the repeatability of the engine in reproducing the California seven-mode cycle because each nitrogen oxide sample was taken from a different cycle run. The repetition of the hydrocarbon, carbon monoxide, carbon dioxide tapes and temperature recordings was employed as a means of determining repeatability. Any run that varied noticeably from the accumulated average of many runs was singled out and rerun. A new  $\text{NO}_x$  sample was taken and analyzed.

### Oxides of Nitrogen

Figures 12 and 13 show a definite correlation between the concentration of nitrogen oxides and the mode (acceleration, deceleration, cruise) in which the engine was operating. The maximum  $\text{NO}_x$  concentration which occurred during the high speed acceleration phase would be expected since the maximum combustion temperature would be obtained during this period. Also the air fuel mixture was leanest during accelerations as shown by the carbon monoxide concentrations of Table III. Both of these enhance the formation of oxides of nitrogen (2, p. 512). During decelerations and low speed cruises the  $\text{NO}_x$

concentration drops off which would be expected again from temperature and air fuel ratio considerations. A very good correlation between  $\text{NO}_x$  concentration at the afterburner inlet (Figure 12) and the inlet temperature (Figure 15) can be observed. During both accelerations of the California Cycle the exhaust gas temperature increases as does the  $\text{NO}_x$  concentration. During the deceleration modes the  $\text{NO}_x$  concentrations decrease along with temperature. The somewhat sharp increase in  $\text{NO}_x$  concentration at the beginning of the first deceleration period at the afterburner inlet can not be explained by the authors. Figure 13 shows that this phenomenon is not present at the afterburner outlet.

The small variation in the plotted  $\text{NO}_x$  concentrations from the line concentration curves of Figures 12 and 13 would be expected in a schlieren type sampling procedure of this nature. These discrepancies may be attributed to: (1) possible slight variation in the cruising speeds and acceleration rates occurring in the California cycle, (2) variation in engine conditions from cycle to cycle such as a mixture distribution and coolant temperatures, (3) changes in ambient conditions and (4) experimental error. Considering the grab sample technique and the dependence on ability of the engine to reproduce the seven-mode cycle, the maximum variation of  $\pm 120$  parts per million oxides of nitrogen in the data is minimal.

Figure 14 which compares the  $\text{NO}_x$  concentrations at the afterburner inlet to the afterburner outlet, corrected for aspirated air dilution, shows a maximum difference of 340 parts per million at time

97 seconds and appreciably less during other portions of the cycle. Considering the entire cycle, it can be concluded that no significant change in concentration of  $\text{NO}_x$  occurred as the exhaust gases pass through the afterburner. In this Figure the outlet concentrations were corrected for dilution brought about by the introduction of aspirated air into the afterburner. Any variation in these two inlet and outlet concentration curves is probably due to the approximations introduced in determining the dilution correction factors which were applied to the outlet concentrations. The amount of air which passed into the afterburner was not measured and therefore another means had to be devised to account for this dilution effect which, of course, decreased the  $\text{NO}_x$  concentration as the exhaust passed through the afterburner. To compute this, a carbon balance was made across the afterburner for every five second period during the cycle. Two assumptions were made in these correction factor calculations: (1) since the n-hexane sensitized non-dispersive infrared analyzer does not respond to all types of hydrocarbons (8, p. 592), it was assumed that the total hydrocarbon concentration was twice that indicated by the infrared analyzer throughout the cycle. A quote from a General Motors Research Laboratories report supports this assumption (9, p. 2):

Trends obtained with both the flame ionization and infrared analyzer were identical although the former instrument gave concentrations more than double those of the latter.

(2) it was also assumed that all hydrocarbons had six carbon atoms. Since carbon monoxide, carbon dioxide, and hydrocarbon concentrations had to be determined for each five second interval along the cycle, any retention of high concentration of gas in the cells beyond their normal residence time (commonly called hangup) could greatly affect the calculated correction factor. The above discussion will serve to explain any variation in the curves of Figures 12, 13, and 14. Ideally the two curves should be identical if the afterburner had no effect on oxides of nitrogen.

#### Afterburner Characteristics

It should be pointed out that the afterburner should have only a slight effect if any, on the oxides of nitrogen and other exhaust gas constituents during high speed cruise and acceleration. At high exhaust gas mass flow rates during these two conditions, when the engine is producing a minimum of carbon monoxide and unburned hydrocarbons, a modulating valve in the afterburner opens and permits a portion of the exhaust gas stream to bypass the afterburner.

At low exhaust gas mass flow rates during idle, low speed cruise (15 mph) and deceleration, exhaust gases pass over the modulating valve, which is closed by the high manifold vacuum, then enter the body of the afterburner and pass into the combustion chamber where fresh air aspirated by the afterburner is mixed with the exhaust gases.



Here they are heated and then ignited by a spark plug. During idle and deceleration the afterburner is operating at maximum conversion of combustibles to carbon dioxide and water.

If there was formation of oxides of nitrogen in the afterburner, they most likely would form only during those modes (idle, low speed cruise and decelerations) of maximum afterburner effectiveness and temperature. These modes comprize 58 percent (on time basis) of the entire seven-mode cycle and therefore a substantial increase in  $\text{NO}_x$  concentration during these modes would have a considerable effect on the cycles overall integrated average concentration.

The data of Tables II and III show that the hydrocarbon and carbon monoxide concentrations were only slightly affected by the afterburner during high speed cruise and accelerating conditions, whereas during idle and deceleration the afterburner was operating effectively. This confirms the manner in which the afterburner operates. Its combustion chamber temperature as shown in Figure 15 also verifies afterburner operation only during idle and deceleration.

The weighted average carbon monoxide and hydrocarbon concentrations for several selected seven-mode cycles as calculated in accordance with the California Code, shows an average reduction of 74.7 percent in hydrocarbons and no substantial reduction in carbon monoxide. It should be pointed out that the carbon monoxide concentration was reduced by the afterburner during idle and low speed

cruise as shown in Table III. This deficiency in carbon monoxide reduction may be caused by the high engine hydrocarbon emission concentration. The weighted average hydrocarbon inlet concentration is approximately twice that emitted from an average automobile. This insufficient oxidation of combustibles indicates the afterburner aspirates an inadequate supply of air for the high concentration of hydrocarbons encountered during this test. This might explain why there were no oxides of nitrogen formed in the afterburner. If all of the oxygen molecules were being used to burn the hydrocarbons, there may be none available for fixation with the nitrogen molecules.

### Engine

The carbon monoxide and hydrocarbon concentrations shown in the steady state results of Table II show that the engine was operating with a rich air fuel mixture. Even though the test engine is designed for truck type service, an air-fuel ratio of 10.8 at idle is an excessively rich mixture. According to the California MVPCB classification method (3, pt. 2, p. 3) an idle concentration of 7.7 percent carbon monoxide classifies the engine on the lean side of the rich classification region. This corresponds to an air fuel ratio of 10.8. The carburetor's float level and idle adjustments were set within specifications outlined in the manufacturer's manual. At leaner idle settings than the one used, the engine failed to idle smoothly. All testing was

conducted without the air cleaner on the carburetor which condition would supposedly produce an even leaner air fuel ratio than normal.

A leaner air fuel ratio, typical of an average automobile, would have been desirable. Such a lean mixture would likely have allowed the afterburner to oxidize the combustible carbon monoxide to carbon dioxide more completely than exhibited during the test. This also might have had an effect on the oxides of nitrogen passing through or formed in the afterburner.

## VI. CONCLUSIONS

The following conclusions can be drawn from the four series of tests conducted with the Kaiser-Jeep Tornado engine and the American Machine and Foundry Company Mark IX afterburner:

1. The total oxides of nitrogen concentrations were essentially unchanged across the afterburner.

2. The progressive grab sampling technique that was used for oxides of nitrogen proved successful. Consistent results over the entire California seven-mode cycle were obtained. The spectrophotometric oxides of nitrogen analyzer operated satisfactorily and gave consistent results.

3. A n-hexane sensitized hydrocarbon analyzer does not measure total unburned hydrocarbon concentrations adequately to compute a carbon balance across the afterburner.

4. The engine-afterburner combination tested did not meet the California requirements pertaining to maximum allowable unburned hydrocarbons and carbon monoxide. This may be attributed to the rich carburetor. The afterburner operated satisfactorily during all testing. No burner instability or failure to operate was noted.

## VII. RECOMMENDATIONS FOR FUTURE WORK

From experience gained in conducting this series of engine-afterburner tests, the following recommendations for future experimentation with this and the related equipment, are suggested:

1. Repeat this test with several representative automotive passenger vehicle engines.
2. Install a larger vacuum pump to reduce delay time in the  $\text{NO}_x$  sampling system.
3. Refine the engine controller mechanism to allow the engine to idle without road load.
4. Secure a catalytic afterburner and conduct similar tests.
5. (a) Reduce hangup in the sampling lines by increasing the flow rate through the non-dispersive infrared analyzer sample system, by-passing the excess gas not needed to maintain proper flow through the detectors.  
  
(b) Secure a small easily drainable water trap.
6. Install transducers for pressures and engine speed to obtain recorded transient data.
7. Procure a leaner carburetor if further afterburner tests are undertaken with the Kaiser-Jeep engine.
8. Acquire an instrument for measuring concentrations of total unburned hydrocarbons in order to compute a more accurate carbon balance across the afterburner or measure the afterburner's aspirated air.

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## APPENDICES



## APPENDIX A

This Appendix contains (a) the equivalent moment of inertia calculations for a hypothetical 4000 pound automobile and (b) flywheel design computations for the simulation of this moment of inertia to engine-dynamometer testing in the laboratory.

Equivalent Moment of Inertia of a 4,000 Pound Automobile

The kinetic energy of a car of stated 4,000 lb<sub>m</sub> that moves at a given linear velocity is:

$$(1) \text{ Kinetic Energy of translation, ft-lb}_f = \frac{(\text{mass, lb}_m)(\text{velocity, ft/sec})^2}{(2)(g_c, \text{lb}_m\text{-ft/lb}_f\text{-sec}^2)}$$

$$= \underline{\text{ft-lb}_f}$$

The kinetic energy of a circular disk rotating at a stated angular velocity (engine velocity) and having a given moment of inertia is:

$$(2) \text{ Kinetic Energy of rotation, ft-lb}_f = \frac{(I, \text{lb}_m\text{-ft}^2)(\text{ang v, rad/sec})^2}{(2)(g_c, \text{lb}_f\text{-ft/lb}_f\text{-sec}^2)}$$

$$= \underline{\text{ft-lb}_f}$$

As the circular disk is to rotate at engine speed, its angular velocity is:

$$(3) \text{ Angular Vel, rad/sec} = \frac{(2\pi \text{ rad/rev})(N, \text{ rev/sec})}{1}$$

$$= \underline{\text{Rad/sec}}$$

$$(4) N, \text{ rev/sec} = \frac{(\text{Vel, ft/sec})(R, \text{ rear axle rev})}{(D, \text{ ft of tire rotation})}$$

$$= \underline{\text{Rev/sec}}$$

Equating (1) and (2) and substituting (3) and (4) gives:

$$\begin{aligned}
 M V^2 / 2 g_c &= \frac{I (2\pi V R/D)^2}{2 g_c} \\
 I, \text{ lb}_m\text{-ft}^2 &= \frac{M D^2 / 4\pi^2 R^2 \text{ lb}_m\text{-ft}^2}{}
 \end{aligned}$$

For our hypothetical 4,000 lb<sub>m</sub> automobile with a 230 cubic inch displacement engine assume:

$$R, \text{ Rear axle ratio} = 3.45$$

$$D, \text{ Rolling diameter of rear wheels (7.50 x 14)} = 2.15 \text{ ft.}$$

$$\begin{aligned}
 I, \text{ lb}_m\text{-ft}^2 &= (4000)(2.15)^2 / (4)(3.45)^2 \pi^2 \\
 &= \underline{388.5 \text{ lb}_m\text{-ft}^2}
 \end{aligned}$$

But this must be increased seven percent for parts rotating at axle speed (7, p. 48) which gives an equivalent moment of inertia of:

$$\begin{aligned}
 I, \text{ lb}_m\text{-ft}^2 &= (388.5)(1.07) \\
 &= \underline{415 \text{ lb}_m\text{-ft}^2}
 \end{aligned}$$

### Flywheel Design

The rotating mass moment of inertia of the dynamometer must be made equal to the equivalent inertia of the hypothetical 4,000 pound automobile. The armature was found to have a moment of inertia of 176 lb<sub>m</sub>-ft<sup>2</sup>. Subtracting this from the equivalent moment of inertia

of the automobile ( $415 \text{ lb}_m\text{-ft}^2$ ) leaves  $239 \text{ lb}_m\text{-ft}^2$  which must be supplied to the armature in the form of an inertia flywheel. Due to weight considerations it was decided to divide the total moment of inertia into two equal inertia flywheels.

It was decided to fabricate the two flywheels with steel plate, 24 inches in diameter.

Moment of Inertia (I) per flywheel =  $239/2$

$$= \underline{119.5 \text{ lb}_m\text{-ft}^2}$$

Moment of inertia (I) for a circular disk

$$= 1/2 M r^2$$

where  $r$  = outer radius of circular disk and  $M = \rho v$  ( $\rho$  = density)

$$(v = \text{volume}) = \rho \pi r^2 d$$

where  $d$  = thickness of the disk

$$\text{Moment of inertia for a circular disk} = \underline{1/2 \rho \pi r^4 d}$$

For steel disks 24 inches in diameter, the required width and weights would be:

$$\begin{aligned} \text{width, inches} &= I / 1/2 \rho \pi r^4 \\ &= \frac{(119.5 \text{ lb}_m\text{-ft}^2)}{1/2 (489 \frac{\text{lb}_m}{\text{ft}^3}) (3.14) (1 \text{ ft})^4} \\ &= 0.156 \text{ ft} \\ &= \underline{1.872 \text{ inches}} \end{aligned}$$

$$\begin{aligned}
 \text{weight, lb} &= \rho \pi r^2 d \\
 &= (489 \frac{\text{lb}_m}{\text{ft}^3})(3.14)(1\text{ft})^2(0.156 \text{ ft}) \\
 &= \underline{239 \text{ lb}}
 \end{aligned}$$

This weight was excessive for existing dynamometer bearings. It was finally decided to fabricate the two inertia flywheels from three inch thick steel plate and hollow out the centers.

Therefore the total moment of inertia for a three inch steel disk; 12 inch radius:

$$\begin{aligned}
 I, \text{ lb}_m\text{-ft}^2 &= 1/2 \rho \pi r^4 d \\
 &= (489 \frac{\text{lb}_m}{\text{ft}^3})(3.14)(1 \text{ ft})^4(0.25 \text{ ft})/2 \\
 &= \underline{191.8 \text{ lb}_m\text{-ft}^2}
 \end{aligned}$$

$$\begin{aligned}
 \text{weight of 3 inch steel disk, lb} &= \rho \pi r^2 d \\
 &= (489 \frac{\text{lb}_m}{\text{ft}^3})(\pi)(1 \text{ ft})^2(0.85 \text{ ft}) \\
 &= \underline{384 \text{ lb}}
 \end{aligned}$$

The center portion of the flywheels was machined out to lighten them and also reduce their inertia to  $119.5 \text{ lb}_m\text{-ft}^2$ . The inertia that can be removed from center of disk leaving a one inch web:

$$\begin{aligned}
 \text{Inertia removed, } \text{lb}_m\text{-ft}^2 &= I \text{ total} - I \text{ reg'd} \\
 &= 191.8 - 119.5 \\
 &= \underline{72.3 \text{ lb}_m\text{-ft}^2}
 \end{aligned}$$

This will be removed in the form of a small circular disk, two

inches thick, inside the larger 24 inch diameter disk.

$$\begin{aligned}
 \text{Radius of disk removed, inches} &= (2 I / \rho \pi d)^{1/4} \\
 &= \left[ \frac{(2)(72.3 \text{ lb}_m\text{-ft}^2)}{(489 \frac{\text{lb}_m}{\text{ft}^3})(\pi)(1/6 \text{ ft})} \right]^{1/4} \\
 &= 0.867 \text{ ft} \\
 &= 10.4 \text{ inches}
 \end{aligned}$$

Approximate weight reduced by machining out center section:

$$\begin{aligned}
 \text{Weight removed, lb} &= \rho \pi r^2 d \\
 &= (489 \frac{\text{lb}_m}{\text{ft}^3})(\pi)(0.867 \text{ ft})^2(1/6 \text{ ft}) \\
 &= \underline{192 \text{ lb}}
 \end{aligned}$$

Weight of the finished flywheels will be slightly greater due to the weight of the hub which was neglected in these calculations. But the approximate weight of the finished flywheels will be:

$$\begin{aligned}
 \text{Weight of flywheels, lb} &= W \text{ total} - W \text{ removed} \\
 &= 384 - 192 \\
 &= \underline{192 \text{ lb}}
 \end{aligned}$$

Weight considerations were the deciding factor in selection of the final configuration of the two flywheels that were designed and constructed. Sketches of the two flywheels are shown in Figures A-1 and A-2.

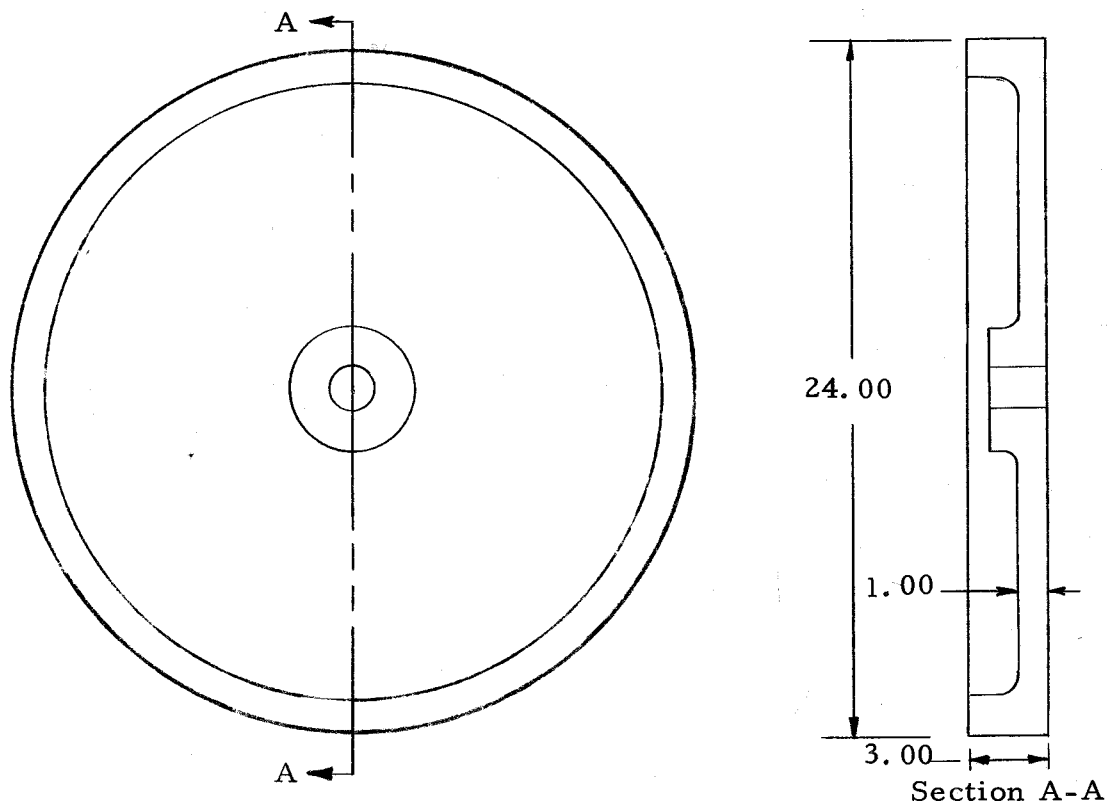


Figure A-1. Sketch of rear flywheel for dynamometer

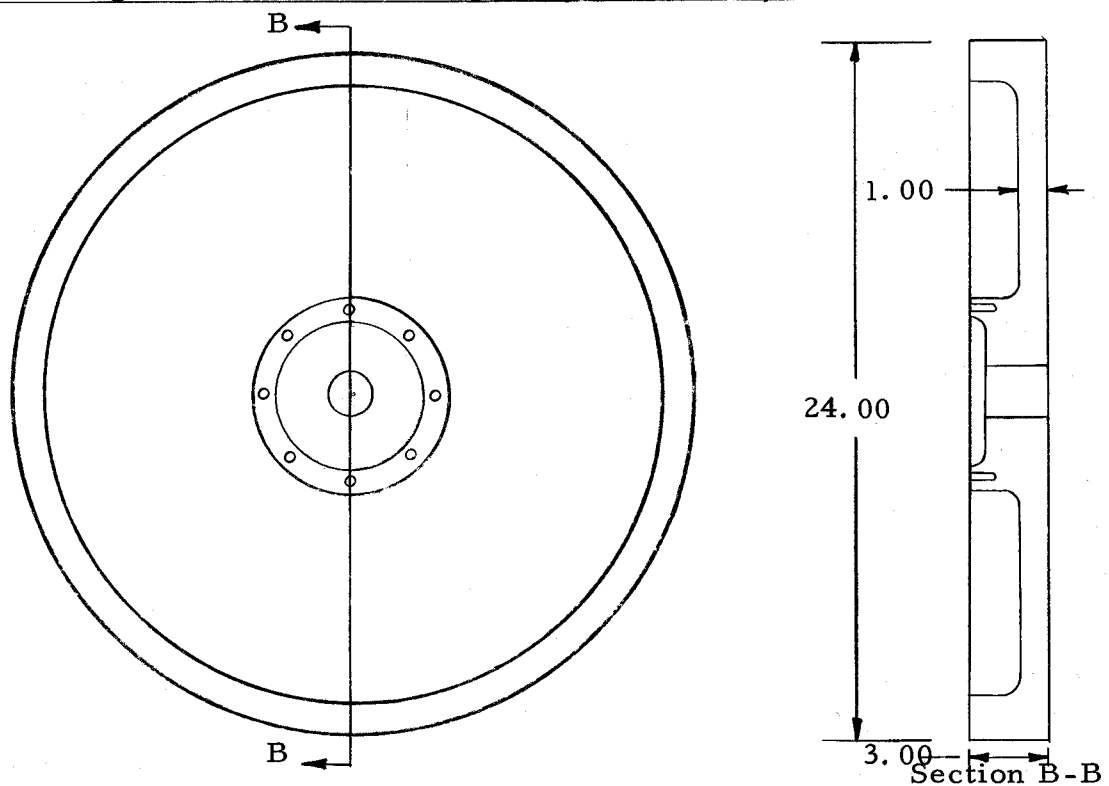


Figure A-2. Sketch of forward flywheel for dynamometer

## APPENDIX B

This appendix contains the road load calculations for the hypothetical 4000 pound automobile, the road load curve from these calculations, and the dynamometer road load curve.

Road Load Calculations

General Motors design equation for axle horsepower to overcome wind and rolling resistance (11, p. 726).

$$\text{Axle power road load, hp} = \frac{V}{375} (K_1 W + K_2 AV^2)$$

nomenclature: W = weight of car, lb

A = frontal area of car, ft<sup>2</sup>

V = velocity, mph

K<sub>1</sub>, K<sub>2</sub> = rolling and air resistance constants

Select: K<sub>1</sub> = 0.0149

K<sub>2</sub> = 0.00149

A = 30 ft<sup>2</sup>

Sample calculation for 15 mph

$$\begin{aligned} \text{Axle power road load, hp} &= \frac{15}{375} 0.0149 (4000) + \\ &\quad 0.00149 (30)(15)^2 \\ &= \underline{2.785 \text{ hp}} \end{aligned}$$

Assuming a rear axle efficiency ( $\eta$ ) of 95%

$$\begin{aligned}
 \text{by definition } \eta_{\text{ axle}} &= \frac{\text{output torque}}{(\text{axle ratio})(\text{input torque})} \\
 \text{Input torque, ft-lb}_f &= \frac{(\text{HP})(5252)}{(\text{rpm})} \\
 \text{Engine speed} &= 675 \text{ rpm} \\
 \text{axle speed} &= 675/3.45 \\
 &= 195 \text{ rpm} \\
 \text{Axle output torque, ft-lb}_f &= \frac{(2.785)(5252)}{(195)} \\
 &= 74.9 \text{ ft-lb}_f \\
 \text{Axle input torque, ft-lb}_f &= \frac{\text{output torque}}{(\eta_{\text{ axle}})(\text{axle ratio})} \\
 &= \frac{74.9}{(0.95)(3.45)} \\
 &= 22.8 \text{ ft-lb}_f
 \end{aligned}$$

Assuming a transmission efficiency of 95%

$$\begin{aligned}
 \text{by definition: } \eta_{\text{ trans}} &= \frac{\text{output torque}}{(\text{input torque})(\text{gear ratio})} \\
 \text{transmission input} & \\
 \text{torque, ft-lb}_f &= \frac{(\text{transmission output torque, ft-lb}_f)}{(\eta_{\text{ trans}})(\text{gear ratio})} \\
 &= \frac{22.8}{(0.95)(1.0)} \\
 &= 24.0 \text{ ft-lb}_f \\
 \text{Engine power required,} & \\
 \text{hp} &= \frac{(\text{torque, ft-lb}_f)(N, \text{ rpm})}{(5252)}
 \end{aligned}$$



$$= \frac{(24)(675)}{(5252)}$$

$$= \underline{3.085 \text{ hp}}$$

Table B-I. ENGINE POWER REQUIRED (CALCULATED)

Vehicle Speed, mph	Axle Power to overcome $R_r$ & $R_w$ , hp	Rear Axle torque output, ft-lb	Rear Axle torque input, ft-lb	Transmission torque input, ft-lb	Engine power, hp
15	2.785	74.9	22.8	24.0	3.085
20	4.13	83.2	25.4	26.75	4.58
25	5.84	94.0	28.65	30.2	6.47
30	7.98	107.1	32.70	34.4	8.85
40	13.99	141.0	43.0	45.3	15.51
50	22.85	184.2	56.2	59.2	25.35
60	35.30	237.0	72.25	76.1	39.05

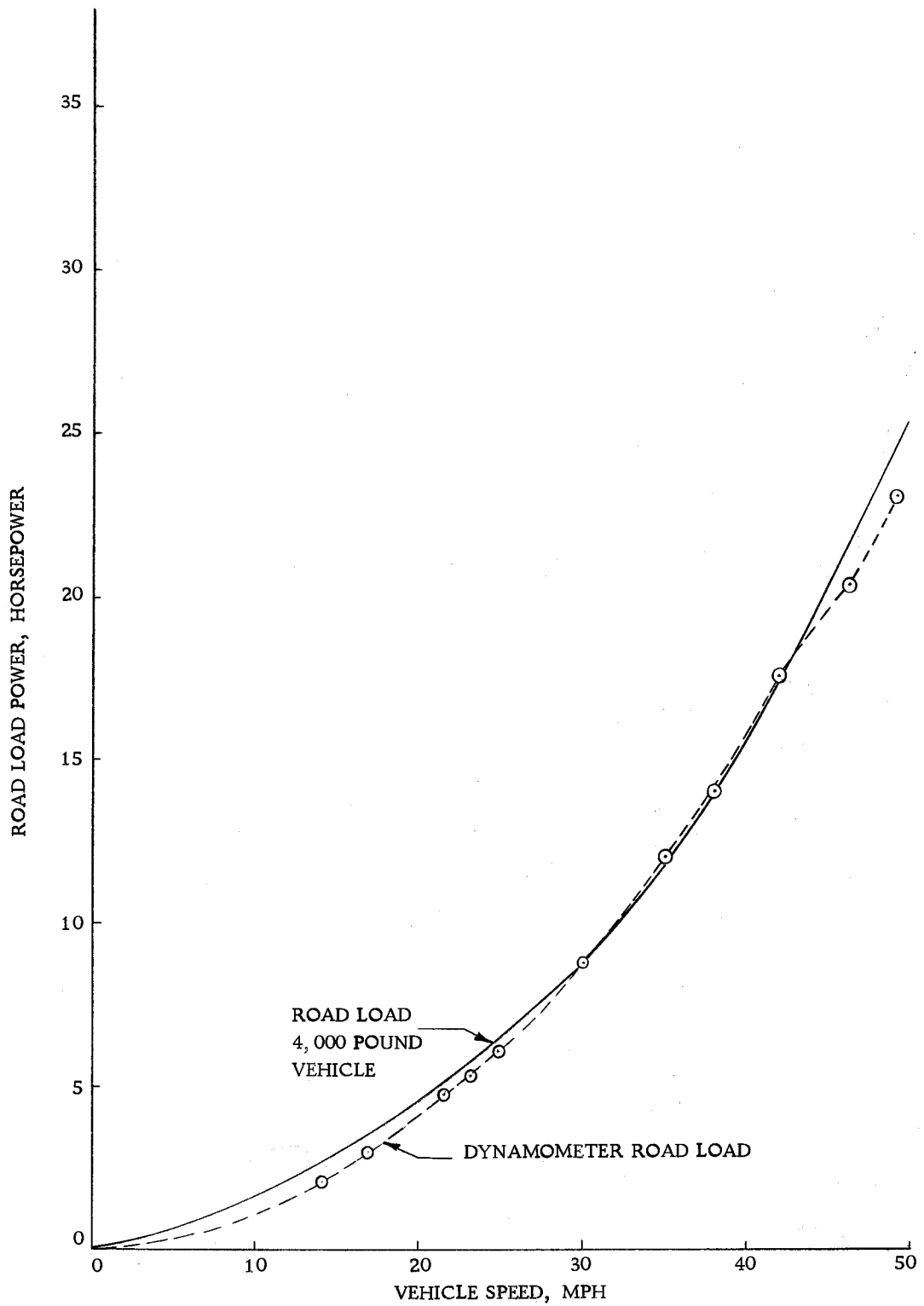


Figure B-1. Dynamometer and 4,000 pound vehicle road load curves

## APPENDIX C

Calibration of Infrared Analyzers

Conversion of recorder deflections to concentrations was accomplished by passing known mixtures of n-hexane, CO, and CO<sub>2</sub> gases through the sampling system and recording the recorder deflections. The procedure used in blending these gases and calibrating the instruments was as follows:

1. Purchased two bottles of gas blends from The Matheson Company, Inc. with the following nominal concentrations:  
(1) 2,000 ppm n-hexane, 10% CO, 15% CO<sub>2</sub> and (2) 10,000 ppm n-hexane, 10% CO, 15% CO<sub>2</sub>.
2. Divided, on the principle of partial pressures, the 10,000 ppm n-hexane Matheson bottle into selected n-hexane concentrations to be used with the 5 1/4 inch hydrocarbon cell. Similar procedure was used in dividing the 2,000 ppm bottle for use with the 13 1/2 inch hydrocarbon cell in the sampling system. The balance gas in the blends was nitrogen.
3. Determined the actual concentration of n-hexane, CO, and CO<sub>2</sub> in the various blends by gas chromatography. Results shown in Table C-I.
4. Passed these known blends through the infrared analyzing sampling system and recorded recorder deflections and

plotted calibration curves, Figure C-1.

TABLE C-I. GAS COMPOSITION FOR CALIBRATING INFRARED ANALYZERS

Composition, Volume Percent in Nitrogen			
<u>Blend*</u>	<u>CO<sub>2</sub></u>	<u>CO</u>	<u>n-hexane</u>
1 (Matheson Blend)	15.3	9.8	.990
2	10.8	6.8	.695
3	6.7	4.2	.430
4 (Matheson Blend)	15.0	10.0	.195
5	11.4	7.4	.145
6	7.5	4.8	.095
7	3.7	2.5	.048

\* Blends 1 through 4 were used to calibrate instruments when the 13 1/2 inch hydrocarbon cell was in use. Blends 4 through 7 were used when the 5 1/4 inch cell was in use.

#### Sample CO and CO<sub>2</sub> Calculations

At 50 mph cruise the CO<sub>2</sub> recorder deflected 7.32 units. From the calibration curves (Figure C-1) this deflection gives a CO<sub>2</sub> concentration of 11.0%. A factor of 1.05 is applied to this concentration to convert it to a dry basis. This assumes saturated gas at 90°F in the analyzer. Therefore the reported CO<sub>2</sub> concentration is 11% x 1.05 = 11.55%. Similar procedure was used on all CO and CO<sub>2</sub> data during steady state conditions.

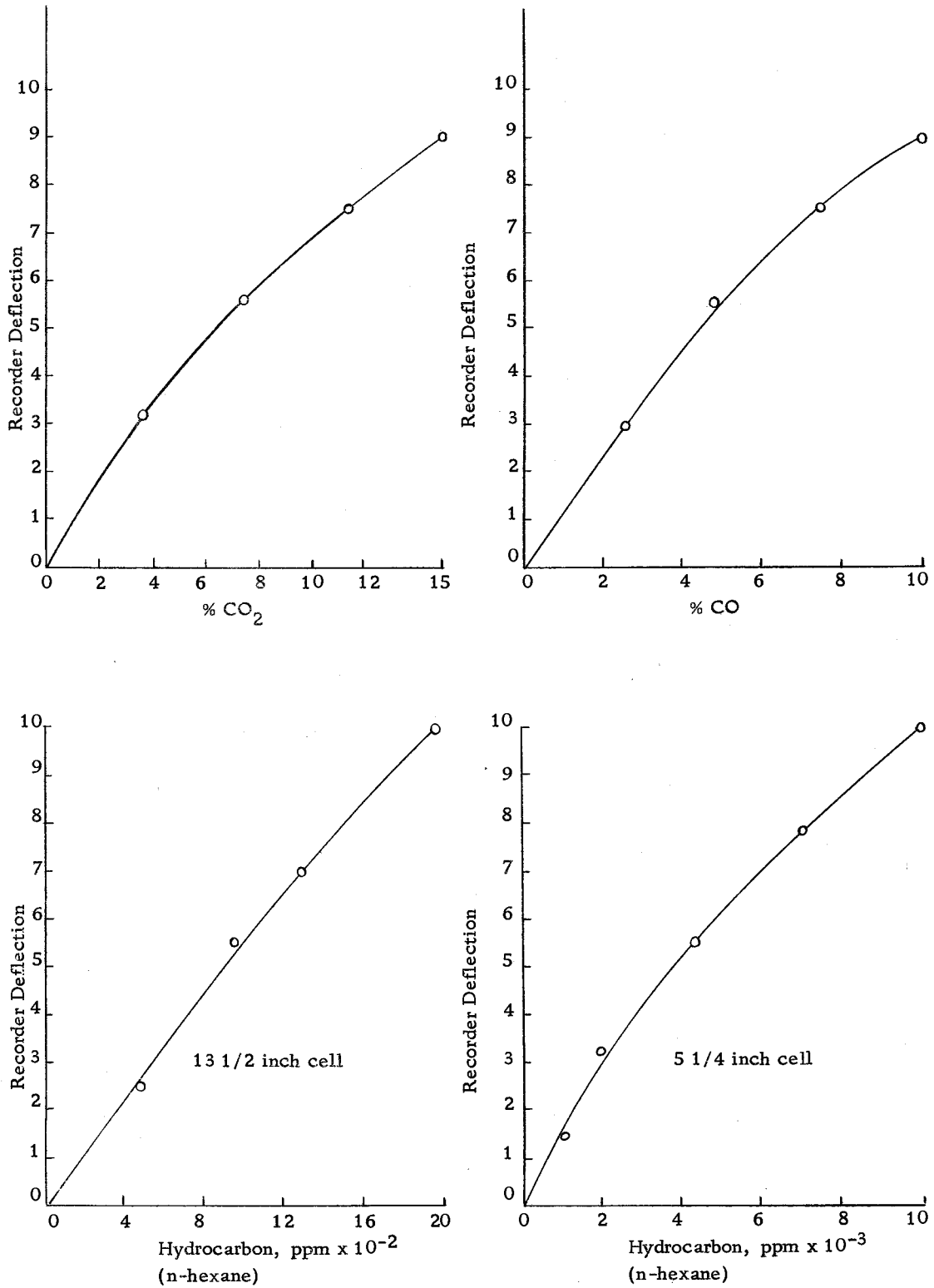


Figure C-1. Non dispersive infrared analyzer calibration curves

The water vapor correction for hydrocarbon concentrations was considered negligible.

All concentrations computed for the California seven-mode cycle were carried out according to the MVPCB procedure.

### Carbon Balance Calculations

Calculations similar to those of steady state conditions were performed on the CO and CO<sub>2</sub> data obtained for use in the carbon balance. The hydrocarbon concentrations determined by the infrared analyzer were doubled and multiplied by six to account for all the carbon atoms. The hydrocarbon, CO, and CO<sub>2</sub> concentrations were added up for each five second interval and the dilution correction factors were calculated as follows:

$$\text{Correction factor} = \frac{\% \text{HC} + \% \text{CO} + \% \text{CO}_2 \text{ @ burner inlet}}{\% \text{HC} + \% \text{CO} + \% \text{CO}_2 \text{ @ burner outlet}}$$

### Sample NO<sub>x</sub> Concentration Determinations

#### A. Calibration Concentrations

Volume of flask: 2175 ml.

Volume of NO injected into evacuated flask: 2 ml.

The flask was then filled with nitrogen to a pressure 31.3 inches Hg as calculated below, based on a 100 ml withdraw and a final pressure of one atmosphere.

$$P = \frac{(29.92 \text{ in. Hg})(2175 \text{ ml} + 100 \text{ ml})}{2175 \text{ ml}} = 31.3 \text{ in. Hg}$$

100 ml was then withdrawn from the flask resulting in a final concentration of:

$$\text{Concentration} = \frac{2 \text{ ml}}{(2175 \text{ ml} + 100 \text{ ml})} \times 10^6 = 880 \text{ ppm}$$

#### B. Calibration of NO<sub>x</sub> analyzer

The 100 ml of NO of known concentration was injected into the test cell which was at 25.5 inch Hg vacuum. The cell was then brought up to atmospheric pressure with oxygen. In approximately 15 minutes, oxidation of the NO to NO<sub>2</sub> is complete. The test cell was then evacuated and purged with oxygen. The change in recorder output in millivolts can then be plotted as a function of oxides of nitrogen concentration. Calibration curves for the three ranges used are shown in Figure C-2.

#### C. NO<sub>x</sub> Determination in Engine Exhaust Gas.

A 100 ml sample of exhaust at atmospheric pressure was injected into the test cell, which was at 25.5 inch Hg. The cell was then brought to atmospheric pressure with oxygen. After 15 minutes the exhaust gas produced a 24 mv (range 2) change in cell output. The test cell was then evacuated and purged with oxygen and the output decreased 24 mv. From Figure C-2: 24 mv (range 2) corresponds to 327 ppm nitrogen oxides.

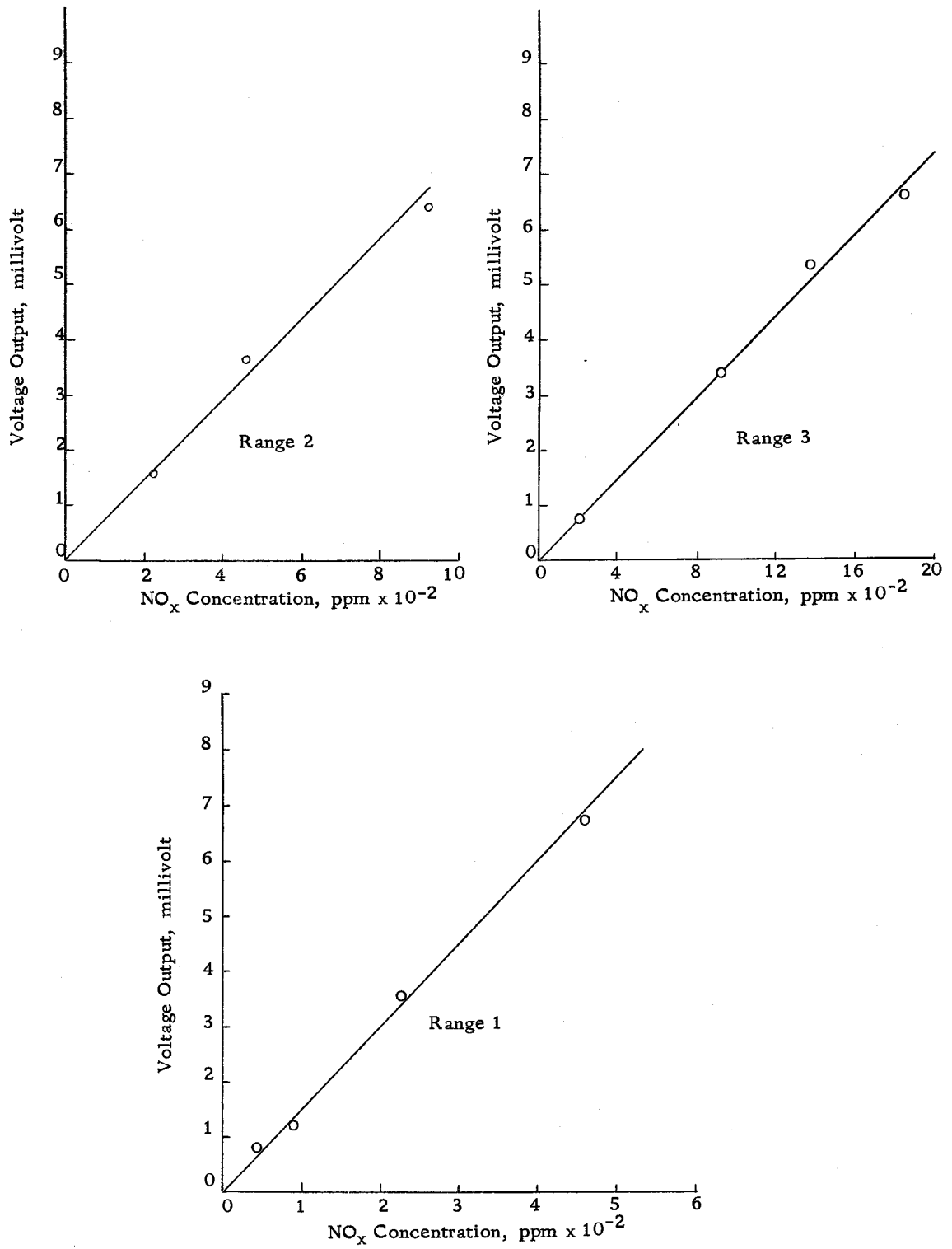


Figure C-2. Nitrogen oxide spectrophotometer calibration curves