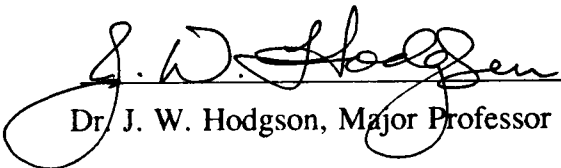
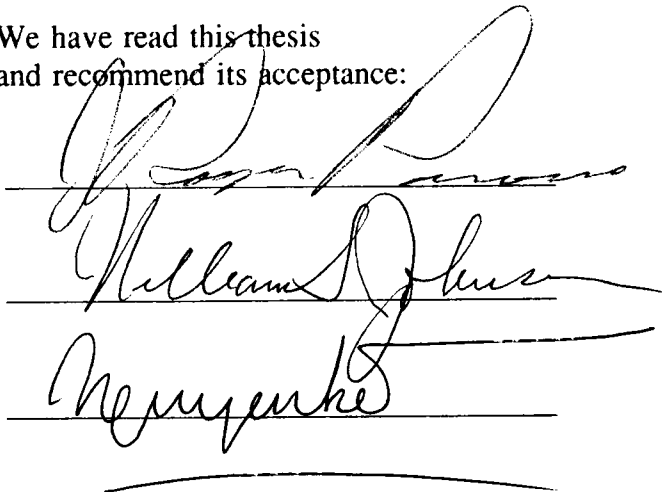


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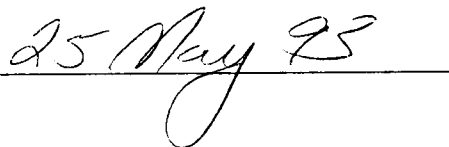
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***THE EVALUATION OF A
COMPUTER CONTROLLED AIR PUMP FOR IMPROVED
AUTOMOBILE EMISSIONS***

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Lori M. Snook

August 1993

DEDICATION

This thesis is dedicated to my mother, who through example has shown me the type of person that I wish to be. Her support and unconditional love throughout my college career were unwavering, and I am grateful to have been blessed with such a friend.

I would also like to dedicate this thesis to my brother, Brian. I have enjoyed his friendship all of my life and would like to thank him for all that we have shared together.

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acquisition.

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I would like to thank my fellow students at the University of Tennessee. Their standard of excellence forced me to work harder to meet them at their level.

Finally, I would like to express my sincere love and appreciation to Jerry Fussell. His love for me, respect for my research, and personal standard of excellence provided me with an atmosphere in which I could excel; not only professionally, but personally. Thank you, Jerry, for your love.

ABSTRACT

Proof-of-concept testing was performed to determine the effectiveness of a computer controlled air pump (CCAP) in reducing the unburned hydrocarbons (UHC) and carbon monoxide (CO) emitted from automobile engines. For the initial phase of testing, a prototype CCAP was designed and evaluated on a dynamometer test-stand at the University of Tennessee. This CCAP maintained the engine's exhaust at a stoichiometric air/fuel ratio by utilizing a second oxygen sensor mounted downstream from the catalyst. In this way, the catalyst's conversion efficiency for CO and UHC was always high, even if the engine was running rich. Results of this steady-state testing indicated that the CCAP was able to reduce UHC and CO emissions without a corresponding increase in oxide of nitrogen (NO_x) emissions. Additionally, catalyst temperatures did not increase dramatically. For the second phase of testing, the CCAP was installed on a vehicle and four sets of emission tests were performed at the Environmental Protection Agency's Environmental Research Center Annex in Research Triangle Park, NC. As a result of testing, it was determined that the CCAP has merit as a system to decrease CO and UHC emissions during acceleration and power enrichment. However, the CCAP must be activated after the catalyst has lit-off (or it can delay catalyst light-off and result in poor emissions). NO_x emissions remained essentially unchanged and catalyst temperatures did not increase by more than 200 °F. Recommendations for further study are made.

PREFACE

"There is no question that our health has improved spectacularly in the past century, but there is a running argument over how this came to be. One thing seems certain: it did not happen because of medicine, or medical science, or the presence of doctors. Much of the credit should go to the plumbers and engineers of the Western World."

- Dr. Lewis Thomas (1)

As an engineer, this thought gives me a feeling of great pride, especially when I consider the source...Dr. Lewis Thomas is a doctor of medicine. For him to attribute the increases in health and life expectancy over the past century to the work of engineers is certainly significant. It commands attention. When I really think about the implications, my view of engineering is transported to a highly altruistic plane. But I also become concerned. I become concerned that in our efforts to do more better and faster, we are losing sight of this true purpose of engineering. What a shame it would be to have come so far, to have earned the praises of modern healers, only to engineer systems which can have a negative impact on our health and well-being.

Because of this concern, I have spent the past year and a half researching a new system to control the harmful emissions from automobiles. It is my desire to assist in making one of the most widely used engineering innovations of the century more benign, and I would encourage all engineers to strive to accomplish the same in their area of expertise.

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LIST OF SYMBOLS AND ABBREVIATIONS

CCAP	Computer Controlled Air Pump
CFV	Critical Flow Venturi
CO	Carbon Monoxide
CVS	Constant Volume Sampler
ECM	Electronic Control Module
EGO	Exhaust Gas Oxygen
EPA	Environmental Protection Agency
FID	Flame Ionization Detector
FTIR	Fourier Transform Infrared Analyzer
FTP	Federal Test Procedure
LDV	Light-duty Vehicle
MAP	Manifold Absolute Pressure
NAAQS	National Ambient Air Quality Standards
NDIR	Non-dispersive Infrared Analyzer
NMHC	Non-methane Hydrocarbon
NO _x	Oxides of Nitrogen
ORNL	Oak Ridge National Laboratory
PAI	Programmed Air Injection
SO ₂	Sulfur Dioxide
TCTC	Temperature Controlled Test Chamber

TWC	Three-way Catalyst
THC	Total Hydrocarbons
UT	University of Tennessee
UDDC	Urban Dynamometer Driving Cycle
UHC	Unburned Hydrocarbons

CHAPTER 1

INTRODUCTION

1.1 Purpose

The purpose of this thesis is to provide automotive engineers and designers with information which could aid them in their efforts to protect the earth's delicate ecosystem from the undesirable products of combustion which originate in automobile engines.

In general, gasoline engines emit some products of combustion which are detrimental to human health. Those limited by the Clean Air Act and its amendments are carbon monoxide (CO), unburned hydrocarbons (UHC), and oxides of nitrogen (NO_x). CO is produced in engines when the fuel is not completely oxidized. When inhaled, CO reacts with hemoglobin in the blood to deprive the body of oxygen. This results in symptoms such as headaches, fatigue, impaired judgement, and even death. Approximately 2/3 of the CO in the earth's atmosphere comes from internal combustion engines (2). UHCs are also formed when fuel is incompletely burned. They react with NO_x (produced when fuel is burned at high temperatures) in the presence of sunlight to form photochemical oxidants (such as ozone). Not only do these oxidants irritate mucus membranes and inflame the eyes and the upper respiratory tract, but they also react to form photochemical smog. Smog can irritate the lungs, cause bronchitis and pneumonia, and lower resistance to influenza and other

respiratory infections (3). The "EPA reported that in 1989, about 67 million people lived in areas where the second-highest ozone concentration, a principal measure of compliance, exceeded the National Ambient Air Quality Standards (NAAQS) concentration" (4).

In addition to causing direct health problems, these emissions have also been linked to environmental problems ranging from acid rain to crop damage. Acid rain is produced when NO_x and sulfur dioxide (SO_2) gases come into contact with water and are converted into sulfuric and nitric acids. Acid rain "turns lakes acidic, kills fish and other aquatic organisms, damages crops, destroys forests, alters soil fertility, and destroys sandstone and marble structures" (3). It causes an estimated ten billion dollars worth of damage per year in the United States alone (2). Besides contributing to the formation of acid rain, NO_x also add an excess supply of nitrate ions to aquatic systems. "This oversupply of nitrates can stimulate extremely rapid growth of algae and other aquatic plants, which depletes the water of vital oxygen and causes massive fish kills" (as in the Chesapeake Bay) (2). The "largest share of NO_x pollution (about 40 percent) comes from the ever-growing number of automobiles" (2). Environmental damage to crops and forests is also caused by ozone (which is formed from the UHCs and NO_x produced in automobiles). "In southern California, millions of ponderosa pines have been damaged by air pollution (mostly ozone) from Los Angeles" (3). As a matter of fact, crop damage in the Los Angeles area was detected as early as 1943 and motivated the first air pollution legislation in California (5).

Since this first legislation was enacted by the state of California in 1948, the

federal government and legislative bodies around the world have established laws which limit emissions from automobiles and trucks. The most recent U.S. legislation, The 1990 Clean Air Act amendments, established a two-phase set of reduced tailpipe emission standards for the United States. Phase I requires the reduction of light-duty motor vehicle (LDV) non-methane hydrocarbon (NMHC) emission rates to 0.25 g/mi, NO_x to 0.40 g/mi, and particulate to 0.08 g/mi (from the current 0.4, 1.0, and 0.2 standards, respectively) by 1994. Phase II, if enacted, will require further reductions of NMHC emission rates to 0.125 g/mi, NO_x to 0.2 g/mi, and CO to 1.7 g/mi (from the current 3.4 standard) by 2003. These requirements are summarized in Table I. In addition to federal regulations, the state of California approved new State vehicle and fuels regulations in September, 1990 requiring even greater reduction of motor vehicle emissions, particularly hydrocarbons (5).

This thesis documents the effectiveness of a computer controlled air pump (CCAP) in reducing CO and UHC emissions (while preventing an increase in NO_x

Table I Current and Future Emissions Requirements for Light Duty Vehicles

Model Year	NMHC	CO	NO _x	Particulate
Current	0.4 g/mile (THC)	3.4 g/mile	1.0 g/mile	0.2 g/mile
1994 - Phase I	0.25 g/mile	3.4 g/mile	0.40 g/mile	0.08 g/mile
2003 - Phase II	0.125 g/mile	1.7 g/mile	0.20 g/mile	0.08 g/mile

emissions) from gasoline powered automobiles. This is done with the intent of aiding automobile manufacturers and designers in their efforts to prevent health hazards and environmental damage from escalating, and to meet stricter state and federal automobile emission regulations. The air injection system described in this thesis uses only existing technology and can therefore be implemented as a solution for today's automobiles.

1.2 Background

Presently, automobile emissions are measured in accordance with the Federal Test Procedure (FTP) (6). For light-duty vehicles (LDVs), this procedure involves the measurement of exhaust emissions while the vehicle is driven according to a prescribed driving schedule (approximately 7 miles long) on a chassis dynamometer. Figure 1 shows a vehicle in a typical test cell and the corresponding emission measuring equipment. For the FTP, the inertia weight of the dynamometer rolls and the aerodynamic power are specified for each vehicle. The vehicle is soaked at 75 °F for 12 hours prior to the test.

The FTP light duty driving cycle is shown in Figure 2 and is organized into four phases: the cold transient phase (phase 1), the cold stabilized phase (phase 2), the hot transient phase (phase 3), and the hot stabilized phase. The cold transient phase is comprised of the first 505 seconds of the test. During this phase, exhaust emissions are typically at their worst because of cold-start enrichment (choke) strategies and catalysts which have not lit-off. The rest of the seven mile drive is

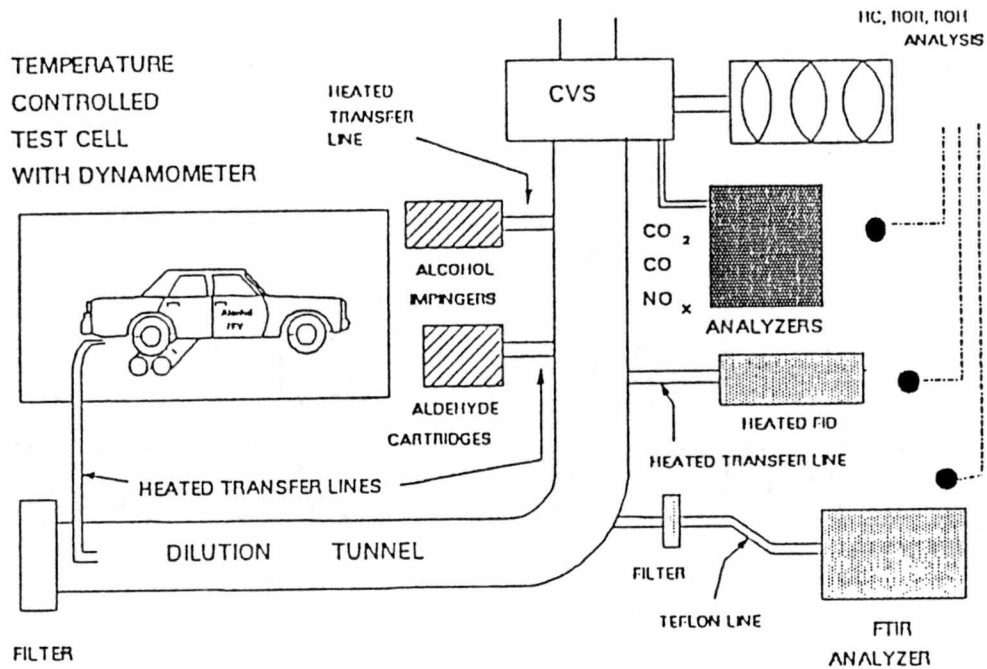


Figure 1 Schematic of automobile emissions sampling system (4)

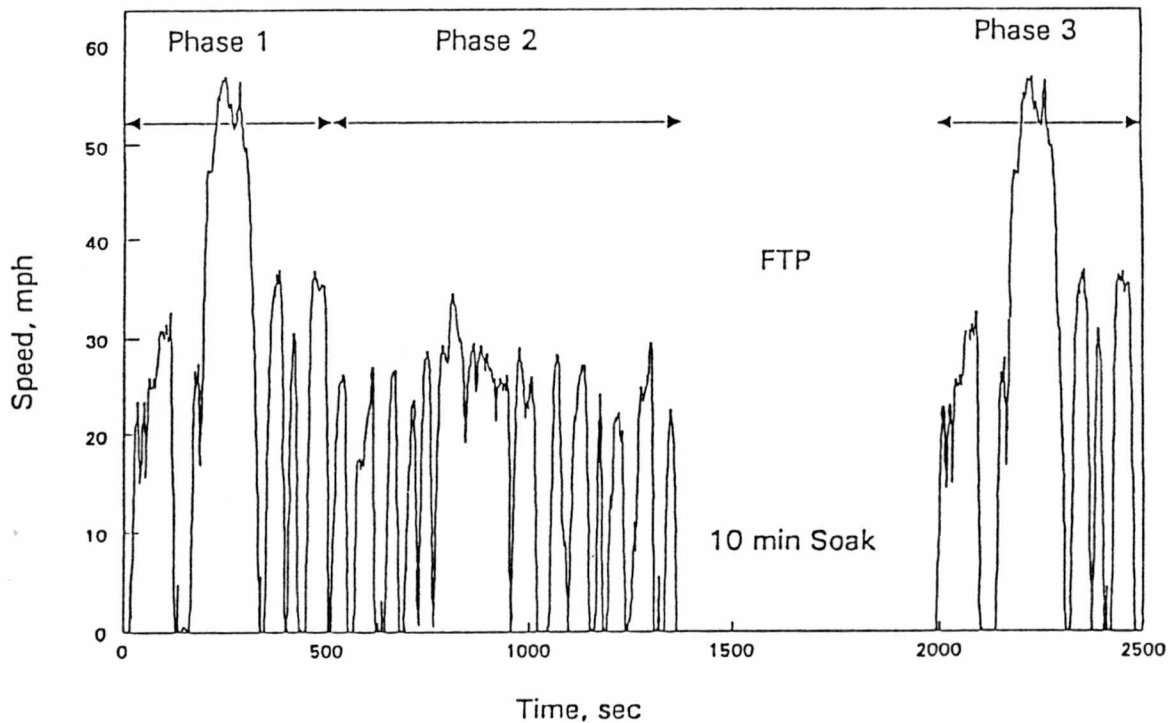


Figure 2 Driving schedule for FTP light duty vehicle emission tests (4)

termed the cold stabilized phase. After the cold stabilized phase is completed, the vehicle is turned off and soaked for 10 minutes. The vehicle is then restarted and the first 505 seconds of the driving cycle are repeated. This is termed the hot transient phase. The hot stabilized phase would be the remainder of the drive, but results are assumed to be the same as in the cold stabilized phase.

Today, the most successful emission control strategy used on LDVs involves three-way catalysts (TWC) with exhaust gas oxygen (EGO) sensor feedback control of the engine's air-fuel ratio. Feedback control is required because the TWC is most effective in reducing NO_x while simultaneously oxidizing CO and UHC when the engine air-fuel ratio is essentially stoichiometric (7). The stoichiometry can be expressed in terms of the equivalence ratio, ϕ , defined as $(F/A)/(F/A)_{\text{stoich}}$. Fuel rich mixtures ($\phi > 1$) result in low CO and UHC conversion, while fuel lean mixtures ($\phi < 1$) give low NO_x conversion (see Figure 3). The problem is compounded because fuel rich conditions create more CO and UHC, while fuel lean conditions (unless very lean) create more NO_x than would be created under stoichiometric conditions (see Figure 4).

During closed loop engine operation, the EGO sensor detects whether the engine is operating fuel rich (low oxygen levels) or fuel lean (high oxygen levels) and instructs the fuel metering system to take corrective action. The net result is a "dithering" of the fuel mixture about the stoichiometric value. The excursions from stoichiometric operation are kept within certain limits to keep the TWC conversion acceptably high. The characteristics of a typical EGO sensor are shown in Figure 5.

There are, however, times when the engine operates with excess fuel. Starting,

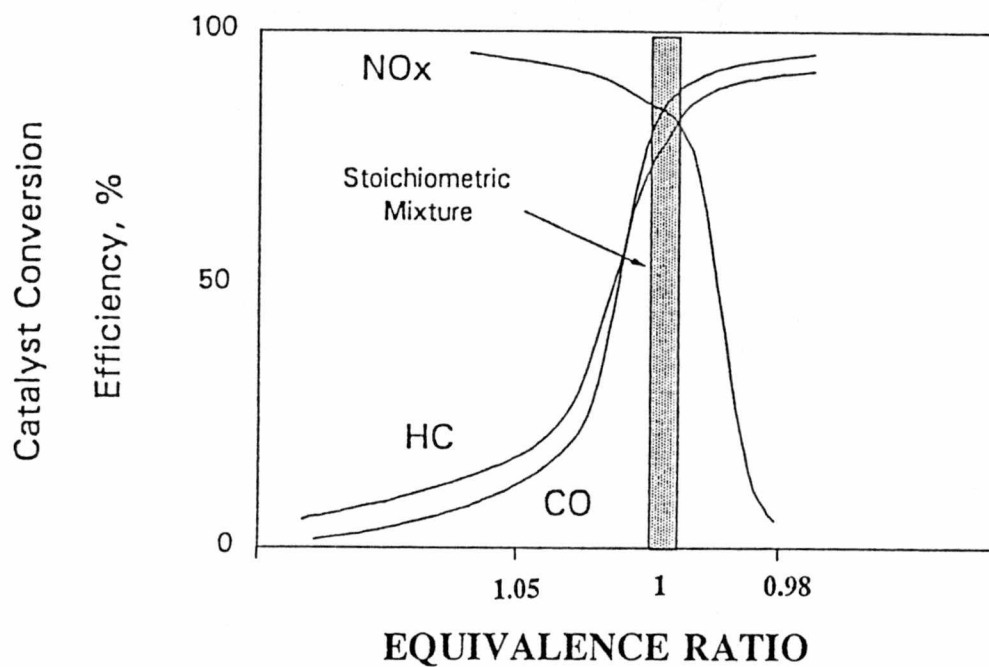


Figure 3 Dependence of catalyst conversion efficiency on air/fuel ratio (4)

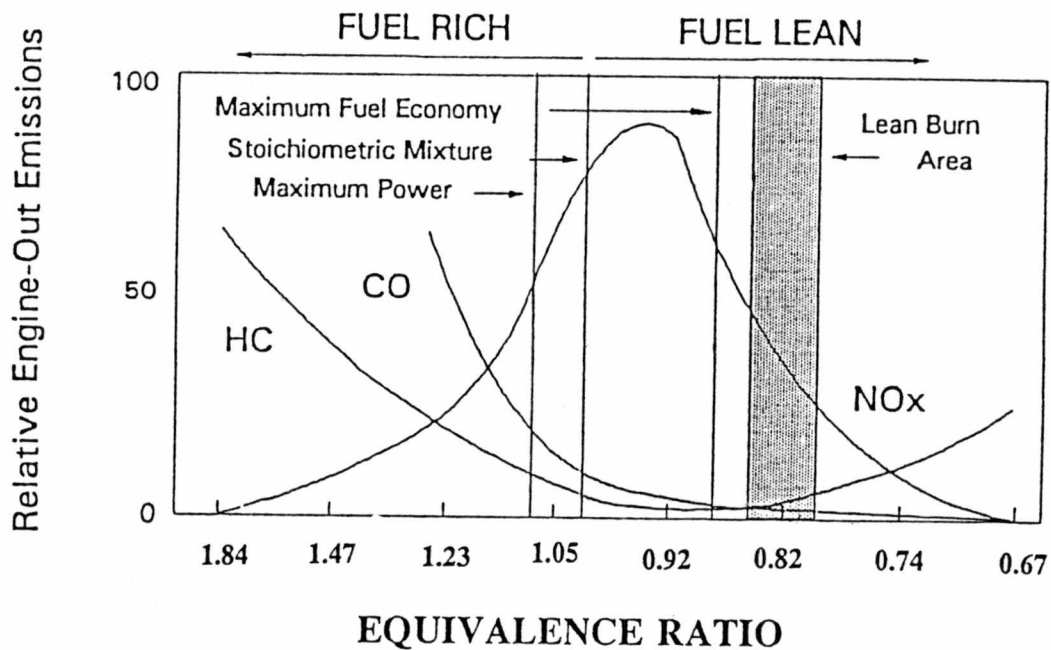


Figure 4 Dependence of engine-out emissions on engine air/fuel ratio (4)

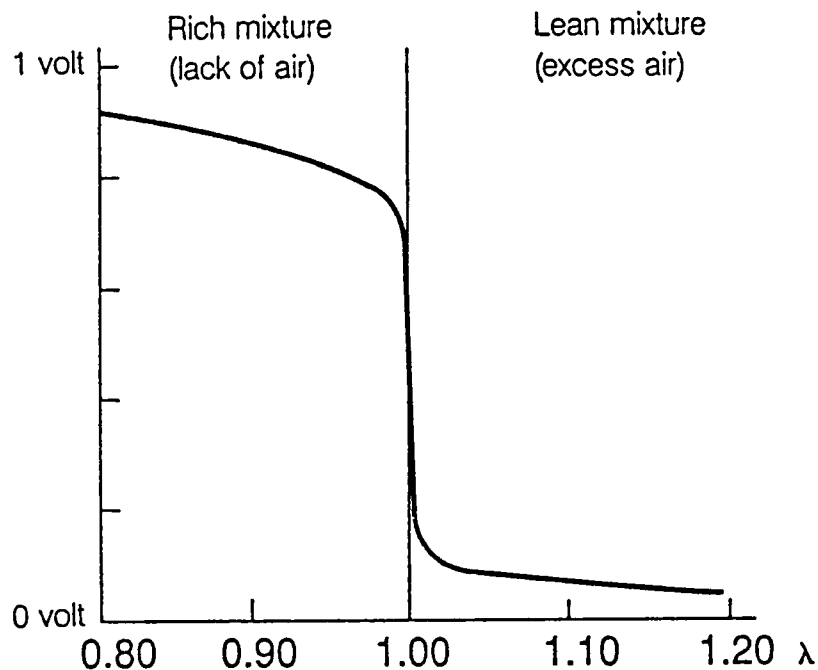


Figure 5 Switching Characteristics of a Typical EGO Sensor (8)

warm-up, acceleration, and power enrichment modes require fuel-rich mixtures for proper engine operation to yield acceptable vehicle driveability. During these times, the production of CO and UHC from the engine will be higher, but the NO_x production will be lower than under stoichiometric operation.

In order to correct this problem, some manufacturers have equipped their engines with air pumps to introduce air upstream from the catalyst during engine warm-up. This air provides additional oxygen to oxidize the CO and UHC produced. Once the engine "warms-up", the flow of air to the exhaust system is terminated.

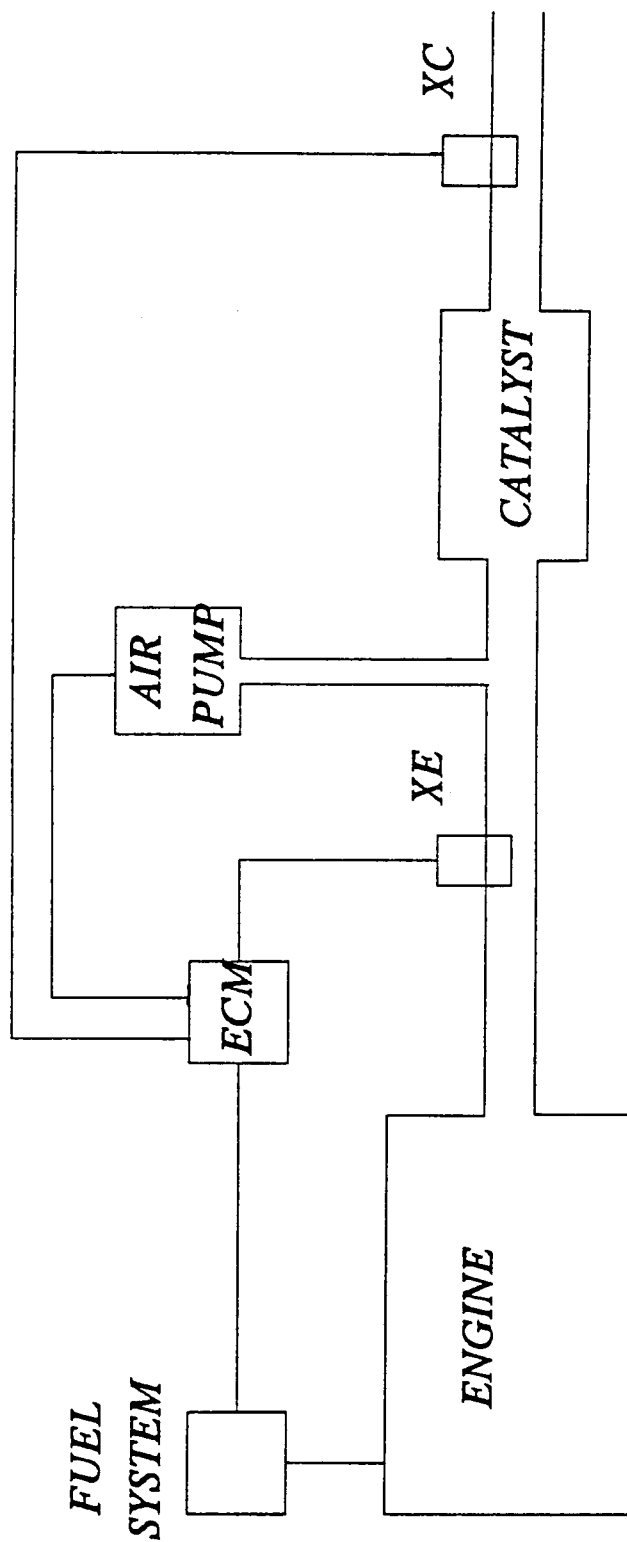
The University of Tennessee's entry in the 1990 Methanol Challenge used such a strategy. Termed programmed air injection (PAI), the system allowed the engine to start and idle for 20 seconds, then introduced air into the exhaust stream (using a pulse

air valve) for 100 seconds (9). "The strategy was to add enough oxygen in the exhaust to react with the unburned fuel, and thus expedite exothermic reactions within the catalytic convertor" (9). The 20 second delay prevented the injected air from delaying catalyst light-off. The air injection was terminated after 100 seconds, when the cold-start enrichment was over and the need for continuous air injection was removed. Further continuous air injection would upset the stoichiometry of the catalyst and would probably result in poor NO_x conversion. This strategy resulted in a 20% decrease in UHC, and a 31% decrease in CO. However NO_x increased by 50% (9). Clearly, the PAI system has potential for improving CO and UHC emissions, but the increase in NO_x emissions is undesirable.

Current thinking is moving toward a design of an air/fuel strategy for the engine which optimizes power and fuel economy, and a separate air/fuel strategy for the catalyst to produce low emissions. Such a decoupling of the two processes should lead to improved efficiency in both systems (10).

1.3 Method of Attack

This investigation examined a system to provide air injection even after the engine had warmed up, so that the catalyst always operated within the window of its best conversion efficiency -- even though the engine might have been operating fuel-rich. This was done by using a second oxygen sensor mounted downstream from the catalyst. The role of this sensor was to control the air injection upstream from the catalyst. A schematic of the system is seen in Figure 6. The schematic shows the



XE: ENGINE OXYGEN SENSOR

XC: CATALYST OXYGEN SENSOR

ECM: ENGINE ELECTRONIC CONTROL MODULE

Figure 6 Schematic of closed-loop air injection system

normal EGO sensor (XE) located upstream from the catalyst to control the engine air/fuel ratio, plus another EGO sensor (XC) to control the catalyst stoichiometry. This was accomplished via feedback to a computer controlled air pump (CCAP).

The project focused on the development of this CCAP using a specific vehicle to create a prototype system. Preliminary testing was performed on a test engine under steady-state conditions using equipment available at the University of Tennessee. Once the concept of the CCAP was proven, the prototype CCAP was designed, fabricated, and installed on a 1987 Buick Regal. Real-time emissions were then determined both with and without the experimental system. Testing for this phase was performed at the EPA facilities at Research Triangle Park, NC.

1.4 Scope

It was anticipated that if the project was successful, the CO and UHC emissions from the test vehicle would be reduced. The extent of these reductions was determined through EPA FTP emission testing. Although the FTP is the standard procedure used by the United States government to measure automobile emissions, the National Research Council believes "that the Federal Test Procedure does not adequately simulate actual driving behavior" (4). Therefore, it is important to note that the effectiveness of the CCAP was only demonstrated with respect to the FTP. Actual results on the road may be more impressive (due to higher accelerations).

As a part of this investigation, temperatures were monitored both upstream and downstream of the catalyst. This was done because it was expected that an increase in

catalytic activity would occur with the CCAP, and possibly cause catalyst failure.

Although this did not occur, it is again important to recall that the vehicle was only tested within the window of the FTP.

The study also determined the effect that the air injection system has on NO_x values. The addition of excess air coupled with high exhaust temperatures might have provided an opportunity for additional NO_x formation. However, oxygen sensors placed downstream from a TWC tend to have a rich bias (11). Therefore, NO_x emissions were not expected to (and did not) rise significantly. Confidence is placed in this result, but it is important to recall that temperatures might have remained low (and thus impeded NO_x production) due to the limitations of the FTP.

No data was obtained to determine the effect of the CCAP on catalyst life. It is possible that the increase in catalytic activity that is caused by the CCAP will shorten the effective life of the catalyst.

Preliminary testing was initially performed on an engine which used natural gas for fuel. Results showed no decrease in UHC when this fuel was used. Therefore, it is important to realize that the results of this investigation may be specific to the fuel used (propane in phase I, and gasoline in phase II). The results should not be extrapolated to other fuels unless the fuel demonstrates similar catalytic activity.

Finally, the CCAP evaluated was designed as a prototype only. Therefore, it was not evaluated on the basis of cost or manufacturability. However, because the prototype used only existing parts, and the controller could be included in the ECM, the system should prove to be a cost effective method to control automobile emissions.

CHAPTER 2

PHASE I: PURPOSE AND DESIGN

2.1 Purpose of Phase I

Phase I of the project focused on "proving the concept" of the Smart Catalyst (or CCAP). It involved the design, installation, and evaluation of a prototype closed-loop air injection system on a dynamometer-mounted test engine. This allowed steady-state exhaust emissions to be measured "in house" and at little cost should the system be unsuccessful. Additionally, Phase I provided insight on selecting a suitable test vehicle for Phase II.

2.2 Phase I Prototype CCAP

The prototype system for Phase I included a controller, an electric centrifugal air pump, a second oxygen sensor, and necessary plumbing components.

The controller chosen was an Autotronic Controls Corporation O₂ air fuel mixture controller (alternate fuels part no. 4045). This controller's original purpose was to maintain a vehicle's air/fuel ratio at stoichiometry when it was run on propane or natural gas metered by Impco gas mixers. It accomplished this task by interpreting the vehicle's EGO signal and then varying the air/fuel mixture by activating a solenoid valve that varied a vacuum draw on a convertor (low pressure regulator) diaphragm. The amount of vacuum applied to this diaphragm determined the engine's air/fuel

ratio.

In this experiment, the mixture controller was used to maintain the catalyst's air/fuel ratio at stoichiometry and it was installed on the test engine in much the same way as described above. However, the controller received input from an oxygen sensor located downstream from the catalyst and the vacuum draw was used to actuate a diverter valve instead of a converter diaphragm.

This diverter valve, when actuated, allowed the air flowing from the air pump to flow into the exhaust, upstream from the catalyst. The diverter valve selected was a standard valve assembly manufactured by Ford (part # E47E-9F491).

The air was supplied to the diverter valve from an electric air pump (GM part # 10090521). Because the air pump was a centrifugal pump, tests were performed to determine if it was capable of providing an adequate amount of air for all engine conditions (See Appendix A). Although this air pump was deemed unacceptable for use in a vehicle, it was deemed acceptable for steady-state testing and was used for Phase I of the experiment.

In order to prevent hot exhaust gases from damaging the diverter valve or air pump, a pulse air valve (Ford part # E3EE-9A487-BA) was used as a check valve and was placed between the diverter valve and the exhaust stream. Figure 7 shows a picture of the air pump, diverter valve, check valve, and air inlet of the prototype CCAP.

A second oxygen sensor was placed downstream of the catalyst (see Figure 8). This oxygen sensor determined if the catalyst's exhaust products were rich or lean and

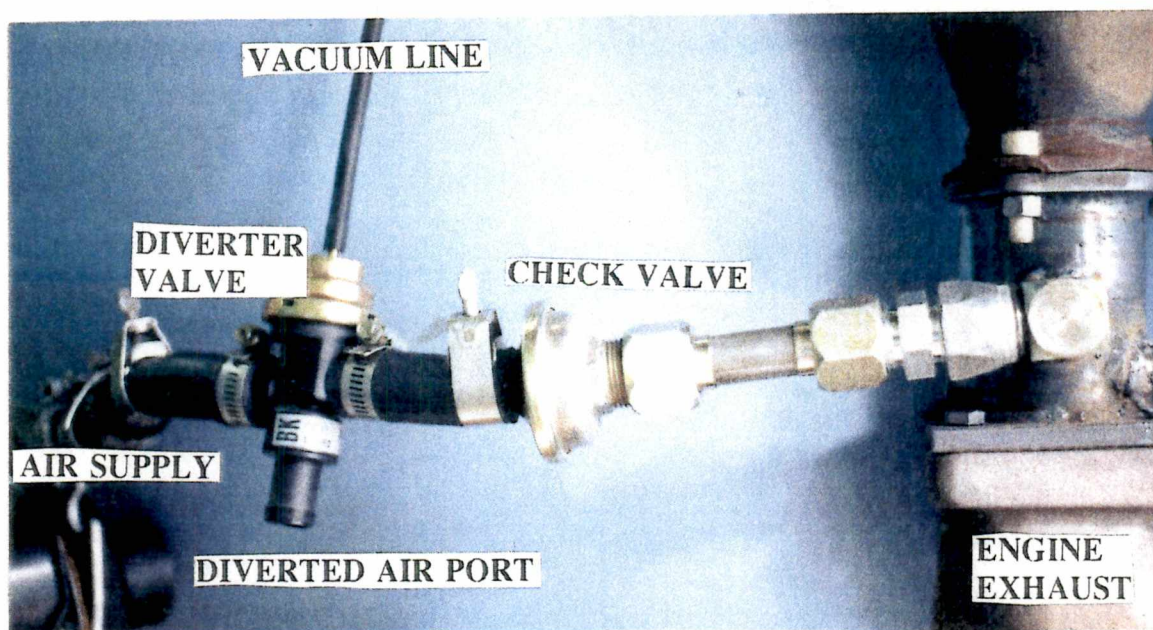


Figure 7 CCAP air flow path (pump to catalyst inlet) for Phase I

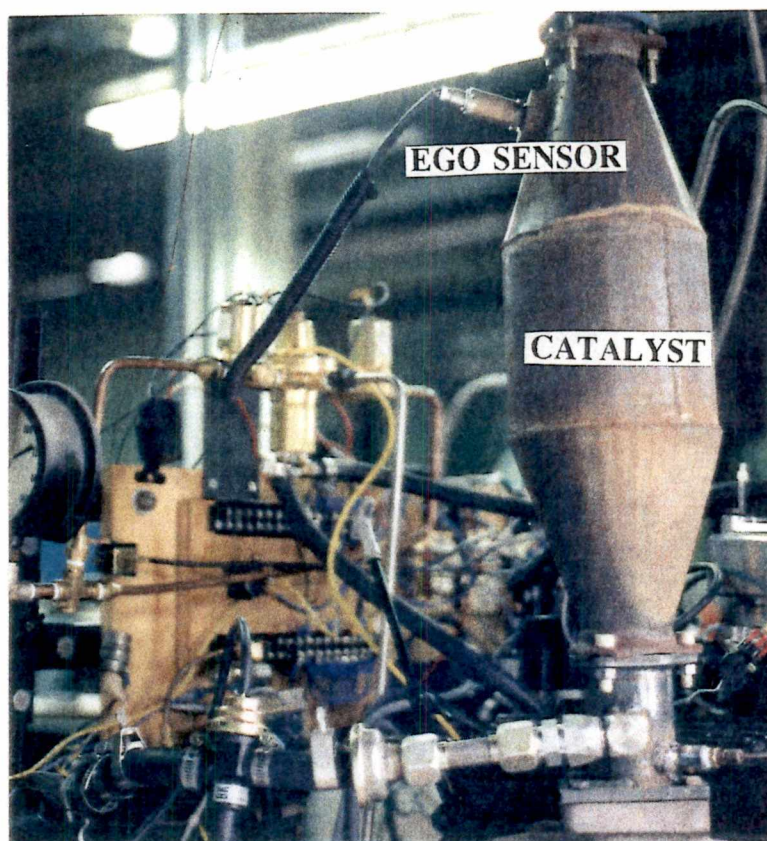


Figure 8 Catalyst and catalyst oxygen sensor for Phase I

then provided this information to the controller.

The entire CCAP system was installed on a GMC 350 cid engine which was coupled to a GE direct current dynamometer. The engine was originally designed to run on gasoline, but a conversion kit was used to allow it to run on natural gas. It was thought that the computer controlled fuel metering system would provide an accurate method of setting slightly rich air/fuel ratios. However, it was later learned that the fuel metering system was not able to hold a precise air/fuel ratio, and a valve was installed to allow the fuel to be metered manually.

2.3 Phase I Test Equipment

The test equipment for Phase I included devices to measure emissions, exhaust temperatures, exhaust gas oxygen voltages, and the engine's manifold absolute pressure (MAP). Also included in the test equipment for Phase I were computers which functioned to sample, reduce, and record this data.

The emissions measured in Phase I were UHCs, CO, and NO_x. UHCs were measured with a Beckman model 400 hydrocarbon analyzer which utilizes the flame ionization method of detection (FID). In essence, this method operates on the principle that "the introduction of a gas sample containing hydrocarbons into a hydrogen diffusion flame will increase the concentration of ions within the flame" (12). This increase in ionization is almost directly proportional to the mass flow rate of carbon atoms into the flame. The ions are collected by a DC voltage between the burner top and a collector electrode, which surrounds the flame, causing current to

flow through the associated electronic measuring circuits (12). The FID used in Phase I provided direct readout on a front-panel meter and a selectable output for an accessory recorder.

An Olson-Horiba non-dispersive infrared analyzer (NDIR) was used to measure CO in Phase I of experimentation. The NDIR functions by detecting the infrared (IR) energy absorption differential between two gas-filled columns exposed to a chopped IR source. This differential causes movement of a flexible, metal diaphragm which separates the sample and reference detector cells. The amplitude of the oscillating diaphragm is a measure of the concentration of CO and is converted from a variable capacitance into a usable signal (12). The NDIR used in this experiment provided direct readout on a front-panel meter and a voltage signal which could be used to calculate the CO concentration in the exhaust gas.

In order to measure the NO_x values in the engine's exhaust stream, a Beckman model 951 NO/ NO_x analyzer was used. This analyzer (a photochemiluminescent analyzer) measures the light from the chemiluminescent reaction of NO and O_3 . In the presence of an excess of O_3 , the light emitted is proportional to the concentration of NO. To measure the concentration of NO_x in a sample, a converter which converts NO_2 into NO at high efficiency is inserted into the input sample stream (12). The light emitted is then measured by a photomultiplier tube and associated electronic circuitry. The NO/ NO_x analyzer used in this experiment provided direct output on a front-panel meter and with a voltage signal which was proportional to the NO_x concentration.

In addition to exhaust gas emission measurements, temperature measurements of the exhaust gas were taken both upstream and downstream from the catalyst. Three type J (copper-constantine) thermocouples were used for this purpose. One thermocouple was mounted at the catalyst inlet, one thermocouple was mounted at the catalyst exit, and the last thermocouple was placed in an ice bath for use as a reference temperature. The thermocouples provided a voltage output to a data acquisition unit.

The EGO voltages at both the exit of the engine and the exit of the catalyst were displayed during the tests on a Tektronics 465 oscilloscope. In this way, the air/fuel ratio of the engine and the catalyst could be observed as the tests progressed. Additionally, the engine's EGO voltage was used as a gage to manually set the engine's air/fuel ratio slightly rich or at stoichiometry, depending on the test being conducted.

Finally, engine MAP was measured with the engine's stock MAP sensor during the tests. This was done to insure that enough vacuum existed to actuate the diverter valve during testing.

All of the data obtained in this steady-state test phase were sampled and reduced with a Hewlett Packard 3497A data acquisition/control unit. The data acquisition unit is a programmable computer which is capable of receiving voltage inputs on several channels and then performing specified data reduction procedures instantaneously. The controller was programmed to sample data from the FID, NDIR, photochemiluminescent analyzer, thermocouples, EGO sensors, and MAP sensor at

user determined intervals. It then converted the voltages into usable information before sending the data to an IBM personal computer for storage. A copy of the data acquisition program is located in Appendix B. A picture of test equipment set-up is seen in Figure 9. Located in the picture, from left to right, are the FID, the photochemiluminescent analyzer, the NDIR, calibration gases, the IBM personal computer, the oscilloscope (under the computer), and the data acquisition unit.

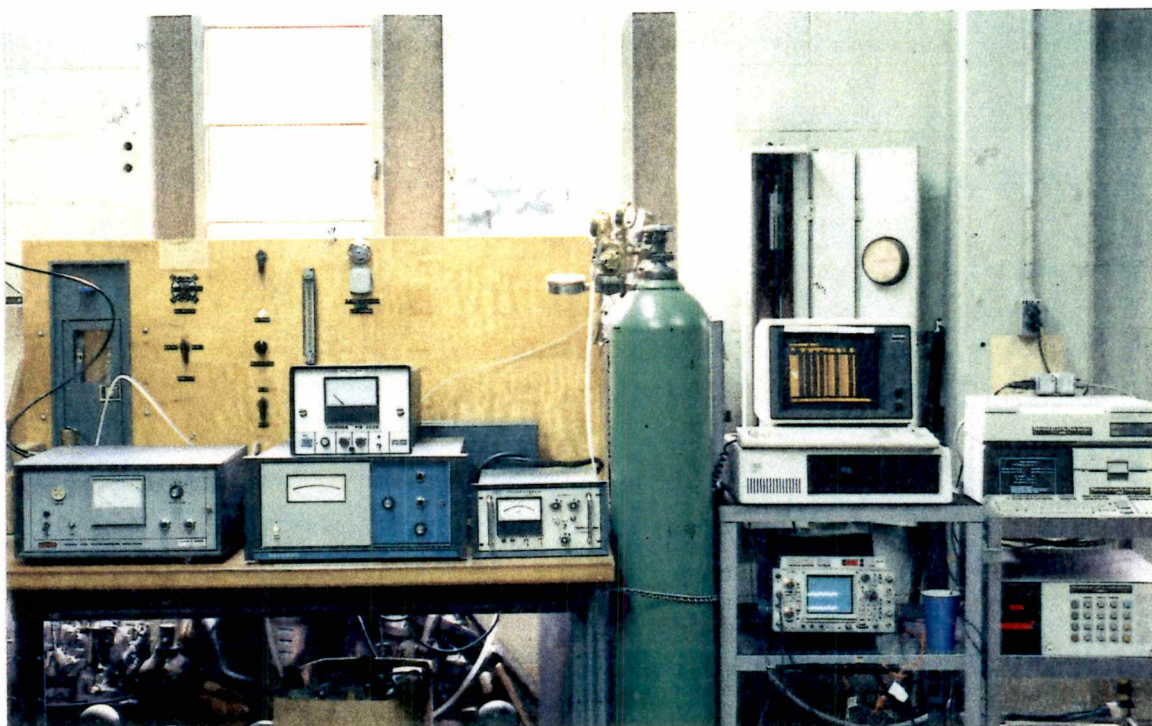


Figure 9 Phase I test equipment

CHAPTER 3

PHASE I: PROCEDURE

3.1 Emission Testing Equipment Calibration and Preparation

To insure precise testing of the air injection system designed for Phase I, a detailed procedure was followed to guarantee that the emission testing equipment was started, calibrated, and operated properly. For the photochemiluminescent analyzer and the NDIR, this involved zeroing the front panel meter, providing time for temperature equilibration, establishing the proper pressures and flow rates for sample and calibration gases, and calibrating the device with a zero and an upscale standard gas. The procedure for starting and calibrating the FID was the same, except that it was also necessary to ignite the hydrogen flame. If more details on the procedures used to calibrate and operate each of these devices are required, they can be found in the respective equipment manuals.

3.2 Phase I Test Procedure

Phase I consisted of a steady-state test to compare emissions data from a rich running engine with air injection, to a rich running engine without air injection. Additionally, data were obtained for an engine running at a stoichiometric air/fuel ratio as a comparison for NO_x levels. The test was performed twice, once with natural gas as the fuel, and once with propane as the fuel. The two fuels were used in order to

aid in the selection of a suitable vehicle for Phase II. The procedure for both tests was the same and is listed below:

1. The emission testing equipment was calibrated and prepared as described in Section 3.1
2. The data acquisition unit and IBM computer were turned on and set-up to sample at the appropriate time interval.
3. The reference thermocouple was placed in a fresh ice bath.
4. The engine oil was checked and the water which functioned as the engine's coolant was turned on.
5. The exhaust fan and power supply to the dynamometer were turned on.
6. A fire extinguisher was placed nearby in case of emergency.
7. A final check was made to insure that all connections were properly made, that the other engine attached to the dynamometer was in neutral, and that no loose rags, etc. were laying on the engine.
8. The motor/generator was turned on.
9. The dynamometer was turned on after the engine speed was set to zero.
10. Slowly, the engine speed was increased and set at 1500 rpm.
11. The fuel flow was increased until the engine's EGO sensor indicated a rich mixture.
12. The system was then allowed to stabilize for several minutes.
13. Data were recorded for a rich engine without air injection.
14. Without changing the engine's air/fuel ratio, the air injection was turned

on.

15. The system was then allowed to stabilize for several minutes.
16. Data were recorded for a rich engine with air injection.
17. The air injection was turned off.
18. The fuel flow was decreased until the engine's EGO sensor indicated a stoichiometric mixture (toggling between rich and lean indication).
19. The system was then allowed to stabilize for several minutes.
20. Data were recorded for a stoichiometric engine without air injection.
21. The system was shut down and all equipment was turned off.

CHAPTER 4

PHASE I: RESULTS AND DISCUSSION OF RESULTS

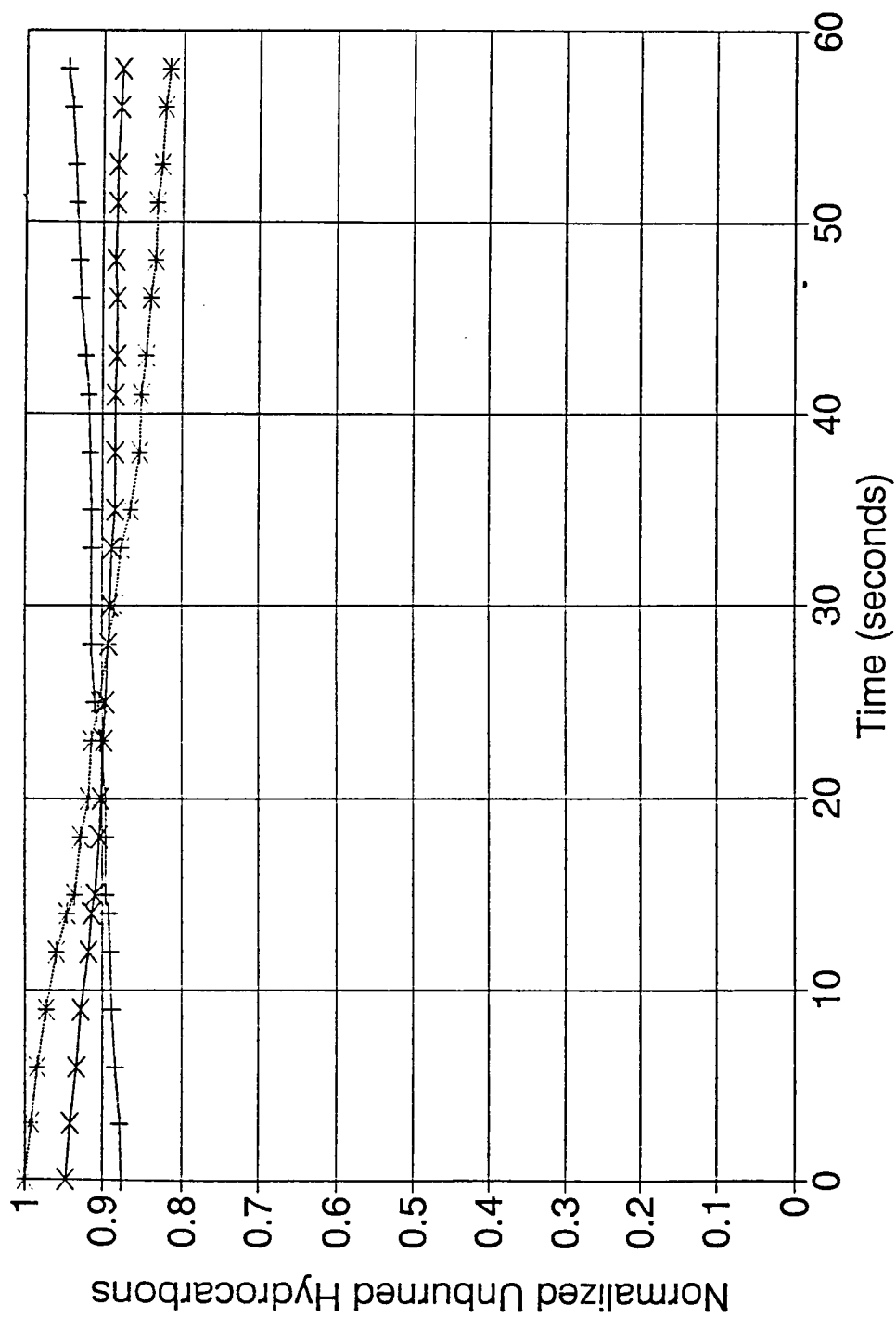
4.1 Results of Phase I Natural Gas Test

Using natural gas as the test fuel, data were obtained which compares "tailpipe" emissions for a rich engine without air injection, a rich engine with air injection, and a stoichiometric engine without air injection. In addition, both catalyst inlet and outlet temperatures and catalyst and engine EGO voltages were recorded for each test case.

Normalized graphs of UHC, CO, and NO_x concentrations versus time for each test case are depicted in Figures 10-12. The data were normalized with respect to the largest measured emission value because confidence was not placed in the accuracy of the emission testing equipment due to its age and the age of the calibration gases. However, confidence was placed in the equipment's precision. Therefore, the normalized data can be used as a comparison between the three test cases.

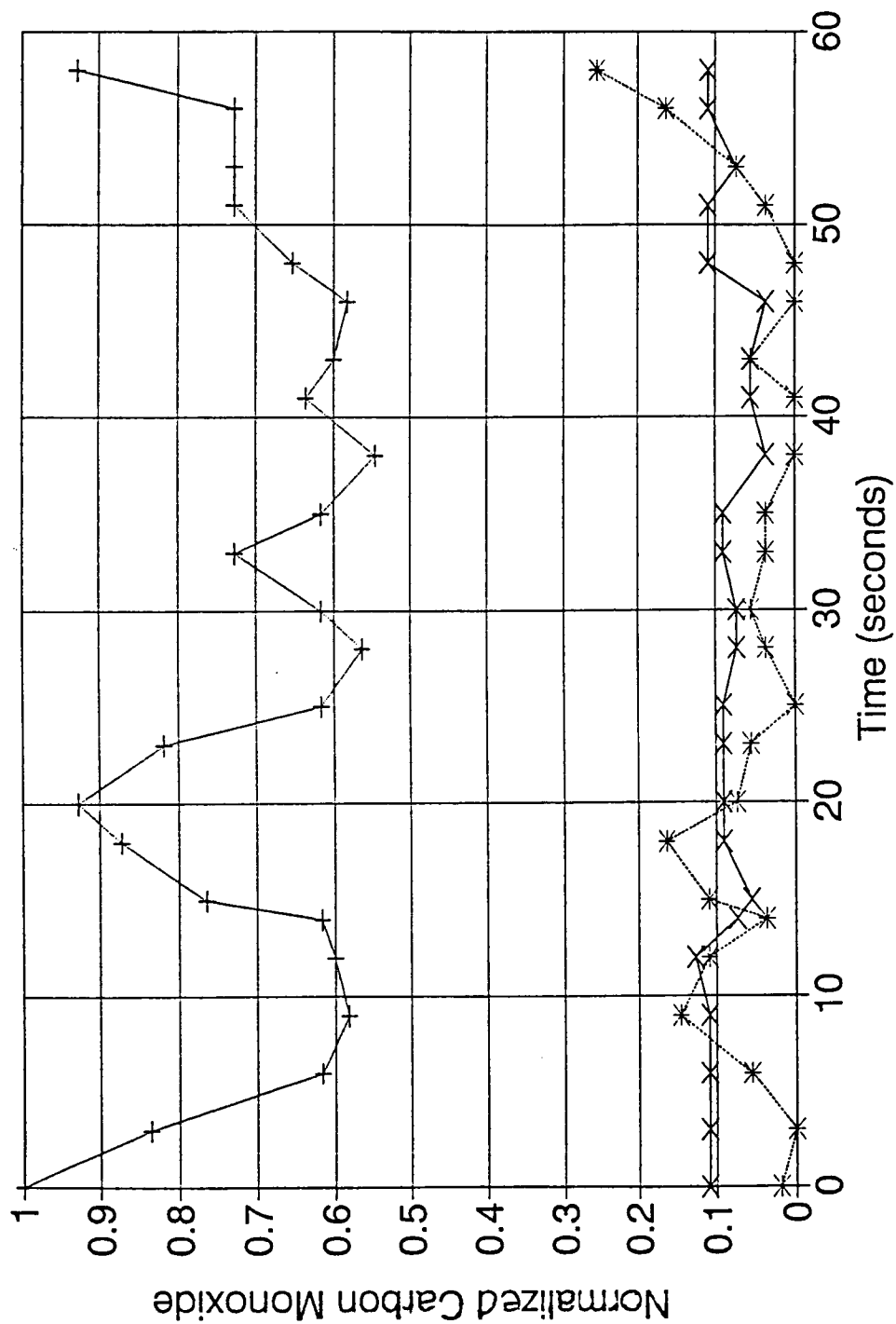
The catalyst inlet and outlet temperatures for each test case are shown in Figure 13. The purpose of this data is to insure that the catalyst inlet temperatures were approximately equal for each case, and to observe the effect the air injection had on catalyst outlet temperatures.

A graph of the engine and catalyst EGO voltages for the natural gas tests is located in Figure 14. This graph can be used to verify the air/fuel ratio of the engine for each test case. Additionally, it is an indication of the CCAP's ability to maintain



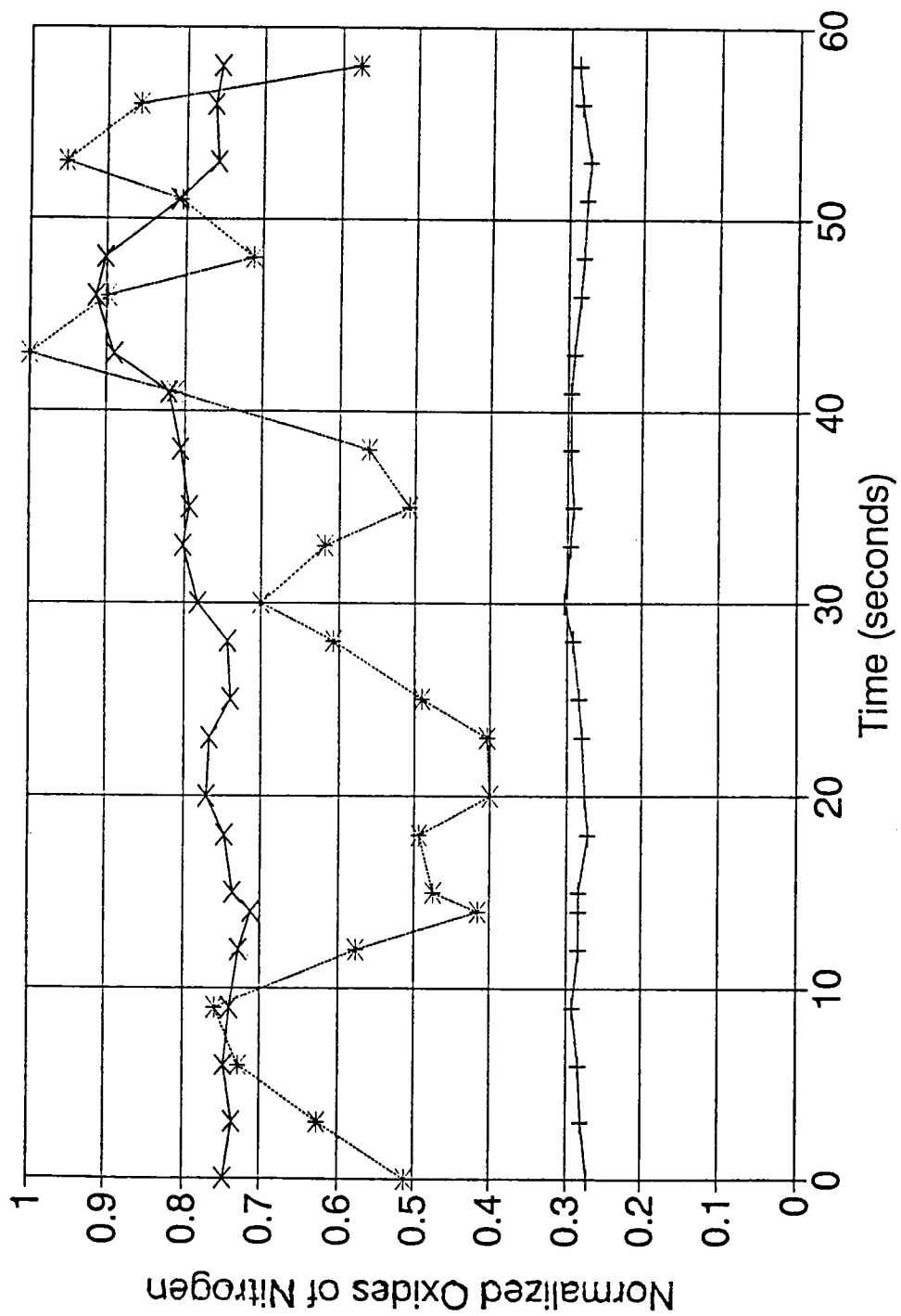
—x— Air On: Rich —+— Air Off: Rich —*— Air Off: Stoich

Figure 10 Normalized HC Data for Natural Gas Engine (Phase I)



—+— Air On: Rich —+— Air Off: Rich —*— Air Off: Stoich —*— Air On: Stoich

Figure 11 Normalized CO Data for Natural Gas Engine (Phase I)



x Air On: Rich + Air Off: Rich * Air Off: Stoich

Figure 12 Normalized NO_x Data for Natural Gas Engine (Phase I)

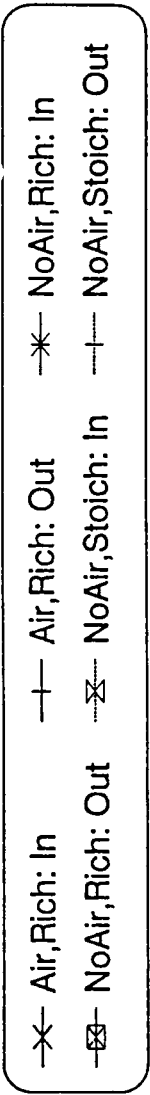
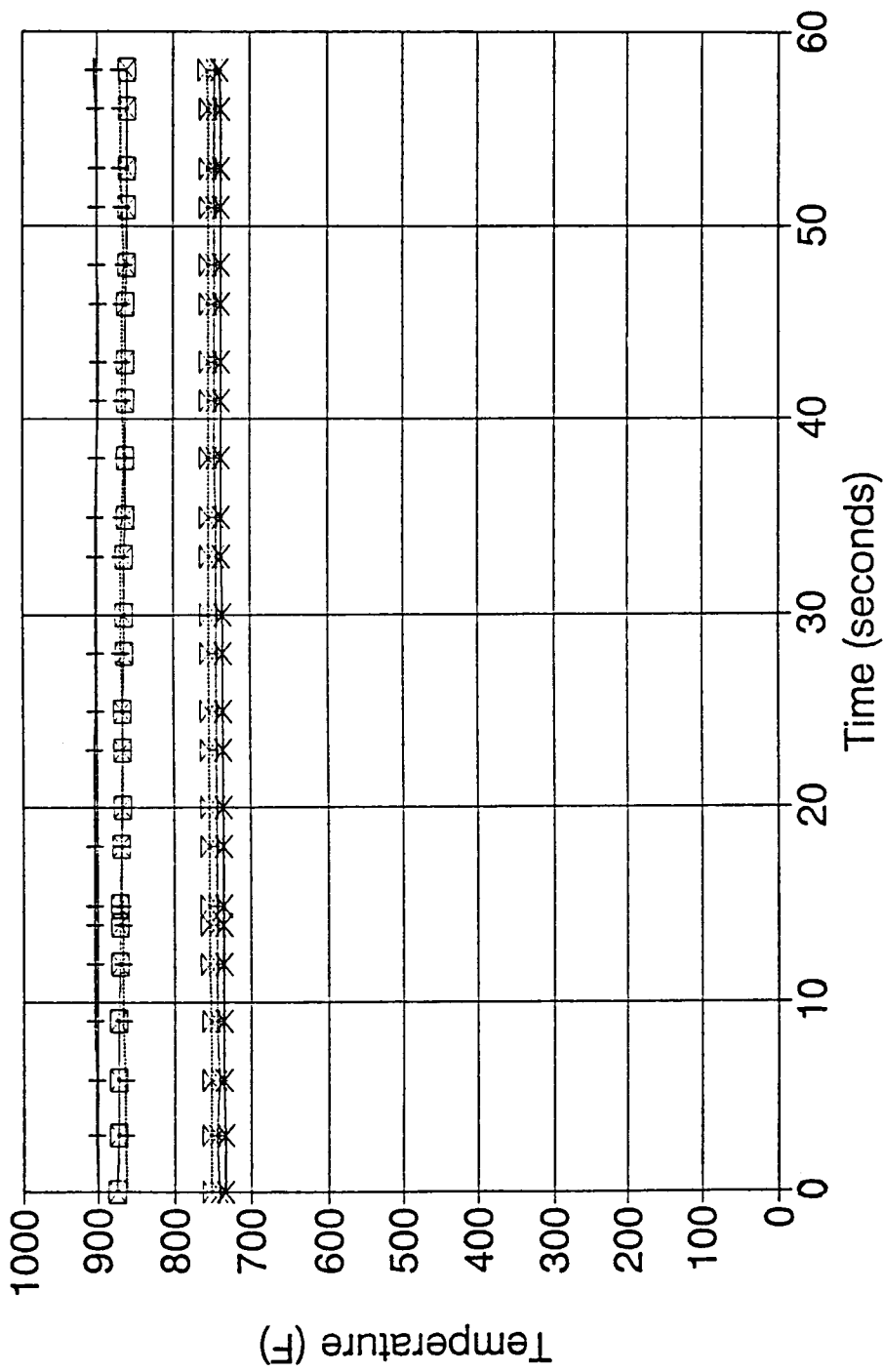


Figure 13 Catalyst Inlet and Outlet Temperatures for Natural Gas Engine (Phase I)

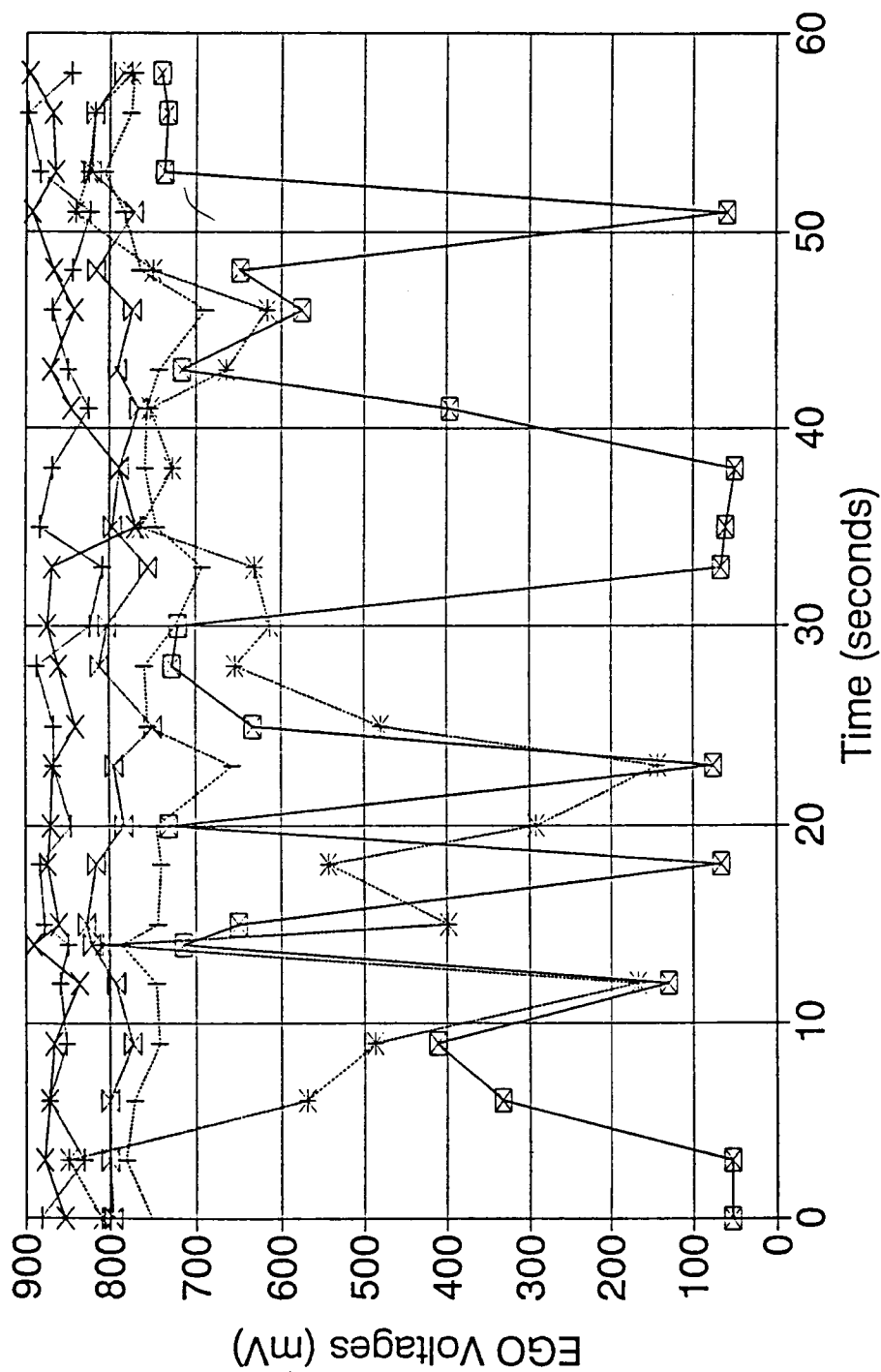


Figure 14 Engine and Catalyst EGO Voltages for Natural Gas Engine (Phase I)

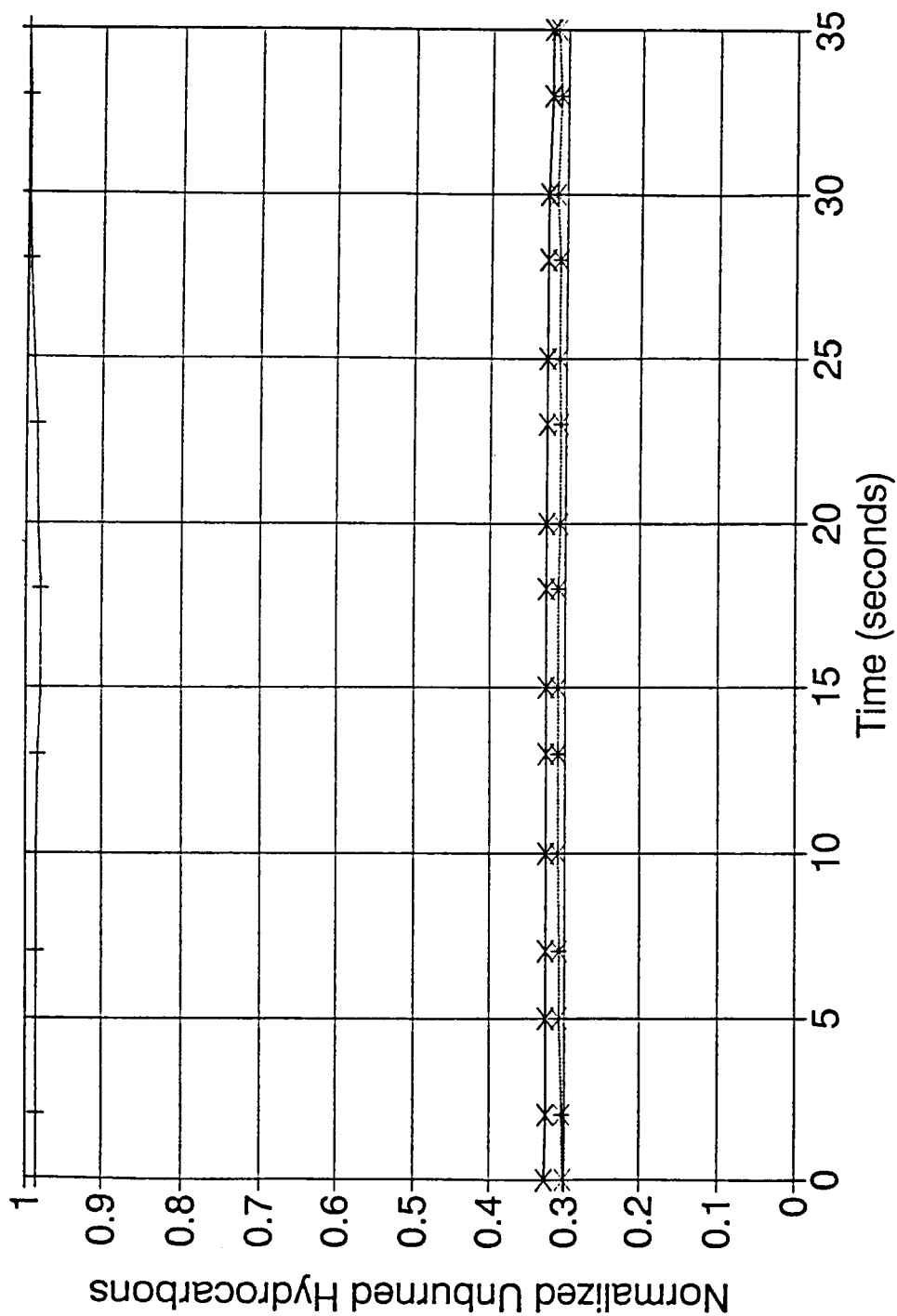
the catalyst's air/fuel ratio at stoichiometry.

4.2 Results of Phase I Propane Test

As detailed in section 3.2, Phase I tests were also performed using propane as the fuel. As with the natural gas tests, data were obtained which compares "tailpipe" emissions for a rich engine without air injection, a rich engine with air injection, and a stoichiometric engine without air injection. Figures 15-17 contain graphs of this information. Additionally, both catalyst inlet and outlet temperatures and engine and catalyst EGO voltages were measured for the propane tests. These are shown in Figures 18 and 19.

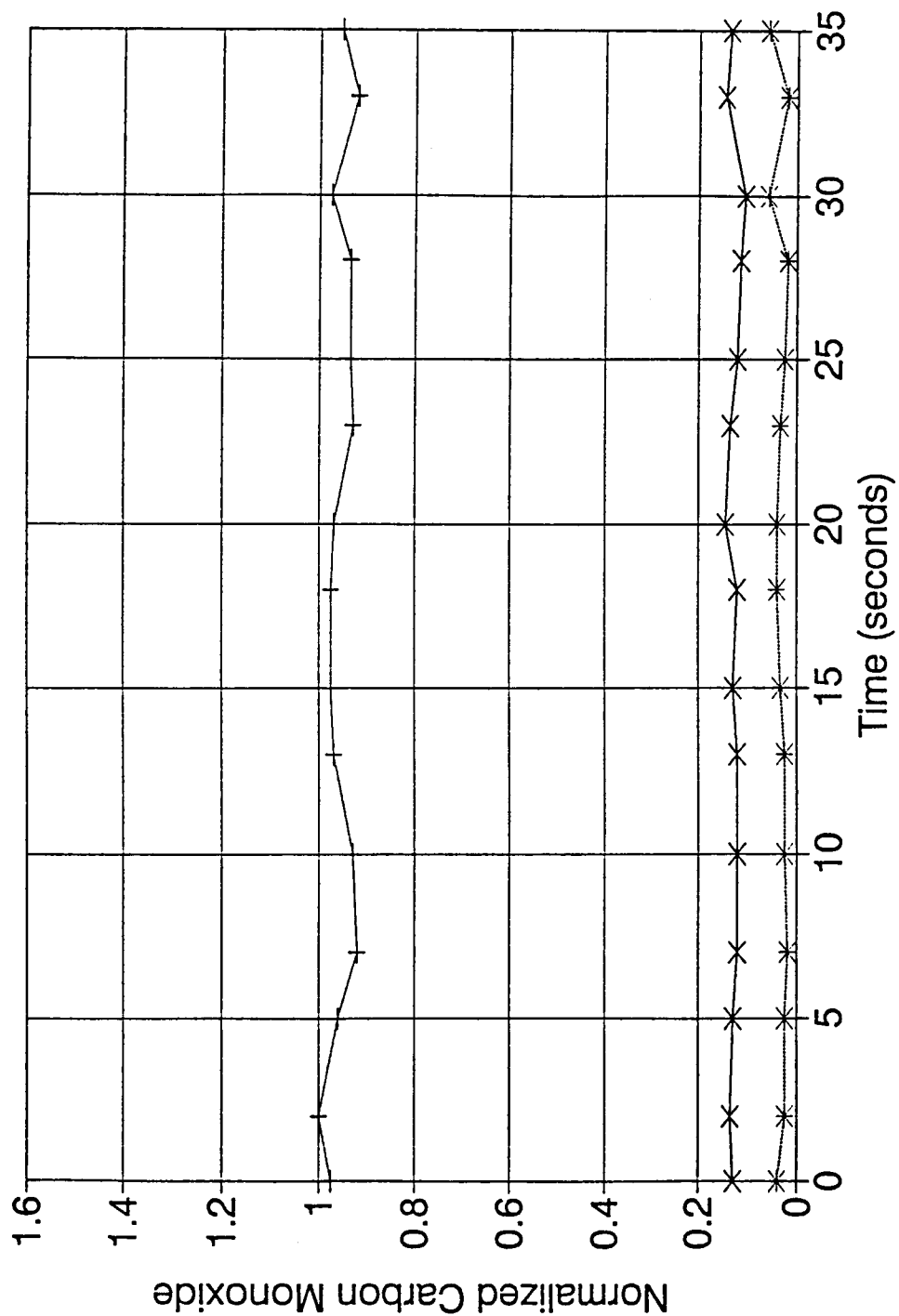
4.3 Discussion of Phase I Results

An examination of the graphs obtained in Phase I allows several conclusions to be made. The first and foremost of these is that the concept of the CCAP has merit. In both of the tests (natural gas and propane), CO values with the air injection and a rich engine were as low as the CO values obtained with a stoichiometric engine. This is an 80-90% decrease in CO levels when compared to the rich engine that ran without air injection. Similar results were seen for UHC emissions, but only in the case of propane. UHC values with the air injection and a rich engine were as low as the UHC values obtained with a stoichiometric engine. This is a 70% decrease in UHC levels when compared to the rich engine that ran without air injection. These dramatic decreases in CO and UHC for the steady-state engine tests indicate that the CCAP



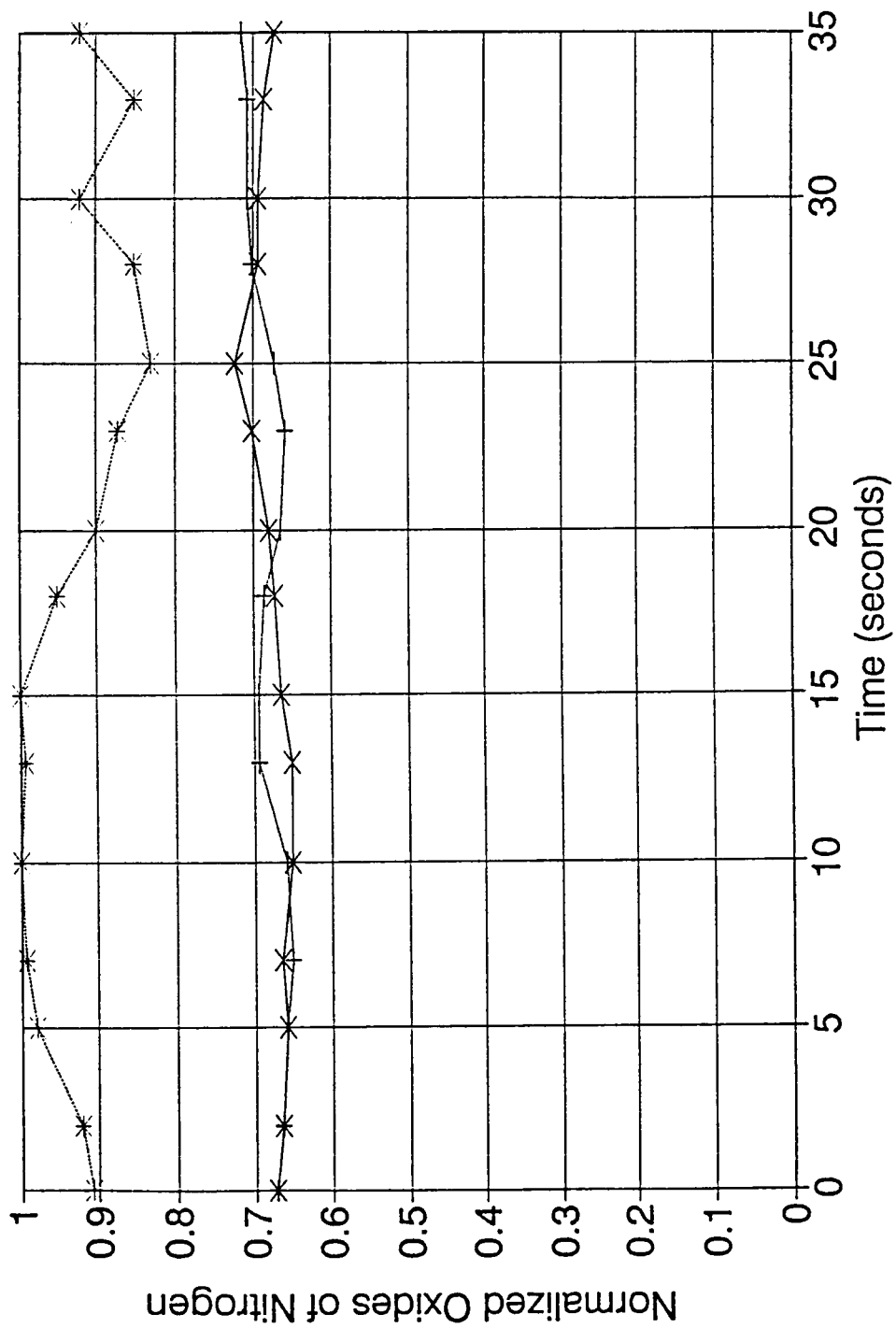
x Air On: Rich + Air Off: Rich * Air Off: Stoich

Figure 15 Normalized HC Data for Propane Engine (Phase I)



x— Air On: Rich +— Air Off: Rich *— Air Off: Stoich

Figure 16 Normalized CO Data for Propane Engine (Phase I)



—+— Air On: Rich - - - * - - - Air Off: Rich . . . * . . . Air Off: Stoich

Figure 17 Normalized NO_x Data for Propane Engine (Phase I)

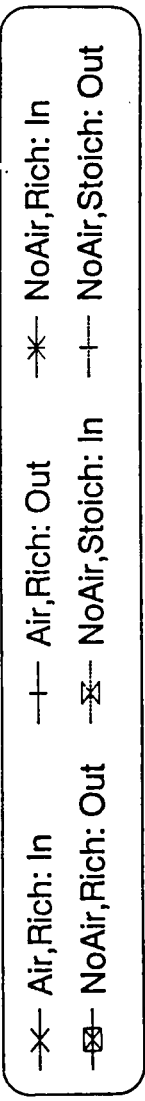
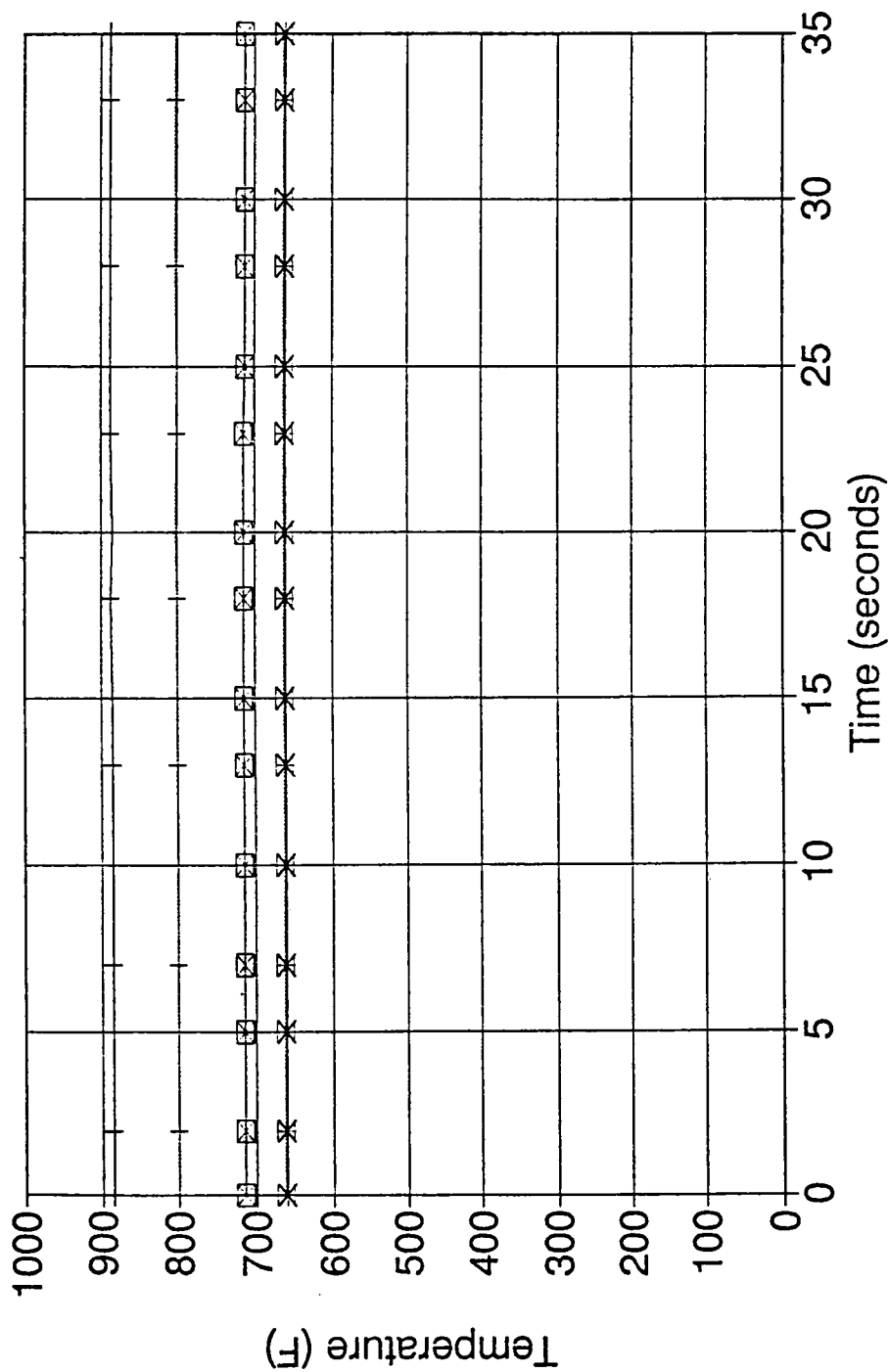


Figure 18 Catalyst Inlet and Outlet Temperatures for Propane Engine (Phase I)

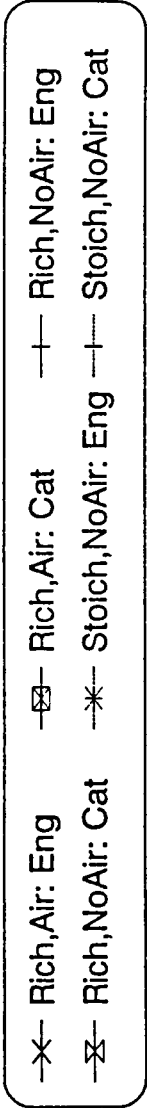
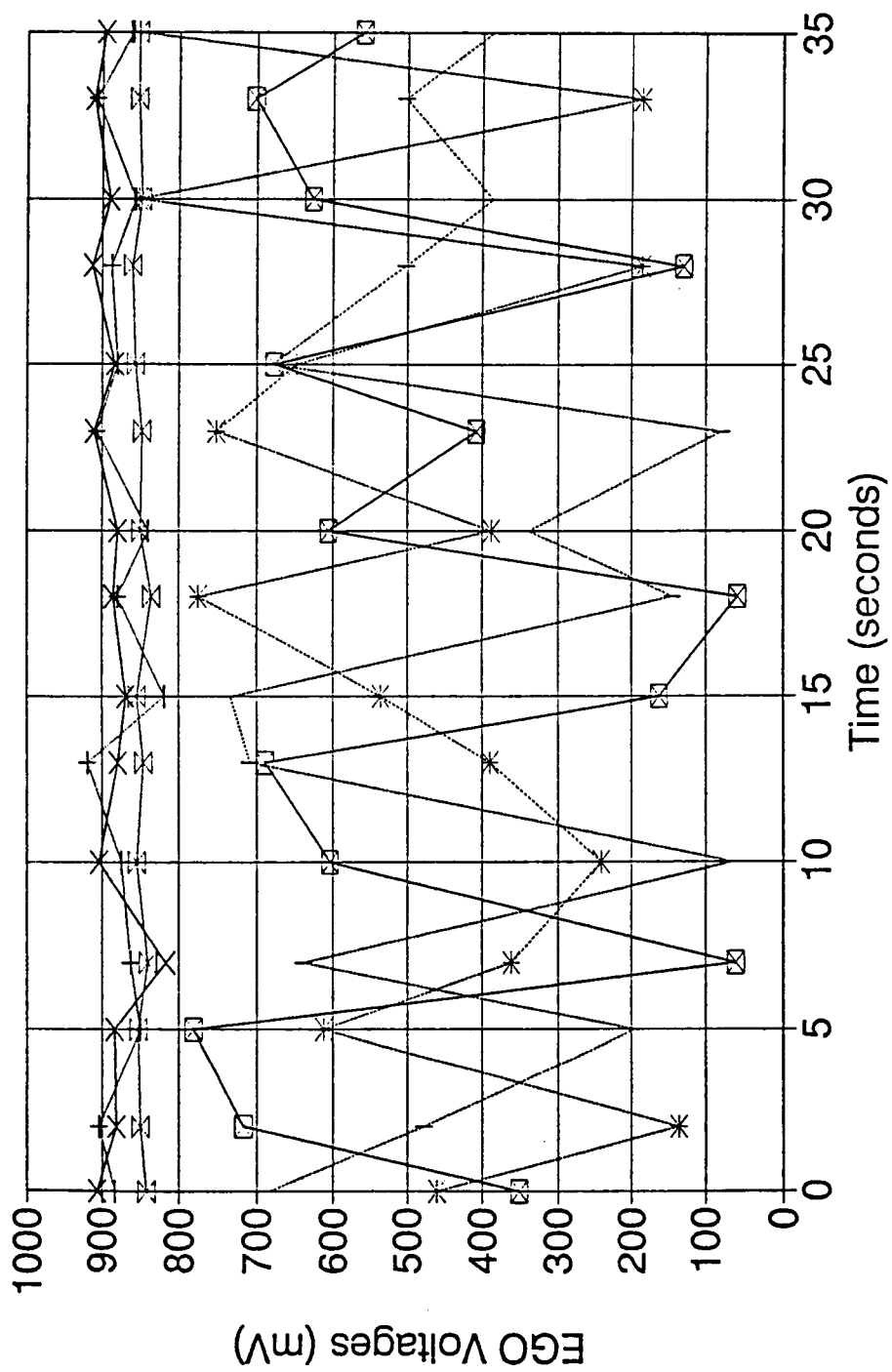


Figure 19 Engine and Catalyst EGO Voltages for Propane Engine (Phase I)

could be an effective control of CO and UHC on automobile.

As was mentioned previously, one of the purposes of Phase I was to aid in determining a suitable test vehicle for Phase II. The UHC data for the natural gas test indicates that the CCAP had no significant effect on UHC. This is believed to have occurred because of the "non-reactive" nature of methane, which is the primary constituent (90%) of the UHC from natural gas fueled engines. Therefore, in order to properly demonstrate the usefulness of the CCAP, a vehicle which runs on a "reactive" hydrocarbon such as gasoline was chosen for use in Phase II of testing.

An examination of the NO_x data from each test indicates that NO_x levels from the rich engine with air injection did not increase above the NO_x levels of the stoichiometric engine. In fact, during the propane test, NO_x levels for the rich engine with air injection remained as low as a rich engine without air injection. This indicates that the CCAP does not have a detrimental effect on NO_x emissions during steady-state engine operation.

Finally, catalyst temperatures were only slightly higher (150 °F) when the rich engine was injected with air. However, the tests were run with the engine under light load. This small temperature rise may increase with an increase in engine speed and load. Therefore, little comfort should be taken from the low catalyst temperatures that were seen during Phase I testing. The effect of the CCAP on catalyst temperature was a question to be resolved in Phase II of the test.

CHAPTER 5

PHASE II: PURPOSE AND DESIGN

5.1 Purpose of Phase II

Phase II of the project focused on investigating the effectiveness of the computer controlled air pump on an automobile. It involved the installation and evaluation of the prototype closed-loop air injection system from Phase I on a 1987 Buick Regal. This allowed the real-time emissions produced by the test vehicle during the FTP to be measured both with and without the CCAP for comparison.

5.2 Phase II Test Vehicle

As stated above, the vehicle chosen for Phase II was a 1987 Buick Regal with a turbocharged 3.8 liter port fuel injected V-6 engine. It is presently one of ten being operated as part of the Federal Methanol Fleet at Oak Ridge National Laboratory (ORNL). The Buick Regal was chosen because it runs on gasoline (a requirement determined from Phase I of testing) and its engine represents "state of the art" technology in that it features sequential port fuel injection with a three-way catalyst and oxygen sensor feedback. Additionally, it is being subjected to periodic emissions testing as part of its role in the fleet.

5.3 Phase II Prototype CCAP

The prototype system designed for Phase II was the same as the CCAP tested in Phase I, with the exception of the air pump, solenoid and diverter valves, and the addition of an electric vacuum pump.

As stated in Section 2.2, the electric air pump used in Phase I was not able to provide an adequate flow of air for use on a vehicle. Therefore, a positive displacement, belt-driven air pump (GM part # 010090521) was used instead. Because of space limitations under the hood of the test vehicle, this air pump was mounted in place of the vehicle's alternator and a battery charger was connected to the battery during testing. This was only possible because the FTP simulates vehicle performance on a chassis dynamometer and the prototype system did not need to be driven on the road. For production use, the air pump location would be considered in the design of the vehicle.

For convenience, the diverter valve and solenoid valve used in Phase I were replaced with a single unit (GM part # 17064177) which performed the same function as the two valves combined. Figure 20 shows this diverter/solenoid valve mounted on the outlet of the belt-driven air pump. The air flows through a hose and is injected into the exhaust (after flowing through a check valve) at the exit of the turbocharger as shown in Figure 21.

The only other change in the prototype CCAP was the addition of an electric vacuum pump. After the first test of the Phase II CCAP, it was observed that at high accelerations, there may not be enough vacuum available to actuate the diverter valve

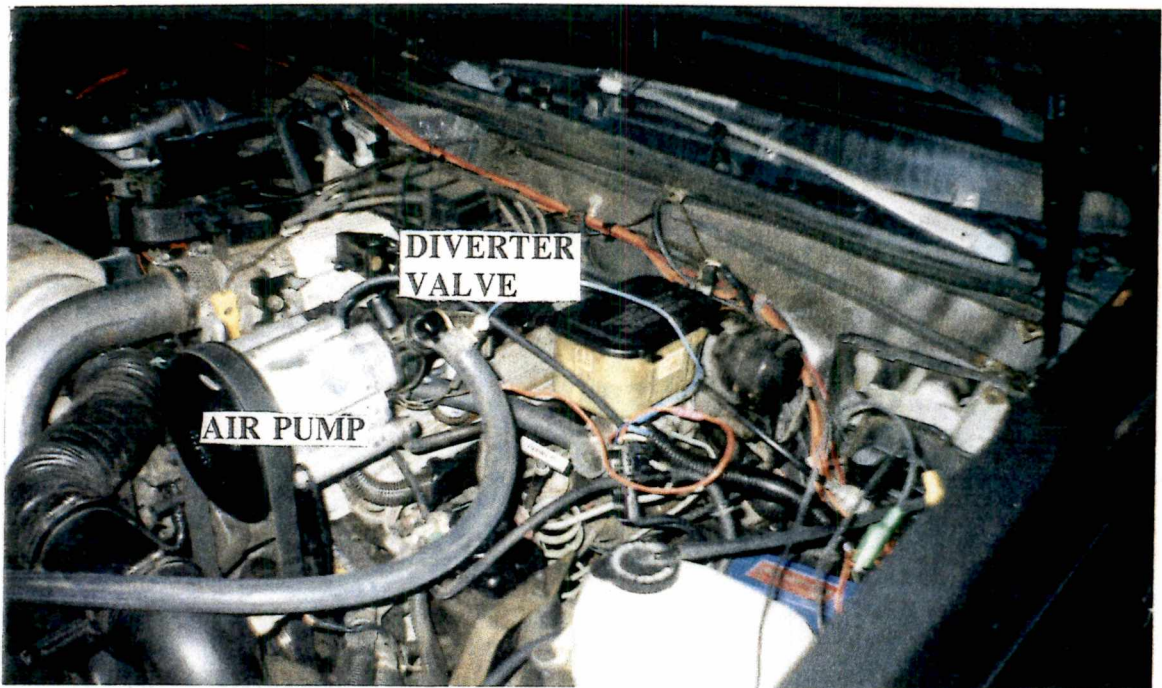


Figure 20 CCAP Mounted on Test Vehicle (Phase II)

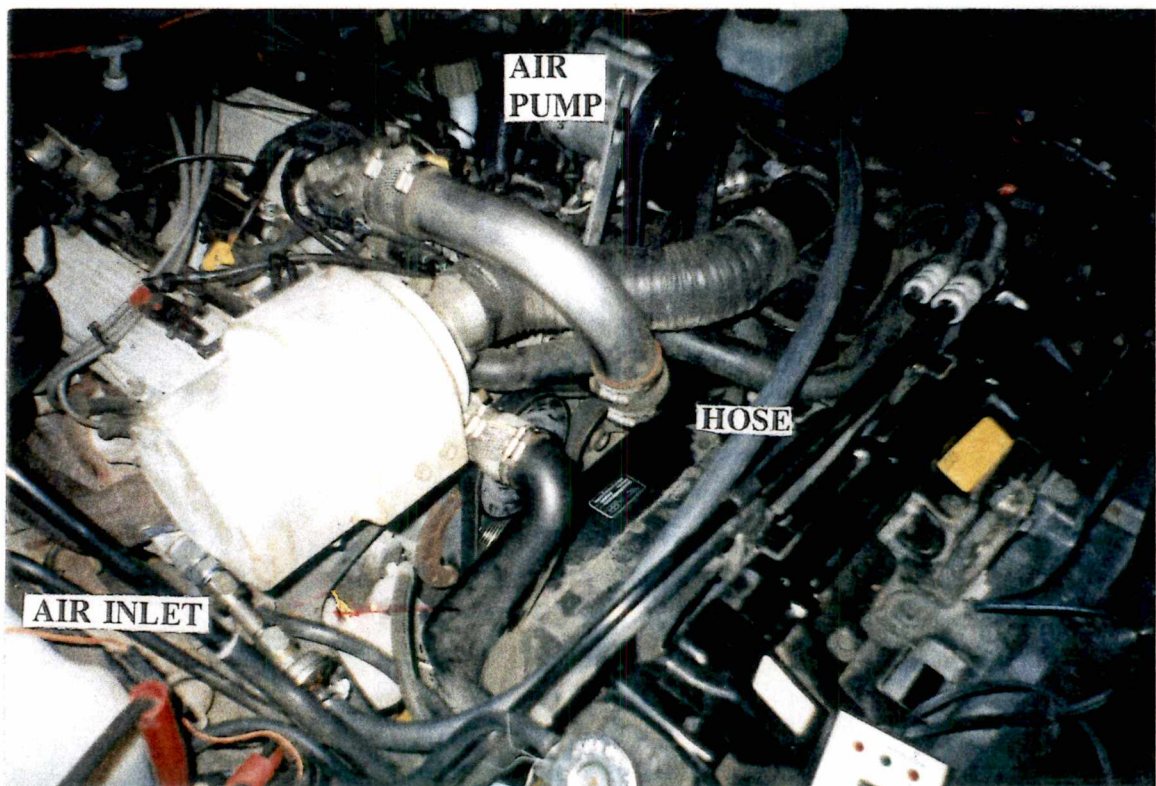


Figure 21 Air Injection Inlet on Test Vehicle for Phase II

(recall that the test vehicle is equipped with a turbocharger). Therefore, an electric vacuum pump (GM part # 1982011) was used to insure that enough vacuum was available for the diverter valve under all conditions.

5.4 Phase II Test Equipment

Phase II tests involved the real-time and total-bag sampling of tailpipe emissions during the Urban Dynamometer Driving Cycle (UDDC) of the FTP (See Chapter 1). These tests were performed at the EPA Environmental Research Center Annex, Research Triangle Park, North Carolina. This facility is equipped with a Horiba constant volume sampler (CVS) system which, through the use of critical flow venturis (CFV), dilutes the vehicle's exhaust with filtered air so that the total combined flow rate of exhaust and dilution air mix is constant for all engine operating conditions. This allows vehicle emissions to be determined on a mass basis. Additionally, the chassis dynamometer used for vehicle road simulation is enclosed within a temperature controlled test chamber (TCTC). The TCTC enables ambient temperatures to be varied from 20°F to 105°F (13). A schematic of the testing facility is shown in Figure 1.

"Exhaust gases from the test vehicle were directed via a 7.6cm diameter, flexible stainless steel line to a 20.3cm diameter dilution tunnel. This line was enclosed within a heat jacket, which was thermostated to prevent temperatures inside from falling below 235°F" (13). Within the dilution tunnel, raw exhaust gas was thoroughly mixed with filtered room air, and the diluted mixture was drawn through

the system at about 650 scfm. Gas samples of diluted exhaust were sampled from the tunnel (13).

In order to determine real-time emissions, THC were measured with a heated Horiba FID (FIA-34A-2), NO_x were measured with a Horiba chemiluminescent analyzer (CLA-53MA), and CO was measured with a Horiba IR analyzer (AIA-23). Data was sampled from the CVS system every second with the data acquisition program "Data Translation Notebook". For comparison, emissions were also measured every three seconds with two different Fourier transform infrared spectrometers (FTIR): the real-time exhaust gas analyzer (REGA) 7000 and the Matson Instruments real-time emissions analyzer (REA).

The total-bag sampling was accomplished with a Horiba bag sampler. For comparison, total-bag emissions were also determined by integrating the three sets of real-time emissions data. Finally, a gas chromatograph was used to determine the speciated hydrocarbons in each bag.

In addition to exhaust gas emission measurements, temperature measurements of the exhaust gas were taken both upstream and downstream from the catalyst. Two type J (copper-constantine) thermocouples were used for this purpose. One thermocouple was mounted at the catalyst inlet, one thermocouple was mounted at the catalyst exit. The thermocouples provided a voltage output to a Campbell Scientific 21X Micrologger. The program used for sampling the exhaust gas temperatures is located in Appendix C.

CHAPTER 6

PHASE II: PROCEDURE

6.1 Phase II Test Procedure

All emission tests conducted on the Buick Regal in Phase II of testing were administered by trained personnel at the Environmental Protection Agency's Environmental Research Center Annex in Research Triangle Park, North Carolina. The UDDC of the FTP was performed for each test in accordance with the procedure outlined in the Federal Register (6). A brief description of this test is also described in Section 1.2 of this thesis.

6.2 Tests Performed in Phase II

A total of four tests were conducted of the CCAP installed on the Buick Regal in Phase II of testing. For each test, an FTP was performed on the vehicle both with and without the CCAP.

For the first pair of FTP tests, the Control vehicle was soaked overnight at room temperature, tested in the morning, force cooled, and retested in the afternoon with the CCAP installed. The CCAP was active at the beginning of the driving cycle.

After this first test was completed, questions arose as to whether enough vacuum was available to actuate the diverter valve when the vehicle was under power (the test vehicle is equipped with a turbocharger). Therefore, a second test was

deemed necessary in order to determine if an auxiliary vacuum pump would improve the CCAP's performance. For this test, the CCAP vehicle was soaked overnight at room temperature, tested in the morning, force cooled, and retested without the CCAP installed.

The second test indicated that the CCAP could cause poor emissions during the cold transient phase of the FTP. Therefore, a third test was performed in which the CCAP was inoperable for the first 110 seconds in order to prevent it from cooling the catalyst and thus delaying catalyst light-off. Because the engine was running poorly during the third test (with the CCAP installed); and also because it was thought that force-cooling the vehicle might have an effect on emission results, a fourth and final test was performed.

For the fourth test, the CCAP vehicle was soaked overnight at room temperature and was tested in the morning. To observe the effect of force-cooling on vehicle emissions, the CCAP vehicle was then force-cooled and retested in the afternoon. It was then allowed to soak at room temperature until the following morning when the control FTP was run. Again, the vehicle was force-cooled and a second control test was run in the afternoon. The CCAP was inactive for the first 110 seconds of the test, an auxiliary vacuum pump was used, and endoline was used as the fuel.

A summary of the tests run in Phase II is shown in Table II.

Table II Summary of FTP Emission Tests Performed in Phase II

Test #	Vacuum Pump Used?	Time CCAP Turned on	Forced Cooled?	Vehicle Problems?
1 - Control			No	No
1 - CCAP	NO	0 seconds	Yes	No
2 - Control			No	No
2 - CCAP	Yes	0 seconds	Yes	No
3 - Control			No	No
3 - CCAP	Yes	110 seconds	Yes	Yes
4 - Control			No	No
4a - Control			Yes	No
4 - CCAP	Yes	110 seconds	No	No
4a - CCAP	Yes	110 seconds	Yes	No

CHAPTER 7

PHASE II: RESULTS AND DISCUSSION OF RESULTS

7.1 Data Obtained in Phase II of Testing

The data obtained in Phase II of testing consists of the total bag emissions and the real-time emissions and temperatures for all four sets of tests. The total bag emissions data is located in Appendix D and the real-time emissions and temperature data is located in Appendix E.

Appendix E contains the real-time emissions and temperatures for the fourth test only. This is because the fourth test was the only test in which the CCAP was optimally installed on a properly operating test vehicle. When viewing the real-time data in Appendix E, it is important to remember that the CCAP was not engaged for the first 110 seconds of the test, and that there was no physical difference between the test and control vehicles for these first 110 seconds. It is also important to note that CCAP emissions peaks which are larger than control peaks do not necessarily indicated poor CCAP performance, as the driver cannot drive the schedule exactly the same for each test. Therefore, the real-time data should only be viewed to determine whether or not most of the CCAP emissions are less than the control emissions.

7.2 Effect of CCAP on Catalyst Light-off Time

As mentioned in Chapter six, the second pair of FTP tests indicated that the

CCAP has a negative impact on catalyst light-off time, when it is activated at the start of the test. It is believed that the room-temperature air that is injected when the engine is running rich, cools the exhaust and delays the catalyst light-off. Figure 22 shows the pre-catalyst and post-catalyst exhaust temperatures which were recorded during the cold transient phase of the second FTP tests. This data confirms that the CCAP's pre-catalyst exhaust temperatures were 25°F to 75°F cooler than the Control's pre-catalyst exhaust temperatures. Additionally, the data in Figure 22 shows that the post-catalyst temperatures of the CCAP were as much as 200°F cooler than the post-catalyst temperatures of the control vehicle. This caused the catalyst of vehicle with the CCAP to light-off approximately 75 seconds after the control vehicle's catalyst light-off.

The UHC and CO data obtained in the second FTP tests indicates that the delay in catalyst light-off time had a negative impact on CO and UHC emissions during the cold transient phase of the test. CO values for bag 1 increased from 16.72 g/mile (control) to 16.89 g/mile (CCAP), and UHC values for bag 1 increased from 1.57 g/mile (control) to 1.73 g/mile (CCAP). In order to prevent the CCAP from having this negative impact on CO and UHC emissions, the CCAP was disengaged for the first 110 seconds of FTP tests three and four.

7.3 Effect of CCAP on UHC and CO Emissions

In the fourth set of tests (the only set in which the CCAP was optimally installed on a properly operating vehicle) the real-time data indicates that the CCAP

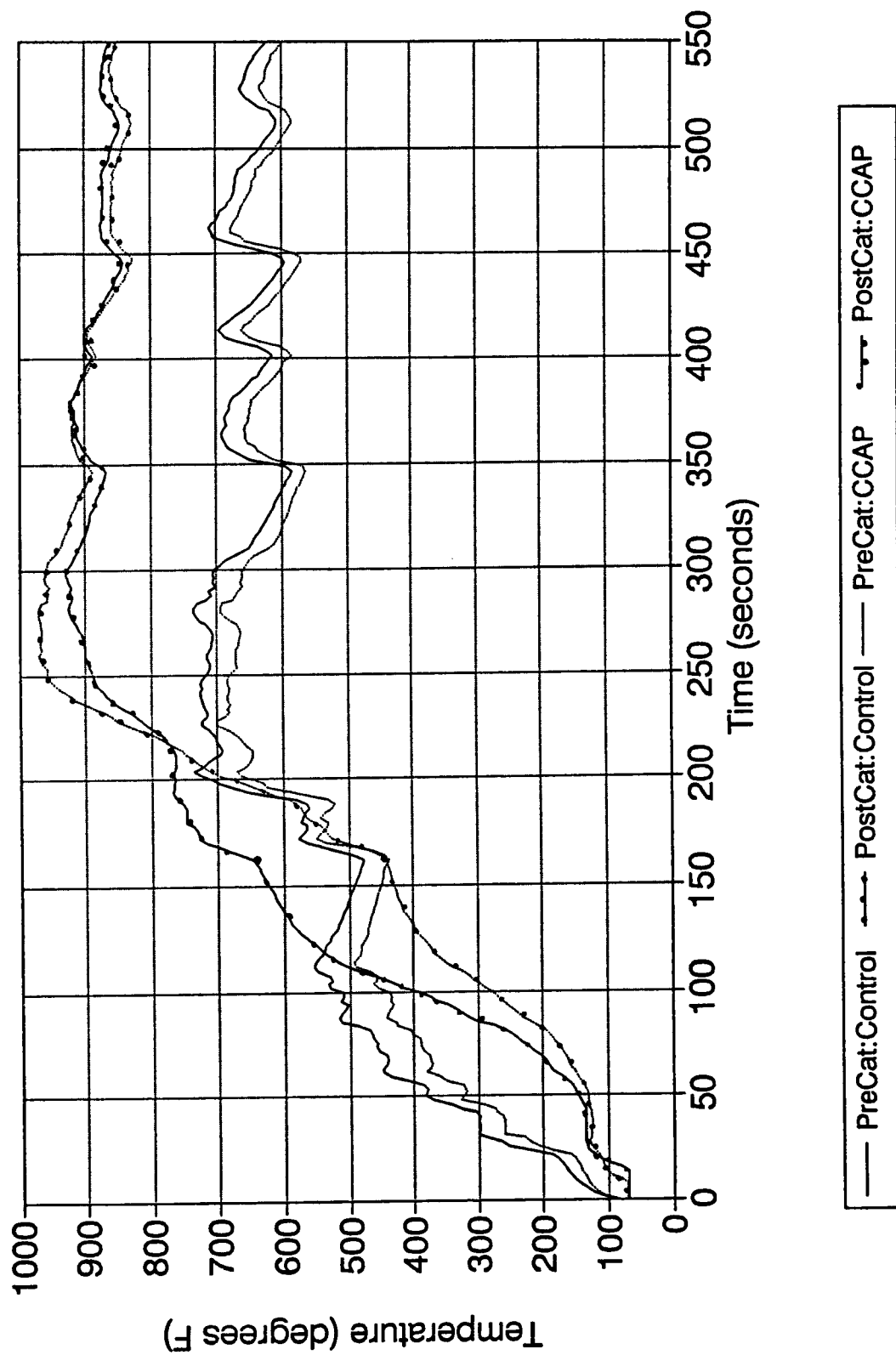


Figure 22 Test 2 Pre-Catalyst and Post-Catalyst Temperatures

was able to improve the UHC and CO emissions of the control vehicle. However, these improvements are not made as obvious by the total bag emissions. This can be explained by examining the real-time UHC and CO emissions which are shown in Figures 23 and 24, respectively. The vehicle with the CCAP had significantly worse emissions during the first 110 seconds of the test. However, this can not be attributed to the CCAP, because it was inoperable during the first 110 seconds of the test. The test vehicle was simply running worse during the CCAP test than it was during the control test. Figures 23 and 24 also show that at 110 seconds, the UHC and CO emissions from the vehicle with the CCAP suddenly improved and became much less than the emissions from the control vehicle. The fact that both the UHC and CO emissions from the CCAP vehicle improved at the instant that the CCAP was activated confirms the success of the system. This point is made even stronger when one considers that for some reason, the CCAP vehicle was operating with worse emissions from the start of the test. The CCAP was not only able to compensate for this, but also improve the emissions over those of the control vehicle.

The CCAP continued to improve emissions into the cold stabilized phase of the FTP. Figure 25 shows the real-time UHC emissions for the cold stabilized phase of the test. It is easy to see that the CCAP was able to decrease the magnitude of emission peaks during accelerations. However, there is one rather large, unexplained UHC peak that occurred during the CCAP test which did not occur during the control test. Therefore, the UHC bag emissions for the cold stabilized phase of test four were the same for the CCAP and control vehicle. The CO bag emissions for the cold

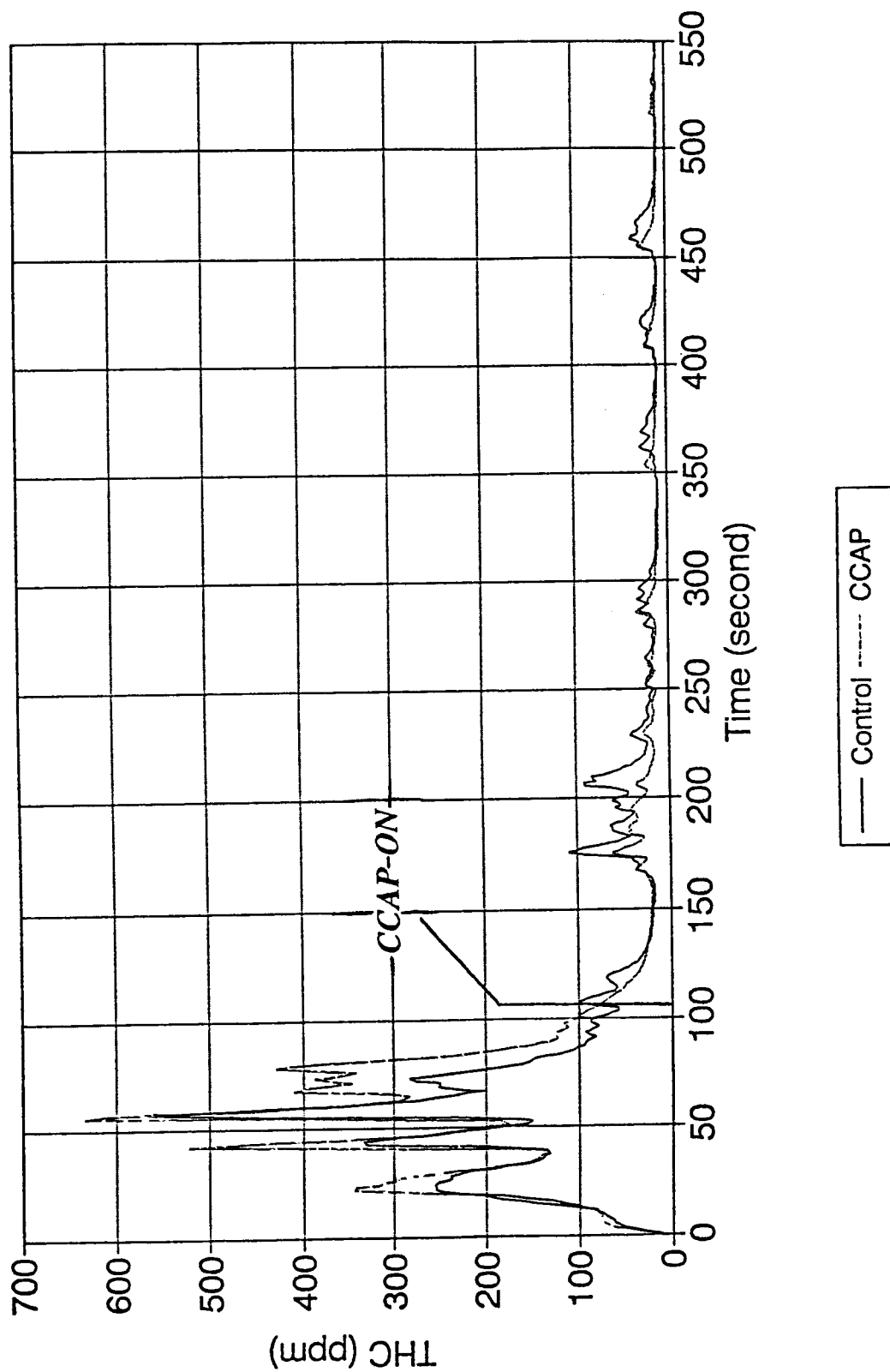


Figure 23 Test 4 UHC Emissions During the Cold Transient Phase

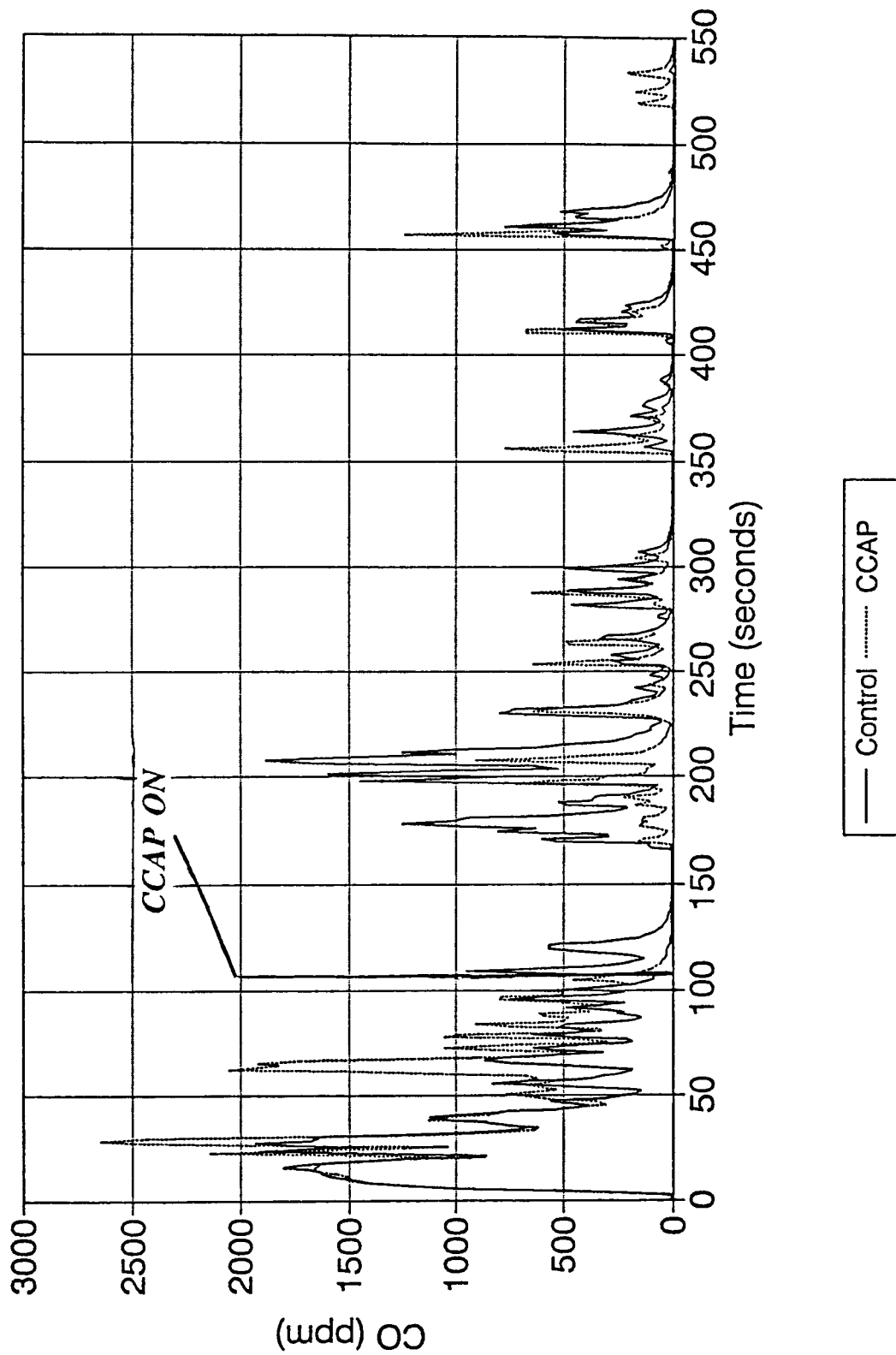


Figure 24 Test 4 CO Emissions During the Cold Transient Phase

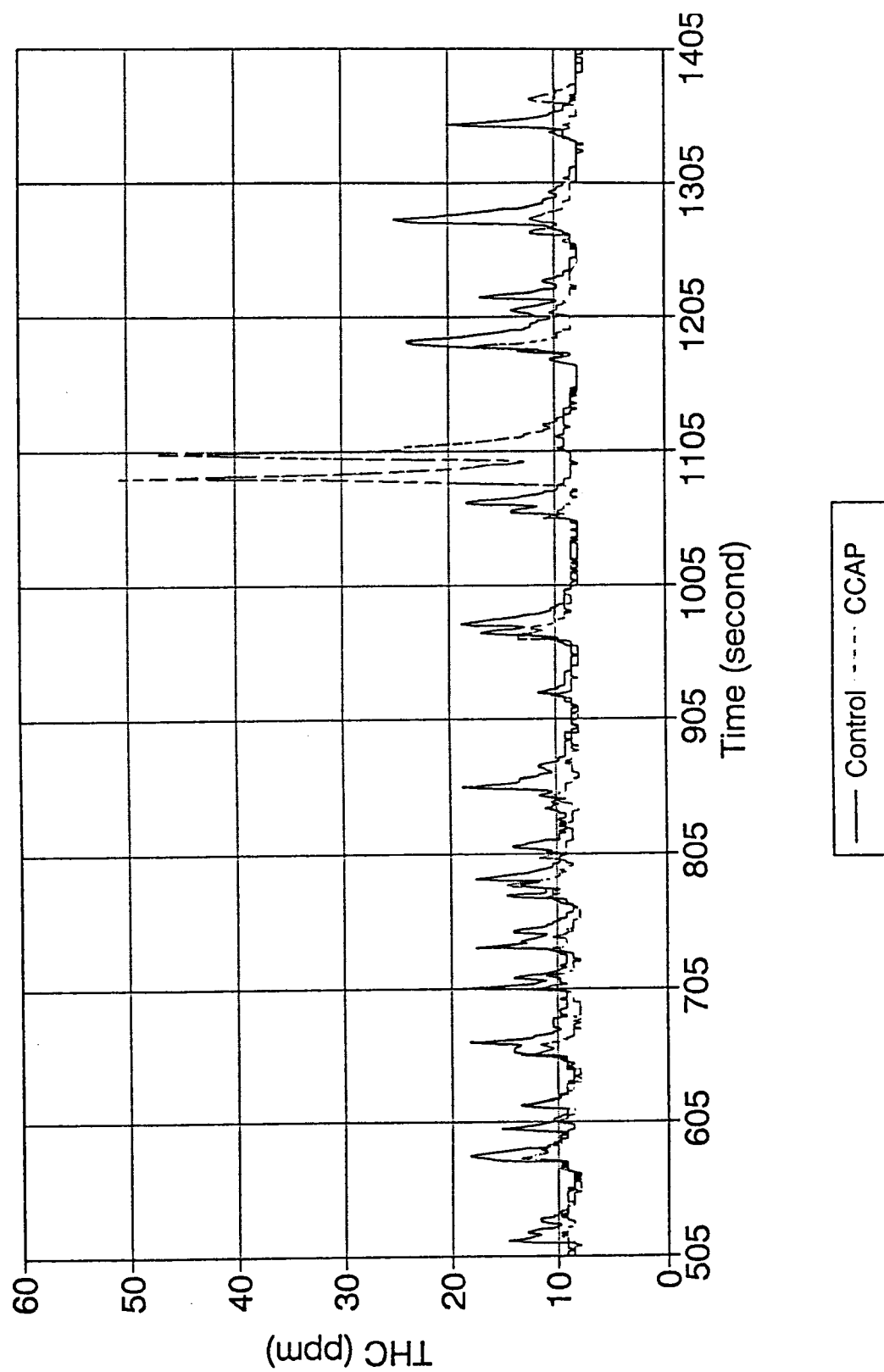


Figure 25 Test 4 UHC Emissions During the Cold Stabilized Phase

stabilized phase did indicate a slight improvement (from 2.59 g/mile to 2.33 g/mile). But this is not a significant change. It is believed that the large CCAP emission peak could have been caused by the vehicle itself, but this can not be verified in any manner (except that based on the first 110 seconds, the CCAP vehicle had been running worse than the control from the beginning of the test).

During the hot transient phase of the FTP, the advantage of using a CCAP system was made most obvious. Figure 26 shows the real-time UHC emissions obtained during this phase. Here, the real-time CCAP UHC emissions remained lower than the control UHC emissions for all conditions. The bag data for the hot transient phase indicates a 45% improvement in UHC emissions (from 0.2 g/mile to 0.11 g/mile) and a 27% improvement in CO emissions (from 3.54 g/mile to 2.57 g/mile).

7.3 Effect of CCAP on NO_x Emissions

The weighted bag data for the fourth set of FTPs indicates that there was very little difference (5%) in NO_x emissions between the CCAP vehicle and the control vehicle (0.6235 g/miles and 0.6601 g/miles, respectively). The percent differences of NO_x emissions for each individual phase ranged from a 15% improvement (during the cold transient phase) to a 12% increase in NO_x emissions (during the hot transient phase). This indicates that a significant improvement can be obtained in CO and UHC emissions without a correspondingly large increase in NO_x emissions.

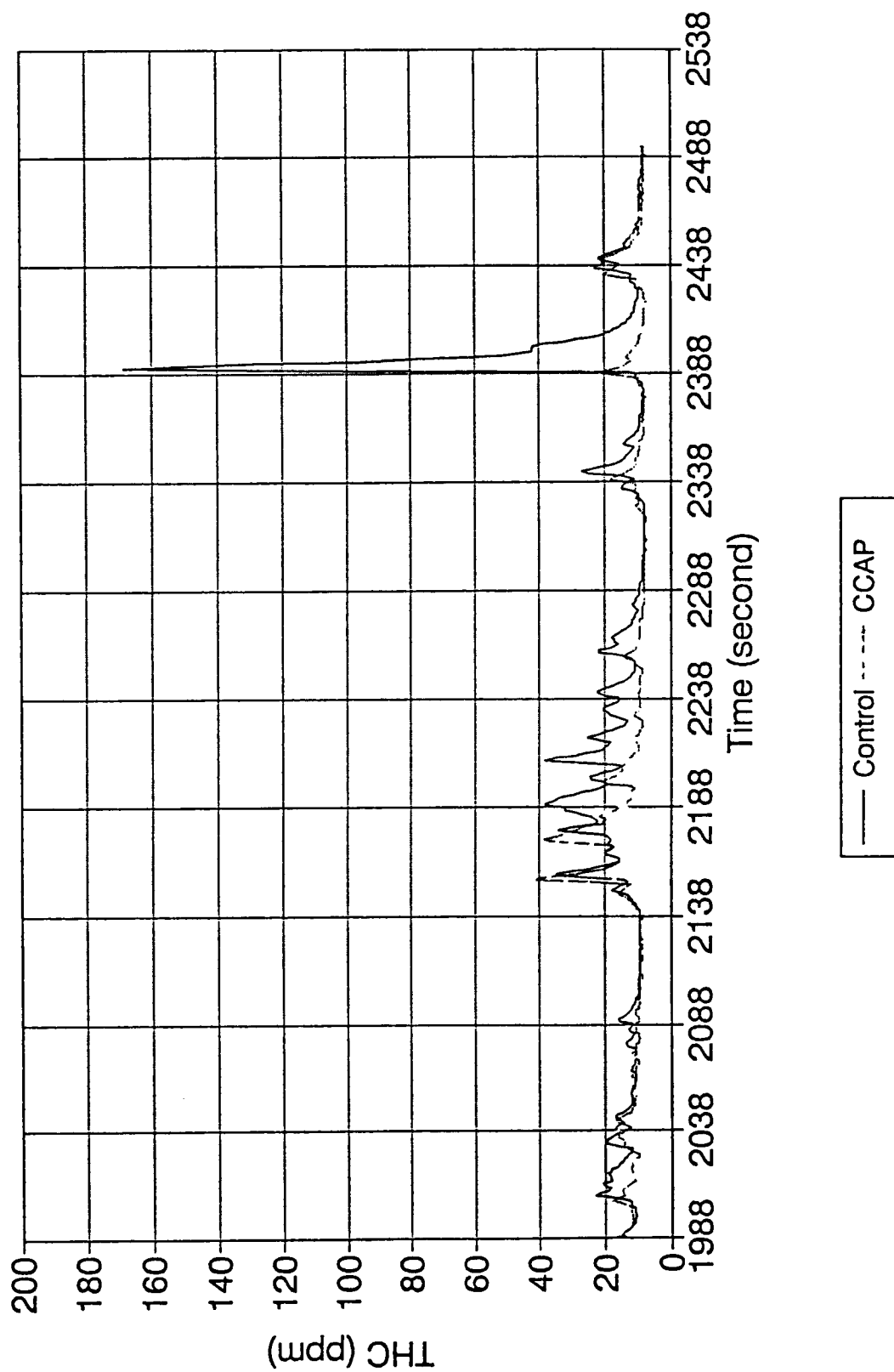


Figure 26 Test 4 UHC Emissions During the Hot Transient Phase

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

As a result of testing, it has been shown that a carefully installed CCAP is effective in obtaining significant improvements in UHC and CO emissions without causing significant increases NO_x emissions. Additionally, the catalyst temperatures were not increased dramatically with the addition of a CCAP.

Additionally, the fourth set of tests indicated that force-cooling a vehicle in order to perform an emission test may cause the CO and UHC emissions to appear better than if the vehicle had been soaked overnight. CO emissions were improved from 5.55 g/mile to 5.43 g/mile during the control test and from 4.79 g/mile to 4.39 g/mile during the CCAP test. UHCs remained unaffected during the CCAP test (0.11 g/mile) and were improved during the control test (from 0.20 g/mile to 0.13 g/mile).

8.2 Recommendations

It is recommended that further development of the CCAP be performed in order to incorporate thermocouple feedback into the system. The results of FTP tests number two demonstrate the importance of activating the CCAP after the catalyst has lit-off. Therefore, a properly optimized CCAP should receive feedback from a catalyst thermocouple in order to prevent it from operating at times when the catalyst

temperature is too low.

It is also recommended that further FTP tests be performed of the CCAP installed on a "dirty" vehicle. The Buick Regal used for testing had very good emissions even before the CCAP was installed (it is believed that its catalyst was extremely effective in storing and releasing oxygen). Therefore, the tests of the CCAP may not have shown the dramatic results that the CCAP is capable of. Additional evaluation of the system in this manner could show its usefulness as a "retro-fit" system for older vehicles which no longer meet state emission standards.

Finally, it is believed that the UDDC of the FTP did not require the Buick Regal to operate under power for a significant amount of time. Therefore, it is recommended that the CCAP be tested with a driving cycle that will require the vehicle to be operated with a significant amount of power enrichment. In this manner, the usefulness of the CCAP could be made more obvious.

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APPENDICES

APPENDIX A

EXPERIMENT TO DETERMINE FLOW CAPACITY OF ELECTRIC AIR PUMP

In order to measure the flow capacity of the electric air pump, the pump was activated for 15.25 seconds. During this time, all of the air flowing through the pump was collected in a bag. Then, the volume of the air in the bag was measured (31,760 ml) by injecting it into an inverted graduated cylinder which was filled with water. It was determined that the pump had a flow capacity of 4.4 cfm (with no backpressure).

In order to determine the required flow rate of air, it was assumed that air would be required to completely oxidize the fuel from a gasoline powered vehicle running 25% rich at 60 mph (with a fuel economy of 25 mpg). The following equations were used:

$$MOLES\ OF\ FUEL = 0.2 * \bar{m}_f = 0.2 * \frac{SPEED * DENSITY_{gasoline}}{FUEL\ ECONOMY * MW_f}$$

$$\dot{V}_{air} = 0.2 * \bar{m}_f * \frac{MW_{air} R_{air} * T_{air}}{P_{air}} * \frac{A}{F_{STOICH}}$$

At atmospheric conditions the required flow of air was determined to be 10.61 cfm. Therefore, the electric vacuum pump was unacceptable for Phase II of testing.

APPENDIX B

DATA ACQUISITION AND REDUCTION PROGRAM

(PHASE I OF TESTING)

```
10! ***** SMARTCAT *****
20!           A DATA ACQUISITION PROGRAM
30!           BY: LORI SNOOK
40!
50!   THIS PROGRAM SAMPLES DATA FROM THE SMART CATALYST
60!   SYSTEM ON THE DYNAMOMETER
70!
80!   CONNECT CHANNELS:  0-TENG V, 1-TCAT V, 2-TREF V, 3-ENGE GOV
90!                       4-CATE GOV, 5-MAP V, 6-HCV, 8-COV,
100!                      9-NOX V
110!
120! ***** INITIALIZE OUTPUT PARAMETERS *****
130   PRINTER IS 1                !PRINTS TO CRT SCREEN
140   BAUD = 9600
150   CONTROL 11,3;BOUD
160   CONTROL 11,4;26             !E,7,1
170   CONTROL 11,5;3
```

```

180!
190! ***** REQUEST INITIAL INFORMATION *****
200  PRINT USING "@,#"
210  GINIT
220  GRAPHICS ON
230  GCLEAR
240  MOVE 0,95
250  LABEL "SMART CATALYST DATA ACQUISITION"
260  MOVE 0,94
270  DRAW 133,94
280  MOVE 0,85
290  CSIZE 4,,5
300  LABEL "ENTER DATA FILE NAME"
310  INPUT File$
320  MOVE 0,75
330  LABEL "ENTER THE SAMPLING INTERVAL (2.4 SECONDS OR MORE)"
340  INPUT Interval
350  IF ABS(Interval)<2.4 THEN
360      Interval = 2.4
370  END IF
380  MOVE 0,75
390  LABEL "SAMPLES WILL BE TAKEN EVERY";Interval;"SECONDS"

```

```
400  MOVE 0,60
410  LABEL "ENTER THE TIME. (HH:MM:SS)"
420  INPUT Hms$
430  SET TIME FNTime$(Hms$)
440  MOVE 0,50
450  LABEL "ENTER THE HC RANGE MULTIPLIER SWITCH"
460  INPUT Hcms
470  MOVE 0,40
480  LABEL "ENTER THE CO RANGE (1:0-3%, 1:0-10%)"
490  INPUT R
500  MOVE 0,30
510  LABEL "ENTER NOX RANGE"
520  INPUT Nr
530  MOVE 0,20
540  LABEL "ENTER THE DATE"
550  INPUT Date$
560  MOVE 0,10
570  LABEL "ENTER ANY KEY TO BEGIN SAMPLING"
580  D=0
590  INPUT A$
600!
610! ***** DRAW GRAPHICS FOR OUTPUT *****
```

620 GCLEAR
630 PEN 1
640 CSIZE 4.5,.6
650 FRAME
660 MOVE 47,88
670 LABEL "TIME:"
680 MOVE 30,80
690 LABEL "MAP (PSIG):"
700 MPVE 75,68
710 LABEL "ENG TEMP (F):"
720 MOVE 75,60
730 LABEL "CAT TEMP (F):"
740 MOVE 4,68
750 LABEL "ENG EGO (MV):"
760 MOVE 4,60
770 LABEL "CAT EGO (MV):"
780 MOVE 35,48
790 LABEL "HC (PPM):"
800 MOVE 38.40
810 LABEL "CO (%):"
820 MOVE 33,32
830 LABEL "NOX (PPM):"

```

840  CSIZE 4,,5
850  MOVE 25,20
860  LABEL "EXECUTE D=1 WHEN FINISHED"
870  MOVE 25,15
880  LABEL "EXECUTE HCMS=# IF CHANGE HC RANGE MULTIPLIER:
890  MOVE 25,20
900  LABEL "EXECUTE R=# FOR CO CHANGE (1:0-3%, 2:0-10%)"
910  MOVE 25,5
920  LABEL "EXECUTE NR=# FOR NOX RANGE CHANGE"
930!
940!  ***** SEND INITIAL OUTPUT TO IBM *****
950  OUTPUT 11;""
960  OUTPUT 11;"DATE OF EXPERIMENT: ";Date$
970  OUTPUT 11;"TIME OF EXPERIMENT: ";FNTime$(TIMEDATE)
980  OUTPUT 11;""
990  OUTPUT 11;" TIME ENGEGO CATEGO ENGTEM CATTEM MAP
    UHC CO NOX"
1000 OUTPUT 11;"      (MV)  (MV)  (F)   (F)  (PSIG)
    (PPM) (%) (PPM)"
1010 OUTPUT 11;""
1020!
1030!  ***** DATA ACQUISITION *****

```

```

1040  CLEAR 709

1050  OUTPUT 709;"AC00"

1060  ENTER 709;Tengv

1070  OUTPUT 709;"AC01"

1080  ENTER 709;Tcatv

1090  OUTPUT 709;"AC02"

1100  ENTER 709;Trefv

1110  OUTPUT 709;"AC03"

1120  ENTER 709;Engegov

1130  OUTPUT 709;"AC04"

1140  ENTER 709;Categov

1150  OUTPUT 709;"AC05"

1160  ENTER 709;Mapv

1170  OUTPUT 709;"AC06"

1180  ENTER 709;Hcv

1190  OUTPUT 709;"AC07"

1200  ENTER 709;Cov

2120  OUTPUT 709;"AC08"

1220  ENTER 709;Noxv

1230!

1240!  ***** DATA REDUCTION *****

1250  Engegov=Engegov*1000          !MV

```

```

1260  Categov=Categov*1000          !MV
1270  Teng=FNTemp(Tengv,Trefv)      !DEG C
1280  Teng=Teng*1.8+32              !DEG F
1290  Tcat=FNTemp(Tcatv,Trefv)      !DEG C
1300  Tcat=Tcat*1.8+32              !DEG F
1310  Map=Mapv*14.7/5-14.7          !PSIG
1320  Hc=Hcv*Hcms                    !DR H'S CORRECTED RANGE
1330  IF R=1 THEN
1340      Co=8.27E-1+1.84E-2*Cov*100+1.14E-4*(100*Cov)^2
1350  ELSE
1360      IF R=2 THEN
1370          Co = 6.52E-2+2.62E-2*Cov*100+7.21E-4*(Cov*100)^2
1380      END IF
1390  END IF
1400  Nox=Noxv*Nr
1410!
1420! ***** REPORT DATA TO SCREEN *****
1430  PRINT USING "@,#"
1440  PRINT USING "2/,24X,9A";FNTime$(TIMEDATE)
1450  PRINT USING "1/,24X,SDD.DD";Map
1460  PRINT USING "2/,12X,DDDD.DD,22X,DDDD.DD";Engegov,Teng
1470  PRINT USING "1/,12X,DDDD.DD,22X,DDDD.DD";Categov,Tcat

```

```

1480 PRINT USING "1/,74X,SDDDDD";Hc
1490 PRINT USING "74X,SDD.DD";Co
1500 PRINT USING "74X,SCCCCC";Nox
1510!
1520! ***** SEND DATA TO IBM *****
1530 Form: IMAGE 9A,2X,4D,3X,4D,3X,3D,3X,4D,2X,SDD.DD,X,S5D,X,
      SDD.DD,X,S5D
1540 OUTPUT 11 USING Form;FNTime$(TIMEDATE),Engegov,Categov,Teng,
      Tcat,Map,Hc,Co,Nox
1550!
1560! ***** END OF PROGRAM *****
1570 WAIT (Interval-2.4)
1580 IF D=1 THEN GOTO 1600
1590 GOTO 1040
1600 GCLEAR
1610 PRINT USING "@,#"
1620 END
1630!
1640 ***** TEMPERATURE FUNCTION *****
1650 DEF FNTemp(Tempv,Refv)
1660 V=(Tempv-Refv)*1000 !MV
1670 Temp=1.9750953E+1*V-1.85426E-1*V^2+8.3683958E-3*V^3-1.33281E-4*V^4

```

```

1680 IF Temp>400 THEN
1690     Temp = 9.2808E+1+5.4464*V+6.535E-1*V^2-1.399E-2*V^3+
           9.936E-5*V^4
1700 END IF
1710 RETURN Temp
1720 FNED
1730!
1740 SUB Repdata
1750 SUBEND
1760!
1770 ***** TIME FUNCTIONS *****
1790 DEF FNNTTime$(T$)
1790 ON ERROR GOTO Err
1800 ENTER T$:H:M:S
1810 RETURN (3600*H+60*M+S)
1820 Err:OFF ERROR
1830 RETURN TIMEDATE MOD 86400
1840 FNEND
1850!
1860 DEF FNTime#(Now)
1870 Now=INT(Now) MOD 86400
1880 H=Now DIV 3600

```

```
1890  M=Now MOD 3600 DIV 60  
1900  S=Now MOD 60  
1910  OUTPUT T$ USING "#,ZZ,K";H,":",M,":",S  
1920  RETURN T$  
1930  FNEND
```

APPENDIX C

DATALOGGER EXHAUST TEMPERATURE

ACQUISITION PROGRAM

01:00	Table
01:1.000	Sample time (seconds)
01:P17	Temperature on panel (reference)
01:0001	Location for reference temperature
02:P14	Thermocouple temperature (A)
01:01	One repetition
02:04	Range code (0-500 mV, slow)
03:01	Input channel of TC A
04:04	TC A type J
05:0001	Reference temperature location
06:0002	Display TC A in location 2
07:1.8	Multiplier (1.8)
08:32	Offset (32)
03:P14	Thermocouple temperature (B)
01:01	One repetition
02:04	Range code (0-500 mV, slow)
03:02	Input channel of TC B

04:04	TC B type J
05:0001	Reference temperature location
06:0003	Display TC B in location 3
07:1.8	Multiplier (1.8)
08:32	Offset (32)
04:P91	If:
01:15	Flag 5 is set
02:10	Set Flag 0
05:P77	Time
01:0011	Store hours, minutes
06:P70	Store:
01:01	One repetition
02:0002	Location 2
07:P70	Store:
01:01	One repetition
02:0003	Location 3

APPENDIX D

TOTAL BAG EMISSIONS DATA (PHASE II)

The following table summarizes the total CO and UHC bag data obtained during Phase II of testing:

Test	F/C?	CCAP?	UHC (g/mile)				CO (g/mile)			
			CT	CS	HT	TOT	CT	CS	HT	TOT
1	No	No	1.54	.11	.25	.44	16.9	2.9	6.26	6.7
1	Yes	Yes	2.07	.08	.16	.51	21.2	1.24	2.97	5.83
2	Yes	No	1.57	.13	.16	.43	16.7	1.93	4.12	5.57
2	No	Yes	1.73	.13	.21	.48	16.9	2.11	2.12	5.15
3	No	No	1.81	.14	.23	.38	19.2	1.36	3.92	5.72
3	Yes	Yes	1.30	.11	.23	.38	9.79	1.19	4.17	3.77
4	No	No	1.28	.13	.20	.38	15.7	2.59	3.54	5.55
4a	Yes	No	1.38	.13	.13	.39	16.1	1.93	3.73	5.34
4	No	Yes	1.43	.13	.11	.39	14.0	2.33	2.57	4.79
4a	Yes	Yes	1.20	.13	.11	.34	12.6	2.09	2.57	4.39

For bags 2 and 3 (the cold stabilized and hot transient phases, respectively) the CO and UHC data varied as shown below.

Pollutant	Bag	CCAP	Control	Effect of CCAP
UHC	2	0.08-0.13	0.11-0.13	negligible
UHC	3	0.11-0.23	0.13-0.25	negligible
CO	2	1.19-2.33	1.36-2.90	positive
CO	3	2.12-4.17	3.73-6.26	positive

The following pages contain the EPA total bag emissions summary for each test performed in Phase II.

TEST 1 WITHOUT CCAP

EPA RUN= 31639 CYCLE= FTP TEST DATE= 2/12/93 2:15
 DRIVER/OPERATOR= WW/VM TEST CELL= A-CFV
 PROGRAM= UT TEST TEMPERATURE= 75
 FUEL= RFA
 EPA VEHICLE ID= BU4646
 COMMENT= U. TENN
 BAROMETRIC PRESSURE= 744.3
 RELATIVE HUMIDITY= 82.7

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5670.00	9785.00	5679.00
DILUTION FACTOR	19.33	30.91	28.59
FUEL ECON. MILES/GAL.	16.67	17.32	25.29
TEST DIST. MILES	3.59	3.89	3.59

HC PPM	59.60	2.62	9.73
HC GRAMS	5.52	0.42	0.90
HC GRAMS/MILE	1.54	0.11	0.25

NOX PPM	13.10	3.90	7.30
NOX GRAMS	4.82	2.48	2.69
NOX GRAMS/MILE	1.34	0.64	0.75

CO PPM	325.00	35.00	120.00
CO GRAMS	60.76	11.29	22.47
CO GRAMS/MILE	16.92	2.90	6.26

CO2 %	0.62	0.39	0.42
CO2 GRAMS	1820.93	1998.26	1236.52
CO2 GRAMS/MILE	507.22	513.69	344.44

** WEIGHTED VALUES **

FUEL ECON. MILES/GAL. 18.7819
 FUEL ECON. BTU/MILE 6087.1911
 HC GRAMS/MILE 0.4412
 NOX GRAMS/MILE 0.8126
 CO GRAMS/MILE 6.7042
 CO2 GRAMS/MILE 466.1786
 OMHCE GRAMS/MILE 0.4412 (ALDEHYDES ABSENT)

TEST 1 WITH CCAP

EPA RUN= 31636 CYCLE= FTP TEST DATE= 2/12/93 8:00
 DRIVER/OPERATOR= WW/VM TEST CELL= A-CFV
 PROGRAM= UT TEST TEMPERATURE= 75
 FUEL= RFA
 EPA VEHICLE ID= BU4646
 COMMENT= U. TENN
 BAROMETRIC PRESSURE= 747.1
 RELATIVE HUMIDITY= 64.4

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5666.00	9775.00	5681.00
DILUTION FACTOR	20.72	33.13	26.37
FUEL ECON. MILES/GAL.	17.96	18.70	23.17
TEST DIST. MILES	3.59	3.89	3.59

HC PPM	80.42	1.83	6.17
HC GRAMS	7.44	0.29	0.57
HC GRAMS/MILE	2.07	0.08	0.16

NOX PPM	12.61	3.21	7.71
NOX GRAMS	4.06	1.78	2.49
NOX GRAMS/MILE	1.13	0.46	0.69

CO PPM	408.00	15.00	57.00
CO GRAMS	76.22	4.83	10.68
CO GRAMS/MILE	21.23	1.24	2.97

CO2 %	0.56	0.37	0.47
CO2 GRAMS	1651.95	1859.08	1372.66
CO2 GRAMS/MILE	460.15	477.91	382.36

** WEIGHTED VALUES **

FUEL ECON. MILES/GAL.	19.5657
FUEL ECON. BTU/MILE	5843.3417
HC GRAMS/MILE	0.5093
NOX GRAMS/MILE	0.6603
CO GRAMS/MILE	5.8291
CO2 GRAMS/MILE	448.1849
OMHCE GRAMS/MILE	0.5093 (ALDEHYDES ABSENT)

TEST 2 WITHOUT CCAP

EPA RUN= 31652 CYCLE= FTP TEST DATE= 3/12/93 1:15
 DRIVER/OPERATOR= NP/VM TEST CELL= A-CFV
 PROGRAM= UT TEST TEMPERATURE= 75
 FUEL= RFA
 EPA VEHICLE ID= BU464G
 COMMENT= FUEL IS RFA & BP
 BAROMETRIC PRESSURE= 756.5
 RELATIVE HUMIDITY= 42.2

 REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5743.00	9902.00	5748.00
DILUTION FACTOR	20.79	31.89	25.09
FUEL ECON. MILES/GAL.	17.96	17.83	21.83
TEST DIST. MILES	3.59	3.89	3.59
HC PPM	60.14	3.09	6.12
HC GRAMS	5.64	0.50	0.57
HC GRAMS/MILE	1.57	0.13	0.16
NOX PPM	11.20	3.40	8.00
NOX GRAMS	3.18	1.66	2.27
NOX GRAMS/MILE	0.89	0.43	0.63
CO PPM	317.00	23.00	78.00
CO GRAMS	60.02	7.51	14.78
CO GRAMS/MILE	16.72	1.93	4.12
CO2 %	0.57	0.38	0.49
CO2 GRAMS	1692.66	1945.50	1451.96
CO2 GRAMS/MILE	471.49	500.13	404.44

** WEIGHTED VALUES **

FUEL ECON. MILES/GAL.	18.7762	
FUEL ECON. BTU/MILE	6089.0393	
HC GRAMS/MILE	0.4341	
NOX GRAMS/MILE	0.5779	
CO GRAMS/MILE	5.5711	
CO2 GRAMS/MILE	468.1268	
OMHCE GRAMS/MILE	0.4341	(ALDEHYDES ABSENT)

TEST 2 WITH CCAP

EPA RUN= 31651 CYCLE= FTP TEST DATE= 3/12/93 7:30
 DRIVER/OPERATOR= NP/VM TEST CELL= A-CFV
 PROGRAM= UT TEST TEMPERATURE= 75
 FUEL= RFA
 EPA VEHICLE ID= BU464G
 COMMENT= FUEL IS RFA & BP
 BAROMETRIC PRESSURE= 759.1
 RELATIVE HUMIDITY= 32.6

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5746.00	9911.00	5757.00
DILUTION FACTOR	21.98	32.79	27.59
FUEL ECON. MILES/GAL.	18.95	18.39	24.17
TEST DIST. MILES	3.59	3.89	3.59
HC PPM	66.18	3.09	8.11
HC GRAMS	6.21	0.50	0.76
HC GRAMS/MILE	1.73	0.13	0.21
NOX PPM	12.81	4.51	7.61
NOX GRAMS	3.45	2.09	2.05
NOX GRAMS/MILE	0.96	0.54	0.57
CO PPM	320.09	25.06	40.07
CO GRAMS	60.64	8.19	7.61
CO GRAMS/MILE	16.89	2.11	2.12
CO2 %	0.53	0.37	0.44
CO2 GRAMS	1566.07	1885.48	1319.59
CO2 GRAMS/MILE	441.80	484.70	367.57

** WEIGHTED VALUES **

FUEL ECON. MILES/GAL.	19.7999	
FUEL ECON. BTU/MILE	5774.2486	
HC GRAMS/MILE	0.4810	
NOX GRAMS/MILE	0.6343	
CO GRAMS/MILE	5.1522	
CO2 GRAMS/MILE	443.9113	
OMHCE GRAMS/MILE	0.4810	(ALDEHYDES ABSENT)

TEST 3 WITHOUT CCAP

EPA RUN= 31558 CYCLE= FTP TEST DATE= 10/19/92 10:00
 DRIVER/OPERATOR= VM/RS TEST CELL= A-CFV
 PROGRAM= MISC TEST TEMPERATURE= 75
 FUEL= SG
 EPA VEHICLE ID= BU4646
 COMMENT= NONE
 BAROMETRIC PRESSURE= 759.6
 RELATIVE HUMIDITY= 39.2

 REGULATED EMISSIONS REPORT RES2

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5746.00	9919.00	5753.00
DILUTION FACTOR	20.24	32.16	24.40
FUEL ECON. MILES/GAL.	17.23	17.77	21.05
TEST DIST. MILES	3.58	3.85	3.58

HC PPM	68.88	3.32	8.65
HC GRAMS	6.47	0.54	0.81
HC GRAMS/MILE	1.81	0.14	0.23

NOX PPM	10.80	3.20	7.10
NOX GRAMS	3.01	1.54	1.98
NOX GRAMS/MILE	0.84	0.40	0.55

CO PPM	362.00	16.00	74.00
CO GRAMS	68.60	5.23	14.04
CO GRAMS/MILE	19.16	1.36	3.92

CO2 %	0.58	0.37	0.50
CO2 GRAMS	1721.53	1918.43	1489.48
CO2 GRAMS/MILE	480.87	498.29	416.06

** WEIGHTED VALUES **

FUEL ECON. MILES/GAL.	18.4345
FUEL ECON. BTU/MILE	
HC GRAMS/MILE	0.5065
NOX GRAMS/MILE	0.5332
CO GRAMS/MILE	5.7225
CO2 GRAMS/MILE	472.2694
OMHCE GRAMS/MILE	0.5065 (ALDEHYDES ABSENT)

TEST 3 WITH CCAP

EPA RUN= 31559 CYCLE= FTP TEST DATE= 10/19/92 1:28
 DRIVER/OPERATOR= VM/RS TEST CELL= A-CFV
 PROGRAM= MISC TEST TEMPERATURE= 75
 FUEL= SG
 EPA VEHICLE ID= BU4646
 COMMENT= FORCE COOLED, W/CCAP
 BAROMETRIC PRESSURE= 759.5
 RELATIVE HUMIDITY= 36.8

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5747.00	9923.00	5727.00
DILUTION FACTOR	22.55	31.95	23.99
FUEL ECON. MILES/GAL.	19.34	17.64	20.75
TEST DIST. MILES	3.58	3.85	3.58

HC PPM	49.55	2.51	8.65
HC GRAMS	4.65	0.41	0.81
HC GRAMS/MILE	1.30	0.11	0.23

NOX PPM	9.70	3.20	10.40
NOX GRAMS	2.67	1.52	2.85
NOX GRAMS/MILE	0.75	0.40	0.80

CO PPM	185.00	14.00	79.00
CO GRAMS	35.05	4.58	14.92
CO GRAMS/MILE	9.79	1.19	4.17

CO2 %	0.53	0.38	0.51
CO2 GRAMS	1577.68	1934.67	1509.54
CO2 GRAMS/MILE	440.69	502.51	421.66

** WEIGHTED VALUES **

FUEL ECON. MILES/GAL.	18.7449	
FUEL ECON. BTU/MILE		
HC GRAMS/MILE	0.3841	
NOX GRAMS/MILE	0.5772	
CO GRAMS/MILE	3.7724	
CO2 GRAMS/MILE	467.7268	
OMHCE GRAMS/MILE	0.3841	(ALDEHYDES ABSENT)

TEST 4 WITHOUT CCAP (MORNING)

EPA RUN= 31661 CYCLE= FTP TEST DATE= 2/23/93 7:45
 DRIVER/OPERATOR= WW/VM TEST CELL= A-CFV
 PROGRAM= UT TEST TEMPERATURE= 75
 FUEL= RFA
 EPA VEHICLE ID= BU464G
 COMMENT= COLD START
 BAROMETRIC PRESSURE= 761.4
 RELATIVE HUMIDITY= 83.2

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5711.00	9863.00	5725.00
DILUTION FACTOR	20.50	30.94	23.89
FUEL ECON. MILES/GAL.	17.61	17.19	22.41
TEST DIST. MILES	3.59	3.89	3.89

HC PPM	47.15	3.10	8.13
HC GRAMS	4.58	0.50	0.76
HC GRAMS/MILE	1.28	0.13	0.20

NOX PPM	11.20	3.00	6.60
NOX GRAMS	4.11	1.90	2.43
NOX GRAMS/MILE	1.14	0.49	0.62

CO PPM	299.00	31.00	73.00
CO GRAMS	56.30	10.08	13.78
CO GRAMS/MILE	15.68	2.59	3.54

CO2 %	0.58	0.39	0.52
CO2 GRAMS	1727.26	2014.18	1534.99
CO2 GRAMS/MILE	481.13	517.78	394.60

** WEIGHTED VALUES **

FUEL ECON. MILES/GAL. 18.4560
 FUEL ECON. BTU/MILE 6194.7023
 HC GRAMS/MILE 0.3829
 NOX GRAMS/MILE 0.6601
 CO GRAMS/MILE 5.5453
 CO2 GRAMS/MILE 476.6287
 DMHCE GRAMS/MILE 0.3829 (ALDEHYDES ABSENT)

TEST 4 WITH CCAP (MORNING)

EPA RUN= 31659 CYCLE= FTP TEST DATE= 3/22/93 7:45
 DRIVER/OPERATOR= WW/VM TEST CELL= A-CFV
 PROGRAM= UT TEST TEMPERATURE= 75
 FUEL= RFA
 EPA VEHICLE ID= B11464G
 COMMENT= NONE
 BAROMETRIC PRESSURE= 762.7
 RELATIVE HUMIDITY= 57.2

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5689.00	9824.00	5700.00
DILUTION FACTOR	20.87	32.30	24.95
FUEL ECON. MILES/GAL.	18.11	18.24	21.88
TEST DIST. MILES	3.59	3.89	3.59

HC PPM	55.14	3.09	4.12
HC GRAMS	5.12	0.50	0.38
HC GRAMS/MILE	1.43	0.13	0.11

NOX PPM	11.30	3.30	8.20
NOX GRAMS	3.46	1.75	2.52
NOX GRAMS/MILE	0.96	0.45	0.70

CO PPM	267.05	28.03	49.04
CO GRAMS	50.09	9.08	9.22
CO GRAMS/MILE	13.95	2.33	2.57

CO2 %	0.57	0.37	0.49
CO2 GRAMS	1685.57	1899.56	1457.58
CO2 GRAMS/MILE	469.52	488.32	406.01

** WEIGHTED VALUES **

FUEL ECON. MILES/GAL. 19.0757
 FUEL ECON. BTU/MILE 5993.4537
 HC GRAMS/MILE 0.3894
 NOX GRAMS/MILE 0.6235
 CO GRAMS/MILE 4.7890
 CO2 GRAMS/MILE 461.9899
 OMHCE GRAMS/MILE 0.3894 (ALDEHYDES ABSENT)

TEST 4 WITHOUT CCAP (FORCE-COOLED)

EPA RUN= 31662 CYCLE= FTP TEST DATE= 3/23/93 1:00
 DRIVER/OPERATOR= WW/VM TEST CELL= A-CFV
 PROGRAM= UT TEST TEMPERATURE= 75
 FUEL= RFA
 EPA VEHICLE ID= BU464G
 COMMENT= FORCED COOLED
 BAROMETRIC PRESSURE= 759.0
 RELATIVE HUMIDITY= 74.8

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5724.00	9885.00	5727.00
DILUTION FACTOR	20.36	31.87	24.04
FUEL ECON. MILES/GAL.	17.38	17.59	20.70
TEST DIST. MILES	3.59	3.89	3.59
HC PPM	53.15	3.09	5.12
HC GRAMS	4.97	0.50	0.48
HC GRAMS/MILE	1.38	0.13	0.13
NOX PPM	10.50	2.40	6.50
NOX GRAMS	3.64	1.44	2.25
NOX GRAMS/MILE	1.01	0.37	0.63
CO PPM	307.10	23.06	71.00
CO GRAMS	57.96	7.52	13.41
CO GRAMS/MILE	16.14	1.93	3.73
CO2 %	0.59	0.39	0.52
CO2 GRAMS	1748.58	1971.93	1535.13
CO2 GRAMS/MILE	487.07	506.92	427.61

** WEIGHTED VALUES **

FUEL ECON. MILES/GAL.	18.2952	
FUEL ECON. BTU/MILE	6249.1325	
HC GRAMS/MILE	0.3882	
NOX GRAMS/MILE	0.5722	
CO GRAMS/MILE	5.3490	
CO2 GRAMS/MILE	481.1956	
OMHCE GRAMS/MILE	0.3882	(ALDEHYDES ABSENT)

TEST 4 WITH CCAP (FORCE-COOLED)

EPA RUN= 31660 CYCLE= FTF TEST DATE= 3/22/93 1:15
 DRIVER/OPERATOR= WW/VM TEST CELL= A-CFV
 PROGRAM= UT TEST TEMPERATURE= 75
 FUEL= RFA
 EPA VEHICLE ID= BU464G
 COMMENT= FORCED COOLED
 BAROMETRIC PRESSURE= 762.3
 RELATIVE HUMIDITY= 67.5

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG 2	BAG 3
VMIX CUBIC FEET	5697.00	9852.00	5712.00
DILUTION FACTOR	21.18	32.56	24.95
FUEL ECON. MILES/GAL.	18.20	18.20	21.71
TEST DIST. MILES	3.59	3.89	3.59

HC PPM	46.14	3.09	4.12
HC GRAMS	4.29	0.50	0.38
HC GRAMS/MILE	1.20	0.13	0.11

NOX PPM	11.50	2.60	7.40
NOX GRAMS	3.77	1.47	2.43
NOX GRAMS/MILE	1.05	0.38	0.68

CO PPM	241.05	25.03	49.04
CO GRAMS	45.28	8.13	9.24
CO GRAMS/MILE	12.61	2.09	2.57

CO2 %	0.57	0.37	0.50
CO2 GRAMS	1687.02	1904.45	1469.17
CO2 GRAMS/MILE	469.92	489.58	409.24

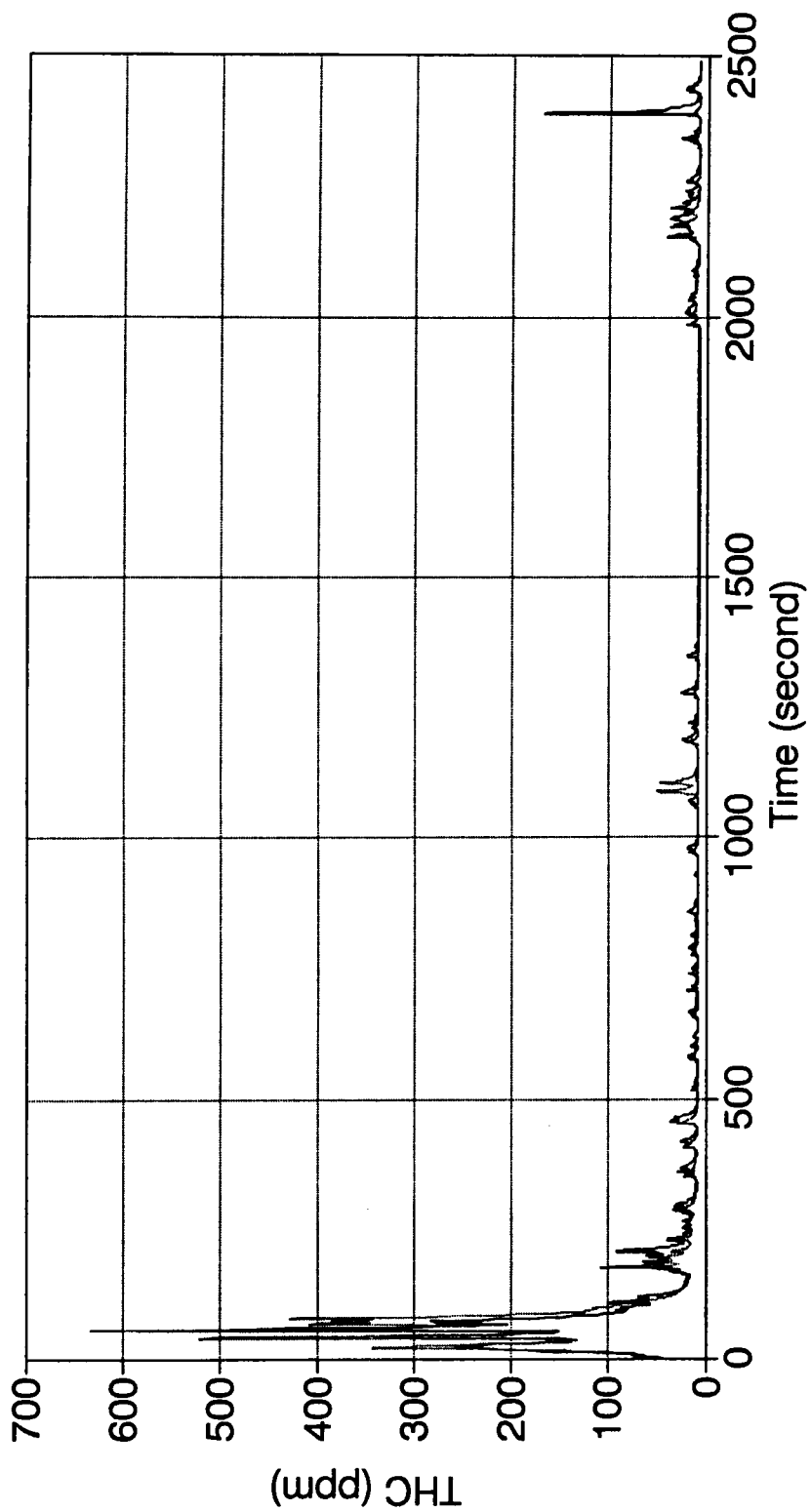
** WEIGHTED VALUES **

FUEL ECON. MILES/GAL.	19.0417
FUEL ECON. BTU/MILE	6004.1350
HC GRAMS/MILE	0.3420
NOX GRAMS/MILE	0.5979
CO GRAMS/MILE	4.3873
CO2 GRAMS/MILE	463.6100
ONHCE GRAMS/MILE	0.3420 (ALDEHYDES ABSENT)

APPENDIX E

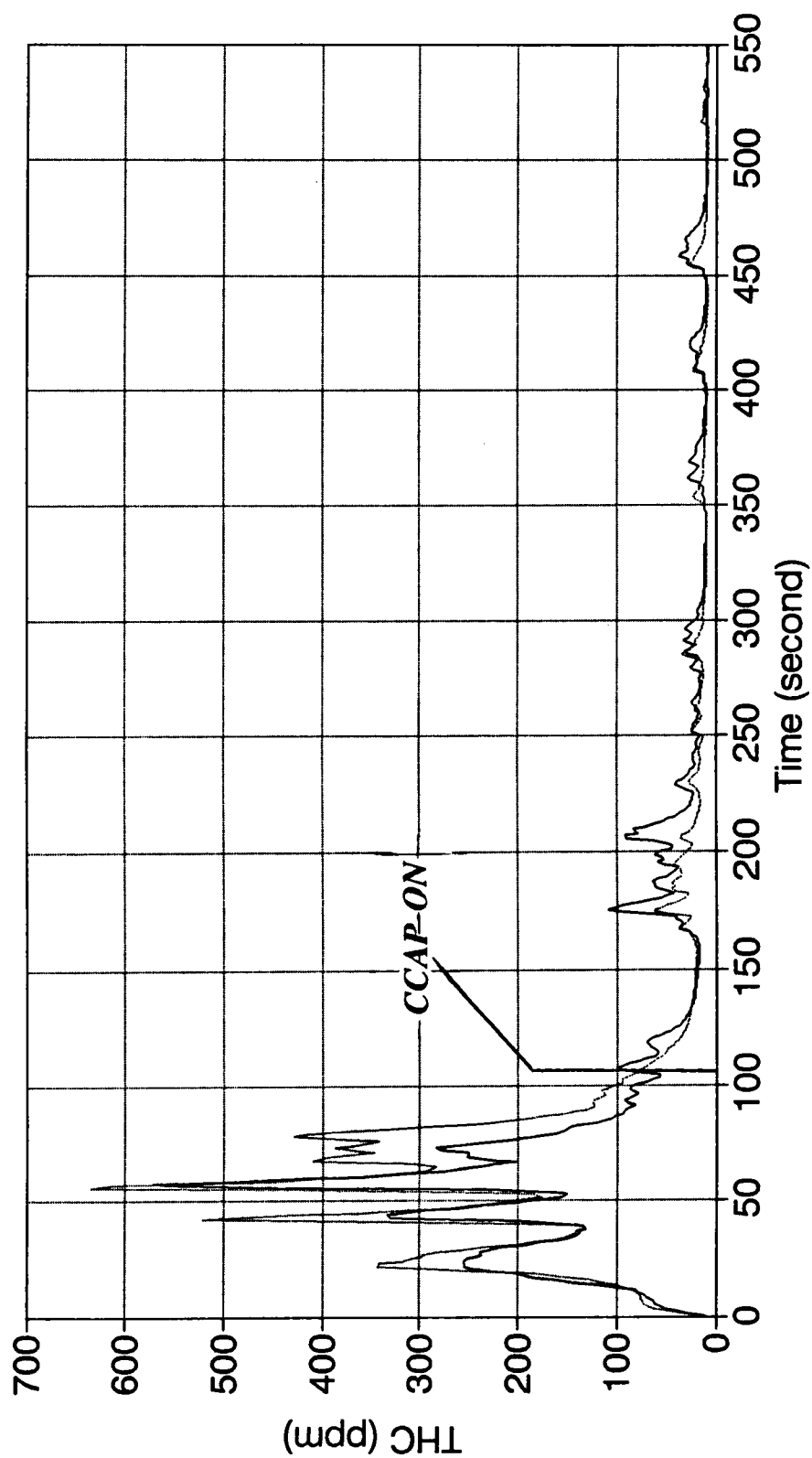
***REAL-TIME EMISSIONS AND TEMPERATURES
IN PHASE II OF TESTING***

Test 4 THC: Entire Cycle



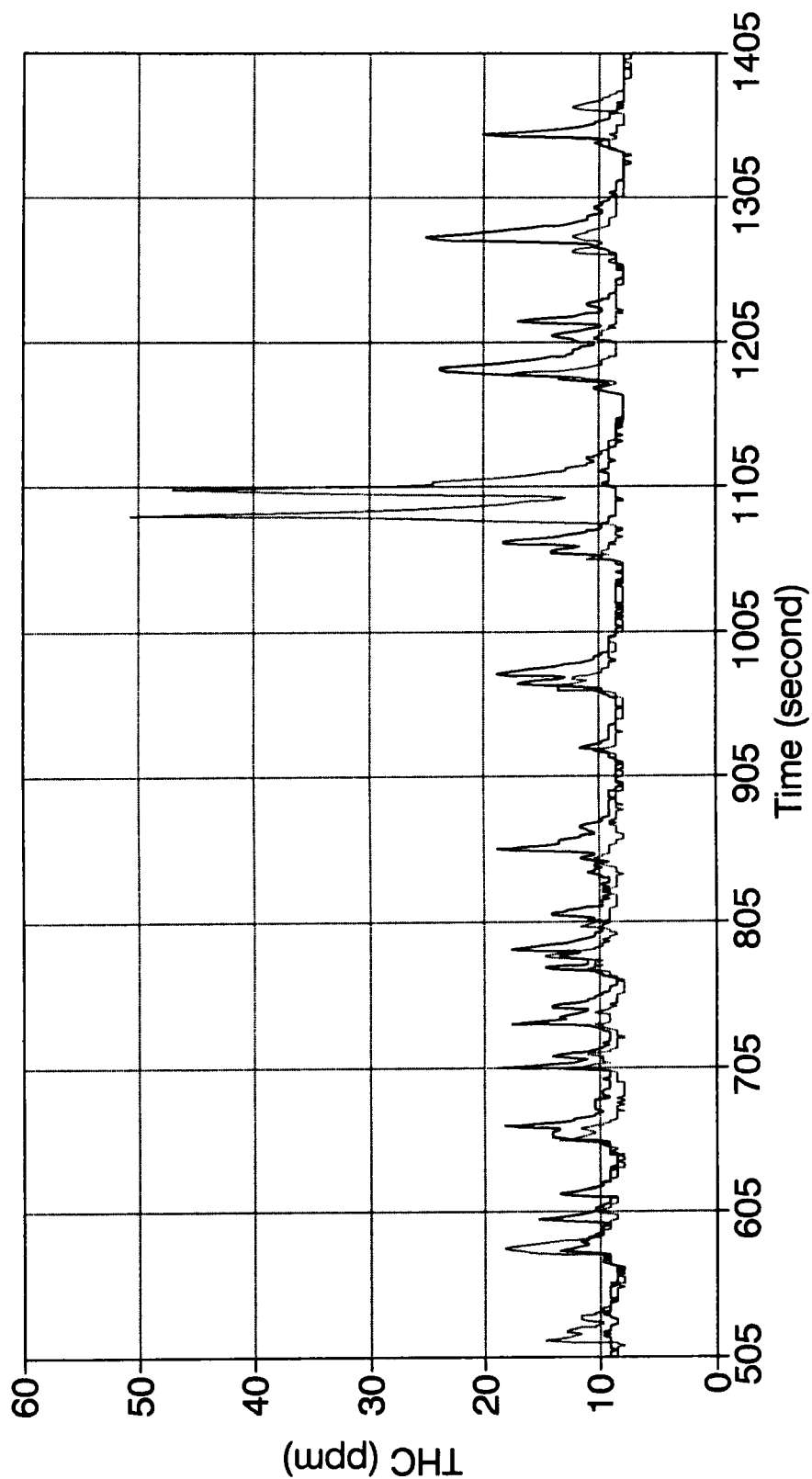
— Control — CCAP

Test 4 THC: Cold Transient Phase



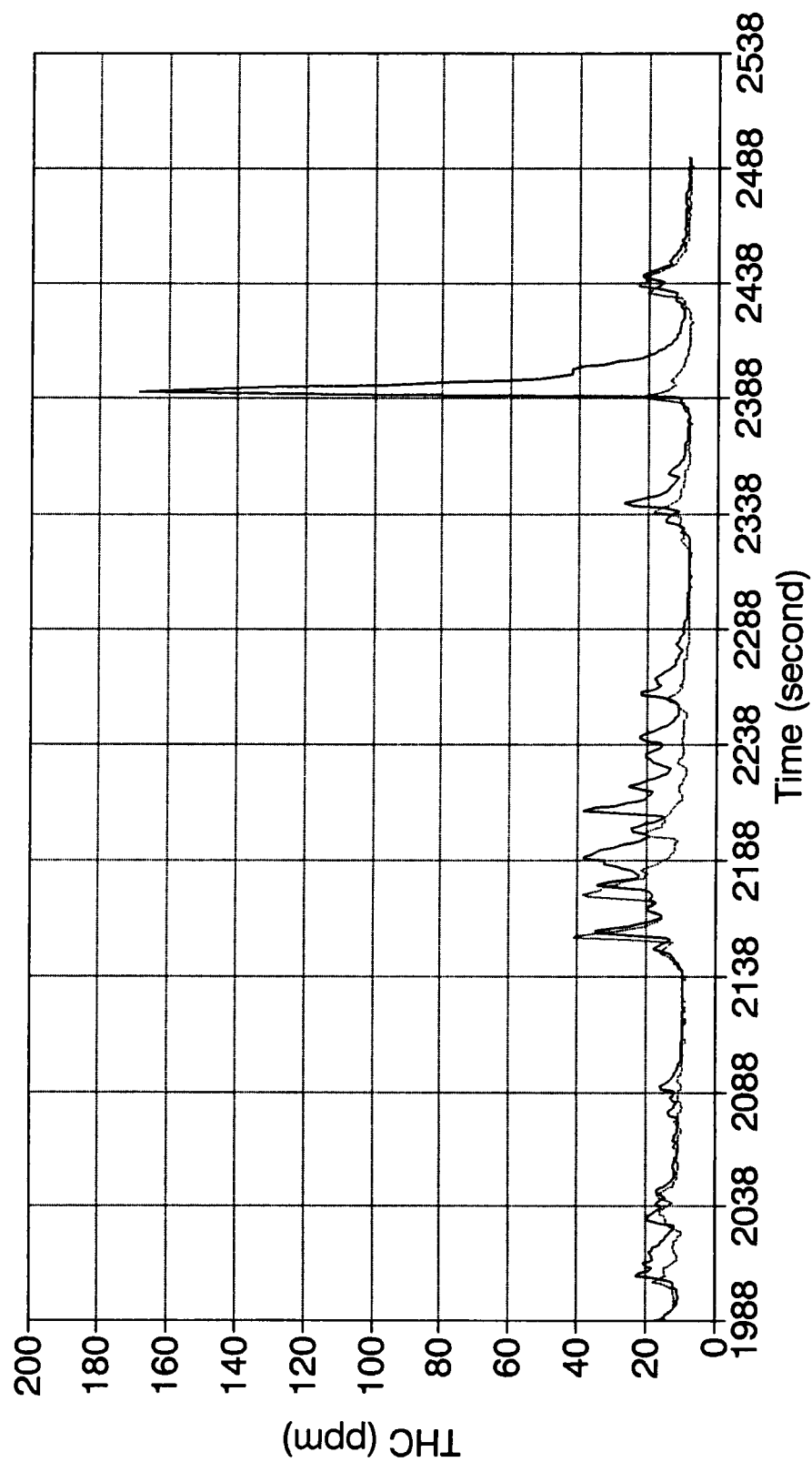
— Control — CCAP

Test 4 THC: Cold Stabilized Phase



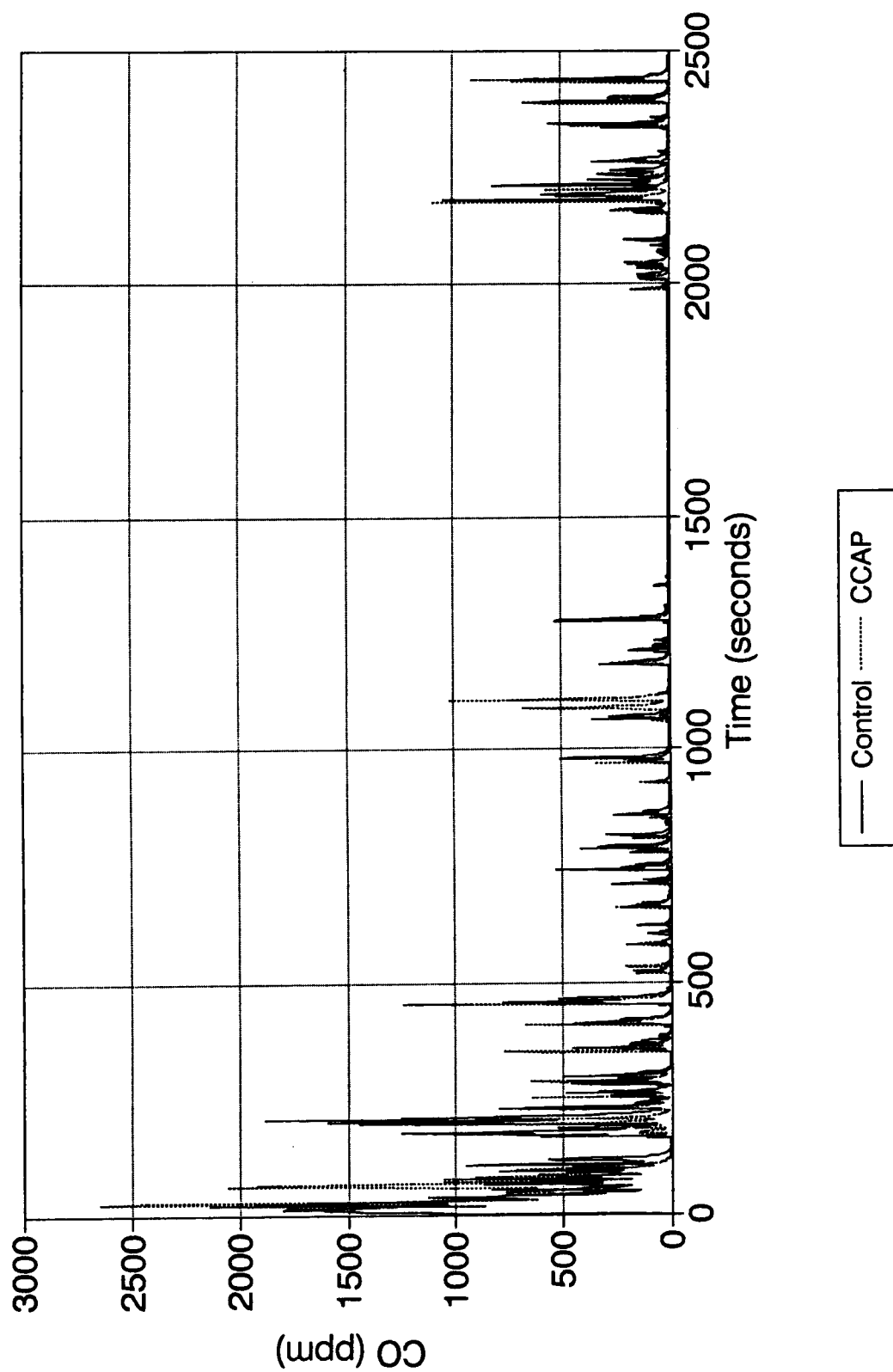
— Control — CCAP

Test 4 THC: Hot Transient Phase

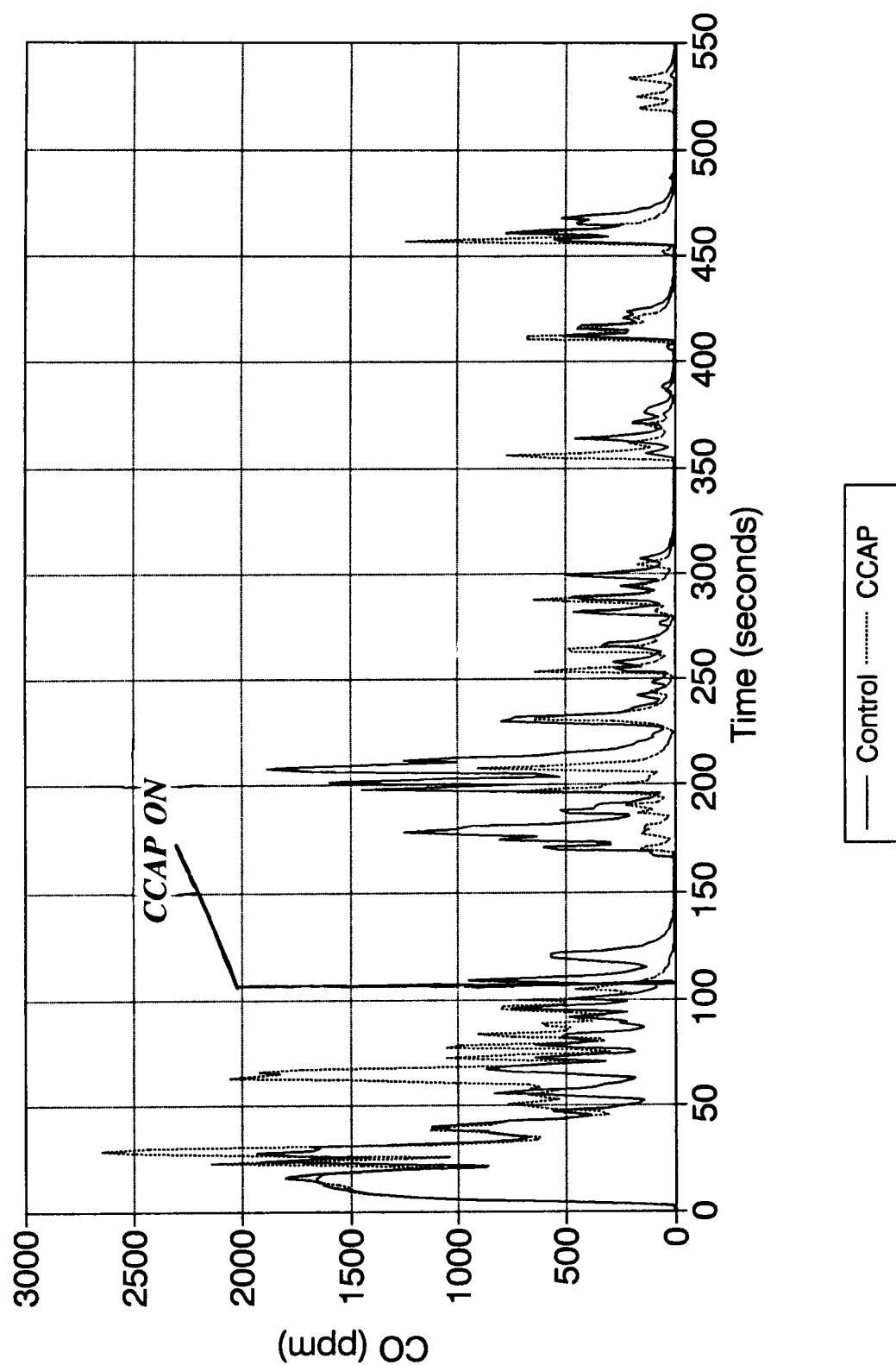


— Control — CCAP

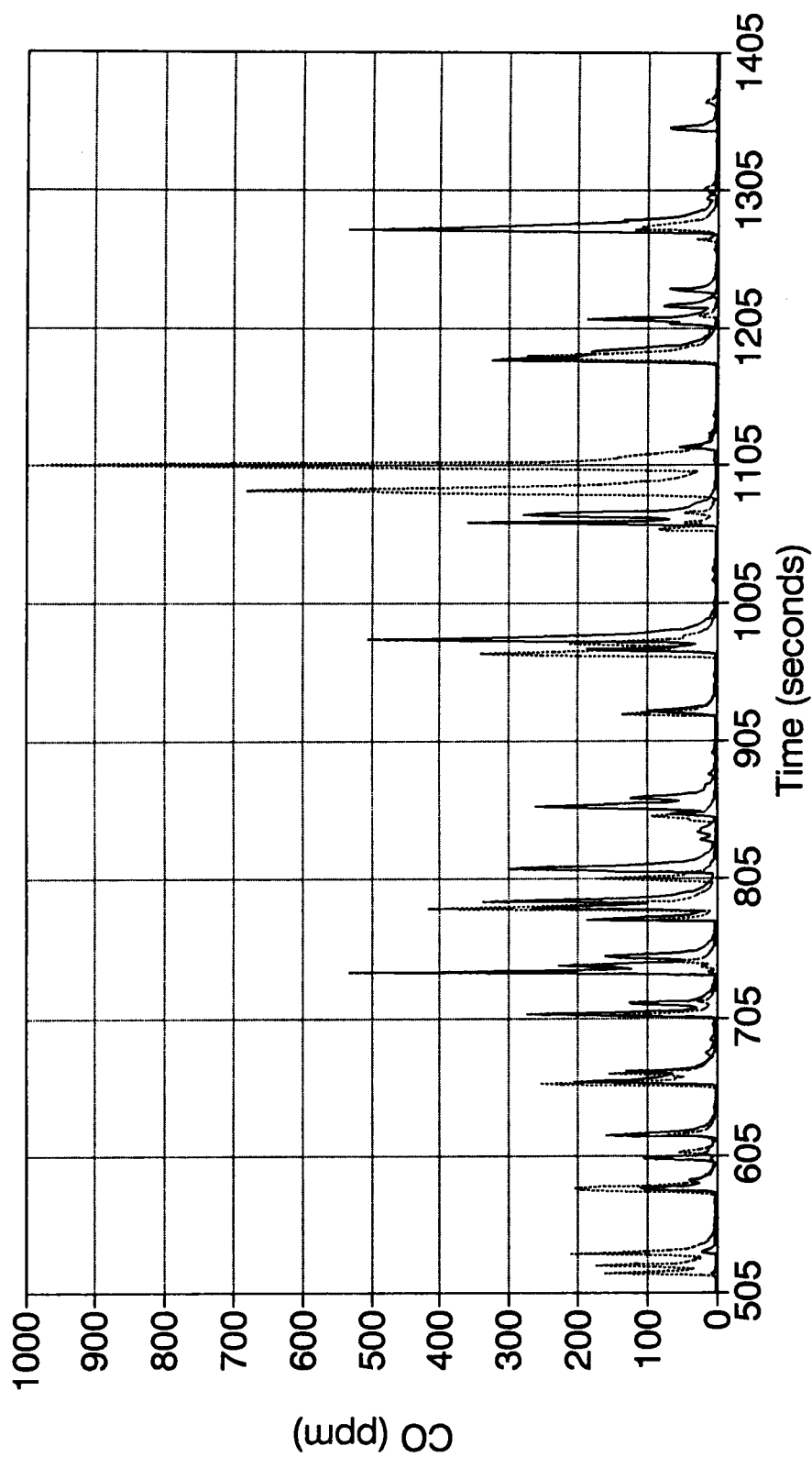
Test 4 CO: Entire Cycle



Test 4 CO: Cold Transient Phase

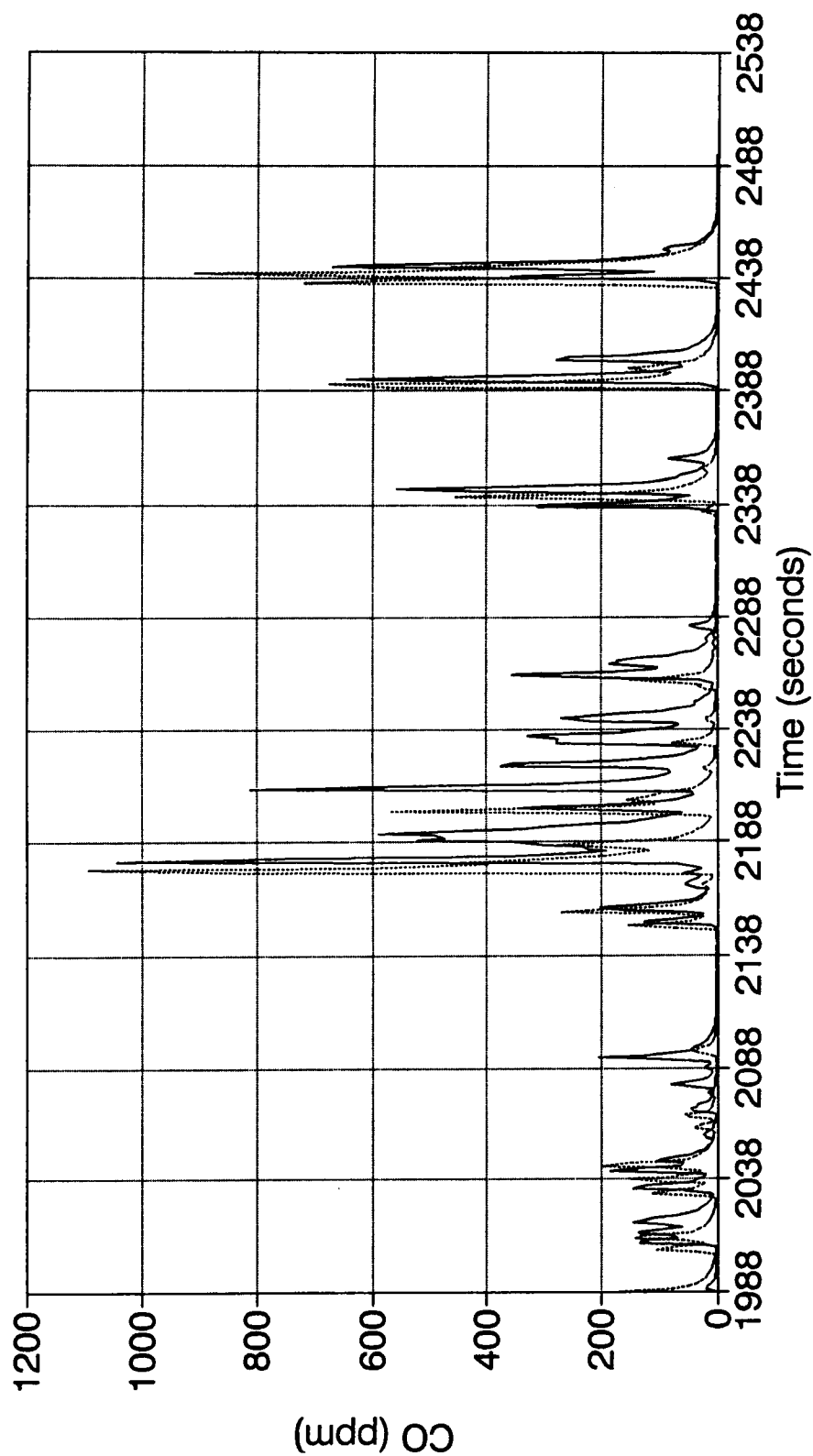


Test 4 CO: Cold Stabilized Phase



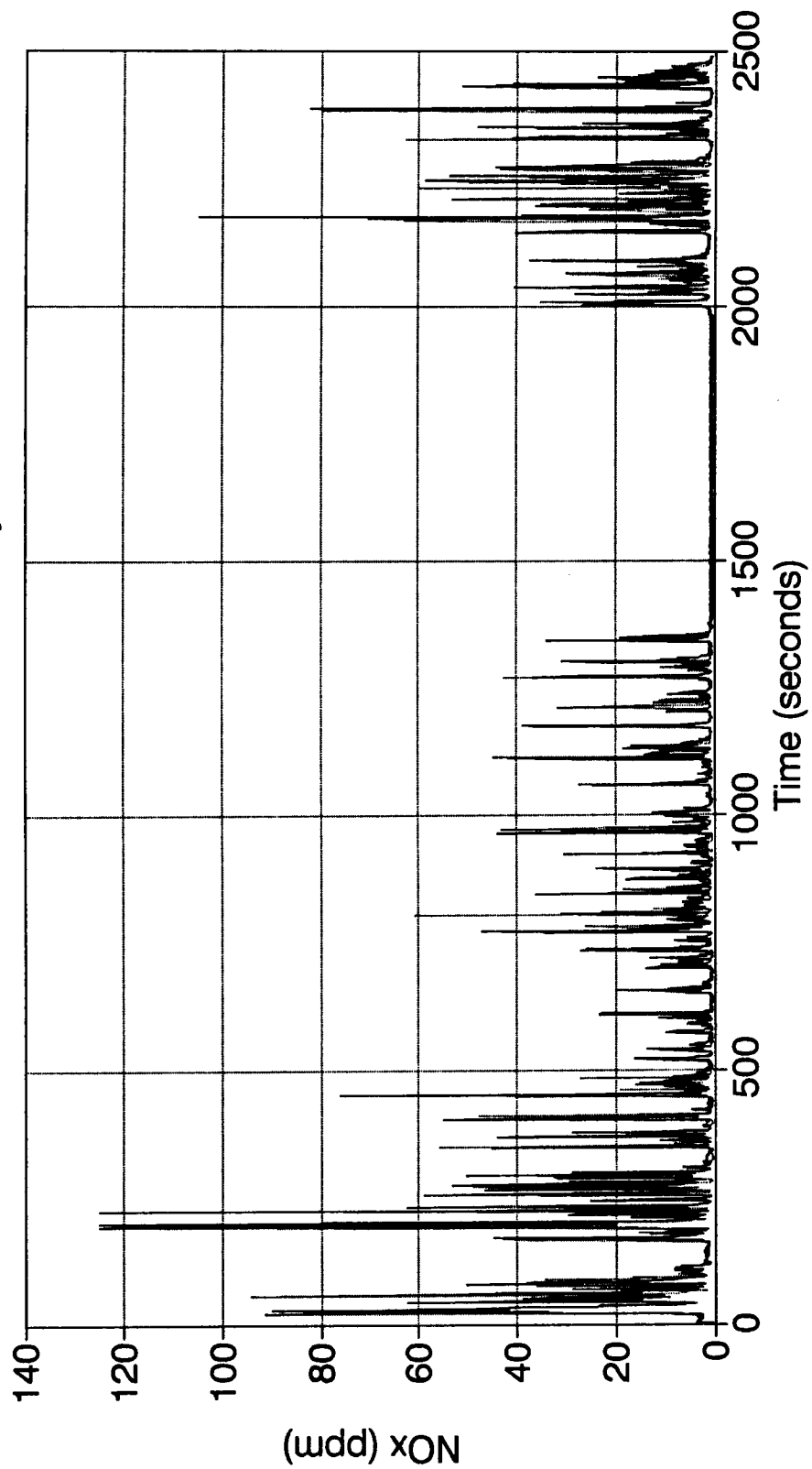
— Control CCAP

Test 4 CO: Hot Transient Phase



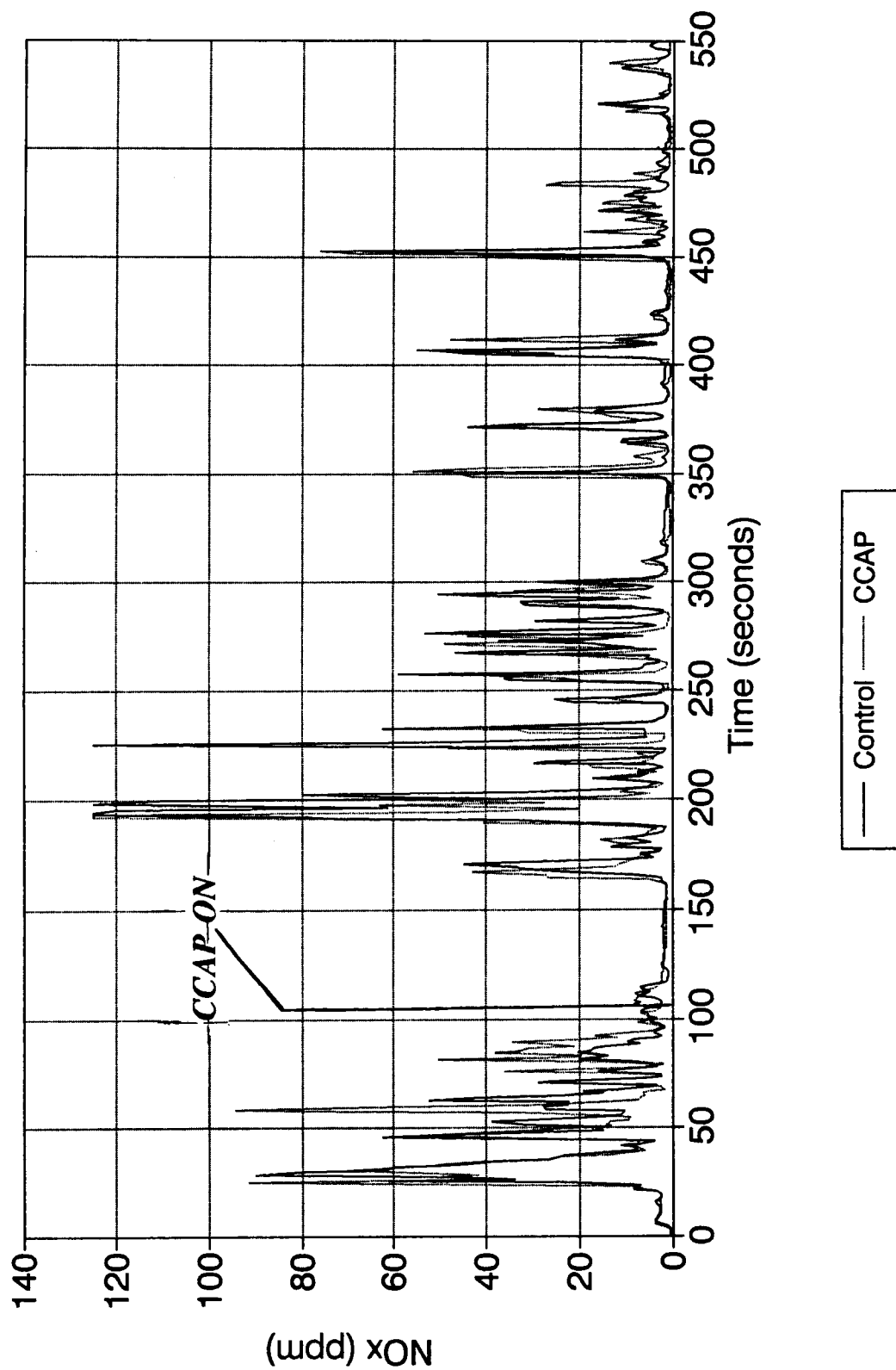
— Control CCAP

Test 4 NOx: Entire Cycle

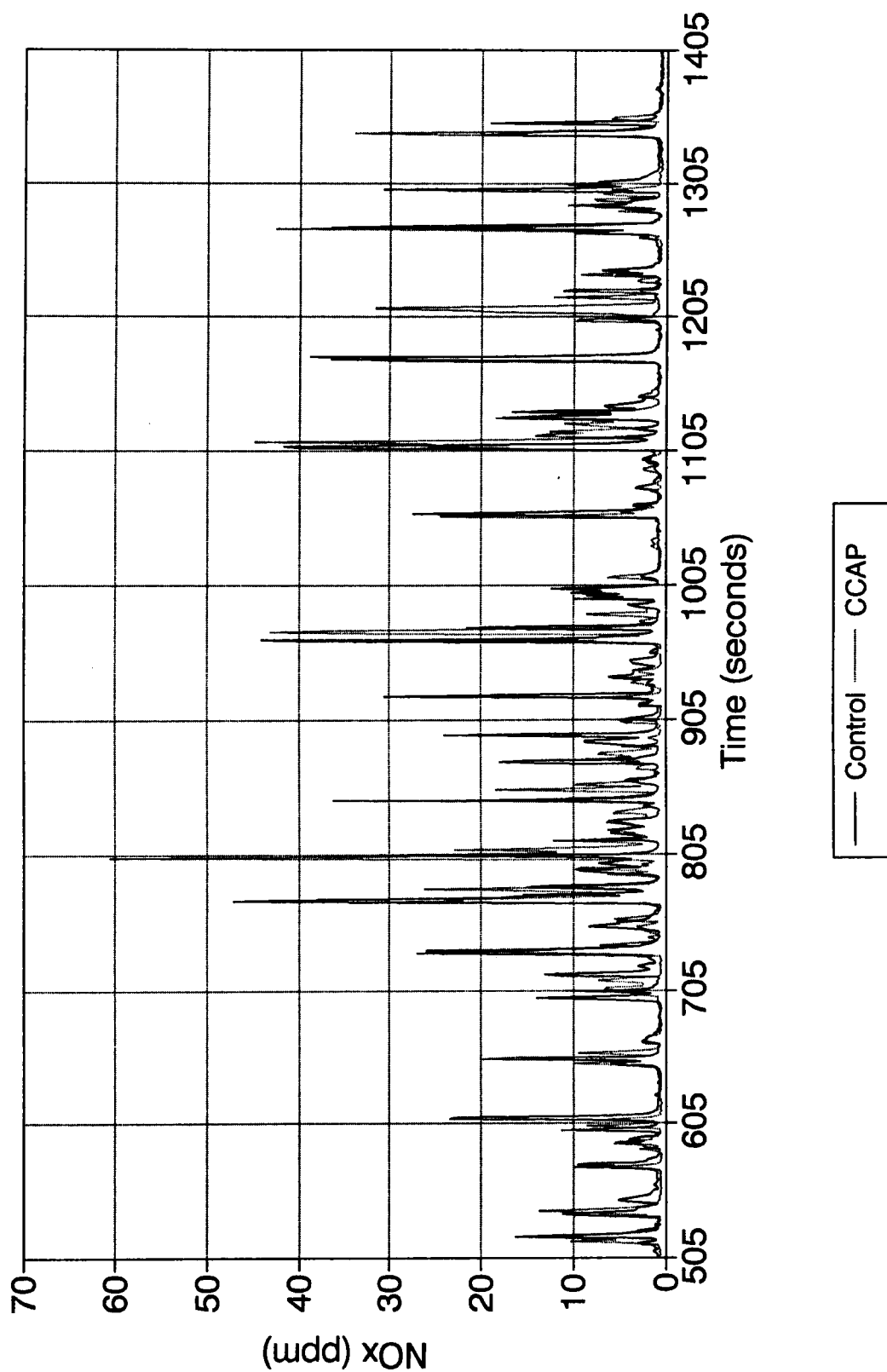


— Control — CCAP

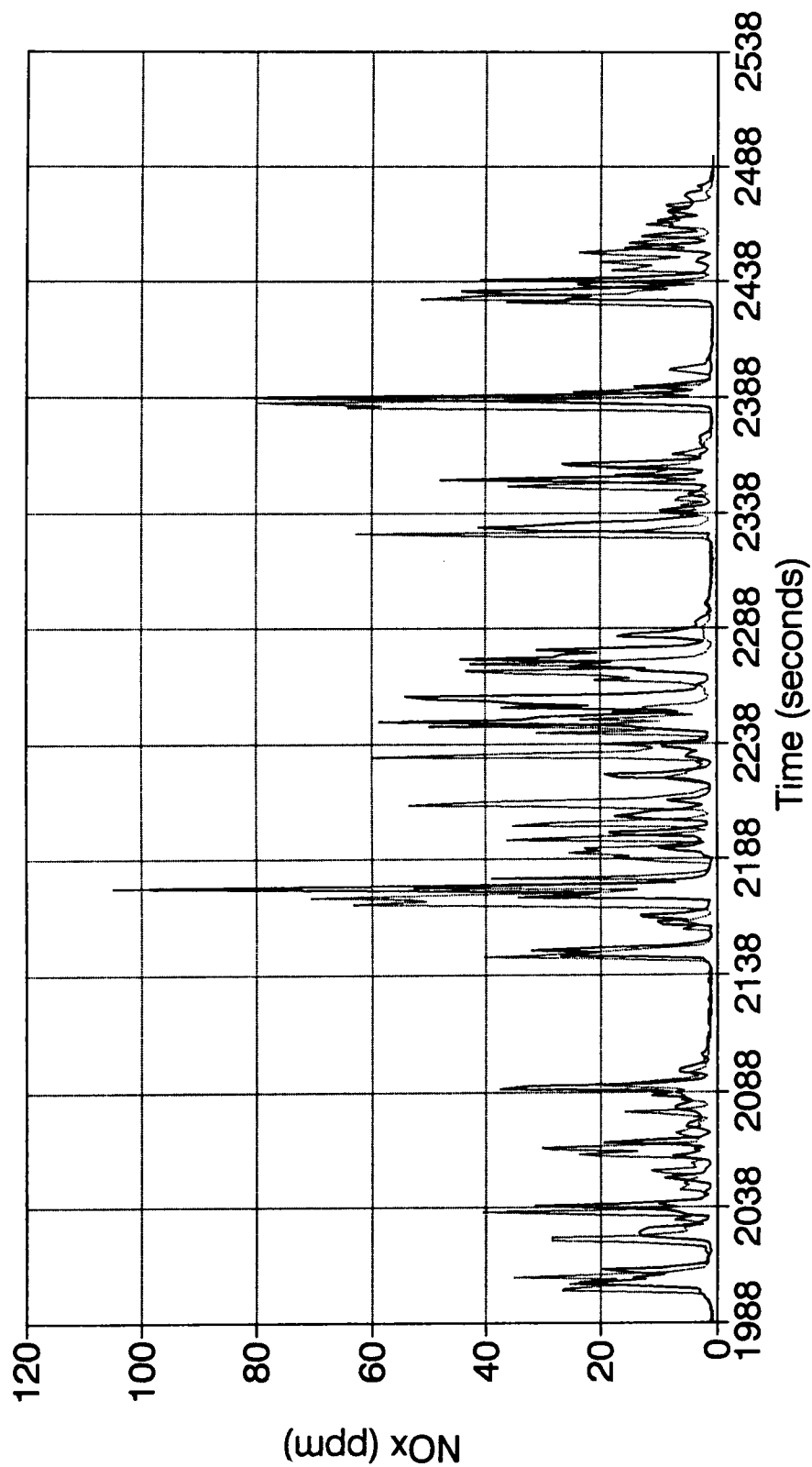
Test 4 NOx: Cold Transient Phase



Test 4 NOx: Cold Stabilized Phase

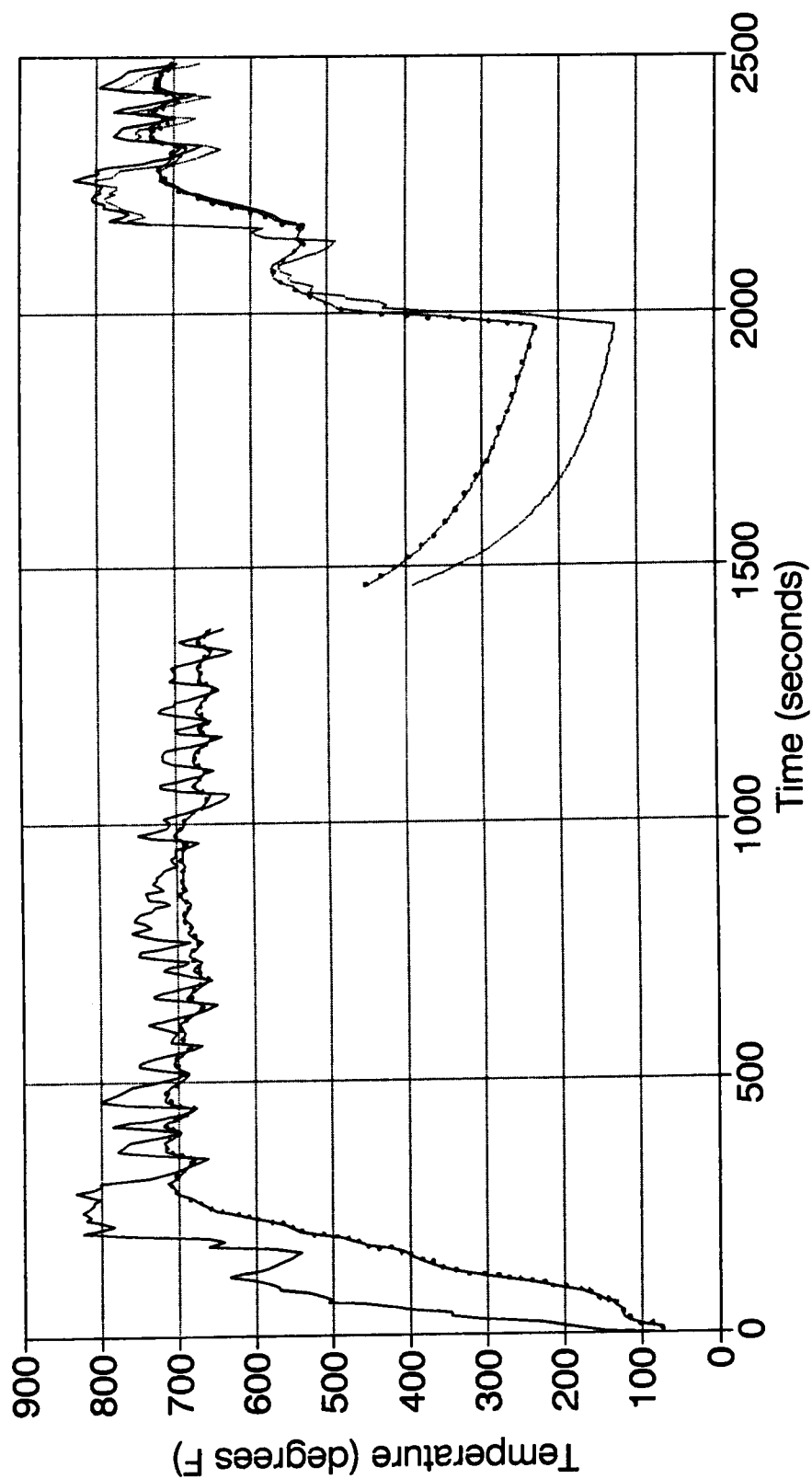


Test 4 NOx: Hot Transient Phase

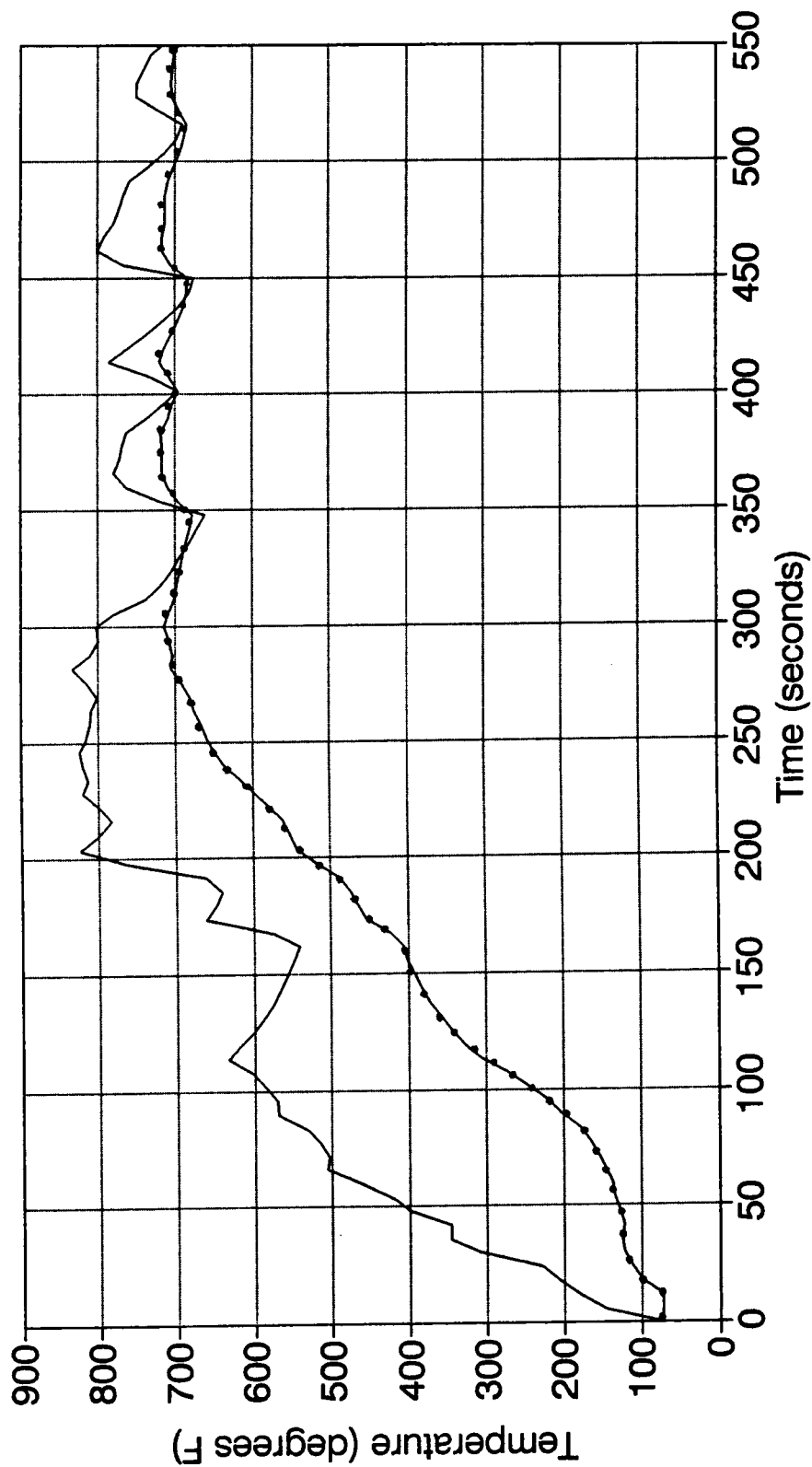


— Control — CCAP

Test 4 Temperatures: Entire Cycle

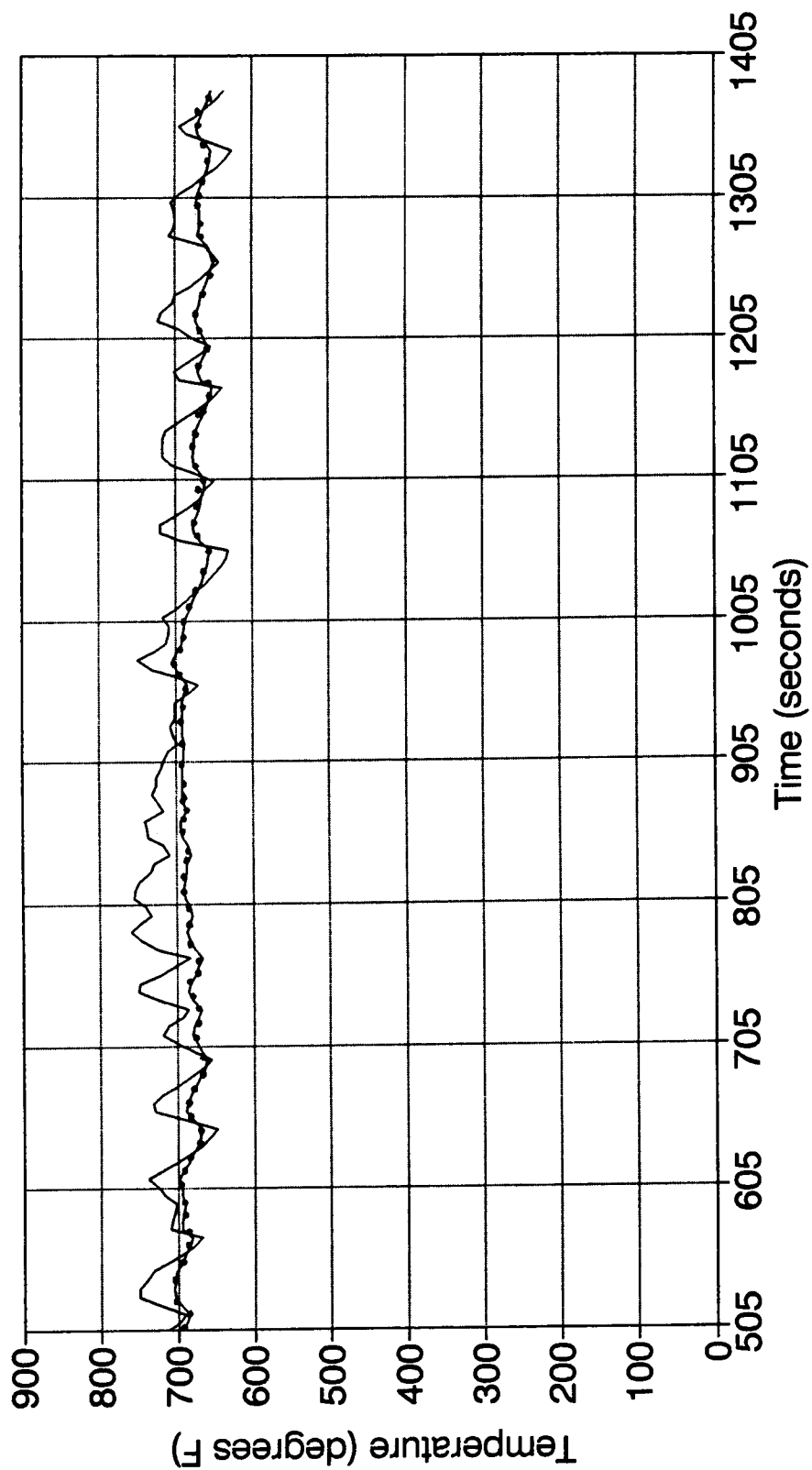


Test 4 Temperatures: Cold Transient



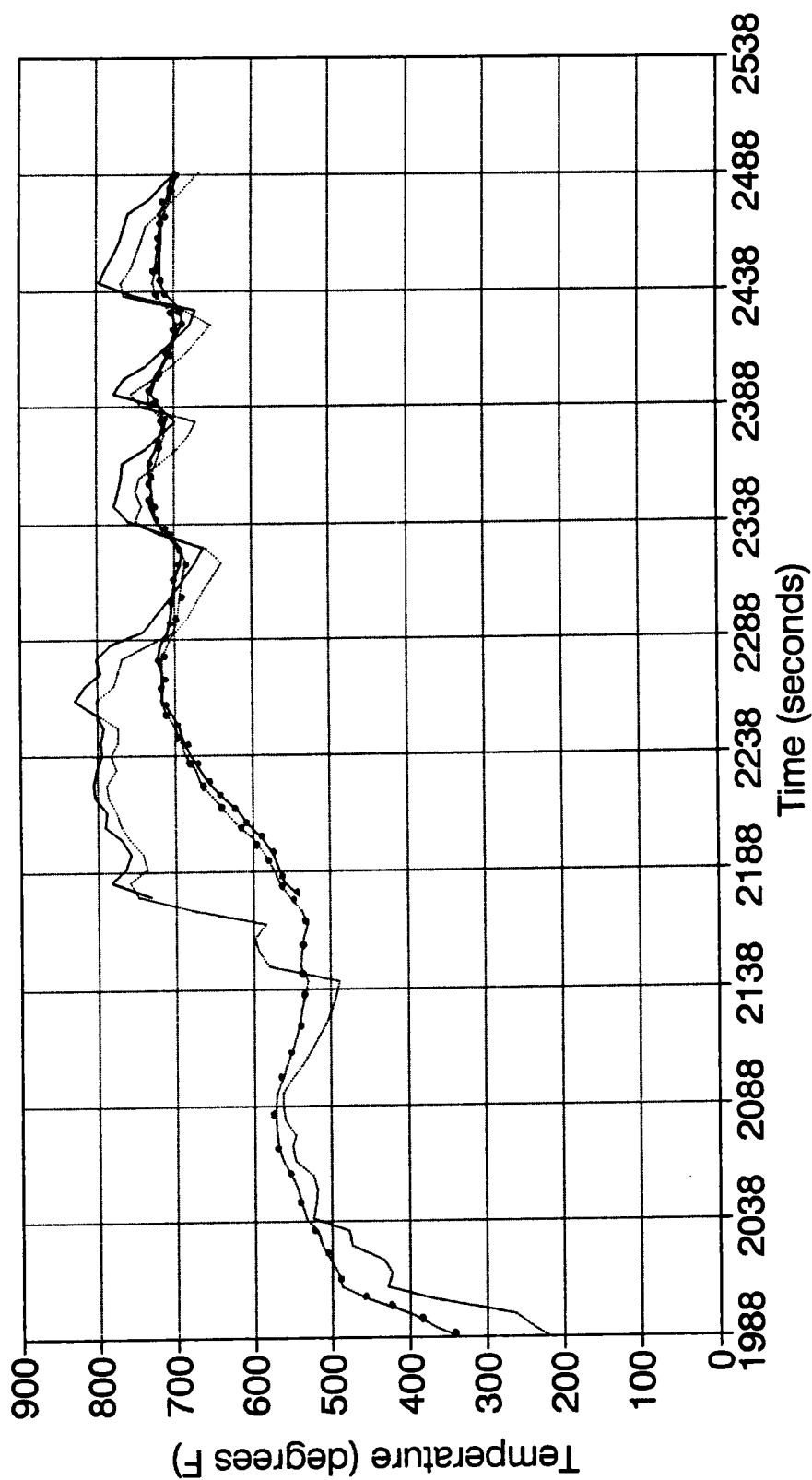
PreCat:Control PostCat:Control PreCat:CCAP PostCat:CCAP

Test 4 Temperatures: Cold Stabilized



— PreCat:Control - - - PostCat:CCAP

Test 4 Temperatures: Hot Transient



— PreCat:Control ··· PostCat:Control — PreCat:CCAP ··· PostCat:CCAP

VITA

Lori Marie Snook was born on March 3, 1970 in Portsmouth, Va. She resided in Virginia until the age of four, when her family moved to Bowie, Md. While in Maryland, she attended several different schools, and graduated from the Eleanor Roosevelt Science and Technology Center in 1988.

Ms. Snook entered the United States Air Force Academy in June 1988 to pursue a B.S. in aeronautical engineering. During her stay at the academy, she was on the dean's, commandant's, and superintendent's lists for outstanding academic and military performance. In the fall of 1989, Ms. Snook transferred to the University of Tennessee to pursue a B.S. in mechanical engineering.

While at the University of Tennessee, Ms. Snook was both the treasurer and chairman of the Society of Automotive Engineers, as well as an active member of Tau Beta Pi, ASME, Pi Tau Sigma, and the Natural Gas Vehicle Challenge. Upon graduation in May of 1992, she was named the Outstanding Senior in the College of Engineering, the Outstanding Senior in Mechanical and Aerospace Engineering, and was recognized for Outstanding Academic Performance in Mechanical and Aerospace Engineering.

In June of 1992, the receipt of both a DuPont Fellowship and Hilton Smith Fellowship allowed Ms. Snook to begin work on her M.S. degree in mechanical engineering. During this time she was also the recipient of a Graduate Research Assistantship. During her graduate career, she made several presentations on natural

gas vehicles and air pollution. In April of 1993, she received a Chancellor's Citation for Extraordinary Professional Promise. She will receive her M.S. in August of 1993.

In the fall of 1993, she will begin work on a PhD in environmental engineering as a National Science Foundation Fellow at the University of Tennessee.