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Sulfate Control Technology Vehicle Testing

SULFATE CONTROL TECHNOLOGY VEHICLE TESTING

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SET	Sulfate Emission Test	2
HWFET	Highway Fuel Economy Test	2
A/F Ratio	Air to Fuel Ratio: Mixture Ratio in LBS of Air/LB of Fuel	4
SEFE	Super Early Fuel Evaporation System	4
EGR	Exhaust Gas Recycle	4
ECU	Electronic Control Unit	6
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SECTION 1

INTRODUCTION

Research described in this report was conducted under EPA Contract No. 68-02-2342, entitled "Sulfate Control Technology Vehicle Testing". The Contract work period spanned from December 1975 to January 1978. The advent of oxidation catalyst emission control systems on 1975 vehicles to control carbon monoxide (CO) and hydrocarbon (HC) emissions raised concern over the formation and emission of sulfates (aerosol sulfuric acid particulates - reference 1). During combustion in the engine most of the gasoline sulfur is oxidized to sulfur dioxide (SO_2). In a non-catalyst equipped vehicle the SO_2 passes through the exhaust system and into the atmosphere undergoing little further oxidation. However, in an oxidation catalyst equipped vehicle the SO_2 is further oxidized to SO_3 over the catalyst along with CO and HC. The resultant sulfur trioxide (SO_3) under exhaust conditions combines with water vapor present from the combustion process to form sulfate ($SO_4^=$) which hydrates to form sulfuric acid. Research programs to determine automotive sulfate emission rates, atmospheric dispersion of sulfates, and human response to sulfates were initiated when public health concerns over sulfate exposure were raised.

When this work was initiated, laboratory studies (2) had found that the dominant factor affecting the rate of sulfate formation (SO_2 oxidation) over oxidation catalysts was the level of oxygen concentration, or, oxygen partial pressure in the feed gas. As the level of oxygen in the catalyst's feed gas was decreased CO and HC oxidation rates fell off, but not as severely as the rate of SO_2 oxidation. At low oxygen partial pressures a "break-point" was found where there was only a small debit in CO and HC conversion efficiencies; yet SO_2 oxidation, and therefore sulfate formation, was almost completely suppressed. Thus, by proper choice of the oxygen partial pressure over an oxidation catalyst, sulfate production could be controlled to low levels without severely affecting CO or HC oxidation.

In 1975 commercial automotive catalysts were oxidation catalysts, which oxidized CO and HC, while leaving NO_x unaffected. Prototype "three-way" catalyst preparations that could simultaneously oxidize and reduce all three (CO, HC and NO_x) automotive gaseous emissions were just becoming available for test work. To operate in this manner, however, the catalyst required that the feed gas proportions of CO, HC, NO_x, and oxygen be very close to a stoichiometric A/F mixture. Because this narrow operating window results in a minimum of excess oxygen over the catalyst, three-way catalysts were also expected to have low sulfate emission levels.

In this contract the design, hardware development, emissions characterization, and long-term durability testing of low sulfate emissions control systems were the research goals. Contract work was divided into three separate tasks:

Task 1 - The design of two catalyst systems which minimized sulfate emissions while maintaining low levels of CO, HC, and NO_x emissions. The first system was to be an oxidation catalyst system making use of the low oxygen partial pressure concept to limit sulfate emissions; while the second was to be a three-way catalyst design for simultaneous control of CO, HC, and NO_x emissions. Systems were to be designed for 80,000 kilometer emission targets of 0.25 g/km HC, 2.1 g/km CO, and 1.2 g/km NO_x on the 1975 CVS COLD-HOT START TEST (FTP). To insure achievement of the 80,000 km emissions limits, 0 km target emission levels were to be 0.12 g/km HC, 1.0 g/km, and 0.6 g/km NO_x (1.2 g/km NO_x if control is by exhaust gas recycle), as measured on the FTP. The sulfate emission target was 6.21 mg/km at 96 km/hr steady state operation. Steady state conditions were chosen for the sulfate testing, rather than the FTP, to minimize the catalyst's storage/release effect on sulfate. This target level corresponds roughly to the sulfate emissions of a non-catalyst equipped vehicle operating under the same cruise conditions (3).

Task 2 - The modification of two vehicles to incorporate the components designed in Task 1. At least one of the vehicles was to be of intermediate size with a V-8 engine. Once assembled, the vehicles emission control systems were to be optimized, so that sulfate and gaseous emissions would meet the specified target levels.

Task 3 - Measure the sulfate, sulfur dioxide, and gaseous emissions of the vehicles at specified intervals over a total accumulation of 80,000 kilometers. Both vehicles would be tested at accumulation points 0 km, 2,000 km, 6,000 km, 30,000 km, 60,000, and 80,000 km. Emissions were to be measured during the test sequence of:

FTP (Federal Test Procedure)
20 Minute Idle Period
2-SET'S (Sulfate Emission Test)
HWFET (Highway Fuel Economy Test)
2-SET'S
2 Hours - 96 km/hr Cruise

The time variation of sulfate emissions, deterioration of catalyst CO, HC, and NO_x conversion efficiencies, and emission control system mechanical hardware durability were among the parameters of importance that would be determined from kilometer accumulation.

An eight month time period was allotted for performance of these contract tasks. As will be discussed in more detail in the report, hardware failures and design inadequacies in the original vehicles chosen necessitated a contract modification (68-03-2342 Modification No. 1) at the expiration of the contract time period. All work on the two original vehicles/emission control systems were stopped, two new vehicles/emission control systems were chosen (Task 1), and their assembly and testing (Tasks 2 and 3) were to be completed within an eight month contract extension. In addition, the modification added hydrogen cyanide (HCN) and ammonia (NH_3) to the set of emissions to be measured during the testing sequence. Hydrogen cyanide and ammonia emissions, like sulfates, are unregulated emissions. The sampling and analytical techniques for determining the tailpipe levels of these unregulated pollutants are discussed in detail in References (4) and (5). Characterization of vehicle HCN and NH_3 emission magnitudes and rates, although not of prime concern to the contract goals, was added so that preliminary data could be quickly accumulated by the EPA.

SECTION 2

OVERVIEW

The purpose of this section is to summarize in concise form the work performed and events that occurred during the contract time period, as well as to establish the "contract tasks" that were completed. A detailed treatment of the information contained in this overview is presented in individual sections that comprise the main body of the report.

Two catalyst system designs were originally chosen to fulfill the requirements of the contract. They were: (1) a "low excess air" vehicle equipped with V-8 engine and oxidation catalyst and (2) a three-way catalyst equipped vehicle with a closed-loop electronically controlled fuel metering system with an oxygen sensor. The low excess air vehicle, by proper control of engine air-fuel ratio (A/F), would maintain the oxidation catalyst at the low oxygen partial pressures necessary for the minimization of sulfate formation. Thus, the vehicle would use the oxidation catalyst for control of CO and HC emissions. By controlling the excess air level over the catalyst, sulfate emissions would be comparable to that of a non-catalyst vehicle. The three-way catalyst equipped vehicle would also require precise control of engine A/F ratio so that the three-way catalyst could be maintained within its' operating window. A prototype system for electronic control of engine A/F ratio developed by the Robert Bosch Corporation was chosen for A/F control on this vehicle. The Bosch fuel injection system (K-JETRONIC) was modified with an oxygen sensor and closed loop feedback control to modulate the amount of fuel injected to the engine; and thus it could maintain a set A/F ratio value, even during transient driving modes. This system made it possible to use a three-way catalyst on a vehicle to simultaneously control CO, HC and NO_x emissions. The requirements of Tasks 1 and 2 were fulfilled by these two designs. One made use of the low oxygen partial pressure effect, and also included a V-8 engine, while the other incorporated a three-way catalyst into a prototype vehicle system.

Once conceptual design of the systems and their expected emissions were established, hardware development and optimization on the vehicles began.

2.1 LOW EXCESS AIR VEHICLE

A 1975 Chevrolet Malibu equipped with a 350 cubic inch displacement V-8 engine was chosen as the vehicle to be modified. The low excess air system that was installed consisted of: a "flat" air-fuel ratio (A/F) carburetor, super early fuel evaporation system (SEFE), close-coupled (warm-up) and main oxidation catalysts, and backpressure modulated (proportional) exhaust gas recirculation (EGR). Carburetion was jetted to provide the proper "slightly lean" A/F necessary to obtain low excess air conditions over the catalysts. In addition, the carburetor was modified to give constant A/F over the full range of engine air demand. This "flatness" of A/F insured that the proper catalyst environment would be maintained regardless of driving mode. To meet the low gaseous emission levels required by the contract, the system design required extremely rapid opening of the carburetor choke. The removal of A/F enrichment due to rapid choke pull off coupled with an already fuel lean mixture was expected to create serious cold driveability problems. To offset this, a SEFE system was included in the vehicle design. Its' function was to divert all of the hot engine exhaust gas through passages in the intake manifold. The heat supplied to the manifold runners and the carburetor base was expected to prevent fuel condensation, and enchance cold driveability. Construction of the SEFE system involved extensive modifications to the intake manifold. To ease fabrication (welding and machining), an aftermarket aluminum manifold was substituted for the production cast iron unit.

Once the low excess air system hardware was installed, optimization of the vehicle began. Poor driveability was experienced upon cold start. The vehicle repeatedly surged, backfired, and stalled during the first (cold) bag of the FTP cycle. The poor cold driveability suggested that the SEFE system was not operating properly. Many problems were identified, for instance, SEFE (Diverter) heat riser valves that did not seal, a defective EGR valve and maldistribution of EGR flow within the intake manifold. All these problems were resolved successfully, yet the vehicle still did not exhibit good cold driveability. Even with the choke set rich to prevent stalls, severe hesitation and sluggish accelerations persisted during warm-up. Exhaust emissions control was also poor. FTP emissions were well above the contract 0 km targets, in fact, they exceeded the 80,000 km limits. The lowest FTP emissions observed were with the SEFE and starter oxidation catalyst out of the system and normal choke opening during cold start operation. However, even under these conditions, emission levels exceeded 0 km targets.

It had become apparent that the vehicles' SEFE system impared cold start driveability, rather than enhancing it. It was suspected that the aluminum manifold conducted too much heat away from the carburetor base, and fuel condensation was causing the repeated stalls. The hesitation and sluggish acceleration performance were also attributed to the SEFE system; since with it disabled, the vehicle performed normally. During SEFE operation the entire engine's exhaust gas was diverted through passages of about one fifth the crossectional area of the vehicles exhaust system. This flow restriction could cause high exhaust back-pressures during accelerations, and result in sluggish performance.

At this point work on the low excess air vehicle was stopped. A new design, or considerable modifications to the original vehicle were required to continue testing. Discussions were held with the EPA to assess alternative low excess air design strategies. Thus Task 1, the conceptual system design, and Task 2, vehicle modification to incorporate the design, were considered to be completed on this vehicle. Task 3, the 80,000 km emissions and durability testing, was never begun due to the high emissions levels and poor driveability experienced during preliminary FTP testing.

2.2 THREE-WAY CATALYST VEHICLE

A 1975 Volvo equipped with a fuel injected 2.0 litre L-4 engine was chosen for modification. Since both the production Volvo, and the advanced feedback controlled fuel injection systems were built by Bosch, little hardware design and fabrication was expected in the fuel metering system modifications needed to incorporate a three-way catalyst. The production fuel injection system could be easily converted to the advanced closed-loop form by the addition of some components, which Bosch agreed to supply.

Components supplied by Bosch were installed on the 1975 Volvo to convert its' fuel injection to the closed loop feedback control system. They included: an oxygen " λ" sensor, electronic control unit (ECU), oxygen sensor threshold voltage trimbox, recalibrated warm-up regulator, fuel distributor with frequency modulated (solenoid) pressure control valve, and a revised air flow rate sensing unit. To complete the system an Engelhard TWC-9 monolithic three-way catalyst was installed in place of the production oxidation catalyst.

In preliminary testing, during which ECU control settings and oxygen sensor threshold voltage levels were optimized, cold engine starting problems were discovered. The engine would start, run about two seconds, and then stall. Restarting required extended engine cranking. Once started, the engine performed poorly (stalls, hesitation, and backfire) until completely warmed up. Hot starting presented no difficulty, and hot engine performance was very good. Because of this behavior, a defective warm-up regulator was suspected. After many recalibrations by Bosch, which resulted in no significant improvement, the entire fuel injection system was returned to Bosch in Chicago. It was found that an incorrect component installation diagram had been furnished with the system. Because of this, the warm-up regulator had been installed backwards, with its' inlet and outlet connections reversed. With the system installed correctly, the engine started and performed smoothly even when cold. Emissions were below 0 km contract target levels.

In addition to the contract tasks, the three-way catalyst Volvo was one of about 70 different vehicles selected by the EPA to be used in another study at ER&E to set up a sulfate test. From a timing point of view it was desirable to complete these studies before initiating the 80,000 kilometer accumulation. It was also felt that the 800 km conditioning required for the sulfate test study would provide a shakedown for the system. After the 800 km accumulation the car stalled repeatedly during start-up. A number of problem areas were indentified: the air bellows between the airflow control sensor and the intake manifold had loosened, the flange at the exhaust manifold had come loose, an intermittant short had developed in the oxygen sensor lead, two fuel injectors leaked, an electrical connection had come loose at the cold start injector, spark plugs that were marginal, and an oxygen sensor that was defective. With these problems repaired the vehicle started normally, and emissions were below 0 km target levels.

Before initiating the 80,000 km accumulation the TWC-9 catalyst, at the EPA's request, was replaced by an Engelhard TWC-9B monolithic three-way catalyst. Emission tests were carried out as required after 2,000 km, 6,000 km, and 15,000 km were accumulated on the vehicle. NO_x levels during cold start FTP's remained constant, while CO and HC levels tended to increase with accumulated kilometers. CO emissions at the 15,000 km point exceeded the 80,000 km target levels. $SO_4^=$ emissions were well below contract target levels for 96 km/hr cruise conditions. A tune-up reduced the CO level to 2.0 gm/km, and km accumulation was resumed. At 27,000 km emissions were checked to see if any deterioration had occurred which could be corrected before the scheduled 30,000 km test sequence. CO again exceeded the maximum target level, while HC and NO_x increased to the 80,000 km limit. Even after replacement of the O_2 sensor, emission levels were very close to the 80,000 km limits. These results indicated that the three-way catalyst had lost much of its' activity.

At this point, for the three -way catalyst vehicle, Tasks 1 and 2 were considered to be completed. Task 3, however, was never completed to the full 80,000 kilometers due to the evident catalyst deterioration seen at 30,000 kilometers.

CONTRACT MODIFICATION

This juncture in the Volvo three-way catalyst vehicle work corresponds to the point in time when contract work was discontinued on the low excess air vehicle. A contract modification was made (September 1976) stating that all contract work on the original vehicles/emission control systems stop immediately, and two new vehicles/emission control systems be chosen for the low excess air and three-way catalyst approaches.

It was decided to restart the three-way catalyst part of the contract using a factory built prototype three-way catalyst equipped Volvo. Through negotiations between the EPA and Volvo of America, a prototype 1977 "Lambda-Sond" Volvo was made available to ER&E for testing. In addition to determining the vehicles' 80,000 km durability for regulated emissions, the levels of unregulated emissions ($SO_4^=$, NH_3, and HCN) would be monitored during the accumulation.

A new conceptual design for the low excess air vehicle was agreed upon. It called for:

(1) An advanced fuel metering system (carburetor or fuel injection) to maintain engine A/F slightly lean of stoichiometric.

(2) Either a prototype mine-mix three-way catalyst or oxidation catalyst.

(3) Back-pressure modulated EGR system.

(4) The limited use of excess air (air pump) during cold start operation.

(5) Optional (depending on the fuel metering system) exhaust gas oxygen sensing and closed loop feedback control.

2.3 THREE-WAY CATALYST VEHICLE - DESIGN #2

A prototype 1977 Volvo with a redesigned 2.0 litre L-4 cylinder engine (overhead camshaft versus the first three-way catalyst vehicle's push-rod operated 2.0 litre engine) and "Lambda-Sond" three-way catalyst system was selected as the vehicle to be tested. The Lambda-Sond system, which is supplied to Volvo by Bosch, was an improved version of the fuel injection system that was installed on the first three-way catalyst demonstration vehicle. It uses electronic feedback control with an oxygen sensor to modulate the vehicle's fuel injection system. A/F ratio is maintained at the desired value by varying the amount of fuel delivered to the engine.

The only vehicle modification made was the substitution of a mine-mix three-way catalyst containing about 5% rhodium in place of the original rhodium enriched certification catalyst (~17% Rh).

The vehicle passed 0 km emissions targets for HC and NO_x with both the certification and mine-mix three-way catalysts. Although CO emissions (with both catalysts) were slightly above the 0 km target, they were well below the 80,000 km maximum level, and durability testing was initiated. The entire 80,000 km of durability testing were successfully completed with only minor malfunctions in the Lambda-Sond system and a few mechanical vehicle failures. For instance, the water pump and engine cooling fan clutch had to be replaced. A small fluid leak developed in the automatic transmission which required a gasket replacement. Finally, near the end of the accumulation interval the right rear wheel bearing seized and caused the right axle shaft to break. After repairing the axle and bearings, kilometer accumulation continued with no further mechanical trouble to the 80,000 km finish. Problems with the Lambda-Sond system included a cracked fuel injector retainer which caused an air leak, one leaking fuel injector, and broken wires to the frequency control solenoid valve on the fuel distributor.

Throughout the 80,000 km durability testing interval both HC and NO_x emissions (as measured on the FTP) remained below the maximum target levels. CO, however, exceeded the maximum target level at 15,000 km and continued to increase with accumulated kilometers. At the final 80,000 km test point, CO emissions were 60% greater than the maximum allowable limit. Raw exhaust emission tests revealed that although CO had increased greatly, conversion efficiency for the catalyst was greater than 60%. Efficiencies for HC and NO_x conversion were about 80% and 60% respectively.

Sulfate ($SO_4^=$) emissions remained well below the maximum target levels (at the 96 km/hr cruise test mode) over the entire test interval.

Thus the prototype 1977 Volvo three-way catalyst vehicle completed the contract tasks. The entire kilometer accumulation was completed with the full set of required emissions measured at the specified intervals. The vehicle, equipped with a mine-mix three-way catalyst met the 80,000 km contract targets of 2.1 CO/0.25 HC/1.2 NO_x (g/km) and 10 mg $SO_4^=$/km, except for CO. Emissions of NH_3 and HCN were also monitored. Both remained at low levels over the durability interval.

2.4 LOW EXCESS AIR VEHICLE - DESIGN #2

A new low excess air vehicle was designed for testing under the contract modification. It consisted of a 1977 California emissions certified Ford Pinto (2.3 litre overhead camshaft L-4 engine, back-pressure modulated EGR, air pump and oxidation catalyst), that was modified for low excess air operation with a Holley closed loop feedback controlled carburetor with oxygen sensor, and an Engelhard monolithic oxidation catalyst. The advantages of this particular design were, (1) installation of the Holly feedback carburetor system on the 1977 Pinto would require a minimum of mechanical work, since 1978 California three-way catalyst Pinto's were to be produced with the same system, (2) Holley agreed to modify the electronic control unit for the feedback carburetor so it could be set for low excess air conditions, rather than three-way catalyst operation, (3) Holley agreed to furnish technical assistance as required, and (4) Engelhard would supply a monolithic catalyst of suitable size and "composition" to provide good conversion activity under low excess air conditions.

Installation of the feedback carburetor system proceeded smoothly after an incorrect installation schematic diagram was replaced by Holley. Optimization was begun to determine the correct electronic control unit (ECU) biasing for low excess air operation. With the production catalyst operating under low excess air conditions, FTP CO emissions were an order of magnitude higher than for the vehicle in stock configuration. Adjustment of automatic choke "pull-off" rate and recalibration of the ECU's cold start enrichment circuit lowered first bag (cold start) CO levels. Weighted FTP CO emissions, though reduced, still exceeded the both 0 and 80,000 km contract targets. Further adjustments would not lower CO emissions.

Catalyst temperature traces indicated that the production Ford monolith required over three minutes to achieve "light-off" on cold start. Substitution of an Engelhard PTX-514 monolith (a known active oxidation catalyst) reduced light-off time to about one minute. Furthermore, first bag CO levels were decreased threefold, and total weighted FTP CO and HC levels were below the 0 km targets. NO_x emissions, however, increased and exceeded the 80,000 km maximum limits. This NO_x increase was attributed to the PTX-514 catalyst's different composition. That is, during rich transients the PTX-514 reduced less NO_x than did the production Ford catalyst. Adding credence to this argument was the fact that raw exhaust (no catalyst) FTP data showed even higher NO_x levels than those seen with the PTX-514.

Increasing EGR rate reduced NO_x to within contract targets, but CO emissions increased slightly. Although CO was slightly above the 0 km target level, it was well below 80,000 km maximum limits. Because of this, it was decided to start kilometer accumulation. The PTX-514 (68 in^3) catalyst was replaced by an Engelhard PTX-516 monolith (102 in^3). It was expected the larger catalyst volume would help offset the effects of catalyst deterioration, making achievement of the 80,000 km goal more certain. With the PTX-516, the vehicle met all contract targets at zero kilometers, and was sent out for the first 2,000 km durability interval.

The feedback carburetor system was plagued with operating and durability problems from the time it was installed. Vacuum control regulator valves which interface the ECU to the feedback carburetor were very susceptible to plugging. Many times during calibration and optimization runs, the regulator valve would become plugged, causing the feedback system to fail full rich. This problem was attributed to the small (0.030 inch) air bleed orifices in the valve which could easily be plugged.

In addition to this problem, the particular feedback carburetor used in the program suffered durability problems. At the end of the first 2,000 km durability interval CO emissions had increased, and the system would not control A/F properly. Holley agreed, at ER&E's request, to send an engineer and repair the failure. He recommended that the carburetor be returned to the factory. It was found that the carburetor had shifted from its original calibration and had to be readjusted.

In repairing the carburetor a transition region instability appeared. In the region of transition from the idle to main jet circuits, raw fuel dripped from the main jet nozzle and puddled on the throttle plate. As a result CO emissions oscillated sharply, and the system could not maintain A/F control. FTP CO emissions were in excess of the 80,000 km limits. The carburetor was returned to Holley for idle/main jet reproportioning. However, they remarked that it could take several iterations to solve the problem. Testing of the repaired carburetor revealed that although the instability speed range had been narrowed, CO emissions were still above contract limits. Another iteration would have to be made to solve the problem.

It was jointly agreed by ER&E and the EPA that contract work on the second low excess air vehicle be terminated based upon achievement of 0 km emission goals.

Thus for the second low excess air vehicle, Tasks 1 and 2 were completed. Task 3, however, was dropped from the contract requirements because of recurring feedback carburetor system failures. The vehicle met all 0 kilometer contract targets, including that for $SO_4^=$. This shows that the low excess air concept does inhibit oxidation catalyst sulfate production, and is technically feasible for application to motor vehicles.

TASK ACCOMPLISHMENT

A summary of the vehicles designed and fabricated, as well as the progress toward completion of required contract tasks is found in Table 2-1.

TABLE 2-1

SUMMARY OF VEHICLES TESTED AND CONTRACT TASKS ACCOMPLISHED

Vehicle	Task 1 (Conceptual Design)	Task 2 (Modification & Fabrication)	Task 3 (80,000 km. Durability Testing)
Low Excess Air Vehicle Design #1 (1975 Chevrolet Malibu)	Completed	Completed	Deleted with EPA Approval
Three-Way Catalyst Vehicle Design #1 (1975 Volvo)	Completed	Completed	Carried to 30,000 km. Stopped with EPA Approval
Three-Way Catalyst Vehicle Design #1 (1977 Prototype "Lambda-Sond" Volvo)	Completed	Completed	Completed
Low Excess Air Vehicle Design #2 (1977 Ford Pinto)	Completed	Completed	Terminated with EPA Approval

SECTION 3

CONCLUSIONS

A total of four vehicles, two low excess air-oxidation catalyst systems and two three-way catalyst systems, were built to demonstrate the feasibility of low sulfate production automotive emission control technology. General conclusions drawn from the testing of these vehicles are summarized below.

Low Excess Air Vehicles

Application of the "low excess air" concept to automotive emission control systems that utilize oxidation catalysts is technically feasible, and controls sulfate emissions to levels comparable to those of non-catalyst vehicles.

To successfully implement the low excess air concept on a vehicle, two key system design criterion have to be met. First, the engine's fuel metering system must be capable of precisely controlling A/F ratio at the required "slightly lean" value regardless of vehicle driving mode. This is necessary so that a low oxygen partial pressure atmosphere is consistently maintained over the oxidation catalyst to minimize sulfate formation. Second, the oxidation catalyst bed must light-off quickly from cold start conditions. This is especially important since catalyst CO and HC conversion efficiencies are reduced when operating under low excess air conditions. The compounding of reduced catalyst conversions with slow light-off would result in unacceptably high tailpipe emission levels.

The design criteria outlined above are a result of experience gained from fabricating and testing of two low excess air demonstration vehicles. It should be kept in mind that although individual system components will vary depending on the particular vehicle application, these two basic design premises must be followed to insure technical success.

Three-Way Catalyst Vehicles

Three-way catalyst's are a viable technology for low sulfate production automotive emission control systems. Testing of the two contract demonstration vehicles has shown that three-way catalyst systems simultaneously control all three regulated emissions (CO, HC, NO_x) to stringent levels, while emitting very low levels of sulfate, ammonia, and hydrogen cyanide.

Vehicle fuel metering is a primary concern in the design of a three-way catalyst system. Unless the three-way catalyst is maintained within it's operating window by precise control of the engine at a stoichiometric A/F ratio, losses in conversion efficiency will be experienced.

In testing of the demonstration vehicles both three-way catalyst's (one preparation rhodium enriched, the other mine-mix) suffered deactivation with age. In general, for both catalysts CO emissions increased significantly with accumulated kilometers, while HC and NO_x emissions also increased, but to a lesser extent.

SECTION 4

RECOMMENDATIONS

Two approaches for low sulfate production automotive emission control systems were evaluated under this contract. Recommendations for future work in these areas are given below.

Low Excess Air-Oxidation Catalyst Systems

Although the low excess air concept was successfully demonstrated, recurring hardware failures in the demonstration vehicle's fuel metering system prevented durability testing. It is expected that the durability problems encountered with the prototype fuel metering system (Holley feedback carburetor system) will be resolved as system production and vehicle application increases.

Future work, then, should be directed toward studying the long-term effects of kilometer accumulation on low excess air system components. In particular, the effect of operating under low excess air conditions on oxidation catalyst deterioration over 80,000 km remains undetermined. Remaining questions to be answered include: the effect of catalyst composition on conversion activity under low excess air conditions, and, the effect of increasing catalyst bed oxygen levels on vehicle tailpipe CO, HC and $SO_4^=$ emission levels.

Three-Way Catalyst Systems

The substantial deactivation seen during durability testing of both rhodium enriched and mine-mix rhodium ratio three-way catalysts pointed out a need for catalyst development work. Since work on this contract was completed several manufacturers have commercialized three-way catalyst vehicles with good 80,000 km. durability. System hardware and catalysts necessary for three-way catalyst operation are durable, and are currently available in production vehicles. The application of feedback carburetor technology to three-way catalyst systems has no technical barriers, other than the durability problems, mentioned in connection with the low excess air catalyst systems.

SECTION 5

LOW EXCESS AIR VEHICLE - DESIGN NO. 1

5.1 DESIGN AND FABRICATION

A 1975 Chevrolet Malibu equipped with a 350 cubic inch displacement V-8 engine and automatic transmission was chosen as the vehicle to be modified. The low excess air system design consisted of:

(1) Research Carburetor

(2) Super Early Fuel Evaportion System (SEFE)

(3) Proportional Exhaust Gas Recirculation (EGR)

(4) "Starter" and "Main" Oxidation Catalysts

A discussion of each of the systems components follows.

Research Carburetor

In order to maintain the low excess air conditions that are necessary for low sulfate production from an oxidation catalyst, the A/F ratio inducted to the engine must be maintained slightly lean of stoichiometric, at approximately A/F = 15/1. Exxon Research and Engineering obtained from General Motors a "research" carburetor that could be jetted to provide a wide range of A/F ratios, was repeatable, and could maintain the set A/F ratio over the full range of throttle openings. This "flatness" of A/F ratio was a necessity for the operation of the low excess air vehicle. Rich deviation from the desired 15/1 A/F ratio would place the catalyst in a reducing regime where conversion levels of CO and HC were low, resulting in increased tailpipe emissions. Lean deviation would not affect conversion levels of the oxidation catalyst, but would increase sulfate production.

The research carburetor was installed on the vehicle in place of the production carburetor. A number of main jets were tested to find the size that gave the desired A/F ratio for low excess air conditions. As can be seen from Table 5-1 A/F ratio was fairly sensitive to changes in main jet diameter. For a fixed main jet diameter, however, A/F ratio was relatively constant across the speed range tested. This A/F flatness is especially apparent when the speed-A/F variations of the production carburetor are compared to those of the research carburetor.

Table 5-1

EFFECT OF MAIN JET SIZE ON A/F RATIO

	Jet Diameter (Inches)	Idle	A/F Ratio At 48 kph	80 kph
Research Carburetor	0.0415	16.2	16.3	16.5
	0.0425	15.4	15.5	15.6
	0.0432	15.0	15.6	15.5
	0.0440	15.9	14.8	14.7
Production Carburetor	0.040	17.3	16.5	15.5

A main jet diameter of 0.0425" was chosen for the test vehicle since it provided the flattest A/F-speed response and was relatively close to the desired A/F ratio.

Super Early Fuel Evaporation System

Since the design of the low excess air vehicle did not include an air pump, catalyst light-off from a cold start would be slow. To compensate for the resultant loss of CO control in Bag 1 (cold bag) of the FTP, it was desired to open the carburetor choke as rapidly as possible. This reduction of A/F enrichment due to rapid dechoking coupled with a nominally lean A/F mixture was expected to create serious cold driveability problems. To offset this a super early fuel evaporation system (SEFE) was designed for the vehicle.

Figure 5-1 shows a pictorial diagram of the SEFE system. In the cold start mode early fuel evaporation (EFE) valves 1 and 2 are closed, and EFE valve 3 is open. Hot exhaust gases from the combustion chambers are blocked from flowing out through the exhaust manifolds. Instead, all of the exhaust gas is diverted internally through the intake manifold's crossover into a plenum chamber. This chamber is vented by an auxiliary exhaust pipe which rejoins the vehicle's exhaust system downstream of the exhaust manifolds. The rapid heating of this plenum, which forms most of the intake manifold floor under the carburetor base, promotes the vaporization of condensed fuel puddles and thus should enhance cold driveability with lean A/F mixtures. In hot mode operation EFE valves 1 and 2 are opened, while EFE valve 3 is closed. Engine exhaust then follows the normal path out of the exhaust manifolds and into the vehicle's exhaust system. The three EFE valves used to divert exhaust gas flow were standard production units with vacuum motor actuators. They were modified for remote switching from the passenger compartment by placing electrically operated solenoid valves in their vacuum supply lines.

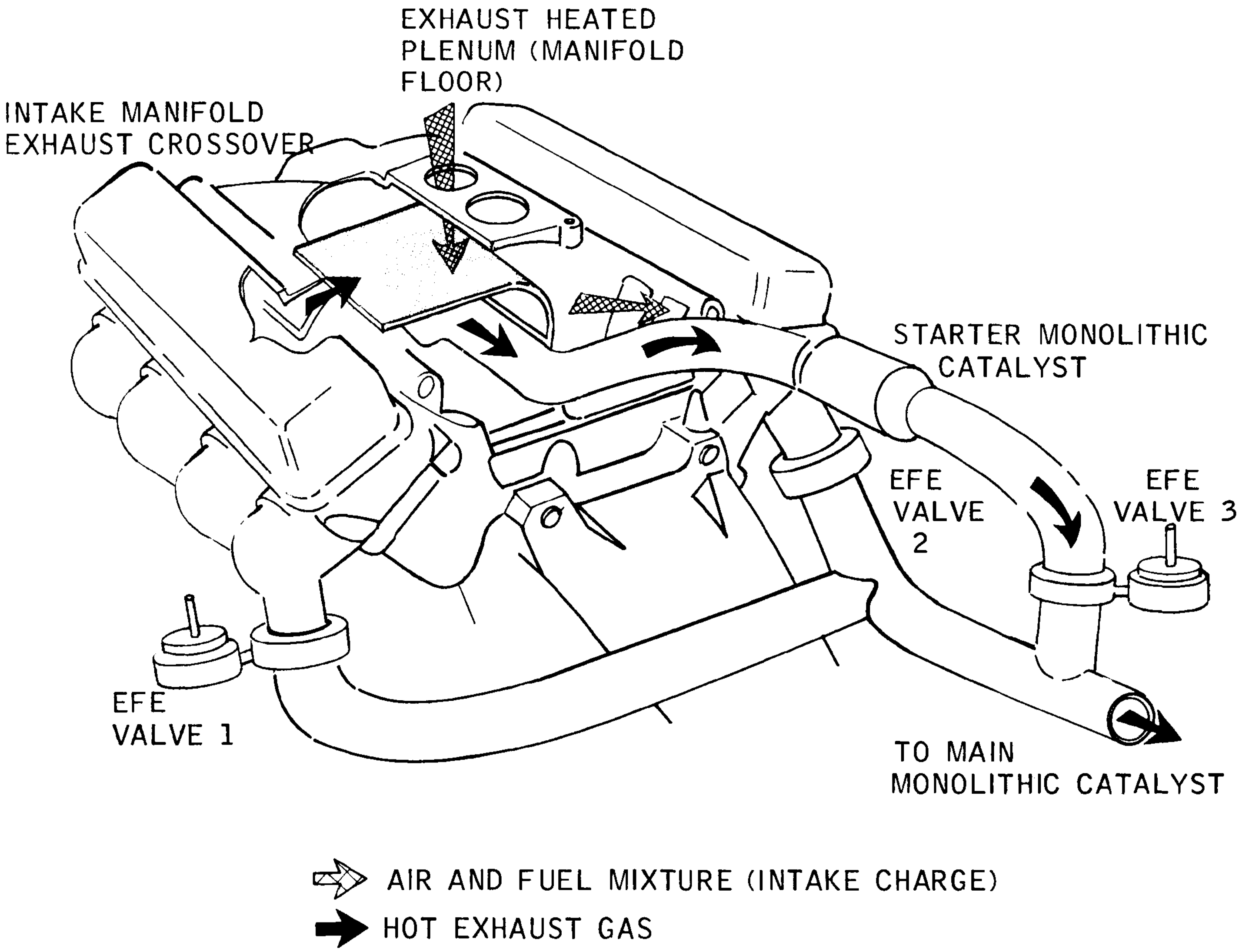


FIGURE 5-1

SEFE SYSTEM PICTORIAL DIAGRAM

The SEFE system differed from production early fuel evaporation systems in that all of the engine exhaust was diverted through the intake manifold. In production systems only one exhaust manifold is partially blocked off during cold start operation. Exhaust gas is diverted up through the intake manifold and out through the opposite cylinder head and exhaust manifold. Production EFE systems, therefore, do not have an auxiliary exhaust passage from the intake manifold. Because there is less total exhaust gas flow, plenum heating rates are slower, and final intake manifold floor temperature is lower than for the SEFE system.

Construction of the SEFE system involved extensive modifications to the intake manifold. To ease fabrication (e.g. welding and machining), a cast aluminum manifold - Edelbrock "Streetmaster" Model 3025 was substituted for the production cast iron manifold. Figure 5-2 is a top view of the aluminum manifold before SEFE modifications were made. In Figure 5-3 the entrance port to the intake manifold exhaust crossover passage is shown within the circle. This passage leads to the exhaust plenum chamber, which forms the heated intake manifold floor under the carburetor base. The plenum chamber, of course, is not visible in the photograph since it is an internal cavity. The chamber boundaries, however, are approximately those shown by the dotted lines. The auxiliary exhaust passage required to vent the plenum chamber is shown in Figure 5-4 and 5-5. The original design specification for a 5.08 cm (2 in.) pipe size could not be met due to space constraints. Instead, a 3.81 cm (1.5 in.) exhaust line was installed. Also shown in Figure 5-5 are the locations of the exhaust crossover passages and the plenum chamber. A bottom view of the aluminum intake manifold is shown in Figure 5-6. In this photograph the transition piece that was fabricated to connect the plenum chamber to the auxiliary exhaust pipe is visible.

The routing of hot exhaust gas through the SEFE system is shown in Figure 5-7. During cold start operation the exhaust manifolds are blocked-off by closed EFE valves. Exhaust is diverted up through the cylinder heads, and into the intake manifolds exhaust crossover passage. This hot gas flows through (and thus heats) the plenum chamber and is vented from the manifold by the auxiliary exhaust passage. The passages and plenum shown in the preceeding figures are internal cavities located beneath the intake manifold floor and runners.

Proportional Exhaust Gas Recycle (EGR) System

The low excess air vehicle design specified exhaust gas recycle (EGR) for control of NO_x emissions to within contract target levels. An EPA supplied EGR valve was installed on the vehicle. Valve calibration was "proportional", that is, the amount it opened was a direct function of the airflow through the engine. The valve was adjustable, in that different springs could be placed in the actuator's

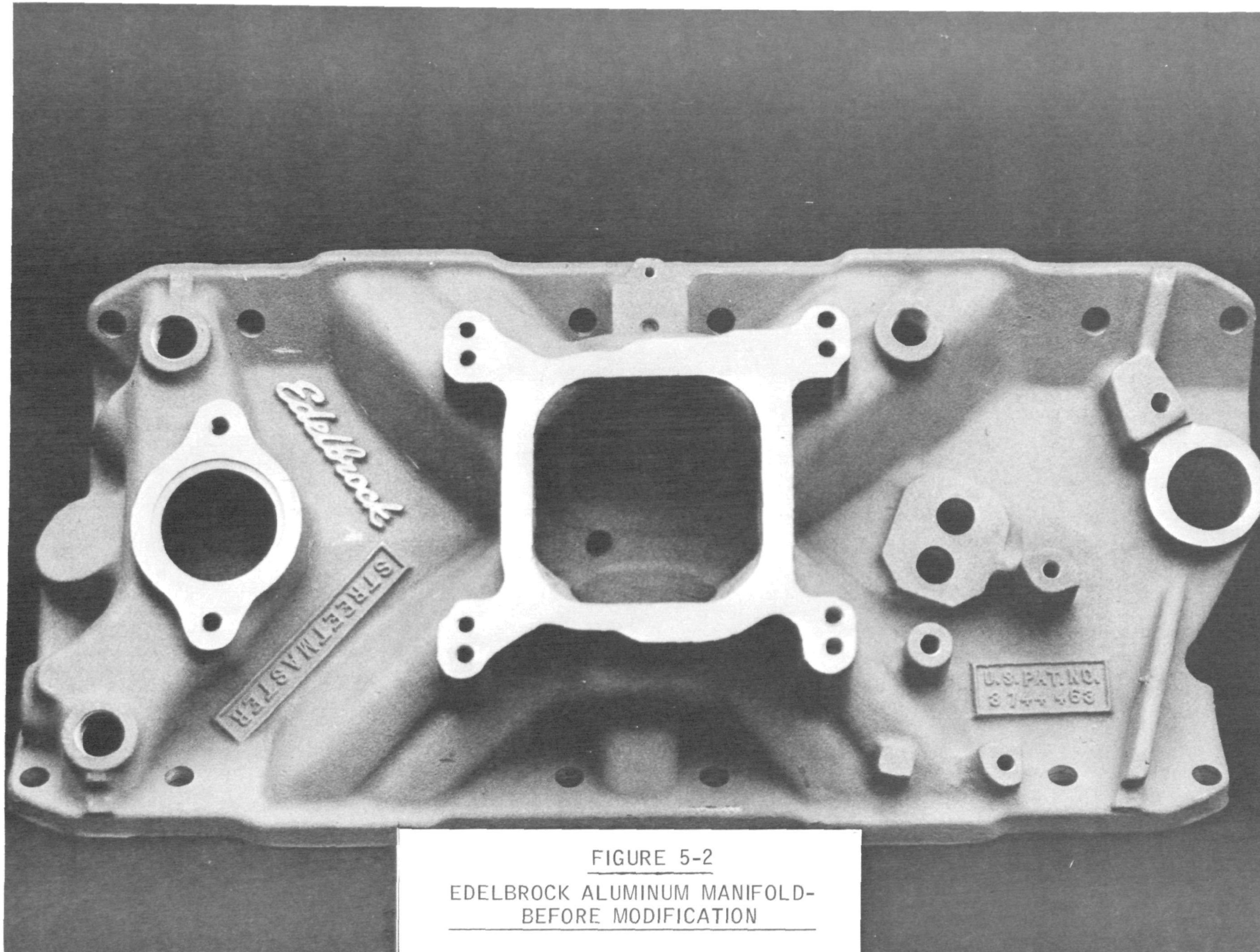


FIGURE 5-2

EDELBROCK ALUMINUM MANIFOLD-
BEFORE MODIFICATION

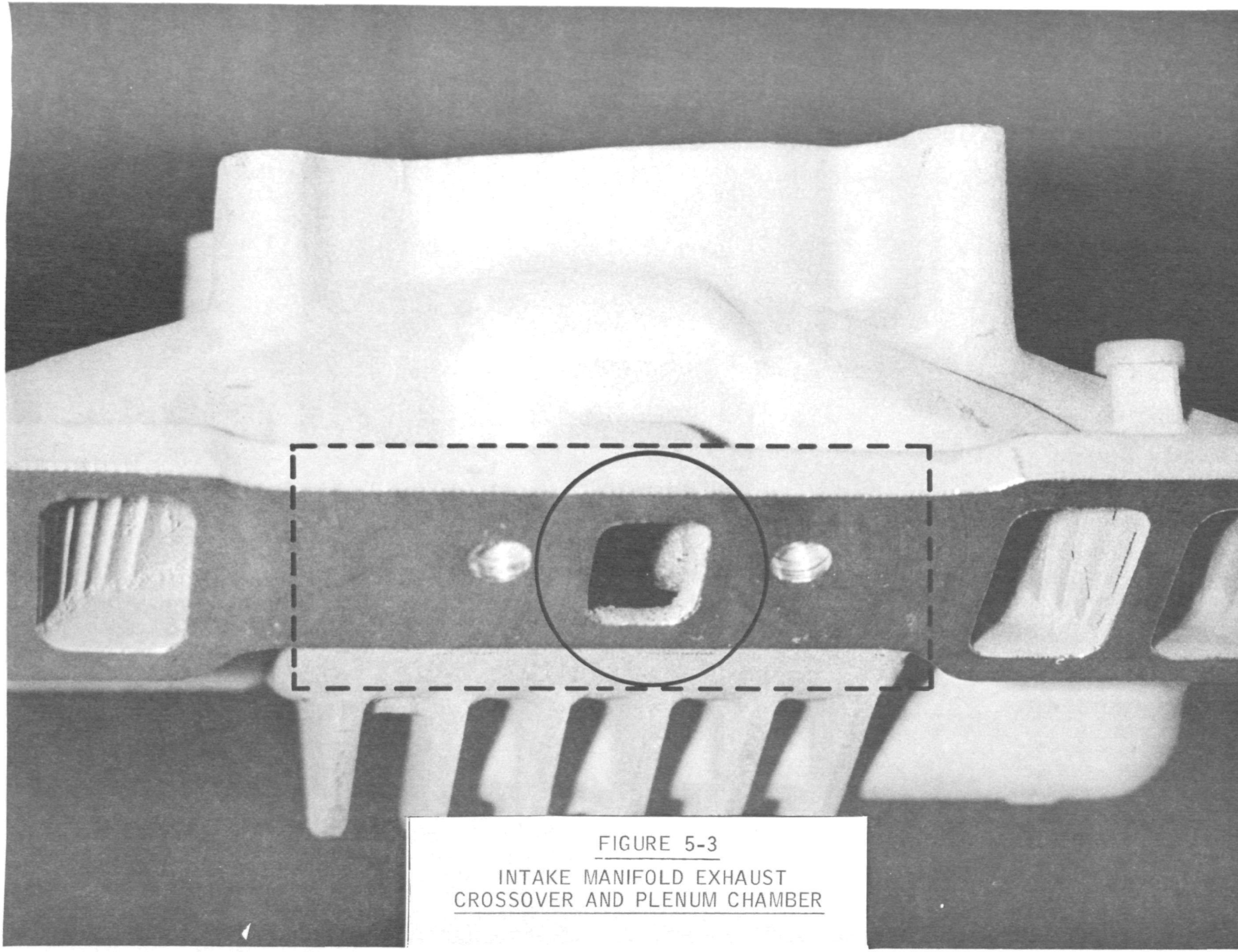


FIGURE 5-3

INTAKE MANIFOLD EXHAUST CROSSOVER AND PLENUM CHAMBER

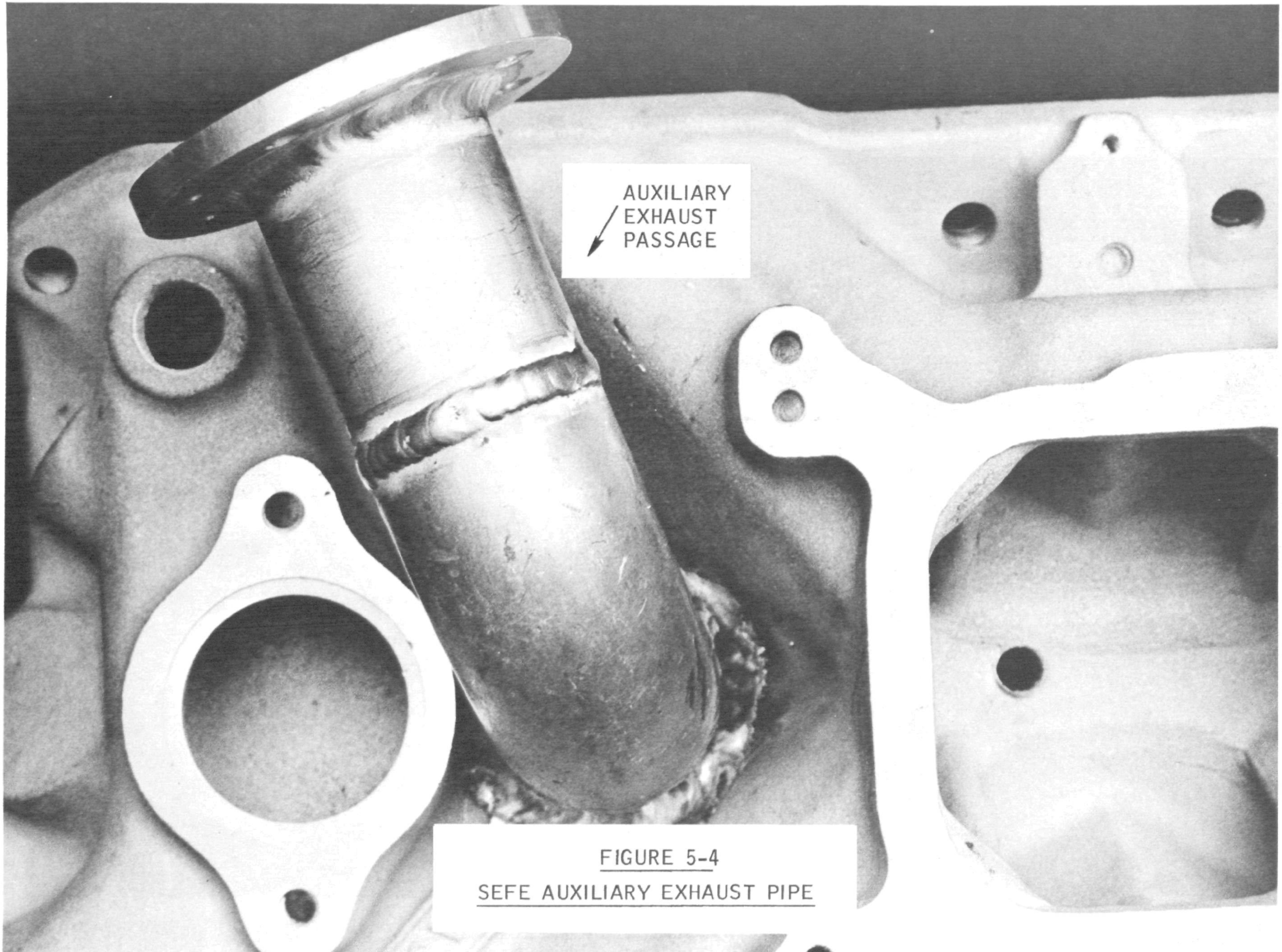


FIGURE 5-4

SEFE AUXILIARY EXHAUST PIPE

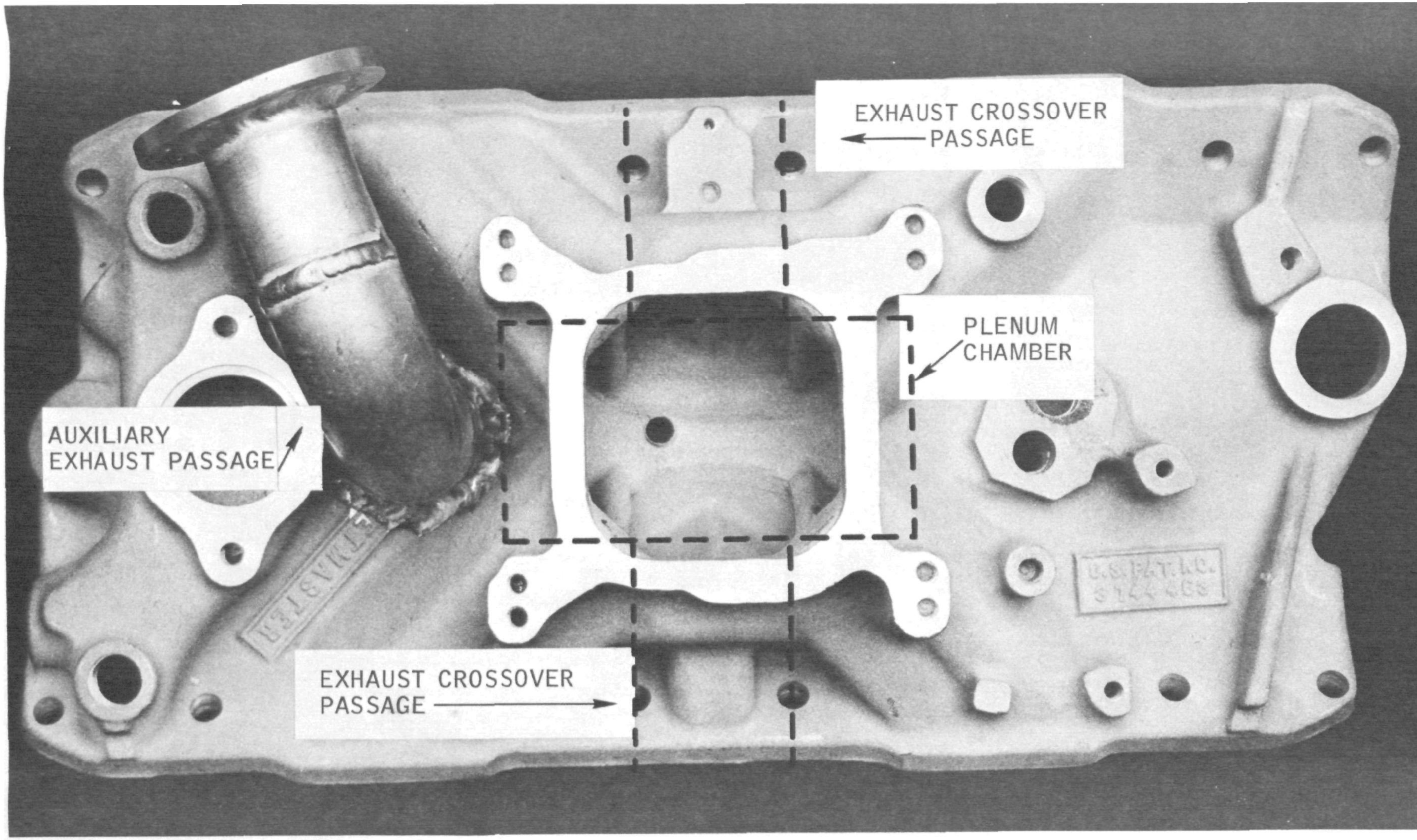


FIGURE 5-5

EDELBROCK ALUMINUM MANIFOLD-
AFTER SEFE MODIFICATION

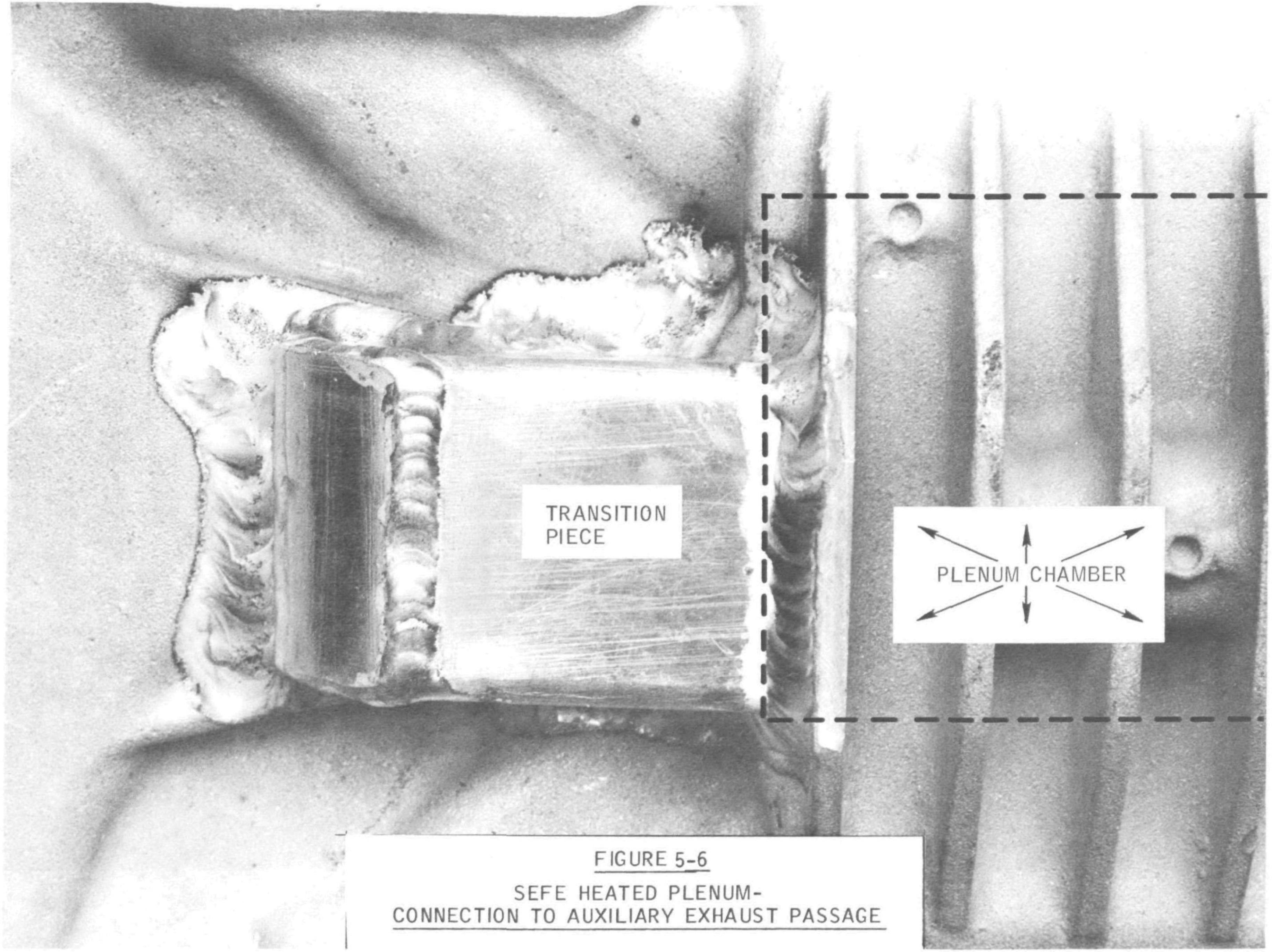


FIGURE 5-6

SEFE HEATED PLENUM-
CONNECTION TO AUXILIARY EXHAUST PASSAGE

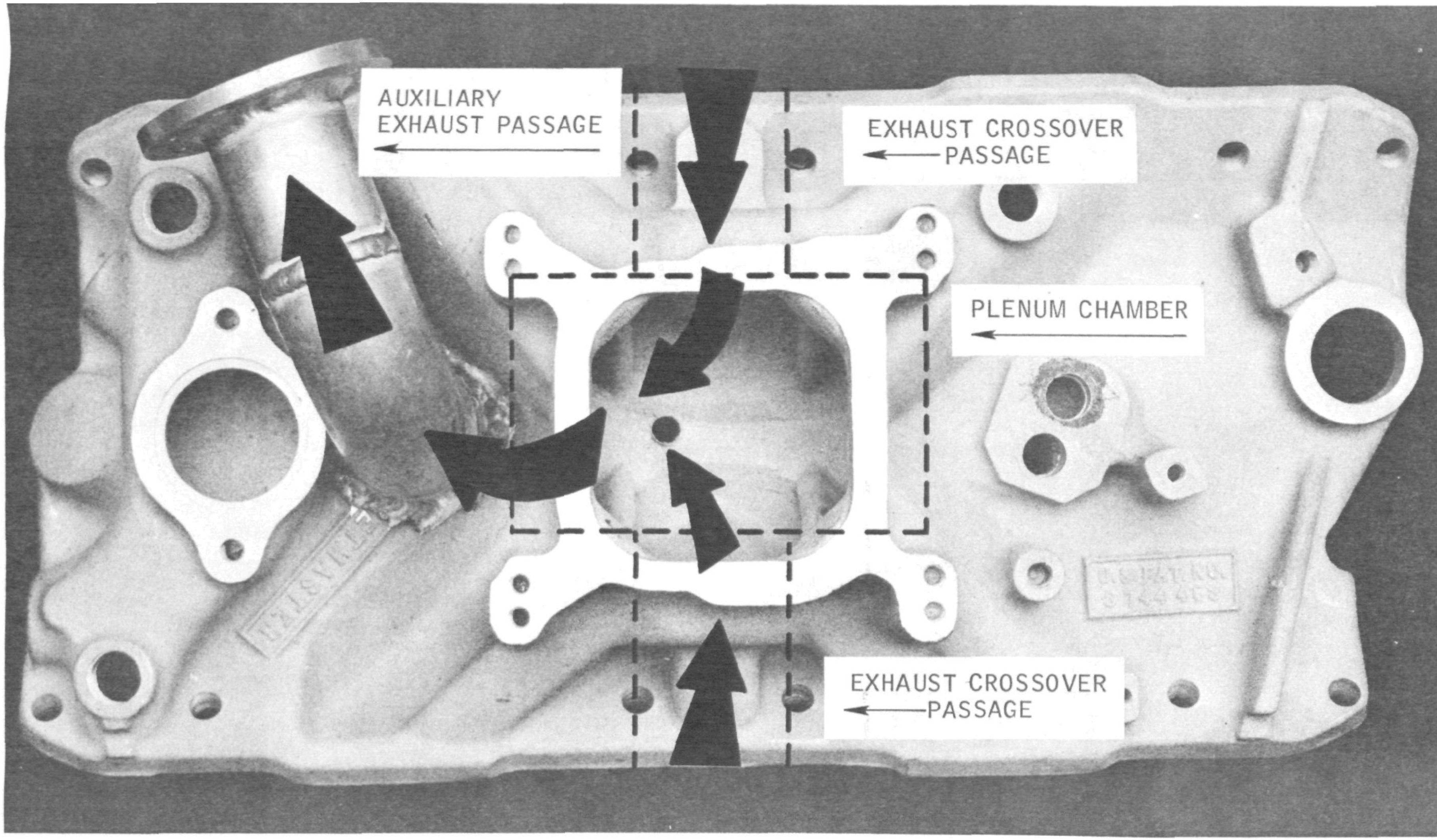


FIGURE 5-7

EXHAUST GAS FLOW THROUGH SEFE MODIFIED INTAKE MANIFOLD vacuum diaphragm assembly, so the EGR schedule could be optimized for NO_x control and driveability. Mixing of the recycle stream with the A/F mixture was under the carburetor base at the EGR entrance port. The location of this port is in the intake manifold floor and is shown in Figure 5-8.

"Starter" and "Main" Oxidation Catalyst System

One can place a small starter oxidation catalyst close-coupled at the engine exhaust manifold when there is slow light-off of the main catalyst bed. The small bed volume, high exhaust gas space velocity, and high input gas temperature, promote rapid light-off of the starter catalyst. Thus, initial emissions on cold start are controlled by the starter catalyst (while the main catalyst bed lights-off).

Slow catalyst light-off was expected for the low excess air vehicle, since its' design did not include an air pump (air injection on cold start). Therefore, the starter/main catalyst configuration was adopted to increase control of cold start emissions. The starter oxidation catalyst bed was located in the auxiliary exhaust passage that vents the intake manifold's plenum chamber. (See Figure 5-1). On cold start, with the SEFE system in operation, the starter catalyst is placed in series with the main catalyst bed. During hot operation, the starter catalyst and SEFE system are not activated, and, therefore, only the main catalyst bed receives exhaust from the engine. Catalysts chosen for use in the system were Matthey-Bishop type 20G platinum monoliths. The catalyst's specifications and bed dimensions are listed in Table 5-2.

Table 5-2

CATALYST SPECIFICATIONS

	Starter Catalyst	Main Catalyst
Noble Metal Loading	Pt, 14.1 gm/litre (40 gm/ft^3)	Same
Substrate	Corning Monolith - 47 Holes/cm^2 (300 holes/in^2)	Same
Monolith Dimensions (Diameter X Length)	D = 9.30 cm X L = 7.60 cm (3.66 in) X (3.0 in)	D = 11.84 cm X L = 15.24 cm (4.66 in) X (6.0 in)
Catalyst Volume	516.0 cm^3 (31.5 in^3)	1678.0 cm^3 (102.3 in^3)

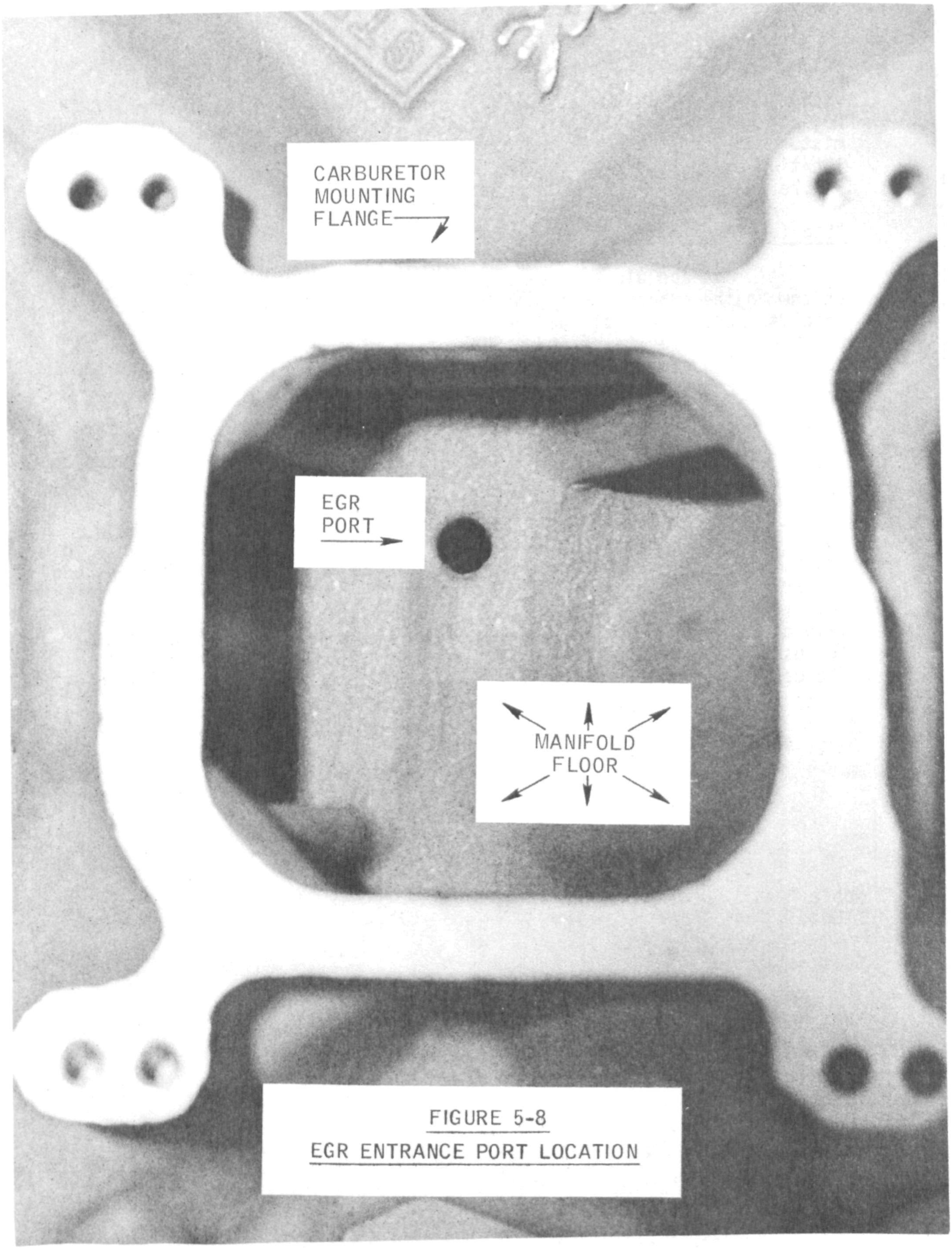


FIGURE 5-8

EGR ENTRANCE PORT LOCATION

5.2 TEST RESULTS

Due to various production difficulties Matthey-Bishop was unable to supply the starter and main catalysts for a period of six months from the order date. During this time initial optimization of the low excess air vehicle was made with sections of blank exhaust pipe in the locations that were to be occupied by the starter and main catalysts. These preliminary tests revealed several problem areas. It was found that the SEFE section of the intake manifold warmed-up very slowly from cold start conditions. The slow heating rate was found to be due in part to poor closure of the EFE valves at the exhaust manifolds. Inspection of the production EFE valves revealed that they had 1.6 mm (1/16 inch) clearance around the edge of the butterfly plate when closed. Stainless steel butterfly plates with reduced edge clearance were fabricated and installed to decrease the amount exhaust gas that could blow-by in the closed position.

Tests with the modified valves showed that they reduced the time required to reach a given under-carburetor temperature to about half that obtained with production EFE valves. The rate of temperature rise (measured with a thermocouple installed in intake manifold floor under the carburetor) observed was 1.2°C/sec. (2.2°F/sec.) for the cold start FTP. Initial temperature of the manifold was 21.1°C (70°F) and final stabilized hot temperature was 132.3°C (270°F) after SEFE operation for approximately 240 seconds. This was only about 1/5 of the rate (5.6°C/sec. = 10°F/sec.) which others (6) had indicated as required for good driveability with rapid choke pull-off. It was suspected that this poor warm-up performance was caused by rapid heat dissipation from the SEFE section due to the aluminum manifold's high thermal conductivity.

Driveability of the low excess air vehicle was poor. During the cold start FTP there were repeated stalls, surging, sluggish acceleration performance, and backfires. Some loss of cold driveability was expected, due to the poor SEFE warm-up characteristics of the aluminum intake manifold. However, even with the engine fully warmed up if the SEFE system was activated, severe engine hesitation, sluggish performance, and backfiring would occur. The backfiring was found to be a result of EGR maldistribution. This was established by installing taps at the left front, left rear, and right rear of the intake manifold. Samples were withdrawn with and without EGR while the engine was run at various steady state conditions. The percent of recycled exhaust (EGR) at the right rear of the intake manifold was generally about twice that of the left front, with the left rear being intermediate. The maldistribution was eliminated by redesigning the EGR inlet so it would introduce the recycled exhaust directly under the carburetor throttle plates.

As previously shown (Figure 5-8) the Edelbrock manifold introduced EGR through a "floor port" which was about 9 cm (3.5 in.) below the carburetor base. A 9 cm (3.5 in.) long by 1.27 cm (0.5 in.) ID aluminum tube with two top ports was threaded into the original EGR port. A schematic diagram of the modified port, and an installed view are shown in Figure 5-9. The redesigned inlet directed EGR flow across the incoming A/F mixture to insure good mixing and distribution would take place. The improvement made in EGR distribution is shown in Table 5-3, which compares percent recycle measured before and after installing the modified inlet.

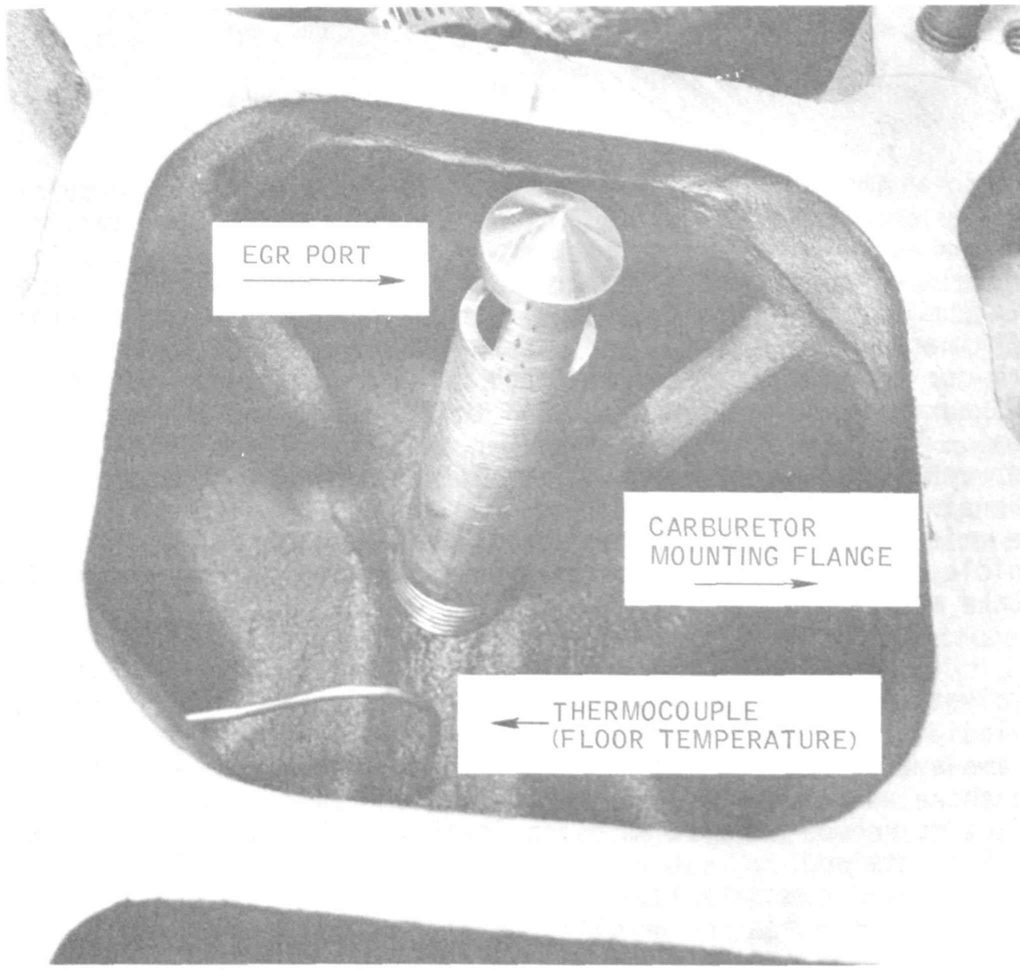
TABLE 5-3

EGR DISTRIBUTION (AT 48 KPH: 30 MPH)

Sample Location	Percent EGR Based on % CO_2	
	Before New Inlet Installed	After New Inlet Installed
Left Front	6.7	8.9
Left Rear	9.9	9.6
Left Reat	12.8	9.9
Avg.	9.8	9.5

Improving the EGR distribution eliminated the backfiring problem with the SEFE system activated; however, stalling and poor acceleration performance continued to occur. A/F ratio enrichment by resetting the choke helped to reduce the tendency to stall on cold start and during warm-up on the FTP. The additional enrichment was necessary to compensate for poor fuel vaporization resulting from slow SEFE heating.

Vehicle performance during both cold and hot start driving modes while the SEFE system operated was poor. During deep throttle acclerations in the FTP (such as the 162 sec.-332 sec. "Big Hill" in Bags 1 and 3) severe hesitation, low engine power output, and sluggish acceleration were experienced. The low excess air vehicle, however, performed normally with the SEFE system switched off. During hot engine operation (no SEFE) exhaust was vented into two 6.35 cm. (2.5 in.) pipes of the production exhaust system. In SEFE mode, however, all exhaust was vented through a 3.81 cm. (1.5 in.) auxiliary exhaust passage. Operation of the SEFE system created approximately a five fold reduction in exhaust flow area. [Total available SEFE flow area: $(3.81\ cm)^2\ /4 = 11.42\ cm^2$, as compared to non-SEFE area: $(6.35\ cm)^2\ /4 = 31.68\ cm^2 \times 2$ exhaust pipes for V-8 engine = $63.35\ cm^2$ total area]. It was felt that a high level of exhaust backpressure developed during deep throttle transients and reduced engine power output, causing hesitation and sluggish accelerations.



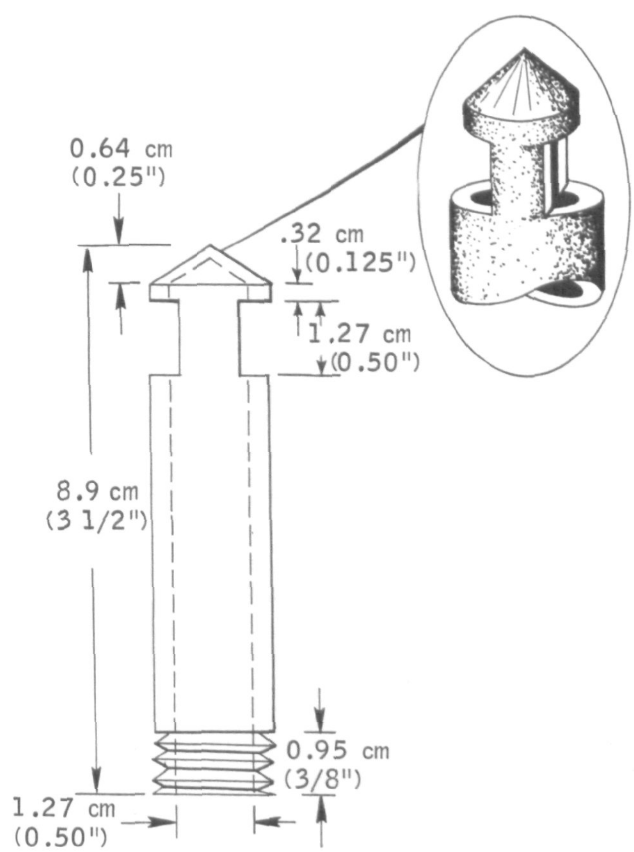


FIGURE 5-9

MODIFIED EGR INLET

Thus, preliminary testing revealed a number of problems with the low excess air vehicle. In particular, the SEFE system did not perform as expected. The function of the system, to promote intake manifold warm-up and fuel vaporization, was never fully realized. The aluminum intake manifold, chosen to ease SEFE system fabrication, had high thermal conductivity and dissipated enough heat to prevent rapid warm-up. Furthermore, due to space constraints during fabrication, the SEFE auxiliary exhaust passage had to be reduced in diameter (crossectional area). The increased exhaust backpressure resulting from this caused poor vehicle performance. The net effect was that the system instead of enhancing cold driveability, degraded it. It was decided to determine the emissions level that could be attained with the low excess air vehicle, before further modifications were made to the SEFE system or intake manifold.

Matthey-Bishop was able initially to supply only the "starter" catalyst bed. Testing proceeded with an Engelhard PTX-IIB platinum-palladium monolith, until the Matthey-Bishop 20G main catalyst bed became available. During testing various adjustments such as leaning the choke and shortening of the accelerator pump stroke were made in an effort to reduce exhaust emission levels. Table 5-4 shows the test results obtained.

TABLE 5-4

LOW EXCESS AIR VEHICLE EXHAUST EMISSION LEVELS

	FTP Emissions, g/km			SEFE
	CO	HC	NOX	System
80,000 km. emission targets	2.1	0.25	1.2	-
0 km. emission targets	1.0	0.12	1.2	-
PTX-IIB main catalyst alone	8.3	0.32	2.3	On
PTX-IIB main & M-B starter catalyst	10.5	0.43	2.0	On
M-B main catalyst alone	4.4	0.36	2.1	On
M-B main & starter catalysts	5.2	0.32	2.2	On
M-B main & starter catalysts (air injection into exhaust manifolds)	4.8	0.14	2.2	On
M-B main catalyst alone (normal crossover heating)	3.5	0.25	2.2	Off

When the SEFE system and starter catalyst were used, the main exhaust lines were closed. All exhaust was vented through the auxiliary passage for the first 240 seconds in Bag 1, and for the first 135 seconds in Bag 3 of the FTP. In this configuration, the starter and main catalyst beds were placed in series. When the main catalyst alone was used, the auxiliary passage was closed (SEFE System Off) and exhaust flowed through the main exhaust lines to the catalyst for the entire FTP.

As shown in the table, lower emission levels were obtained without the SEFE system/starter catalyst, both with the PTX-IIB and Matthey-Bishop main catalysts. The latter tended to give the lowest emission levels overall. The lowest emission levels were obtained with the vehicle operating in the normal manner. That is, using only the main catalyst, without SEFE operation, allowing the exhaust to cross over through the intake manifold from the driver to passenger side of the engine for the first 135 seconds of both Bags 1 and 3. However, it should be noted that in all cases, exhaust emission levels were above both 0 and 80,000 km target levels. The poor emissions performance of the low excess air vehicle was attributable to a number of factors such as; design shortcomings in the SEFE system, lack of air injection on cold start, and relatively small catalyst volumes.

Poor control of CO, for example, had a number of causes. Enrichment of A/F ratio to reduce cold start stall-outs, which reduced the oxygen content in the exhaust, tended to increase catalyst bed light-off time. Operation of the SEFE system/starter catalyst itself created problems of high exhaust backpressure. The higher level of CO consistently seen with the starter catalyst was suspected to be a result of having to run at near wide open throttle conditions on FTP accelerations. The addition of an airpump to supply secondary air injection at the exhaust manifold reduced catalyst light-off time and improved the control of cold start CO and HC emissions (airpump operating during the first 150 seconds of Bag 1). However, as shown in Table 5-4, overall FTP emissions remained above contract targets. At this time, an instability in the research carburetor was found. During testing carburetion often became unstable, and frequently went rich. The problem was traced to a temperature instability in the carburetor, which was aggrevated by the SEFE system increasing the carburetor body temperature. In Table 5-5 A/F ratios for the low excess air vehicle at two temperatures are displayed. Note that although A/F ratio for a particular temperature remained "flat" with speed variations, as temperature increased the A/F became rich.

Table 5-5

RESEARCH CARBURETOR TEMPERATURE INSTABILITY

Speed		A/F Ratio	
(kph)	(mph)	24°C (75°F)	29°C (84°F)
IDLE	IDLE	15.4	14.8
16	10	14.8	14.7
32	20	15.3	14.6
48	30	15.1	14.8
64	40	14.9	14.6
80	50	14.9	14.4
96	60	15.0	14.5

Thus, the low excess air vehicle could not meet any of the contract emission level targets. A number of problem areas remained unresolved, and would require extensive redesign and modifications to the vehicle. Rather than pursue this path, it was decided to stop work on the vehicle. A second low excess air vehicle was built, and is described in Section 8 of this report.

SECTION 6

THREE-WAY CATALYST VEHICLE - DESIGN NO. 1

6.1 DESIGN AND FABRICATION

A 1975 Volvo equipped with a fuel injected 2.0 litre displacement L-4 cylinder engine was chosen for modification. A prototype K-JETRONIC fuel injection system, developed by the Robert Bosch Corporation, using closed loop electronic feedback control with an oxygen sensor was installed on the vehicle. Such a system was expected to provide the precise control of engine A/F ratio necessary for efficient operation of a three-way catalyst within its' conversion window. The conversion to the advanced closed loop feedback control system consisted of replacing production Volvo fuel injection system parts (also Bosch built) with prototype parts supplied by Bosch. Components installed in the modification included: an oxygen (λ) sensor, electronic control unit (ECU), oxygen sensor threshold voltage trimbox, recalibrated warm-up regulator, fuel distributor with frequency (solenoid) pressure control valve, and revised air flow rate sensing unit. To complete the system, an Engelhard TWC-9 monolithic three-way catalyst was installed (replacing the production oxidation catalyst).

A simplified pictorial diagram of the Bosch closed loop feedback control fuel injection system is shown in Figure 6-1. A functional description of each of the components follows:

1. ELECTRIC FUEL PUMP - a roller cell fuel pump driven by an electric motor, pumps fuel from the fuel tank into the fuel injection system.

2. FUEL ACCUMULATOR - holds the fuel pressure constant for an extended length of time after the engine has been turned off. This prevents the formation of gasoline vapor bubbles (fuel percolation: vapor lock), and as a result improves hot engine starting.

3. FUEL FILTER - protects the fuel distributor and the fuel injector nozzles against clogging and damage from dirt.

4. FREQUENCY SOLENOID PRESSURE CONTROL VALVE - signals from an electronic control unit, based upon exhaust oxygen content (determined by an oxygen sensor), open and close this magnetic solenoid valve. Air-fuel mixture is varied by changing the primary circuit control pressure in the Mixture Control Unit. Decreasing primary control pressure increases fuel flow (enriching the A/F mixture), and corresponds to an increase in solenoid valve duty cycle or "% on" time. Decreasing the solenoid valve duty cycle, increases primary control pressure and leans the A/F mixture, due to decreased fuel flow.

5. WARM-UP REGULATOR - controls the pressure acting against the top of the control plunger. During cold start operation the control plunger pressure is reduced enriching the A/F mixtures to aid cold driveability. An electrically heated bimetallic strip switches the regulator off after the warm-up period, and prevents regulator operation under hot start conditions.

6. MIXTURE CONTROL UNIT - consists of the air-flow sensor and the fuel distributor. The air drawn into the engine, the volume flow-rate of which depends on the position of the throttle plate, lifts the air-flow sensor plate, and at the same time the control plunger in the fuel distributor is lifted by a shorter lever arm against the hydraulic primary control pressure. The amount of fuel required for the volume of air flowing through the air-flow sensor is metered in this way and is fed through the metering slits to the individual injection valves.

7. PRIMARY CIRCUIT PRESSURE REGULATOR - holds the primary fuel circuit pressure at a constant value. Adjustment of the primary circuit regulator affects the amount of fuel flow for a given air-flow rate.

8. DIFFERENTIAL PRESSURE VALVE - designed to assure that the volumetric flow of fuel depends only on the crossectional areas of the metering slits.

9. METERING SLITS - the fuel flows through the metering slits, one for each cylinder of the engine, depending only on the crossectional area of the slits opened by the control plunger as it is moved up and down by the air-flow sensor plate.

10. START VALVE - sprays additional fuel into the intake manifold during cold start operation to compensate for reduced fuel vaporization.

11. AUXILIARY AIR DEVICE - feeds more air to the engine during warm up (to increase engine idle speed), then closes the by-pass channel around the throttle plate by means of an electrically heated bimetallic strip.

12. THERMO-TIME-SWITCH - controls the length of time the cold start valve operates upon cold start, as well as preventing valve opening above a certain temperature limit.

13. INJECTION VALVE - sprays the precisely metered fuel into the intake manifold, and is continuously open after the engine is started.

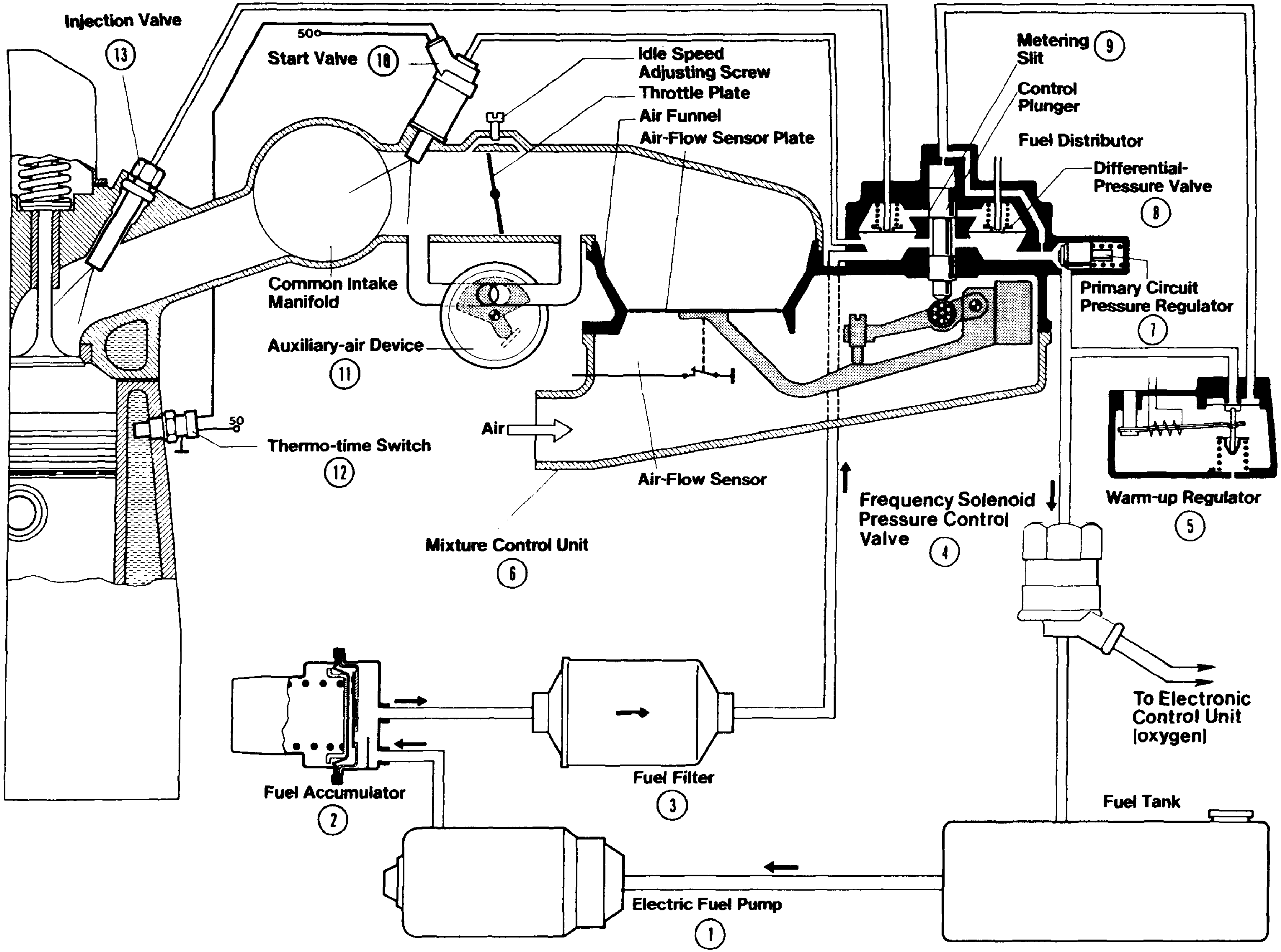


FIGURE 6-1

BOSCH K-JETRONIC FEEDBACK FUEL INJECTION SYSTEM PICTORIAL DIAGRAM

It is not within the scope of this report to describe in great detail how the Bosch feedback fuel injection system operates. Rather, the reader is referred to Bosch technical papers (7,8) for the design and operation of the continuous fuel injection system, as well as detailed descriptions of the feedback control system's electronics (9). A simplified "action circle" of the feedback control fuel injection system's logic is found in Figure 6-2. It shows how the system compensates for variations in the air-fuel mixture, so that a desired A/F value is maintained.

6.2 TEST RESULTS

During preliminary testing, in which ECU control settings and oxygen sensor threshold voltage levels were optimized, a problem with cold engine operation was found. Upon cold start, the engine would run about two seconds, and then stall out. Restarting of the engine required extended starter cranking. After restart, vehicle performance was poor with stalling, hesitation and backfire until the engine was fully warmed up. Hot starting and hot engine performance, however, were normal. This type of behaviour indicated that the warm-up regulator (supplied with the feedback fuel injection system) was not operating properly. Bosch felt that although the warm-up regulator had been set to provide a lean cold start A/F ratio (to minimize CO emissions), this should not cause the poor driveability being experienced. They agreed that the warm-up regulator could be malfunctioning and suggested it be returned for a calibration check.

Bosch recalibrated the regulator and returned it with some additional components (e.g. acceleration enrichment system with manifold absolute pressure sensing) to help improve cold start engine performance. Testing after installation of these modified parts showed that the start-up and cold driveability difficulties previously experienced were corrected. The feedback system, however, could not maintain stable A/F ratio control and FTP emissions were above maximum contract target levels. The entire feedback fuel injection system was returned to Bosch in Chicago for diagnostic testing. It was discovered that an incorrect component installation diagram had been furnished with the system. Because of this the Warm-up regulator had been installed backwards, with its' inlet and outlet connections reversed. With the warm-up regulator installed correctly the feedback system maintained A/F ratio control, and emissions were below 0 km contract targets, as shown in Table 6-1.

TABLE 6-1

THREE-WAY CATALYST VOLVO EXHAUST EMISSIONS
PRELIMINARY TEST

	FTP Emissions, g/km		
	CO	HC	NO_x
80,000 km. emissions target	2.1	0.25	1.2
0 km. emissions target	1.0	0.12	0.6
Measured emissions	0.87	0.12	0.52

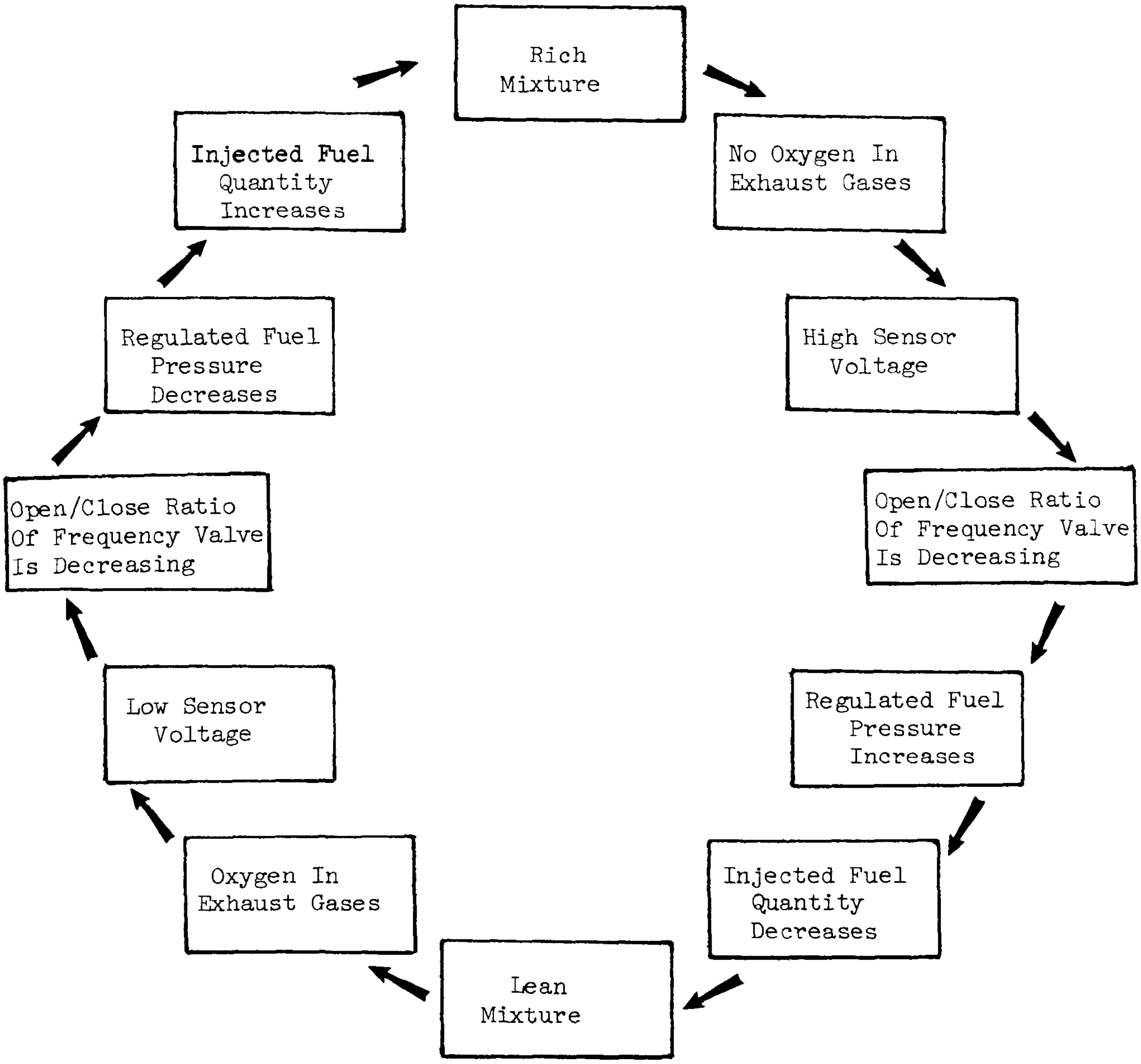


FIGURE 6-2

"ACTION CIRCLE" OF FEEDBACK CONTROLLED FUEL INJECTION SYSTEM'S LOGIC

In addition to the contract tasks the three-way catalyst Volvo was one of approximately seventy vehicles selected by the EPA to be used in a study to standardize sulfate testing. It was desirable, from a timing point of view, to complete these studies before starting the 80,000 km durability accumulation. It was felt that the 800 km of conditioning required for the sulfate test study would provide a good initial shakedown for the vehicle. After accumulating 800 km on the modified AMA driving schedule, as required for the test procedure and sulfate standard study, the car stalled repeatedly during start up and the feedback fuel injection system often went out of control during FTP and SET testing.

A number of problem areas were found upon inspection of the vehicle. (1) The air bellows between the air flow sensor unit and the intake manifold had come loose, which could affect the A/F ratio. Since air leaks after the airflow sensor do not increase fuel flowrate, a net leaning-out of the air fuel mixture inducted to the engine would take place. If the air leak rate was substantial the feedback control system could become "pinned" at its full-rich limit trying to bring the A/F ratio back to a stoichiometric value, causing a loss of A/F control. (2) The flange connection of the exhaust header pipe to the engine exhaust manifold had come loose and opened slightly, probably due to vibration. Any air leakage into the exhaust pipe would be seen by the oxygen sensor (located about 2 cm upstream of the flange) as a lean A/F mixture, and could result in the same condition as previously described. And (3) an intermittant short had developed in the output lead from the oxygen sensor.

With these areas repaired the feedback system was able to maintain A/F control, however, the vehicle still stalled on start up. A complete engine tune-up was carried out in an effort to determine the reason for the repeated stall-outs. Three possible contributing factors were found: (1) two fuel injectors leaked, one sprayed fuel continuously, while the second leaked fuel at a rate three times faster than Bosch specifications. Two new injectors were installed. (2) The spark plugs (which had accumulated a total of 3830 km) were marginal on a firing voltage breakdown test and were replaced. (It is interesting to note that the spark plug from the cylinder with the leaking injector was fouled, confirming the failure of the injector). And (3) an electrical lead between the thermo-time switch and the cold start injector was loose, and was giving intermittant contact. Thus on cold start, the injector necessary to supply additional enrichment may not have operated. Following these repairs the vehicle started smoothly, and the feedback control system was able to maintain A/F control. Emissions levels for the FTP, however, were above those seen before the 800 km shakedown accumulation. Testing revealed that the feedback control system's oxygen sensor had begun to lose activity. Installation of a new oxygen sensor reduced FTP emissions to previous levels (seen before the shakedown run).

Before initiating the 80,000 km durability accumulation the TWC-9 catalyst was replaced, at the EPA's request, by an Engelhard TWC-9B Monolithic three-way catalyst. FTP emissions remained well below the 0 km contract targets for kilometer accumulation initiation, and are found in Table 6-2.

TABLE 6-2

THREE-WAY CATALYST VOLVO EXHAUST EMISSIONS

0 KILOMETER TEST

	FTP Emissions, g/km		
	CO	HC	NOX
80,000 km emissions targets	2.1	0.25	1.2
0 km emissions targets	1.0	0.12	0.6
Measured emissions: TWC-9B	1.0	0.09	0.41

A summary of the three-way catalyst Volvo emission data for the entire kilometer accumulation is found in Table 6-3. Kilometer accumulation was carried out using the modified AMA cycle and a commercial unleaded fuel containing 312 ppm of sulfur, 0.01 g Pb/gal, and 0.70 mg P/gal. Emission tests at the specified accumulation intervals were run using Indolene fuel containing 299 ppm of sulfur.

Emissions tests were carried out at 2000 km, 6000 km, and 15,000 km accumulation points (as well as a preliminary test at 150 km). The NO_x levels during cold start FTP's remained fairly constant, while CO and HC tended to increase with accumulated kilometers. CO emissions at the 15,000 km point exceeded the 80,000 km maximum contract targets, and FTP fuel economy was about 10 to 20 percent lower than for FTP tests at lower kilometer distances. A check showed that the breaker point dwell angle had increased from the desired 61° to 71° due to rubbing block wear. This 10° change in dwell resulted in a substantially retarded ignition timing. An oil and filter change, as well as a complete tune-up was performed (spark plugs, ignition points, condenser) on the vehicle. An FTP was run after the tune-up and showed that emissions and fuel economy had returned to previous levels. Kilometer accumulation was resumed, and cold start FTP's were run at approximately 27,000 km to determine if any degradation in emission control had occurred which could be corrected before the testing required at the 30,000 km accumulation interval. Based on an average of two tests CO emissions had increased to about 2.8 g/km, while HC and NO_x had increased to the maximum target levels of 0.25 and 1.2 g/km respectively. Replacement of the oxygen sensor reduced CO and HC emissions to 1.8 g/km and 0.20 g/km respectively, however, NO_x remained unchanged at the maximum level of 1.2 g/km. These results indicated that the three-way catalyst had begun to lose its' NO_x conversion activity.

Emissions testing at the 30,000 km interval confirmed the three-way catalyst's loss of activity, and kilometer accumulation for the three-way catalyst vehicle was stopped.

In general, sulfate emissions during the kilometer accumulation ranged between less than 0.1 to 2.3 percent of the sulfur in the fuel, depending on the test cycle being run. Conversion levels of fuel sulfur to sulfate were highest on the FTP driving cycle and were in the range of 0.6 to 2.3 percent, while the levels at 96 km/hr cruise were the lowest, ranging from less than 0.1 to a maximum of 0.8 percent. Sulfate emissions for 96 km/hr cruise conditions ranged from 0.2 mg/km to 0.8 mg/km, and were well below the contract target of 6.2 mg/km. In fact, sulfate emissions for any driving cycle regardless of accumulated kilometers remained well below the maximum contract target.

Although kilometer accumulation had to be terminated at 30,000 km because of catalyst deactivation, the three-way Volvo demonstrated that low levels of exhaust emissions could be attained without a sulfate emissions penalty. It was decided to restart the three-way catalyst phase of the contract work with a prototype 1977 Volvo "Lambda-Sond" vehicle to demonstrate the full 80,000 km durability. A discussion of this second three-way catalyst vehicle follows immediately in Section 7 of this report.

TABLE 6-3

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST-EQUIPPED VOLVO

(Test Fuel = Indolene with 299 ppm S)

km	Date	Test	Emissions, g/km			Emissions, mg/km		% Fuel S As		% Fuel S Recovered	Fuel Economy, mpg
			CO	HC	NO_x	$SO_4^=$	SO_2	$SO_4^=$	SO_2		
150	2/19/76	FTP	1.21	0.27	0.60	1.7	21	1.7	31	32.7	15.5
	"	SET 1	0.03	0.01	0.94	0.8	61	1.0	122	123	20.8
	"	SET 2	0.05	0.02	1.03	1.0	61	1.4	122	123	20.8
	"	FET	0.02	0.02	1.16	0.9	72	1.3	154	155	22.3
	"	SET 3(a)	0.06	0.02	0.82	0.8	52	1.0	105	106	21.0
	2/24/76	FTP (b)	1.36	0.15	0.48	1.6	31	1.7	49	51	16.3
	"	SET 4	0.05	0.01	0.68	0.7	63	1.0	133	134	22.1
	"	96-1	0.03	0.03	1.43	0.4		0.6			
	"	96-2	0.01	0.02	1.60	0.6	67	0.8	142	143	22.0
	"	96-3	0.02	0.02	1.48	0.8		1.1			
	"	96.4	0.01	0.02	1.43	0.6		0.8			
	2/25/76	FTP (c)	0.89	0.08	0.80	1.4	32	1.6	52	54	16.8
2 000	3/2/76	FTP	1.62	0.16	0.69	0.9	32	0.9	47.9	48.8	15.8
	"	SET 1	0.09	0.02	0.78	0.4	53	0.5	109	109	21.5
	"	SET 2	0.07	0.02	0.87	0.3	46	0.4	95.8	96.2	21.5
	"	FET	0.04	0.02	0.98	0.3	51	0.4	116	116	23.6
	"	SET 3	0.10	0.02	0.83	0.2	57	0.3	121	121	22.1
	"	SET 4	0.09	0.02	0.83	0.2	51	0.3	109	109	22.1
	"	96-1	0.02	0.01	1.80	0.4		0.6			
	"	96-2	0.01	0.01	1.90	0.3	56	0.5	119	120	22.1
	"	96-3	0.01	0.01	1.90	0.4		0.5			
	"	96.4	0.02	0.01	1.83	0.5		0.7			
	3/5/76	FTP (d)	8.63	0.66	2.71	1.4	(e)	---	---	---	17.0

(a) Test series interrupted following this test due to dynamometer breakdown.
(b) Test series was resumed with a cold start FTP.
(c) Cold start FTP made with 400 mv. setting on oxygen sensor control compared to 450 mv. used for all prior tests in this series. 400 mv. setting used in all subsequent tests.
(d) Run without catalyst
(e) Sample lost

TABLE 6-3 (Continued)

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST-EQUIPPED VOLVO

(Test Fuel = Indolene with 299 ppm S)

km	Date	Test	Emissions, g/km CO	Emissions, g/km HC	Emissions, g/km NO_x	Emissions, mg/km $SO_4^=$	Emissions, mg/km SO_2	% Fuel S As $SO_4^=$	% Fuel S As SO_2	% Fuel S Recovered	Fuel Economy, mpg
6 000	3/17/76	FTP	1.68	0.13	0.79	1.5	32	1.6	55.1	56.7	17.7
	"	SET 1	0.23	0.01	0.88	1.0	54	1.4	117	118	22.4
	"	SET 2	0.18	0.01	0.96	0.4	42	0.6	115	116	23.1
	"	FET	0.08	0.13	1.14	0.9	57	1.5	137	139	24.9
	"	SET 3	0.23	0.01	1.09	0.8	51	1.1	103	104	20.9
	"	SET 4	0.21	0.02	1.04	0.7	50	1.0	103	104	21.3
	"	96-1	0.03	0.002	1.81	0.5	57	0.7	126	126	23.0
	"	96-2	0.001	0.0	1.68	0.2		0.3			
	"	96-3	0.02	0.0	1.79	0.4		0.5			
	"	96-4	0.02	0.01	1.62	0.2		0.4			
6 325	3/18/76	Oil, Oil Filter Changed, Plugs Replaced									
15 000	3/31/76	FTP (f)	2.86	0.19	0.78	2.2	66	1.9	85.2	87.1	13.5
	"	SET 1	1.10	0.02	0.78	1.0	64	1.2	119	120	19.4
	"	SET 2	0.93	0.02	0.76	0.6	58	0.7	105	106	19.0
	"	FET	0.62	0.02	0.53	0.7	55	0.9	108	109	20.5
	"	SET 3	1.00	0.03	0.73	0.5	48	0.6	86.5	87.1	18.8
	"	SET 4	1.05	0.02	0.71	0.5	41	0.6	72.6	73.1	18.6
	"	96-1	0.73	0.004	0.82	0.7	64	1.0	126	126	20.3
	"	96-2	0.79	0.001	0.77	0.3		0.4			
	"	96-3	0.75	0.002	0.65	0.3		0.4			
	"	96-4	0.95	0.004	0.65	0.2		0.2			

TABLE 6-3 (Continued)

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST-EQUIPPED VOLVO

(Test Fuel = Indolene with 299 ppm S)

km	Date	Test	Emissions, g/km CO	HC	NO_x	Emissions, mg/km $SO_4^=$	SO_2	%Fuel S As $SO_4^=$	SO_2	% Fuel S Recovered	Fuel Economy, mpg
15 400	4/2/76	FTP (f)	2.66	0.16	1.09	1.4	43	1.2	55.3	56.4	13.4
15 410	4/4/76	Oil, Oil Filter Changed, Plugs and Points Replaced, Timing and Dwell Set									
15 420	4/6/76	FTP (g)	2.05	0.22	0.80	0.6	(e)	0.6	----	----	15.4
26 780	5/7/76	FTP	2.94	0.28	1.25	2.1	65	2.0	93.6	95.6	15.1
	5/10/76	FTP	2.58	0.22	1.06	2.3	34	2.3	51.1	53.4	15.4
26 840	5/12/76	FTP (h)	1.95	0.21	1.30	0.9	64	0.8	95.1	95.8	15.5
	5/13/76	FTP	1.71	0.19	1.17	1.0	52	1.0	77.3	78.3	15.4
30 000	6/17/76	FTP	1.28	0.20	1.19	0.9	56	0.9	85.6	86.5	15.9
	6/17/76	SET-1	0.38	0.04	1.35	0.4	65	0.5	135.6	136.1	21.5
	6/17/76	SET-2	0.34	0	1.40	0.4	54	0.5	114.6	115.1	21.8
	6/17/76	FET	0.15	0.03	1.31	0.6	28	0.9	64.0	64.9	24.2
	6/17/76	SET-3	0.35	0.05	1.31	0.5	55	0.6	114.9	115.5	21.6
	6/17/76	SET-4	0.33	0.05	1.28	0.4	55	0.6	117.1	117.7	22.0
	6/17/76	96 km	0.17	0.012	1.80	0.5	62	0.1	133.3	133.4	22.4
	6/17/76	96 km	0.30	0.012	1.74	0.3		<0.1			
	6/17/76	96 km	0.327	0	1.96	0.3		<0.1			
	6/17/76	96 km	0.541	0.22	1.77	0.2		<0.1			
	6/17/76	FTP	1.90	0.19	1.04	1.0	48	1.0	72.6	73.6	15.9

(e) Sample lost.

(f) A second FTP was carried out on 4/2 at the 15 000 km point because the cycle follower stuck several times during the initial FTP on 3/31 which made the run about 2 minutes longer than normal.

(g) This FTP was carried out after tune-up.

(h) A new oxygen sensor was installed prior to this test.

SECTION 7

THREE-WAY CATALYST VEHICLE - DESIGN NO. 2

7.1 DESIGN AND FABRICATION

A prototype 1977 Volvo with 2.0 litre overhead camshaft L-4 cylinder engine and "Lambda Sond" three-way catalyst system was selected to demonstrate 80,000 km of durability under the contract modification. Through EPA negotiation, the vehicle was supplied to ER&E for testing by Volvo of America. The Lambda Sond system, which is supplied to Volvo by Bosch, is an upadated and improved version of the feedback fuel injection that was installed on the first Volvo three-way catalyst demonstration vehicle. It uses electronic feedback control with an oxygen sensor to modulate the vehicle's fuel injection system. The desired A/F ratio is maintained by varying the amount of fuel injected into the engine. The Volvo Lambda Sond System is virtually unchanged from the Bosch feedback fuel injection system previously described in both system components, and in system operational logic. See Figure 7-1. Rather than repeat the description already given, the reader is redirected to the previous section (6.1), as well as to Volvo's technical literature (10,11) for complete details of the Lambda Sond System.

The only modification made to the vehicle was the substitution of a "mine-mix" three-way catalyst containing about 5% rhodium in place of the original certification catalyst, about 17% rhodium, supplied with the vehicle.

7.2 TEST RESULTS

The vehicle passed 0 km FTP emissions targets for HC and NO_X with both the certification and mine-mix catalysts. Although FTP CO emissions (with both catalysts) were slightly above the 0 km target level, they were well below the 80,000 km maximum, and durability testing was begun. See Table 7-1.

TABLE 7-1

PRELIMINARY (0 km.) FTP EXHAUST EMISSIONS

Run	Catalyst Type	Emissions (g/km)		
		CO	HC	NOX
FTP#1	Certification	1.39	0.11	0.10
FTP#2	Mine-Mix	1.22	0.13	0.13
FTP#3	Mine-Mix	1.55	0.12	0.20
Targets	0 km	1.00	0.12	0.60
	80,000 km	2.10	0.25	1.20

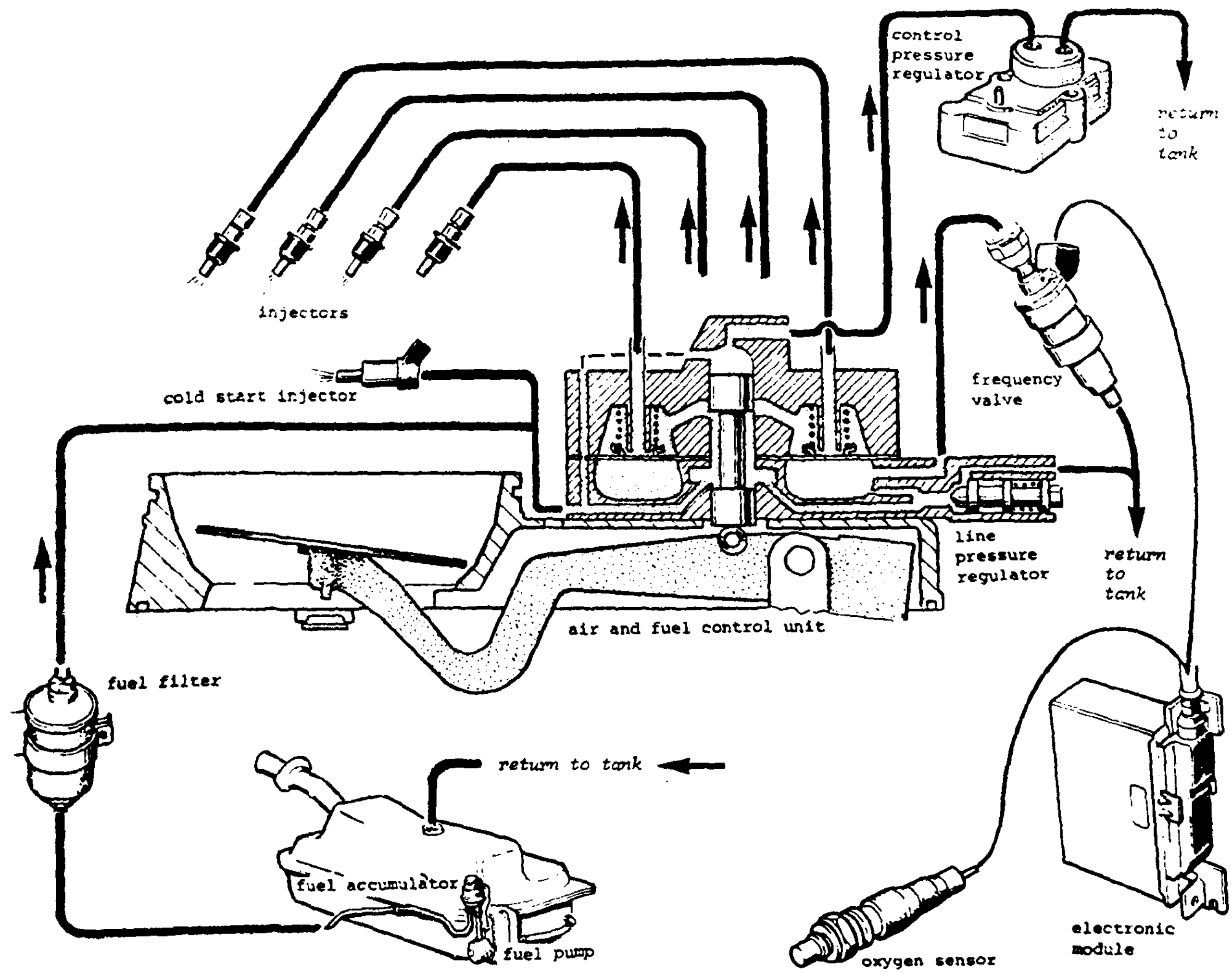


FIGURE 7-1

VOLVO LAMBDA-SOND FEEDBACK CONTROL
FUEL INJECTION SYSTEM

Kilometer accumulation was carried out using the modified AMA cycle and a commercial unleaded fuel containing 312 ppm of sulfur, 0.01 g Pb/gal, and 0.70 mg P/gal. Emission testing was carried out using Indolene containing 299 ppm of sulfur. The test sequence consisted of the Federal Test Procedure (FTP), two Sulfate Emissions Tests (SET), a Highway Fuel Economy Test (HWFET), two SET's, and two hours of 96 km/hr steady state cruise. In addition to the 80,000 km durability testing for regulated emissions, sulfate ($SO_4^=$), and sulfur dioxide (SO_2), the contract modification added hydrogen cyanide (HCN) and ammonia (NH_3) to the test list of unregulated pollutants.

Routine maintenance was performed according to manufacturer's recommendations and was scheduled with respect to the absolute mileage of the engine, which was 9,520 km (5,916 miles) when the catalyst was changed and testing began. Table 7-2 contains a compilation of all scheduled and unscheduled maintenance performed to the vehicle.

In addition to routine maintenance a number of repairs were made. At 6,000 km a new water pump was installed because the one on the vehicle was making noise. It was decided to adopt a policy of preventative part replacement and maintenance, rather than wait for a total failure. That is, in the case of the water pump, to replace the noisy unit before outright failure occurred. For the same reason the cooling fan clutch was replaced at 15,000 km when it began to make noise and show signs of excessive vibration.

At 37,814 km, during a routine check, it was noticed that the vehicle had developed an unsteady idle condition. Engine idle speed varied by about 300 rpm about the set-point, with stable periods of one to two minutes. Inspection of the fuel injection system revealed two cracked fuel injector retainers. The idle speed cycling that was observed was a result of rich-to-lean A/F excursions of the Lambda-Sond feedback control system trying to compensate for air leakage at the fuel injectors. Volvo of America replaced the fuel injectors and their retainers, and recalibrated idle speed and carbon monoxide settings to manufacturers specifications. The oxygen sensor was also replaced after installation of the new injectors as a precaution against the possibility of sensor burn-out during calibration adjustments. The catalyst was also removed from the vehicle during system troubleshooting and recalibration to protect it from damage.

At 60,000 km vehicle kilometer accumulation was stopped for emission testing. At this time it was discovered, after noting poor driveability and abnormally high FTP hydrocarbon levels, that one spark plug was completely bridged by a piece of engine deposit. Exhaust temperature traces before and after the catalyst indicated that the spark plug bridging occurred at approximately 56,200 km. The problem was not discovered until 3,800 km later because of a four day (holiday) weekend. During the misfire condition, the catalyst overtemperature safety did not trip. It was set for engine shutdown at 1550°F which Engelhard Industries (the catalyst manufacturer) specified as a safe upper limit catalyst operating temperature. Before the misfire condition occurred, the temperature gradient across the catalyst (outlet-inlet gas temperatures) was approximately 400°F. During misfire this gradient increased to 650°F. Inlet temperatures to the catalyst during misfire, which were generally lower than those before misfire, varied over a range from 550°F to a maximum 850°F. The exit temperatures during misfire varied from 1150°F to a maximum of 1450°F. These exotherms did not change from the onset of plug misfire to the discovery of the problem 3,800 km later. The fact that catalyst exotherms were unchanged throughout misfire, coupled with a maximum catalyst temperature one hundred degrees below a safe upper limit specification, was an assurance that catalyst damage did not take place. However, as a precaution, the oxygen sensor was changed because of its' possible sensitivity to a misfire condition.

Near the end of the 60,000 km test sequence two more malfunctions occurred. The vehicle began operating in an open loop mode and would not control A/F ratio. It was found that the feedback control system wires that lead to the frequency control solenoid valve had been cut and shorted by rubbing against the fuel return line. The wires were replaced and rerouted away from any contact points to prevent future reoccurence. With the vehicle operating properly the 60,000 km test sequence was completed. At this time a fluid leak from the automatic transmission was noted. The transmission kickdown cable and gasket were replaced, and the old transmission fluid was flushed and replaced. The vehicle was then sent out to complete the durability accumulation.

Finally, at 77,806 km, the right rear axle bearing seized and caused the right rear axle shaft to break. No apparent damage occurred to the rear axle carrier housing, so the shaft and bearings were renewed. After repairing this failure, kilometer accumulation continued to the full 80,000 km with no further trouble.

A summary of the emission test data for this vehicle during the 80,000 km durability accumulation is found in Table 7-3. Emissions tests were performed at accumulation points of 2,182 km, 6,000 km, 15,000 km, 30,000 km, 60,000 km, and 80,000 km (as well as an initial test at 0 km). In general, CO and NO_x emission levels on the FTP driving cycle increased with accumulated kilometers. HC emissions, though not as severely affected, were also increased by the end of durability testing. The vehicle exceeded the maximum FTP CO contract target (2.1 g/km) at 15,000 km, with CO increasing to 3.36 g/km at the final 80,000 km test point. HC and NO_x emission levels, however, remained below contract targets throughout the entire durability accumulation. A test run made without the three-way catalyst mounted (engine-out emissions) at 80,000 km showed that the catalyst was still more than 60% active for CO oxidation, with HC and NO_x conversion levels of 80% and 60%, respectively.

It is not felt that the deterioration seen in the performance of the three-way catalyst was related to, or influenced by, the engine misfire condition that occurred at 56,200 km. As shown in Figure 7-2, the emissions of all three regulated pollutants increased smoothly with accumulated kilometers. The fact that there was no significant emissions discontinuity at the 56,200 km point, in addition to the constant catalyst exotherms during misfire (mentioned previously) are excellent assurances that the emissions degradation seen was due solely to catalyst deterioration with increasing kilometers.

Table 7-2

MAINTENANCE PERFORMED TO THREE-WAY CATALYST
VOLVO DESIGN #2

km Durability 0 km = 5,916 miles	Services, etc.
374	• Oil and filter change
2 000	• Adjusted toothed belt • Installed "625" O_2 sensor in lieu of "4209"
6 000	• Installed new water pump • Replaced engine coolant
15 000	• Installed new fan clutch
15 320	• Oil and filter change • Installed new spark plugs • Adjusted toothed belt
20 134	• Replaced oil fill cap gasket
30 353	• Installed new O_2 sensor
37 814	• New injectors and retainers, new O_2 sensor
42 294	• Oil and filter change
56 134	• Oil and filter change
60 000	• New plugs, new O_2 sensor, Fixed fuel regulator and replaced connections to fuel return lines and fuel distributor
60 400	• Repair kick-down cable, drain and recharge transmission.
62 534	• New timing belt, plugs, evaporative control filter
65 972	• Oil and filter change
77 806	• Repaired or replaced right rear axle, brake lining, etc. as necessary

TABLE 7-3

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST EQUIPPED VOLVO-DESIGN #2

(Test Fuel = Indolene with 299 ppm S)

<table>
<tr><th rowspan="2">Km</th><th rowspan="2">Date</th><th rowspan="2">Test</th><th colspan="3">Emissions, g/km</th><th colspan="4">Emissions, mg/km</th><th colspan="2">% Fuel S As</th><th rowspan="2">% Fuel S Recovered</th><th rowspan="2"># Fuel Used (Carbon Balance)</th></tr>
<tr><th>CO</th><th>HC</th><th>NOx</th><th>HCN</th><th>NH_3</th><th>$SO_4^=$</th><th>SO_2</th><th>$SO_4^=$</th><th>SO_2</th></tr>
<tr><td>0</td><td>8/10/76</td><td>FTP</td><td>1.220</td><td>0.130</td><td>0.130</td><td><1.4</td><td>42</td><td>2.3</td><td>6.3</td><td>2.32</td><td>9.36</td><td>11.68</td><td>4.36</td></tr>
<tr><td></td><td>"</td><td>SET-1</td><td>0.099</td><td>0.031</td><td>0.041</td><td><1.2</td><td>28</td><td>0.84</td><td>31.9</td><td>0.12</td><td>66.96</td><td>67.08</td><td>3.84</td></tr>
<tr><td></td><td>"</td><td>SET-2</td><td>0.111</td><td>0.023</td><td>0.038</td><td><1.7</td><td>40</td><td>0.69</td><td>68.2</td><td>0.09</td><td>139.60</td><td>139.69</td><td>3.94</td></tr>
<tr><td></td><td>"</td><td>FET</td><td>0.080</td><td>0.025</td><td>0.065</td><td><1.2</td><td>18</td><td>0.76</td><td>45.6</td><td>1.19</td><td>106.16</td><td>107.35</td><td>2.60</td></tr>
<tr><td></td><td>"</td><td>SET-3</td><td>0.071</td><td>0.029</td><td>0.075</td><td><1.2</td><td>25</td><td>0.68</td><td>47.3</td><td>0.93</td><td>98.54</td><td>99.47</td><td>3.88</td></tr>
<tr><td></td><td>"</td><td>SET-4</td><td>0.072</td><td>0.022</td><td>0.043</td><td><1.3</td><td>37</td><td>0.58</td><td>108.1</td><td>0.82</td><td>232.06</td><td>232.88</td><td>3.76</td></tr>
<tr><td></td><td>"</td><td>96 km-1</td><td>0.059</td><td>0</td><td>0.016</td><td rowspan="4"><0.15</td><td rowspan="4">62</td><td>0.27</td><td rowspan="4">48.9</td><td rowspan="4">0.95</td><td rowspan="4">123.43</td><td rowspan="4">124.38</td><td>4.69*</td></tr>
<tr><td></td><td>"</td><td>96 km-2</td><td>0.129</td><td>0</td><td>0.010</td><td>0.62</td><td>4.68*</td></tr>
<tr><td></td><td>"</td><td>96 km-3</td><td>0.136</td><td>0.014</td><td>0.007</td><td>0.96</td><td>4.68*</td></tr>
<tr><td></td><td>"</td><td>96 km-4</td><td>0.153</td><td>0.009</td><td>0.010</td><td>0.42</td><td>4.76*</td></tr>
<tr><td></td><td>"</td><td>2nd FTP</td><td>1.550</td><td>0.120</td><td>0.200</td><td><1.5</td><td>54</td><td>0.72</td><td>30</td><td>0.71</td><td>45.15</td><td>45.86</td><td>4.34</td></tr>
</table>

* 20 minute fuel consumption

TABLE 7-3 (Continued)

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST EQUIPPED VOLVO-DESIGN #2

(Test Fuel = Indolene with 299 ppm S)

Km	Date	Test	Emissions, g/km CO	HC	NOx	Emissions, mg/km HCN	NH_3	$SO_4^=$	SO_2	% Fuel S As $SO_4^=$	SO_2	% Fuel S Recovered	# Fuel Used (Carbon Balance)
2182	8/26/76	FTP	2.189	0.184	0.287	2.9	13	0.87	38.2	0.88	60.12	60.99	4.29
	"	SET-1	0.475	0.059	0.218	<1.2	27	0.57	62.6	0.78	132.2	133.07	3.88
	"	SET-2	0.449	0.046	0.176	<1.2	51	0.61	48.0	0.88	104.21	105.09	3.78
	"	FET	0.480	0.032	0.137	<1.6	57	0.55	39.6	0.86	93.63	94.49	2.57
	"	SET-3	0.420	0.043	0.258	<1.9	55	0.70	44.3	0.97	93.88	94.85	3.87
	"	SET-4	0.387	0.047	0.211	<1.8	52	1.2	46.6	1.60	98.89	100.50	3.86
	"	96 km-1	0.201	0.010	0.165	<0.14	0.34	0.40	50.5	0.53	121.84	122.37	5.01*
	"	96 km-2	0.195	0	0.150			0.44					5.11*
	"	96 km-3	0.137	0	0.155			0.27					5.08*
	"	96 km-4	0.127	0	0.153			0.27					5.05*
	8/27/76	2nd FTP	1.351	0.117	0.320	1.8	34	0.88	273.0		42.46	43.35	4.34
	8/28/76	3rd FTP**	1.861	0.132	0.486	--	--	--	--	--	--	--	4.69

(Values <0.14, 0.34, 50.5, 0.53, 121.84 and 122.37 are bracketed across the four 96 km runs.)

* 20 minute fuel consumption

** O_2 sensor changed before run

TABLE 7-3 (Continued)

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST EQUIPPED VOLVO-DESIGN #2

(Test Fuel = Indolene with 299 ppm S)

Km	Date	Test	Emissions, g/km			Emissions, mg/km				% Fuel S As		% Fuel S Recovered	# Fuel Used (Carbon Balance)
			CO	HC	NOx	HCN	NH_3	$SO_4^=$	SO_2	$SO_4^=$	SO_2		
6000	9/8/76	FTP	1.718	0.115	0.314	<1.6	7.9	1.51	30.9	1.62	81.08	82.70	4.05
	"	SET-1	0.196	0.026	0.373	<1.2	15.1	0.47	78.1	0.67	169.91	170.58	3.77
	"	SET-2	0.121	0.035	0.243	<1.2	11.4	0.30	50.2	0.44	112.39	112.84	3.66
	"	FET	0.122	0.015	0.182	<1.6	20.5	0.50	51.2	0.81	127.79	128.60	2.46
	"	SET-3	0.218	0.027	0.300	<1.2	13.6	0.49	50.1	0.69	109.28	109.96	3.76
	"	SET-4	0.169	0.024	0.282	<1.2	16.6	0.076	53.3	0.12	118.25	118.36	3.86
	"	96 km-1	0.213	0.016	0.189	<0.14 (96 km-1 to 96 km-4)	81.7 (96 km-1 to 96 km-4)	0.28	55.7 (96 km-1 to 96 km-4)	0.60 (96 km-1 to 96 km-4)	133.24 (96 km-1 to 96 km-4)	133.84 (96 km-1 to 96 km-4)	5.19*
	"	96 km-2	0.240	0.004	0.196			0.41					5.03*
	"	96 km-3	0.322	0.026	0.208			0.40					5.11*
	"	96 km-4	0.275	0.022	0.175			0.46					5.10*

* 20 minute fuel consumption

TABLE 7-3 (Continued)

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST EQUIPPED VOLVO-DESIGN #2

(Test Fuel = Indolene with 299 ppm S)

			Emissions, g/km			Emissions, mg/km				% Fuel S As		% Fuel S	# Fuel Used
Km	Date	Test	CO	HC	NOx	HCN	NH_3	$SO_4^=$	SO_2	$SO_4^=$	SO_2	Recovered	(Carbon Balance)
15 000	9/22/76	FTP	2.508	0.162	0.375	<1.5	<7	1.6	88.4	1.42	120.20	121.62	4.97
	"	SET-1	0.362	0.035	0.290	<1.2	<6	0.66	73.4	0.94	160.47	161.41	3.75
	"	SET-2	0.413	0.033	0.272	<1.2	18	0.55	45.2	0.79	99.21	100.00	3.74
	"	FET	0.303	0.024	0.237	<1.5	14	0.59	44.2	0.93	105.81	106.74	2.54
	"	SET-3	0.414	0.019	0.326	<1.2	8	1.1	42.0	1.47	88.27	89.74	3.91
	"	SET-4	0.414	0.041	0.333	<1.2	23	0.56	44.9	0.78	95.34	96.12	3.86
	"	96 km-1	0.108	0.0	0.308			0.30					5.19*
	"	96 km-2	0.094	0.02	0.301	0.2	16	0.20	52.6	0.23	123.61	123.84	5.28*
	"	96 km-3	0.094	0.012	0.295			0.19					5.18*
	"	96 km-4	0.094	0.013	0.280			0.21					5.16*

* 20 minute fuel consumption

TABLE 7-3 (Continued)

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST EQUIPPED VOLVO-DESIGN #2

(Test Fuel = Indolene with 299 ppm S)

			Emissions, g/km			Emissions, mg/km				% Fuel S As		% Fuel S	# Fuel Used
Km	Date	Test	CO	HC	NOx	HCN	NH_3	$SO_4^=$	SO_2	$SO_4^=$	SO_2	Recovered	(Carbon Balance)
30 000	10/12/76	FTP	3.000	0.135	0.549	< 1.4	12	2.0	26.8	2.21	43.26	45.47	4.04
	"	SET-1	0.802	0.037	0.562	< 1.1	9	0.87	49.2	1.23	104.63	105.86	3.79
	"	SET-2	0.640	0.040	0.571	< 1.1	22	0.50	34.3	0.72	75.45	76.17	3.67
	"	FET	0.245	0.028	0.660	2.7	15	0.46	41.9	0.68	93.96	94.64	2.70
	"	SET-3	0.882	0.073	0.668	< 1.1	16	1.1	34.8	1.48	72.13	73.61	3.89
	"	SET-4	0.690	0.046	0.627	< 1.2	23	0.51	24.2	0.72	51.70	52.42	3.77
	"	96 km-1	0.132	0.019	0.974	<0.1	3	0.41	55.7	3.56	182.65	186.21	5.45*
	"	96 km-2	0.095	0.004	1.050			0.33					5.43*
	"	96 km-3	0.096	0.021	1.199			0.48					5.52*
	"	96 km-4	0.097	0.015	1.121			0.40					5.41*
	10/13/76	FTP (2nd)**	2.327	0.132	0.641	--	--	--	--	--	--	--	4.17

(Values for HCN, NH_3, SO_2, % Fuel S As $SO_4^=$, % Fuel S As SO_2 and % Fuel S Recovered are bracketed across the four 96 km tests.)

* 20 minute fuel consumption

** after new O_2 sensor

TABLE 7-3 (Continued)

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST EQUIPPED VOLVO-DESIGN #2

(Test Fuel = Indolene with 299 ppm S)

<table>
<tr><th rowspan="2">Km</th><th rowspan="2">Date</th><th rowspan="2">Test</th><th colspan="3">Emissions, g/km</th><th colspan="4">Emissions, mg/km</th><th colspan="2">% Fuel S As</th><th rowspan="2">% Fuel S Recovered</th><th rowspan="2"># Fuel Used (Carbon Balance)</th></tr>
<tr><th>CO</th><th>HC</th><th>NOx</th><th>HCN</th><th>NH_3</th><th>$SO_4^=$</th><th>SO_2</th><th>$SO_4^=$</th><th>SO_2</th></tr>
<tr><td>60 000</td><td>12/9/76</td><td>FTP</td><td>2.727</td><td>0.176</td><td>0.765</td><td>7.8</td><td>6.8</td><td>3.4</td><td>0.0**</td><td>3.88</td><td>--</td><td>--</td><td>3.81</td></tr>
<tr><td></td><td>"</td><td>SET-1</td><td>0.747</td><td>0.057</td><td>0.786</td><td>3.2</td><td>10.5</td><td>1.1</td><td>56.61</td><td>1.62</td><td>121.79</td><td>123.41</td><td>3.75</td></tr>
<tr><td></td><td>"</td><td>SET-2</td><td>0.751</td><td>0.055</td><td>0.755</td><td>4.2</td><td>22.1</td><td>0.93</td><td>-- **</td><td>1.38</td><td>--</td><td>--</td><td>3.61</td></tr>
<tr><td></td><td>"</td><td>FET</td><td>0.679</td><td>0.050</td><td>0.698</td><td>3.1</td><td>31.6</td><td>0.69</td><td>34.63</td><td>1.12</td><td>84.50</td><td>85.62</td><td>2.48</td></tr>
<tr><td></td><td>"</td><td>SET-3</td><td>0.841</td><td>0.053</td><td>0.791</td><td>4.0</td><td>13.4</td><td>0.93</td><td>0.0**</td><td>1.37</td><td>--</td><td>--</td><td>3.66</td></tr>
<tr><td></td><td>"</td><td>SET-4</td><td>0.706</td><td>0.052</td><td>0.785</td><td><2.2</td><td>2.7</td><td>0.76</td><td>24.07</td><td>1.13</td><td>53.64</td><td>54.77</td><td>3.62</td></tr>
<tr><td></td><td>"</td><td>96 km-1</td><td>0.663</td><td>0.041</td><td>0.922</td><td rowspan="4">2.3</td><td rowspan="4">54.1</td><td>0.60</td><td rowspan="4">52.09</td><td rowspan="4">0.13</td><td rowspan="4">180.21</td><td rowspan="4">180.74</td><td>5.06*</td></tr>
<tr><td></td><td>"</td><td>96 km-2</td><td>0.771</td><td>0.038</td><td>1.001</td><td>0.27</td><td>5.10*</td></tr>
<tr><td></td><td>"</td><td>96 km-3</td><td>0.788</td><td>0.031</td><td>1.000</td><td>0.19</td><td>5.25*</td></tr>
<tr><td></td><td>"</td><td>96 km-4</td><td>0.724</td><td>0.029</td><td>1.025</td><td>0.33</td><td>5.17*</td></tr>
</table>

* 20 minute fuel consumption

** bubbler not good or no inflection in titration

TABLE 7-3 (Continued)

SUMMARY OF KILOMETER ACCUMULATION EMISSION DATA FOR THREE-WAY CATALYST EQUIPPED VOLVO-DESIGN #2

(Test Fuel = Indolene with 299 ppm S)

			Emissions, g/km			Emissions, mg/km				% Fuel S As		% Fuel S Recovered	# Fuel Used (Carbon Balance)
Km	Date	Test	CO	HC	NOx	HCN	NH_3	$SO_4^=$	SO_2	$SO_4^=$	SO_2		
80 000	2/4/77	FTP	3.356	0.200	0.954	4.21	30.45	8.072	29.0	9.84	52.98	62.82	3.57
	"	SET-1	0.980	0.066	1.037	17.50	14.22	0.54	33.9	0.83	78.44	79.27	3.49
	"	SET-2	0.636	0.049	1.106	2.02	5.56	0.58	50.8	0.88	116.42	117.30	3.52
	"	FET	0.645	0.054	1.080	1.48	3.56	0.43	71.8	0.71	176.49	177.20	2.46
	"	SET-3	1.088	0.070	1.163	4.21	40.59	0.61	30.9	0.87	65.86	66.73	3.79
	"	SET-4	0.958	0.056	1.085	4.30	46.92	0.29	32.8	0.43	73.82	74.25	3.58
	"	96 km-1	0.642	0.047	1.533			0.20					5.37*
	"	96 km-2	0.742	0.046	1.573	0.31	43.11	0.45	44.0	0.14	145.80	145.94	5.37*
	"	96 km-3	0.790	0.046	1.573			0.063					5.37*
	"	96 km-4	0.750	0.043	1.613			0.087					5.37*
	2/4/77	FTP**	8.899	0.888	2.301	--	--	--	--	--	--	--	3.83

* 20 minute fuel consumption

** without a catalyst

A detailed examination of tailpipe CO emissions is also useful to illustrate the three-way catalyst's deactivation history. FTP CO emissions began to increase steadily starting at the 6,000 km accumulation point (well in advance of the misfire condition). The percent increase in CO emissions (a function of catalyst deactivation) within each successive accumulation interval, as well as a normalized percent increase per 1,000 km (which normalizes the varying kilometer length of each accumulation), is presented in Table 7-4.

TABLE 7-4

FTP CO EMISSIONS: THREE-WAY CATALYST VEHICLE - DESIGN #2

Accumulation Interval (km)	FTP CO Emissions (g/km)	ΔCO Emissions During Interval (%)	Normalized ΔCO Emissions (Δ%/1000 km)
6000	1.718		
15000	2.508	+45.98	+5.11
30000	3.000	+19.62	+1.31
30000*	2.327*		
60000	2.727	+17.19	+0.573
80000	3.356	+23.07	+1.15

*FTP after new O_2 sensor installed

The largest CO increase seen was during the accumulation interval from 6,000 km to 15,000 km. Successive intervals show continued catalyst deactivation for CO oxidation, but at a reduced rate. It should be noted that the deactivation (normalized percent) for the 60,000 to 80,000 km interval after the misfire is lower than those of the 6,000 km-15,000 km and 15,000 km-30,000 km intervals. That CO emissions did not increase abnormally after the misfire occurrence further reinforces the fact that the emissions increases seen were due to catalyst deactivation with accumulated kilometers.

Sulfate emissions during the kilometer accumulation ranged between less than 0.1 to 9.8 percent of the sulfur in the fuel, depending on the test cycle being performed. Conversion of fuel sulfur to sulfate was highest during the FTP driving cycle and was in the range of 0.88 to 9.84 percent, while conversion levels at 96 km/hr cruise were generally less, ranging from 0.13 to 3.56 percent. Sulfate emissions for 96 km/hr steady state cruise conditions were in the range of 0.06 to 0.96 mg/km, and were well below the contract target of 6.2 mg/km.

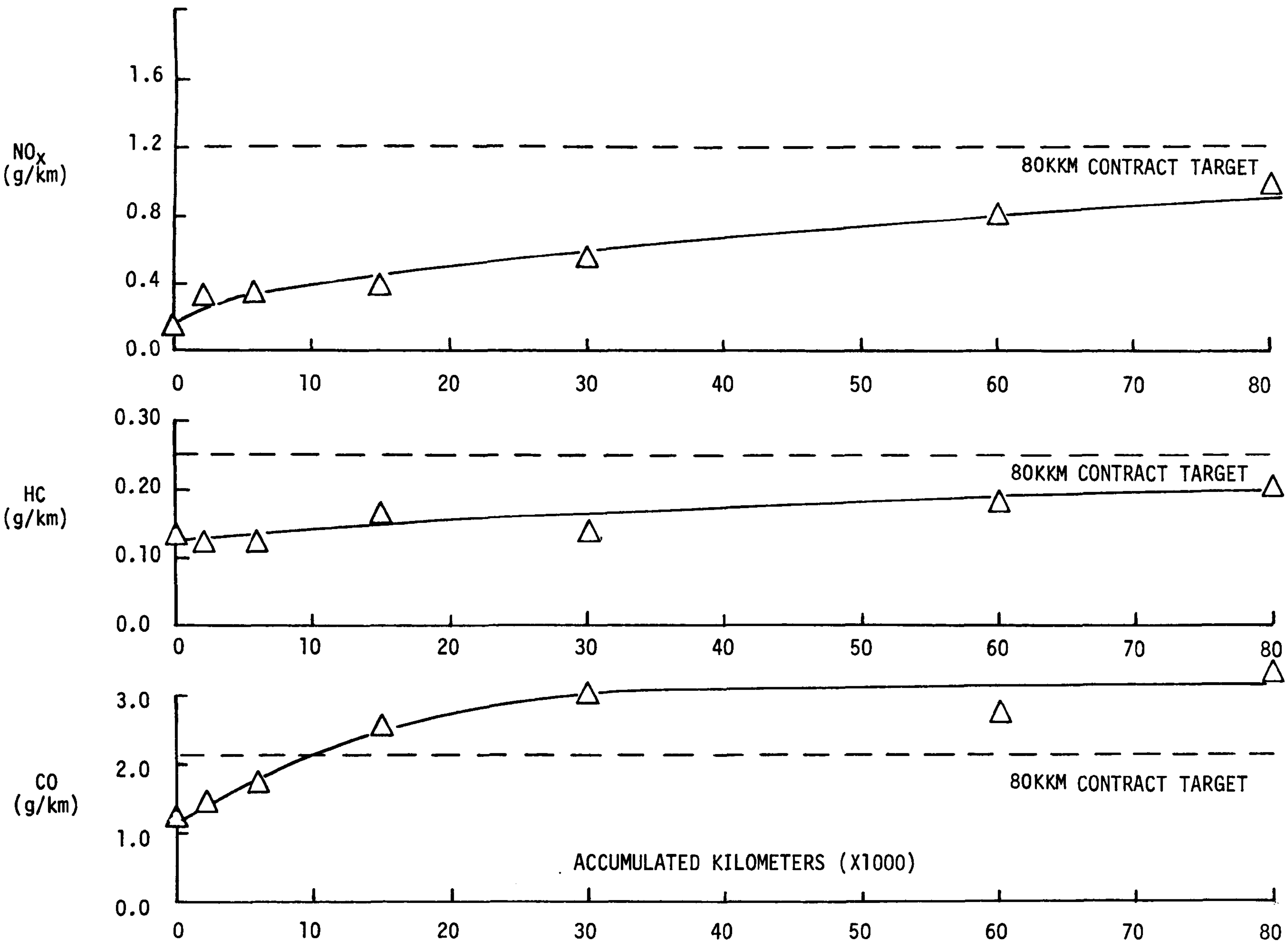


FIGURE 7-2

REGULATED EMISSIONS VS. ACCUMULATED KILOMETERS

THREE-WAY CATALYST VEHICLE DESIGN NO. 2

Emissions of ammonia (NH_3) and hydrogen cyanide (HCN) remained low throughout the 80,000 km of durability testing. Ammonia emission rates ranged from less than 0.34 mg/km to a maximum of 81.7 mg/km. Hydrogen cyanide emission rates were in the range of less than 0.1 mg/km to a maximum of 17.5 mg/km. There was no apparent correlation for either NH_3 or HCN emission rates with the type of driving cycle performed, or with accumulated kilometers. There was, however, an increase in HCN emissions at the 60,000 km and 80,000 km test intervals, as compared to previous test points. No other emission increased as dramatically at these test points, and there is no obvious explanation for the discontinuous increase in HCN emission rate observed.

In conclusion, the 1977 three-way catalyst Lambda-Sond Volvo completed the full 80,000 km of durability testing. The vehicle met all of the 80,000 km contract targets, except for CO. It is interesting to note that although the vehicle exceeded the 80,000 km CO contract targets, it met the 1977-1979 California certification targets of 5.6 gpk CO, 0.26 gpk HC, and 0.95 gpk NO_x, and with a mine-mix catalyst. Emissions of NH_3 and HCN were also monitored during durability testing, and in general remained low. Testing of this vehicle confirmed that three-way catalysts were a viable method of automotive emission control. Three-way catalyst systems can control regulated pollutants (CO, HC and NO_x) to stringent levels and emit low levels of unregulated pollutants such as sulfate.

SECTION 8

LOW EXCESS AIR VEHICLE - DESIGN #2

8.1 DESIGN AND FABRICATION

A new low excess air vehicle was designed and tested under the contract modification. A 1977 California emissions certified Ford Pinto (2.3 litre overhead camshaft L-4 cylinder engine, backpressure modulated EGR, airpump and oxidation catalyst) was modified for low excess air operation with a Holley closed-loop feedback controlled carburetor with oxygen sensor, and an Engelhard monolithic oxidation catalyst. The advantages of this particular design were (1) the installation of the Holley vacuum modulated feedback carburetor system on the 1977 Pinto would require a minimum of mechanical modification, since 1978 California three-way catalyst Pinto's were to be built by Ford with the Holley system as production equipment, (2) Holley agreed to modify the electronic control unit for the feedback carburetor so it could be set for low excess air conditions, rather than for three-way catalyst operation, (3) Holley agreed to furnish technical assistance as required, and (4) Engelhard agreed to supply a monolithic catalyst of suitable size and "composition" to provide good conversion activity under low excess air conditions.

A schematic of the Holley closed-loop feedback controlled carburetor system is found in Figure 8-1. As was described for the previous feedback systems, a desired A/F ratio is maintained by varying the amount of fuel delivered to the engine. In the Holley system, feedback controlled airbleeds and main fuel jets are modulated by an electronic control unit in response to changing signals from an oxygen sensor (located in the exhaust stream). A major difference of the Holley system compared to other feedback control fuel metering systems is that it retains the carburetor as the basic fuel metering device. Feedback carburetor metering elements are modulated by a control vacuum signal. An electro-pneumatic interface, the vacuum control regulator valve, converts the electronic signals from the ECU to control vacuum levels that set the carburetor's airbleeds and metering jets to give the desired A/F ratio. A high ECU "on-time" (high duty cycle) results in an increased control vacuum level, closing off the feedback main jets and leans the A/F ratio. A description of the feedback control system's logic and operating sequence is found in Figure 8-2. A schematic diagram of the feedback carburetor and vacuum control regulator valve is shown in Figure 8-3.

In addition to the exhaust gas oxygen sensor, the ECU receives input signals from two other sensors. A throttle operation sensor signals the ECU to provide a rich A/F ratio during wide open throttle operation for power enrichment. An engine coolant temperature sensor switches the ECU to operate in an "open-loop" mode during cold start operation. In this mode ECU signals are preset to a level that enriches the A/F ratio and gives enchanced cold driveability. Spurious signals

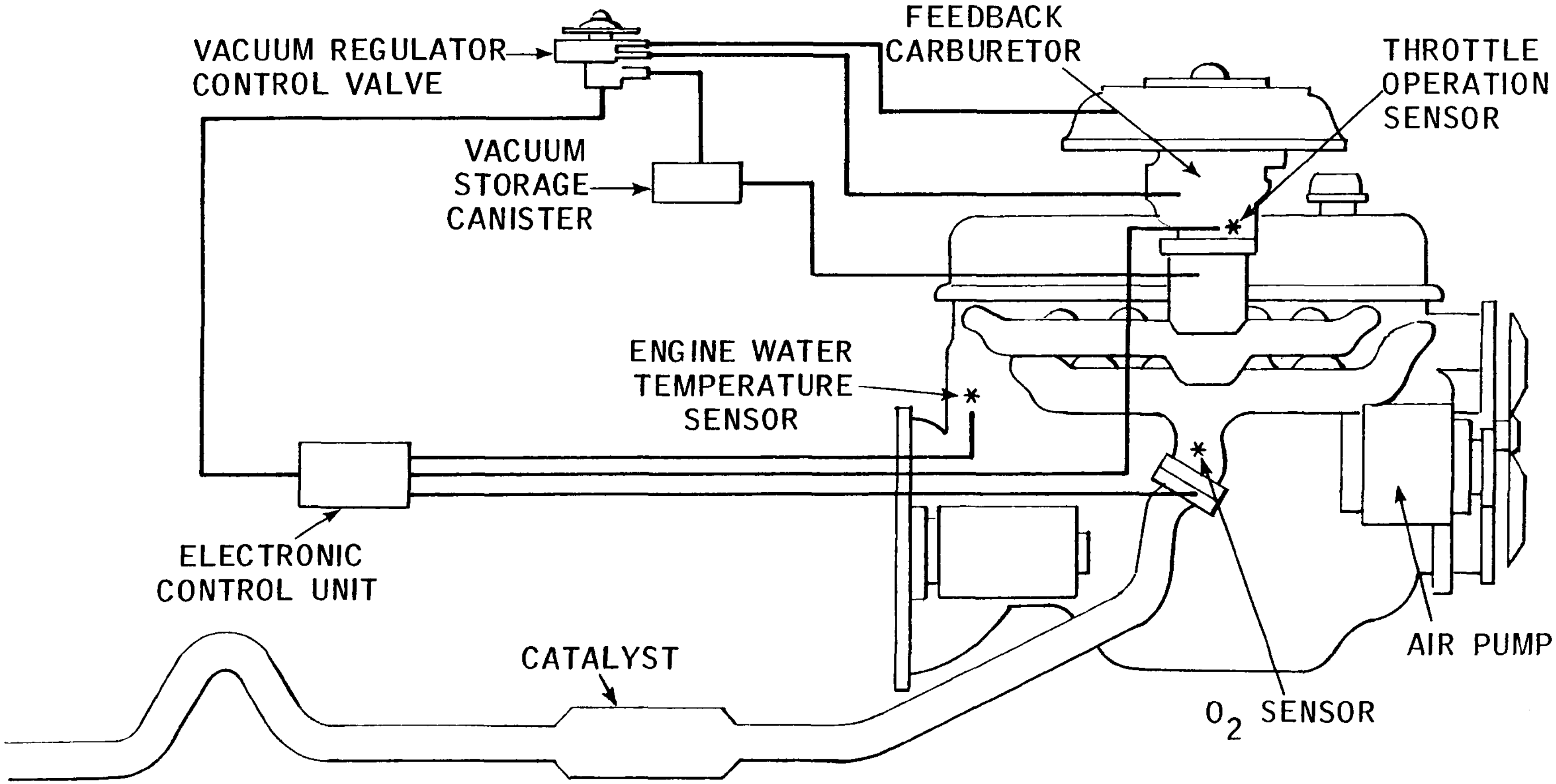


FIGURE 8-1

HOLLEY FEEDBACK CARBURETOR SYSTEM PICTORIAL DIAGRAM

ENGINE OPERATING CONDITION →	OXYGEN SENSOR OUTPUT →	ECU →	VACUUM SOLENOID REGULATOR VALVE →	VACUUM SIGNAL TO CARBURETOR F.B. CIRCUIT →	POSITION OF METERING ROD →	FUEL FLOW →	RESULTANT CORRECTIONS
RICH of Stoichiometry	High Output Voltage (>1.0 Volt)	Directs Vac.Sol.-Reg. To Greater "On Time" (50-→100%)	Increased Duty Cycle Results In Higher Output Vacuum (>2.5 in. Hg)	>2.5 in. Hg Signal Pulls Metering Rod Up (Smaller Orifice)	Higher Position For Decrease In F.B. Fuel Flow	Decreased	Toward LEAN
LEAN of Stoichiometry	Low Output Voltage (<0.35 Volt)	Directs Vac.Sol.-Reg. To Less "On Time" (50%→0)	Decreased Duty Cycle Results In Lower Output Vacuum (<2.5 in. Hg)	<2.5 in. Hg Signal Moves Metering Rod Down (Larger Orifice)	Lower Position For Increased F.B. Fuel Flow	Increased	Toward RICH

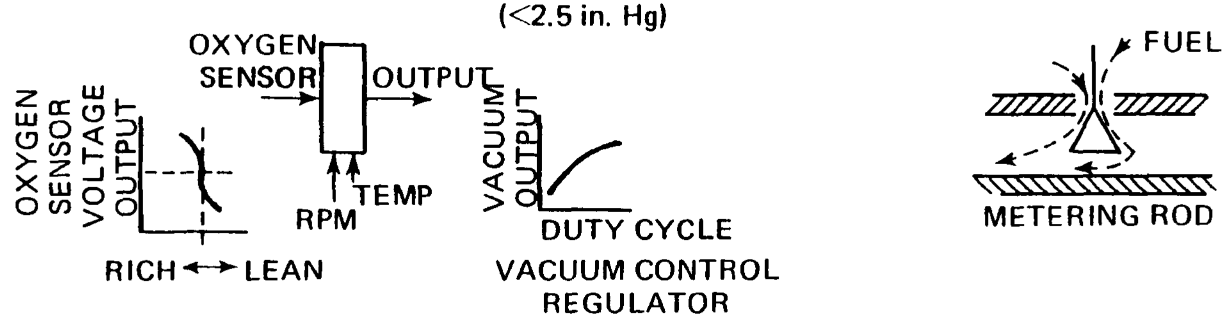


FIGURE 8-2

HOLLEY FEEDBACK CARBURETOR SYSTEM OPERATIONAL LOGIC

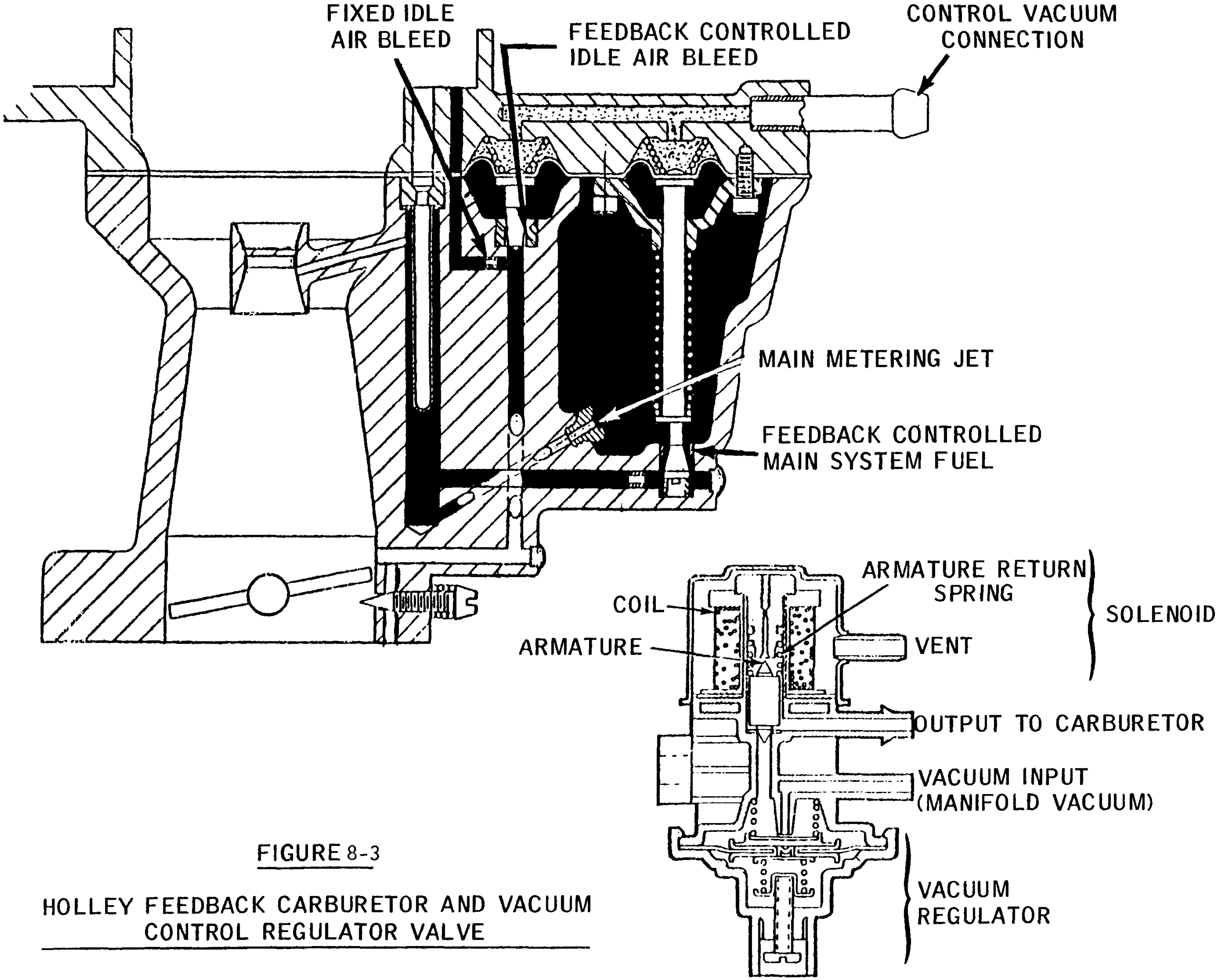


FIGURE 8-3

HOLLEY FEEDBACK CARBURETOR AND VACUUM
CONTROL REGULATOR VALVE

from the oxygen sensor, which has not yet heated up to operating temperature, are disregarded. When the engine coolant temperature reaches approximately 38°C (100°F) the sensor opens and the ECU assumes closed-loop control. Signals from the oxygen sensor are then used to maintain the engine A/F ratio at the desired value. A more detailed treatment of the Holley system's operation can be found in reference (12).

Holley modified the electronic control unit, at ER&E's request, so that the control reference voltage (above which a lean correction signal is generated/below which a rich correction signal is generated) could be set at any value desired. Typical oxygen sensor voltage response is in the overall range of 0 to 1000 millivolts, with approximately 500 mv. representing a stoichiometric A/F ratio. The oxygen sensor's characteristic response curve is found in Figure 8-4. By setting an ECU reference voltage of 500 mv (point C on Figure 8-4), a stoichiometric A/F ratio would be maintained, since any sensor output >500 mv drives the system lean and <500 mv drives the system rich. Thus, by a proper choice of the ECU reference voltage the A/F ratio can be biased slightly lean or rich of stoichiometric. For example a reference level of ~750 mv (A) would result in an A/F slightly rich of stoichiometric (any time the sensor voltage is <750 mv the ECU would send out a rich correction signal, and thus would spend a greater percentage of it's time rich), while a reference level of ~150 mv (B) would result in a slightly lean A/F ratio. A practical limit to the range of adjustability is when the reference voltage reaches either "shoulder" of the oxygen sensor curve. Sensitivity (change in mv output for A/F change) becomes low on the shoulder as compared to the almost infinite slope near the inflection point, making A/F control very unstable and imprecise.

When the feedback carburetor system was first installed on the vehicle it would not control A/F ratio. Troubleshooting revealed that the vacuum control regulator valve (VCRV) was not providing a control signal to the carburetor's feedback input port. Inspection of the valve by Holley revealed that it had become plugged with rubber particles. It was suspected that as rubber vacuum tubing was forced on the valve's ports its inner surface was abraded. The resultant rubber dust plugged the regulator's airbleeds when vacuum was applied, rendering the valve inoperative.

Upon installation of a new VCRV, baselining of the feedback carburetor system began. A correlation between the electronic control unit's reference voltage setting and A/F ratio was determined and the ECU was biased "slightly lean" for low excess air operation. Previous work done at ER&E had shown that the "break-point" of low sulfate production with high levels of CO and HC conversion occurred over an oxidation catalyst at about 0.5% oxygen in the exhaust gas. As seen in Table 8-1, a setting of "200" on the reference voltage potentiometer (arbitrary 0-1000 scale on a ten-turn helipot) resulted in the desired after-catalyst oxygen level, and corresponded to an A/F ratio of approximately 15.2.

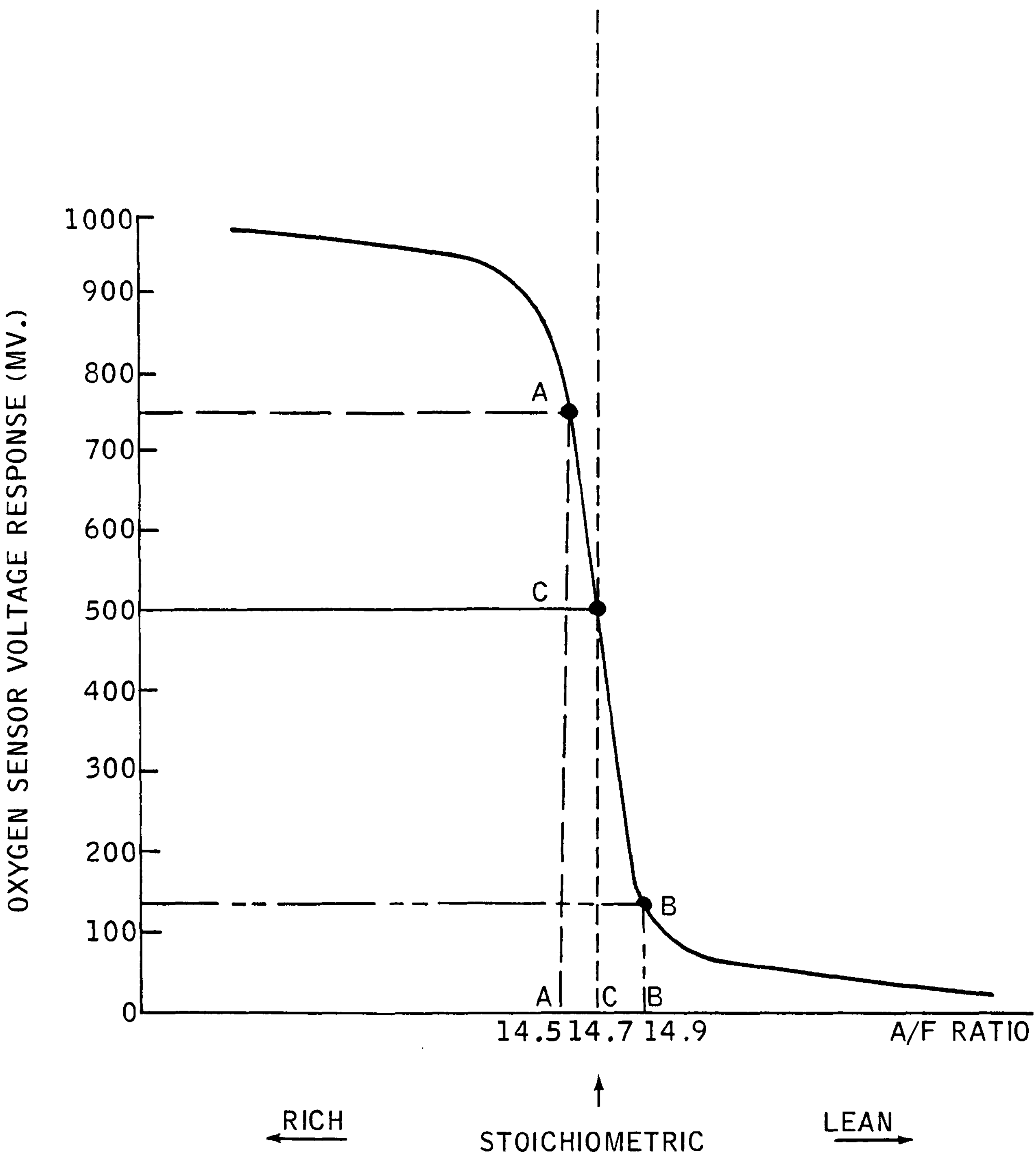


FIGURE 8-4

OXYGEN SENSOR VOLTAGE RESPONSE CURVE

Table 8-1

REFERENCE VOLTAGE POTENTIOMETER SETTING VS. A/F RATIO

40 mph - Steady State Conditions, Air Pump Off

Potentiometer Setting	A/F Ratio	O_2% After-Catalyst
490	13.84	0
470	14.10	0
400	14.65	0
300	14.95	0.15
250	15.05	0.20
200	15.20	0.51
100	15.35	0.65
0	15.75	0.9

A check was also made to insure that as vehicle speed varied, carburetor stoichiometry remained close to the desired set-point. As seen in Table 8-2, the A/F ratio variation with speed was slight, indicating the feedback system was tracking properly.

Table 8-2

A/F RATIO VS. VEHICLE SPEED

Vehicle Speed, mph	A/F Ratio
0-Idle	14.90
20	15.15
30	15.20
40	15.20
50	15.35

8.2 TEST RESULTS

FTP emissions with the feedback system installed were an order of magnitude higher for CO, when compared to the stock "as received" vehicle. HC and NO_x emissions were not as severely affected. It should be noted that installation of the feedback carburetor system increased FTP fuel economy by almost 0.5 km/liter (1 mpg) as shown in Table 8-3. Both tests were conducted with the production Ford catalyst mounted on the vehicle. The low excess air vehicle used air injection only on cold start to aid catalyst light-off, while the production vehicle had continuous air injection to promote oxidation over the catalyst. It was suspected that the lack of continuous air injection during the FTP cycle contributed to the increase in CO and HC emissions seen for the feedback carbureted vehicle.

TABLE 8-3

FTP EMISSIONS (g/km)
(Average of Three Tests)

	Vehicle With Production Carburetor Air Pump Operating	Vehicle With Feedback Carburetor 1 Min Air Injection, ECU @ 200
CO	0.60	2.53
HC	0.12	0.18
NO_x	0.92	1.25
Fuel Economy (km/liter)	9.9 (23.6 mpg)	10.3 (24.4 mpg)

Raw emissions concentrations indicated that almost all of the CO produced during the test (85%) was being emitted during the FTP's first bag. Re-setting the automatic choke for lean operation (faster opening), however, did not significantly reduce first bag CO emissions. To check the electronic control units' open-loop cold start enrichment circuit a switch was installed so that the feedback system could be placed in a cold start mode at any time desired. With a fully-warmed up engine engaging the cold start enrichment circuit resulted in a lean A/F ratio of about 16.0/1, rather than giving A/F enrichment. Driveability of the vehicle was poor due to engine misfire from the lean mixture. CO and HC emissions were increased while operating in this open-loop mode. The electronic control unit was reset slightly rich (A/F = 14.5) to augment normal choke action during cold start operation. Recalibration of the electronic control unit's open-loop circuit coupled with the leaned choke reduced FTP Bag 1 CO emissions. However the total weighted CO emissions remained above 0 km targets as shown in Table 8-4. Further adjustment would not lower CO emissions.

TABLE 8-4

FTP Emissions (g/km)
RECALIBRATED COLD START CIRCUIT
ECU @ 200, 1 MIN. AIR INJECTION
(Average of Three Tests)

	Production Ford Catalyst	EPA 0 KM. Contact Targets
CO	1.50	1.00
HC	0.12	0.12
NO_x	1.26	1.20

Catalyst temperature traces indicated that the production Ford catalyst took over three minutes to light-off during cold start operation. The Ford monolith was removed and replaced by a fresh Engelhard PTX-514 monolith (a known active oxidation catalyst) so that light-off times for the two could be compared. Light-off time for the PTX-514 was approximately one minute, which confirmed the suspicion that the Ford catalyst had deactivated. Most importantly, Bag 1 CO emissions were decreased by a factor of three, while total weighted FTP CO and HC emissions were below contract targets. See Table 8-5. Repeated FTP tests insured that the low emissions seen were not just a result of the "edge" of a fresh catalyst. It was felt that the Ford catalyst deactivated during the calibration of the feedback carburetor system's cold start circuits (choke duration, electronic control unit A/F enrichment circuit, air pump injection time). The A/F ratio during these tests became very rich (<13/1) and air was being injected to the catalyst. It was suspected that the high heat levels generated from oxidizing the CO deactivated the catalyst sufficiently to produce slow light off.

TABLE 8-5

FTP EMISSIONS (g/km)
ENGELHARD PTX-514 MONOLITH
ECU @ 200, 2 MIN. AIR INJECTION
(Four Test Average)

CO	0.72
HC	0.11
NO_x	1.89
Fuel Economy (km/liter)	10.3 (24.4 mpg)

Although the vehicle met CO and HC 0 km contract targets, NO_x emissions exceeded the 80,000 km maximum limits. The NO_x increase was attributed to the PTX-514 catalyst's different composition. That is, during rich transients the PTX-514 reduced less NO_x than did the production Ford catalyst, raising tailpipe NO_x levels. Adding support to this argument was the fact that raw exhaust (no catalyst) FTP data showed higher levels of NO_x than with the PTX-514 mounted. To bring NO_x emissions back to within acceptable levels, the EGR recycle rate was increased. Connecting the EGR system to the carburetor's "spark port" (instead of the "EGR port" normally used) gave higher amplitude vacuum signals at the EGR valve. This pulled the valve further open, and increased EGR rate. This solution avoided complicated machining of the valve body, which could have resulted in a leaky EGR valve. It should be noted that even though vacuum amplitude was increased, EGR vacuum modulation depended only on exhaust backpressure. Since the backpressure transducer was not modified, the schedule of EGR valve operation was unchanged, although recycle rate was increased. Replicate FTP testing showed that NO_x was reduced by this modification, HC and fuel economy were unaffected, and CO was increased. Sulfate emissions for these runs were below the 6.21 mg/km contract target, as shown in Table 8-6. Driveability (as perceived during emissions test runs) suffered noticeably from the increased EGR rate, particularly during accelerations where engine roughness and surging occurred.

TABLE 8-6

FTP EMISSIONS (g/km)
ENGELHARD PTX-514 MONOLITH
ECU @ 200, 2 MIN AIR INJECTION, SPARK PORT EGR

	FTP A	FTP B
CO	1.33	1.31
HC	0.12	0.09
NO_x	1.15	1.12
Fuel Economy (km/liter)	10.3 (24.4 mpg)	10.4 (24.8 mpg)
SO_4 = (mg/km)	4.1	3.2

Although FTP CO emissions were above 0 km contract targets, they were well below the 80,000 km maximum limits, and the EPA gave approval for initiating kilometer accumulation. The PTX-514 catalyst (68 in^3) used during vehicle optimization and baseline testing was replaced by the PTX-516 (102 in^3) monolithic catalyst purchased for the contract work. It was felt that the larger catalyst volume would better offset the effects of aging and deterioration, making attainment of the 80,000 km goals more certain. Out of the two experimental preparations purchased, Engelhard recommended Serial #112178-029 for our application. With this catalyst the vehicle met all 0 km contract targets and was sent out for the first 2,000 km of durability testing. See Table 8-7.

TABLE 8-7

FTP EMISSIONS (g/km)
ENGELHARD PTX-516 MONOLITH
ECU @ 200, 2 MIN. AIR INJECTION, SPARK PORT EGR
(Single Test)

CO	0.70
HC	0.08
NO_x	0.91
Fuel Economy (km/liter)	10.21 (24.3 mpg)
SO_4 = (mg/km)	2.6

The Holley feedback carburetor system was plagued with operating and durability problems from the time it was installed. The vacuum control regulator valve (VCRV) which interfaces the ECU to the feedback carburetor was extremely susceptible to plugging with particulate matter. Many times during calibration and optimization runs, the valve would plug and cause a loss of A/F control. The result of this was high CO production due to the "full-rich" failure mode of the feedback carburetor. Holley attributed the valve's particulate sensitivity to two very small air bleeds (0.6350 mm = .025 in., 0.7620 mm = .030 in) in the vacuum regulator assembly.

In addition to this problem, the particular feedback carburetor used in the program also suffered from a lack of durability. At the end of the first 2,000 km accumulation interval, CO emissions had increased drastically (Table 8-8). In fact, they exceeded the 80,000 km maximum limit. The system, once again, would not control A/F ratio at the desired set-point. The VCRV was operating, however its control signals were abnormal and asymmetric, with extended time spent at high vacuum (full lean signal) and short periods of low vacuum (full rich signal). Time averaged A/F ratios were rich ($\leq$14/1), which correlates with the high CO, low NO_x, and low sulfate emissions observed. The

TABLE 8-8

FTP EMISSIONS (g/km)
AFTER 2,000 KM DURABILITY INTERVAL
PTX-516, ECU @ 200, 2 MIN. AIR INJECTION,
LEAN CHOKE, SPARK PORT EGR
(Single Test)

CO	2.55
HC	0.13
NO_x	0.78
Fuel Economy (km/liter)	10.5 (24.9 mpg)
SO_4 (mg/km)	0.59

engine was checked for ignition system problems, but none were found. In addition, replacement of the oxygen sensor had no effect on the loss of A/F control or abnormal control vacuum pattern.

Holley agreed, at ER&E's request, to send an engineer to diagnose and repair the failure. It was found that as underhood temperature increased, A/F ratio control became erratic. After studying the airbox curve (A/F ratio vs air flow) of the carburetor sent with the system, the engineer felt the loss of A/F control was due to a carburetor malfunction. The feedback carburetor is prone to idle circuit percolation which causes a lean A/F. The feedback system responds by going rich. However, the airbox curve shows A/F control is nonlinear (Figure 8-5) in the idle/off-idle air flow regions (up to 30 scfm). A change from stoichiometric (2.5" control vacuum) to full rich (0" control vacuum) produced a much larger A/F correction than going from stoichiometric to full lean (5.0" control vacuum). Thus, the loss of A/F control could be explained in this way. The carburetor is driven rich by the ECU to compensate for the percolation induced lean A/F. However, the A/F goes too rich. The ECU drives the carburetor full lean for an extended time in an attempt to remain at the set point A/F. Since the exhaust is now lean, the ECU drives the carburetor rich, restarting the entire cycle. This correlates with the high, then low control vacuum cycling observed. Although the carburetor was nonlinear when originally received, there were no cycling problems. Because of this it was suspected that the carburetor had shifted stoichiometry and become even more nonlinear than shown on the original airbox curve. It was recommended the carburetor be returned to Holley for inspection and recalibration.

Figure 8-6 is the airbox curve of the defective feedback carburetor. Note that the stoichiometric curve (2.5" control vacuum) is displaced lean from its original calibration shown on the previous airbox curve. As air flow increases, the 2.5" control vacuum curve begins to approach a stoichiometric A/F ratio. The full lean (5" control vacuum) curve was shifted so far lean it was off the A/F scale and does not appear on the airbox figure. Thus, the feedback carburetor had shifted drastically in calibration during the 2,000 km durability accumulation.

Figure 8-7 is the airbox curve for the recalibrated feedback carburetor. The three control vacuum curves are linearly spaced in idle and off-idle air flow regions and have been aligned to provide the correct A/F ratios. Steady states were run to check the ECU reference voltage setting vs. A/F ratio for the recalibrated carburetor. In the speed range of 10 mph to about 40 mph CO emissions were very high, and there was no A/F control. CO emissions oscillated wildly, with peaks up to 1% above mean levels. CO emissions only became stable above 45 mph. Because of these oscillations, A/F ratio could not be determined accurately. An FTP was run at previous reference voltage settings to see if the CO oscillations had a great impact on weighted emissions. As seen in Table 8-9, the CO emission level of the vehicle was higher than when the feedback carburetor first failed.

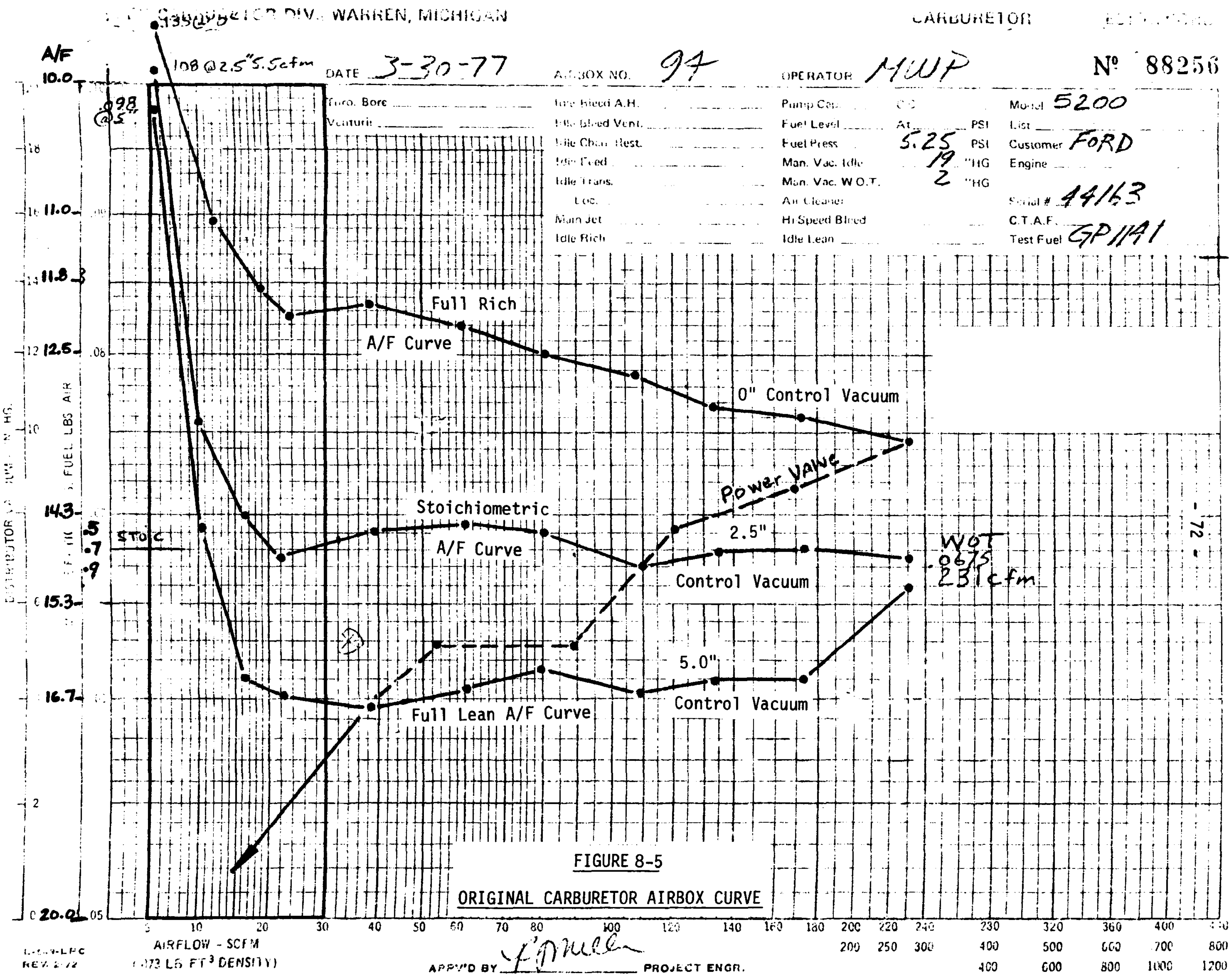


FIGURE 8-5

ORIGINAL CARBURETOR AIRBOX CURVE

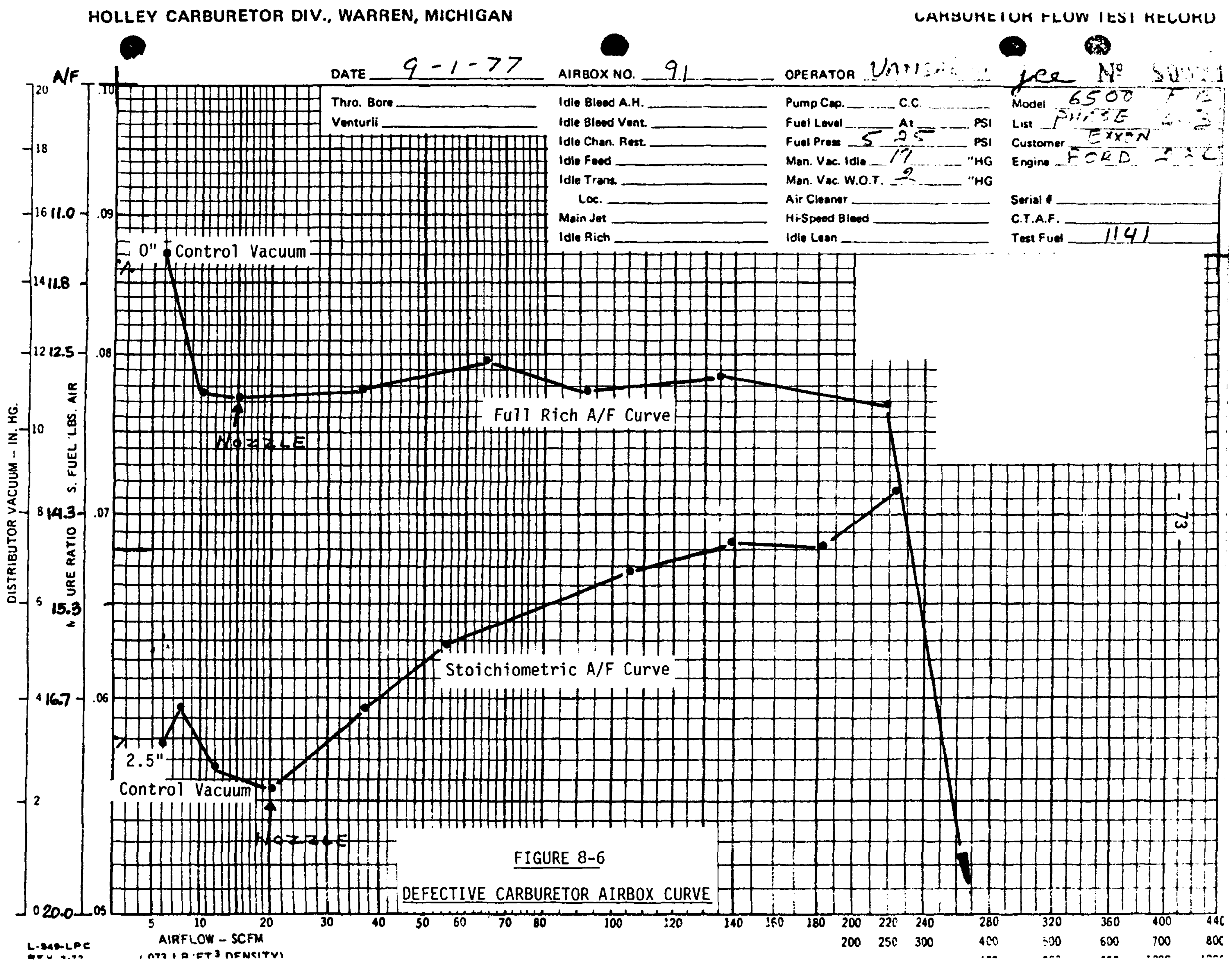


FIGURE 8-6

DEFECTIVE CARBURETOR AIRBOX CURVE

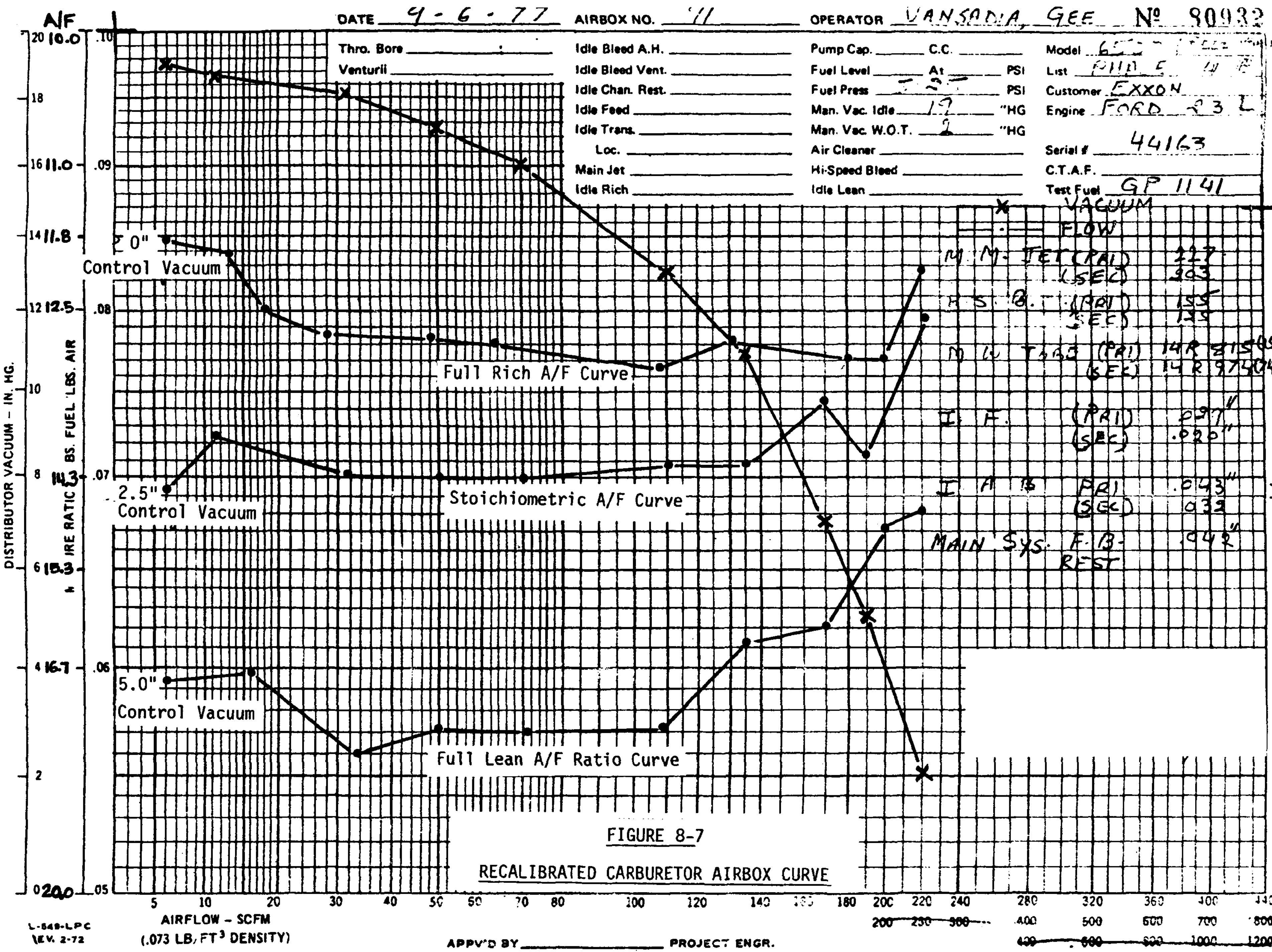


FIGURE 8-7

RECALIBRATED CARBURETOR AIRBOX CURVE

TABLE 8-9

FTP EMISSIONS (g/km)
RECALIBRATED CARBURETOR
PTX-516, ECU @ 200, 2 MIN. AIR INJECTION,
LEAN CHOKE, SPARK PORT EGR
(Single Test)

CO	3.04
HC	0.14
NO_x	0.63

Because of the speed range involved, a transition problem between the idle and main jet circuits was suspected. This was confirmed by looking down the carburetor venturi while the vehicle was held at steady speeds. At approximately 12 mph, fuel started to drip out of the main nozzle and puddle on the throttle plate. The frequency of the CO oscillations correlated with the fuel drop rate out of the main nozzle. As vehicle speed (engine rpm) was increased, the main nozzle continued to drip fuel until at 38 mph, atomization began to take place. By 45 mph, the main nozzle was spraying fuel, and coincidentally the CO oscillations smoothed out considerably. At 60 mph, only the main jet was in operation. CO emissions were steady with very little oscillation, and A/F control was good, as shown in Figure 8-8.

Holley agreed with the diagnoses of a transition region instability, remarking that this "sloppy main-jet startup" problem had been seen on other feedback carburetors. The carburetor was returned to Holley for reproportioning of the idle/main jet circuits. They remarked, however, that it could take several iterations to resolve the instability. Testing of the reproportioned carburetor revealed that although the instability speed range had been narrowed, CO emissions were still above 80,000 km contract limits. Another iteration would have to be made to solve the problem.

It was agreed by both ER&E and the EPA that contract work on the second low excess air vehicle be terminated based upon its achievement of 0 km emission goals.

A number of factors influenced this decision. Optimization of the feedback carburetor system for low excess air operation was hampered by recurring hardware failures. A significant portion of the contract performance time period was spent waiting for new system components, or for repairs and recalibration of failed pieces. These operating difficulties were not expected to improve during kilometer accumulation. It was expected that repair turn-around time would increase, as Holley had to meet committments to manufacture feedback carburetors for Ford and General Motors. The fact that the 80,000 km durability accumulation would be extremely time-consuming and costly, coupled with the general de-emphasis of vehicular $SO_4^=$ emissions, led to the decision to drop durability testing from the contract requirements.

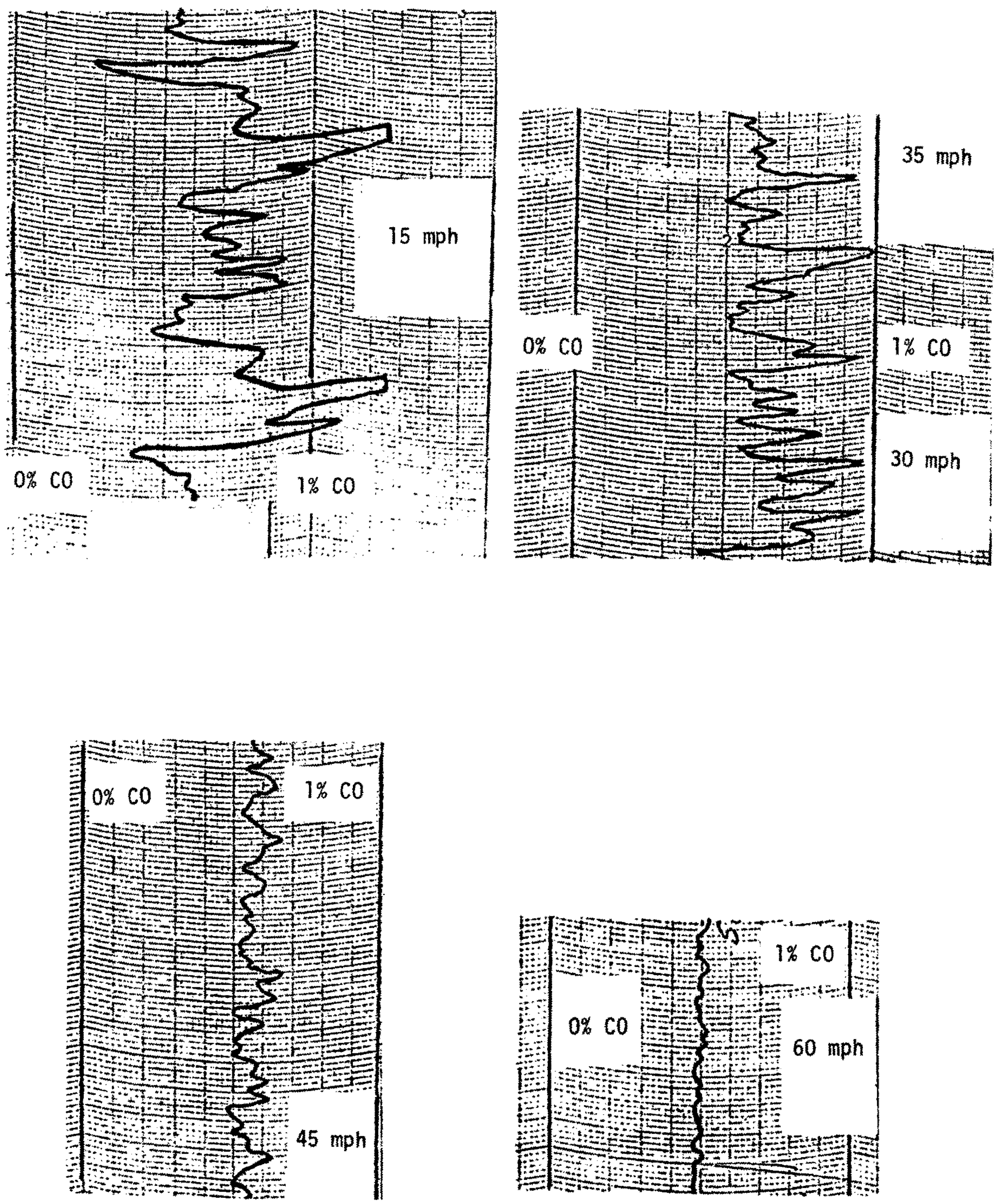


FIGURE 8-8

CO EMISSION STABILITY AT VARIOUS VEHICLE SPEEDS

Although kilometer accumulation was never completed due to recurring system hardware failures, it is important to realize that the low excess air vehicle met all 0 km contract targets for exhaust emissions. Even though system durability data was not obtained, the application and demonstration of the low excess air concept for vehicle sulfate emission control technology was a large percentage of the contract requirements; and, in itself, a substantial technical achievement.

SECTION 9

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