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EFFECT OF TIMED SECONDARY-AIR INJECTION ON AUTOMOTIVE EMISSIONS

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16. Abstract

A single cylinder of an automotive V-8 engine was fitted with an electronically timed system for the pulsed injection of secondary air. A straight-tube exhaust minimized any mixing other than that produced by secondary-air pulsing. The device was operated over a range of engine loads and speeds. Effects attributable to secondary-air pulsing were found, but emission levels were generally no better than using the engine's own injection system. Under nontypical fast-idle, no-load conditions, emission levels were reduced by roughly a factor of 2.

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SUMMARY

As part of an overall program relating to automotive thermal reactors, a study was made of mixing effects using an electronically timed system for the pulsed injection of secondary air. An automotive V-8 engine was mounted on a stand and connected to a dynamometer. A single cylinder was fitted with an electronically timed secondary-air injection system and with a straight-tube exhaust system designed to reduce mixing other than that produced by secondary-air pulsing. The device was operated over a range of engine speeds and engine loads.

Effects attributable to secondary-air pulsing were found, but, in general, emission levels were no better than with the engine's own injection system. Under nontypical fast-idle (1400 and 1800 rpm), no-load conditions, emission levels were reduced by roughly a factor of 2. This work indicates little likelihood of successful commercial application.

INTRODUCTION

Part of the nationwide program aimed at reducing emissions from automobiles has centered on the thermal reactor. Significant research has been directed at the design and performance of such devices; however, it is far from clear that a detailed understanding of their operation is available. Generally speaking, it has been assumed that an adequate reactor volume, an adequate reactor temperature, and an adequate supply of air injected into the exhaust should produce a relatively low level of emissions.

An integral part of the thermal reactor is the use of secondary air injected into the hot exhaust system to oxidize the carbon monoxide and hydrocarbon emissions discharged from the engine. The level of nitrogen oxides (NO_x) emissions is established by the conditions attained within the cylinder during combustion and is not affected by treatment of the gas in the reactor.

Thermal reactors have been used to decrease emission levels markedly (refs. 1

and 2). Experimental (refs. 1 and 2) and theoretical (refs. 3 and 4) work has indicated that the adequate temperature for the reactor is about 1000 K (1400° F). Work has been done on the proper amount of injection air for use with an ordinary manifold (refs. 5 and 6) and with a reactor (ref. 2), and there are clear indications that the delivery of air close to the exhaust valve is desirable (ref. 2). Reactor volume requirements have been tested (refs. 1, 2, and 6).

In this report we test the hypothesis that above the adequate temperature the thermal reactor is a mixing-limited device and examine whether emission levels can be reduced by an improved mixing scheme. Except for an early technique of injecting air through the exhaust valve (ref. 1) and for a report published since this study was begun (ref. 7), both of which involve methods of timed air injection, relatively little emphasis has been given to the detailed mechanism of the way that air is introduced. The usual air injection system consists of a pump, driven by the engine, connected to a manifold system with air passages leading to each exhaust port. The pump operates at a speed directly proportional to engine speed. At any given speed air flows to each exhaust port at about a constant rate, except when the exhaust valve opens. Then, as the cylinder blows down, the air flow to that port is at least momentarily reduced (or even cut off) right at the instant of the greatest flow of hot exhaust gas. During the subsequent period of injected air flow, the air collects as a slug in the exhaust port and is blown downstream, relatively unmixed, when the valve next opens.

However, suppose the secondary air were injected at substantially higher mass flow rates, but for a much shorter period of time coinciding with the flow of exhaust gas from the cylinder. Then, just as the injection point near the exhaust valve promotes reduced emissions (promotes mixing), timing the secondary air pulse directly into the hot burst of exhaust gas should certainly promote mixing (reduce emissions). With improved mixing, possibly the size and complexity of the thermal reactor might be significantly reduced.

Accordingly, an experiment was designed to test the aforementioned hypothesis. A single cylinder of an automotive V-8 engine was fitted with an electronically timed and synchronized secondary-air injection system and with a separate straight-tube exhaust system designed to reduce mixing other than that induced by secondary-air pulsing. The device was operated over a range of engine speeds and loads. The time of pulse injection was varied across the entire engine cycle (720 crankshaft degrees), and the amount of injected air was varied widely to be sure that no unusual effects occurred in the region of normal engine operation which might indicate a sudden change in cleanup mechanism.

The results obtained generally support those of reference 7. The major difference in the two studies is that the work of reference 7 involved a complete engine in a vehicle fitted with a thermal reactor and run on a California cycle so as to produce only averaged emission results, whereas the results of the device described here should produce enough detail to indicate something about mechanisms.

EXPERIMENTAL

The Engine

A 1969 model, 7700-cubic-centimeter (472-in.^{3}) displacement V-8 engine with an automatic transmission was coupled to an eddy current dynamometer. A more detailed description of the facility is given in reference 8. Operation was limited to steady-state speed and load. This engine included secondary-air injection through air passages cast in the heads. The air system was modified externally so that the flow from the air pump could be controlled to either bank of cylinders. In these experiments three flow levels were used as reference points for comparison with the air injection system; no flow, standard flow, and maximum flow (about $1\frac{1}{2}$ times standard flow, i.e., no flow to the other bank).

The engine was operated initially with standard carburetor as delivered and subsequently with a somewhat richer carburetor. The standard carburetor was operated using premium leaded fuel at an air-fuel ratio of 15.5, while the richer carburetor was fueled with a unleaded premium at an air-fuel ratio of 14.5.

Pulsed Secondary-Air Injector System

A device was constructed to introduce timed pulses of secondary air into the exhaust port of the front right cylinder of this engine (fig. 1). The tip of the stainless-steel injector tube was sealed and holes were drilled in the wall to facilitate mixing.

The timed injection system amounted to a metering system and consisted of four high response electric piloted valves arranged in tandem pairs (fig. 2(a)). The source pressure and the volume between each pair of valves were selected to produce an amount of air roughly equivalent to that of the engine's own injection system. The measuring volumes were charged and discharged by operating the upstream and downstream valves alternately; the two downstream valves were operated alternately to produce timed pulses. Four valves (two pairs) merely doubled the maximum speed at which the system could operate.

Figure 2(b) indicates the operational sequence of the valves. An oscilloscope with a four-way chopped beam could monitor this display during operation although one channel normally monitored a spark plug pulse to be sure that the device remained properly phased. D1 and D2 are synchronization delays and T1 and T2 are valve opening pulses produced by a modular pulse generator. Figure 3 is a block diagram of the electronic circuit; a description of the circuit is presented in the appendix.

The normally closed valves were energized with dc current. A minimum electrical pulse of 7 to 8 milliseconds was required to produce a full pressure pulse developing at 9 milliseconds, peaking at about 10 milliseconds, and tailing off at 15 to 16 milliseconds (fig. 2(c)). To insure that the valves opened completely, 10-millisecond electrical pulses were used. The valve closed about 10 milliseconds after the electrical signal was removed. This left the valve open after the metering volume had emptied (blown down); the extra open time after the pulse apparently had no effect.

The timed air injector was an integral part of the special exhaust system shown in figure 4. (The V-8 engine had equally spaced exhaust ports; therefore, the regular manifold was simply moved over and a blank off plate attached to the unused manifold opening.) The long straight tube was sized to contain approximately the exhaust from a single cylinder cycle plus its associated injection air. It was hoped that mixing along the tube would be minimized except for that induced by the pulsed air. The cooling at the bottom was intended to quench any delayed reactions. The large plenum mixed the exhaust from five to ten successive engine cycles to assure that the sample taken for analysis would not depend on the physical location of the sampling point as would happen if the intermittent flow in the long tube were sampled (ref. 2).

Gas Analysis

The sample for gas analysis was pumped through nondispersive infrared (NDIR) analyzers. Hydrocarbon (HC in terms of hexane, C_6H_{14}), carbon monoxide (CO), and carbon dioxide (CO_2) were determined. All emission data presented herein have been corrected to uniform dry exhaust volume concentrations as prescribed in the Federal Test Procedures (refs. 9 and 10). The correction is made by multiplying the measured values, %CO, %CO_2, and ppm HC, by a correction or dilution factor, 15%/N, where $N = 6(\%HC) + \%CO + \%CO_2$. (The value 15% approximates dry stoichiometric mixtures; the correction factor is somewhat arbitrary and appears in slightly different forms.) The purpose of the correction is to avoid apparent depression of emission levels by the addition of secondary air in varying and/or excessive amounts. The factor N is a limited measure of overall air-fuel ratio. It is "limited" in the sense that at any given engine operating conditions (constant air-fuel ratio), N decreases as the amount of secondary air increases - a constant N means a steady supply of secondary air.

Test Procedure

For a typical experimental run, the engine and the valve control system were warmed up, the dynamometer and engine controls set to produce specified speed and load (manifold vacuum), and the calibration of the NDIR's checked from the previous run. Then using the engine's own injection system, emission data were taken, as reference points, at no-air, standard-air, and maximum-air conditions. A normal run for the timed air injection system involved emission data taken with variations in time delay and/or source pressure. At the end of a run, the reference points were repeated and the calibration of the NDIR's checked. During the typical 1-hour run, the change in calibration of the NDIR's was not significant. The reference points normally showed that some drift had occurred in an hour or so. Such changes apparently took place gradually and usually the first few data points were repeated at the end of the run to reduce the significance of this drift and/or experimental error in the reference points. Over and above gradual changes in engine operating conditions, a likely source of drift was the marked changes in the ambient test-cell temperature to which the analyzing instruments and electronic control circuits were exposed.

The amount of secondary air furnished by the injector depended upon the secondary-air pressure used to charge the measuring volumes. For the first "emissions versus timing" run under any specific speed and load conditions, secondary-air pressure was selected to produce a flow roughly equivalent to the volume air flow of the engine's own injection system. For subsequent runs, the pressure was adjusted somewhat in accordance with "emissions versus secondary-air pressure" curves of earlier runs.

DISCUSSION OF DATA

Data were taken using the pulsed secondary-air injection system in two modes; one, an "emissions versus timing" mode, and the other, "emissions versus secondary air pressure." Selected examples of the first will be presented to show the main effects observed and followed by a single example of the second. Only hydrocarbon emission data are presented here. Carbon monoxide emission data are generally similar, but show smaller percentage changes. The factor N occurring in the data correction factor, 15%/N, sometimes showed small variations for values corresponding to the time of cylinder blow down. This suggests the possibility that the flow of secondary air might have been slightly impeded by the relatively high-pressure, high-velocity gas surrounding the injector tube. However, it is hard to attribute the results presented here to such a minor perturbation (especially as it will be indicated that air flow is not a sensitive variable). Some limited temperature data, both gas and tube wall, were obtained.

Figure 5 shows a rather striking example of the curve developed as the relative timing of the air pulse was varied. The straight line indicates the reference level for the no-air injection condition, while the shaded area gives the range of reference levels for the engine's own air injection system. Generally, there is little difference between the standard-flow and the maximum-flow air emission reference levels and little difference between levels before and after the run. The little peak drawn in the lower left corner of figure 5 indicates an arbitrary position and the approximate width of the air pulse; the square datum point is that corresponding to the indicated position of the peak. Other data points are the result of changing the phase of the injection air pulse relative to the engine cycle (valve opening). The opening and closing times of the exhaust valve are shown as indicated in the factory shop manual, 70° before TDC (top dead center) and 58° after BDC (bottom dead center).

Figure 5 is for the emission level of hydrocarbon under conditions of engine idle, light load, and uninsulated exhaust tube. Overall this is probably the least favorable set of operating conditions tested from an emission point of view; namely, low fuel consumption, high heat loss from the exhaust tube, and, therefore, the greatest chance of quenching the reaction by injecting cold air into the cylinder blow down. The curve clearly indicates a strong effect on emission levels from the timing of the pulsed air, but, except in the region between exhaust valve opening and bottom dead center, the effect is not at all favorable compared with the engine's own continuous-air injection system.

Figure 6 shows three fairly typical plots. These curves, for 1800 rpm and 54×10^{3} N/m^{2} (16 in. Hg) manifold vacuum, are representative of the operating conditions used during this work. Figure 6(a) is for the standard carburetor using leaded fuel and an uninsulated exhaust system; figure 6(b) is for the standard carburetor using leaded fuel and with about 5 centimeters of fiberglass insulation covering the 90-centimeter exhaust pipe; figure 6(c) is for a slightly richer carburetor using unleaded fuel and with the insulated exhaust pipe.

A comparison of figure 6(a) with figures 6(b) and (c) (note the scale break on fig. 6(a)) indicates that the lack of insulation reduces the cleanup operation considerably and, regardless of mixing, apparently keeps the system in a temperature regime which is kinetics controlled. The curve in figure 5 is also for uninsulated conditions and shows excursions that are likely associated with relatively low temperatures. In fact, the data suggest that the pulsing of cold secondary injection air directly into the hot blow down from the cylinder tends to quench the desired reactions in cases where the temperature level may be marginal.

Figures 6(b) and (c) are for similar conditions except for differences in carburetion and fuel. Figure 6(b) is for $A/F = 15.5$ and leaded fuel while figure 6(c) is for $A/F = 14.5$ and unleaded fuel. The data sets were taken at considerably different times; however, assuming that the differences are not attributable to time differences or fuel differences, these results are compatible with others (ref. 2). Richer conditions have generally been found to clean up better, presumably due to higher temperatures in the exhaust (reactor) regions - a kinetic effect. However, the variation along each curve would appear to be attributable to the mixing effects attributable to timed air injection. In these curves, the pulsed air data show no improvement over the reference points for the engine's own air injection system. At this speed the timed air injection pulse has become relatively wide and the detailed structure may well be averaged out to some extent.

Figure 7 shows two curves which are not typical of usual engine-operating conditions, but which are selected for exactly that reason. They represent fast-idle conditions and are a general indication of the mixing effects produced by timed air injection which it had been hoped to find for more typical operating conditions. Here the emission levels with timed air injection are, in fact, lower than with the engine's own air injection system. The minima occur after cylinder blow down during the period when the piston is exhausting the chamber; this is the period richest in hydrocarbon emissions (refs. 11 and 12). Similarly reduced emission levels for the same fast-idle conditions were also observed under the conditions of leaner carburetion and insulated exhaust.

Figure 8 shows a single example of the emissions versus secondary-air pressure data for 1000 rpm, idle conditions. For these curves, a series of phase settings (relative times) was selected from the structured parts of the previous sorts of curves. For each phase setting chosen, emission data were taken for a series of increasing values of secondary-air pressure. A definite upturn occurred in a few cases, but usually the curves flattened out as shown here. There is no evidence in this work that much more air will produce any improvement in emission levels. There is no indication of any sudden change of emission level with a gradual change in air flow such as to indicate a change in the physical or chemical mechanism of the cleanup.

In principle, figure 8 merely represents a cross plot of emissions versus time curves taken over a range of secondary-air pressures. They should be equivalent, but, in practice, they do not seem always to be so. Therefore, each type has been considered for its own usefulness; no effort has been made to resolve the apparent inconsistencies which exceeded the usual reproducibility of the measurements. One possible explanation for such inconsistencies may well involve the fact that the "equivalent" operating conditions for each sort of data actually represent quite a different sequence of operating conditions for the previous 10 to 15 minutes. Emission data were taken when emission levels had apparently stabilized following a change in operating conditions, usually about 45 seconds for a mild change.

Unfortunately, under the operating conditions yielding these results, the engine exhaust is relatively well cleaned up. The problem, to some extent, becomes not how clean it is, but whether it is dirty enough really to test a cleanup procedure.

CONCLUDING REMARKS

The emission levels of an automotive engine were measured using a timed secondary-air injection unit with a special exhaust system to minimize uncontrolled mixing. A variety of warmed-up, steady-state operating conditions were used. The following observations summarize the results:

1. Timed air injection studies have produced results which indicate that mixing effects attributable to air pulsing do exist.

2. These effects appear, in this work, to be significant only in limited, and rather unrealistic, operational regimes.

3. Coupled with the results of Glass, Kim, and Kraus (ref. 7) applying to an entire engine, it appears that timed secondary-air injection can, at best, be used only in conjunction with a variety of other techniques to reduce vehicle exhaust emissions to the levels currently contemplated by federal regulations.

4. The complexity of a practical timed air injection device, together with its relatively limited effectiveness (at best a factor of 2), suggest that the introduction of such systems is not likely.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 1, 1972,
770-18.

APPENDIX - THE VALVE DRIVER SYSTEM

The use of an electrical, rather than a mechanical, air injection system seems well justified. A belt drive was clearly not feasible because of the high degree of synchronization required; a chain drive apparently would have required an engine shut down each time a change in phasing was desired. The electrical system provides the complete flexibility desired; namely, completely variable phasing and variable duration valve opening pulses - each at the turn of a knob. In fact, the system easily incorporates variability that was never fully utilized. Nonetheless, the 10-millisecond open time of even these fast acting solenoid valves is marginal at even moderate speeds, and it is the blow down feature of the metering system which makes the system acceptable.

The valve driver system was designed to operate four valves, arranged in tandem pairs (fig. 2(a)), to produce pulses of air synchronously with the operation of the exhaust valve for the engine cylinder under study. The metering volumes between each tandem pair of valves charge and discharge by operating the upstream and downstream valves alternately; the two downstream valves operate alternately to produce air pulses. Four valves (two pairs) simply increase the engine speed at which the valve system can operate.

The electrical system is synchronized to the engine by a trigger device mounted on the fly wheel and a magnetic pickup. The system is phased to the appropriate alternate flywheel pulse by the ignition pulse of an appropriate spark plug. Finer phasing is obtained by pulse delay circuits. The heart of the system is a modular pulse generator. A block diagram of the system appears in figure 3.

The magnetic pickup produces two electrical pulses from the flywheel for each injected air pulse desired. Flip-flop 1 eliminates the extraneous pulse, while proper phasing of the remaining pulse is provided by a signal from an appropriate spark plug. (The spark plug itself cannot be used for synchronization because ignition times are modified by the speed (centrifugal advance) and operating conditions (vacuum advance) of the engine.) In retrospect, it would have been better (although more difficult mechanically) to synchronize to the distributor shaft and to avoid the electrical phasing problem which was created by extraneous pulses from the flywheel.

Flip-flop 1 triggers a PRF (pulse repetition frequency) unit in the modular pulse generator. The PRF unit provides a properly shaped synchronization pulse and also furnishes a self-contained signal for operating the valve driver system for test purposes without running the engine.

The synchronization pulse from the PRF unit triggers the first of four pulse/delay units in the modular pulse generator. The pulse/delay unit generates a negative pulse of adjustable duration; moreover, the leading and trailing edges of this pulse serve as separate synchronization pulses coincident or delayed with respect to the input trigger pulse. The first pulse/delay unit is designated D1 (see also fig. 2(b)).

The coincident synchronization pulse from D1 triggers flip-flop 2. The outputs of flip-flop 2 are fed to four gated amplifiers. Each gated amplifier requires two coexistent negative pulses for operation (turn on). The first is furnished by flip-flop 2 and lasts for an entire engine cycle; it determines which pair of gated amplifiers may operate during a given engine cycle. The second negative pulse is furnished by one of the pulse/delay units in the modular pulse generator; it determines exactly when and for how long during each engine cycle a given gated amplifier is to operate.

The delayed synchronization pulse from D1 triggers pulse/delay unit T1. The negative pulse of adjustable duration from T1 operates the gated amplifiers of valve A and valve C alternately as determined by the negative output of flip-flop 2.

The delayed synchronization pulse from D1 also triggers pulse/delay unit D2 which in turn produces a further delayed synchronization pulse which triggers pulse/delay unit T2. The negative pulse of variable duration from T2 operates the gated amplifiers of valves B and D alternately as permitted by the output of flip-flop 2.

When a gated amplifier is turned on, it generates a positive output pulse of duration determined by T1 or T2, as applicable. The leading edge of this pulse is differentiated, fed through an emitter follower, and turns on the appropriate SCR valve driver - dc static switch employing silicon controlled rectifiers. The trailing edge of the gated amplifier output pulse is differentiated, fed through an inverter, and turns off the SCR valve driver.

The SCR valve driver switches external 28-volt power to activate or deactivate the corresponding solenoid valve. The solenoid valves themselves were equipped with electromagnetic interference (EMI) suppression devices to protect the control circuits.

In practice, no real reason was ever found to use delay D2 (although a small delay was useful for identification on the scope), and there was no reason to use a value of T2 different than T1. It should be noted that the time intervals represented by D1 + T1 and D1 + D2 + T2 cannot exceed the permissive period allowed by the action of flip-flop 2. In practice, this means that no T1 or T2 pulse can begin within a time period T1 or T2 of the end of an engine cycle as defined by the flywheel synchronization point, because flip-flop 2 simply removes its permissive negative pulse before T1 or T2 is completed. Practically, this means that the position of the pickup point on the flywheel relative to the operation of the exhaust valve is significant in locating a small range of crank angles (corresponding to T1 and T2) where data cannot be obtained.

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[a]A number of the references have been reprinted in two volumes published by the Society of Automotive Engineers. In these cases, in addition to the primary reference, an abbreviated reference will be given to the collected works: e.g., Vol. 6, pp. 1-6, or Vol. 12, pp. 103-120.

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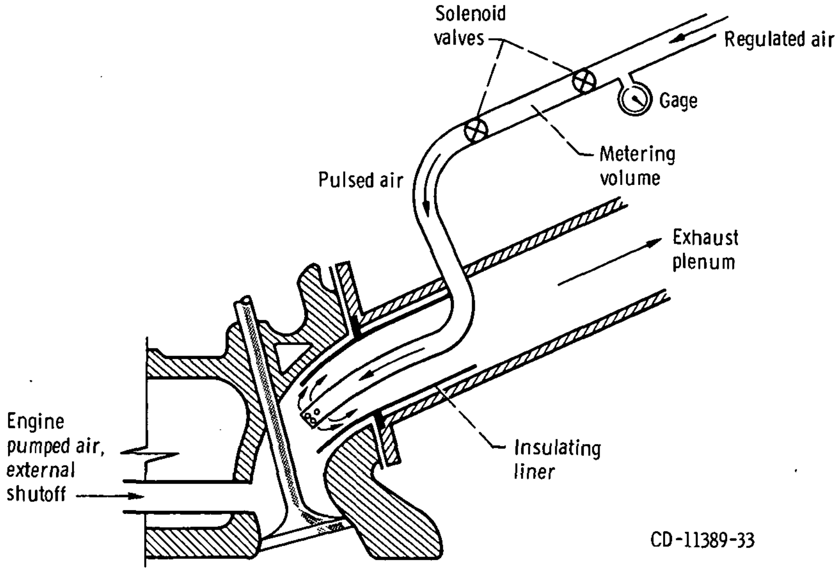
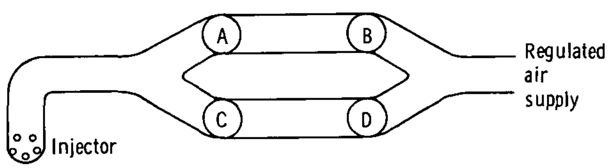
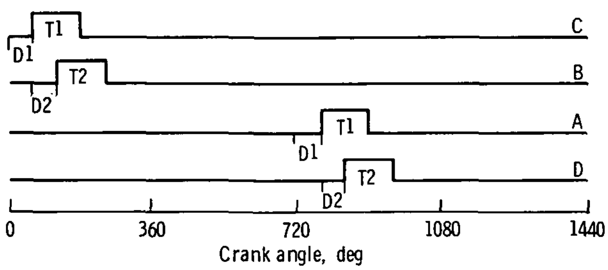


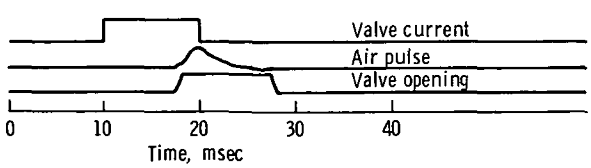
Figure 1. - Secondary-air injector system.



(a) Metering system.



(b) Valve operating schedule; one complete valve cycle equals two complete engine cycles and four complete crankshaft cycles (revolutions).



(c) Valve operation, showing mechanical delay.

Figure 2. - Timed air injection system.

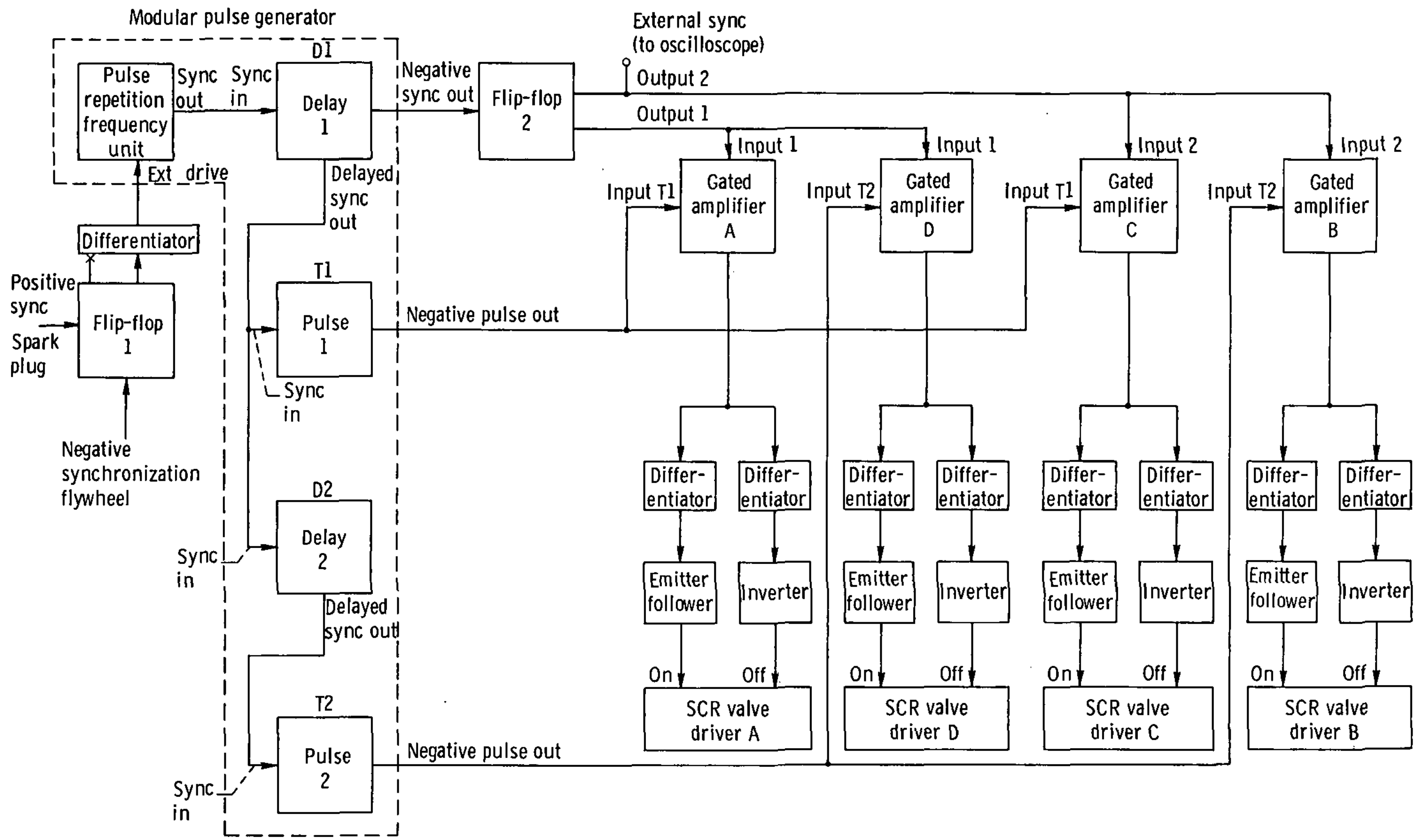


Figure 3. - Valve driver system block diagram (D1, T1, D2, and T2 are pulse/delay units).

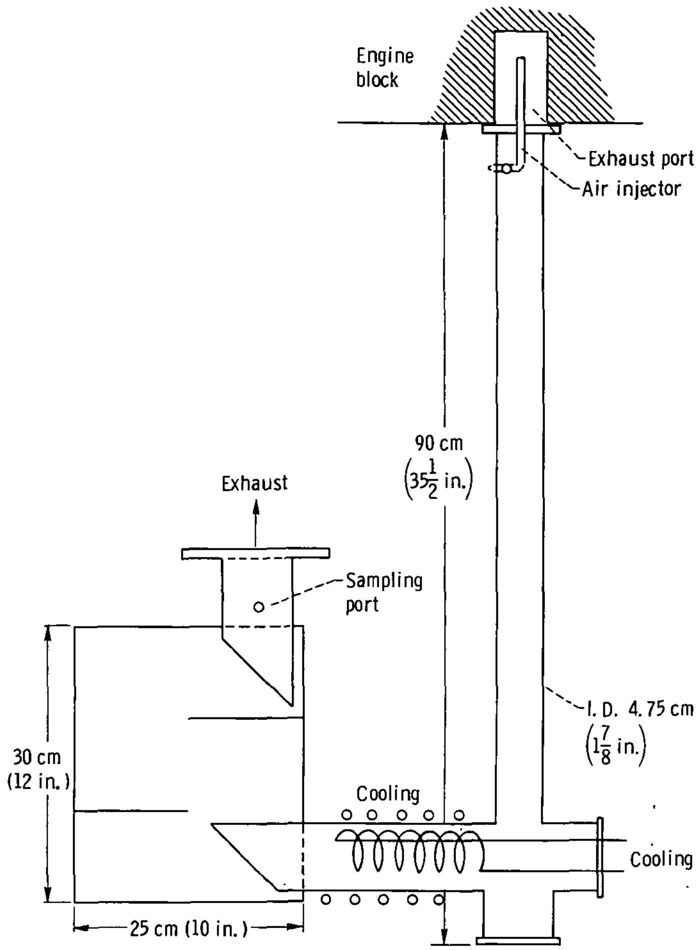


Figure 4. - Timed air injector and exhaust system.

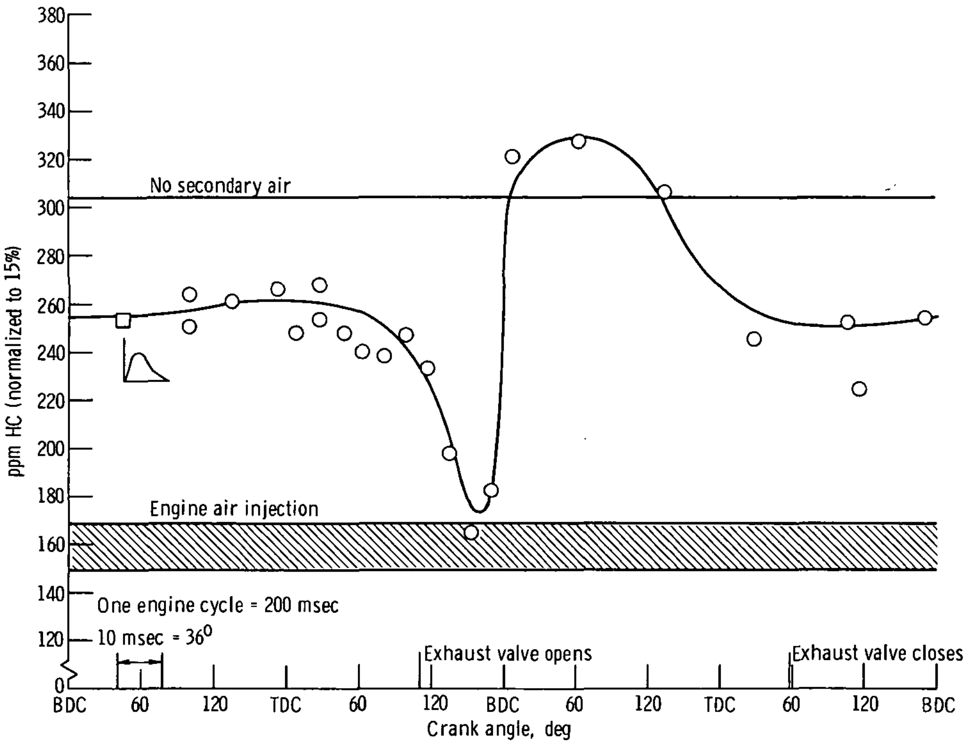
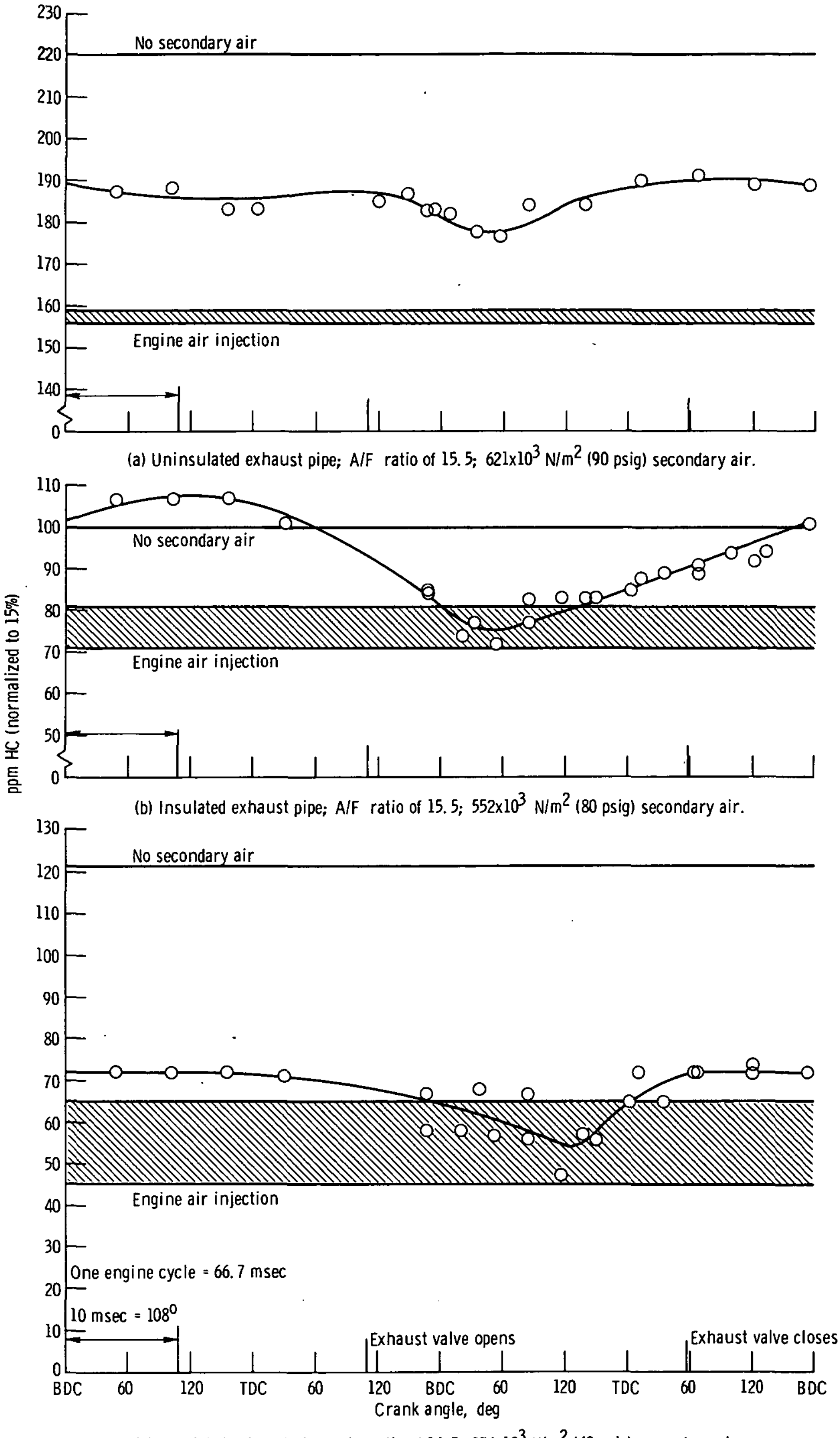
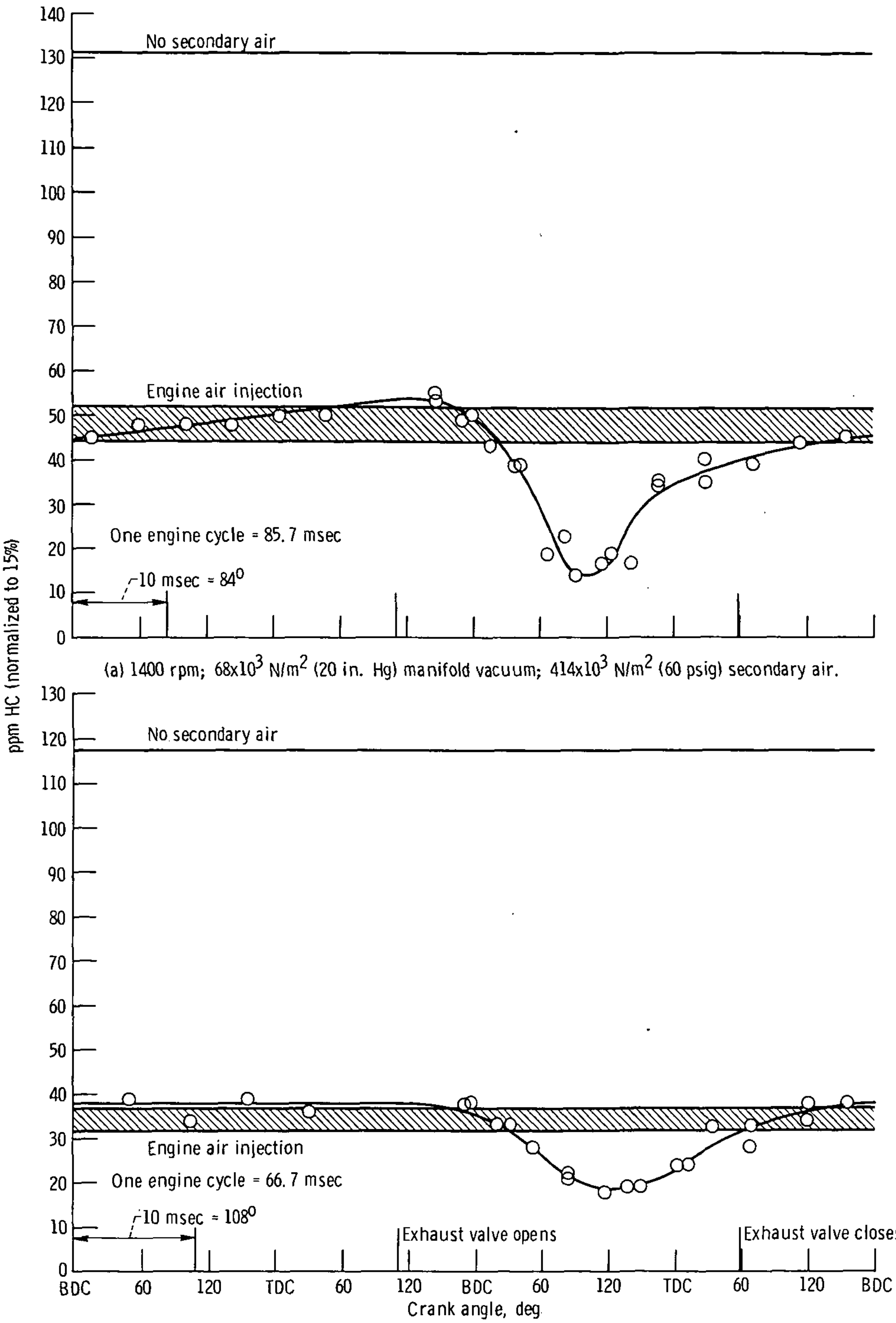


Figure 5. - Hydrocarbon emissions as a function of timed secondary-air injection pulses at A/F ratio of 15.5 with uninsulated exhaust pipe. 600 rpm; 61×10^3 N/m^2 (18 in. Hg) manifold vacuum; 345×10^3 N/m^2 (50 psig) secondary air; and 10-millisecond pulses.



(c) Insulated exhaust pipe; A/F ratio of 14.5; 276×10^3 N/m^2 (40 psig) secondary air.

Figure 6. - Hydrocarbon emissions as a function of timed secondary-air injection pulses. 1800 rpm; 54×10^3 N/m^2 (16 in. Hg) manifold vacuum; 10-millisecond pulses.



(b) 1800 rpm; 68×10^3 N/m^2 (20 in. Hg) manifold vacuum; 276×10^3 N/m^2 (40 psig) secondary air.

Figure 7. - Hydrocarbon emissions as a function of timed secondary-air injection pulses at A/F ratio of 14.5 with insulated exhaust pipe. 10-millisecond air pulses.

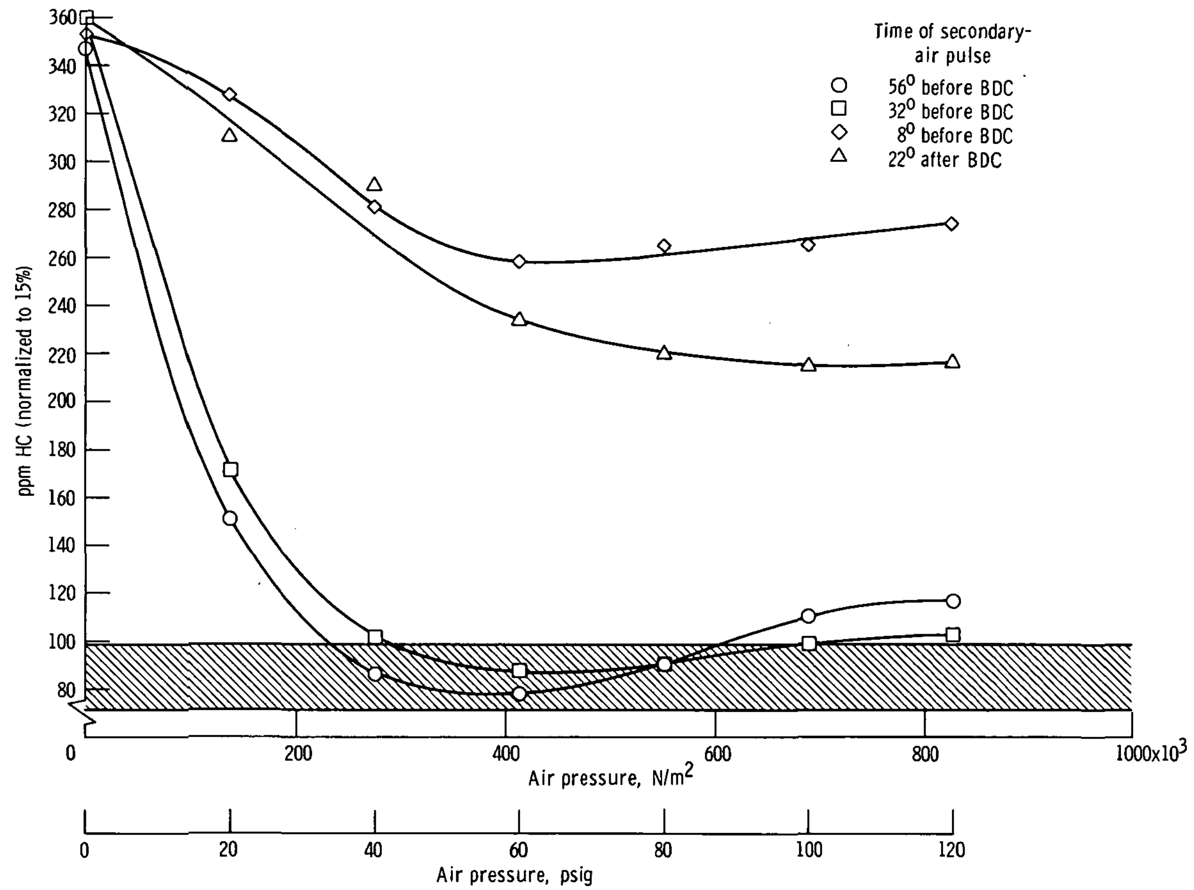


Figure 8. - Hydrocarbon emissions as a function of secondary injection air pressure (proportional to air flow) at A/F ratio of 15.5 with insulated exhaust pipe. 1000 rpm; 69×10^3 N/m^2 (20.5 in. Hg) manifold vacuum; 10-millisecond air pulses. (Exhaust valve opens 70^0 before BDC).

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