15. EMISSIONS AND NEW TECHNOLOGY PROGRAMS FOR CONVENTIONAL SPARK-IGNITION AIRCRAFT ENGINES

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After the Environmental Protection Agency (EPA) issued exhaust emissions standards for general-aviation engines in 1973, NASA embarked on a number of programs to develop and demonstrate technology and to aid industry in developing and demonstrating exhaust pollution reduction techniques for those engines. The program has since been expanded to include improved performance and other areas of new technology for general-aviation internal combustion engines that are not necessarily being pursued by industry. A long-range technology plan in support of general-aviation engines has been formulated and is being implemented at the Lewis Research Center. For completeness, this paper briefly describes the overall program and presents in detail that part of the program that represents the in-house effort at Lewis.

LEWIS OVERALL INTERNAL COMBUSTION ENGINE PROGRAM

Three areas of government and industry effort involving conventional general-aviation piston engines are part of a coordinated overall plan:

(1) FAA/NASA Joint Program

(2) NASA Contract Exhaust Emissions Pollution Reduction Program

(3) NASA In-House Emissions Reduction and New Technology Program

FAA/NASA Joint Program

The objectives of this program are to establish emissions levels of current general-aviation piston engines and to investigate minor engine modifications to safely reduce emissions to the EPA 1979 standards. Co-funded studies by the Federal Aviation Administration (FAA) and NASA are now underway with the two primary engine firms building general-aviation piston engines, Avco Lycoming and Teledyne Continental Motors ,

(1) To experimentally characterize the emissions from 10 representative aircraft piston engines, and

(2) To assess the feasibility of "leaning out" and spark timing changes for emissions reduction and to demonstrate the most satisfactory approaches to compliance for presently manufactured aircraft engines based on minimum engine changes that could quickly be adapted to and introduced on production models.

NASA Contract Exhaust Emissions Pollution Reduction Program

The overall objectives of this program are to establish and demonstrate by 1979, at the two engine manufacturers, technology that will safely reduce general-aviation intermittent combustion engine exhaust emissions to the EPA 1979 standards or better. Adverse effects on performance, cost, weight, and reliability must be held to a minimum. The two engine manufacturers each are investigating and demonstrating one major and two minor engine modifications that have the potential of significantly reducing exhaust emissions. The modifications are based on current state-of-the-art technology and will require a longer time to progress from experimental to preprototype engines than those in the FAA/NASA program.

NASA In-House Emissions Reduction and New Technology Program

The objectives of this program are to identify and demonstrate technology to safely reduce exhaust emissions and improve performance and to pursue other areas of new technology that are not necessarily being worked on by the industry. The benefits could be any one or a combination of reduced emissions, improved performance, improved reliability, reduced specific fuel consumption, reduced maintenance, and lower cost. In contrast to the work under contract with the engine manufacturers, the work at Lewis is concentrated on longer term solutions requiring additional or new analytical and/or experimental technology. Specific programs that are presently active are

(1) Temperature-humidity correlations

(2) Improved fuel injection

(3) Otto-cycle analytical simulation

(4) Improved engine cooling

Areas of work that have been identified for future study are

(1) High-energy ignition systems

(2) Automated engine controls

(3) Assessment of alternative fuels and engine modifications needed to use alternative fuels

(4) Improved induction and carburetion systems

The active programs are described in some detail, and the future work is described briefly.

Active programs. - The following programs are presently active.

Temperature-humidity correlations: The objective of this program is to develop a correlation and correction factor for the effects of ambient-air temperature and humidity on engine exhaust emissions levels and performance. Test results to date have shown that ambient-air temperature and humidity significantly affect data and may make comparisons between different test sites difficult on a modal or per-cycle basis. The general program involves an experimental effort being conducted on two aircraft engines (Lycoming O-320D and Continental TSIO-360C) on a dynamometer test stand. The two engines are being tested over their entire operating range. In particular, the tests are being conducted in the modes of the EPA emissions cycle at fixed, controlled temperature and humidity conditions over a range of fuel-air ratios. Correlation of emissions will first be attempted for each of the modes on the basis of fuel-air ratios and pounds per mode. An overall correlation of the raw emissions and modes will then be attempted, and finally comparisons will be made between the two engines. Based on these results, we are hoping to develop some generalized correction factors so that engine test results obtained under any ambient conditions can be corrected back to some standard reference conditions such as 59° F and zero percent relative humidity. The normalized test results of identical engines tested at different test sites and ambient conditions could then be directly compared.

Improved fuel injection: The primary objective of this program is to determine and demonstrate the potential of a pulsed fuel-injection system to reduce exhaust emissions and specific fuel consumption and to improve performance. A more precise fuel control would reduce variations in cylinder-to-cylinder and cycle-to-cycle fuel-air ratios, thereby allowing leaner engine operation than the present continuous-flow systems. A secondary objective of this program is to determine the effects of the various injection-controlling parameters (droplet size, spray pattern, fuel flow, fuel pressure, nozzle geometry, and injection timing) and just how much these parameters could vary and still yield both acceptable performance and emissions reduction.

Gasoline fuel-injection systems have been around since the Wright brothers, and various systems specifically for aircraft engines were worked on as early as the 1920's. They were pursued very sporadically and separately from engine development until the advent of World War II. Under military sponsorship in the 1940's and in conjunction with Wright and Pratt & Whitney, production fuel-injection systems for radial engines were developed and manufactured. These systems fed fuel to each cylinder individually from a mechanical plunger-type pump. After World War II, these systems were adapted to horizontally opposed engines. In the late 1950's and early 1960's, continuous-injection systems, which were much simpler, more reliable, and less costly, were introduced. These are essentially the same systems used today.

Present automotive fuel-injection systems are more sophisticated and at a higher state of development than those for aircraft. Some of these systems could possibly be adapted to aircraft engine use. The Lewis program is not directed toward adapting existing systems but is involved with fundamentals of sprays and fuel timing and their effects on emissions and performance.

A literature search on fuel-injection work has been performed, and the information is being summarized. There is a lack of consistent information that is applicable to aircraft and other engines. Most basic work either has not been reported completely or has not been reported at all and may be proprietary. Sporadic work was done by NACA up to and during World War II. Some limited work was performed by NACA on single-cylinder engines, and also some basic work was done on nozzles primarily furnished by the companies developing the injectors. No work was done toward a complete fuel-injection system, and much of what was done is apparently not translatable into today's applications. Some generalizations can be taken from the early work and will serve as a guide to our program.

After experimental visualization techniques were established, bench testing of existing injectors under ambient conditions was begun. All previous visualization work reported in the literature was done with liquids other than gasoline for safety reasons. The commonly used substitute for gasoline for injector and nozzle calibration and testing is Stoddard solvent, a commercially available dry cleaning fluid. It has viscosity, surface tension, and density properties similar to those of gasoline. We visually compared water, Stoddard solvent, and gasoline under identical conditions through a number of different injectors. Performance with water was drastically different, giving poor atomization relative to that with Stoddard solvent and gasoline. Visually, the patterns with Stoddard solvent and gasoline looked similar under certain conditions. Under other conditions, however, the Stoddard solvent showed a much better and more atomized spray pattern. This, coupled with the fact that our safety personnel consider Stoddard solvent to be just as hazardous in our facilities as gasoline, dictated the choice of gasoline for the visualization work.

We are in the process of testing a number of injectors under their design operating conditions. For aircraft engine injectors, we have defined seven operating modes that cover normal engine operation. The five modes from the EPA emissions mode cycle are taxi/idle (out), takeoff, climb, approach, and taxi/idle (in). However, since the engine operates in the cruise mode 95 percent of the time, we chose cruise performance and cruise economy as being equally important and representative of most normal operation. We have just completed bench testing an injector for a Continental TSIO-360 engine that is now running on our dynamometer test stand. The testing was conducted by spraying fuel into air at the same flow rates and the same shroud air pressure differentials ΔP's. Figure 15-1 shows the operating modes. The main factor affecting injector performance was shroud-to-manifold ΔP. Where there was some ΔP, the injector fuel flow was maximized to some extent. Figure 15-1(a), idle and taxi (which were visually similar) and figure 15-1(d), cruise economy, did have shroud ΔP's and therefore fuel atomization. Figure 15-1(b), takeoff, and figure 15-1(c), climbout, approach, and cruise performance (which were visually similar), had no shroud ΔP's. The fuel came out as an almost solid stream of large droplets.

Work is underway to set up an injector flow test facility in order to control test conditions for visualization of flow patterns under simulated service conditions. A number of injectors will be fabricated and visually tested to observe various injector flow patterns. The visual flow patterns will be correlated with the relative performance and emissions from tests of these injectors in a single cylinder or an aircraft engine. The fuel injector/inlet manifold configuration will be as similar as possible to that of a standard aircraft engine. It is expected that these tests will, on a first-order basis, indicate the range and performance sensitivity of the injection variables, which will have to be verified later in a multicylinder aircraft engine.

To evaluate the complete injector system, the intake and exhaust manifolds of one cylinder of a water-cooled multicylinder engine will be isolated and fitted with a simulated aircraft engine intake configuration including an injector. This configuration is being used since the unmodified cylinders will maintain engine speed over a much wider range of conditions, in the isolated cylinder, than could be obtained by testing with a single-cylinder engine. Use of a water-cooled engine reduces cost and risk of damage to the engine. A research electronic control system will be used to vary the fuel-injection pulse timing and flow. The complete breadboard injection system will be functionally demonstrated over a wide range of test conditions. The breadboard system will then be adapted to an actual aircraft engine, and improvements in performance and emissions will be evaluated relative to those obtained with the standard injection system.

Otto-cycle program: Lewis has been trying for some time to develop an analytical computer program simulating the Otto cycle in a spark-ignition internal combustion engine. The objective of this program is to produce a generalized analytical model that can be used to predict emissions levels and engine performance for a broad range of design and operating conditions. Limited experimental data could then be used to more finely tune the computer program for a specific engine and make possible a rapidly calculated engine performance map.

The program is composed of the various combustion, gas dynamic, and heat transport processes that have to be accurately described throughout the thermodynamic cycle in order to handle variations set up by different engine geometries and operating modes. The program computes a series of individual state points, more than 1000 over one cycle, which includes intake and exhaust blowdown and mixing. Figure 15-2 is a representative sketch of the pressure/volume diagram over which the individual calculations are made. At present, the program includes very limited ability to predict emissions levels and performance, including effects of residual-gas mass fraction, exhaust-gas recirculation mass fractions, and supercharging. The program is now being verified by comparing emissions and performance of an automotive V-8 engine. Eventually, performance and emissions of a number of actual engines of different sizes, geometries, and operating ranges will be compared with those predicted by the computer program.

The basis for the computer program is Lewis' activities in thermodynamics and combustion and in particular the Lewis chemical equilibrium and chemical kinetics programs. Since the combustion process is the most difficult to model, this then becomes the heart of the program.

To date, oxides-of-nitrogen (NO_x) emissions have been fairly accurately predicted when the combustion interval was accurately known. Because chemical equilibrium was used during combustion, carbon monoxide (CO) predictions were very low or almost zero. For the same reason, no hydrocarbons (HC) were formed in the model since all of the carbon goes to carbon dioxide (CO_2). Considerable work has recently been done on the program to be able to predict CO and HC. A new numerical integration technique for very rapid reactions has been incorporated in the program and is being checked out. This will now allow chemical kinetics to be used during the combustion process, as well as during the expansion process. No results have yet been obtained with the new technique.

The computer program can calculate relative differences in engine performance, but agreement with actual engine performance is poor at most conditions. The reason is that the Otto-cycle model does not yet include valve timing, variation in intake fuel-air charge, and prediction of the charge when the inlet valve closes. These will be included in the computer program at a later date after the new integration technique is working.

A program to supply experimental engine data to support development of the analytical model is in progress. In addition to supplying engine emissions and performance data, these tests will also supply data on such important factors in determining model accuracy as heat loss, inlet flow characteristics, combustion products, and combustion intervals. To aid in this experimental work, instrumentation has been designed and built and is being tested to determine on a per-cycle, per-cylinder basis the combustion interval and the indicated mean effective pressure. These formerly were manually calculated from photographs of the combustion chamber pressure after testing. The mass fraction burned as an interim step is now determined on line in real time. A sample of oscilloscope traces of three successive cycles of the combustion chamber pressure and the mass fraction burned at a lean medium-power condition are shown in figure 15-3. Both the combustion chamber pressure and the on-line-determined mass fraction burned as a percentage of the maximum value are shown as functions of crank angle degrees. Two traces represent normal combustion and the third represents increased ignition lag and slow burning due to a very lean mixture. The combustion interval of about 80° can be measured from the curve of mass fraction burned. We have defined the combustion interval as the time that it takes to go from 10 to 90 percent of the mass fraction burned.

The on-line determination of the mass fraction burned of the charge was compared, at good combustion conditions, with that obtained with a digital planimeter connected to a minicomputer. Figure 15-4 is a computer plot of the rate of change of combustion chamber pressure and the mass fraction burned as functions of crank angle degrees using the planimeter method. Superimposed on the mass-fraction-burned curve is a series of dots representing values that were taken from an oscilloscope trace of the on-line measurement of mass fraction burned at the same test conditions. The agreement is very good. It is planned to very shortly have a direct digital output reading of combustion interval and apparent flame speed. The apparent flame speed is an average velocity of the flame in the combustion chamber. The distance used is that from the spark plug to the furthermost point in the combustion chamber at 90-percent mass fraction burned. The time interval is that required to go from 10 to 90 percent of the mass fraction burned.

Engine-indicated mean effective pressure (imep) in real time is continuously calculated by another prototype instrument currently under test. The work done on a per-cycle basis is measured directly. Using the combustion chamber pressure, a running integral of the change in pressure and volume as a function of crank angle is continuously summed over the 720° of one cycle to give one value. One-hundred consecutive cycles of imep are calculated, stored, and averaged to also give one mean value. In addition, the standard deviation is also calculated. The 100 cycles are displayed on an oscilloscope in a bar-graph output. The mean value of imep and its standard deviation are digitally displayed. Also, any of the individual imep values can be selectively read out. Figure 15-5 shows six sets of imep bargraphs for different operating conditions taken on an automotive V-8 engine that is being used for both instrument research purposes and in support of the Otto-cycle program. The six conditions are engine startup, idle at 1000 rpm, and engine operation at 2000 rpm and identical power at three equivalence ratios, stoichiometric ($\phi = 1.0$) and lean ($\phi = 0.81$ and 0.77). Also, engine operation at 2000 rpm and the lean limit is shown. It is a rather dramatic presentation of both slow combustion and misfires.

Improved engine cooling: The objective of this program is to generate, for analysis and design purposes, information on engine cylinder cooling consisting of both analytical and experimental data. This would include data and correlations for analysis, design, and optimization of finned cylinder heads, cooling airflow, and pressure drop. Work will be performed both in-house at Lewis and on contract.

A great amount of research was done in the early NACA days on cooling fin analysis and optimization. The major thrust of this work was toward overall minimum weight, airflow pressure drop, and highest heat transfer. Research has also been done for automotive air-cooled engines. General conclusions have been that the cooling fins should be as thin as possible and that there should be as many as practical, with spacing being a function of flow and pressure drop with fin flow length being as short as possible. During this same time period, research was done by NACA on baffling for radial engines, some of this technology can be applied to in-line engines. Cylinder baffling design is very important and depends on the specific cylinder-head finned configuration. It properly needs to be an integral part of the overall specific cooling design and the engine itself. Small variations in spacing or excessive clearance between the baffles and fins can cause a short circuit in the cooling flow and a substantial reduction in its effectiveness.

An initial analytical effort is now underway to define and analyze fin thickness, spacing, heat transfer, and flow and their effects on cylinder wall temperature. A computer program of a two-dimensional model of a single flow channel has been written and is being used to calculate cylinder wall temperatures at the end of the airflow path. Fin cooling is analyzed by looking at it as a system consisting of a heat exchanger with all of its interrelationships of fin, channel configurations, flows, and temperature differentials ΔT's. With the long, narrow, heat flow path from the front to the back of today's cylinders, it is possible to have a few hundred degrees temperature difference between the inlet and outlet air temperature, which is almost directly related to cylinder wall temperature differences at the corresponding air-fin locations. This initial computer work does not consider fin weight as an optimizing factor. The effect of weight sensitivity on finned configurations at this point is academic until a generalized cylinder-head configuration is modeled and the main heat paths and overall heat transfer are considered. Finned samples will be tested and the results correlated with this initial analytical work. Cylinder heads instrumented with thermocouples will be tested by the engine manufacturers. This information will be used to help determine major heat flow paths and to aid in analytically modeling these heat flow paths as possible parts of an overall cylinder-head analytical model.

In addition to the cooling fin analysis, and as a separate effort, such concepts for improving cooling as local forced-air cooling and shaft fans will be evaluated for their potential contribution to cooling.

Future programs. - As part of a long-range planning effort, new research that may reduce emissions and improve technology has been identified. The benefits could be any one or a combination of reduced emissions, reduced specific fuel consumption (sfc), reduced maintenance, lower cost, increased performance, and greater reliability. Specific areas of research that could be pursued as our resources allow are as follows:

High-energy ignition systems: Ignition systems with increased ignition energy and/or duration may have the potential to significantly reduce emissions, improve performance, and allow leaner engine operation. A unique ignition system that can provide significant amounts of increased ignition energy over any specified length of time to the spark plugs has been designed and an experimental model built. A system that can provide multiple sparks and the sustained arc system would also be adapted to and installed on an aircraft engine for testing. The relative effects of increased ignition energy from each system on engine performance and emissions compared with the standard ignition system would be evaluated. Based on this evaluation, an advanced ignition system might be designed and tested (perhaps as part of an automated engine control system) on an aircraft engine.

Automated engine controls: The objective of this program would be to determine and demonstrate the potential of an automated engine control (preprogrammed single-lever type) to operate an engine at preset conditions for various power levels, exhaust emissions within the EPA standards, minimum fuel consumption and yet provide the required safety margin for response and performance. Included in this control would be throttle/propeller pitch, fuel-air ratio, spark advance, and turbocharging.

System requirements would be defined along with the controlling and controllable parameters. Available experimental data on the sensitivity of input parameters would be used in a systems analysis to assist in the selection of control parameters and a system concept. A research breadboard system would be assembled and tested on an aircraft engine.

Technology from other areas of the general-aviation program (fuel injection, ignition, systems cooling) could be inputs to this specific program. It might also be necessary to evaluate the state of the art of control sensors and controls.

Assessment of engine modifications for and use of alternative fuels: The objective of this program would be to evaluate other available gasolines or synthetic fuels derived from either coal or organic materials as alternatives to existing aviation fuel. Alternative fuels would be evaluated for unmodified engines. Also to a limited extent, engine modifications needed to use these fuels would be explored.

An assessment would be made of what engine changes and modifications would be necessary and practical to be able to use other available fuels with lower octane ratings and/or volatility characteristics and a wider tolerance on fuel specifications. Automotive no-lead gasoline or a derivative thereof would be a primary candidate because of its availability. Synthetic aviation fuel would be obtained for testing with current engines. Tests would be made to check for any emissions and/or performance differences. An endurance test could be proposed to determine if there might be any long-term effects on the engine and its performance or maintainability.

Improved induction and carburetion systems: The objective of this program would be to evaluate the potential of improved engine induction and carburetion systems to significantly improve engine operating conditions and performance. Present-day carbureted aircraft engines consistently run at leaner fuel-air ratios in the rear cylinders because the throttle plate deflects the fuel droplets toward the front cylinder. This maldistribution detrimentally affects both engine emissions and individual cylinder-head temperatures. This program would also complement and interface with the programs for engine modifications required to use alternative fuels and automated engine controls. Varying fuel-air ratios as a function of power demand (throttle position) may be required in order to help meet the EPA emission standards.

SUMMARY

In summary, the Lewis in-house program is pursuing new and/or improved technology for internal combustion engines that could be of long-term benefit to the industry. Specific areas of interest have been identified, a long-range program has been planned, and a number of efforts are underway.

1. Engine testing on a Lycoming O-320 engine for baseline performance and temperature-humidity correlations has been completed. A preliminary data report on the baseline testing has been published, and a preliminary data report on temperature-humidity effects on emissions is being reviewed. Engine performance and emissions testing on a Continental TSIO-360 has just been started. Preliminary data analysis shows a definite trend and strong effect of ambient temperature and humidity on emissions.

2. Initial bench testing of existing aircraft injectors is in progress and shows that there is room for improvement.

3. An Otto-cycle computer program is under development. Chemical kinetics has just been incorporated in the combustion process, which should allow the prediction of hydrocarbons and carbon monoxide, which heretofore has not been possible. On-line engine indicated mean effective pressure and flame speed instrumentation, which has wide general applicability, is being developed and show good results in the experimental testing supporting the analytical effort.

4. A two-dimensional, fin-channel, cooling-airflow computer program has been written to study configuration effects on cylinder wall temperature. Results to date show that the change in wall temperature along a fin flow passage is almost exactly equal to the adjacent cooling-air temperature rise. One cylinder head has been thermocoupled, and another will be, for testing by the engine manufacturers. Main heat flow paths will be determined to aid in analytical modeling.

5. Other promising technology areas have been identified for possible future work. These are high-energy ignition systems, automated engine controls, alternative fuels and required engine modification, and improved induction and carburetion.

DISCUSSION

Q - C. Rembleske: NASA is to be congratulated on going back into this area. What are your projections for the completion of your research into reciprocating engines?

A - W. Wintucky: Our goal is to complete the temperature-humidity correlations within a year. The fuel-injection research will take several years and to get this on an aircraft engine will take a little longer. The cooling program effort is probably the longest program. It is an evolutionary program in that it is somewhat dependent on what we find out as we go along. The program is adjusted accordingly. This is also what we are doing with the Otto-cycle program. In that program, it will probably be 3 years before we have a model that could be used to generalize and predict emissions and performance.

COMMENT - M. Krasner: I would like to clarify what Bill has said. Obviously, the final fruits of these sorts of research programs may take some time to be realized. But we are fortunate, in this case, in dealing with the limited number of people involved in the industry. It is easy for us, since we are already in contact with them, to quickly and directly relay information we have developed. And we intend to do so even ahead of our regular reporting times.

Q - W. Wiseman: In your future programs you listed the investigation of alternative fuels, and you mentioned the problem that now exists with the use of 100 low lead fuel as a substitute for 80/87. Because of that problem, there is a rapidly growing interest in using automotive gasoline for aircraft. Do you plan to investigate the possibility of using automotive gasoline for aircraft?

A - W. Wintucky: To go from 100/130 octane to automotive fuel requires a drastic modification to an aircraft engine. We would be looking at what engine changes would be necessary and whether it is feasible, in the first place, to take that drastic a step and go back to using lower octane fuel with the broad range of specifications in which this fuel is produced.

COMMENT - W. Wiseman: Of course, the trend is toward unleaded automotive gasoline and, at the moment, octane is not a problem for the automobile.

Q - E. Becker: About 12 years ago the Army issued Military Specification 46005 with regard to reducing the logistics problem of ground vehicles and aircraft operating on different fuels. Is there any current interest in pursuing that particular effort or in branching out from it to develop a more common base fuel for both ground vehicles and aircraft.

A - W. Wintucky: I don't know.

COMMENT - G. Kittredge: We in the EPA are extremely pleased to see the rebirth of NASA's independent efforts in this very important area. I have a comment that deals with water injection as applied to diesel NO_x control. That has been looked at by the automotive industry and the diesel engine manufacturers as a NO_x suppression measure, and it has always been found wanting because of the additional fluid needed to be carried along. This would be an even more serious constraint in an aeronautical application. The automotive industry has gone to exhaust gas recirculation instead because that uses fluid already aboard the vehicle and carries no particular penalty.

Q - L. Waters: Several needs motivate the investigation of these areas of technology. In my view the most urgent one, by far, is fuel conservation. I might say that GAMA enthusiastically supports these investigations, and we certainly wish to be involved and give our input. We believe the programs described are in the right organization, that is, in NASA. They are not programs for the engine companies. Lastly, on behalf of my people, I would certainly like to register my vote of confidence in NASA for the type of programs they have devised and their pertinence to industry needs. The bar graphs you showed indicate the great cycle-to-cycle variation that occurs upon leaning. The richer condition showed a much more suitable cycle-to-cycle maximum pressure. We cannot determine anything but the gross effects of the cycle-to-cycle dispersions presently by just studying the exhaust gas. Do you believe that with your program it will be possible to say whether or not low-pressure cycles are worse emitters than high-pressure cycles and perhaps point the way to combustion development in that sense?

A - W. Wintucky: In our Otto-cycle experimental effort we will try to determine the combustion species on a per-cycle basis as they are produced and correlate them with the combustion process itself. This is a very difficult thing to do, and we may not be able to do it.

Q - D. Powell: You mentioned a single lever to control the fuel-air ratio. Are you contemplating the control of rpm with that single level also?

A - W. Wintucky: A single-lever system would probably be a power demand or certain type of performance condition control. The pilot would set it and the controller or controls would automatically set a number of things including rpm for best power, performance, emissions, or economy - whatever the compromise was at that particular condition.

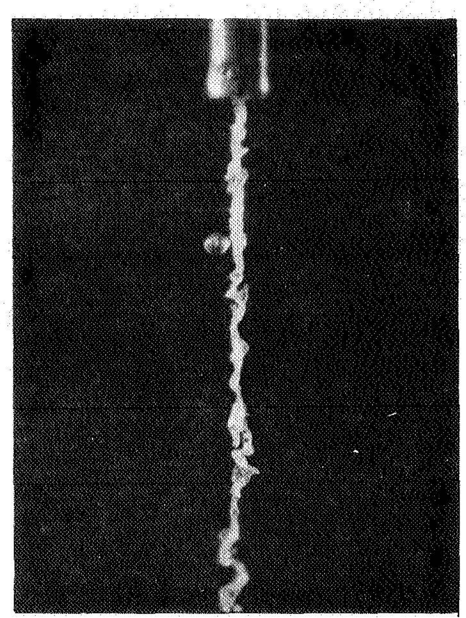
Q - F. Riddell: When you started work on the fuel injector, did anybody contact both Porsche and Bosch?

A - W. Wintucky: Bosch only.

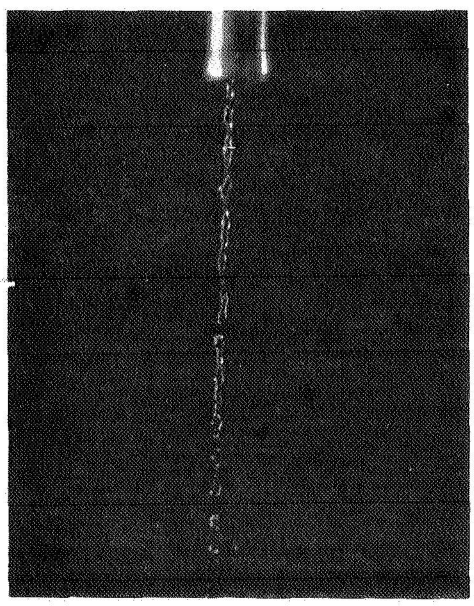
COMMENT - F. Riddell: It is my recollection that the original work on the Porsche 911 car was with the Bosch L jetronic, an electronic timed injector, and their original statements were that this was the only way that they could meet the EPA limits on emission. About a year later, they took the timed injector off and went to the continuous flow, K jetronic mechanical system. They said they had found no difference in emissions on their engines. They have been using the Bosch K jetronic injectors ever since. We are talking about going in the opposite direction from what Porsche did. There is no doubt that the timed injector is much more expensive.

COMMENT - W. Wintucky: Porsche had electronic reliability problems with the L jetronic system and switched to the K jetronic mechanical system because it was proven and in production. The decision was not based on basic pulsed versus continuous flow system performance.

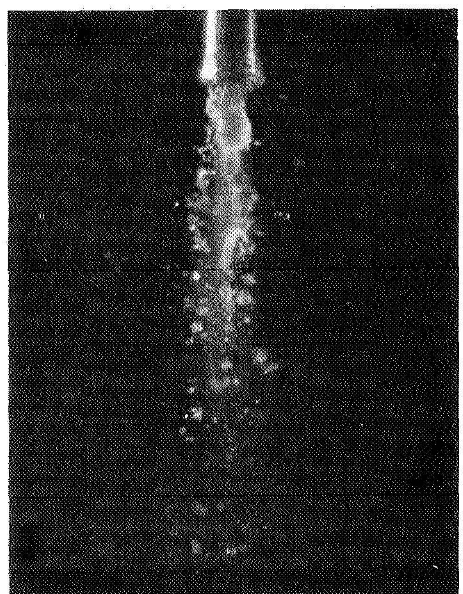
(a) Idle and taxi.



(b) Takeoff.



(c) Climb, approach, and cruise performance.



(d) Takeoff.

Figure 15-1

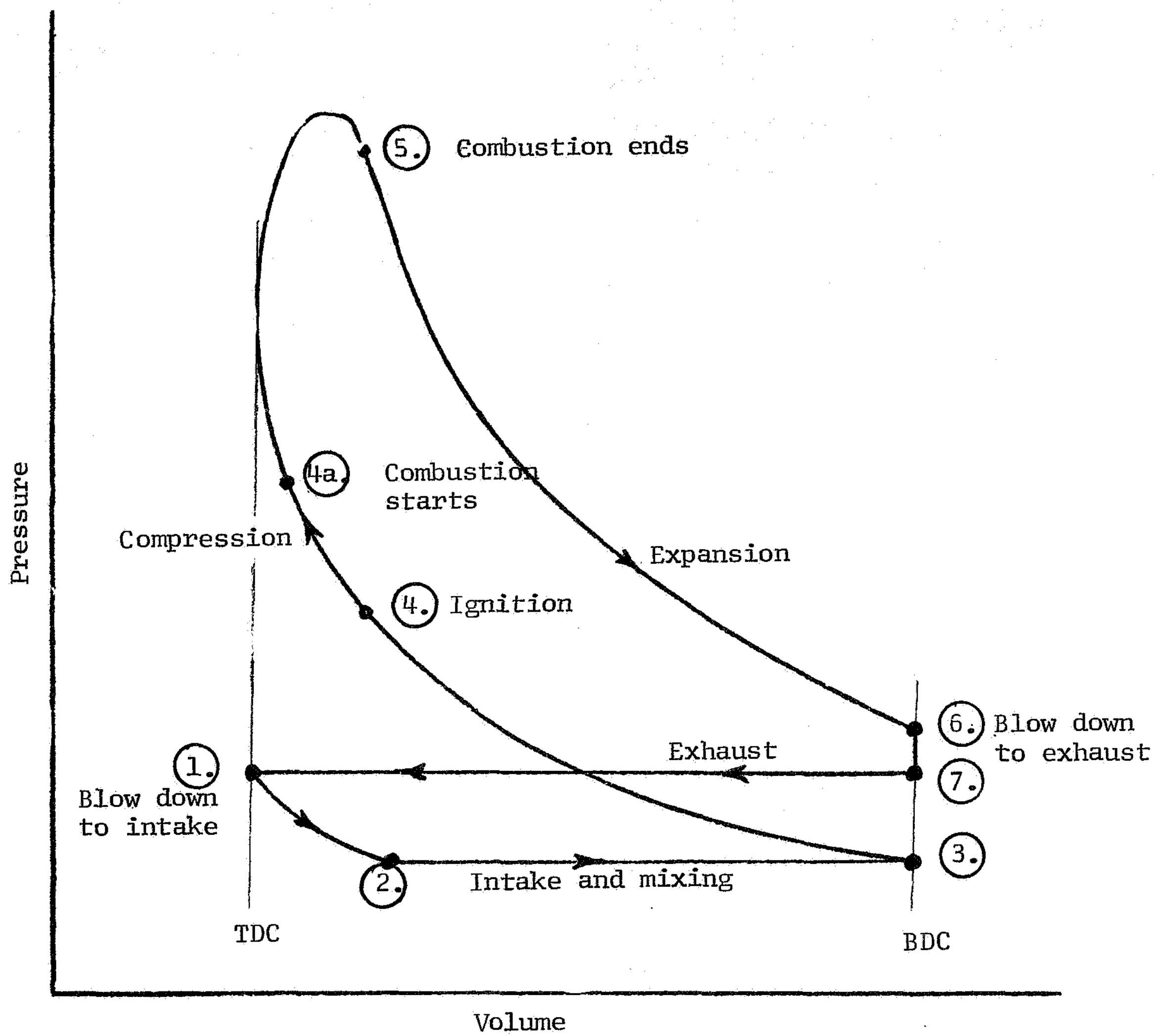

5. Combustion ends
4a. Combustion starts
Compression
Expansion
4. Ignition
6. Blow down to exhaust
Exhaust
1. Blow down to intake
7.
3.
2. Intake and mixing
TDC
BDC
Pressure
Volume

Figure 15-2

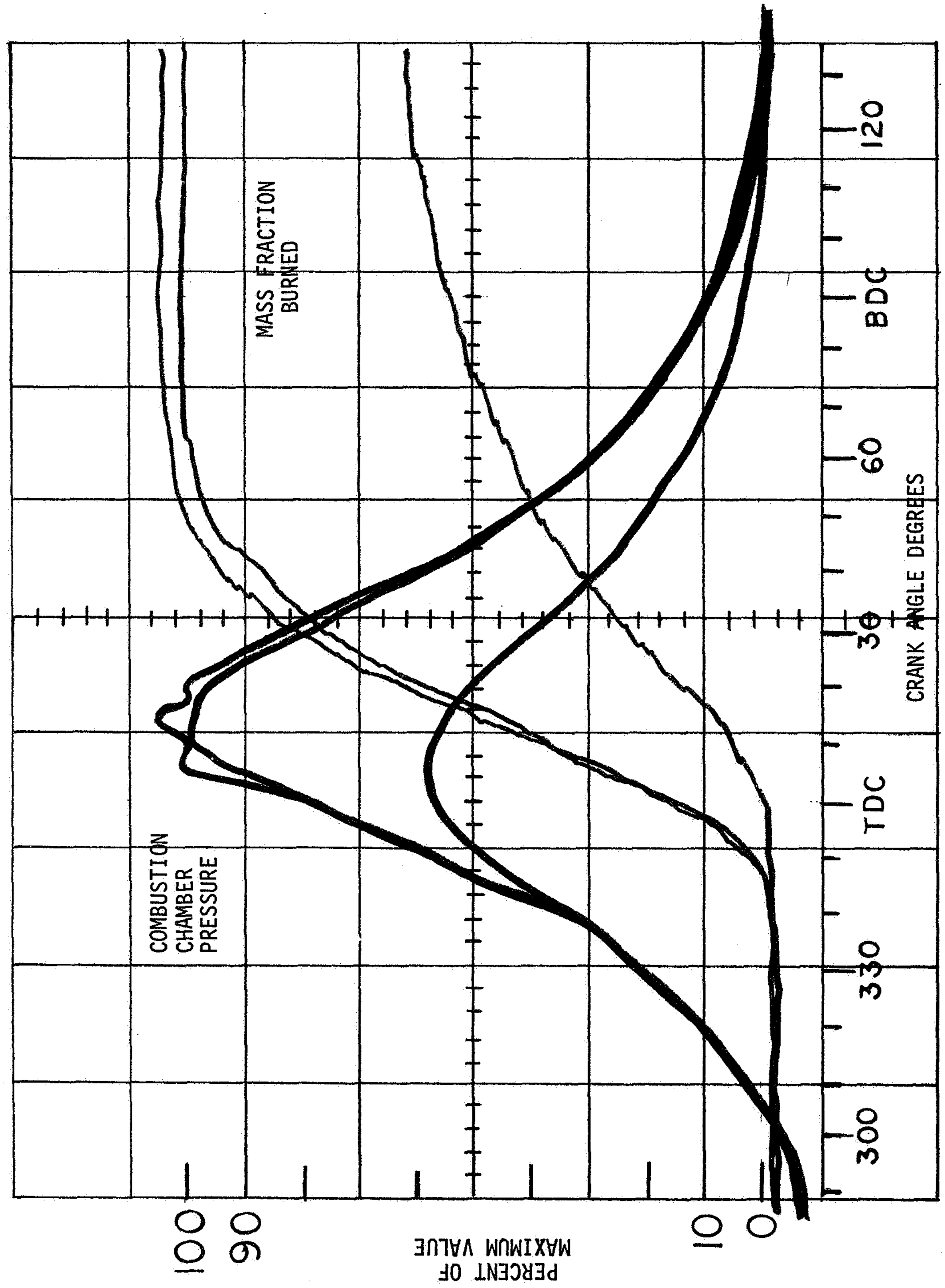
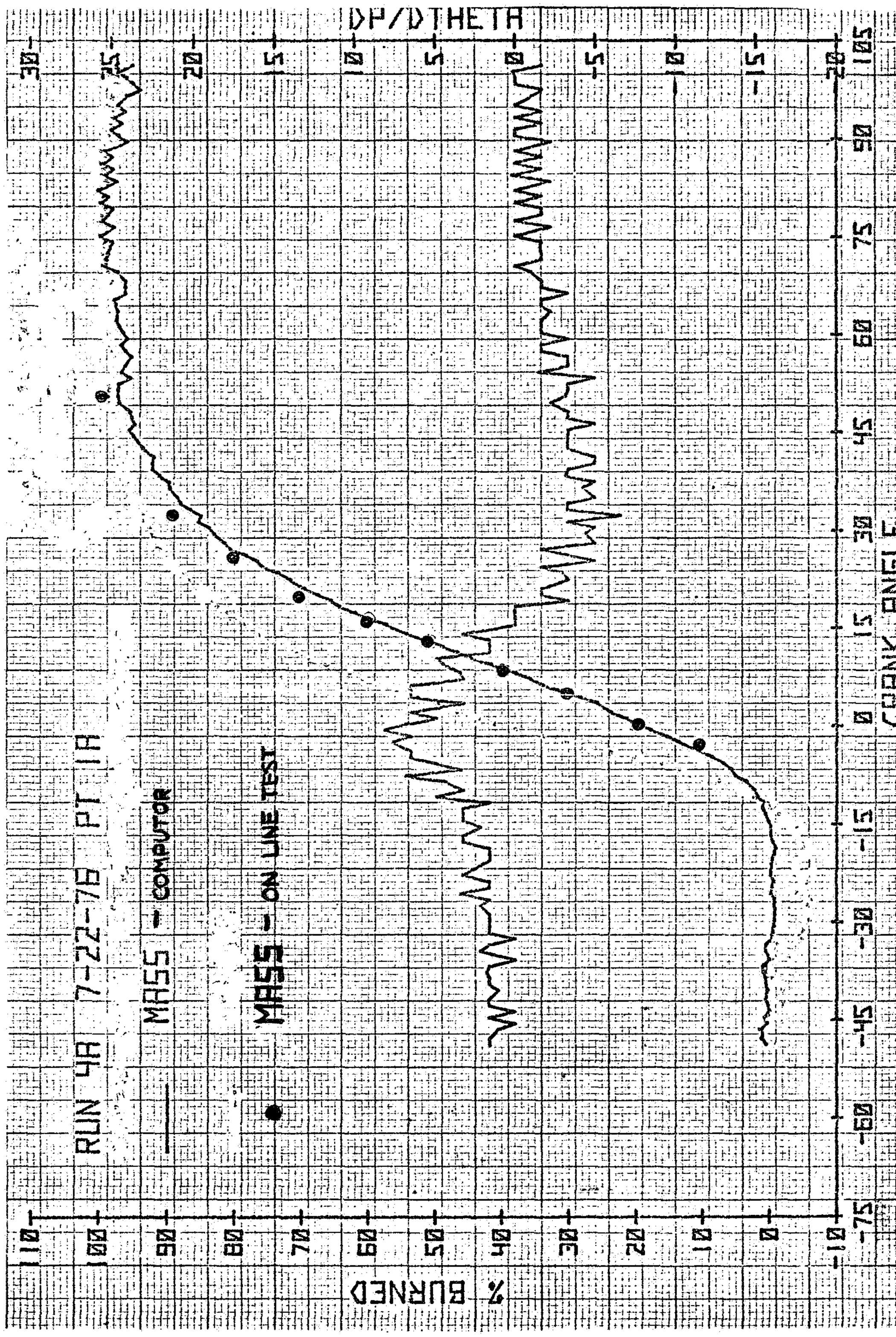
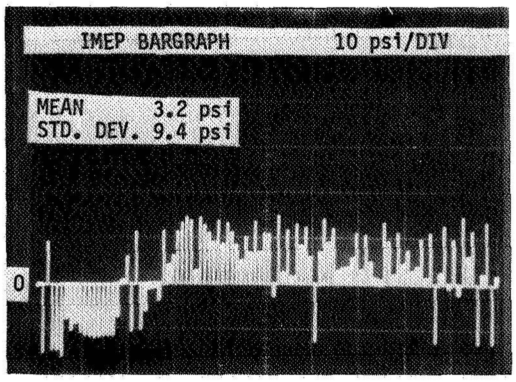

COMBUSTION CHAMBER PRESSURE
MASS FRACTION BURNED
PERCENT OF MAXIMUM VALUE
100
90
10
0
300
330
TDC
30
60
BDC
120
CRANK ANGLE DEGREES

Figure 15-3

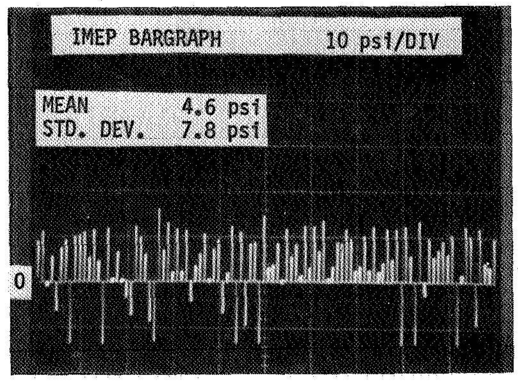


DP/DTHETA
RUN 4A 7-22-76 PT 1A
MASS — COMPUTOR
MASS — ON LINE TEST
% BURNED
CRANK ANGLE

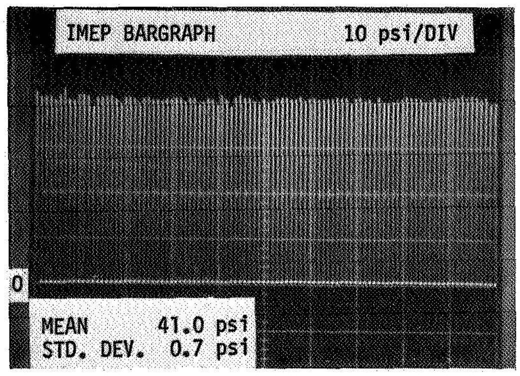
Figure 15-4



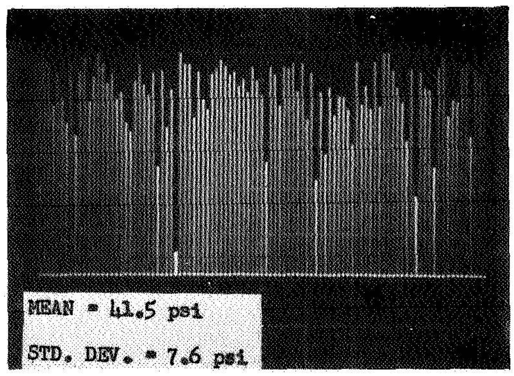
ENGINE STARTUP



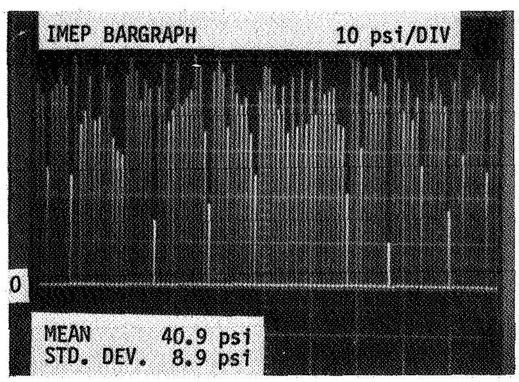
1000 RPM IDLE



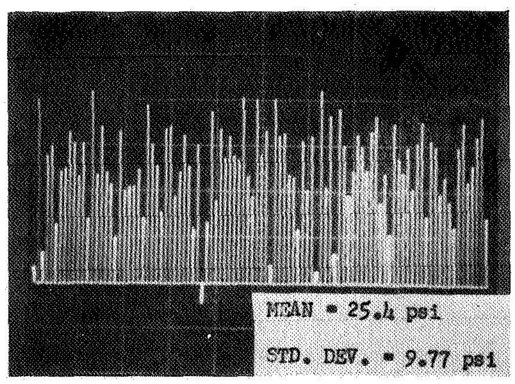
rpm = 2140 , T = 88 ft. lb. , ϕ = 1.0



rpm = 2140 , T = 88 ft. lb. ϕ = 0.81



rpm = 2140 , T = 88 ft. lb. ϕ = 0.77



LEAN LIMIT ϕ = 0.66

Figure 15-5