THE UNIVERSITY OF MICHIGAN
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Department of Mechanical Engineering

Progress Report

DIESEL ENGINE IGNITION AND COMBUSTION

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OBJECT

The object of this investigation is to learn more about the influence of engine variables on ignition delay and combustion phenomena in an engine cylinder, especially under the conditions corresponding to very high supercharge.

INTRODUCTION

There is military interest in diesel engines which can operate with very high supercharge pressures; an engine intake air pipe pressure of 5 atmospheres can be considered as an objective. A supercharge pressure of 5 atmospheres for an engine of 10:1 compression ratio will result in a cylinder air pressure at the time of fuel injection of approximately 1800 psi, with a corresponding air temperature of approximately 1700°R.

This project was initiated to investigate ignition and combustion phenomena attending these high pressures and temperatures in an engine cylinder.

The approach during the first year, covered by this progress report, has been threefold, as follows:

1. To conduct a literature survey to more clearly establish the present state of the art of diesel ignition and combustion as it relates to wide ranges of air pressure and temperature.

2. To begin the assembly of engine equipment and instrumentation for the observation and measurement of combustion phenomena in a single cylinder engine, and to make initial measurements of such items as ignition, in preparation for later work.

3. To make tests of a bench rig of an accumulator-type fuel injection system which would be adaptable to use with a one-shot (one firing cycle) operation of the test engine. Such a system also has the possible merit of being capable of a wider range of maximum to minimum injection quantity, and thus have advantages for a highly supercharged engine.

The bibliography listed under item 1 above is presented in ORA Report No. 06720-1-P.

The progress in preparing the engine and test equipment together with preliminary combustion observations is contained in Part I of this report.

The work done with the accumulator fuel injection system is presented in Part II of this report.

PART I

DEVELOPMENT OF ENGINE INSTRUMENTATION FOR COMBUSTION STUDIES

INTRODUCTION

During the first year of the project the object has been to assemble engine equipment and instrumentation, and to develop techniques and personnel capability for studying the combustion process in a diesel cylinder. This has been done with a single-cylinder Nordberg engine. Within the next year this engine will be replaced with a new high output single-cylinder research engine to be supplied by the U. S. Army for the research program.

DESCRIPTION

The equipment has been assembled around a one-cylinder Nordberg engine, Model 4FS1, of 4-1/2 in. bore by 5-1/4 in. stroke with a displacement of 83.5 $in.^3$ This engine has a Lanova-type combustion chamber. The engine is shown on Fig. 1, with some of the auxiliary equipment. The engine equipment falls into two categories—control and measurement of air flow to the engine, and measurements related to the combustion process.

AIR FLOW CONTROL

Provision has been made to supply the engine with air at any pressure from 0 to 3 atmospheres and any temperature from 75 to 450°F with a mass flow rate from 0 to 485 lb/hr. By later modification of the air measuring system at least 5 atmospheres of engine air supply pressure can be provided.

The laboratory compressed air is used to supply the engine through a critical flow air meter as shown in Fig. 2, item 7. The critical flow design was selected as it permits accurate air flow measurements regardless of downstream pressure fluctuations caused by the one-cylinder engine and also provides an easy means of supplying and controlling the air supercharge pressure. The air meter consists of four critical flow orifices piped and valved together in such a manner that any or all of the orifices can be used to supply the engine. The upstream air pressure can be regulated to give any engine inlet air pressure or air flow desired within the range of the air meter. The air meter was built and calibrated to ±1.0% accuracy in The University of Michigan laboratories. Calibration curves for the orifices have been plotted and copies are available for use.

1. Nordberg model 4FS1 engine
2. Instrumentated injector
3. Provisions for solar cell and pressure pickup in head (hidden)
4. Exhaust surge tank
5. Intake surge tank
6. Intake air heater
7. Back side of critical flow air meter
8. Back of dynamometer console

Fig. 1. Photograph of Nordberg engine.

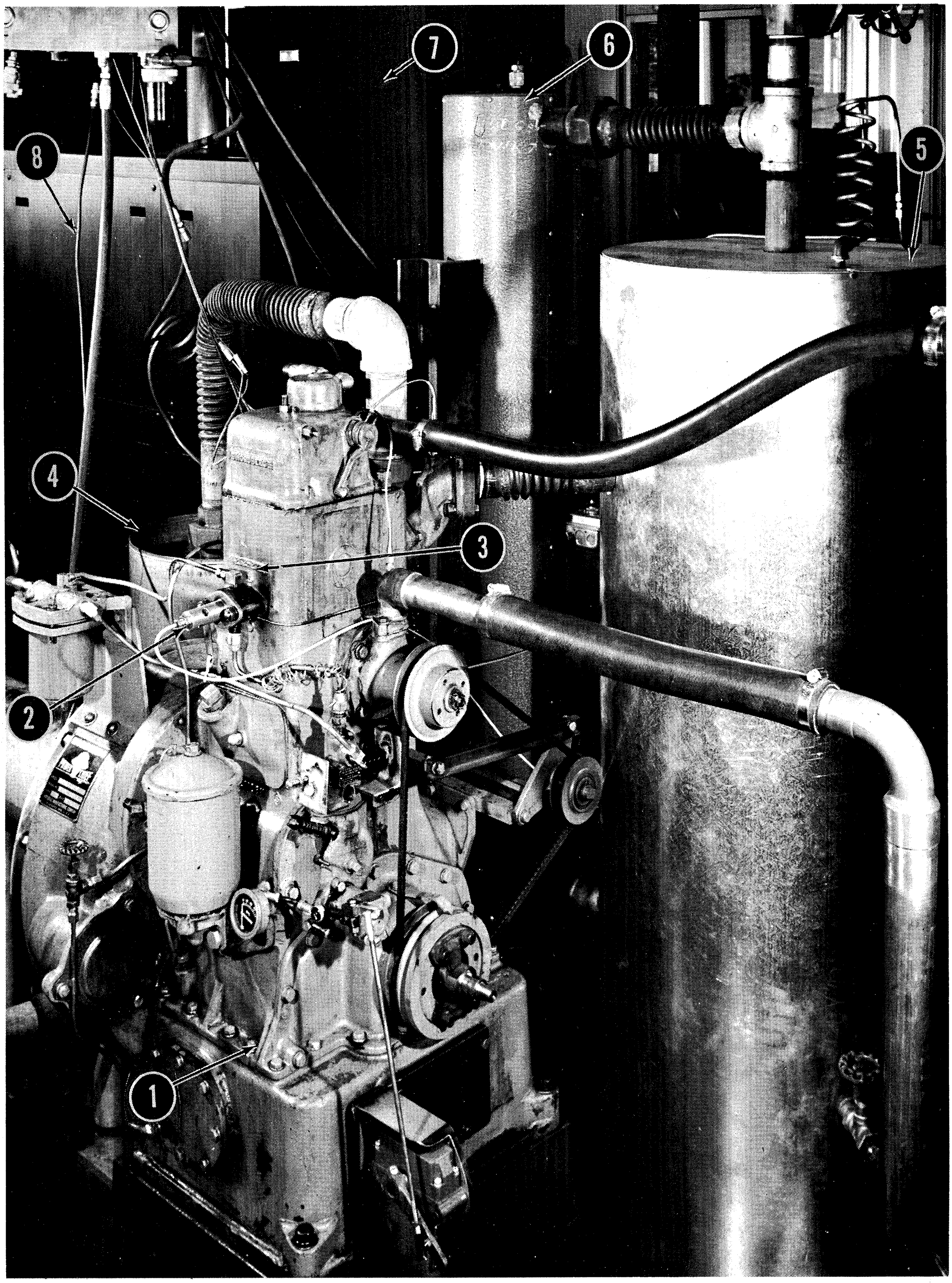


Fig. 1

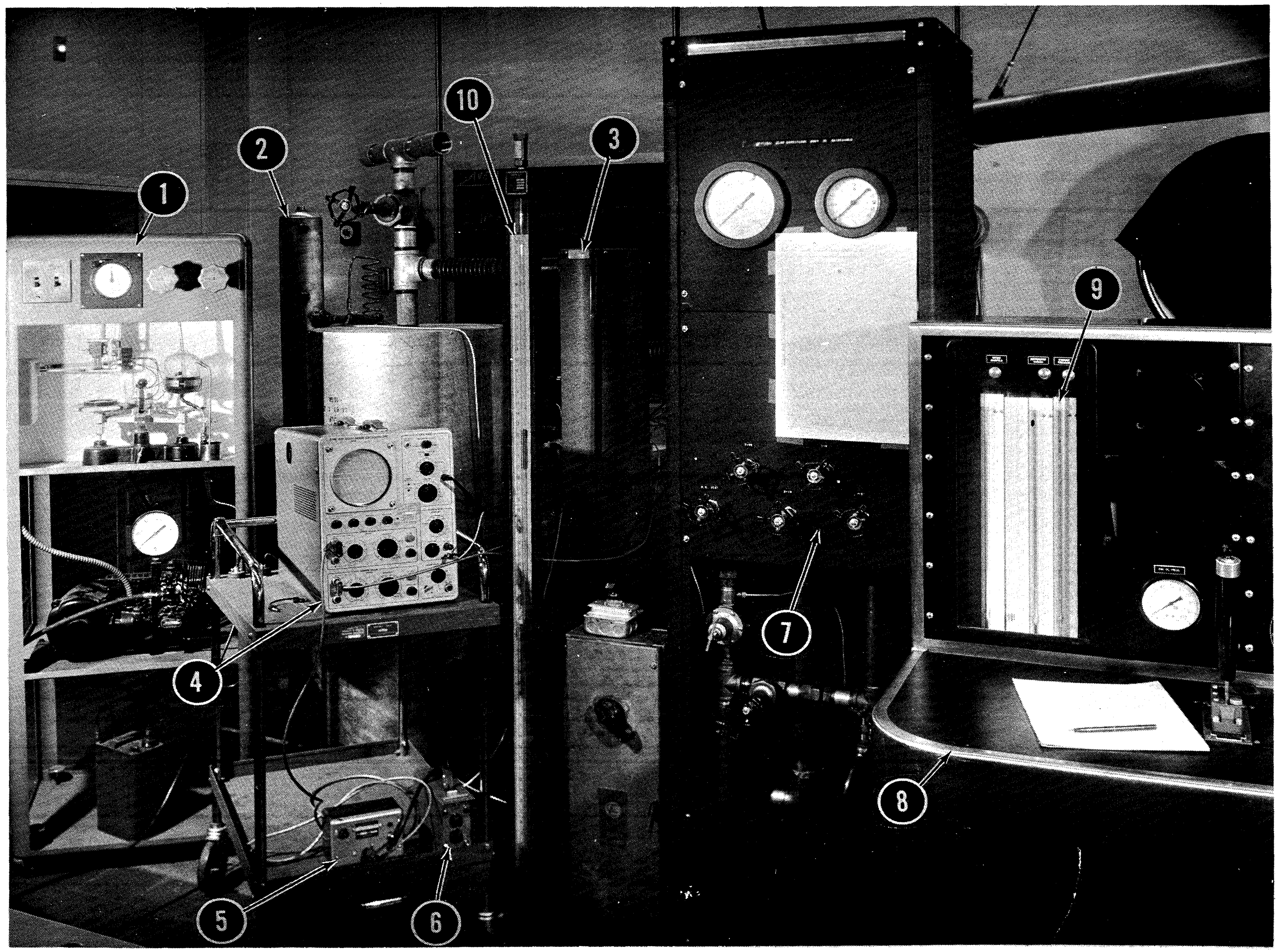


Fig. 2

1. Fuel weighing stand
2. Cooling tower
3. Intake air heater
4. Oscilloscope
5. Distance detector power supply
6. Kistler charge amplifier
7. Critical flow air meter
8. Dynamometer console
9. Exhaust pressure manometer
10. Intake air manometer

Fig. 2. Photograph of test cell and instrumentation.

After the air leaves the air meter it is passed through a Chromalox electric air heater of 20 kilowatt capacity, as shown in Fig. 1, item 6. The heater is thermostatically controlled and has the capacity to heat the maximum air flow from room temperature to 450°F. Smaller air flows can be heated to temperatures up to a maximum temperature of approximately 800°F.

From the air heater the air is directed to an inlet air surge tank of 5.6 ft^3 capacity, as shown in Fig. 1, item 5. The purpose of this tank is to exclude the possibility of inlet air pressure fluctuations due to a resonant condition in engine air supply system. The tank is connected to the engine by a 10-in. section of flexible metal tubing and is insulated to reduce heat losses from the air.

A surge tank of 2.4 ft^3 capacity, shown in Fig. 1, item 4, is connected to the exhaust manifold of the engine by a 4-ft length of tubing. Immediately after the tank is a gate valve to regulate engine exhaust back pressure.

The remainder of the equipment connected to the engine is typical for a test cell installation and includes a dynamometer for motoring or absorbing power, fuel and cooling water supply, fuel weighting stand, and an electronic counter for determining engine speed. Also included is a Honeywell-Brown Electronik self-balancing potentiometer for measuring temperatures.

The above equipment makes it possible to measure or control at least the following variables:

1. Inlet air pressure, temperature, and mass flow;
2. Exhaust temperature and pressure;
3. Fuel consumption and power output; and
4. Engine speed and pertinent temperature.

COMBUSTION MEASUREMENTS

Ignition delay is defined as the time delay from the injection of the first fuel into the combustion chamber until combustion begins. To measure the ignition delay it is necessary to measure both the point in time when fuel injection begins and the point in time when combustion begins, the difference being the ignition delay.

The Nordberg engine uses a Bosch injection pump and a Bosch nozzle holder with a single hole nozzle and pintle-type pop-off valve for injection. The nozzle holder has been modified so that a Bently D-152 distance detector system can be used to sense the motion of the nozzle pintle. Injection is judged to begin at the instant the pintle lift begins. Most, if not all, investigations use the pintle lift method to determine the beginning of injection but most use either a capacitance-type pick-up or a linear differential transformer (L.D.T.) to sense the pintle motion. We selected the Bently system to detect pintle motion because it is as easy to adapt to the injector as either the capacitance pick-up or the L.D.T., and the general instrumentation is self-contained, and easier to operate than the other two systems. Experience to date indicates the pintle lift is a very stable measurement of the beginning of injection and should yield an error of less than 1/20 millisec in determining the beginning of injection. This can be seen by reference to the oscilloscope photographs, Fig. 3, each of which is at least six pintle lift cycles superimposed on one photograph. Note that the six pintle lift traces appear to be but one trace due to the excellent repeatability of the pintle lift motion.

At the present time we have two means of determining when combustion begins. The first is a pressure time trace of cylinder pressure. In this method combustion is judged to begin when the compression pressure deviates from an ideal compression due to the addition of combustion heat. Kistler pressure measurement equipment is available in the laboratory for this type of study but to date we have not made extensive use of it.

The second method of determining the beginning of combustion, and the method toward which we have directed most of our effort, is to detect the light in the combustion chamber. The light will be at a very low level before combustion begins and will rise as the combustion process proceeds. Combustion is judged to begin at the first change of intensity of light in the combustion chamber. To detect combustion light we are using a silicon solar cell behind a 3/8-in. diameter quartz window in the combustion chamber. This cell has a response time of 20 microseconds and is sensitive to light in the range of 4000 to 110,000 angstroms wavelength. The main advantage of using the solar cell to detect the beginning of combustion is its low cost and very simple circuitry. Repeatability of the solar cell appears to be excellent as reference to Fig. 3 shows. The solar cell traces have a maximum variability of 0.4 millisecond which could, in part at least, be due to a variation in the combustion process. The solar cell pick-up was designed and built in the Instrument Shop of The University of Michigan.

The delay period has been noted below the trace photographs of Fig. 3. These times are the interval between the start of the lift of the injector pintle and the trace which indicates that the solar cell is receiving light from the combustion.

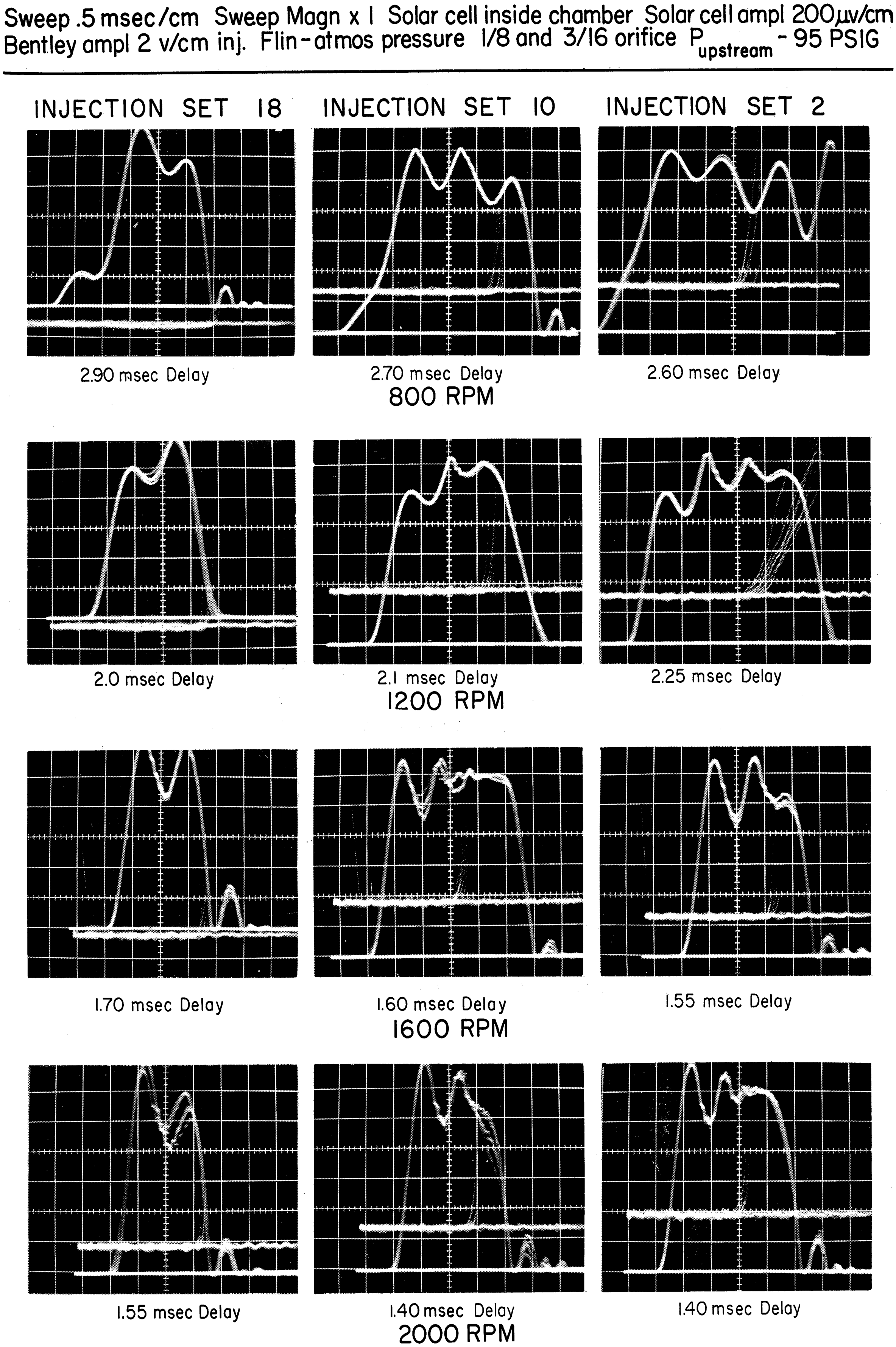


Fig. 3. Oscilloscope traces to determine engine ignition delay.

PART II

THE ACCUMULATOR FUEL INJECTION SYSTEM

INTRODUCTION

Investigation of the diesel engine combustion characteristics at very high pressures may make it desirable to operate the engine with only single firing cycles (one-shot operation) to avoid mechanical and thermal difficulties with the engine. Mainly for this reason it was decided to make some preliminary tests of an accumulator-type system, which would be adaptable to the single injection requirement.

The accumulator system also offers theoretical advantage concerning two pressing requirements of high output ordnance diesel engines.

The first requirement is an injection system that can accurately deliver the small amount of fuel required at idle, which is essentially the same for a low and a high BMEP engine, and that can accurately deliver the large amount of fuel required at full load, which is proportionally higher as the BMEP increases. The ratio of maximum fuel delivered to minimum fuel delivered is termed the turndown ratio and can be seen to increase directly as the engine BMEP is increased. The ability of current injection systems to produce a satisfactory turndown ratio at present outputs is being pressed and it is reasonable to expect acture problems in this area when outputs are significantly raised.

The second requirement is a standard injection system which can be fitted to a large range of engine sizes with only minor changes to the injection system itself. It is felt that the accumulator system has the potential of satisfying both of the above requirements.

DESCRIPTION OF THE INJECTION SYSTEM

Figure 4 is a schematic of the elements of an accumulator system. The principle of operation of this system is that of storing the energy required to inject the fuel in an accumulator. Since the fuel has compressibility, as measured by the bulk modulus of the fuel, this mode of energy storage is analogous to storing energy in a spring. The amount of fuel injected will depend on the amount of energy stored which in turn depends only on the volume of the accumulator, the bulk modulus of the fuel and the pressure under which it is stored.

Figure 4 shows the basic elements which comprise an accumulator injection system, as follows:

1. High pressure pump;
2. Master accumulator and high-pressure relief valve;
3. Timed distributor;
4. Slave accumulator; and
5. Nozzle holder.

The function of the high-pressure pump is to supply fuel at a pressure somewhat above the pressure to which the accumulator is being charged. A range of pressures from 2000 to 10,000 psi would be quite practical. The quantity of fuel pumped by the high-pressure supply pump need not be metered but it must be approximately twice the amount actually required for injection.

The purpose of the master accumulator is to reduce the pulses from the high-pressure supply pump and to provide a reservoir so that small volume changes in the system do not cause large pressure changes. The high pressure relief valve could be a throttle or governor controlled valve, in either event this is the point in the system where external control over the amount of fuel injected is maintained.

The timer-distributor has two functions. First, it must provide communication of the fuel pressure from the master accumulator to the nozzle. Second, at the proper time in the engine cycle it must stop flow from the master accumulator to the nozzle and vent the pressure above the nozzle plunger to atmospheric, which permits injection to take place as described below.

The nozzle assembly is the same in construction, and operation as a standard pintle-type nozzle except that it has provisions for subjecting the top side of the pintle to the pressure from the timed distributor. Thus the fuel pressure as well as the usual spring hold the nozzled closed. One side of the slave accumulator is connected to the injection fuel passage in the nozzle holder, the other side is connected to the timed distributor.

The events which take place in the nozzle holder slave accumulator assembly over an injection cycle is as follows: The timer distributor allows communication of the pressure in the master accumulator to the nozzle assembly and slave accumulator. Injection does not take place as the fuel pressure is aiding the spring to hold the pintle closed in the nozzle holder. Fuel flows to the slave accumulator until a zero pressure difference exists across the check valve in the slave accumulator and at this point the system is ready for an injection. The nozzle assembly top line is then vented to atmospheric pressure by the timer distributor. The pressure in the accumulator does not decrease since the check valve is closed but the pressure on the top side of the pintle in the nozzle holder is reduced so that only the spring is holding the pintle down. The pressure in the slave accumulator is high enough, say 4000 psi, so that the spring force on the pintle is overcome and injection occurs. The amount of fuel injected is determined by the initial pressure in the slave accumulator, the accumulator volume and the bulk modulus of the fuel. The cycle is repeated when the timer distributor allows communication of pressure from the master accumulator to the nozzle holder-slave accumulator line.

TESTS OF AN ACCUMULATOR SYSTEM

A bench rig of an injection system using the accumulator principle has been built from parts available in our Automotive Laboratory. Figure 5 is a diagram showing the arrangement of the system as used for the bench tests. Figure 6 is a photograph of the bench rig, showing the components and much of the plumbing. The timers, or interrupters, of Figs. 5 and 6 were made by producing a steel block to hold a conventional diesel injection pump plunger and sleeve. The valving action was obtained by rotating the standard pump plungers in the sleeves. The cog belt drives and vari-speed motor which provide the variable speed of rotation can be noted on Fig. 6.

TESTING OF ACCUMULATOR SYSTEM

Preliminary tests were run with the system described to learn about its merits and problems. These tests were run with frequency of injection from 200 to 1250 injections per minute, and with the accumulator pressure varied from 4000 to 7000 psi. These tests were run with an accumulator volume of 0.29 in.^{3} The results of these tests are shown on Fig. 7. It will be noted that the injection nozzle delivery of the experimental equipment is greater than that predicted by hydraulic theory, especially at the higher pressures.

In an effort to better understand the hydraulic phenomena that were occurring, a Kistler pick-up was installed in the injector, to sense the pressure in the line joining the injector to the accumulator. Four typical photographs of oscilloscope pressure traces are shown on Fig. 8.

Photograph Fig. 8(b) shows substantial fluctuation of the nozzle supply pressure during successive cycles. Figure 8(c) indicates that at 1000 cycles minute the pressure hardly had fully built up before the discharge occurred. Figure 8(d) shows that at 1250 cycles/minute the maximum nozzle pressure was falling off, probably due to insufficient charging time.

From this preliminary bench work we have learned that the volume of liquid in the parts of the system subject to fluctuation must be kept at a very minimum, consistent with adequate size of flow passage. Also, the quality of the parts must be of a high order to minimize leakages and obtain consistent operation.

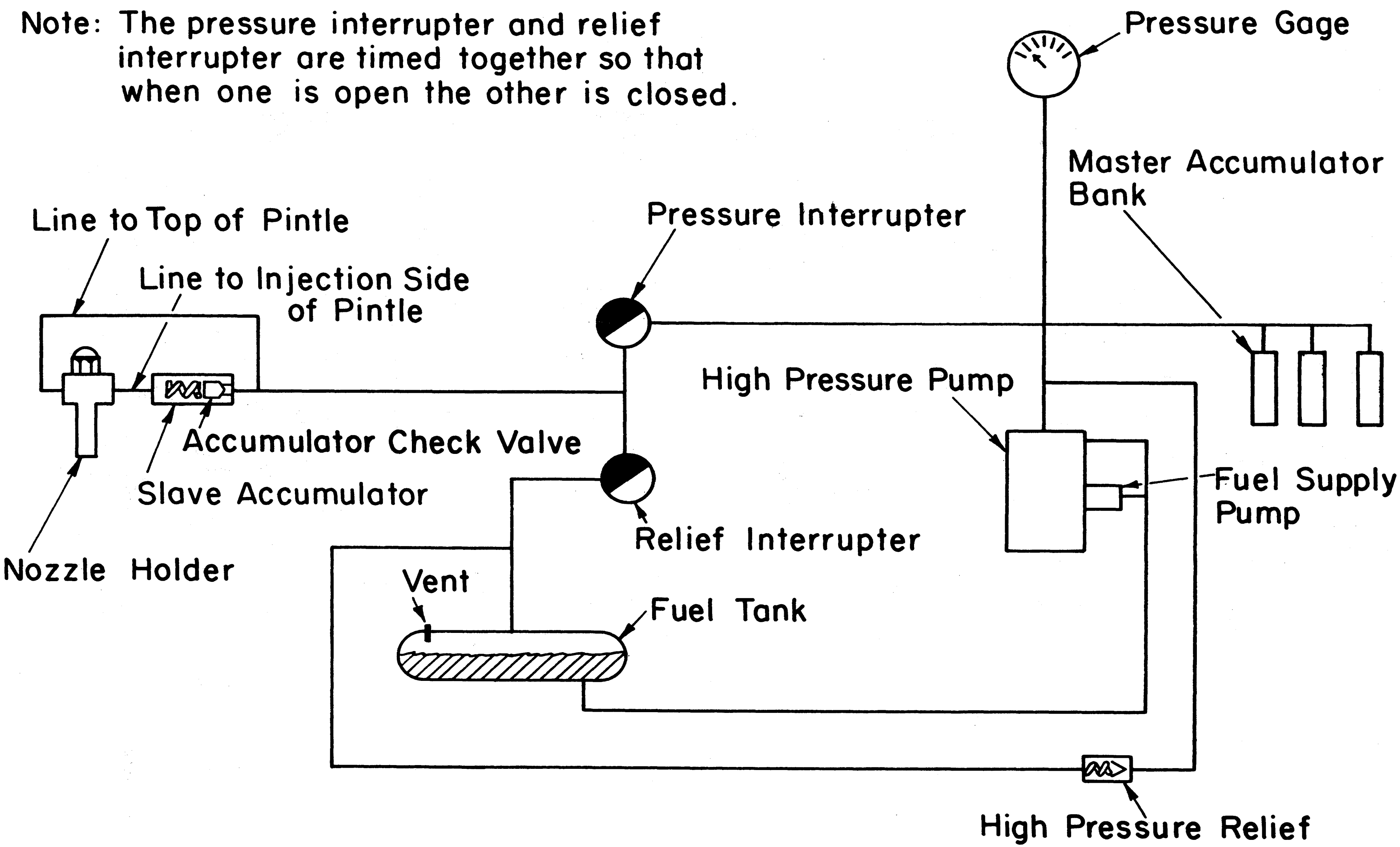


Fig. 5. Diagram of accumulator system as built for bench testing.

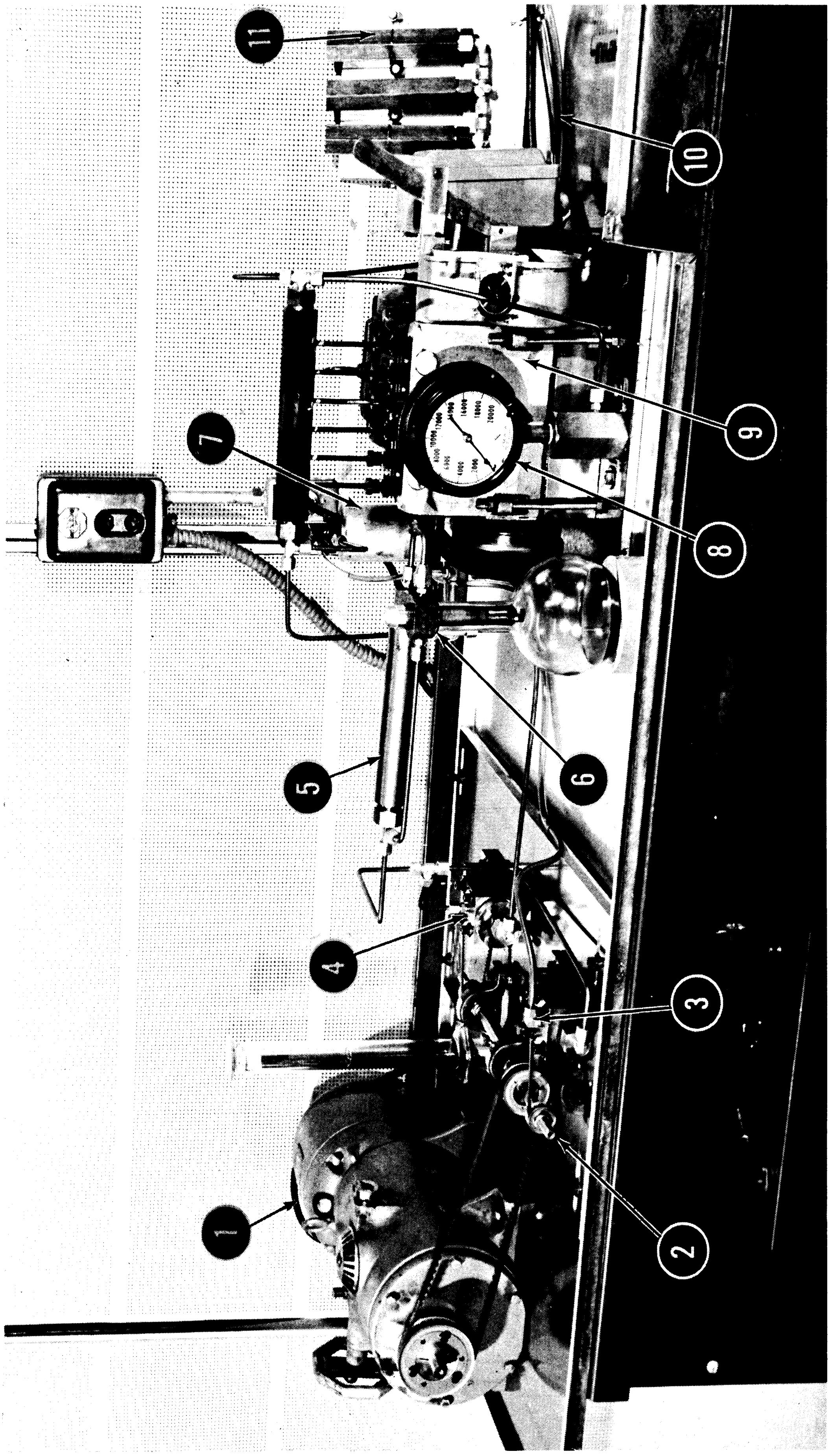


Fig. 6

1. Variable speed drive
2. Jack shift to time interrupter
3. Relief interrupter
4. Pressure interrupter
5. Slave accumulator
6. Nozzle accumulator
7. High pressure relief valve
8. 20,000 psi pressure gage
9. High pressure pump
10. Lines to fuel tank and low pressure pump
11. Master accumulator bank

Fig. 6. Photograph of bench rig—accumulator injection system.

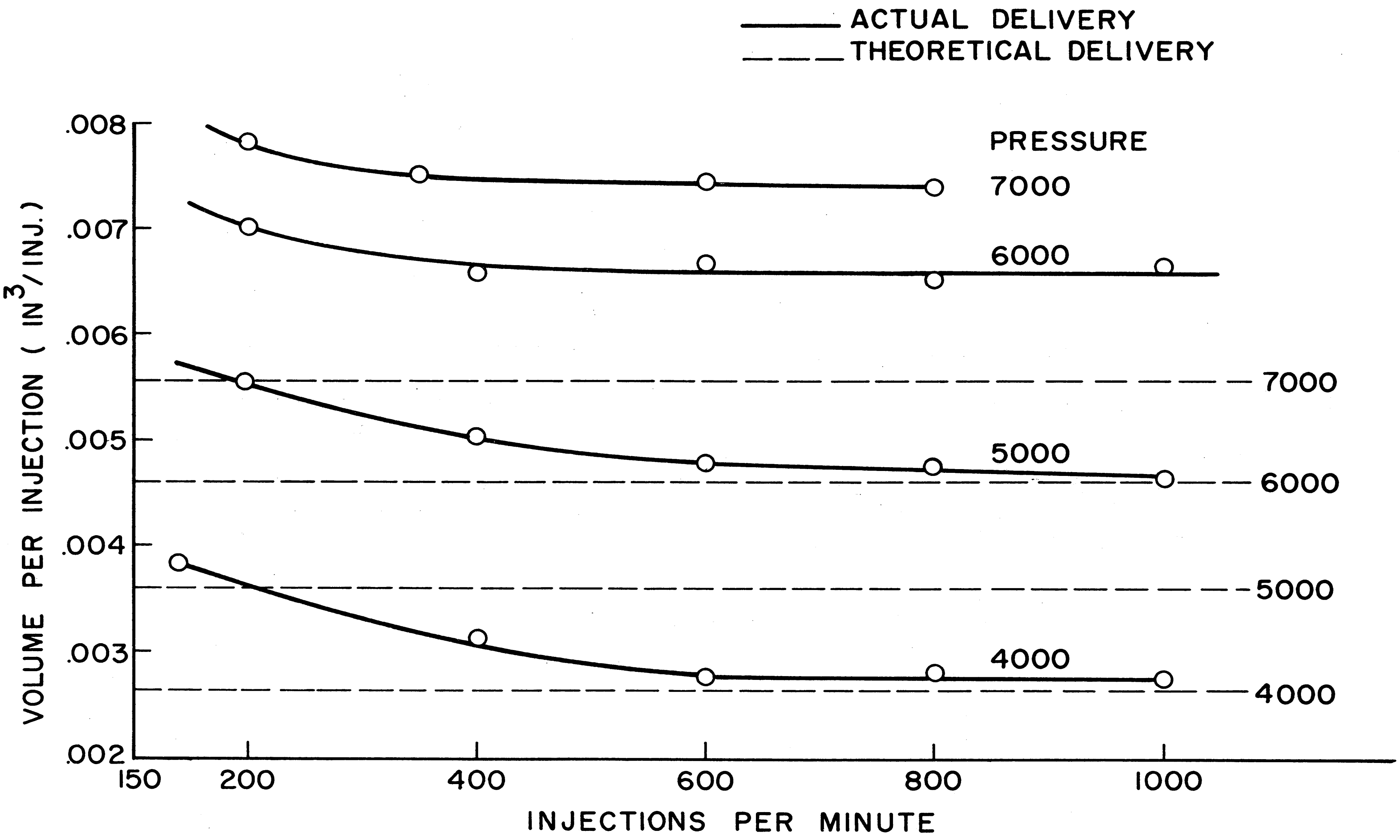
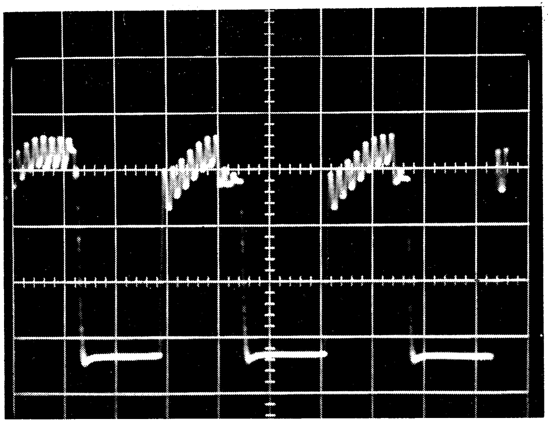
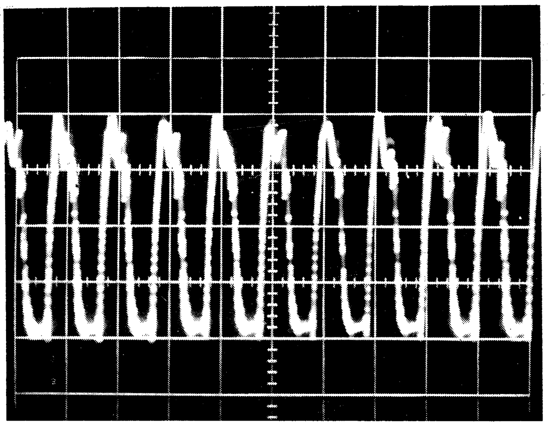


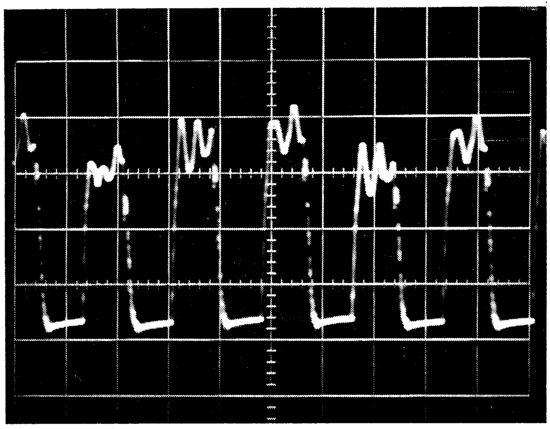
Fig. 7. Performance characteristics of accumulator injection system (accumulator vol. = 0.29 in.^{3}).



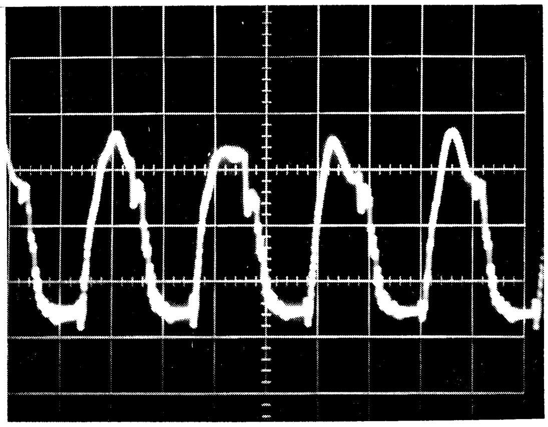
(a)
Time sweep .1 sec/cm
Calibration 1000 psi/cm
Speed 200 RPM



(c)
Time sweep 50 msec/cm
Calibration 1000 psi/cm
Speed 1000 RPM



(b)
Time sweep 50 msec/cm
Calibration 1000 psi/cm
Speed 600 RPM



(d)
Time sweep 20 msec/cm
Calibration 1000 psi/cm
Speed 1250 RPM

Fig. 8. Transient pressures at nozzle of accumulator injection system. (valve closing pressure = 1600 psi; accumulator vol. = 0.29 in.^{3}).

To obtain a quality of performance suitable for operating the test engine, the bench system would have to be quite completely re-engineered and many new precision parts built. It has been decided that instead we will, at least for our initial test work, use the regular engine injection system. If single shot operation is desired, it will be done by rapidly positioning the pump rack from no load to the desired load position.