DIESEL INJECTION OF COAL-WATER SLURRY

BY

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Submitted to the Department of Ocean Engineering in partial fulfillment of the requirements for the degree of Master of Science in Naval Architecture and Marine Engineering and Master of Science in Mechanical Engineering.

ABSTRACT

The use of coal-water slurry as a diesel engine fuel can lead to a reduction in fuel costs in large bore diesel engines. A single injection, high-pressure bomb was used to study the spray characteristics of coal slurry injected from a modified high-pressure pintle nozzle at injection pressures up to 4200 psi and bomb pressures up to 1400 psi. Each injection was filmed using a high speed camera and the films were analyzed for spray velocities and spray patterns. Baseline series of injections were conducted with water and No.2 diesel fuel. These injections and films show that for the four different types of coal slurries tested, as well as for water and No.2 diesel fuel, the injection velocity at the nozzle exit is not sensitive to fuel types, and may be obtained by using a flow coefficient which only depends on the internal geometry of the nozzle. Still photographs were made to determine the drop sizes using a 500 nanosecond flash tube which was able to "freeze" the droplets of coal slurry during the injection. Atomization of the slurry was generally poor and the majority of the slurry remained as large globules.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

I. INTRODUCTION

A. BACKGROUND

The concept of using a coal-based fuel in a diesel engine dates back to the 1890's to Rudolph Diesel's early experiments with powdered coal. His colleague, Pawlikowski, met success prior to World War I with his RUPA engine which used compressed air to inject coal dust into the engine. Research in the U.S. on the use of coal-based fuels in diesel engines did not begin until the late 1940's and fuel injection difficulties and wear problems showed little promise. Engine tests in 1979 on a slow-speed two-stroke diesel using a pulverized coal-water slurry demonstrated finally that it was feasible to use coal-based fuel in a diesel cycle, and relatively high fuel conversion efficiencies were obtained.(Ref.1)

B. INCENTIVES

The motivation for the use of coal-water slurry is to provide a long term readily available energy resource. The depletion of oil supplies and the dependence on imported oil has created interest in the abundant domestic coal supplies. Handling problems with powdered coals are avoided to a large extent with coal slurries, and of the various possible slurries that can be used, coal-water slurry seems to be the most economical.(Ref. 2) The presence of water in the slurry amounts to a small energy penalty, 3%-7% of the energy in the coal, depending on the coal concentration in the slurry.(Ref.3) Despite this penalty, available literature suggests that there may be a considerable savings in fuel costs for large medium-speed and slow-speed diesel engines such as in stationary power plants, marine propulsion systems, and railroad locomotives.(Ref.4,5) Indications from thermodynamic analyses of the combustion of coal-water slurry show that the possibility exists also to reduce the peak combustion temperature and thus reduce the NOx emissions from the diesel engine.(Ref.1)

Several engine tests have been conducted using coal-oil slurries and coal-jet fuel slurries and coal-water slurries with little investigation of injection properties of the slurry.(Ref.6,7) The completeness and duration of combustion of coal-water slurry is greatly affected by the atomization (and subsequently the penetration) of the injection spray. Tests done in simulated diesel environments showed incomplete combustion due to inadequate spray atomization of coal-water slurry which they felt could also result in spray impingement on the cylinder walls.(Ref.2) It is believed that the droplet sizes in the spray may in fact be more significant than the fuel-air mixing rate as the limiting step in combustion of coal-water slurry because the droplet size will eventually determine the general time scale for evaporation of the water, and ignition of the coal particles.(Ref.4)

The significant energy penalties associated with the use of twin-fluid atomizers (air-blast atomizers) make the use of mechanical injection systems worthy of further study for use in diesel engines.

Some extensive work has been done on the injection and atomization of coal, charcoal, and coke particles in diesel fuel at various conditions (Ref.8), but less is known about the diesel injection and atomization of coal particles in water. It is hoped that this thesis will shed some light on this subject.

C. INITIAL SIZING OF THE EQUIPMENT

Since coal burns much slower than diesel fuel, the use of coal slurry as a viable fuel for diesel engines will be restricted to large, slow or medium-speed engines in which a longer allowable time for combustion exists. A rough estimate of the smallest diesel engine that could conceivably use coal slurry is one with a bore of eight inches. Multi-hole centerline fuel injection common in this size engine was simulated in this work by using a single hole injector with a pintle nozzle and injecting from the side of a four inch diameter chamber. Consequently, the bomb used for the injection testing was designed with a four inch bore which also corresponded exactly to the bore of the Rapid Compression Machine which will be used for combustion research in the future.

II. MATERIALS AND EQUIPMENT

A. SLURRIES

Four different coal slurries were used in the injection tests, and each was composed of approximately 50% coal and 50% water by mass. Small amounts of chemical additives were used to keep the slurries from agglomeration and settling, and to vary the transport properties. The most extensive testing and high speed filming was done on the slurry supplied by Resource Engineering Incorporated (referred to as the REI slurry). The other three slurries were supplied by AMAX Corporation and were basically similar except they were each of different viscosities (referred to as AMAX A,B,C).

1. Properties

Table 1 lists some of the pertinent physical properties of the four slurries. The differences in coal, water, and additive percentages were necessary to achieve the different viscosities in the three AMAX slurries. Differences in the ultimate analysis and the

TABLE 1

		REI slurry	AMAX A	AMAX B	AMAX C
% COAL		50.3	51.4	51.1	51.8
% WATER		49.7	47.7	47.62	47.68
% ADDITIVES					
Reagent			0.90	1.28	0.52
Stabilizer			0.0031	0.0046	0.0016
Surfactant/Dispers.		1.10			
Anti-foam		0.05			
ULTIMATE ANALYSIS OF COAL	C	85.06	81.15	81.15	81.15
	H	5.41	5.42	5.42	5.42
	O	6.72	10.93	10.93	10.93
	N	1.49	1.75	1.75	1.75
	S	0.68	0.75	0.75	0.75
	Cl	0.15	-	-	-
	V	0.0003	-	-	-
PROXIMATE ANALYSIS OF COAL	% ash	0.49	0.54	0.54	0.54
	% vol	37.97	34.8	34.8	34.8
	% carb	61.54	64.66	64.66	64.66
PARTICLE SIZE DISTRIBUTION in microns	< 5	20.5 %	52.4 %	52.4 %	52.4 %
	5-10	45.5 %	32.7 %	32.7 %	32.7 %
	11-20	33.5 %	11.9 %	11.9 %	11.9 %
	>20	0.5 %	3.0 %	3.0 %	3.0 %
	mean	7.0	6.2	6.2	6.2
DENSITY (kg/m3)		1088	1051	1120	1112
VISCOSITY (cps)		254 @12.6/sec	580 @1000/sec	260 @1000/sec	780 @1000/sec
HEATING VALUE (kJ/kg)		16,575	17,141	17,141	17,274

proximate analysis of the coal between the REI and the AMAX slurries are the result of different coals used by the manufacturers, and although the mean particle size of the REI slurry and the AMAX slurries are similar, the size distributions are very different. The slurry densities are all similar. The viscosities were supplied by the slurry manufacturers and here it should be noted that since slurry is a non-Newtonian fluid, the viscosity is dependent on the shear rate. The REI slurry has a viscosity of 254 centipoise at a shear rate of 12.62 sec^{-1} while the viscosities of the AMAX slurries were measured at a shear rate of 1000 sec^{-1} therefore making exact comparisons not possible.

2. Energies

The net energy per unit mass of the REI slurry was calculated from the coal energy content (the value was provided by the manufacturer), the percentages of coal and water in the slurry, and the energy required to vaporize the water. The basic equation is as follows:

$$HV_{slurry} = (\%coal)(HV_{coal}) - (\%water)(vap.energy_{water})$$

where the heating values are in kJ/kg and the vaporization energy of water is 2260 kJ/kg.

For the REI slurry, the heating value was determined to be 16,575 kJ/kg which is approximately 2.5 times less than that of diesel fuel. This means that the total volume of slurry injected would have to be 2.5 times larger than that of diesel fuel to produce the same amount of work.

The heating values of the AMAX slurries were provided by the manufacturer and are also summarized in Table 1.

3. Stoichiometry

The stoichiometric ratio is the ratio of the mass of air to the mass of fuel for complete combustion to occur. For example, approximately 15.04 grams of air are needed to completely combust 1.0 grams of diesel fuel, therefore the stoichiometric ratio of mass of air to mass of fuel is 15.04 for diesel fuel. This is determined by first balancing a simplified chemical equation for combustion to find the number of moles of air necessary for complete combustion (combustion in which there is neither unburned fuel or unused air remaining in the combustion products). The comparison of the number of moles of air (oxygen plus nitrogen) times the molecular weight of air to the number of moles of fuel times the molecular weight of the fuel is thus the air to fuel ratio by mass for complete combustion, i.e., the stoichiometric ratio.

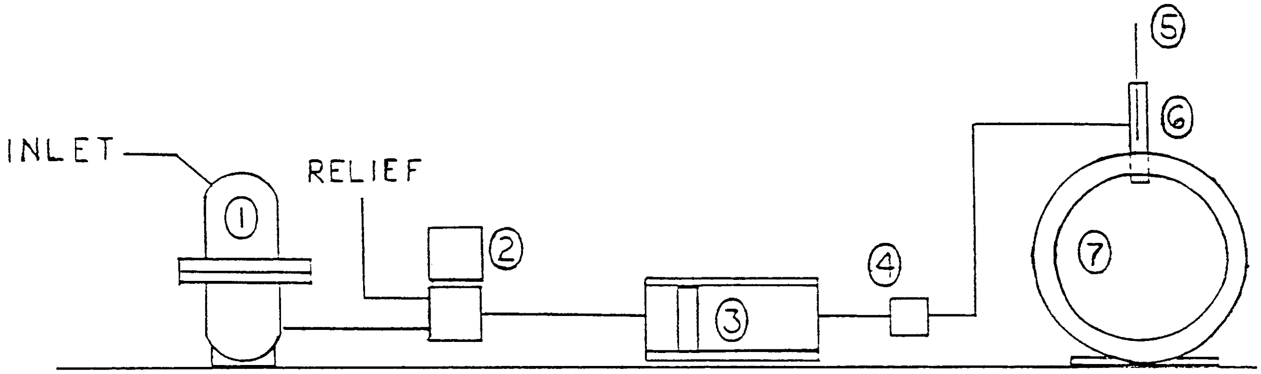
To determine the stoiciometric ratio for coal slurry, several assumptions/simplifications were made. It was assumed that only the carbon and the hydrogen in the coal actually reacted with the air, and that the remainder of the coal components had little effect on the reaction. The water in the slurry was also assumed to have little effect, merely passing through the equation to appear as water vapor in the combustion products. The stoichiometric ratio for the REI slurry was calculated to be 5.84:1 mass of air to the mass of slurry and for the AMAX slurries, 5.66:1. The slight differences between slurries is due to the slightly different chemical compositions of the coals used.

B. INJECTION / HIGH SPEED MOVIE TESTS

The basic injection system is shown in Figure 1. A constant pressure is applied on a working fluid through the inlet on the accumulator (element #1), up to a three-way D.C. solenoid valve (element #2). When the solenoid is energized, the pressure travels through the working fluid up to a free-floating piston (element #3) which separates the working fluid from the fuel to be

FIGURE 1

DIAGRAM OF THE INJECTION SYSTEM



injected. Consequently, the fuel is pressurized past a pressure transducer (element #4) into the injector (element #6) mounted on the top of the high-pressure bomb and causes the injector needle to lift. The needle lift is measured by a Hall-Effect needle lift sensor (element #5). The high-pressure stainless steel bomb (element #7) has a clearance of 1.0 inch and is 4.0 inches in diameter. Two 1.5 inch thick Pyrex windows allow for viewing and filming the injection spray.

1. The Bomb

The bomb was made of 304 stainless steel with a four inch diameter bore and a one inch clearance. A pyrex window was used on each side of the clearance volume to allow for viewing the injection and each was 4.75 inches in diameter and 1.5 inches thick. The bomb and windows were designed for testing up to 1500 psi internal pressure with an adequate safety margin. The windows were sealed with o-rings on the inside and were held in place from the outside with stainless steel flanges and teflon gaskets. The injector was mounted on the top of the bomb and nitrogen was used to pressurize the bomb.

2. The Injector and Nozzle

The injector used was a commercially available standard Robert Bosch injector (part # 0-431-201-021) with an opening pressure which was variable through the use of an adjustment screw. The nozzle used was an American Bosch ADN-4S-1 (single hole) pintle nozzle. It was chosen because it is both commonly used and relatively inexpensive. This last feature was deemed desirable because significant permanent nozzle clogging was foreseen which would necessitate replacement nozzles. Nozzle clogging did occur frequently but the nozzles were fairly easy to clean. This will be discussed in more detail in a later section.

With a pintle nozzle, the spray pattern is dependent on the shape, or flair, of the needle tip and the internal profile of the orifice. The present nozzle had a straight passage and therefore produced a narrow spray pattern. This nozzle was acceptable for comparison of atomization properties of the slurries and it was never intended to be the choice for optimal spray characteristics. Plans for future research include the design of a different nozzle expressly for coal slurry which will be optimized for atomization properties and spray pattern for the particular engine geometry.

3. The Needle Lift Sensor

A Hall-Effect "Microsensor" was used to record the needle lift of the injector. A samarian-cobalt magnet was mounted to the lower spring seat in the injector with high temperature epoxy. This spring seat rode directly on top of the needle and the resulting changes in the magnetic field with the needle movement were picked up by the sensor. The sensor itself was mounted through the leak-off fitting on the top of the injector. Actual distances as converted from the needle lift sensor were highly dependent on the initial distance of the end of the sensor from the magnet. However, the timing of the needle lift was most useful and the point where maximum needle lift occurred was clearly visible.

4. The Pressure Transducer

A Data Instruments AB-5000 pressure transducer with a maximum rating of 5000 psi was used to measure rail pressure in the fuel line prior to the injector for the injection tests.

5. The Solenoid Valve

A three-way 28 volt DC solenoid valve was used to control the injection pulse. It was commercially available from Circle Seal Corporation and was rated for 6000 psi applications. In a de-energized status, the injection rail line was open to atmospheric pressure via the normally open port in the solenoid. When energized, this port was sealed off and the pressurized port was opened to the injection rail line. The action of the solenoid lift itself imposed a minimum on the injection duration partly because of the pressure equalization of the three ports as the solenoid needle was lifting but not yet seated. Attempts to reduce the injection duration further than a certain value would simply result in a pressure rise at the injector insufficient to lift the injector needle. The relatively small passages in the solenoid valve led to clogging of the solenoid valve by the slurry and will be discussed in more detail in a later section. The o-rings, seats, and seals in the valve did not stand up to repeated use with coal slurry and had to be frequently replaced.

6. The Accumulator

The accumulator acted as a pressurized reservoir. It was made from 316 stainless steel schedule 80 pipe, 316 stainless steel schedule 80 end caps, and 150 psi 316 stainless steel flanges. The flanges had an additional four bolt holes drilled to make them eight hole flanges to prevent leakage through deflection of the flanges. The end caps and flanges were professionally vacuum welded to two short pipe sections in such a way that the accumulator could be taken apart at the middle. A 304 stainless steel stir shaft was installed through the top end cap and was sealed with a thrust bearing and two o-rings. This shaft was driven by a high-torque, low-rpm motor mounted to the outside of the accumulator. The original intent of this stir shaft was to keep the slurry agitated during periods between injection tests when the accumulator was not pressurized. In practice, this was necessary very few times as the accumulator was kept pressurized for the most part and later, the system was modified and slurry was replaced in the accumulator with another working fluid. The shaft seal though held very well.

7. The Piston Interface

This device was used to isolate the coal slurry from the solenoid control valve. It is a five inch long, 304 stainless steel cylinder flanged at each end enclosing a free-floating aluminum piston inside. The two inch diameter, one inch thick piston was sealed with an o-ring in a groove cut into the piston. The device was initially designed to be an interface between high pressure air and the fuel that was being injected. However, the increasing volume on the air side of the piston as the piston moved greatly effected the time that the fuel was actually pressurized, and injection durations shortened with each successive injection until the fuel was not pressurized long enough to lift the injection needle. The solution involved using the piston as the interface between two different fluids, the fuel being tested and another liquid. Diesel fuel was chosen as this other liquid because of its lubricative properties which would prolong the solenoid valve performance.

8. Valves and Tubing

Concern over possible leaking and clogging of the valves led to the choice of ball valves over other types due to the sweeping motion of the ball which would tend to clean the seats. The valves used in the injection system were two-way stainless steel ball valves rated to a maximum operating pressure of 6000 psi. They were supplied with Kel-F ball seats, Teflon stem packing and Teflon retainer seals. Throughout the testing, these valves did not leak, clog, or exhibit signs of excessive wear despite extensive testing with slurry.

The tubing used was stainless steel 1/4 inch (O.D.) tubing with a wall thickness of .035 inches. It was rated to a working pressure of approximately 6300 psi.

9. The Movie Camera and Lens

The movie camera used was a Hycam II 16mm motion picture camera operating on a rotating prism principle and was used with a Kern lens of 75mm f/1.9. The camera is equipped with an electronic speed control with an operating range of 20 to 11,000 full frames/sec. Kodak 4-X reversal film type 7277 (black and white) was used for all of the injection tests. With 100 feet long rolls of film, a frame rate of 6000 frames/sec was used as that was the fastest rate at which a essentially constant film speed was obtainable. A triggering signal was sent from the camera to correspond with this constant frame rate through the use of a built-in feature which converted electronic speed control tachometer pulses to feet of film that had passed through the camera. When the count reached a value corresponding to the selected triggering film footage determined from performance charts, the triggering signal was sent to the control system and the injection event would be started.

10. Lighting

Three 300 Watt lamps were used to provide sufficient light for the filming. The light from these goose-neck lamps was bounced off of a 98% reflective card positioned behind the bomb so that the filmed tests would be back-lit. Direct frontal lighting produced a picture that was inferior to those with back-lighting which showed density variations in the spray patterns very clearly.

11. Controls

Each injection test was begun by starting the movie camera. Based on acceleration graphs for the camera, the film length of 52 feet was used as the point at which the triggering signal was sent from the camera to the controller. A manual fire button could also be used to trigger the event for trial injections. The controller was a DCI preset counter comparator with which the duration of the energizing voltage for the solenoid valve was set. The minimum duration for which the solenoid could be energized and injection would still occur was approximately 70 to 80 milliseconds for the coal slurries, water, and diesel fuel. These minimum durations both resulted in injection durations of between

30 and 40 milliseconds. When the triggering signal reached the controller, a signal was also sent to the oscilloscope which triggered it to begin recording both the injector needle lift and the rail line fuel pressure.

12. Data Acquisition

The rail line fuel pressure trace and the injector needle lift trace were monitored and recorded on an oscilloscope which received an external trigger from the control system. Recorded simultaneously, these two signals were extremely useful in troubleshooting the system in the early stages of the testing. In the actual injection tests, the traces were a history of the event and a photograph was made of the oscilloscope screen to permanently record the traces.

13. The Air Compressor

A small, portable high pressure air compressor was used as the source of the injection pressure and was very convenient. It was capable of producing 5000 psi air at a flow rate of 3.0 cubic feet per minute and was equipped with self-relieving regulator.

14. The Rolling Mixer

A problem that must be faced when dealing with a slurry is that of settling of the solid matter. Because the REI coal slurry which was used extensively had in it relatively small amounts of chemical additives, it tended to settle out rather quickly. The ten gallon shipment settled to an almost impenetrable sludge on the bottom of the barrel before it was ready to be tested and had to be returned to the manufacturer for remixing. A rolling mixer was then constructed which could spin three, one gallon jugs of the slurry at 100 rpm thus keeping the slurry homogenous. The mixer was an arrangement of two parallel shafts padded with short sections of rubber hose on which the jugs rode. One of the shafts was driven by a small electric motor and the second shaft was driven off of the first with an o-ring belt.

C. INJECTION / STILL PHOTOGRAPHY TESTS

1. The Camera

The camera used to take the still photographs was specially designed at Arthur D. Little, Inc. to use three separate lenses simultaneously to photograph different areas of the bomb as the injection occurred. One lens had no magnification but was used to record a relatively large part of the spray for general observations about the overall spray. Two other lenses of 5:1 magnification were focused on smaller, but overlapping parts of the spray with one recording the image across the core of the spray and the other recording the image more at the edge of the spray. The lenses were separated by a series of baffles internal to the camera and thus provided three separate and distinct images of the injection on the film. A Graflock type holder was mounted at the back of the camera to hold a type 545 Land film holder. The film was Polaroid 4x5 Land Film type 55/positive-negative which provided both an immediate picture of the injection to determine if the injection was captured and a fine grain, high resolution negative from which enlargements were later made.

The camera was mounted on a jack stand and abutted one window of the bomb with a frontpiece that fit snuggly inside the flange on the bomb that held the window in place. It was focused by moving the entire camera closer to or further from the window while viewing through the back of the camera. A feature of the camera that was very important was that the lenses could be moved as a unit vertically, horizontally, or both with respect to the frontpiece so that photographs could be taken at various locations in the bomb (top, middle, bottom). The total travel of the lenses was approximately 2.5 inches.

2. The Light Source

Lighting for the photographs was provided by a 500 nanosecond Xenon flash tube. It was held in place on the opposite side of the bomb from the camera about 1.5 inches away from the outside of the window. A light diffuser with a diameter of approximately 1.5 inches was held in front of the flash tube against the window to provide a diffused back-lighting.

3. The Controls

The film was exposed not by the action of a shutter, but by the 500 nanosecond flash of light into an otherwise shrouded bomb. This meant that a delay circuit had to be employed to synchronize the flash with the injection event. This delay was designed at A.D. Little, Inc. and received its start signal from the "fire" button of the injection system controls. After the prescribed delay, a 15,000 volt pulse was sent to the flash tube circuitry and the 500 nanosecond flash occurred. The sensitivity of the adjustable delay control was such that the length of the injection had to be increased somewhat to ensure that the event was actually captured on film.

III. SLURRY HANDLING

Coal slurry must be handled in a way different from more conventional liquid fuels. Suspended in water, the slurry is a very fine dust that is subject to settling and which also can clog or partially clog almost any passage. Whereas most liquid fuels are basically uneffected by small amounts of evaporation when exposed to air, the water in coal slurry will evaporate and leave a slurry of a different composition or worse, coal sludge. Another significant problem that coal slurry creates in the fuel injection system is that of wear. The following sections will discuss problems and solutions found in the handling of coal slurry.

A. SETTLING

The REI slurry was received just over one month before the injection system was completed and therefore was stored and undisturbed for that time. The settling that occured was so severe that manual mixing was impossible and mechanical mixing was very difficult. The entire sample had to be returned to the manufacturer for remixing which involved mechanical stirring with a large propeller at a high speed for several hours. This settling exhibited the need for a device that could mix the slurry on a daily basis. The rolling mixer was then designed to meet this need by spinning one gallon jugs of the slurry at about 100 rpm. The jugs of slurry were stored on their sides so that any settling that did occur would be remixed by the spinning action of the slurry itself. If done daily, fifteen minutes of spinning would keep the slurry in its original state, and approximately thirty minutes of spinning would negate a weekend's settling. The AMAX slurry had larger amounts of stabilizers added to them and did not exhibit settling as quickly as the REI slurry did. A thorough mixing on the rolling mixer once or twice a week was sufficient to keep the samples homogenous.

B. CLOGGING

In general, clogging occurred in small passages in which the slurry had to lay for any period of time. The clogging mechanism appeared to be one in which the coal particles in the slurry agglomerated along the walls and eventually blocked the passage, a process distinctly different from slurry drying. Most of the clogs could be dislodged with running water and a thin piece of wire, but could definitely not be dislodged by trying to operate the system with a higher pressure.

The most critical clogging occurred in the nozzle. Initially, it was observed that clogs built up around the needle tip of the pintle nozzle and caused the needle to become seized in the nozzle body. Once the needle was seized, the clogs built up through the three fuel ports in the nozzle and sometimes into the injector body. Clogging of this type was eliminated for the most part by increasing the diametric clearance between the nozzle body and the needle by .001 inches. Nozzle clogging continued to occur after the modification but was not as frequent, and then only after slurry sat in the injector and nozzle for a period of time. With the REI slurry, this period of time was approximately 5-7 minutes whereas with the AMAX slurries the period of time extended to well over one hour.

Clogging also occurred regularly in the solenoid valve due to the small passages internal to the valve mechanism. Again, clogging appeared to be the result of the water being displaced by coal particles. This problem was alleviated only by changing the injection system so that slurry would not have to pass through the solenoid valve. This was accomplished by employing a two-fluid system in which diesel fuel was used as a sort of hydraulic fluid to relay the injection pressure to the slurry via a free-floating piston interface.

C. DRYING

Drying only ever appeared to occur when the slurry was actually exposed to open air for a short period of time such as when the clogs were being removed from the nozzle and the tubing to which the injector was attached was exposed to the air. With great care, a short application of pressure could clear the plug of dried/partly dried slurry from the end of the .25 inch tubing if the tubing had only been exposed for a short time. If left exposed to the air for an extended time (1/2 hour or more) running water and manual extraction was required.

D. WEAR

The abrasiveness of the coal particles in the slurry created wear problems in both the nozzle and the solenoid valve. The noticeable wear in the nozzle occured in the seat between the needle and the nozzle body. Excessive wear was deemed to have occurred when the pressurized nitrogen in the bomb forced its way up into the nozzle and displaced the slurry from the inside of the nozzle and injector. Close-up inspection of the needle seat showed pits and scoring, and although inspection of the seat inside the nozzle was impossible, it is plausible to assume that it was equally worn.

Significant wear was also observed in the solenoid valve when slurry was routinely passing through it. The wear manifested itself when the valve seals and seats allowed the slurry to leak through the valve. Inspection showed that although the stainless steel valve was in perfect condition, the soft, rubber seats were missing large pieces. Also the several o-rings used as seals inside the valve were frequently observed to be missing large scallop shaped chunks. These could have been caused by abrasion due to the coal particles, but were more likely caused in the installation of the o-rings as they were slid past the several ports in the valve housing. The frequent clogging of the solenoid valve resulted in frequent removal and reinstallation of these o-rings which only increased the risk of damage to them. This problem was eliminated when the slurry was removed from the solenoid valve in favor of the two-fluid injection system.

IV. PROCEDURES

A. INJECTION / HIGH SPEED MOVIE TESTS

1. Test Matrix

Three different injection pressures were used along with three different bomb pressures for the series of injection tests which were conducted. These tests were filmed using the high speed camera. The injection pressures were 2000 psi, 3000 psi, and 4200 psi and were chosen to cover a wide range of pressures within the limits of the injection system. The bomb pressures were chosen to be atmospheric pressure, 600 psi, and 1400 psi (pressurized with nitrogen at room temperature) to cover a large range of chamber environment densities (1.1 kg/m^3, 47.8 kg/m^3, and 107.9 kg/m^3 respectively). The first series was done with the REI slurry at the selected conditions and looked very promising. Differences in spray pattern were noticeable and the time required for the injection to penetrate to the opposite wall varied with the injection pressure. These results will be discussed in a later section.

A baseline series was done for the same test conditions with No.2 diesel fuel because much is known about injection of diesel fuel and a second baseline series was done with water for a direct comparison with the water-based coal slurry. The three AMAX slurries with the various viscosities were only tested at two conditions for a simple comparison with REI slurry. A complete test matrix is shown in Table 2.

2. System Evolution

The injection system underwent two major modifications as injection tests were being done. The modifications had no effect on the actual injection of the slurries, water, or diesel fuel, but had significant effect on the repeatability and reliability of the system as a whole and are worthwhile discussing.

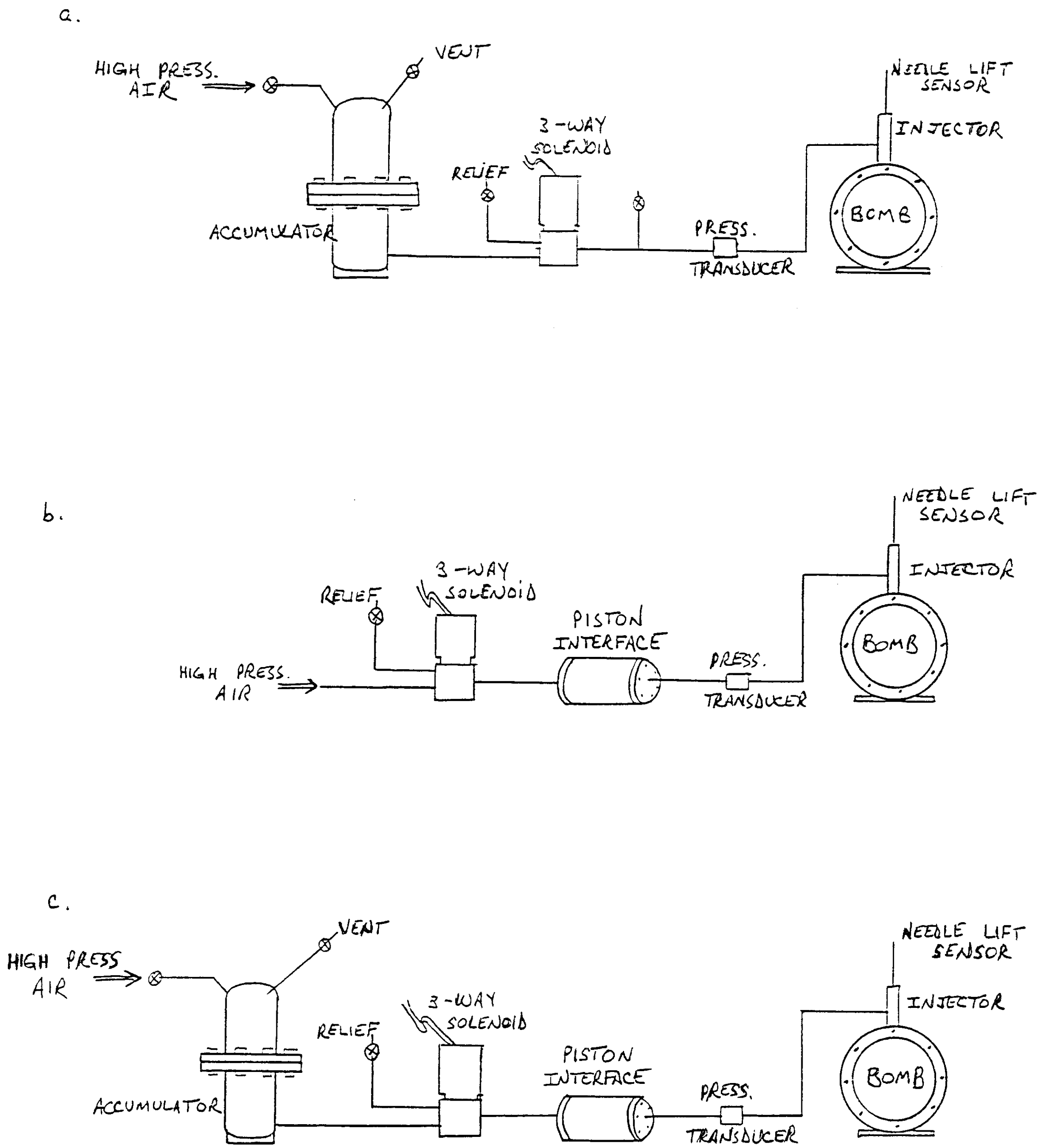
Figure 2a. shows the original system in which slurry was constantly pressurized to injection pressure in the accumulator and tubing up to the normally closed port in the solenoid valve, and additional slurry filled the tubing up to the nozzle. When the solenoid valve was lifted and sealed off the relief port (normally open), the pressure traveled through the tubing to the nozzle tip and built up until a pressure was reached high enough to lift the needle and cause an injection. When the solenoid valve was dropped, the pressure was relieved through the relief port (normally open) and the injection

TABLE 2

	atmospheric bomb	600 psi bomb	1400 psi bomb
2000 psi injection	REI slurry	REI slurry water Diesel fuel	REI slurry water Diesel fuel
3000 psi injection	REI slurry AMAX A,B,C	REI slurry water Diesel fuel AMAX A,B,C	REI slurry water Diesel fuel
4200 psi injection		REI slurry water Diesel fuel	REI slurry water Diesel fuel

FIGURE 2

INJECTION SYSTEM EVOLUTION



was halted. The problem with this system was clogging and wear of the solenoid valve. The clogging was very frequent and was very time consuming to remove.

The solution was to redesign the system so that slurry did not have to be in or pass through the solenoid valve. This was done by using a two-fliud system with a free-floating piston interface to separate the two fluids. The high pressure air source was plumbed directly to the normally closed port of the solenoid where the pressurized slurry had previously been as shown in Figure 2b. When the solenoid valve was lifted, the pressure would build up on the air side of the piston causing the piston to travel the short distance necessary until the pressure was equalized on the opposite side which was filled with slurry. The resulting pressure increase in the rail fuel line would cause the needle to lift and injection to occur. The closing of the solenoid valve would relieve the pressure on the air side of the piston which would again move and equalize the pressure on the slurry side. An initial normal injection would be followed by successively shorter injections until the pressure pulse was not long enough to cause a pressure rise at the needle tip sufficient to lift the needle. The problem was simply that with each injection, the piston was translated a small but finite distance which increased the volume of the cylinder that had to be filled with air on the following injection attempt.

Since the solenoid valve lift time was kept constant, the increased time required to build up sufficient injection pressure on the air side of the piston resulted in a shorter time of injection. A possible solution would have been to alter the solenoid valve lift time with each injection, but this would have been imprecise and repeatable injections would have been impossible.

A better alternative was to replace the air side of the system with a fluid, and diesel fuel was chosen because it would also keep the internal seals of the solenoid valve lubricated. The system is shown in Figure 2c. that was used successfully for a large number of injection tests. Diesel fuel was pressurized in the accumulator as slurry had been in the initial setup and diesel fuel also filled the system up to the piston interface although at atmospheric pressure. The lifting of the solenoid pressurized the diesel fuel and in turn the piston interface which increased the pressure on the slurry up to the nozzle and injection occurred as usual. Pressure was relieved on the diesel fuel through the relief port of the solenoid valve the same as it had been when slurry and then air was used.

When the bomb was first pressurized with nitrogen, the windows fogged up completely. This minor problem was corrected by drilling a second hole in the bomb which could be capped and through which nitrogen was allowed to pass removing the moist air prior to actual pressurization.

3. Method

The high speed movie camera was set up prior to filling the injection system. The camera was mounted on a very heavy, sturdy base to prevent movement during operation due to the high torque of the film drive motor and once the gross location and height adjustments were made, the base was not moved. The camera was focused on a plane approximately in the middle of the clearance between the bomb windows, but at a distance of four feet and with a 75mm lens, slight distance discrepancies were not important. The magnification was such that the whole bomb (4 inch inside diameter) covered roughly the full field of view. The focus was rechecked between injection tests because the bomb was frequently bumped as it was being cleaned after an injection. The film was loaded into the camera next and the camera was ready.

It was easiest to use the injection system when starting with it completely empty of all working fluids. To use the system, all of the air in the system had to first be evacuated. The vacuum was first applied to the slurry side which also sucked the free floating piston to its limit on that side. With the vacuum sealed on that side, the valve to the slurry supply was opened and slurry was sucked into the system. The vacuum was then shifted to the diesel fuel side and with the valve to the slurry supply still open, the free floating piston was sucked to its limit on the diesel fuel side pulling additional slurry into the system and filling it. With a vacuum sealed on that side, the valve was opened to the accumulator which was filled with diesel fuel which was allowed to fill the vacuum on its side of the piston. At this point, the system was completely filled with the two working fluids with no pockets of air present. To check the system, several injections were always made prior to every test shot ensuring that there were no clogs and that the pressure rise in the fuel rail line was that which was set at the air compressor regulator. These test injections were made into open air outside of the bomb. If the system was operating correctly, the injector was then bolted into the side of the bomb and the bomb was pressurized with nitrogen to the desired density.

The delayed signal from the camera triggered the injection and the camera was started by switching the remote camera switch to the "on" position.

After the injection was completed and the camera had stopped, the bomb was depressurized, a window was removed and the slurry was cleaned from the inside of the bomb. With the window replaced and a new roll of film in the camera, the system was again ready provided no clogs had formed in the meantime.

4. Other Instrumentation

The pressure trace in the rail fuel line and the injector needle lift were monitored and they were very useful in determining where the problems were in the system. For example, an incomplete pressure rise in the fuel rail line could either have been due to the presence of air on one or both sides of the piston interface, or possibly due to the piston having reached the limit of its travel. A complete pressure rise in the fuel line with no needle lift or only a very short uneven needle lift meant that the injector and/or nozzle were clogged. The duration of the needle lift (the injection time) was closely observed because problem-free injections were very repeatable and thus different durations for successive injections signalled trouble.

B. INJECTION / STILL PHOTOGRAPHY TESTS

1. Test Matrix

The most extensive testing with the still photography apparatus was done with the AMAX A slurry because more information was known for the AMAX slurries than the REI slurry such as exact additive amounts and also the relationships for those slurries between shear stress and shear rate over a wide range of shear rates. Tests with the AMAX A slurry were conducted with the bomb pressurized to 600 psi with nitrogen and injection pressures of 3000 and 4200 psi to compare droplet size differences due to different driving pressures. The location of the three lenses also was varied from top to bottom within their travel limits which amounted to just over one inch in either direction from the center of the bomb window. Several tests were also conducted with the AMAX B slurry at an injection pressure of 3000 psi and a bomb pressure of 600 psi to compare droplet size differences between slurries essentially identical except for their viscosities (AMAX A - 580cp, AMAX B - 260cp). A complete test matrix is shown in Table 3.

2. Method

For the still photography tests, the slurry injection system was unchanged from the earlier high speed movie injection tests. Prior to the first injection, the still photography camera was positioned and focused on the center plane of the clearance between the bomb windows. The distance from the camera body to the bomb flange was noted and for subsequent injection tests, the camera was returned to this distance and

TABLE 3

	near top of bomb	at middle of bomb	near bottom of bomb
AMAX A 3000 psi inj. 600 psi bomb	2 tests	3 tests	2 tests
AMAX A 4200 psi inj. 600 psi bomb	1 test	1 test	
AMAX B 3000 psi inj. 600 psi bomb	1 test	1 test	1 test

refocusing for each shot was not needed. For each test, the film was loaded into the Land film holder and the holder was then placed in the camera's Graflock holder. The film was exposed just prior to the injection by removing the film cover. As mentioned earlier, the flash tube was triggered from a delay circuit operating off of the injection system "fire" button, and it was this flash that provided the light for the capture of the injection on film. After the injection was over, the film cover was replaced and the film was developed according to the manufacturer's instructions. The bomb was then cleaned, new film was loaded, the vertical position of the lenses was adjusted if desired, and the system was ready for another test pending developed clogs.

V. RESULTS AND DISCUSSION

A. HIGH SPEED MOVIES

1. Spray Penetration Analysis

Tracings of the visible fuel jet boundary were made every few frames for each movie from the start of injection until the spray impacted the opposite wall of the bomb. From these tracings, graphs were made of the time history of the penetration distance of the spray. Typical penetration histories are shown in Figure 3. Samples from several movies are shown in Plate 2. A tangent is fitted to the early part of the tip penetration trajectories to obtain an initial velocity of the spray. This velocity is correlated to the injection pressure and the bomb pressure.

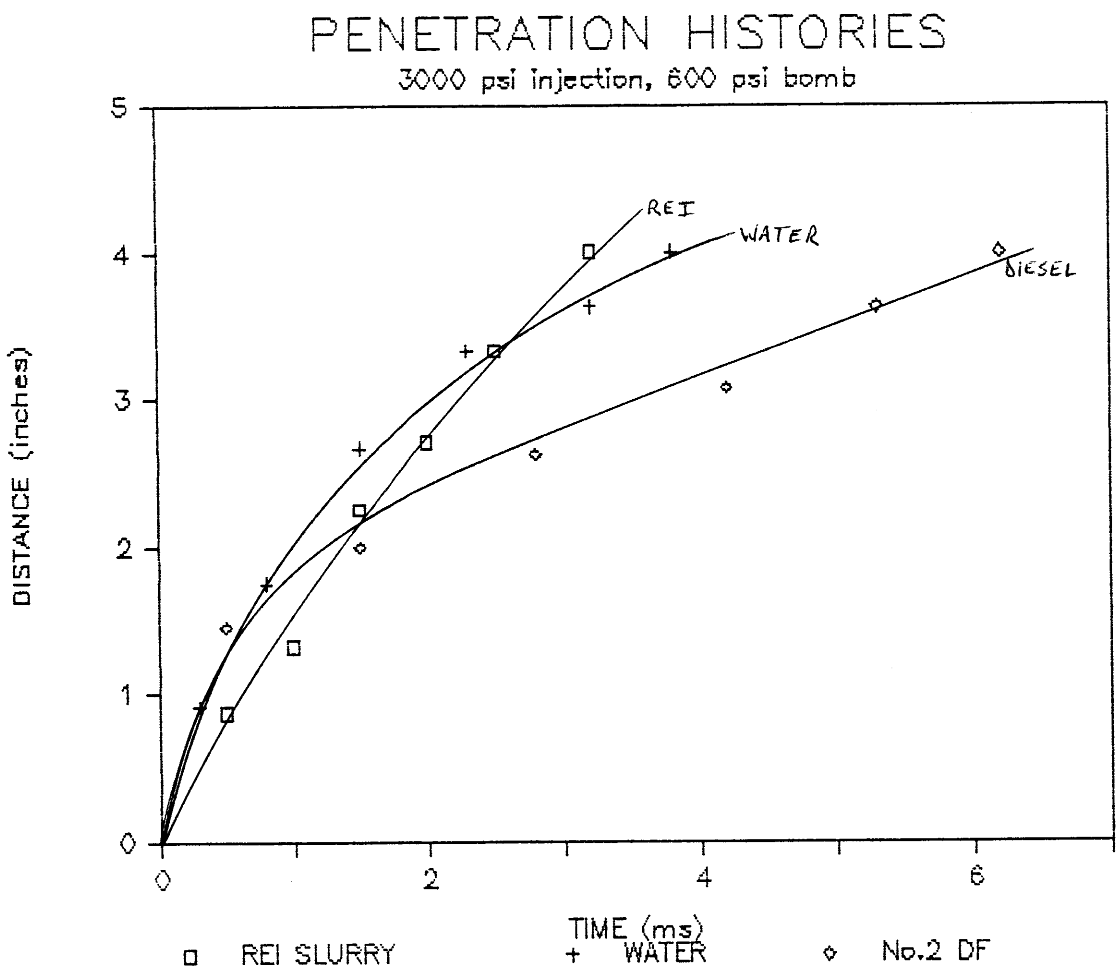
The injection velocity for liquid fuel injection may be correlated in the form of

$$U_{inj} = KU_o$$
$$U_o = [\ 2(P_{inj} - P_{bomb})/\rho\ ]^{½}$$

where: U_o is the theoretical initial velocity for an idealized flow with no head loss,

FIGURE 3

TYPICAL PENETRATION HISTORIES



P_{inj} is the injection pressure,

P_{bomb} is the pressure in the bomb,

p is the density of the fuel being injected,

K is a flow coefficient depending on nozzle geometry

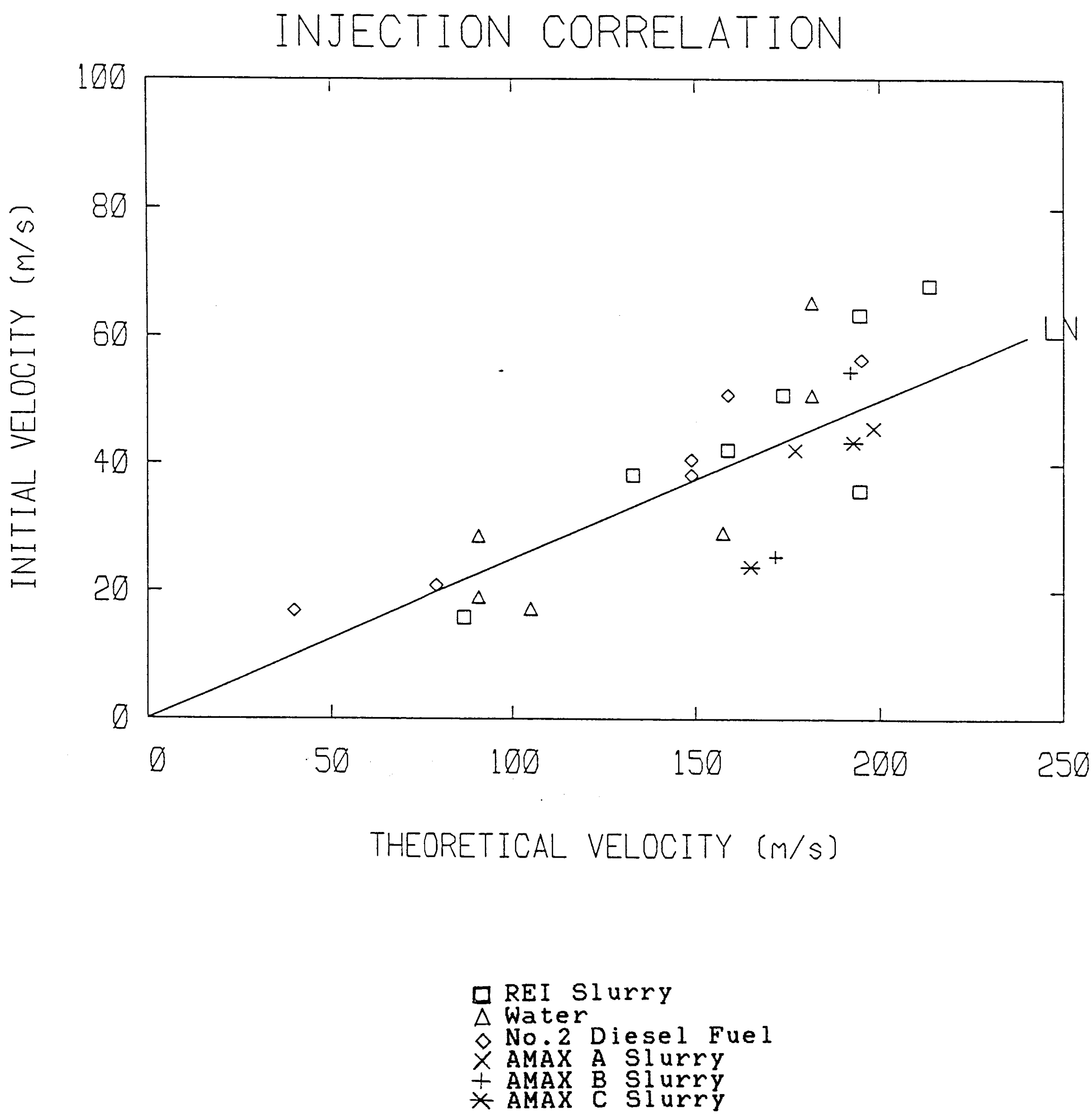
For a high enough jet Reynolds Number (Re > 10^4, based on jet velocity and orifice diameter), the value of K is approximately constant, and therefore the injection velocity is not sensitive to the viscosity of the fuel. The validity of this correlation as applied to coal slurry is examined here.

The initial velocities from the movies and the corresponding values for U_o obtained from the injection conditions were plotted against each other in Figure 4. The experimental values cover a wide range of fuel types, injection pressures, and bomb pressures. It can be seen that the injection velocities for REI slurry, water, No.2 diesel fuel, and the AMAX slurries for the range of injection conditions fall along the same line,

$$U_{inj} = .25(2(P_{inj}-P_{bomb})/p)^{½}$$

The particular value for the flow coefficient (0.25 in this case) is dependent on the nozzle internal geometry, and would be different for different nozzles. More significantly, however, is the existence of such a correlation. This is because such a correlation would

FIGURE 4


INJECTION CORRELATION
INITIAL VELOCITY (m/s)
100
80
60
40
20
0
0
50
100
150
200
250
LN
THEORETICAL VELOCITY (m/s)
REI Slurry
Water
No.2 Diesel Fuel
AMAX A Slurry
AMAX B Slurry
AMAX C Slurry

enable the injection velocity of coal slurry to be calculated if the corresponding velocity for diesel fuel injection is known for the particular injector. Much of the latter is known by the injector/nozzle manufacturers who have extensive data bases on the flow of diesel fuel through their nozzles. The amount of coal slurry injected based on the U_{inj}, the orifice size, and the injection duration is consistent with experiments conducted in which the slurry from an injection was actually collected and weighed.

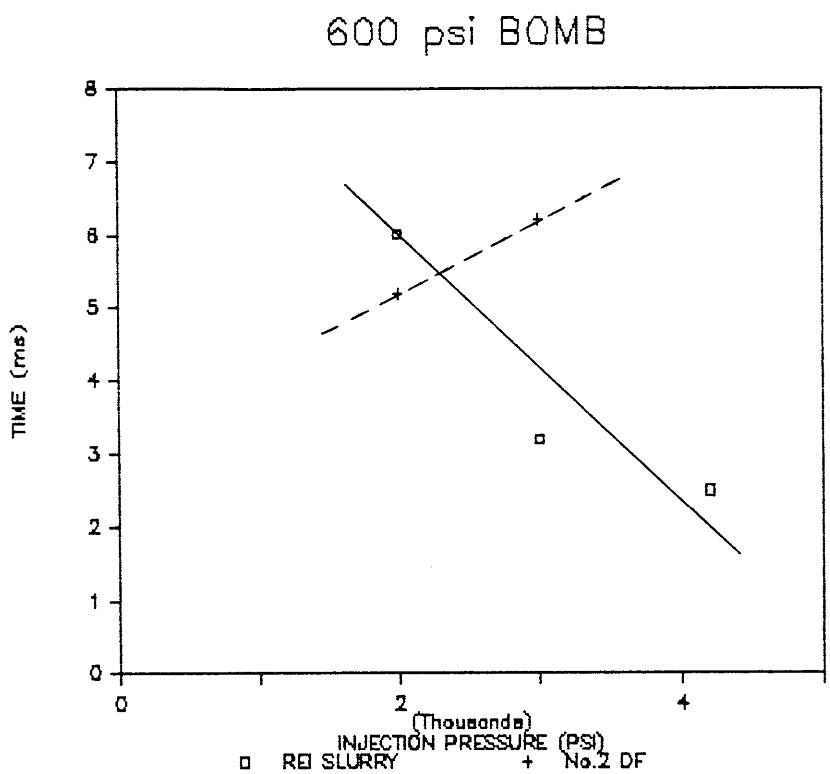
2. Penetration Times

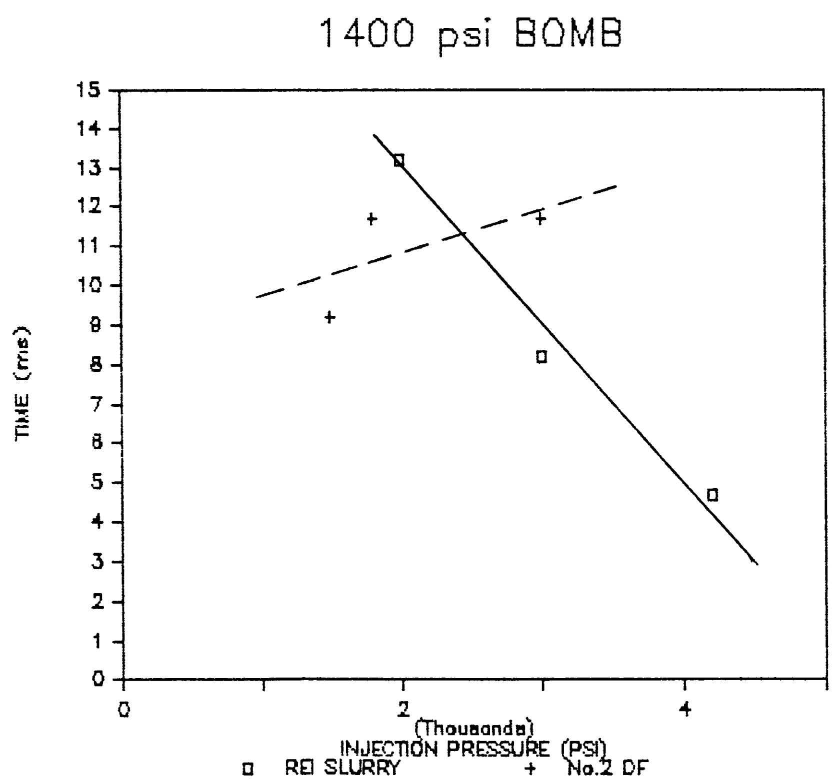
The time for the spray to penetrate the distance across the bomb and impact the opposite wall is a rough indication of how well the spray is being atomized. Sprays that penetrate more slowly can be said to be better atomized as smaller droplets have much faster momentum transfer with the ambient fluid, and tend to be effected more by the dense environment in the bomb. The data was analysed to view the effects of injection pressure and bomb pressure on the spray penetration and comparisons were also made between the fuels tested.

With the bomb pressure constant, increasing the injection pressure decreased the time for complete penetration monotonically for the REI slurry. The results are shown in Figure 5. For No.2 diesel fuel, increasing the injection pressure had the opposite effect, with the time of penetration increasing as the injection pressure was raised. These results may be explained in terms of the atomizing properties of the fuels. The time to penetrate a fixed distance depends on the initial spray velocity and the rate of momentum transfer of the fuel droplets to the charge air. For the diesel spray, the initial injection velocity increases with the pressure drop across the nozzle, but the resulting atomization yields much finer droplets. The much faster momentum loss of the fine droplets to the charge air overpowers the increase in initial velocity, and the overall penetration time increases. For the coal slurry spray, the surface energy that holds the drop together is much larger than that of the diesel droplet of the same size. This is because of the surface tension difference between diesel fuel and water, and more importantly, the significant presence of the extra liquid-coal particle interface. As a result, the droplets are rather large, and they do not exchange momentum readily with the charge air. The penetration time would, therefore, be mainly dependent on the initial velocity. With an increasing nozzle pressure drop, therefore, a shorter penetration time is obtained. An interesting note is that there appears to be a certain injection pressure ($\approx$ 2300psi) below which diesel fuel

FIGURE 5

PENETRATION TIME VS INJECTION PRESSURE





penetrates faster than the slurry and above which slurry penetrates faster in both the 600 psi bomb and the 1400 psi bomb. Increasing the injection pressure appeared to have no effect on the penetration time of water which is likely the result of slightly increased atomization sufficient enough to slow the droplets and partially overcome the larger initial velocity thus resulting in what appears to be a constant penetration time independent of injection pressure.

For a constant injection pressure, the times for the sprays to penetrate to the opposite wall increased as the pressure in the bomb increased for each fuel and water tested. These results were expected as a denser environment would invariably slow the penetration of a spray through it.

No trend in the penetration time could be seen between the three AMAX slurries each with a different viscosity. The AMAX slurries were essentially comparable to the REI slurry as far as the penetration time is concerned. However, based solely on observations of the high speed movies, the AMAX slurries did not appear as finely dispersed as the REI slurry did. This difference was most likely due to the differences in additives in the two slurries. The REI slurry had no stabilizer added - a gel-network forming additive to retard settling - and consequently appeared to atomize better. Unfortunately though, the REI slurry settled very quickly and was therefore much more difficult to work with.

3. The Cone Angles

The full cone angle was measured for each injection directly from the high speed movies at a point in the injection after the spray had initially impacted the wall and while the spray was still at a steady state. Generally, increasing the bomb pressure tended to increase the cone angle at a given injection pressure for all of the fuels tested. This tendency also explains why the penetration time increased with increasing bomb pressure. The denser the gas in the bomb, the more gas becomes entrained in the spray which both widens the spray (cone angle) and consequently slows it.

The AMAX slurries appeared to have larger cone angles than the REI slurry at identical conditions, but as with the penetration times, no trend was observable based on the viscosity differences of the three AMAX slurries.

As with the effect of injection pressure on the cone angle analysis, the overall cone angle analyses were subject to considerable data scatter and were relatively inconclusive. This may have been caused to a large extent by the nozzle with which the tests were conducted. The ADN-4S-1 nozzle was not designed to produce a spray with a large cone angle and therefore may not have produced marked differences in the cone angles of the various fuels and at the various conditions tested.

B. STILL PHOTOGRAPHS

The droplet sizes were manually measured and counted for each of the higher magnification still photographs which were enlarged to 20 times actual size. Representative photographs are shown in Plate 3. In general, the results showed that the atomization of the slurry was poor with the largest percentage of droplets in the range of 50-75 microns. In addition to a numerical average, a mass average was calculated for each still photograph as the mass average reflects the importance of the volume and thus the mass of the particle. These are shown in Table 4. The particles mass will ultimately determine the amount of water in each droplet that will have to be evaporated before the coal can begin to combust. As was clearly seen in the lower magnification pictures, the majority of the injected fuel did not form droplets at all but remained in a fairly concentrated core and traveled relatively straight down until contact was made with the opposite wall.

TABLE 4

SLURRY	INJECTION CONDITIONS inj/bomb psi	APPROXIMATE BOMB LOC.	NUMERICAL AVERAGE microns	MASS AVERAGE microns
AMAX A	3000/600	TOP	55	72
AMAX A	3000/600	TOP	50	61
AMAX A	3000/600	MIDDLE	63	83
AMAX A	3000/600	MIDDLE	65	98
AMAX A	3000/600	MIDDLE	81	112
AMAX A	3000/600	MIDDLE	58	86
AMAX A	3000/600	MIDDLE	67	84
AMAX A	3000/600	MIDDLE	71	96
AMAX A	3000/600	MIDDLE	65	86
AMAX A	3000/600	BOTTOM	78	101
AMAX A	3000/600	BOTTOM	76	96
AMAX A	4200/600	TOP	74	109
AMAX A	4200/600	MIDDLE	90	120
AMAX A	4200/600	MIDDLE	62	89
AMAX B	3000/600	TOP	53	71
AMAX B	3000/600	MIDDLE	70	86
AMAX B	3000/600	MIDDLE	64	82
AMAX B	3000/600	BOTTOM	98	120

From comparisons of identical slurries under identical conditions, it was observed that the average particle size in the injection increased from near the top of the bomb, through the middle of the bomb, to near the bottom of the bomb. This was not the result of the smaller droplets agglomerating, but was the result of some of the slurry that was in the tight core near the top diffusing outward and forming relatively large droplets during the course of the injection.

Particle size distributions were plotted for each photograph to aid comparisons of the droplet sizes in the spray. These are enclosed in Appendix B. The size distributions did not vary appreciably from the AMAX A slurry to the AMAX B slurry at any of the three locations where still photographs were taken. This finding was in general agreement with other results which found no significant difference in spray characteristics attributable to the different viscosities of the slurries.

VI. CONCLUSIONS

1. Diesel injections of coal-water slurry with identical pressure traces and needle lift traces are possible with a standard diesel injector to which only minor modifications were made.

2. The injection velocities at the nozzle exit may be correlated to the pressure drop across the nozzle and the density of the fuel. The correlation was found to be uniformly valid for No.2 diesel fuel, coal-water slurry, and water from a standard diesel injector. For the particular nozzle used, the correlation is in terms of a flow coefficient of 0.25.

3. Most of the slurry injected did not atomize well and remained in the relatively tight core. That part of the injection that did atomize had a mean droplet size in the range of 50-70 microns.

4. The droplet size distribution of atomized coal-water slurry does not appear to be effected by increasing injection pressure.

5. There was no significant difference and no trend in comparisons of the spray properties of the three AMAX slurries of different viscosities.

VII. FUTURE RESEARCH

There are several recommendations for further research to be done in the area of the use of coal-water slurry in diesel engines. Not the least of these recommendations is an in-depth study of the effects of chemical additives on the atomization properties and surface tension of the slurry. The atomization is crucial for combustion to occur even with a pilot injection, yet indications from this work show that a fundamental trade-off may exist between the need for good atomization and the need to be able to handle the slurry without excessive settling and clogging problems. More extensive testing needs to be done to clarify the observation in this work that the viscosity of the slurry has little effect on the atomization of the slurry. Surface tension and chemical additives may have more impact on the atomization than previously believed.

Combustion tests are the next step for the slurry and tests are being planned on the Rapid Compression Machine at M.I.T. A new injector and a new nozzle need to be designed which will provide the necessary flow rates for coal-water slurry and which take into account the clogging tendencies of the slurry. Relatively large openings and passages along with large clearances between moving parts are almost necessities.

Finally, bomb injection tests with multi-hole type nozzles should be conducted to note the differences and similarities of the injection properties of these two types of nozzles as multi-hole nozzles will eventually be used in actual engine tests.

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APPENDIX A

PLATES

1. Injection system
2. High speed movie comparison

   Film clips are in the following order from left to right: AMAX B Slurry, REI Slurry, Water, No2. Diesel Fuel. All were taken at identical conditions of 3000 psi injection pressure and 600 psi bomb pressure.

3. Droplet Still Photographs

   #1. 3000psi injection/600psi bomb, AMAX A, top

   #2. 3000psi injection/600psi bomb, AMAX A, middle

   #3. 3000psi injection/600psi bomb, AMAX A, bottom

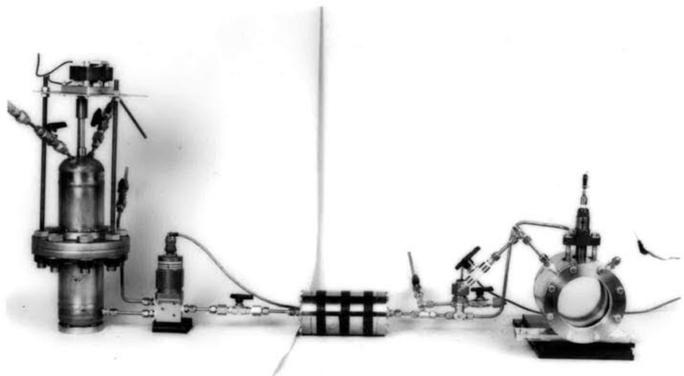
   #4. 3000psi injection/600psi bomb, AMAX B, middle

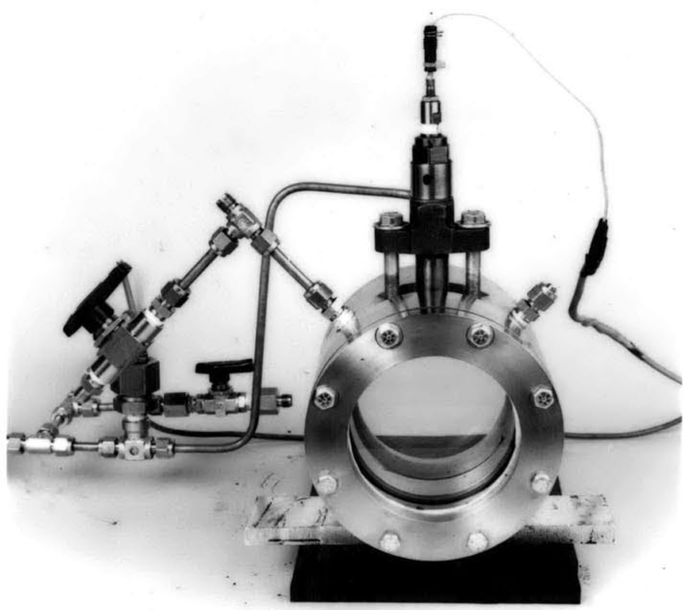
   NOTE: Scale on Droplet Still Photographs is

   1 inch = 2120 microns

   0.02 inch $\approx$ 42 microns

PLATE 1





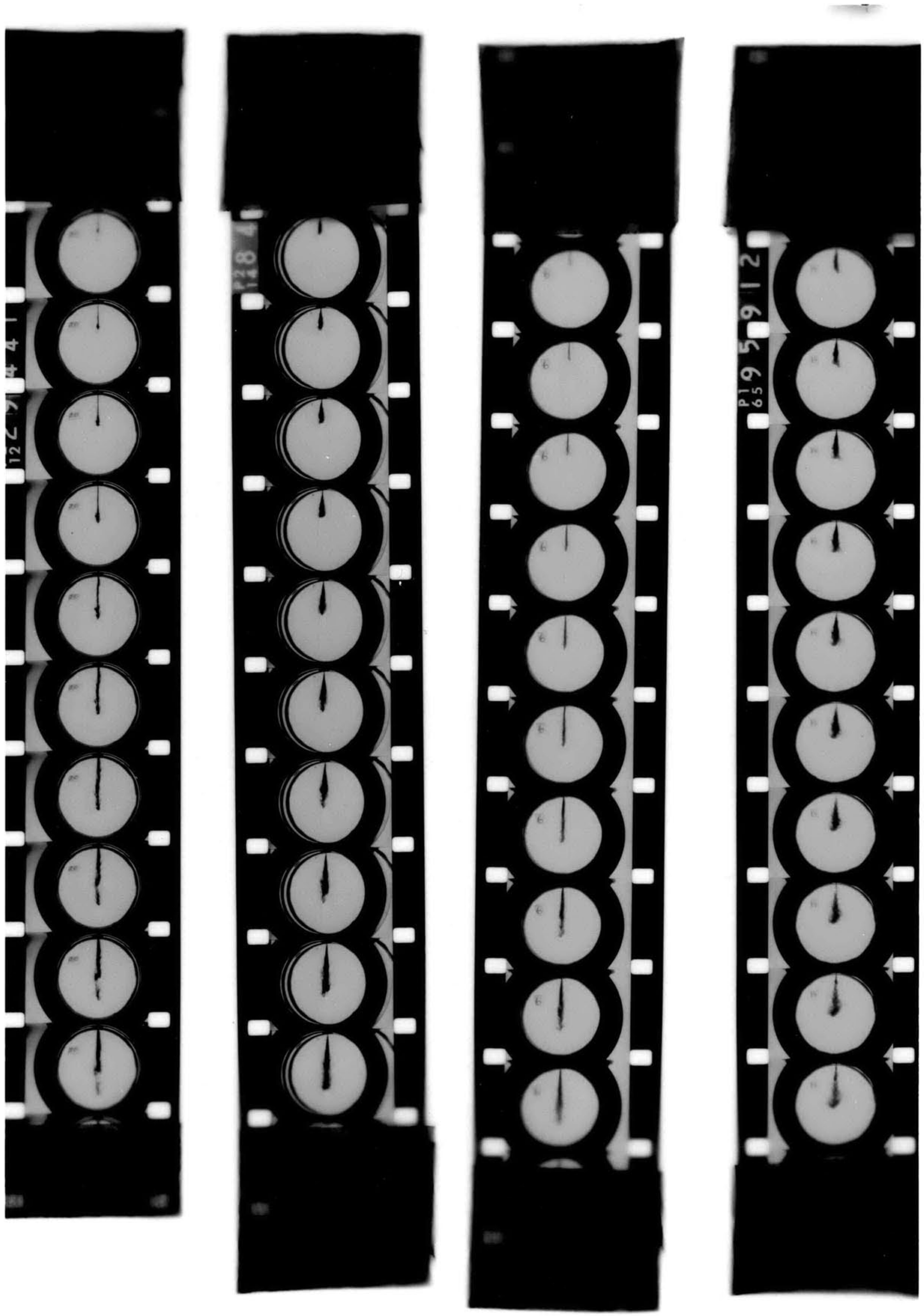


PLATE 3, #1

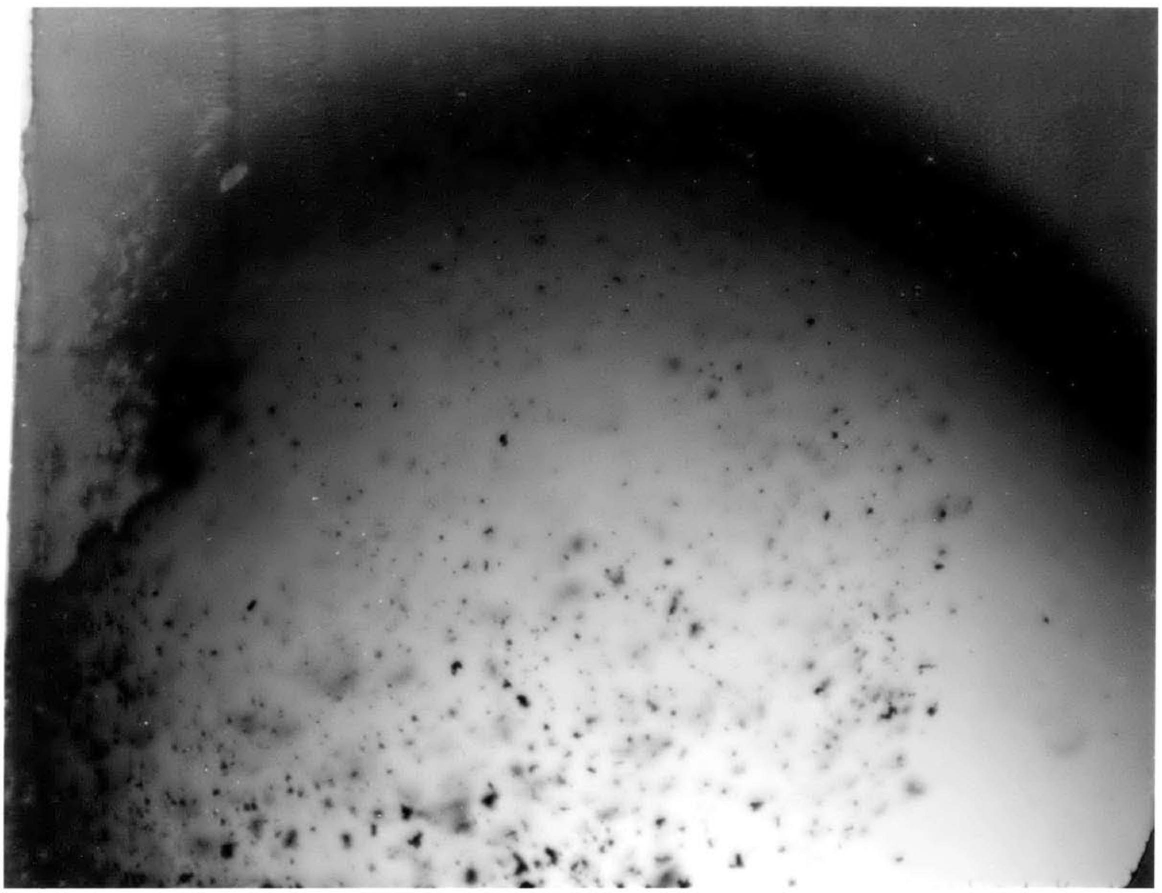
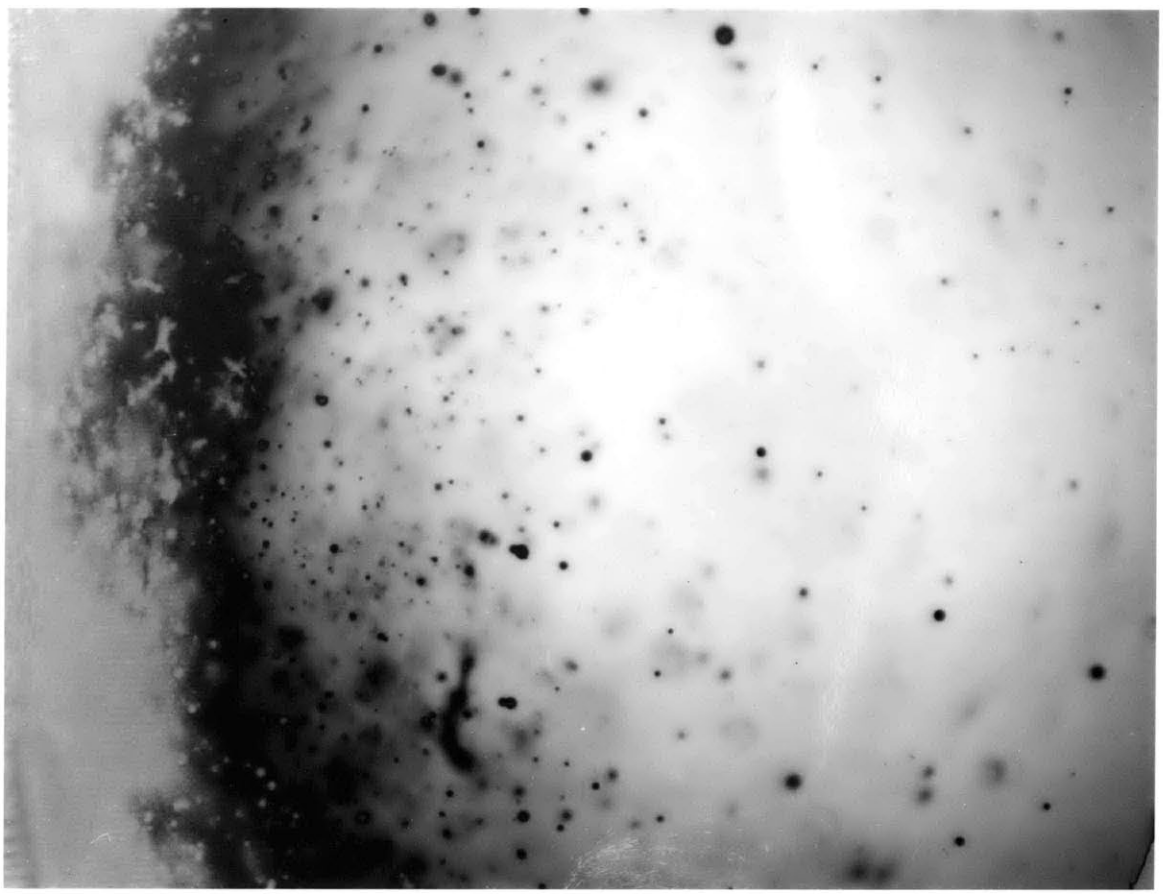


PLATE 3, #2

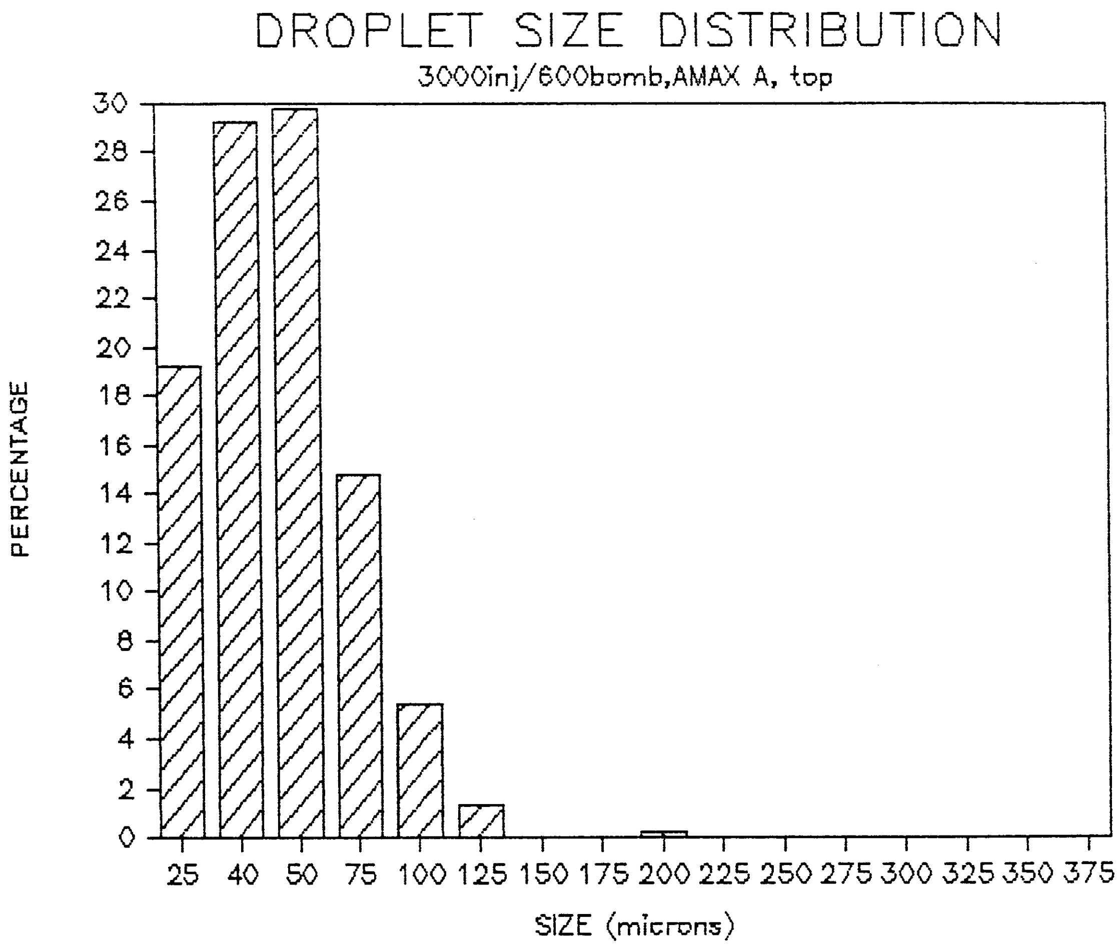
PLATE 3, #3

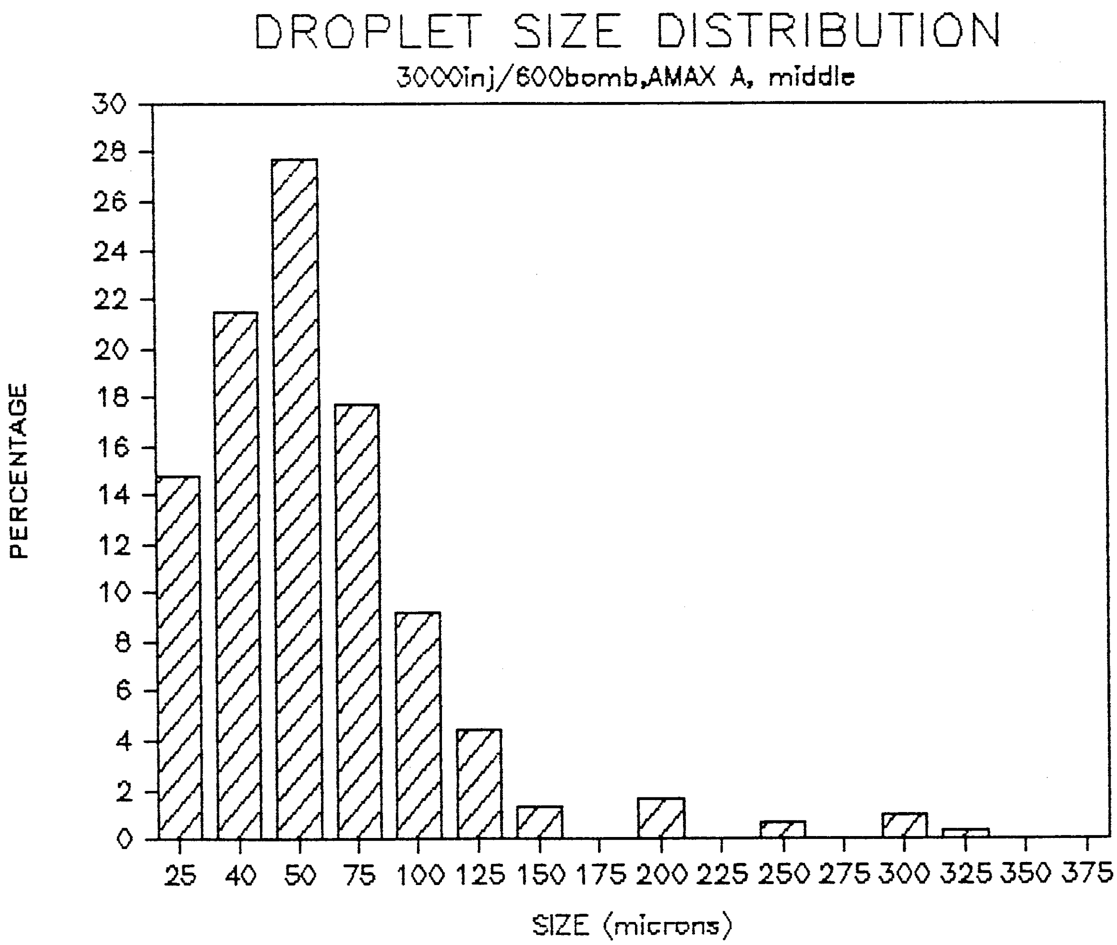
PLATE 3, #4

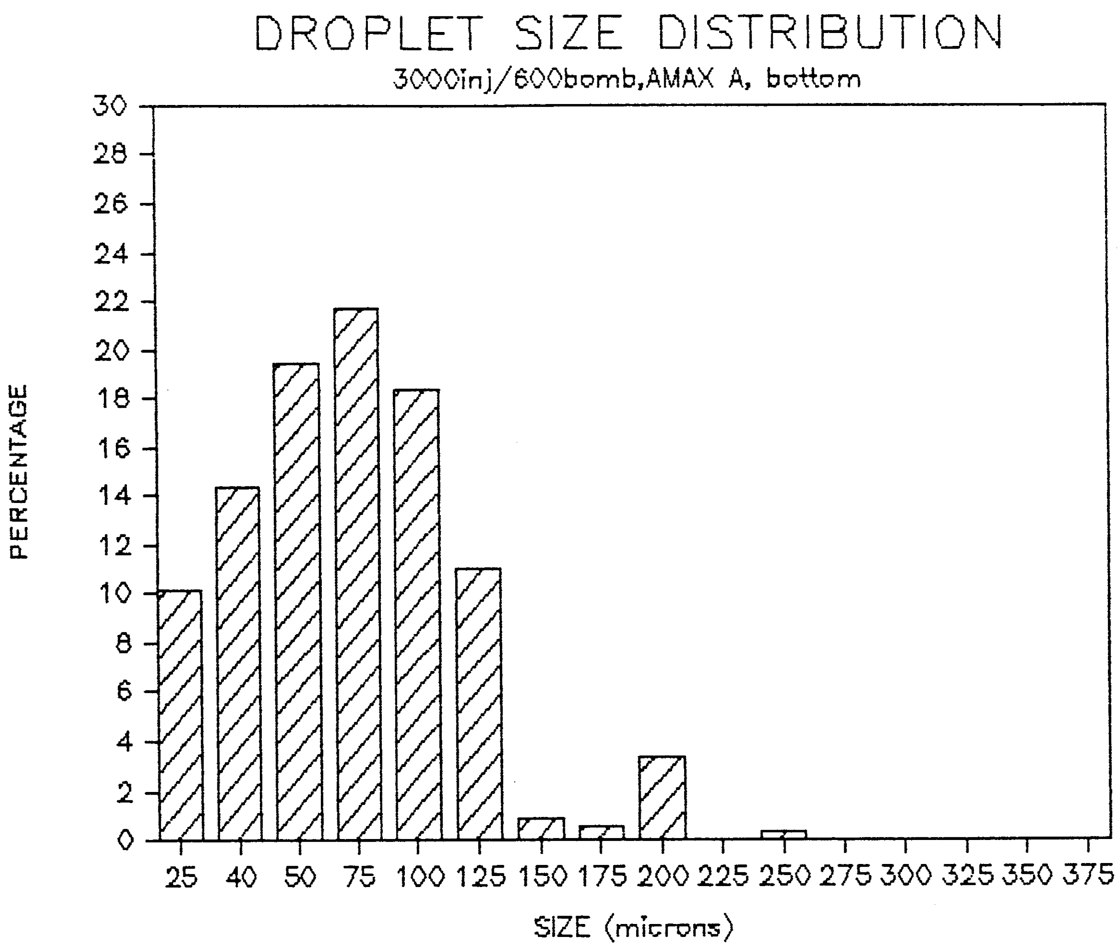


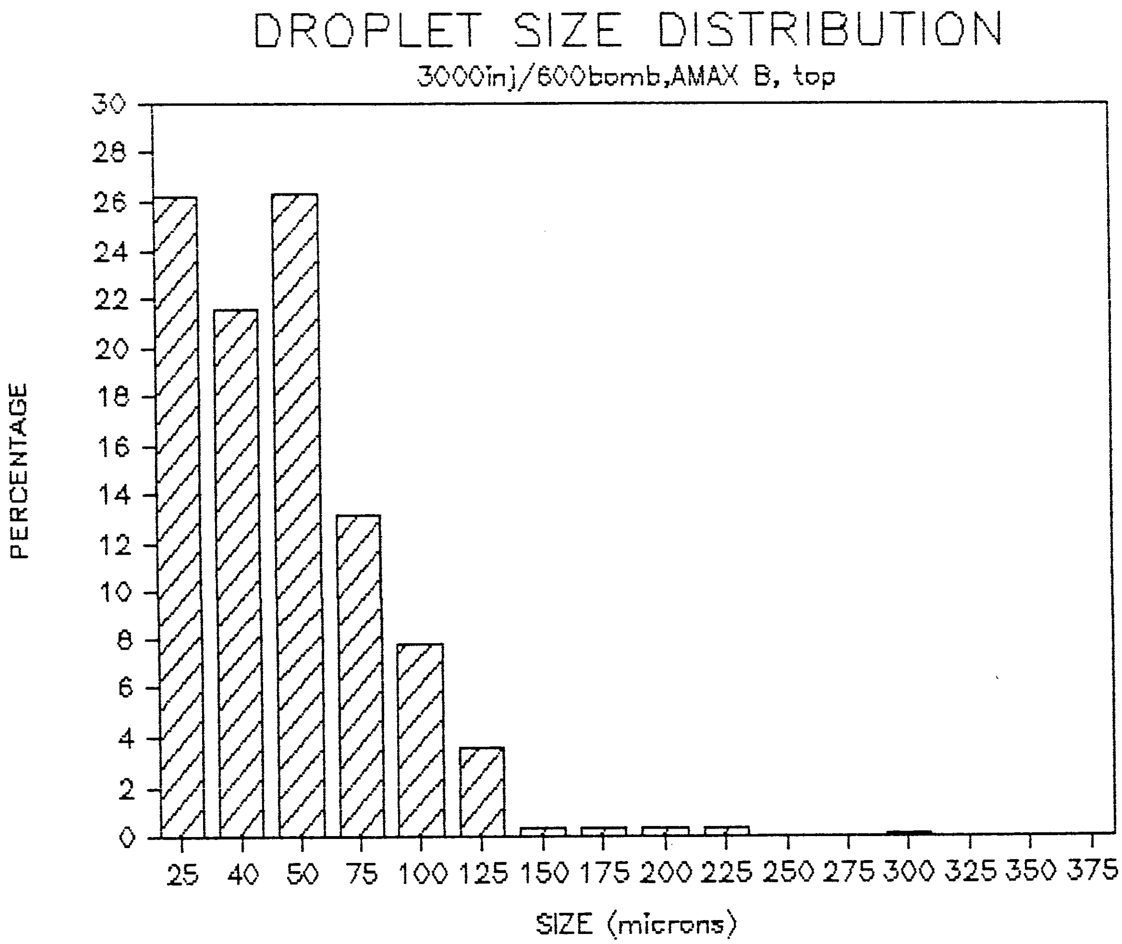
APPENDIX B

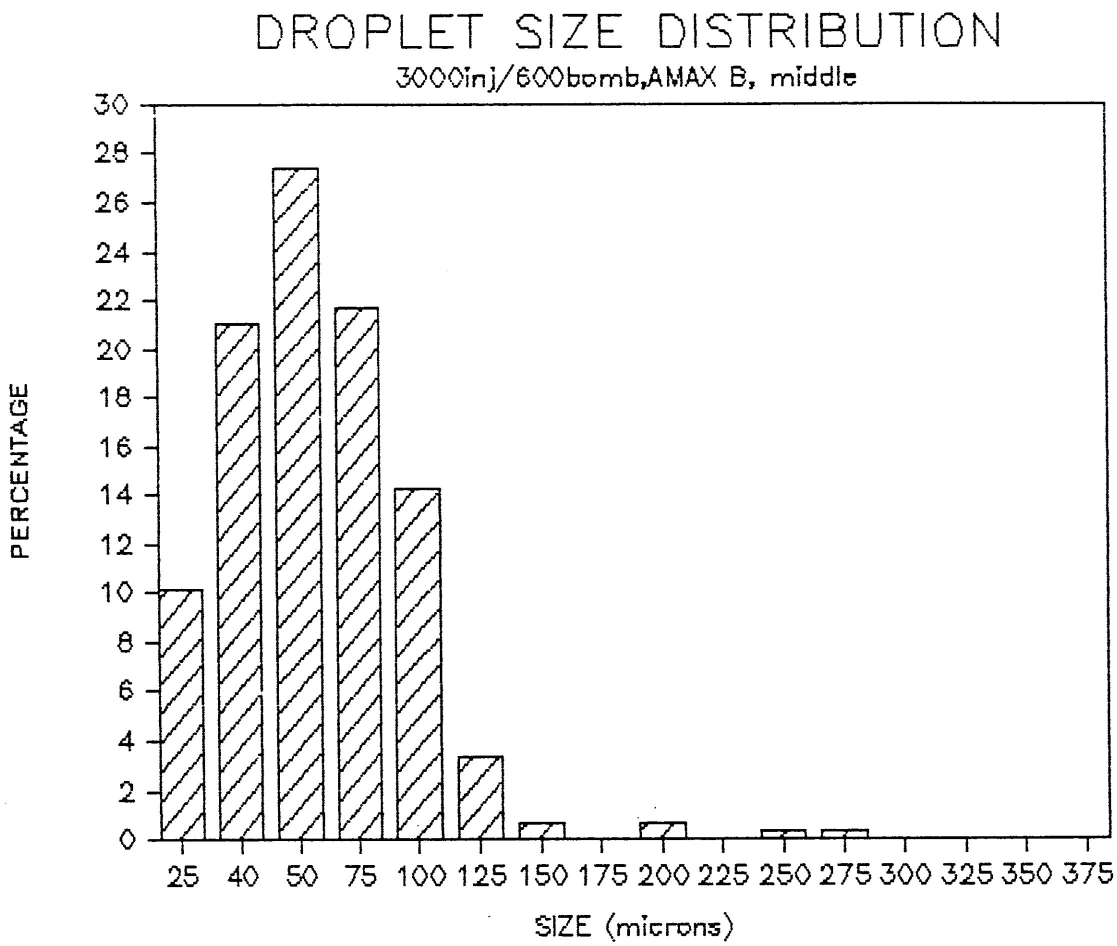
Droplet Size Distribution Bar Graphs for various conditions as labeled.

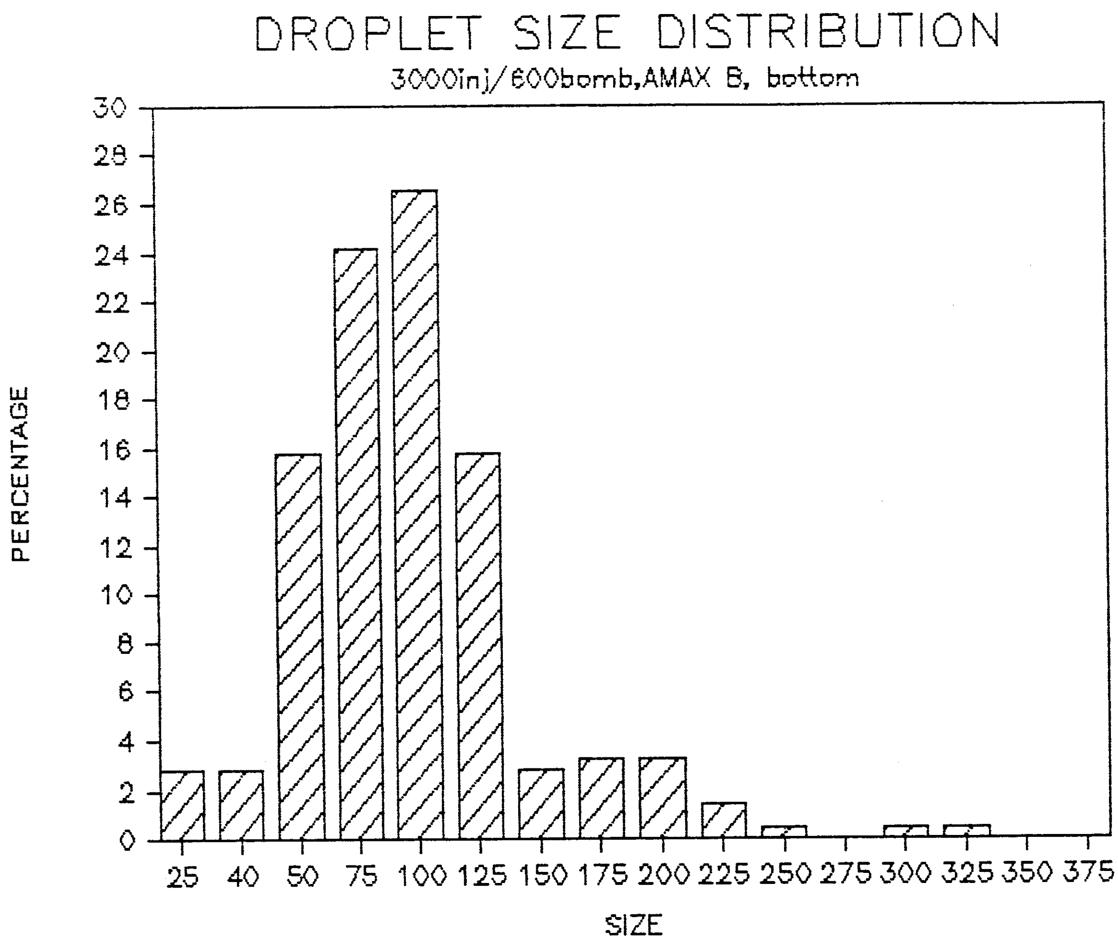

DROPLET SIZE DISTRIBUTION
3000inj/600bomb,AMAX A, top
PERCENTAGE
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
25 40 50 75 100 125 150 175 200 225 250 275 300 325 350 375
SIZE (microns)

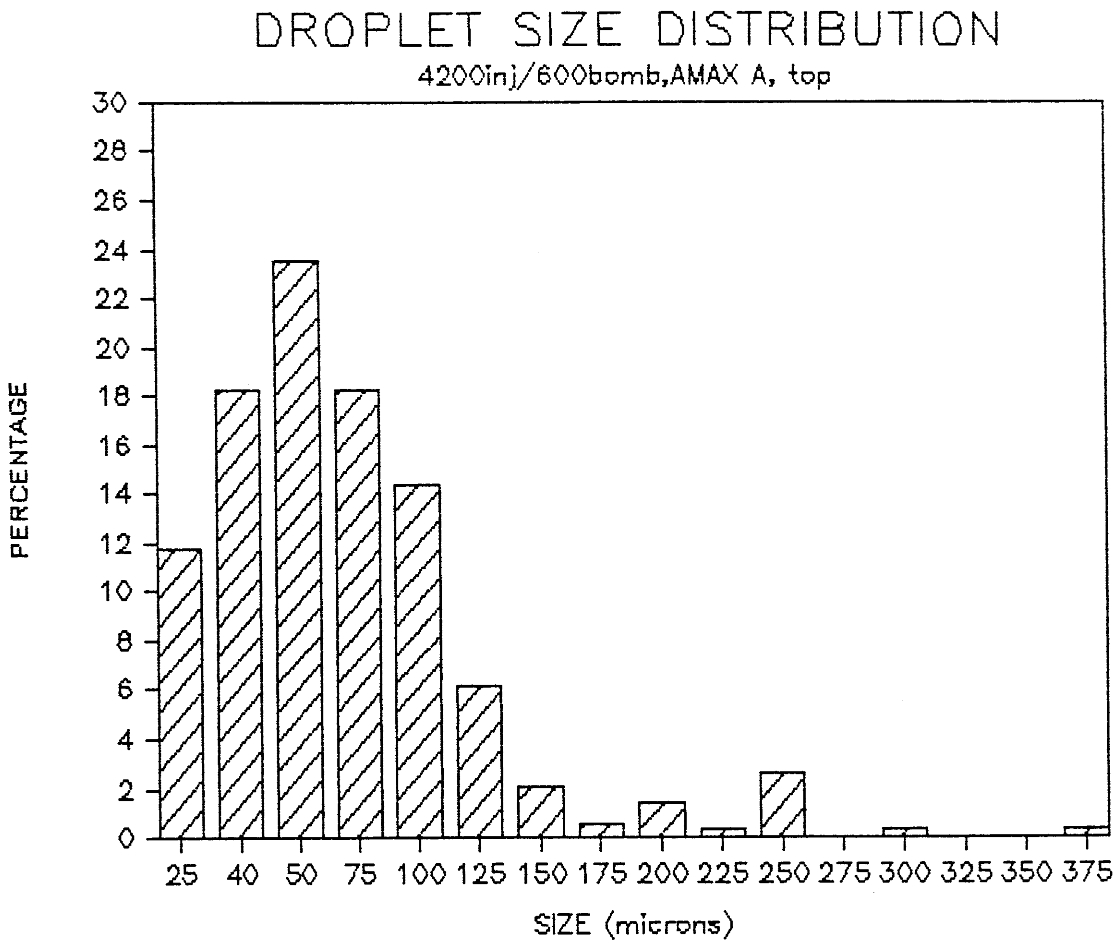

DROPLET SIZE DISTRIBUTION
3000inj/600bomb,AMAX A, middle
PERCENTAGE
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
25 40 50 75 100 125 150 175 200 225 250 275 300 325 350 375
SIZE (microns)

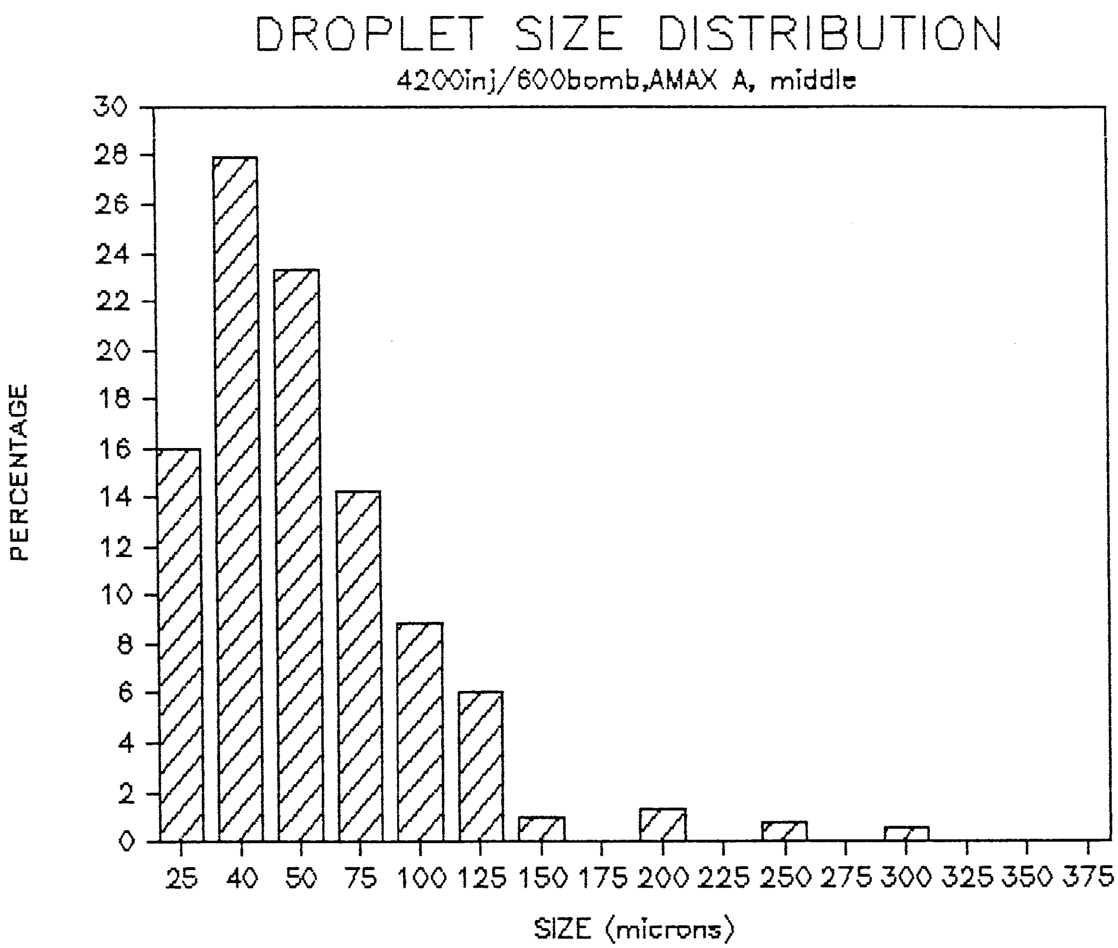

DROPLET SIZE DISTRIBUTION
3000inj/600bomb,AMAX A, bottom
PERCENTAGE
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
25 40 50 75 100 125 150 175 200 225 250 275 300 325 350 375
SIZE (microns)


DROPLET SIZE DISTRIBUTION
3000inj/600bomb,AMAX B, top
PERCENTAGE
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
25
40
50
75
100
125
150
175
200
225
250
275
300
325
350
375
SIZE (microns)


DROPLET SIZE DISTRIBUTION
3000inj/600bomb,AMAX B, middle
PERCENTAGE
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
25 40 50 75 100 125 150 175 200 225 250 275 300 325 350 375
SIZE (microns)


DROPLET SIZE DISTRIBUTION
3000inj/600bomb,AMAX B, bottom
PERCENTAGE
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
25 40 50 75 100 125 150 175 200 225 250 275 300 325 350 375
SIZE


DROPLET SIZE DISTRIBUTION
4200inj/600bomb,AMAX A, top
PERCENTAGE
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
25 40 50 75 100 125 150 175 200 225 250 275 300 325 350 375
SIZE (microns)



DROPLET SIZE DISTRIBUTION
4200inj/600bomb,AMAX A, middle
PERCENTAGE
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
25 40 50 75 100 125 150 175 200 225 250 275 300 325 350 375
SIZE (microns)