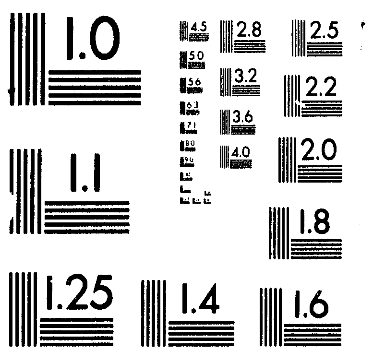
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Characterization of Coal-Water Slurry Fuel Sprays from Diesel Engine Injectors

Topical Report

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ABSTRACT

Experiments were conducted to characterize coal-water slurry fuel sprays from diesel engine injectors. Since the combustion event is a strong function of the fuel spray, full characterization of the spray is a necessity for successful engine design and for modeling of the combustion process. Two experimental facilities were used at TAMU to study the injection of coal slurry fuels. The first experimental facility incorporates General Electric locomotive engine components (injection pump, fuel line, and nozzle) and a specially designed diaphragm to separate the abrasive coal slurry fuel from the moving parts of the pump. The second experimental facility is based on an accumulator injector from General Electric. Instrumentation includes instantaneous needle lift and fuel line pressure. A pressurized visualization chamber was used to provide a spray environment which simulated the engine gas density and permitted the use of spray diagnostic techniques.

The study was divided into two phases: (1) overall characterization of the spray, and (2) detailed droplet size and size distribution characterization. The first phase included high speed movies and direct photography (coupled with short duration light sources). Specific characteristics such as spray growth, penetration and shape, and cone angles were determined as functions of operating conditions and nozzle design.

In addition to this overall characterization of the spray, the second phase of this study characterized the details of the atomization quality. A laser diffraction imaging technique was used to examine the atomization quality by measuring the droplet size and droplet size distribution in the spray. Both spatial and temporal droplet size variations were investigated in detail as a function of fuel injection pressure, nozzle orifice dimensions and background air condition. The drop-size measurement study in conjunction with the spray visualization provides a good knowledge base of isothermal CWS diesel sprays and insures a sound foundation for the study of CWS diesel engine combustion.

INTRODUCTION

This report is the final doumentation of a project directed at determining the fuel injection and atomization qualities of sprays from diesel engine injection systems using coal-water slurry fuels. The work was conducted at Texas A&M University between February 1991 and June 1993. The following part of this section discusses the background of coal fueled engines and fuel injection systems.

The steadily decreasing world supply of petroleum has intensified the search for suitable alternative fuels. The most attractive fuels at the present time appear to be natural gas, alcohols and coal. Coal is attractive because it is domestically abundant. Although the coal may be synthesized into a liquid fuel suitable for use in an internal combustion engine, Caton and Rosegay (1984) have observed that considerable energy may be saved if coal is used directly as a fuel for an engine. The thermodynamic gains realized by the use of solid coal (as opposed to coal-derived synthetic fuels) have created renewed interest in coal-slurries; particularly coal-water slurries. To optimize the design of a slurry-burning diesel engine, data are required to relate the atomization characteristics of coal-water slurry as a function of relevant independent variables such as coal loading, injection pressure and nozzle size. A need exists to determine if models for diesel fuel atomization are applicable to coal-water slurry sprays.

For engine applications, coal-water slurry is a mixture of finely ground coal (with mean particle size on the order of 10 microns or less) mixed with water and additives. Additives are used to improve the viscosity and suspension characteristics of the slurry. Coals used in a slurry are physically and/or chemically cleaned to remove most of the ash and sulfur present in the coal.

The next sub-section summarizes the history of the use of coal in compression-ignition engines and the following sub-section summarizes previous studies of coal water slurry sprays from diesel engine injection systems. Subsequent major sections in this report are project description, results and discussion, conclusions, references, and appendices.

History of Solid-Fuel Use in Compression-Ignition Engines

The concept of using coal as a fuel for a diesel engine is not a new idea. As noted by Caton and Rosegay (1984) and by Soehngen (1976), Rudolph Diesel attempted to fuel his invention, the diesel engine, using coal dust. By inducting the dust into the intake manifold, Diesel operated his engine for seven minutes. Upon completion of the test, he examined the engine and found heavy wear of all critical engine components.

From the time of Diesel's attempt up to the end of World War II, at least five German manufacturers researched the use of coal dust as a fuel for diesel engines (Soehngen, 1976; Caton and Rosegay, 1984). Each company attempted to use various forms of dust injection for fuel delivery to the cylinder. The first attempt was by Rudolpf Pawlikowski, a former employee of Diesel's who founded Kosmos Machine Works (Soehngen, 1976; Caton and Rosegay, 1984; Pawlikowski, 1928; Morrison, 1928).

the Department of Energy (DOE) sponsorship include the following companies: General Electric, Cooper Bessemer, General Motors (Electromotive Division) and Detroit Diesel. Other groups that have investigated the use of coal in compression-ignition engines include Arthur D. Little, Incorporated, Texas A&M University, Southwest Research Institute and Adiabatics Incorporated.

History of Coal-Slurry Fuel Injection Systems

Although engineering development activities for a successful coal-fueled reciprocating engine have continued for nearly one-hundred years (Soehngen, 1976; Caton and Rosegay, 1984), only recently have engines been operated with coal fuels for extended periods (Hsu, 1992; and Rao *et al.*, 1992). These recent successes have been dependent on successful fuel injection systems. To progress in this area, fundamental information is needed on the fuel injection process of coal-water slurry fuels.

Five previous studies on characterizing coal water slurry sprays from diesel engine injection systems have been reported. The first known study that included at least an attempt at characterizing a coal-slurry spray from a diesel engine injector was reported by Phatak and Gurney (1985). Nelson *et al.* (1985) obtained both shadowgraphs and droplet size distribution data for coal-water slurry from engine injectors. Yu *et al.* (1989) reported the results from experiments which used a pneumatic, single-shot fuel delivery system. The injector was a pintle nozzle with injection pressures from 70 to 170 MPa (10000 to 25000 psia).

Dodge *et al.* (1992) reported results from a continuous and an intermittent injection system. Their results indicated that cone angles of the coal-water slurry increased with the increase in the injection pressure in contrast with the cone angles for diesel fuel which were constant with injection pressure. Also, they observed that the atomization of coal-water slurry did not depend on the coal loading in the slurry.

Overall Project Goal

The goal of this research project was to determine the overall characteristics of coal-water slurry fuel sprays as a function of operating conditions and fuel specifications using (1) a positive-displacement fuel injection system and (2) a state-of-the-art accumulator fuel injection system. The first phase of this project characterized coal-water slurry fuel sprays using a modified positive displacement fuel injection system (Seshadri, 1991). The second phase of the project provided additional information on the atomization process of coal water slurry fuels from an accumulator injector and extended the data to fuel pressures up to 109 MPa (Payne, 1993). In addition, this second phase provided an empirical correlation for a coal water slurry fuel for spray tip penetration and initial jet velocity as a function of time, orifice diameter, coal loading, gas density in the engine, and accumulator fuel pressure.

Engine tests conducted by General Electric – Transportation Systems in the mid-1980s demonstrated that modified conventional fuel injection systems were not completely satisfactory for coal water slurry. An accumulator fuel injection system, therefore, was designed and constructed (Leonard and Fiske, 1987) to provide better and more consistent atomization of coal-water slurry fuels. This new accumulator system has been successfully tested on single cylinder medium-speed locomotive engines (Hsu *et al.*, 1989). In one configuration, a conventional jerk pump is used to pump diesel oil into one side of a small chamber which is divided into two sections by a diaphragm. The other side of the diaphragm contains coal-water slurry which would be pressurized by the action of diaphragm. The pressurized coal water slurry then flows into the fuel chamber of the accumulator injector. A fast acting servo-valve, which is electronically activated, is mounted on the injector to open the needle. Further details of this accumulator fuel injection design and its operation are described by Hsu *et al.* (1989). For the current investigation, the pressurized fluids were provided by a separate and independent hydraulic system to avoid the complications of the use of a jerk pump.

Specific Objectives

The objectives of this work were to fully characterize the coal-water slurry fuel sprays from two fuel injection systems (FIS): (1) a positive-displacement FIS and (2) an accumulator FIS, and to develop a correlation for computing the spray penetration. Specifically, the spray plume penetration was determined as a function of time, orifice diameter, coal loading, gas density in the engine, and fuel pressure.

PROJECT DESCRIPTION

Two experimental facilities were used during the course of this project: (1.) a modified positive-displacement fuel injection system, and (2.) an accumulator fuel injection system.

Experimental Facility: Positive-Displacement FIS

The overall injection facility for the positive-displacement fuel injection apparatus incorporated two fuel systems: one provides the diesel fuel used by the jerk-pump and the second provides the fuel, either diesel or slurry, which is injected by the nozzle. A mechanical drive system using an electric motor was use to drive a cam. Attached to the drive shaft is a large (150 kg) flywheel which minimizes variations in the rotational speed of the cam. The cam-follower mechanism translates the rotation of the cam into the reciprocating motion needed by the jerk-pump.

The high-pressure fuel system comprises: (1) the jerk-pump, (2) the diaphragm pump, (3) a check valve mounted on the diaphragm pump, and (4) the injector nozzle. The jerk-pump is a Bendix fuel pump which is used on many types of medium-speed diesel engines. The only modification to the pump is the addition of a diesel fuel outlet passage which enables the diesel fuel to circulate through the jerk-pump. A stainless-steel diaphragm has been inserted between the jerk-pump and the injector nozzle. The purpose of the diaphragm is to isolate the jerk-pump from the abrasive coal particles by using diesel fuel on the jerk-pump side and coal-water slurry on the nozzle side. This design is similar to that used by Leonard and Fiske (1986). The system operates in the same way as the conventional system except that in the modified system the diesel fuel which is forced out of the jerk-pump is used to increase the pressure on one side of the diaphragm. The pressure is transferred through the diaphragm to the coal-water slurry side of the pump—this forces coal-water slurry down the fuel line and into the injection nozzle. Typical injection pressures for this study were of the order of 30 MPa.

For the results reported here, the nozzle tips had only one hole. Although the full displacement of the jerk pump was utilized, fuel line pressures were representative of multi-hole nozzles. This was because the volume of the overall injection system was significantly increased due to the diaphragm and additional pipe length. Actual applications have minimized this additional volume to accomodate multi-hole nozzles (Hsu, 1988a; Hsu, 1988b; Hsu *et al.*, 1989).

The nozzle was a standard Bendix injector used on medium-speed diesel engines. Modifications to the nozzle were limited to the installation of a needle lift transducer, increasing clearances in the needle valve assembly, and the use of custom nozzle tips. The fuel pressure was measured by the use of an in-line strain gauge pressure transducer.

The custom nozzle tips allowed the use of various nozzle tip geometries with various numbers and sizes of orifices. Three sizes of single hole nozzle tips were prepared for this study. The holes had a sharp-edged exit and a length-to-diameter ratio of 8. Although the details of the nozzle tip geometry are important in affecting the spray (Reitz and Bracco, 1982), this aspect was outside the scope of the present study. The nozzle holes were obtained by electro-discharge machining (EDM).

The final aspect of the injection facility is the pressurized chamber. In one direction the fuel spray was directed while in the perpendicular direction visualization of the spray was possible through high pressure windows. The spray was back-lighted through one window and photographed through the other. High-speed (11,000 frames/sec), 16 mm movies of the spray were obtained.

Experimental Facility: Accumulator System FIS

The accumulator injector has four major sections. The lower section is the nozzle tip assembly. For purposes of this investigation, the original nozzle tip has been replaced with a two-piece assembly to permit construction and use of custom nozzle tips. Three sizes of single hole nozzle tips were prepared for this study with nominal nozzle tip diameters of 0.2, 0.4 and 0.6 mm. The actual tip diameters were determined by analyzing photographs from scanning electron microscopy and were 0.196, 0.39 and 0.57 mm. The holes had a sharp-edged exit and a length-to-diameter ratio of 5.

The section above the nozzle tip contains the fuel chamber and fuel inlet. The top sections contain the servo-valve and passages for the various fluids. These fluids and the servo-valve are described below in the operation details. The needle is located in the center and spans the length of the injector. The fuel pressure was measured by the use of a calibrated strain gauge mounted on the injector body and the needle lift was measured by the use of a proximity transducer. Since the accumulator was designed for multiple nozzle openings with about ten times the amount of flow, using one opening resulted in a constant pressure injection for the first few milliseconds. Typical injection pressures for this study were between 25 and 109 MPa and needle lift duration was typically 5 ms.

A special hydraulic system was used to supply all the pressurized fluids for this investigation. The accumulator injector was mounted on a pressure vessel. In one direction the fuel spray was directed while in the perpendicular direction visualization of the spray was possible through high pressure windows. The spray was back-lighted through one window and photographed through the other. High-speed (up to 11,000 frames/sec), 16 mm movies of the spray were obtained.

Experimental Procedures for the Accumulator FIS and Test Matrix

The experimental procedure included the following steps. First, the hydraulic system was used to pressurize all fluids. Once the accumulator was filled with coal water slurry and pressurized to the desired pressure, the movie camera was started and, when the speed of the film was greater than about 8000 frames per second, an electronic trigger signal was sent to the servo-valve controller and to the data acquisition system. When the servo-valve was activated, oil at about 27 MPa flowed under the needle lift piston and forced the needle open. At the end of the injection, which is pre-set, the servo-valve switched off the 27 MPa oil and the close oil (at 25 MPa) caused the needle to close.

Table 1 lists the major experimental test parameters which were investigated. The base case included the following set of parameters: 50% (by mass) coal loading, 0.4 mm diameter nozzle tip, coal water slurry pressure of 82 MPa (12,000 psi), and a chamber density of 25 kg/m^3 (which corresponds to the full load conditions of the GE locomotive engine (Hsu, 1988a; Hsu, 1988b; and Hsu *et al.*, 1989). The fuels used included additional concentrations of coal-water slurry, water and diesel fuel. Additional parameters which were investigated included nozzle tip diameters of 0.2 and 0.6 mm, coal water slurry pressures of between 28 and 109 MPa (4000 and 16000 psi), and chamber densities of 1.2 and 17 kg/m^3.

RESULTS AND DISCUSSION

The major results of this project have been presented in a series of technical papers and reports. The following is a chronological list of these papers and reports:

1. K. D. Kihm and J. A. Caton, "Particle Size Characteristics from Digitally Processed Images of Scanning Electron Microscope (SEM) Photographs of Coal-Water Slurry Samples," Report No. CF–91–01, Texas A&M University, Department of Mechanical Engineering, January 1991.
2. B. Dickinson and J. A. Caton, "Settling Properties of Coal-Water Slurries," Report No. CF–91–02, Texas A&M University, Department of Mechanical Engineering, March 1991.
3. J. A. Caton, K. D. Kihm, A. K. Seshadri, and G. Zicterman, "Micronized-Coal-Water Slurry Sprays from a Diesel Engine Positive Displacement Fuel Injection System," Proceedings of the Central States Section/Combustion Institute Spring Technical Meeting, Paper No. 58, pp. 361–366, April 1991.
4. K. D. Kihm and J. A. Caton, "Apparent Viscosity of Coal-Water Slurry Fuels — Review of Viscometry Techniques and Measured Data," Report

Table 1. Experimental Test Matrix				
Case	Fuel	Tip (mm)	Fuel Pressure (MPa)	Density (kg/m^3)
Base	CWM50	0.4	82	25
Fuels	CWM40 CWM55 WATER DIESEL	0.4	82	25
Tip	CWM50	0.2 0.6	82	25
Fuel Pressure	CWM50	0.4	28 56 68 109	25
Density	CWM50	0.4	82	1.2 17

No. CF–91–03, Texas A&M University, Department of Mechanical Engineering, June 1991.

5. J. A. Caton and K. D. Kihm, "Coal-Water Slurry Atomization Characteristics," Proceedings of the Eighth Annual Coal-Fueled Heat Engines and Gas Stream Cleanup Systems Contractors Review Meeting, U. S. Department of Energy, Morgantown Energy Technology Center, pp. 273–282, July 1991.

6. A. K. Seshadri, J. A. Caton and K. D. Kihm, "Coal-Water Slurry Spray Characteristics of a Positive Displacement Fuel Injection System," *Coal-Fueled Diesel Engines 1992*, Eds. J. A. Caton and H. A. Webb, ICE-Vol. 16, Energy-sources Technology Conference and Exhibition, American Society of Mechanical Engineers, Internal Combustion Engine Division Symposium, Houston, TX, pp. 55–62, January 1992.

7. J. A. Caton, A. K. Seshadri, and K. D. Kihm, "Spray Tip Penetration and Cone Angles for Coal-Water Slurry Using a Modified Medium-Speed Diesel Engine Injection System," Proceedings of the Central States Section/Combustion Institute Spring Technical Meeting, pp. 234–239, April 1992.

8. A. K. Seshadri, J. A. Caton and K. D. Kihm, "Coal-Water Slurry Spray Characteristics of a Positive Displacement Fuel Injection System," *ASME Transactions — Journal of Engineering for Gas Turbines and Power*,

Vol. 114, No. 3, pp. 528–533, July 1992.

9. K. D. Kihm and J. A. Caton, "Synchronization of a Laser Diffraction Drop Sizing Technique with Intermittent Spray Systems," *Journal of Applied Optics*, Vol. 31, No. 23, pp. 1914–1916, 1992.

10. J. A. Caton, S. E. Payne, D. P. Terracina, and K. D. Kihm, "Coal-Water Slurry Spray Characteristics of an Electronically-Controlled Accumulator Fuel Injection System," Energy-sources Technology Conference and Exhibition, American Society of Mechanical Engineers, Internal Combustion Engine Division Symposium, Houston, TX, *Coal-Fueled Diesel Engines 1993*, Eds. J. A. Caton and H. A. Webb, ICE-Vol. 19, pp. 25–32, February 1993.

11. K. D. Kihm, D. P. Terracina, S. E. Payne and J. A. Caton, "Synchronized Droplet Size Measurements for Coal-Water Slurry (CWS) Diesel Sprays of an Electronically-Controlled Fuel Injection System," Energy-sources Technology Conference and Exhibition, American Society of Mechanical Engineers, Internal Combustion Engine Division Symposium, Houston, TX, *Coal-Fueled Diesel Engines 1993*, Eds. J. A. Caton and H. A. Webb, ICE-Vol. 19, pp. 33–42, February 1993.

12. K. D. Kihm, D. P. Terracina, S. E. Payne and J. A. Caton, "Properly Synchronized Measurements of Droplet Sizes for High-Pressure Intermittent Coal-Water Slurry Fuel Sprays," Proceedings of the 1993 Joint Central and Eastern States Section/Combustion Institute Spring Technical Meeting, Paper No. 50, pp. 271–275, March 1993.

13. J. A. Caton, S. E. Payne, D. P. Terracina, and K. D. Kihm, "Coal-Water Slurry Sprays from an Electronically-Controlled Accumulator Fuel Injection System: Break-up Distances and Times," Proceedings of the 1993 Joint Central and Eastern States Section/Combustion Institute Spring Technical Meeting, Paper No. 76, pp. 405–409, March 1993.

Appendices A through F include detail listings of the data and reduced quantities for all cases studied for the accumulator injection system for both coal-water slurry and diesel fuel. For convenience, key references (3, 5–7, and 9–13) have been included in appendix G. These papers constitute the bulk of the report on the results of this project.

The following brief discussion summarizes some of the findings included in the above references. The majority of this brief discussion focusses on the results from the accumulator injection system. Complete details are provided in the attached papers in the appendices.

Fuels Characterization

The basic slurry fuel was a commercially available coal-water slurry obtained from Otisca Industries. The details of this slurry have been reported elsewhere (Hsu and Confer, 1991). In summary, the base coal-water slurry contained 50% coal, 48% water, 1% lignosulphonate, and 1% Triton X-114. The coal used was a high-volatile subbituminous which was cleaned to less than 0.8% ash (on a dry coal basis) with a measured Sauter mean particle diameter of 3.0 μ. A second sample of Otisca coal water slurry fuel with a mean particle diameter of 8.0 μ was tried in these experiments, but no successful injections were achieved. The results of this study, therefore, should not be generalized to all coal water slurry fuels.

Spray Characterization

From the high-speed movie frames, spray propagation and development were determined. The propagation of the fuel jet is rapid at the start. This represents the period of penetration of a largely intact liquid core region. After this initial period, the liquid core breaks apart (break-up). Associated with this break-up is the development of a head vortex. The size of the head vortex increases due to additional fuel from the injector on one side (upstream) and due to entrained gas on the other sides.

To complete the detailed analysis of the spray development, each frame of each movie was traced using a motion analyzer. The edge of the spray was selected as the location of the edge of the dark image of the spray. The accuracy of this determination was estimated as 5% and is discussed in more detail in the above references.

From the spray outlines, the fuel jet penetration as a function of time was determined. To illustrate the degree of accuracy in determining the spray tip location, separate interpretations of one of the base case movies (film number 26) were conducted and all interpretations are in good agreement. In fact, the experimental uncertainty described above generally was greater than the uncertainty in locating the spray tip. Interpretations for the other movies demonstrated similar character (Payne, 1993).

This work was based on only one spray plume, whereas typically eight to twenty spray plumes would be used. The typical spray plume is directed downward toward the piston at a 15° angle. For certain cases, the fuel jet would impinge on the piston bowl about 1.0 ms after the start of injection. Typical ignition delays for coal-water slurry for these conditions are greater than 1.5 ms (Hsu, 1988a; Hsu, 1988b; Hsu *et al.*, 1989) and, hence, these results indicate that at least some fuel impingement occurs. The consequences of this finding on the ignition and combustion processes in the engine are discussed by Hsu *et al.* (1992).

Based on the experimental data from these experiments, a correlation was developed for computing the spray tip penetration as a function of time for coal water slurry fuels. Although many correlations exist for spray tip penetration for diesel fuel (see *e. g.*, Dent, 1971; and, Hay and Jones, 1972), none have been reported for coal water slurry fuels. The correlation that was developed was based on a modified form of a correlation originally presented by Arai *et al.* (1984) for diesel fuel. The modifications included increased penetrations and initial jet velocities, and the use of coal water slurry properties.

The expressions for the spray tip penetration, s, for coal water slurry are as follows:

$$\text{For } 0 < t < t_b, \quad s = 0.897\, x_c \left(\frac{2\,\Delta P}{\rho_\ell}\right)^{0.5} t \tag{1}$$

$$\text{For } t > t_b, \quad s = 6.79\, x_c \left(\frac{\Delta P}{\rho_g}\right)^{0.25} (d \cdot t)^{0.5} \tag{2}$$

$$\text{where, } t_b = 28.65 \frac{\rho_\ell \cdot d}{(\rho_g\, \Delta P)^{0.5}} \tag{3}$$

$$\text{also, } V_{jet_{initial}} = 0.897\, x_c \left(\frac{2\,\Delta P}{\rho_\ell}\right)^{0.5} \tag{4}$$

where x_c is the mass fraction of coal in the slurry, ΔP is the difference between the fuel pressure and the chamber pressure, ρ_ℓ is the density of the injected fluid, t is the time since injection, ρ_g is the density of the chamber gas, d is the nozzle orifice diameter, t_b is the time until break-up of the spray jet, and $V_{jet_{initial}}$ is the initial jet velocity.

The agreement of the correlation with the experimental data was good. In addition, the experimental values of the initial jet velocities were obtained by examining the first two frames of each movie. Although some data scatter is evident, the correlation provides a good fit to the data. The correlation also provided a good fit to the earlier data from the positive displacement fuel injection system (Sheshadri, 1991). For the experiments with the accumulator injector, the initial jet velocities ranged between about 100 to 180 m/s. Also, for coal water slurry fuels no successful injections were possible for fuel pressures below about 25 MPa (3700 psi).

The following discussion will focus on the effects of the major parameters of the injection process on the fuel jet penetration and on the break-up time using results from the above correlation. Confirming experimental data is available from Payne (1992). Although the break-up distance, 49 mm, was independent of fuel pressure, the break-up time varied between 0.23 and 0.63 ms for pressures between 140 and 20 MPa, respectively. The break-up time is a good indication of the quality of the atomization process. Break-up times indicate when the liquid core of the spray jet has disintegrated. The major portion of the atomization of the spray, therefore, will start sooner for short break-up times.

The spray tip penetration is independent of nozzle orifice size until after break-up. Break-up times and distances for the three orifices were: 0.15 ms and 24.6 mm for the 0.2 mm orifice; 0.30 ms and 49.0 mm for the 0.4 mm orifice; and 0.44 ms and 71.7 mm for the 0.6 mm orifice. The spray tip penetration is independent of chamber densities until after break-up. Break-up times and distances for the four chamber densities were: 1.37 ms and 224 mm for a density of 1.2 kg/m^3; 0.67 ms and 110 mm for a density of 5.0 kg/m^3; 0.48 ms and 78 mm for a density of 10.0 kg/m^3; and 0.30 ms and 49 mm for a density of 25.0 kg/m^3. The effect of chamber density on the spray character is significant. For the low chamber density, the spray penetrates rapidly and does not spread out when compared to the high chamber density case. The break-up distances for the low chamber densitj are 4.6 times greater than the break-up times for the high chamber density case for any specific orifice size.

For water and diesel the original correlation of Arai *et al.* (1984) was used. Although the effects of the fluid are modest, the coal water slurry does exhibit greater penetration, and longer break-up times and distances than the other two fluids. Injections were not possible for 55% coal water slurry. Also, as mentioned above, a second sample of coal water slurry with a mean particle size of 8 μ could not be successfully injected.

In addition to penetration distances, the cone angles of the sprays were determined from the movies. The cone angle of a spray is not well defined and no standard procedure is available. One approach is to use the arc tangent of the spray width divided by the axial distance from the nozzle tip to the measurement location (Caton *et al.*, 1992). For this study, the measurement location was 60 mm (150 nozzle orifice diameters) downstream from the nozzle tip. This location was selected so as to include as much of the spray as possible without being near the wall region. This distance is also representative of the distance to the piston bowl in a medium-speed diesel engine.

For the chosen measurement location, the spray arrives at about 0.45 ms after injection. For the period between 2 and 8 ms, the time-averaged cone angle for this coal-water slurry case was 13.6°. For the positive-displacement injection system, the smallest cone angle was 10.2°and the largest cone angel was 16.4°. The cone angles for the accumulator fuel injection system are much more steady with respect to time than those for the positive-displacement fuel injection system (Caton *et al.*, 1993). This is because the current work does not use an intermittent injection system as in the previous work. Also, the value of the cone angles are similar for the two systems even though the conditions were different. Other investigators (Dodge *et al.*, 1992) have reported narrower coal-water slurry sprays with cone angles of between 1 and 10°, depending on fuel injection pressure.

SUMMARY and CONCLUSIONS

Experiments were completed to characterize coal-water slurry sprays from an electronically-controlled accumulator fuel injection system of a diesel engine. Injection pressures between 28 and 109 MPa, nozzle orifice diameters between 0.2 and 0.6 mm, and coal-water slurry fuels with between 0 and 55% (by mass) coal were studied. The sprays were injected into a pressurized chamber equipped with windows. High speed movies and instantaneous fuel pressures were obtained.

The conclusions of this investigation include the following:

1. For the base conditions, the break-up time was 0.30 ms for this coal-water slurry. Break-up times increased with increasing nozzle orifice size, with decreasing fuel

pressure, and with decreasing chamber density.

2. An empirical correlation was developed for coal water slurry for both spray tip penetration and initial jet velocity. Results of this study and the correlation are specific to the tested coal water slurry and are not general for other coal water slurry fuels.
3. For the conditions of this study, the spray tip penetration and initial jet velocity was 15% greater for coal water slurry than for diesel fuel or water.
4. For this coal water slurry, no injections were possible for fuel pressures less than 25 MPa (3700 psi) or for coal mass fractions greater than 0.53.
5. Cone angles of the sprays were dependent on the operating conditions and fluid, as well as the time and location of the measurement. The time-averaged cone angle was 13.6° for the coal-water slurry for the base conditions.

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APPENDIX A

TABLE OF EXPERIMENTAL DATA FOR CWS

Film no.	Fuel	Wt% and Additive	Nozzle Size (mm)	Pressure (psi) Fuel Line	Pressure (psi) Purge Line	Pressure (psi) Chamber	Trigger Speed (%)	Pulse Duration (msec)	Sampling Frequency (Hz)	Run Duration (sec)	Notes
1	CWS	40, twice	0.4 C	NA	NA	300	70	NA	NA	NA	no inj, film destroyed
2	CWS	40, twice	0.4 C	NA	NA	300	70	NA	NA	NA	no inj, film destroyed
3	CWS	40, twice	0.4 C	NA	NA	300	70	NA	NA	NA	no inj, film destroyed
4	CWS	43, twice	0.4 C	NA	NA	300	70	NA	NA	NA	good run, film developed
5	CWS	43, twice	0.4 C	9400	9600	300	70	6.32	NA	NA	no inj, inj clogged, film destroyed
6	Water	none	0.4 C	NA	NA	300	70	NA	NA	NA	good run, film developed
7	CWS	42, twice	0.4 C	9400	10000	300	70	NA	8000	0.5	no inj, elec problem, film destroyed
8	CWS	42, twice	0.4 C	9600	10000	300	70	6.51	NA	NA	good run, film developed
9	CWS	42, twice	0.4 C	9200	9400	300	70	NA	NA	NA	film developed, no inj
10	CWS	42, twice	0.4 C	9400	9600	300	70	NA	NA	NA	no inj, inj temporary clog
11	CWS	42, twice	0.4 C	10600	11200	300	70	7.56	NA	NA	good run, developed; no timings lights
12	CWS	42, twice	0.4 C	9400	10000	300	70	7.01	NA	NA	good run, developed; no timings lights
13	CWS	42, twice	0.4 C	7000	7400	300	70	6.57	NA	NA	lens cap on, but everything ok
14	CWS	42, twice	0.4 C	7000	7200	300	70	6.57	NA	NA	good run, developed; no timings lights
15	CWS	42, twice	0.4 C	9400	9600	300	70	7.05	4000	2	good run, developed; no timings lights
16	CWS	42, twice	0.4 C	9000	9200	300	70	5.14	4000	2	good run, developed, no timings lights
17	CWS	42, twice	0.4 C	8600	9000	300	70	5.61	4000	2	good run, developed, no timings lights
18	CWS	42, twice	0.4 C	8600	9000	300	70	6.57	4000	2	good run, developed; no timings lights
19	CWS	42, twice	0.4 C	10400	10600	300	71	5.64	4000	2	G R,D, offset(.148) lights 1000/sec
20	CWS	42, twice	0.4 C	10200	10600	300	71	6.57	4000	2	G R D; off(0.148) lights 100/sec

Film no.	Fuel	Wt% and Additive	Nozzle Size (mm)	Pressure (psi) Fuel Line	Pressure (psi) Purge Line	Pressure (psi) Chamber	Trigger Speed (%)	Pulse Duration (msec)	Sampling Frequency (Hz)	Run Duration (sec)	Notes
21	CWS	42, twice	0.4 C	10000	10700	300	71	5.66	4000	2	G R,D, offset(.148) lights 100/sec
22	CWS	42, twice	0.4 C	9000	9600	300	71	6.56	4000	2	G R, D; offset(.674) lights 100/sec
23	CWS	42, twice	0.4 C	9000	9600	300	70	7.46	4000	2	G R, D, offset(.674)
24	CWS	42, twice	0.4 C	8800	9400	300	70	7.46	4000	2	G R, D; offset(.674) lights 1000/sec
25	CWS	42, twice	0.4 C	9200	9800	300	71	NA	4000	2	G R, D; offset(.674)
26	CWS	50, twice	0.4 C	12200	12400	300	72	4.69	4000	2	G R, D; offset(.634) lights 1000/sec
27	CWS	50, twice	0.4 C	12000	13000	300	70	4.69	4000	2	G R, D; offset(.634) lights 1000/sec
28	CWS	50, twice	0.4 C	15000	15200	300	70	4.69	4000	2	G R, D; offset(.634) lights 1000/sec
29	CWS	50, twice	0.4 C	15000	15600	300	72	4.69	4000	2	G R, D, offset(.634) lights 1000/sec
30	CWS	50, twice	0.4 C	10000	10300	300	72	4.7	4000	2	G R, D; offset (.410) lights 1000/sec
31	CWS	50, twice	0.4 C	9850	10200	300	83	4.7	4000	2	GR,D;offset(.442) pump off,0psi cham
32	CWS	50, twice	0.4 C	9850	10100	300	83	4.69	4000	2	GR,D;offset(.442) pump off,0psi cham
33	CWS	50, twice	0.4 C	7800	8200	300	79	4.69	4000	2	GR,D;offset(.442) pump off,0psi cham
34	CWS	50, twice	0.4 C	7800	8400	300	80	4.69	4000	2	GR,D,offset(.442) pump off,0psi cham
35	CWS	50, twice	0.4 C	5000	5200	300	83	4.7	4000	2	GR,D;offset(.423)pump off,0psi cham
36	CWS	50, twice	0.4 C	5000	5200	300	80	4.7	4000	2	GR,D;offset(.423)pump off,0psi cham
37	CWS	50, twice	0.4 C	12000	12350	0	80	4.7	4000	2	GR,D;offset(.471)pump off,0psi
38	CWS	50, twice	0.4 C	11900	12350	0	80	4.69	4000	2	GR,D;offset(.471)pump off,0psi
39	CWS	50, twice	0.4 C	5000	5400	300	80	4.69	4000	2	GR,D;offset(.471)pump off,0psi
40	CWS	50, twice	0.4 C	5050	5400	300	80	4.7	4000	2	GR,D,offset(.471)pump off,0psi

Film no.	Fuel	Wt% and Additive	Nozzle Size (mm)	Pressure (psi) Fuel Line	Pressure (psi) Purge Line	Pressure (psi) Chamber	Trigger Speed (%)	Pulse Duration (msec)	Sampling Frequency (Hz)	Run Duration (sec)	Notes
41	CWS	50, twice	0.4 C	4050	4450	300	80	4.7	4000	2	GR,D;offset(471),pump off 0psi chamb
42	CWS	50, twice	0.4 C	4200	4400	300	80	4.7	4000	2	GR,D;offset(.471),pump off 0psi chamb
43	CWS	50, twice	0.4 C	3000	3600	300	71.8	4.68	4000	2	GR,D;offset(432)
44	CWS	50, twice	0.4 C	2900	3600	300	80	4.69	4000	2	GR,D;offset(432) no timing lights
45	CWS	50, twice	0.4 C	2000	2100	300	80	4.69	4000	2	no injection
46	CWS	50, twice	0.6 C	12000	12200	300	80	4.69	4000	2	GR,D;offset(432) noisy data
47	CWS	50, twice	0.6 C	12000	12400	300	80	4.69	4000	2	GR,D;offset(432) no timing lights
48	CWS	50, twice	0.2 C	12000	12600	300	80	4.69	4000	2	no injection
49	H2O	none	0.4 C	12000	12000	300	NA	4.68	4000	2	GR,D;offset(.363) no timing lights
50	H2O	none	0.4 C	12200	12200	300	NA	4.68	4000	2	GR,D;OS(.363) No TL input line long
51	CWS	40, twice	0.4 C	12000	12200	300	NA	4.68	4000	2	GR,D;offset(363) no timing lights
52	CWS	40, twice	0.4 C	12000	12600	300	NA	4.68	4000	2	GR,D;offset(363) no timing lights
53	CWS	50, twice	0.4 C	11700	12100	300	80	4.68	4000	2	GR,D;offset(366) no timing lights
54	CWS	50, twice	0.4 C	12000	12500	300	80	4.68	4000	2	GR,D,offset(366) no timing lights
55	CWS	50, twice	0.2 C	11900	12200	300	80.8	4.7	4000	2	clogged
56	H2O	none	0.4 C	12000	12000	300	82	4.7	4000	2	GR,D;offset(283) Tchamber=21.8 C
57	H2O	none	0.4 C	12000	12000	300	83	5.11	4000	2	GR,D;offset(.283) Tchamber=23.3 C
58	CWS	40, twice	0.4 C	11850	12000	300	80	5.11	4000	2	GR,D;offset(.283) Tchamber=23.5 C
59	CWS	40, twice	0.4 C	11800	12000	300	88	5.11	4000	2	GR,D;offset(283) Tchamber=22.5 C
60	CWS	50, twice	0.4 C	11800	12000	300	88	5.11	4000	2	GR,D;offset(.884) Tchamber=23 C

Film no.	Fuel	Wt% and Additive	Nozzle Size (mm)	Pressure (psi) Fuel Line	Pressure (psi) Purge Line	Pressure (psi) Chamber	Trigger Speed (%)	Pulse Duration (msec)	Sampling Frequency (Hz)	Run Duration (sec)	Notes
61	CWS	50, twice	0.4 C	11800	12000	300	88	5.11	4000	2	GR,D;offset(.864) Tchamber=23 C
62	CWS	50, twice	0.6 C	12000	12200	300	89	5.11	4000	2	GR,D;offset(1.2) Tchamber=23 C
63	CWS	50, twice	0.6 C	12000	12200	300	84	5.11	4000	2	GR,D;offset(1.2) Tchamber=23 C
64	CWS	50, twice	0.2 C	12000	12400	300	90	5.11	4000	2	GR,D;offset(1.2) Tchamber=23 C
65	CWS	50, twice	0.2 C	12000	12200	300	85	5.11	4000	2	no inj, developed. Tchamber=23 C
66	CWS	50, twice	0.4 C	8000	8100	300	85	NA	4000	2	inj weak,D;OS(.34) Tchamber=23.0 C
67	CWS	50, twice	0.4 C	8000	8100	300	85	NA	4000	2	no inj,ND;OS(.26) Tchamber=22.5 C
68	CWS	50, twice	0.4 C	8100	8200	300	80	5.07	4000	2	GR,D;offset(.26) Tchamber=25.0 C
69	CWS	50, twice	0.4 C	7800	8000	300	81	5.08	4000	2	GR,D;offset(.26) Tchamber=24.0 C
70	CWS	50, twice	0.4 C	11800	12200	0	87	5.08	4000	2	GR,D;offset(.26) Tchamber=23.7 C
71	CWS	50, twice	0.4 C	5000	5500	300	81	5.1	4000	2	GR,D;offset(.105) Tchamber=21.4 C
72	CWS	50, twice	0.4 C	5300	5000	300	81	5.11	4000	2	GR,D;offset(.105) Tchamber=21.2 C
73	CWS	50, twice	0.4 C	4100	4300	300	81	5.08	4000	2	GR,D;offset(.105) Tchamber=21.1 C
74	CWS	50, twice	0.4 C	4000	4300	300	84	5.11	4000	2	GR,D;offset(.105) Tchamber=21.2 C
75	CWS	50, twice	0.4 C	12000	12300	0	82	5.08	4000	2	GR,D;offset(.389) T chamber=23.3 C
76	CWS	50, twice	0.4 C	11800	12200	0	88	5.09	4000	2	GR,D;offset(.389) T chamber=23.0 C
77	CWS	50, twice	0.4 C	3000	3300	300	80.1	5.09	4000	2	GR,D;offset(.389) T chamber=24.5 C
78	CWS	50, twice	0.4 C	3000	3200	300	81	5.09	4000	2	no injection T chamber=23.8 C

APPENDIX B

TABLE OF REDUCED EXPERIMENTAL DATA FOR CWS

Film no.	Fuel	Wt% and Additive	Nozzle Size (mm)	Actual Fuel Pressure (psi)		Temperature (C)		Needle Lift Duration (msec)		Spray Duration (msec)	Film Speed Initial/avg. (frames/sec)	Initial Jet Velocity (m/s)
				Before inj	After inj	Fuel	Chamber	Closed End	Open End			
1	CWS	40, twice	0.4 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
2	CWS	40, twice	0.4 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
3	CWS	40, twice	0.4 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
4	CWS	43, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
5	CWS	43, twice	0.4 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
6	Water	none	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
7	CWS	42, twice	0.4 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
8	CWS	42, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
9	CWS	42, twice	0.4 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
10	CWS	42, twice	0.4 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
11	CWS	42, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
12	CWS	42, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
13	CWS	42, twice	0.4 C	lens cap on	lens cap on	NA	NA	lens cap on	lens cap on	lens cap on	lens cap on	lens cap on
14	CWS	42, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
15	CWS	42, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
16	CWS	42, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
17	CWS	42, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
18	CWS	42, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
19	CWS	42, twice	0.4 C	10800	10800	NA	NA	6.85	32.2	DATA NA	/7400	172.9 (JBS)
20	CWS	42, twice	0.4 C	11200	11000	NA	NA	6.33	32.3	DATA NA	/7200	117.7 (JBS)

Film no.	Fuel	Wt% and Additive	Nozzle Size (mm)	Actual Fuel Pressure (psi) Before inj	Actual Fuel Pressure (psi) After inj	Temperature (C) Fuel	Temperature (C) Chamber	Needle Lift Duration (msec) Closed End	Needle Lift Duration (msec) Open End	Spray Duration (msec)	Film Speed initial/avg. (frames/sec)	Initial Jet Velocity (m/s)
21	CWS	42, twice	0.4 C	10640	10400	NA	NA	6 83	56 2	DATA NA	/7200	133 9 (U&S)
22	CWS	42, twice	0.4 C	10073	10023	NA	NA	6 69	19 95	DATA NA	/7250	[illegible] 2 (U&S)
23	CWS	42, twice	0.4 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
24	CWS	42, twice	0.4 C	10272	8200	NA	NA	415 7	534 6	DATA NA	/7000	145 2 (U&S)
25	CWS	42, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	DATA NA	/7100	163 3 (U&S)
26	CWS	50, twice	0.4 C	DATA NA	DATA NA	NA	NA	DATA NA	DATA NA	DATA NA	/7143	158 8 (U&S)
27	CWS	50, twice	0.4 C	11900	10420	NA	NA	308 8	352 6	DATA NA	/6615	181 7 (S)
28	CWS	50, twice	0.4 C	12675	9080	NA	NA	999 4	1071	DATA NA	/7105	147 7 (U&S)
29	CWS	50, twice	0.4 C	12668	9798	NA	NA	1007	1083	DATA NA	/7308	126 9 (S)
30	CWS	50, twice	0.4 C	9925	9868	NA	NA	5 09	17 6	DATA NA	/7294	143 9 (U&S)
31	CWS	50, twice	0.4 C	10100	10080	NA	NA	6.3	27 5	DATA NA	/8500	129 3 (U&S)
32	CWS	50, twice	0.4 C	10020	9920	NA	NA	7 6	49 2	DATA NA	/8222	210.7 (S)
33	CWS	50, twice	0.4 C	8160	8260	NA	NA	6	24 5	DATA NA	7900/	147.2 (S)
34	CWS	50, twice	0.4 C	8200	8270	NA	NA	60	66 7	dim T.L	dim T L	dim T L
35	CWS	50, twice	0.4 C	5120	5120	NA	NA	4.1	6 2	dim T.L	dim T L	dim T.L
36	CWS	50, twice	0.4 C	5110	5120	NA	NA	4.24	6 5	dim T.L	dim T L	dim T.L
37	CWS	50, twice	0.4 C	12040	11370	NA	NA	113.6	172 7	dim T.L	dim T L	dim T.L
38	CWS	50, twice	0.4 C	12130	11500	NA	NA	93.1	148	dim T.L	dim T.L	dim T L
39	CWS	50, twice	0.4 C	5240	5290	NA	NA	3 5	7	dim T.L	dim T.L	dim T.L
40	CWS	50, twice	0.4 C	5330	5390	NA	NA	4 8	7 2	dim T.L	dim T L	dim T L

Film no.	Fuel	Wt% and Additive	Nozzle Size (mm)	Actual Fuel Pressure (psi)		Temperature (C)		Needle Lift Duration (msec)		Spray Duration (msec)	Film Speed initial/avg. (frames/sec)	Initial Jet Velocity (m/s)
				Before inj	After inj	Fuel	Chamber	Closed End	Open End			
41	CWS	50, twice	0.4 C	4320	4465	NA	NA	4.53	7.36	dim T.L	dim T.L	dim T.L
42	CWS	50, twice	0.4 C	4440	4512	NA	NA	4.2	7.22	dim T.L	dim T.L	dim T.L
43	CWS	50, twice	0.4 C	4526	4539	NA	NA	3.42	7.23	dim T.L	dim T.L	dim T.L
44	CWS	50, twice	0.4 C	4529	4550	NA	NA	0.5	7.29	dim T.L	dim T.L	dim T.L
45	CWS	50, twice	0.4 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
46	CWS	50, twice	0.6 C	noisy data	noisy data	NA	NA	noisy data	noisy data	dim T.L	dim T.L	dim T.L
47	CWS	50, twice	0.6 C	13142	12873	NA	NA	2.49	31.81	dim T.L	dim T.L	dim T.L
48	CWS	50, twice	0.2 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
49	H2O	none	0.4 C	11922	11564	NA	NA	87.68	122.23	dim T.L	dim T.L	dim T.L
50	H2O	none	0.4 C	DATA NA	0	NA	NA	DATA NA	DATA NA	dim T.L	dim T.L	dim T.L
51	CWS	40, twice	0.4 C	12200	11308	NA	NA	153.7	195.5	dim T.L	dim T.L	dim T.L
52	CWS	40, twice	0.4 C	12684	11530	NA	NA	203.2	255.6	dim T.L	dim T.L	dim T.L
53	CWS	50, twice	0.4 C	12117	11508	NA	NA	208.8	252.6	dim T.L	dim T.L	dim T.L
54	CWS	50, twice	0.4 C	NA	NA	NA	NA	565.8	675.9	dim T.L	dim T.L	dim T.L
55	CWS	50, twice	0.2 C	no inj	no inj	NA	NA	no inj	no inj	no inj	no inj	no inj
56	H2O	none	0.4 C	11688	11180	NA	21.6	85.4	131.5	44.1	8200/8433	141.5 (S)
57	H2O	none	0.4 C	11800	11345	NA	23.3	74	116	41.5	8333/8404	112.6 (S)
58	CWS	40, twice	0.4 C	11825	10810	NA	23.5	232.6	266.5	39.8	8000/8244	89.44 (S)
59	CWS	40, twice	0.4 C	12000	10924	NA	22.5	186.3	256.2	40.1	8400/8563	178.4 (S)
60	CWS	50, twice	0.4 C	10210	9400	NA	23	101.1	149.6	> 67.2	8687/8834	135.9 (U&S)

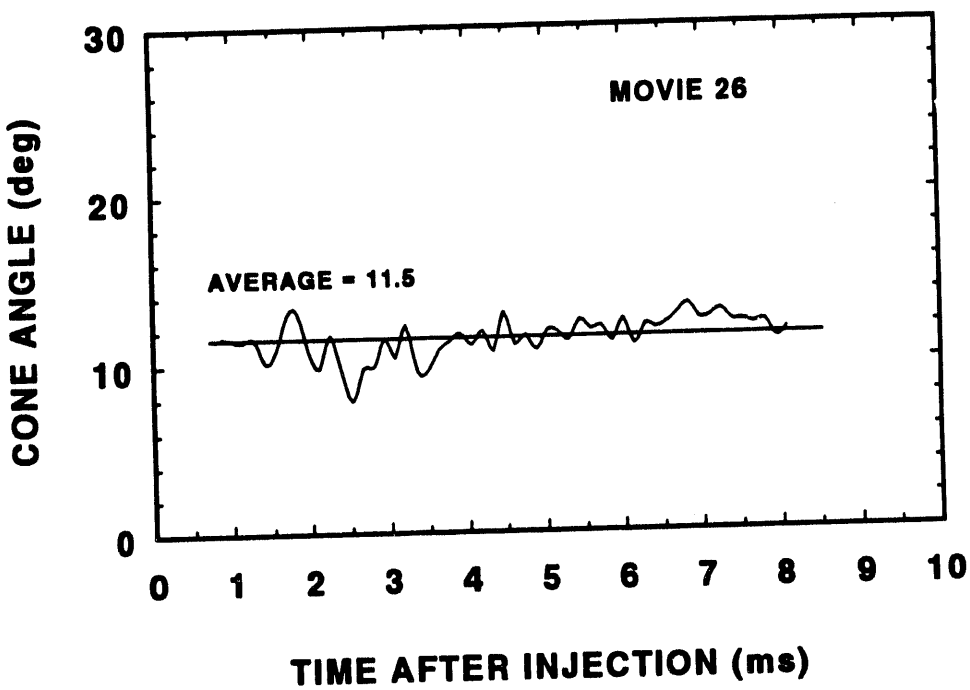
Film no.	Fuel	Wt% and Additive	Nozzle Size (mm)	Actual Fuel Pressure (psi)		Temperature (C)		Needle Lift Duration (msec)		Spray Duration (msec)	Film Speed initial/avg. (frames/sec)	Initial Jet Velocity (m/s)
				Before inj	After inj	Fuel	Chamber	Closed End	Open End			
61	CWS	50, twice	0.4 C	9865	12402	NA	23.6	148	201.5	> 55.8	8600/8987	213.4 (J&S)
62	CWS	50, twice	0.8 C	9600	9560	NA	23.6	49.6	71	70.7	8867/9058	251.1 (J&S)
63	CWS	50, twice	0.6 C	9829	9144	NA	23	74.1	122.4	> 67.4	8400/8807	202.8 (J&S)
64	CWS	50, twice	0.2 C	9808	9770	NA	23	>490	>490	59.8	9000/9253	113.0 (J&S)
65	CWS	50, twice	0.2 C	no inj	no inj	NA	23	no inj	no inj	no inj	no inj	no inj
66	CWS	50, twice	0.4 C	weak inj	weak inj	NA	23	weak inj	weak inj	weak inj	weak inj	weak inj
67	CWS	50, twice	0.4 C	no inj	no inj	NA	22.5	no inj	no inj	no inj	no inj	no inj
68	CWS	50, twice	0.4 C	8000	7928	NA	25	4.8	20.3	99.9	8047/8438	127.7
69	CWS	50, twice	0.4 C	8220	6897	NA	24	372.5	417.5	31.1	8100/8244	101.6 (S&L)
70	CWS	50, twice	0.4 C	12187	3930	NA	23.7	>1546	>1546	167.6	8067/8709	167.6 (S&L)
71	CWS	50, twice	0.4 C	5945	6778	NA	21.4	4.45	12.1	14.8	8067/8222	142.4 (S&L)
72	CWS	50, twice	0.4 C	8073	6170	NA	21.2	4.3	11.5	DATA NA	8117/	107.3 (S&L)
73	CWS	50, twice	0.4 C	5740	5565	NA	21.1	4.4	8.5	DATA NA	8133/	42.8 (S&L)
74	CWS	50, twice	0.4 C	5443	5258	NA	21.2	4.5	8.5	DATA NA	8367/	51.1 (S&L)
75	CWS	50, twice	0.4 C	11348	10390	NA	23.3	82.3	40.8	DATA NA	8200/	262.1 (B)
76	CWS	50, twice	0.4 C	11303	8256	NA	23	637	712	DATA NA	8800/	333.9 (B)
77	CWS	50, twice	0.4 C	no inj	no inj	NA	24.5	no inj	no inj	no inj	no inj	no inj
78	CWS	50, twice	0.4 C	4580	4380	NA	23.9	4.78	8.07	DATA NA	8133/	107.1 (B)

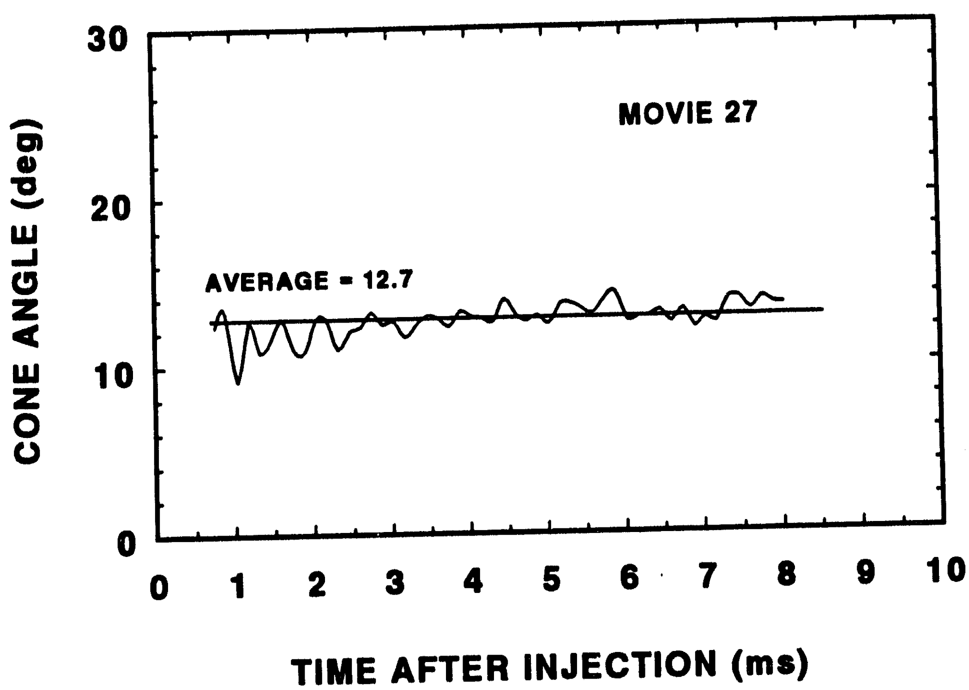
APPENDIX C

TABLE OF CONE ANGLES FOR CWS

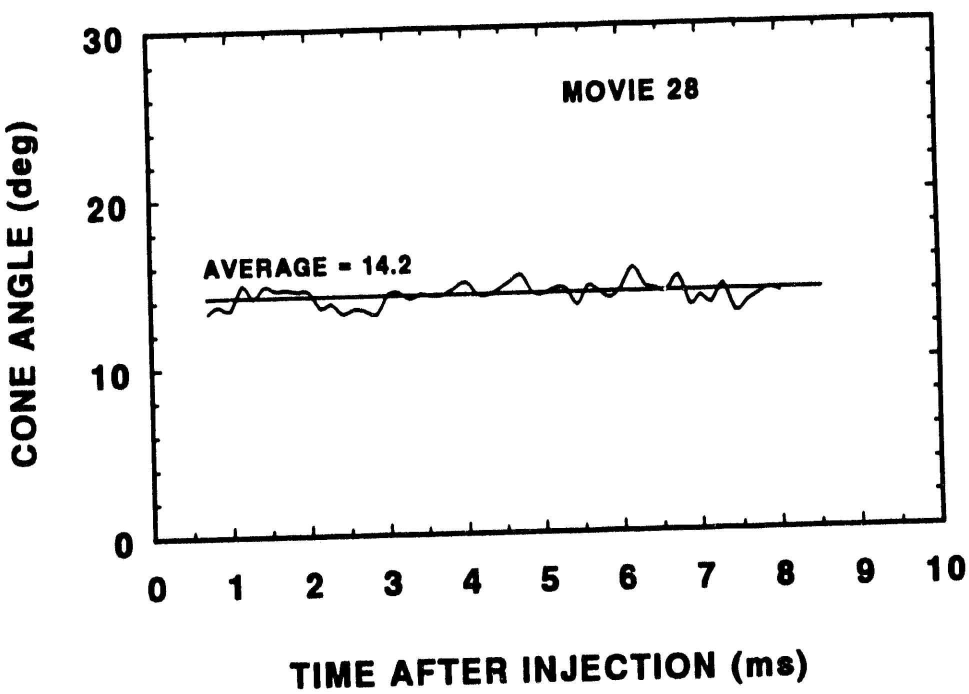
CONE ANGLES FOR CWS AND H_2O CASES

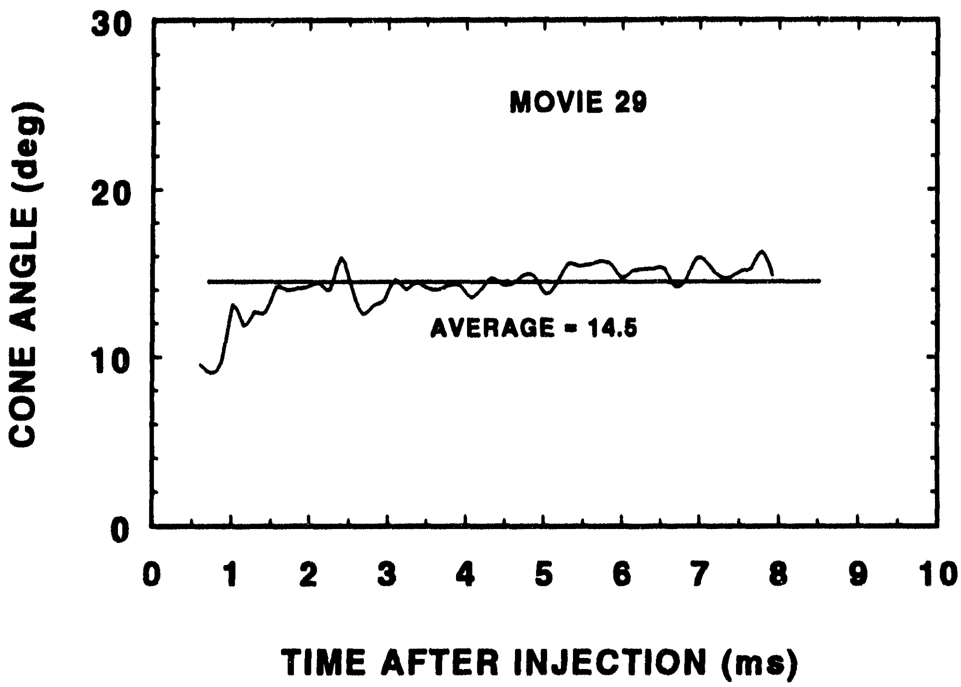
Move #	Pressure (psi)	Nozzle Orifice Diameter (mm)	CWS (%)	Average Cone Angle
1-25	Bad or Unusable			
26	12150	0.39	50	11.5
27	11900	0.39	50	12.7
28	12880	0.39	50	14.2
29	12870	0.39	50	14.5
30	9930	0.39	50	12.0
31	10100	0.39	50	12.4
32	10020	0.39	50	12.7
33	8160	0.39	50	12.2
34-45	Dim Timing Lights or No Injection			
46	12000	0.570	50	14.3
47-58	Dim Timing Lights or No Injection			
59	12000	0.39	40	15.2
60-61	No Data			
62	9800	0.57	50	13.2
63	9830	0.57	50	10.6
64	9810	0.39	50	11.7
65-67	Weak or No Injection			
68	8000	0.39	50	12.5
69	8220	0.39	50	13.5
71	5950	0.39	50	11.7
72	6070	0.39	50	11.1
73	5740	0.39	50	10.6
74	5443	0.39	50	10.9
75	11350	0.39	50	16.0
76	11300	0.39	50	15.4
77	No Injection			
78	4560	0.39	50	21.7
79-93	Bad or No Injection			
94	11950	0.39	0(H_2O)	20.1
95	11950	0.39	0(H_2O)	18.1

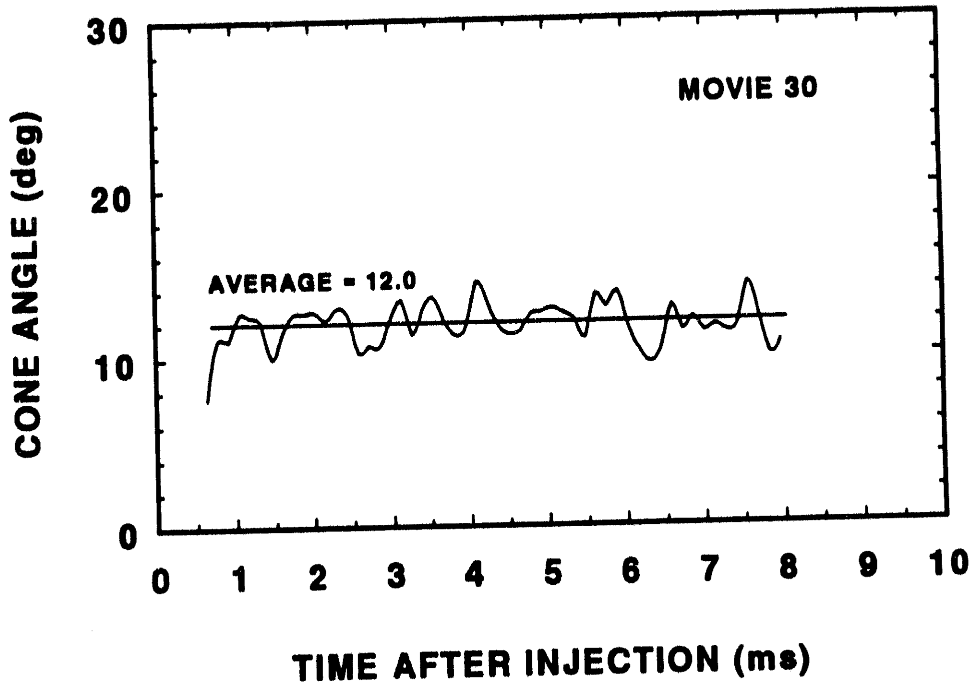

MOVIE 26
AVERAGE = 11.5
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
0
10
20
30
0 1 2 3 4 5 6 7 8 9 10

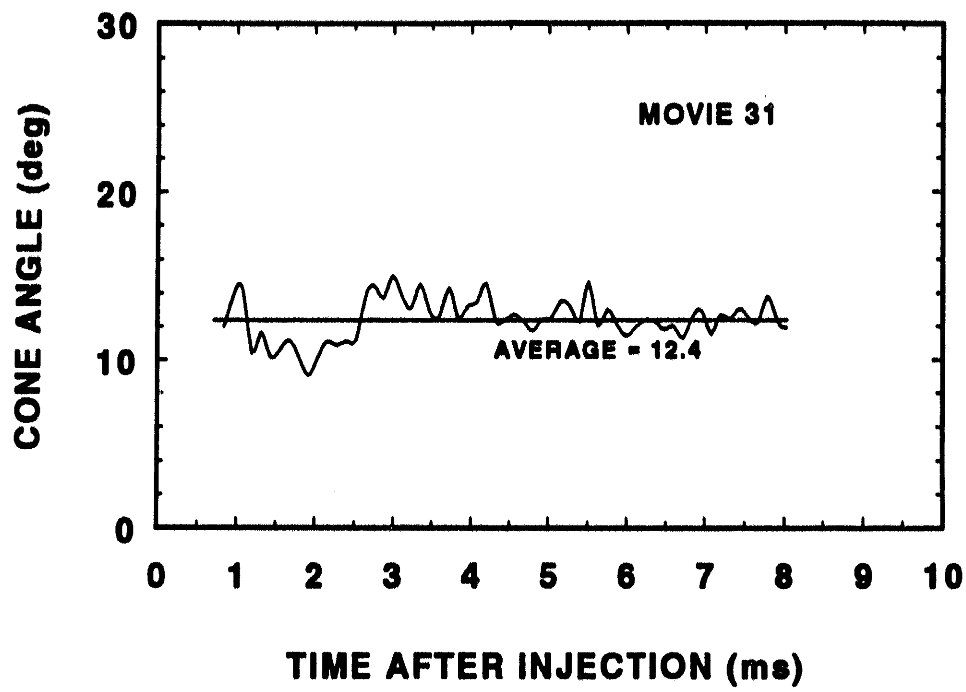


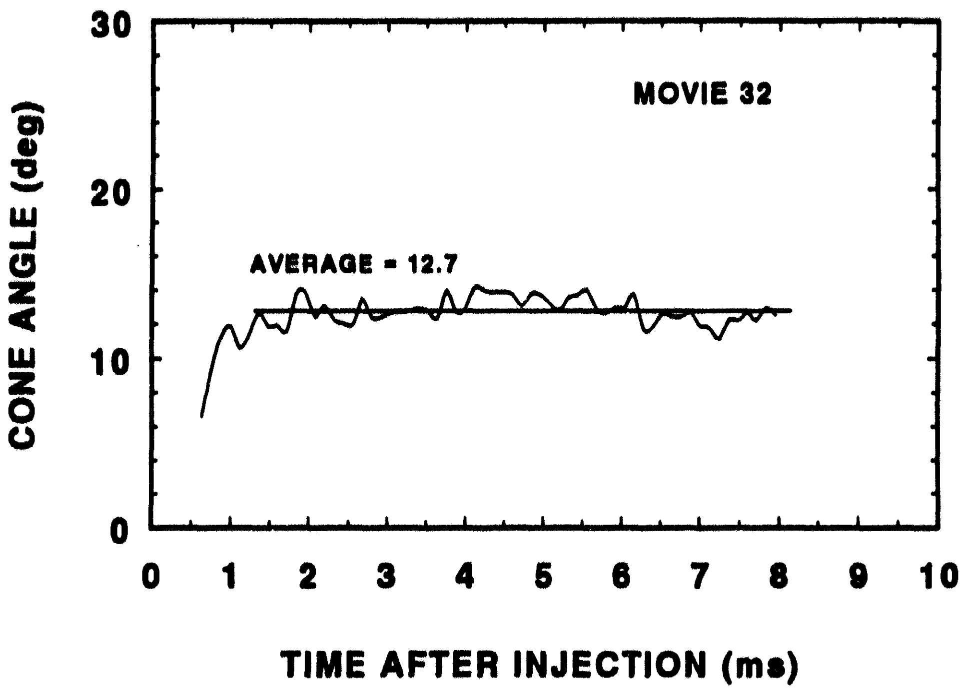
MOVIE 27
AVERAGE = 12.7
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
0
10
20
30
0
1
2
3
4
5
6
7
8
9
10


MOVIE 28
AVERAGE = 14.2
CONE ANGLE (deg)
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

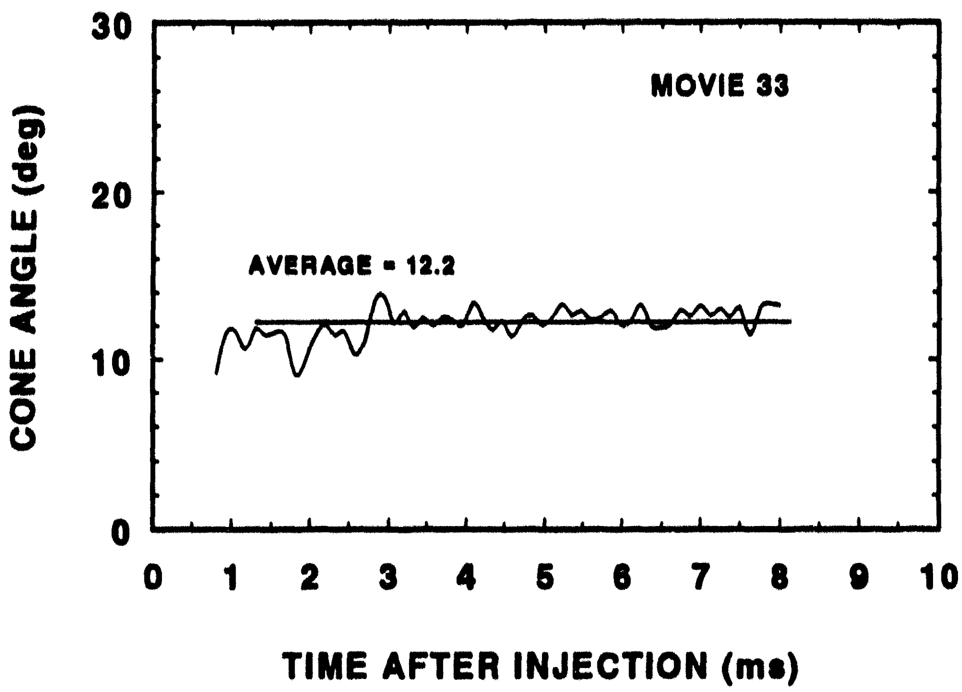

MOVIE 29
AVERAGE = 14.5
CONE ANGLE (deg)
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)


30
20
10
0
CONE ANGLE (deg)
MOVIE 30
AVERAGE = 12.0
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)

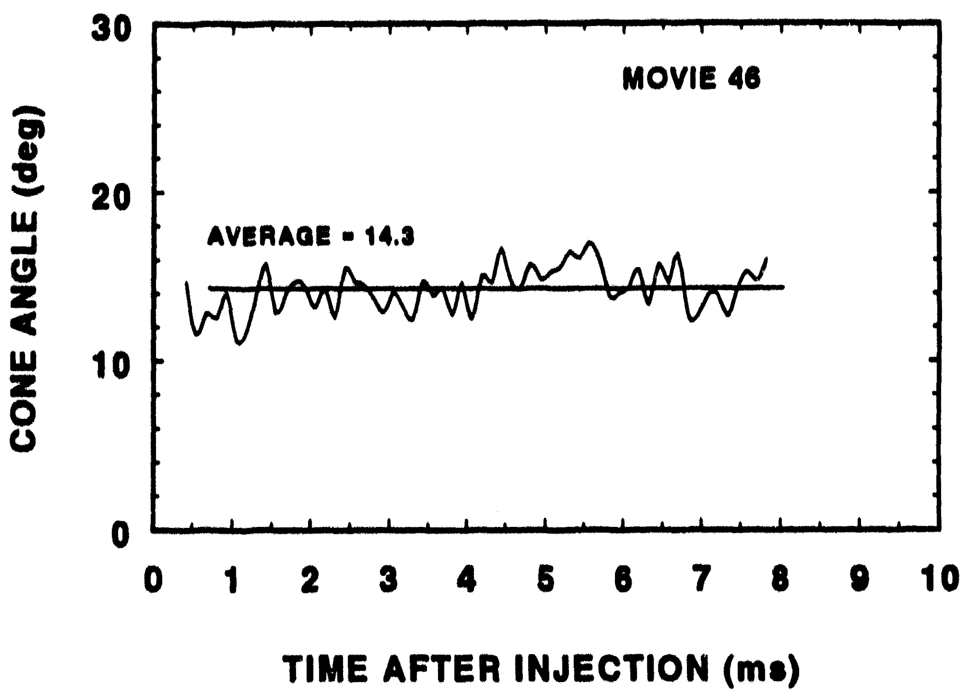

MOVIE 31
AVERAGE = 12.4
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
0
10
20
30
0 1 2 3 4 5 6 7 8 9 10

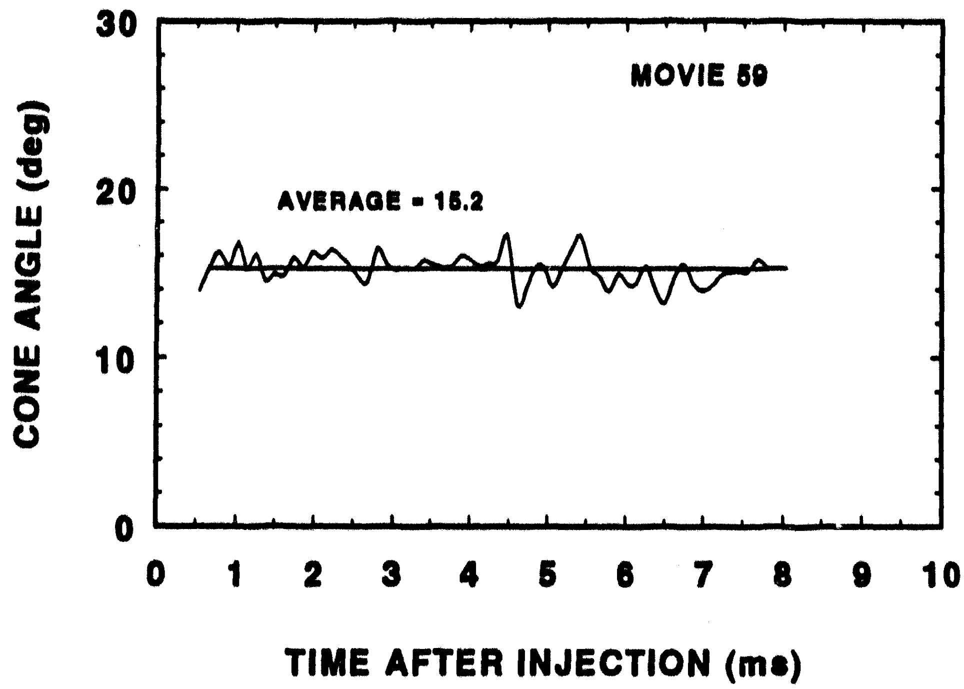


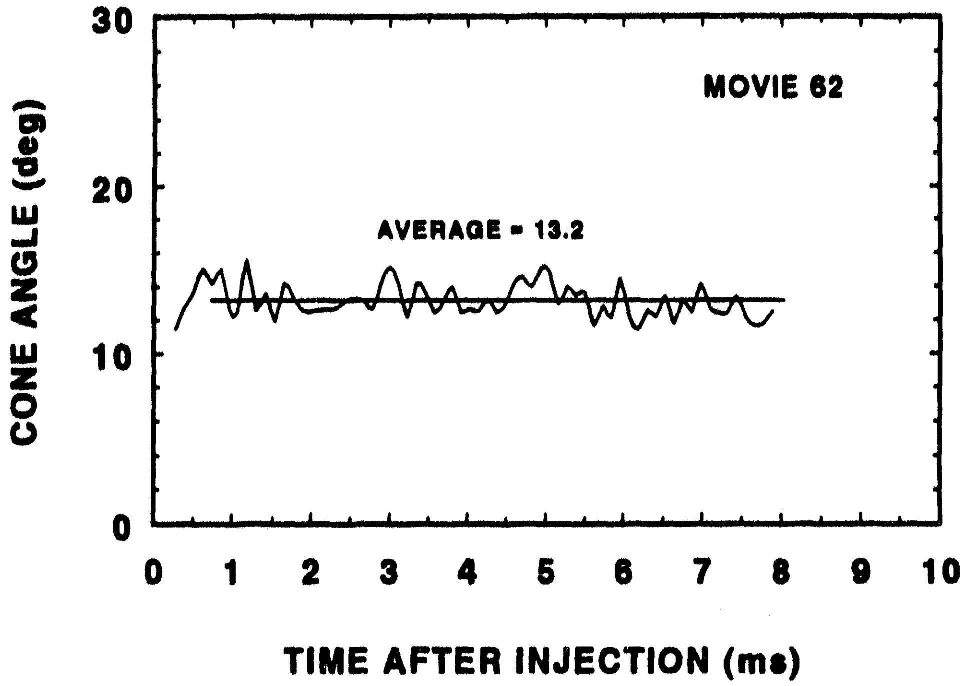
MOVIE 32
AVERAGE = 12.7
CONE ANGLE (deg)
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

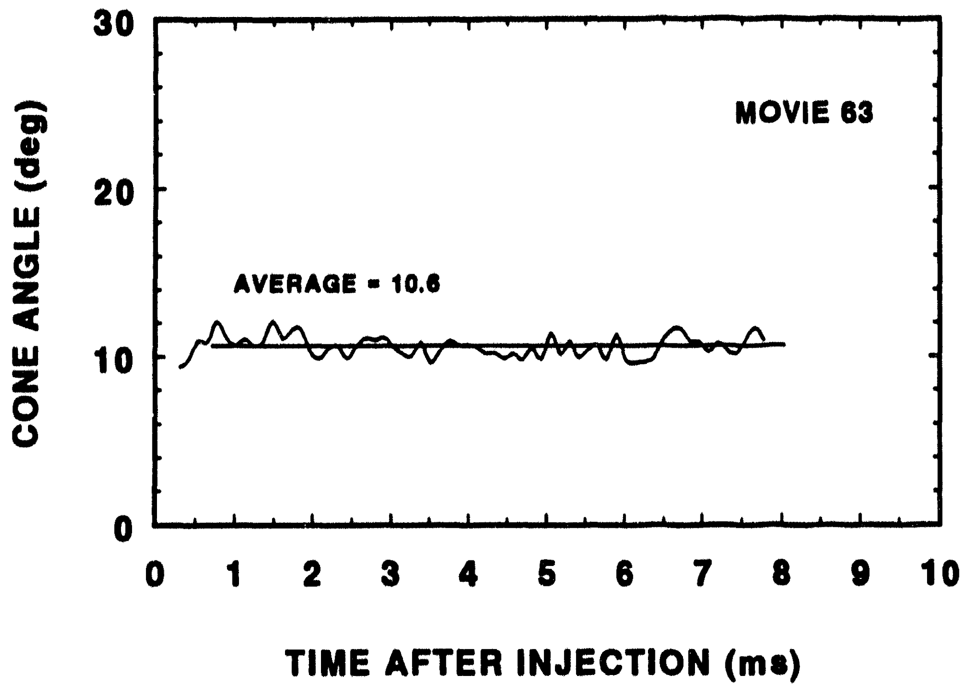


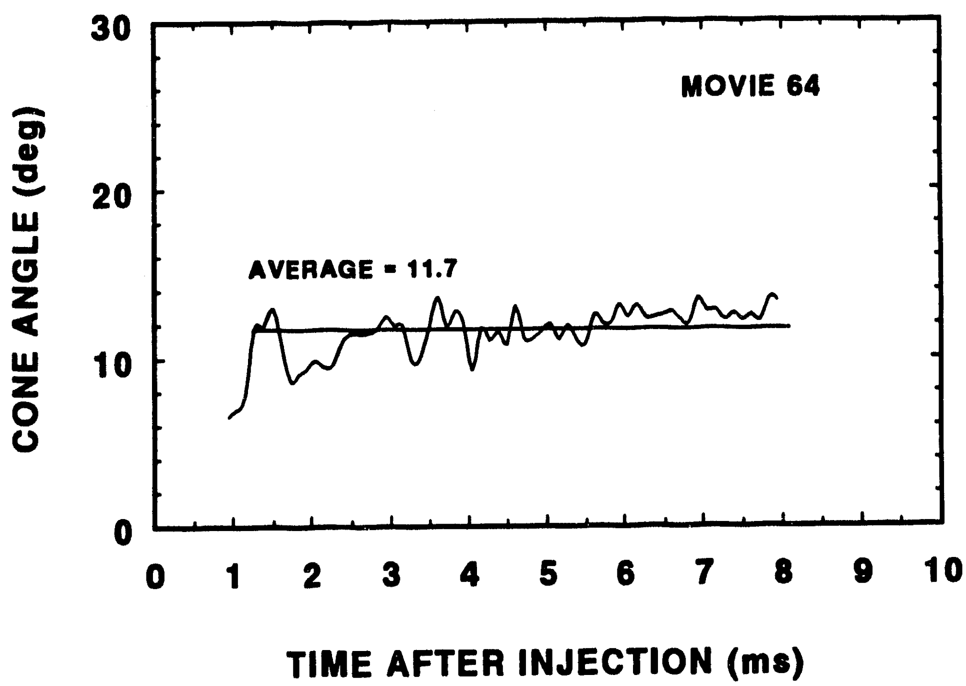
30
20
10
0
MOVIE 33
AVERAGE = 12.2
CONE ANGLE (deg)
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

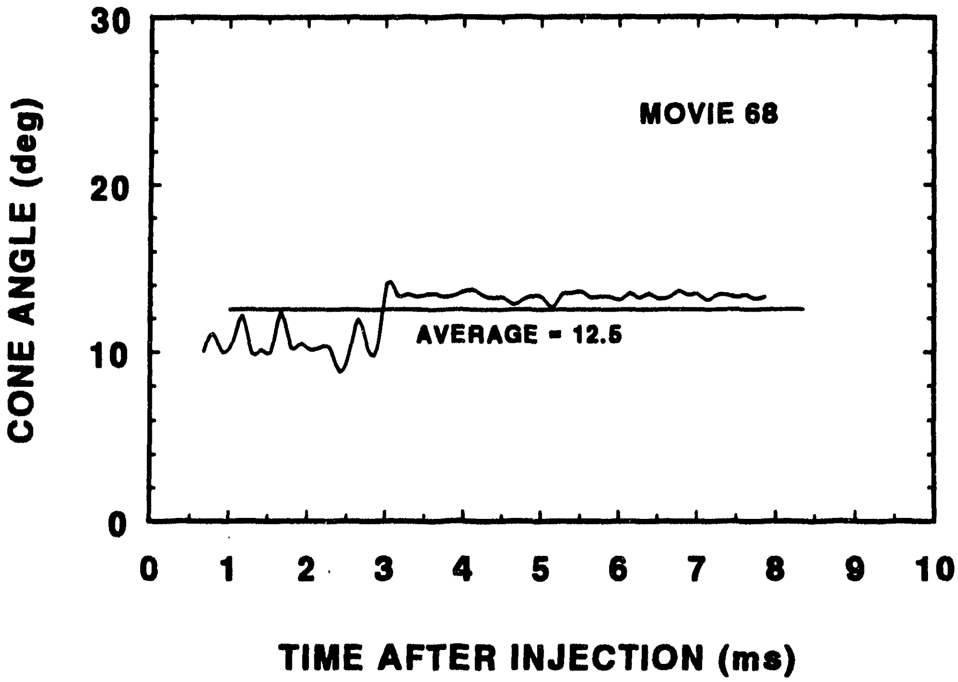

MOVIE 46
AVERAGE = 14.3
CONE ANGLE (deg)
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)


MOVIE 59
AVERAGE = 15.2
CONE ANGLE (deg)
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

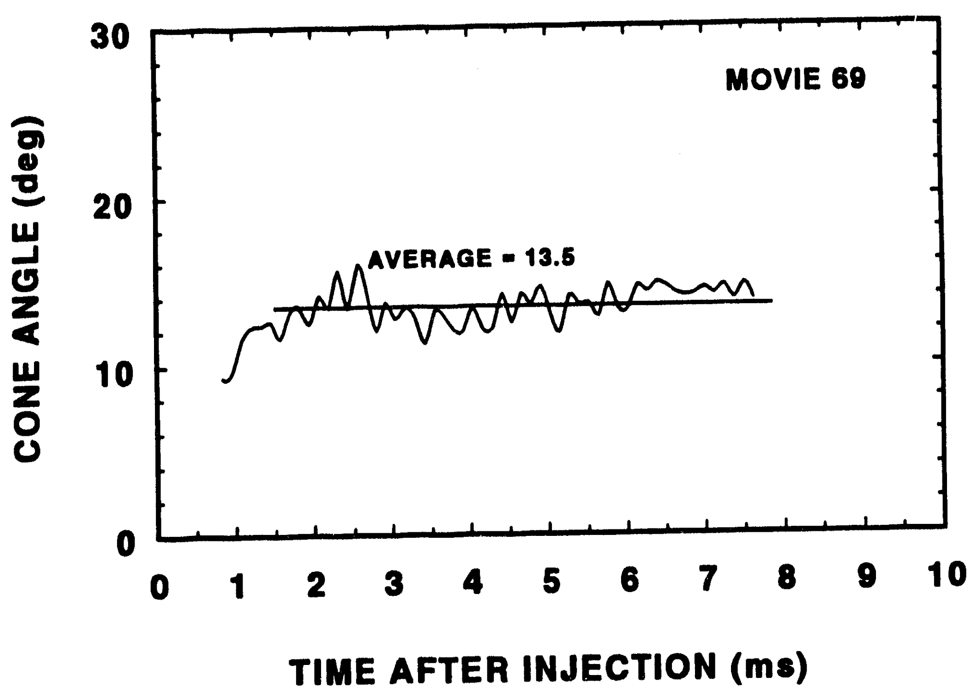

MOVIE 62
AVERAGE = 13.2
CONE ANGLE (deg)
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

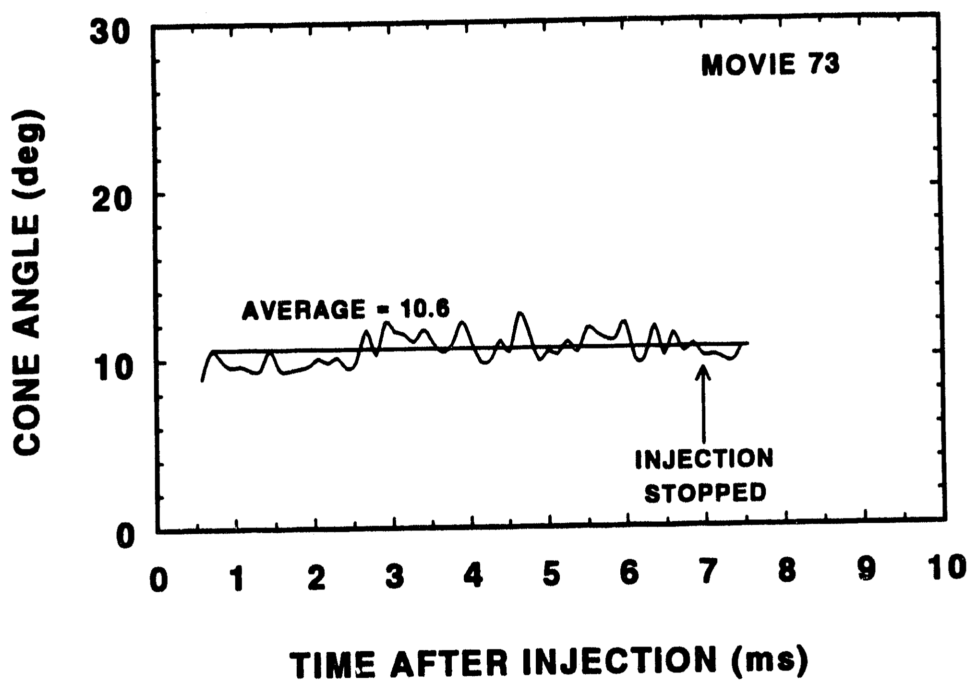

CONE ANGLE (deg)
30
20
10
0
MOVIE 63
AVERAGE = 10.6
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)

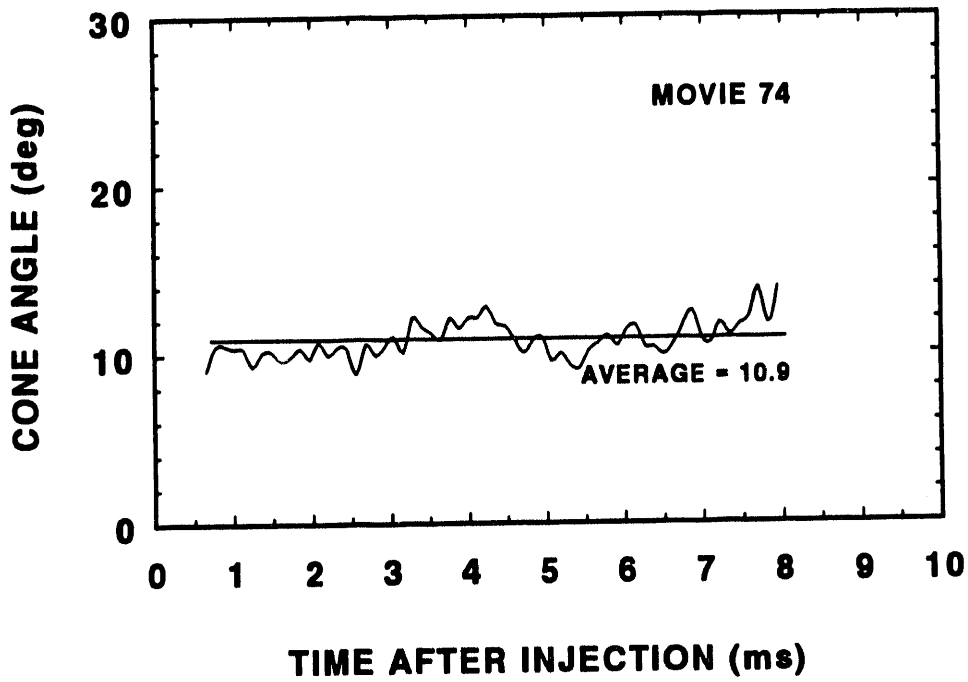

MOVIE 64
AVERAGE = 11.7
CONE ANGLE (deg)
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)



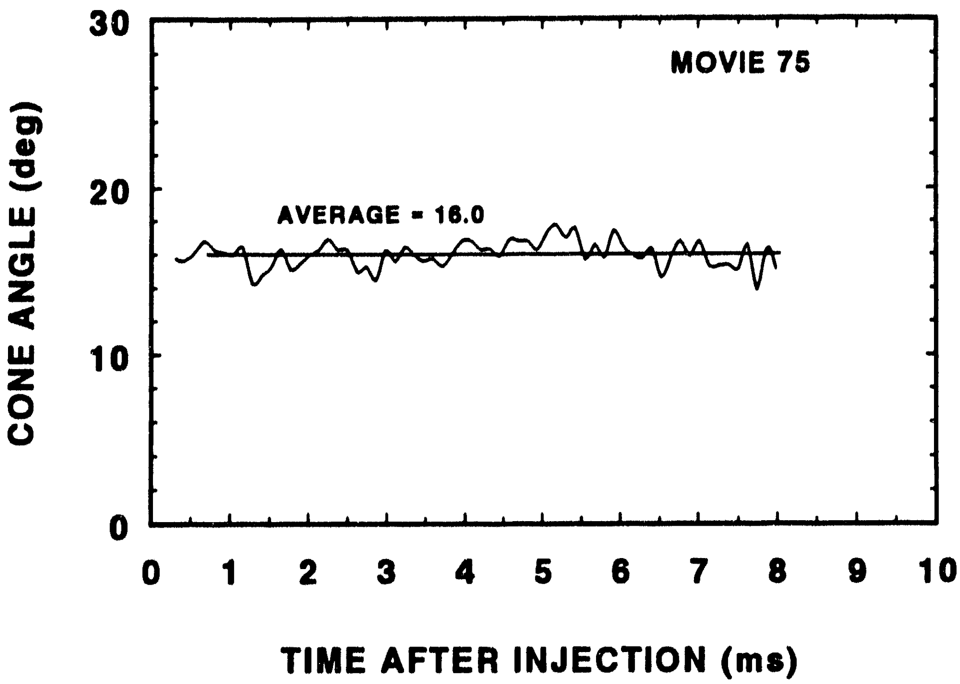
30
20
10
0
CONE ANGLE (deg)
MOVIE 68
AVERAGE = 12.5
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)


MOVIE 69
AVERAGE = 13.5
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
0
10
20
30
0
1
2
3
4
5
6
7
8
9
10

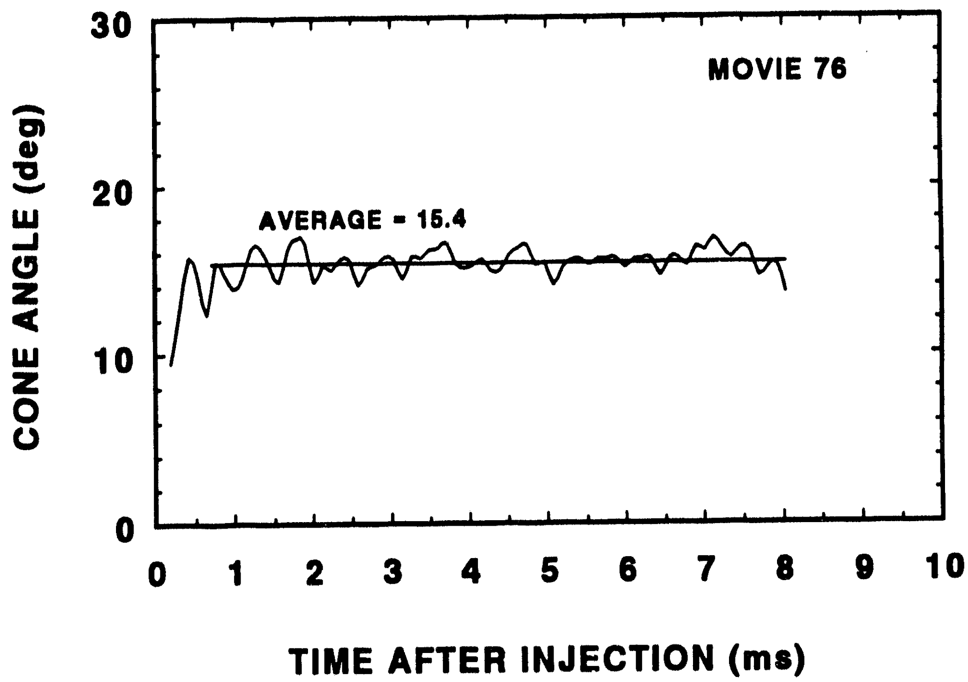

MOVIE 73
AVERAGE = 10.6
INJECTION
STOPPED
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10

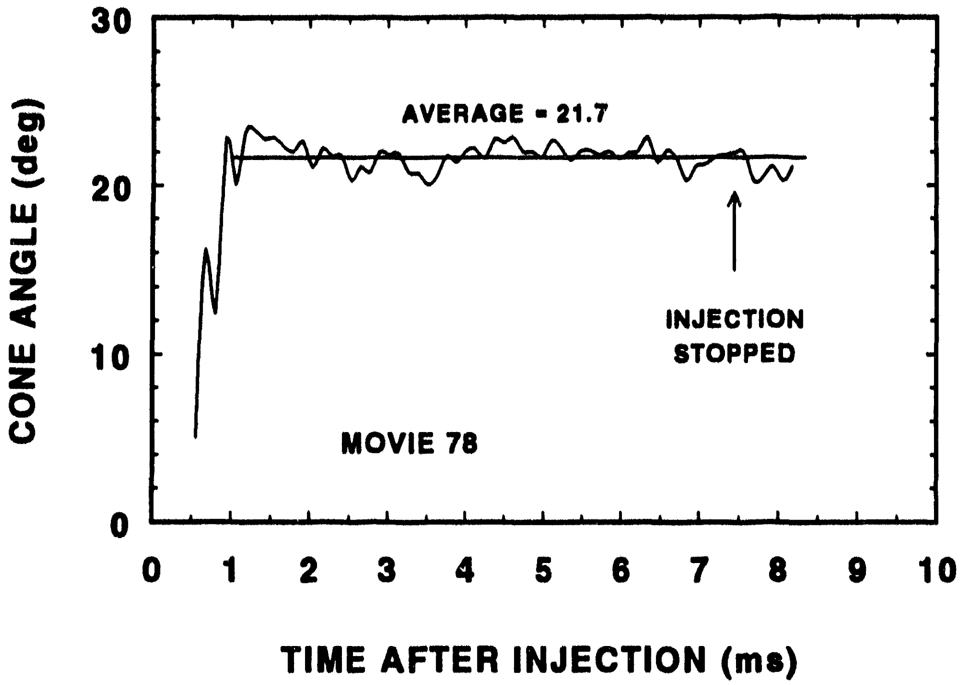


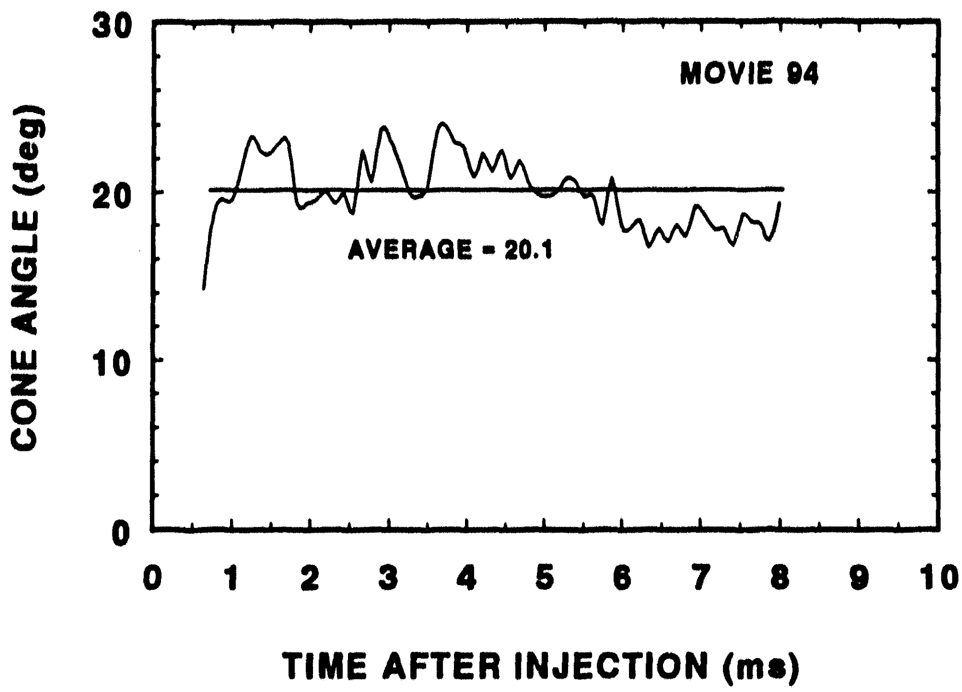
MOVIE 74
AVERAGE = 10.9
CONE ANGLE (deg)
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

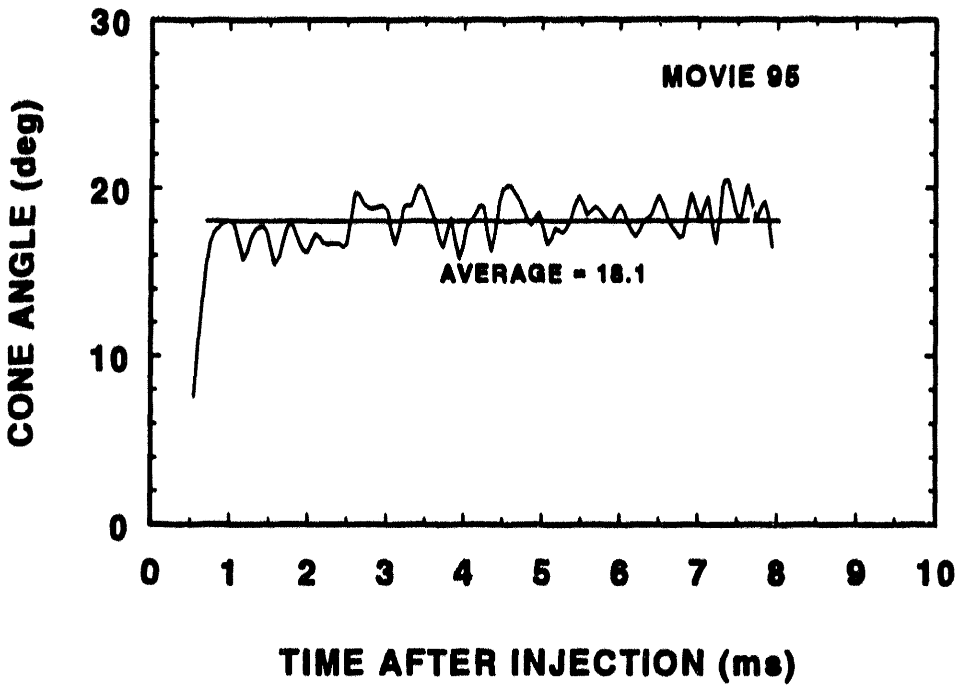


30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
MOVIE 75
AVERAGE = 16.0
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)


MOVIE 76
AVERAGE = 15.4
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
0
10
20
30
0
1
2
3
4
5
6
7
8
9
10


CONE ANGLE (deg)
30
20
10
0
AVERAGE = 21.7
INJECTION
STOPPED
MOVIE 78
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)


30
20
10
0
CONE ANGLE (deg)
MOVIE 94
AVERAGE = 20.1
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)



MOVIE 95
AVERAGE = 18.1
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
0
10
20
30
0 1 2 3 4 5 6 7 8 9 10

APPENDIX D

TABLE OF EXPERIMENTAL DATA FOR DF2

Film no.	Fuel	Nozzle Size (mm)	Pressure (psi)			Trigger Speed (%)	Pulse Duration (msec)	Sampling Frequency (Hz)	Run Duration (sec)	Notes
			Fuel Line	Purge Line	Chamber					
96	DF2	0.4 C	8000	8000	300	95	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
97	DF2	0.4 C	8000	8000	300	no injection	no injection	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
98	DF2	0.4 C	8000	8000	300	83	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
99	DF2	0.4 C	6000	6000	300	85	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
100	DF2	0.4 C	6000	6000	300	87	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
101	DF2	0.4 C	5000	5000	300	81	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
102	DF2	0.4 C	5000	5000	300	79	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
103	DF2	0.4 C	4000	4000	300	71	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
104	DF2	0.4 C	4000	4000	300	75	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
105	DF2	0.4 C	3000	3000	300	91	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
106	DF2	0.4 C	3000	3000	300	94	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
107	DF2	0.4 C	2000	2000	300	82	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
108	DF2	0.4 C	2000	2000	300	94	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
109	DF2	0.4 C	10000	10000	300	85	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
110	DF2	0.4 C	10000	10000	300	97	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
111	DF2	0.4 C	10000	10000	300	82	DATA NA	4000	2	GR,D;offset(4.25) T Chamber=22.8 C
112	DF2	0.4 C	12000	12000	0	86	DATA NA	4000	2	GR,D:offset(4.0932) T chamber=23 C
113	DF2	0.4 C	12000	12000	0	88	DATA NA	4000	2	GR,D:offset(4.0932) T chamber=23 C
114	DF2	0.4 C	12000	12000	300	74	DATA NA	4000	2	GR,D:offset(4.0932) T chamber=23 C
115	DF2	0.4 C	12000	12000	300	85	DATA NA	4000	2	GR,D:offset(4.0932) T chamber=23 C
116	DF2	0.4 C	12000	12000	300	84	DATA NA	4000	2	GR,D:offset(4.0932) T chamber=23 C
117	DF2	0.2 C	12000	12000	300	83	DATA NA	4000	2	GR,D;offset(4.075) T chamber=23
118	DF2	0.2 C	12000	12000	300	88	DATA NA	4000	2	GR,D;offset(4.075) T chamber=23
119	DF2	0.2 C	12000	12000	300	80	DATA NA	4000	2	GR,D;offset(4.075) T chamber=23
120	DF2	0.6 C	12000	12000	300	81	DATA NA	4000	2	GR,D;offset(4.058) T chamber=22.9 C
121	DF2	0.6 C	12000	12000	300	86	DATA NA	4000	2	GR,D;offset(4.058) T chamber=22.9 C

APPENDIX E

TABLE OF REDUCED EXPERIMENTAL DATA FOR DF2

Film no.	Fuel	Nozzle Size (mm)	Actual Fuel Pressure Before inj (psi)	Spray Duration (msec)	Film Speed initial/avg. (frames/sec)	Initial Jet Velocity (m/s)	Cone Angle (deg)
96	DF2	0.4 C	7911	2.743	9500/	132	21.253
97	DF2	0.4 C	7911	no inj	no inj	no inj	no inj
98	DF2	0.4 C	7911	1.882	8333/	142	22.907
99	DF2	0.4 C	5892	2.558	8553/	122	23.426
100	DF2	0.4 C	5892	2.472	8660/	143	23.026
101	DF2	0.4 C	4882	2.438	8067/	120	23.181
102	DF2	0.4 C	4882	3.309	7900/	94.96	23.003
103	DF2	0.4 C	3873	3.281	7133/	100.08	22.045
104	DF2	0.4 C	3873	4.615	7500/	99.3	22.808
105	DF2	0.4 C	2863	2.705	9133/	119.19	25.46
106	DF2	0.4 C	2863	4.336	9433/	106.21	23.091
107	DF2	0.4 C	1853	3.294	8200/	79.67	20.231
108	DF2	0.4 C	1853	4.303	9433/	70.88	20.433
109	DF2	0.4 C	9930	> 7.701	8456/	106.85	24.569
110	DF2	0.4 C	9930	> 8.063	9744/	180.93	23.031
111	DF2	0.4 C	9930	5.309	8233/	109.42	23.091
112	DF2	0.4 C	11950	DATA NA	8625/	DATA NA	DATA NA
113	DF2	0.4 C	11950	> 7.557	8750/	314.74	12.284
114	DF2	0.4 C	11950	> 8.195	7375/	186.07	20.981
115	DF2	0.4 C	11950	> 7.919	8500/	184.41	22.318
116	DF2	0.4 C	11950	> 8.327	8375/	116.97	22.288
117	DF2	0.2 C	11950	> 7.685	8250/	167.52	18.361
118	DF2	0.2 C	11950	> 7.925	8750	185.53	19.262
119	DF2	0.2 C	11950	> 7.582	8000/	152.48	16.091
120	DF2	0.6 C	11950	> 7.791	8125/	277.97	14.792
121	DF2	0.6 C	11950	> 8.071	8625/	245.52	14.837

APPENDIX F

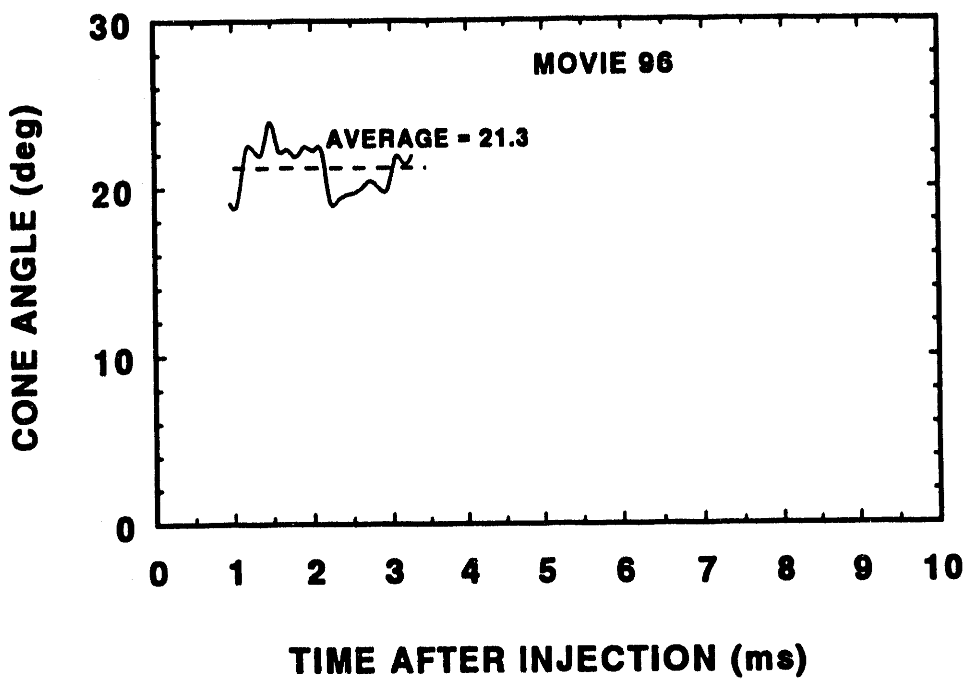
TABLE OF CONE ANGLES FOR DF2

Table 1 Cone angles for diesel movies

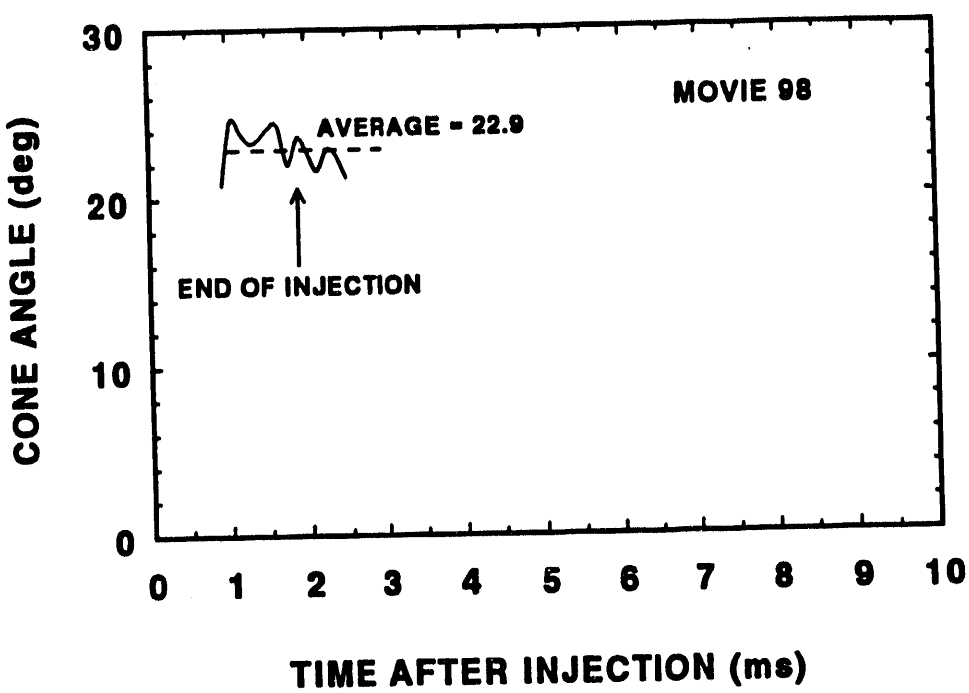
Movie #	Initial true fuel line pressure (psi)	Nozzle orifice diameter (mm)	Chamber pressure (psi)	Average cone angle from Steve's data (deg.)	Average cone angle from Leo's data (deg.)
96	7910	0.39	300		21.25
97	7910	0.39	300	no injection	no injection
98	7910	0.39	300		22.91
99	5890	0.39	300		23.43
100	5890	0.39	300		23.03
101	4880	0.39	300		23.18
102	4880	0.39	300		23.00
103	3870	0.39	300		22.05
104	3870	0.39	300		22.81
105	2860	0.39	300		25.46
106	2860	0.39	300		23.09
107	1850	0.39	300		20.23
108	1850	0.39	300		19.10

Table 2 Cone angles for diesel movies

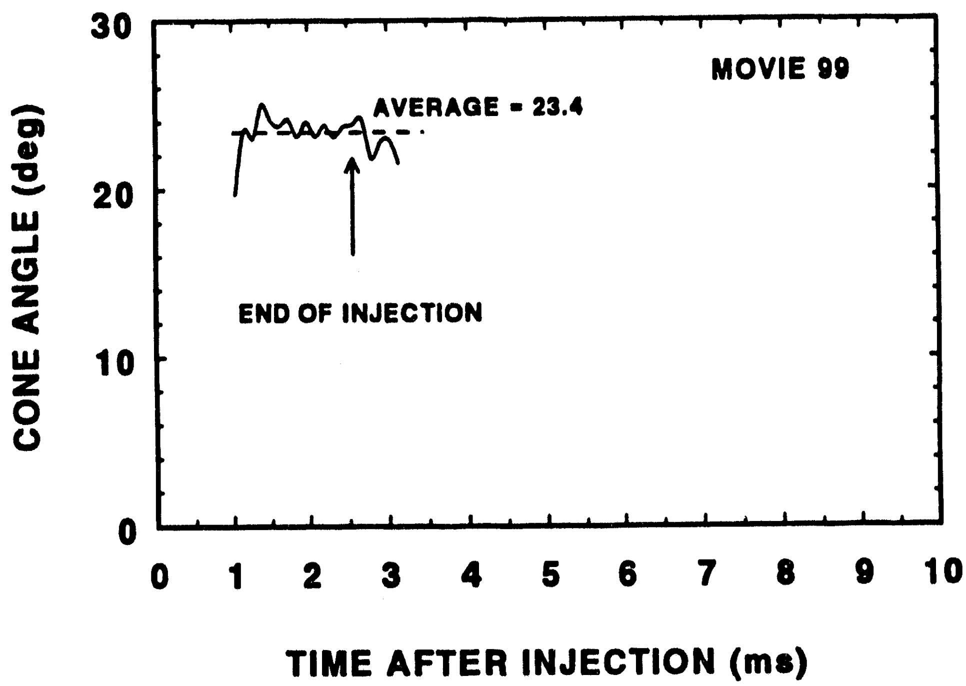
Movie #	Initial true fuel line pressure (psi)	Nozzle orifice diameter (mm)	Chamber pressure (psi)	Average cone angle from Steve's data (deg.)	Average cone angle from Leo's data (deg.)
109	9930	0.39	300		24.57
110	9930	0.39	300		23.03
111	9930	0.39	300	23.09	
112	11950	0.39	0	Time data NA	Time data NA
113	11950	0.39	0	12.28	
114	11950	0.39	300	20.70	21.27
115	11950	0.39	300		22.32
116	11950	0.39	300		22.29
117	11950	0.196	300	18.36	
118	11950	0.196	300	19.26	
119	11950	0.196	300	16.09	
120	11950	0.57	300		14.79
121	11950	0.57	300		14.84



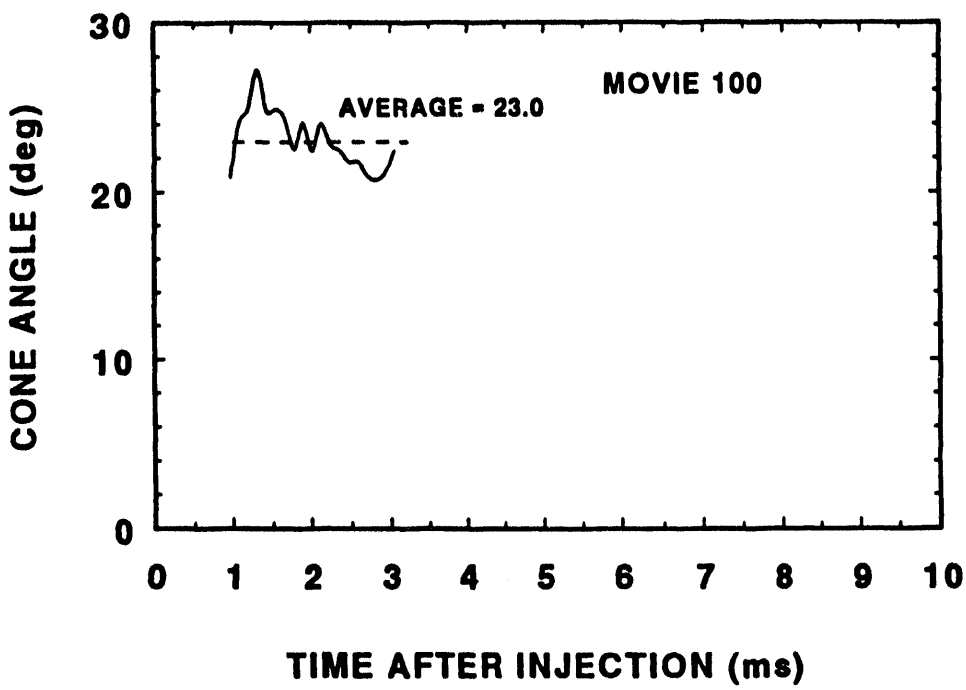
MOVIE 96
AVERAGE = 21.3
CONE ANGLE (deg)
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

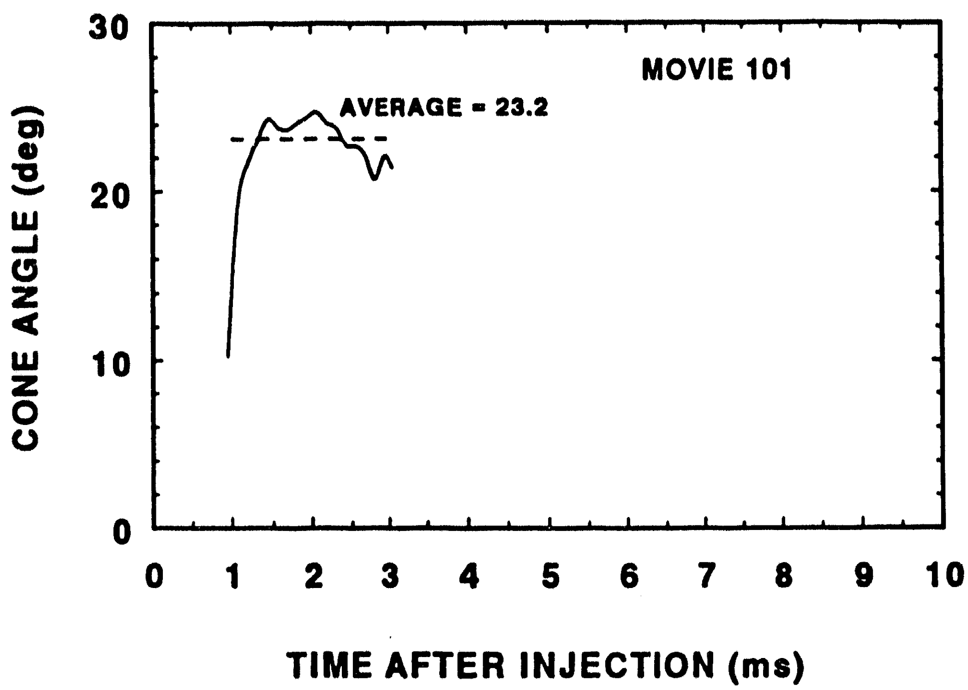


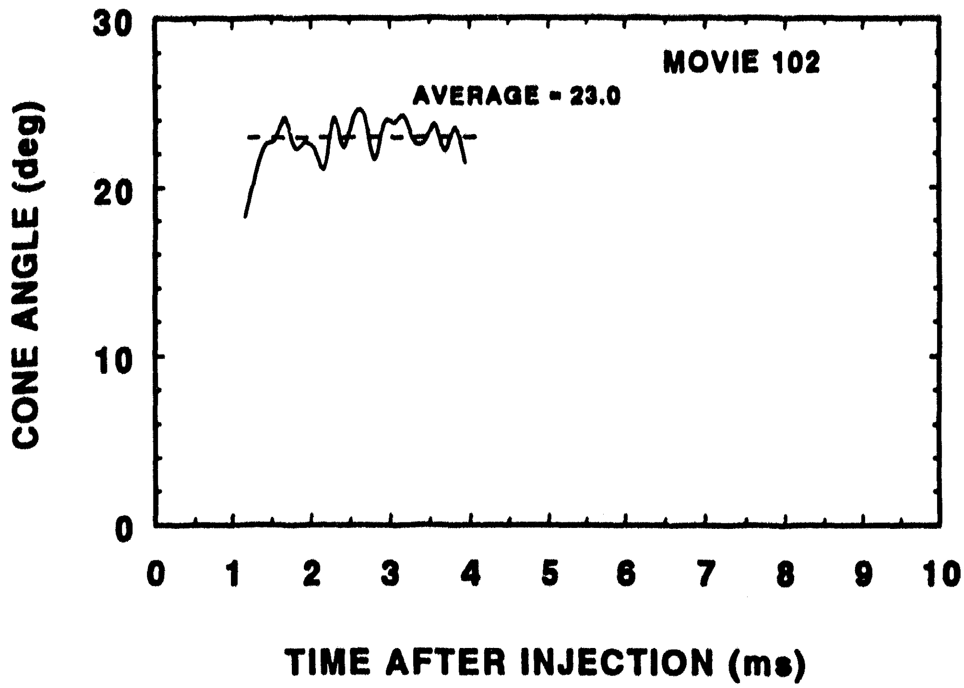
30
20
10
0
CONE ANGLE (deg)
MOVIE 98
AVERAGE = 22.9
END OF INJECTION
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)



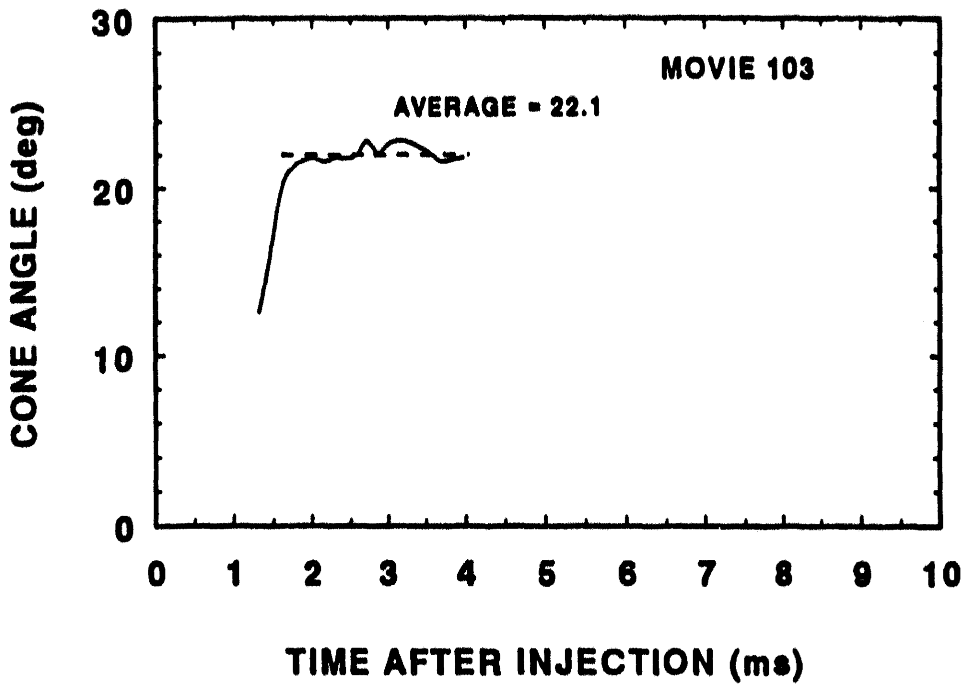
MOVIE 99
AVERAGE = 23.4
END OF INJECTION
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10


30
20
10
0
CONE ANGLE (deg)
MOVIE 100
AVERAGE = 23.0
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

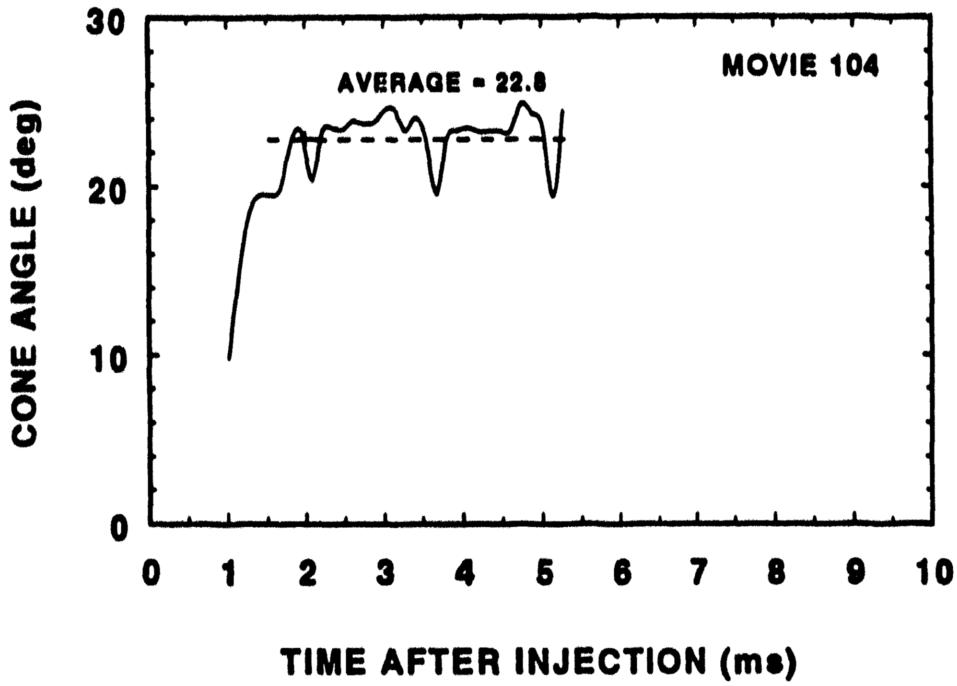

CONE ANGLE (deg)
30
20
10
0
MOVIE 101
AVERAGE = 23.2
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

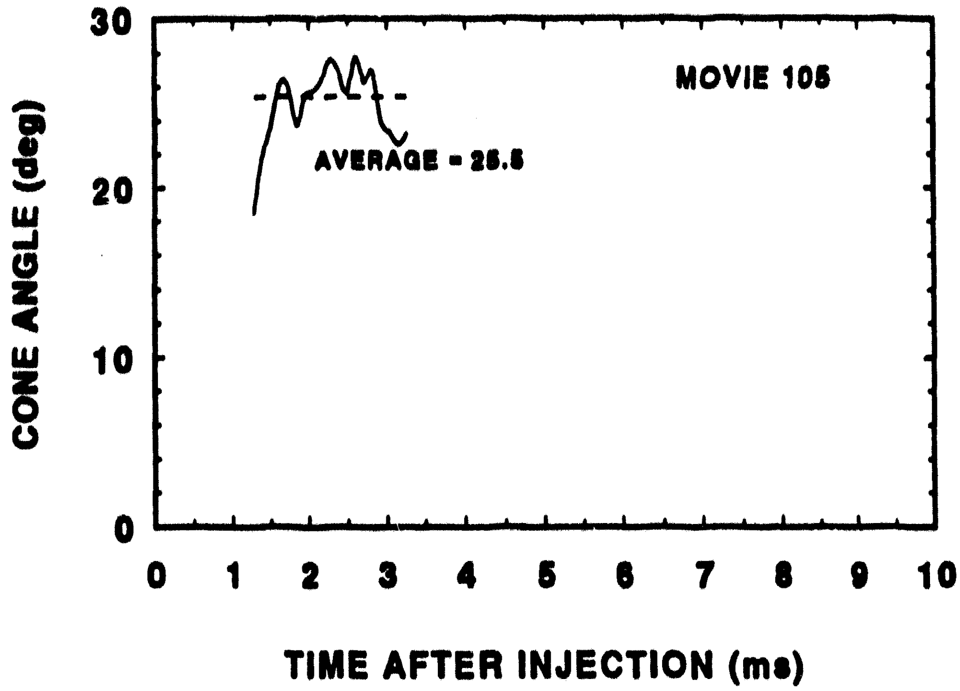


CONE ANGLE (deg)
30
20
10
0
MOVIE 102
AVERAGE = 23.0
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

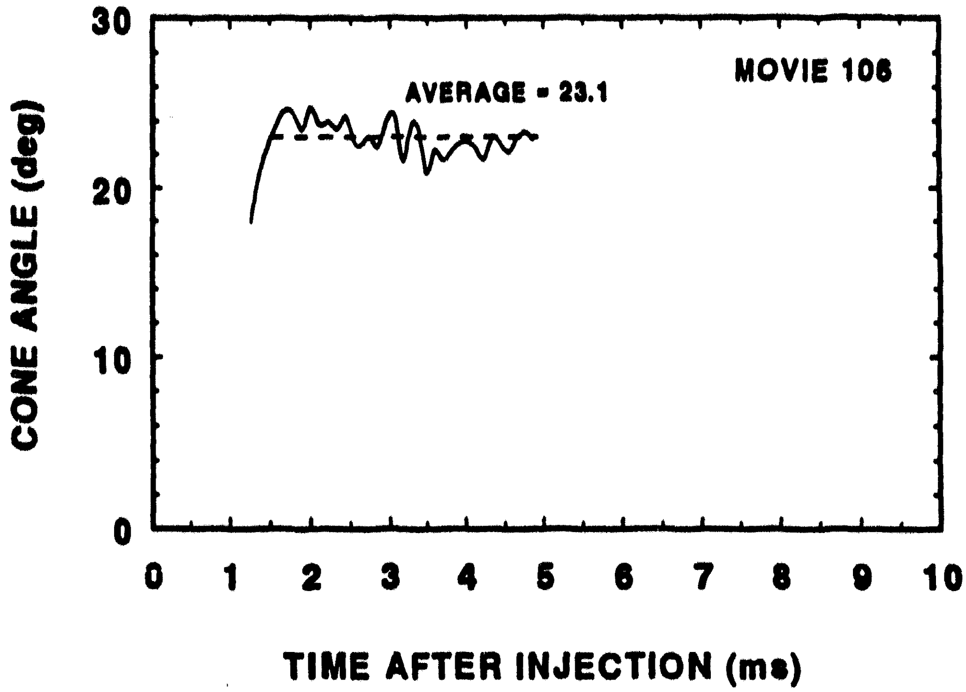


CONE ANGLE (deg)
30
20
10
0
MOVIE 103
AVERAGE = 22.1
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

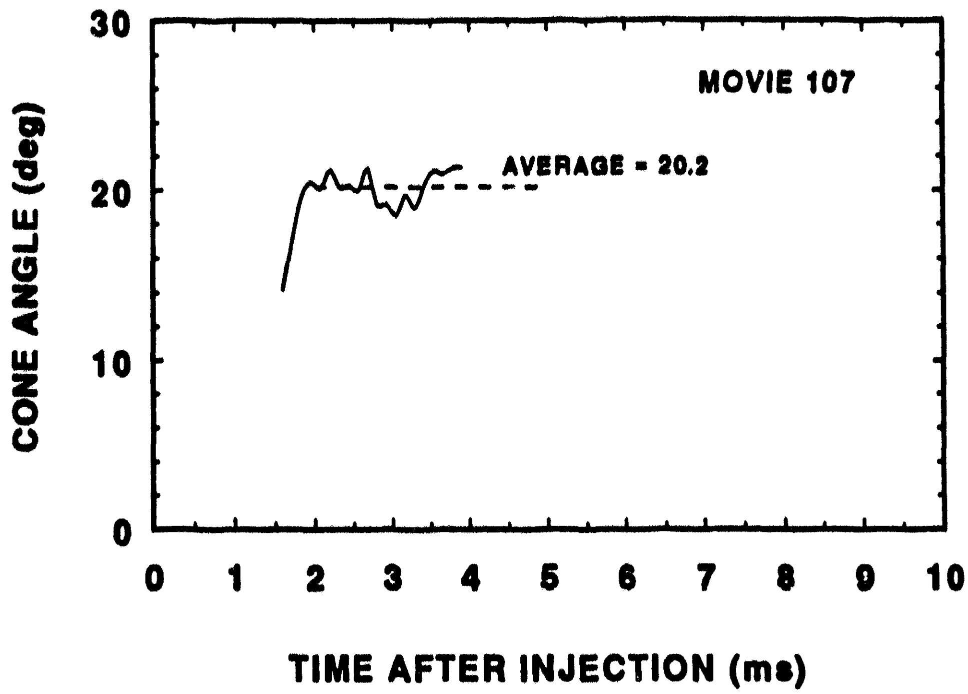

30
20
10
0
CONE ANGLE (deg)
AVERAGE = 22.8
MOVIE 104
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)



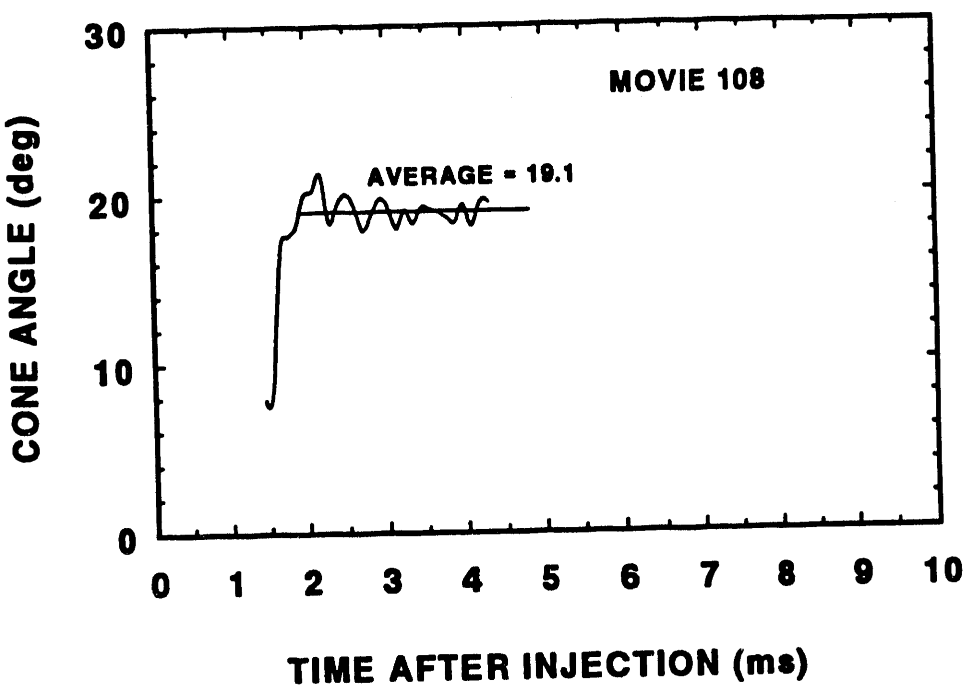
MOVIE 105
AVERAGE = 25.5
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)



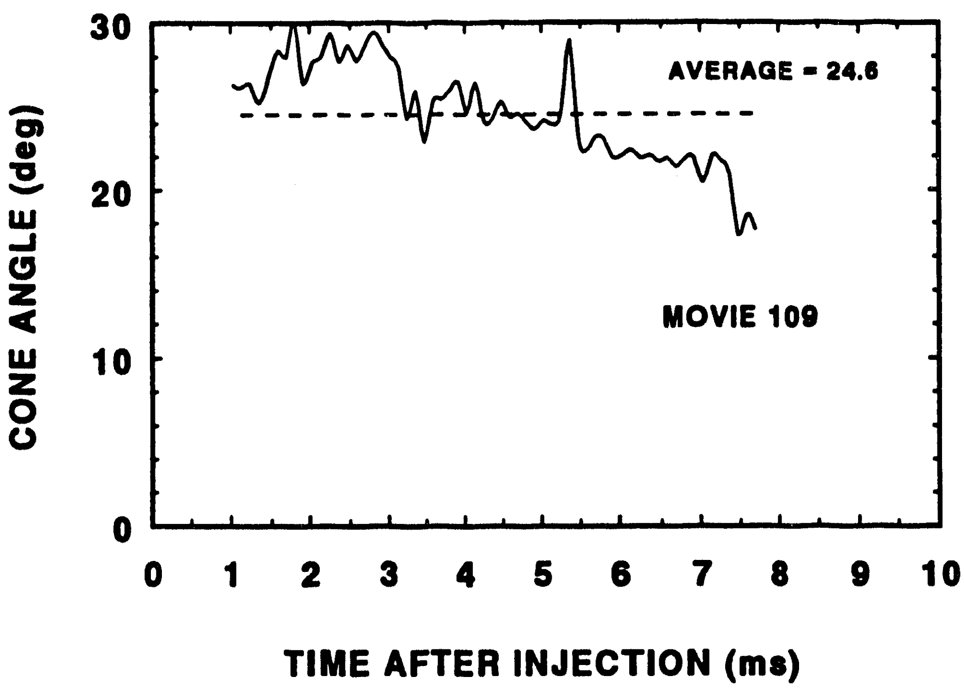
30
20
10
0
CONE ANGLE (deg)
MOVIE 106
AVERAGE = 23.1
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)



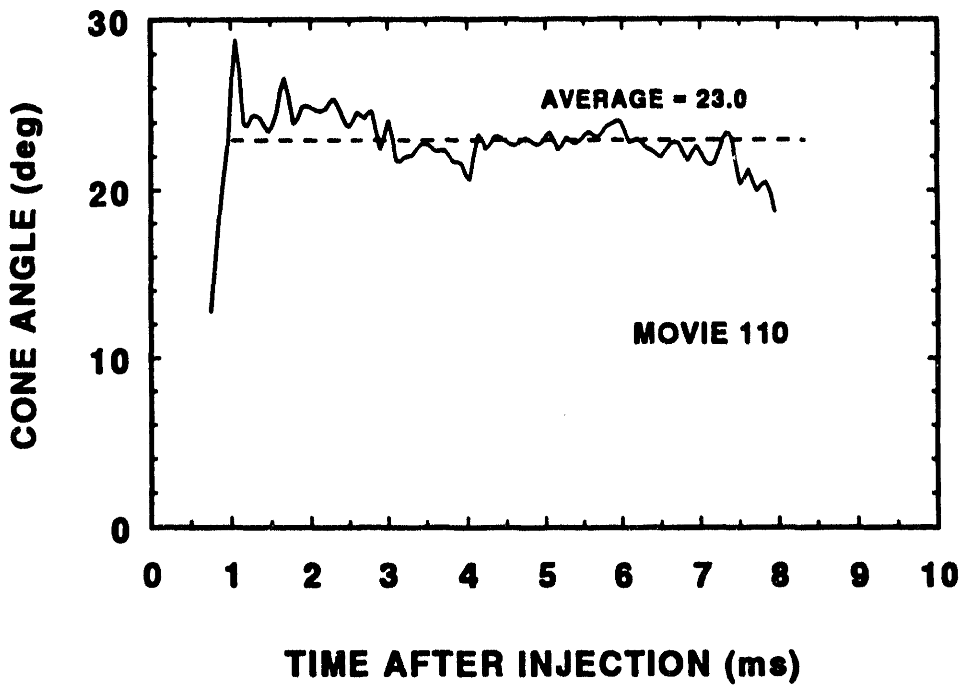
30
20
10
0
CONE ANGLE (deg)
MOVIE 107
AVERAGE = 20.2
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)



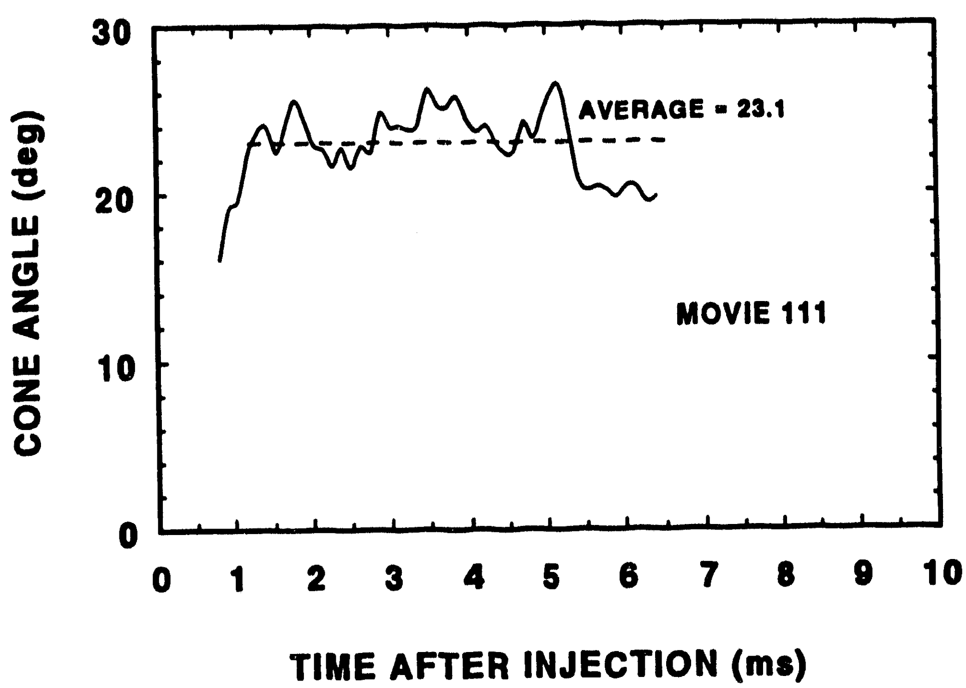
MOVIE 108
AVERAGE = 19.1
CONE ANGLE (deg)
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)



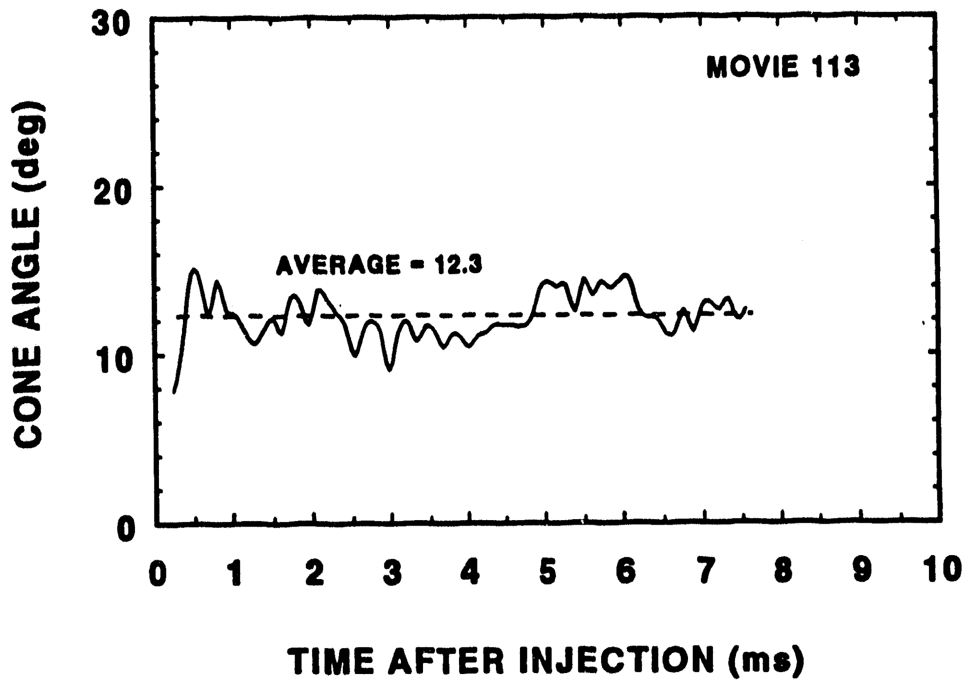
CONE ANGLE (deg)
30
20
10
0
AVERAGE = 24.6
MOVIE 109
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

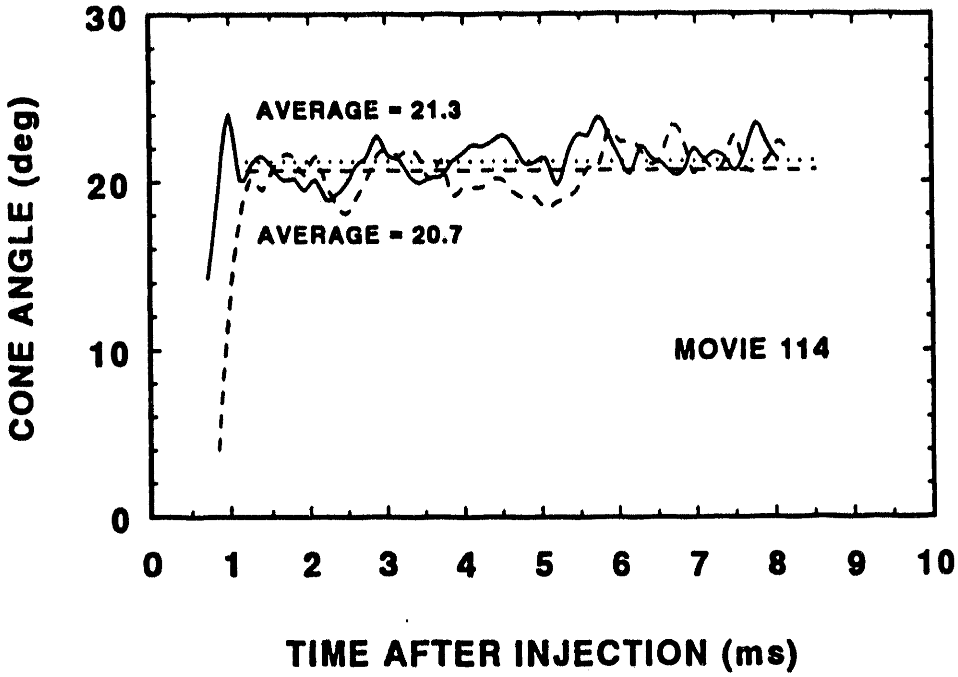


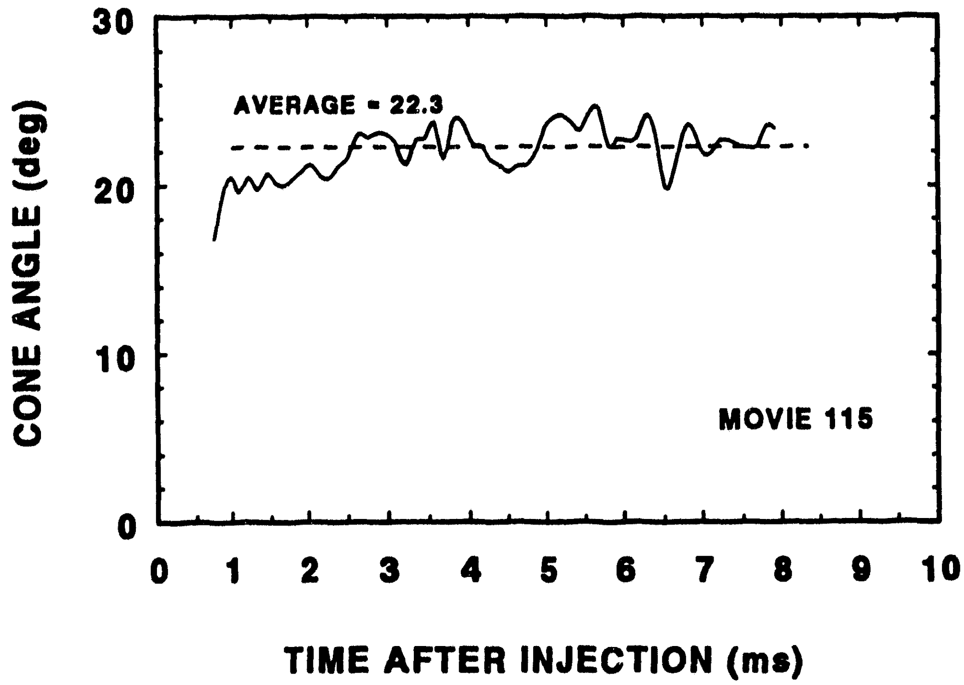
AVERAGE = 23.0
MOVIE 110
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
0
10
20
30
0
1
2
3
4
5
6
7
8
9
10

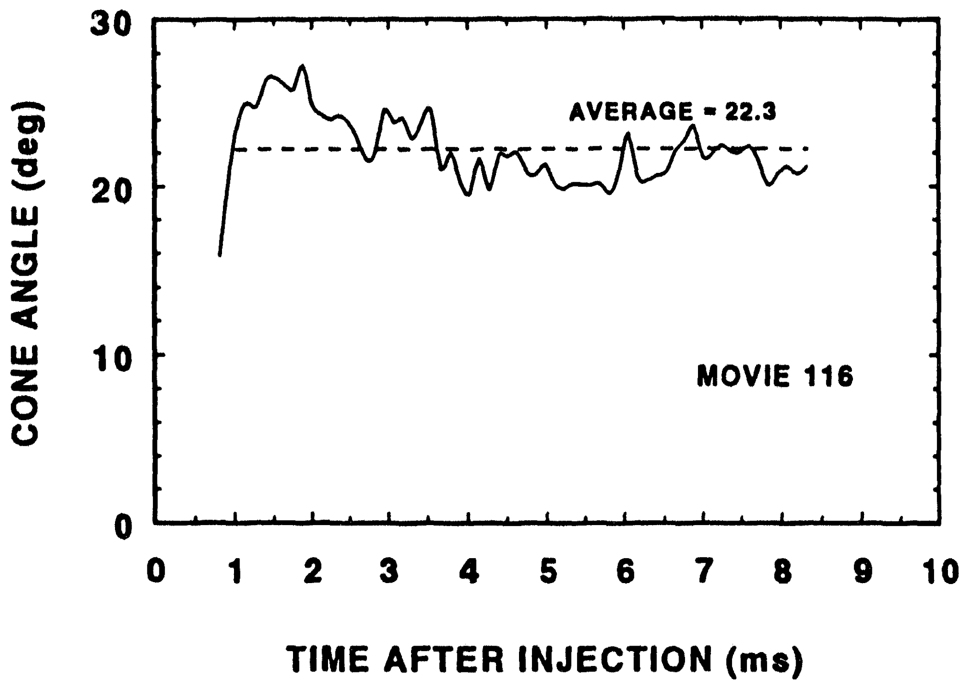


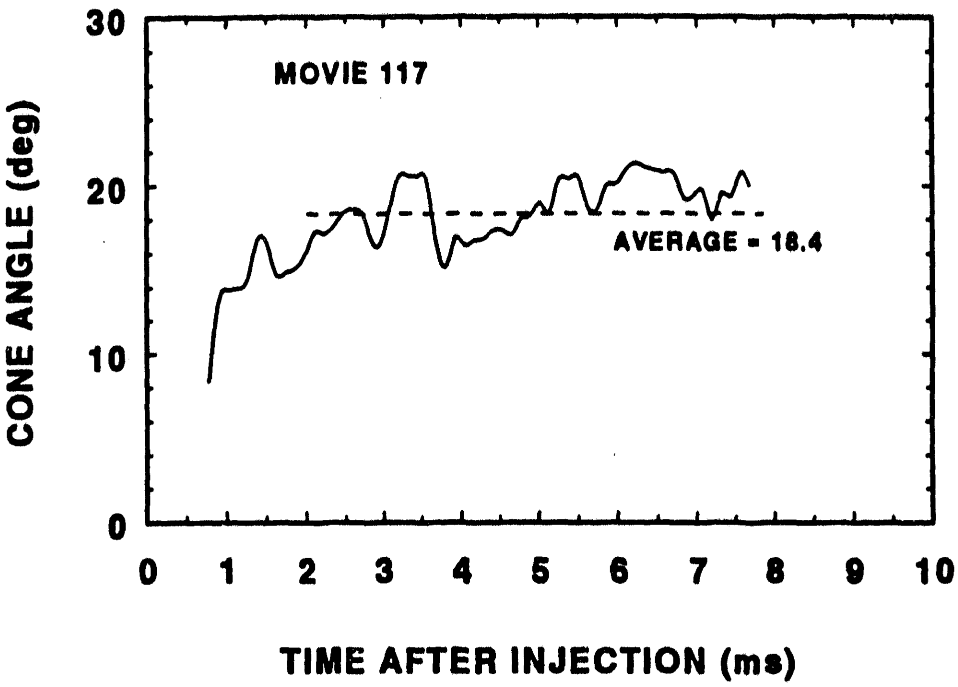
30
20
10
0
CONE ANGLE (deg)
AVERAGE = 23.1
MOVIE 111
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

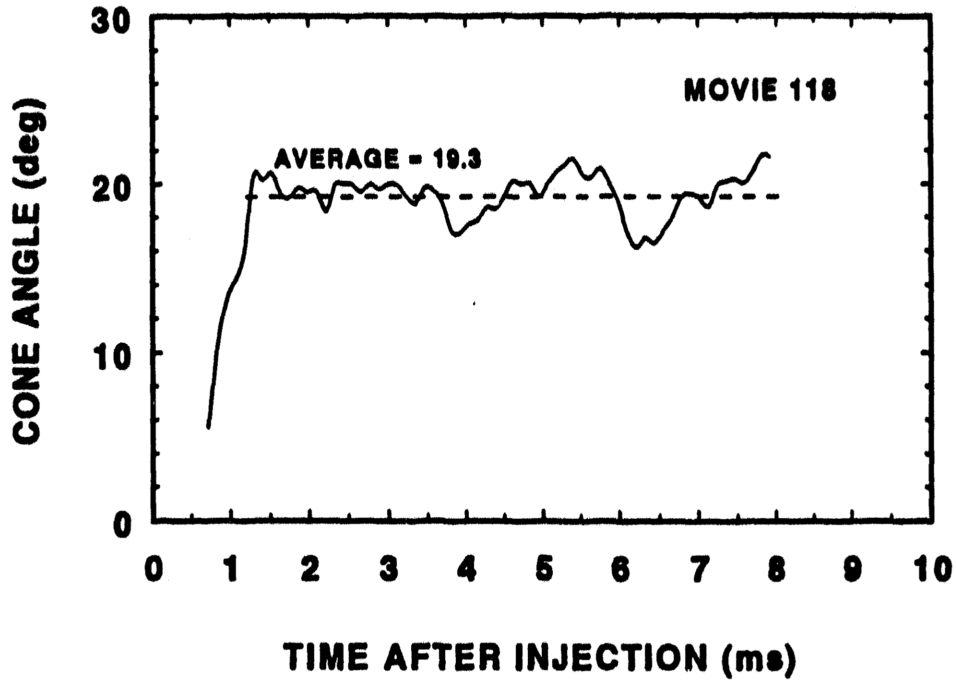

30
20
10
0
CONE ANGLE (deg)
MOVIE 113
AVERAGE = 12.3
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)


AVERAGE = 21.3
AVERAGE = 20.7
MOVIE 114
CONE ANGLE (deg)
TIME AFTER INJECTION (ms)
0
10
20
30
0
1
2
3
4
5
6
7
8
9
10

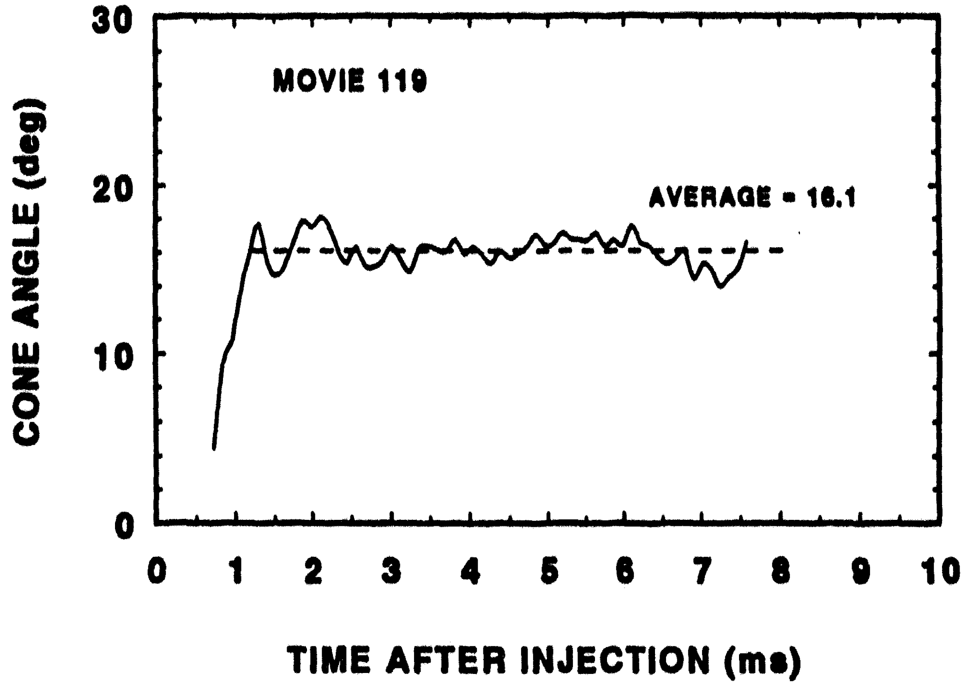

30
20
10
0
CONE ANGLE (deg)
AVERAGE = 22.3
MOVIE 115
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)

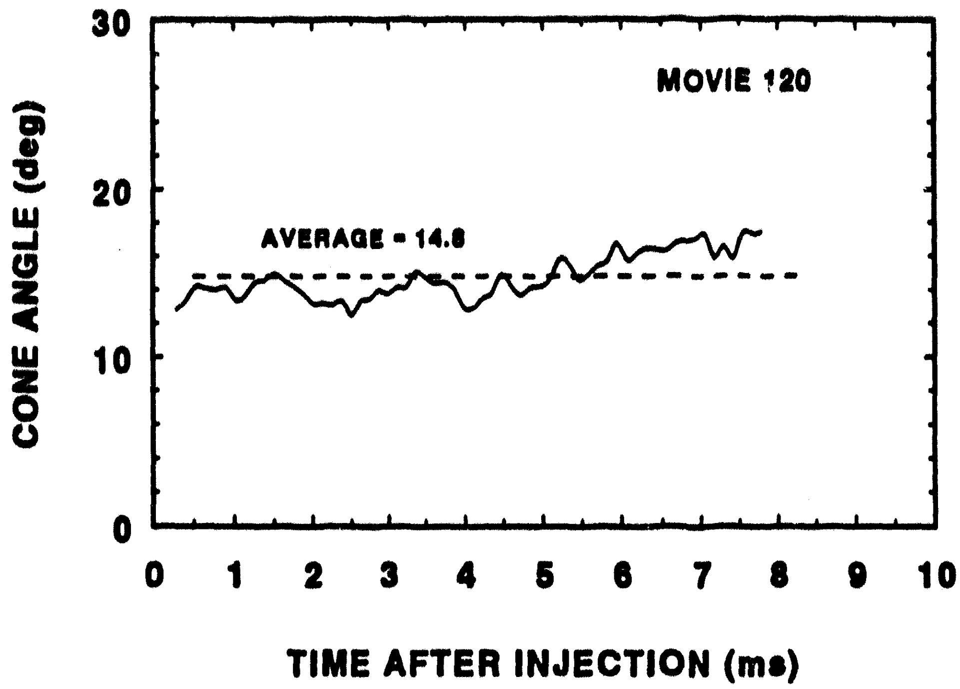

30
20
10
0
CONE ANGLE (deg)
AVERAGE = 22.3
MOVIE 116
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)


30
20
10
0
MOVIE 117
AVERAGE = 18.4
CONE ANGLE (deg)
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

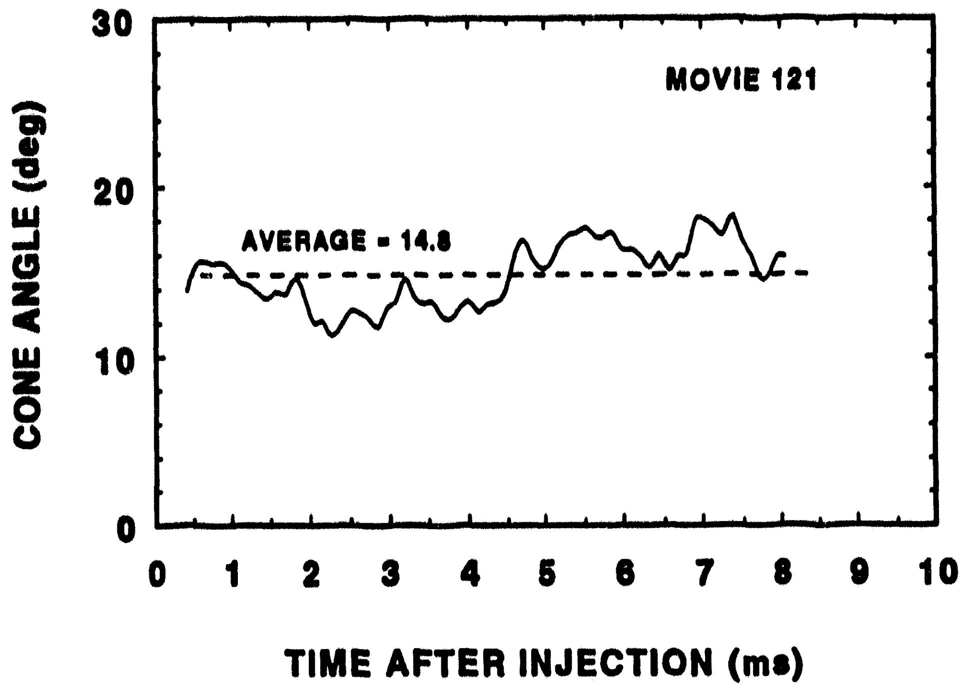


CONE ANGLE (deg)
30
20
10
0
MOVIE 118
AVERAGE = 19.3
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)


MOVIE 119
AVERAGE = 16.1
CONE ANGLE (deg)
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)



MOVIE 120
AVERAGE = 14.8
CONE ANGLE (deg)
30
20
10
0
0 1 2 3 4 5 6 7 8 9 10
TIME AFTER INJECTION (ms)



30
20
10
0
CONE ANGLE (deg)
MOVIE 121
AVERAGE = 14.8
0
1
2
3
4
5
6
7
8
9
10
TIME AFTER INJECTION (ms)

APPENDIX G

COLLECTION OF TECHNICAL PAPERS

The major results of this project have been presented in the attached nine (9) technical papers and reports. The following is a chronological list of these papers and reports:

1. J. A. Caton, K. D. Kihm, A. K. Seshadri, and G. Zicterman, "Micronized-Coal-Water Slurry Sprays from a Diesel Engine Positive Displacement Fuel Injection System," Proceedings of the Central States Section/Combustion Institute Spring Technical Meeting, Paper No. 58, pp. 361–366, April 1991.
2. J. A. Caton and K. D. Kihm, "Coal-Water Slurry Atomization Characteristics," Proceedings of the Eighth Annual Coal-Fueled Heat Engines and Gas Stream Cleanup Systems Contractors Review Meeting, U. S. Department of Energy, Morgantown Energy Technology Center, pp. 273–282, July 1991.
3. A. K. Seshadri, J. A. Caton and K. D. Kihm, "Coal-Water Slurry Spray Characteristics of a Positive Displacement Fuel Injection System," *Coal-Fueled Diesel Engines 1992*, Eds. J. A. Caton and H. A. Webb, ICE-Vol. 16, Energy-sources Technology Conference and Exhibition, American Society of Mechanical Engineers, Internal Combustion Engine Division Symposium, Houston, TX, pp. 55–62, January 1992; also, *ASME Transactions — Journal of Engineering for Gas Turbines and Power*, Vol. 114, No. 3, pp. 528–533, July 1992.
4. J. A. Caton, A. K. Seshadri, and K. D. Kihm, "Spray Tip Penetration and Cone Angles for Coal-Water Slurry Using a Modified Medium-Speed Diesel Engine Injection System," Proceedings of the Central States Section/Combustion Institute Spring Technical Meeting, pp. 234–239, April 1992.
5. K. D. Kihm and J. A. Caton, "Synchronization of a Laser Diffraction Drop Sizing Technique with Intermittent Spray Systems," *Journal of Applied Optics*, Vol. 31, No. 23, pp. 1914–1916, 1992.
6. J. A. Caton, S. E. Payne, D. P. Terracina, and K. D. Kihm, "Coal-Water Slurry Spray Characteristics of an Electronically-Controlled Accumulator Fuel Injection System," Energy-sources Technology Conference and Exhibition, American Society of Mechanical Engineers, Internal Combustion Engine Division Symposium, Houston, TX, *Coal-Fueled Diesel Engines 1993*, Eds. J. A. Caton and H. A. Webb, ICE-Vol. 19, pp. 25–32, February 1993.
7. K. D. Kihm, D. P. Terracina, S. E. Payne and J. A. Caton, "Synchronized Droplet Size Measurements for Coal-Water Slurry (CWS) Diesel Sprays of an Electronically-Controlled Fuel Injection System," Energy-sources Technology Conference and Exhibition, American Society of Mechanical Engineers, Internal Combustion Engine Division Symposium, Houston, TX, *Coal-Fueled Diesel Engines 1993*, Eds. J. A. Caton and H. A. Webb, ICE-Vol. 19, pp. 33–42, February 1993.
8. K. D. Kihm, D. P. Terracina, S. E. Payne and J. A. Caton, "Properly Synchronized Measurements of Droplet Sizes for High-Pressure Intermittent Coal-Water Slurry Fuel Sprays," Proceedings of the 1993 Joint Central and Eastern States Section/Combustion Institute Spring Technical Meeting, Paper No. 50, pp. 271–275, March 1993.
9. J. A. Caton, S. E. Payne, D. P. Terracina, and K. D. Kihm, "Coal-Water Slurry Sprays from an Electronically-Controlled Accumulator Fuel Injection System: Break-up Distances and Times," Proceedings of the 1993 Joint Central and Eastern States Section/Combustion Institute Spring Technical Meeting, Paper No. 76, pp. 405–409, March 1993.

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