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**NASA TECHNICAL
MEMORANDUM**

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CHARACTERIZATION OF SPARK-IGNITION ENGINE
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**PHOTOGRAPHIC CHARACTERIZATION OF
SPARK-IGNITION ENGINE FUEL INJECTORS**

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16. Abstract <p>Manifold port fuel injectors suitable for use in general aviation spark-ignition engines were evaluated qualitatively on the basis of fuel spray characteristics. Photographs were taken at various fuel flow rates or pressure levels. Mechanically and electronically operated pintle injectors generally produced the most atomization. The plain-orifice injectors used on most fuel-injected general aviation engines did not atomize the fuel when sprayed into quiescent air.</p>			
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PHOTOGRAPHIC CHARACTERIZATION OF SPARK-IGNITION

ENGINE FUEL INJECTORS

by Peggy L. Evanich

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SUMMARY

Fuel injector atomization characteristics are being studied in relation to emission and fuel consumption data for several general aviation spark-ignition engines. A qualitative evaluation was made of manifold port fuel injectors suitable for use in these types of engines.

Several injectors were tested by spraying fuel into quiescent air at flows specified for particular engines as defined by the Environmental Protection Agency (EPA) five-mode aircraft operating cycle. Other injectors were tested at constant fuel pressure, as specified by the manufacturers. Comparisons of water and fuel sprays showed that the two fluids do not result in similar atomization characteristics.

Mechanically and electronically operated pintle injectors exhibited the best overall atomization characteristics. Plain-orifice injectors currently in use on the Avco-Lycoming IO-320 engine and the Teledyne-Continental TSIO-360-C engine imparted no atomization to the fuel under the conditions tested. Two types of experimental injectors, a modified pintle injector equipped with multihole plates and a modified plain-orifice nozzle with a multihole plug, were also tested, but no improvements in atomization were evident.

INTRODUCTION

NASA is involved in a research and technology program related to general aviation engines. The overall objective of the program is to establish and demonstrate the technology which will safely reduce general aviation piston engine exhaust emissions and fuel consumption. One area of technology that is being pursued to accomplish these goals is improved manifold port fuel injection.

The degree of fuel atomization influences the degree of homogeneity of the fuel/air mixture which directly influences the combustion process. A lean-limit extension and reduced exhaust emissions may be possible with improved

homogeneity of the charge, but neither has been fully substantiated (refs. 1 to 4). Any program that endeavors to improve emissions and performance of an engine via fuel injection would be greatly aided by studies of fuel atomization in that engine, a part of which is to characterize the fuel spray.

A qualitative evaluation of spark-ignition engine manifold port fuel injectors suitable for general aviation engines has been performed using photographic data. The relative degrees of atomization, cone angle, and overall spray appearance were compared for the various injectors for fuel flow requirements defined by the EPA five-mode aircraft operating cycle. Current aircraft fuel injectors, commercially-available automotive fuel injectors, and several experimental injectors with multihole configurations were evaluated.

APPARATUS AND PROCEDURE

Test Facility

A schematic of the fuel injector spray rig is shown in figure 1. A high pressure air supply was used to pressurize the test fluid which was then filtered. The fluid was metered and routed to the injector. Maximum flow rate was 24 pounds per hour. For the constant pressure injectors, pressures varied 30 to 90 psig. One injector that is used on turbocharged aircraft engines was equipped with an air shroud connected to the turbocharger compressor discharge. The high pressure air supply was also used to supply this air at 0 to 11.5 psig. An electronic power supply was used to operate the electronic injectors with 12 volts.

The spray photographs were taken using a reflected light method. A 4 by 5 inch Graphic camera with a Polaroid adapter, a 127-millimeter lens, and Type 55 or 52 Polaroid film was used. Illumination was provided by an Edgerton microflash unit which was synchronized with the camera shutter. Camera shutter speed was 1/200 second; the strobe duration was 0.1 microsecond. The spray chamber consisted of a rectangular box, 6 by 6 by 8 inches, with plastic windows for strobe illumination and camera access. The injectors were fixed at the top surface of the chamber, spraying vertically downward into ambient air.

Aviation fuel, 100/130 octane, was used in all tests; a few tests were repeated using water for comparison purposes only. The physical properties of both fluids are given in table I.

Test Procedure

Each injector was positioned separately in the test rig. Fluid in the accumulator was pressurized using the air supply and regulated to the correct level for constant pressure nozzles, or the flow rate was adjusted for the variable flow injectors. For shrouded injectors, the shroud air pressure was adjusted, then the fuel flow rate was set. When the fuel spray became fully developed, the photograph was taken.

Injectors Tested

Five different types of injectors were tested: plain-orifice; mechanical pintle; electronic pintle; a modified plain-orifice, and a modified electronic pintle, both using showerhead configurations. The particular injectors tested were:

- (1) Simmonds 571341 Injector, mechanical outward opening pintle, 70 psi opening pressure, used for ordnance and aircraft engines
- (2) Bosch 043-750-200-4 Injector, mechanical outward opening pintle, 45 psi opening pressure, used in Bosch K-Jetronic fuel injection systems
- (3) Bosch 0-280-150-151 Injector, electronic solenoid actuated inward opening pintle, used in Bosch L-Jetronic fuel injection systems
- (4) Lucas 073143 Injector, electronic solenoid actuated inward opening pintle injector, used in Lucas electronic fuel injection systems
- (5) General Motors 1607247 electronic solenoid actuated inward opening pintle injector, used in General Motors automotive engines
- (6) General Motors 1606771 electronic solenoid actuated inward opening pintle injector, used in General Motors automotive engines
- (7) Teledyne-Continental Motors 633608-13E, plain-orifice, low pressure injector, used on Teledyne-Continental Motors TSIO-360-C engine
- (8) Bendix L74151, plain-orifice, low pressure injector, used on Avco-Lycoming IO-320 engine
- (9) Teledyne-Continental Motors 627335, modified plain-orifice, low pressure injector, three injectors total
- (10) Modified Bosch L-Jetronic electronic solenoid actuated inward opening pintle injector, four configurations

The modified Bosch L-Jetronic injector, shown in figure 2, was fabricated by drilling out part of the pintle on the injector. Small circular plates with

various diameter laser-drilled holes were then fastened to the nozzle opening. Holes were drilled to diameters of 0.002, 0.004, 0.010, and 0.040 inch.

The Teledyne-Continental Motors 627335 injectors, that were modified with collimated hole structure (CHS) elements, were fabricated by the Technetics Division of Brunswick Corporation. The standard injector is shown in figure 3. The CHS, invented by the Brunswick Corporation, consists of a cylindrical stainless steel plug fabricated with 200 circular holes of 0.002 inch in diameter. One plug was inserted into each injector (fig. 4), each plug a different length; 0.1026, 0.1536, and 0.2033 inch. Each injector was tested at its maximum flow rate, 18.2, 12.3, and 9.3 pounds per hour, respectively. The maximum flow rate of each modified injector varied with the different size plugs since at constant pressure the flow rate through a modified injector dropped as compared to the standard injector.

Most injector flow rate and/or shroud air pressures were established according to the fuel flow requirements of the Teledyne-Continental Motors TSIO-360-C engine which is being used for pollution and fuel consumption programs at NASA Lewis Research Center. The Bendix L 74151 Injector flow rates were based upon data from a carburetted Avco-Lycoming O-320-D1AD engine, which can be retrofitted with a fuel injection system. The complete test matrix for all injectors is tabulated in table II.

RESULTS AND DISCUSSION

The Simmonds 571341 Injector was pressurized with aviation fuel at 70, 80, and 90 psig with no apparent difference in atomization characteristics (figs. 5 to 7). The injector yielded a soft, 65° conical spray. The fuel appears to be finely atomized and well-distributed. Each photograph also indicates a slight pulsation of the spray caused by the oscillation of the injector spring under pressure which activates the mechanical pintle.

This injector was also pressurized with 90 psig water (fig. 8) and resulted in a conical spray similar to the fuel spray. The major difference was the quality of atomization. Whereas the fuel spray exhibited a fine mist, the water was ejected in irregularly-shaped masses of fluid and large discernible droplets of water.

The Bosch K-Jetronic injector at 48 psig fuel pressure performed similarly to the Simmonds injector, except the spray cone angle was 30° (fig. 9). A water spray at 48 psig formed more masses of water than distinct droplets (fig. 10).

Based upon these fuel-water comparisons, it was decided not to use water for further testing. Although water is completely safe to use for test purposes, it was not at all similar to fuel in its atomization characteristics for the same injector.

The Lucas, Bosch, and General Motors electronic injectors, basically of the same design, differ mainly in their respective fuel flow rates. Thus, the spray characteristics were quite similar. Each produced a soft, even spray, but had different spray cone angles. The Lucas injector (fig. 1) resulted in a 25° cone angle. Figure 12 shows the Bosch L-Jetronic injector spray 18° cone angle. The General Motors 1607247 injector, used on Cadillac Seville engines, also showed an 18° cone angle (fig. 13). Used on larger Cadillac engines, the General Motors 1606771 injector in figure 14 shows a 12° spray cone angle. The electronic injectors were pressurized with fuel at 40 psig, except the General Motors 160771 which was pressurized at 36 psig.

Figures 15 to 22 show the atomization characteristics of the Teledyne-Continental Motors 633608-13E injector which is in use on their current production model TSIO-360-C engine. This injector is equipped with an air shroud that is connected to the turbocharger compressor discharge outlet. Eight fuel flow rates and compressor discharge pressures corrected for ambient conditions, were chosen to simulate the idle, taxi, takeoff, climb, approach, cruise economy, cruise performance, and recommended cruise operating modes for the TSIO-360-C engine as tabulated in table II.

Varying degrees of atomization occur at idle, taxi, approach, cruise economy, cruise performance, and recommended cruise (figs. 15 to 20). The amount of atomization appears to be a strong function of the compressor discharge pressure. At idle, where this pressure is highest relative to manifold pressure, the atomized fuel forms a fine mist. As this differential pressure is decreased, the atomization continues to degrade until at the takeoff and climb conditions, where the compressor discharge pressure is zero relative to manifold pressure, no atomization exists. The fuel is injected as a stream of fluid for these two modes (figs. 21 and 22).

The Bendix L74151 injector is used on the Avco-Lycoming naturally-aspirated IO-320-D1AD engine. No fuel atomization occurred at any of the five operating modes tested for this engine: idle, taxi, takeoff, climb, and approach. Fuel dribbled from the injector at idle and taxi (figs. 23 and 24), and discharged as a stream at the other three conditions (figs. 25 to 27).

The modified TCM injector resulted in steady streams of fuel, apparently unaffected by the CHS plug. The injectors were further modified by removing the nozzle assembly at section A-A (fig. 4). This was done so that any atomization that might occur would not be negated by forcing the liquid into a stream

within the nozzle. As shown in figures 28 to 30, atomization did not occur with any of these modified injectors.

The four (4) experimental injector plates had numbers of various sized holes drilled using a laser. Two single-hole 0.010- and 0.040-inch plates were tested at fuel pressures of 40 and 30 psig, respectively. The 0.010-inch hole plate gave a dense cone shaped spray (fig. 31) near the orifice with a cone angle of approximately 18° . The fluid appears to atomize more fully as the distance from the orifice increases. The 0.040-inch hole plate did not atomize the fuel except for a few negligible isolated droplets (fig. 32).

Two plates were drilled with a grid of holes: thirty-three 0.002-inch holes, and twenty-one 0.004-inch holes. Neither grid (figs. 33 and 34) produced any atomization of the fluid.

SUMMARY OF RESULTS

Qualitative comparisons of manifold-port fuel injectors were conducted using photographic data of fully developed fuel sprays into quiescent air in order to screen injectors for further investigation. The Simmonds mechanical pintle injector and the Bosch K-Jetronic injector show good atomization characteristics. The four electronic pintle injectors that were similar in design and performance did not exhibit the fineness of atomization that the mechanically-operated injectors did. The experimental, modified L-Jetronic injectors offered no improvement, and often showed a degradation of the fuel spray characteristics.

Under the test conditions (injection into quiescent air), the Bendix plain-orifice injector did not atomize the fuel, and the Teledyne-Continental Motors shrouded injector fully atomized the fuel only under the conditions for idle and taxi. The Teledyne-Continental injectors fitted with the CHS plugs show no improvement over the plain-orifice injectors.

A subsequent effort to quantify these parameters would form a logical extension of these test results. It would then be desirable to correlate such atomization characteristics with performance and emissions data from an actual engine equipped with fully quantified manifold port fuel injectors.

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1. Robinson, J. A.; and Brehob, W. M.: The Influence of Improved Mixture Quality on Engine Exhaust Emissions and Performance. *J. Air Pollut. Contr. Assoc.*, vol. 17, no. 7, July 1967, pp. 446-453.
2. Lindsay, R.; et. al.: Influence of Homogeneous Charge on the Exhaust Emissions of Hydrocarbons, Carbon Monoxide and Nitric Oxide from a Multicylinder Engine. SAE Paper 710588, June 1971.
3. Quader, A. A.: Lean Combustion and the Misfire Limit in Spark Ignition Engines. SAE Paper 741055, Oct. 1974.
4. Matthes, W. R.; and McGill, R. N.: Effects of the Degree of Fuel Atomization on Single Cylinder Engine Performance. SAE Paper 760117, Feb. 1976.

TABLE I. - TEST FLUID PROPERTIES AT 20° C^a

	Specific gravity	Surface tension, dynes/cm	Viscosity, cS
100/130 Aviation fuel	0.7352	23.6	0.607
Water	1.0028	71.3	.993

^aProperties determined at NASA Lewis Research Center, December 1977.

TABLE II. - TEST MATRIX

Injector	Fuel flow or pressure	Shroud air pressure (a)	Mode
Teledyne-Continental TSIO-360-C 633608-13E	1.3 lb/hr	8.6 psig	Idle
	2.6	11.5	Taxi
	23.8		Takeoff
	18.3		Climb
	10.4	5.76	Approach
	7.0	5.2	Cruise economy
	16.0	.43	Cruise performance
	11.3	.58	Cruise recommended
Simmonds 571341	70 psig		
	80		
	90		
Bosch K-Jetronic 0437-502-004	45 psig		
Bosch L-Jetronic 0280-150-151	40 psig		
Lucas Electronic 073143	40 psig		
Bendix 160771	40 psig		
Bendix 1607247	40 psig		
	1.2		Idle
	2.0		Taxi
	20.0		Takeoff
	15.2		Climb
Bendix L74151 IO-320	10.3		Approach
	9.3 lb/hr		
	12.3		
Collimated holes	0.2033 x 0.059 in.		
	0.1535 x 0.059 in.		
	0.1026 x 0.059 in.		
Experimental nozzle	0.002 (33 total grid)	30 psig	
	0.004 (21 total grid)	30	
	0.010 (hole)	40	
	0.04 (hole)	30	

^aShroud air pressure = $\frac{\text{Turbocharger compressor discharge pressure}}{\text{Engine manifold pressure}} \times \text{atmospheric pressure.}$

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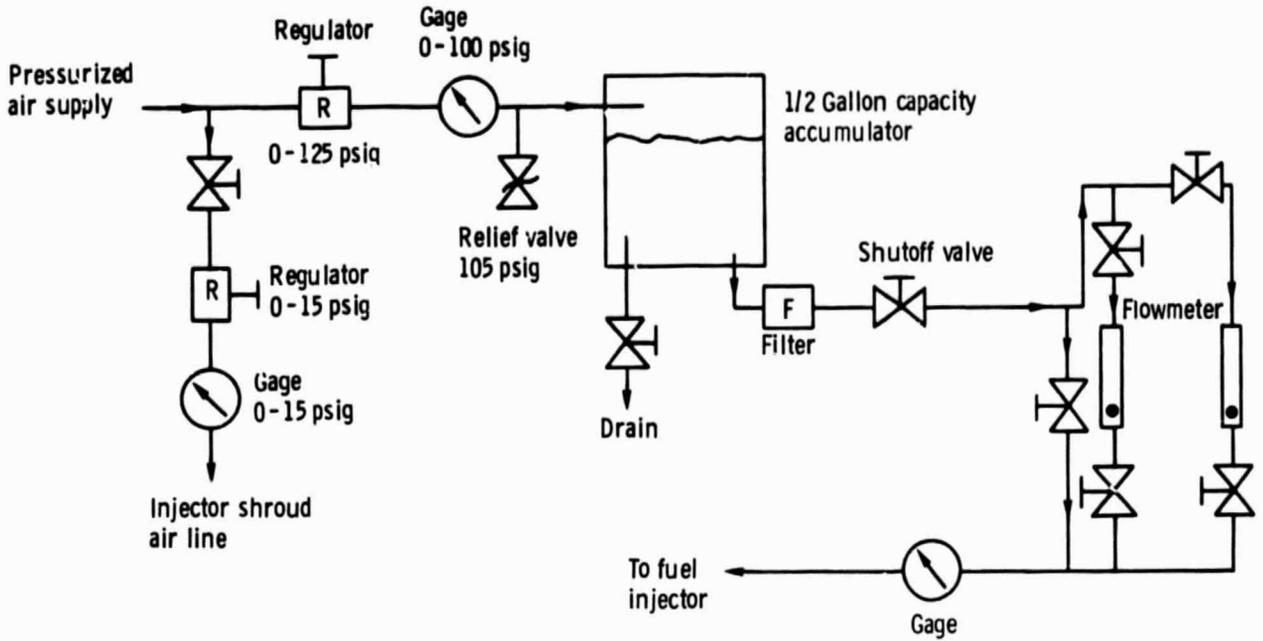


Figure 1. - Fuel injector spray rig.

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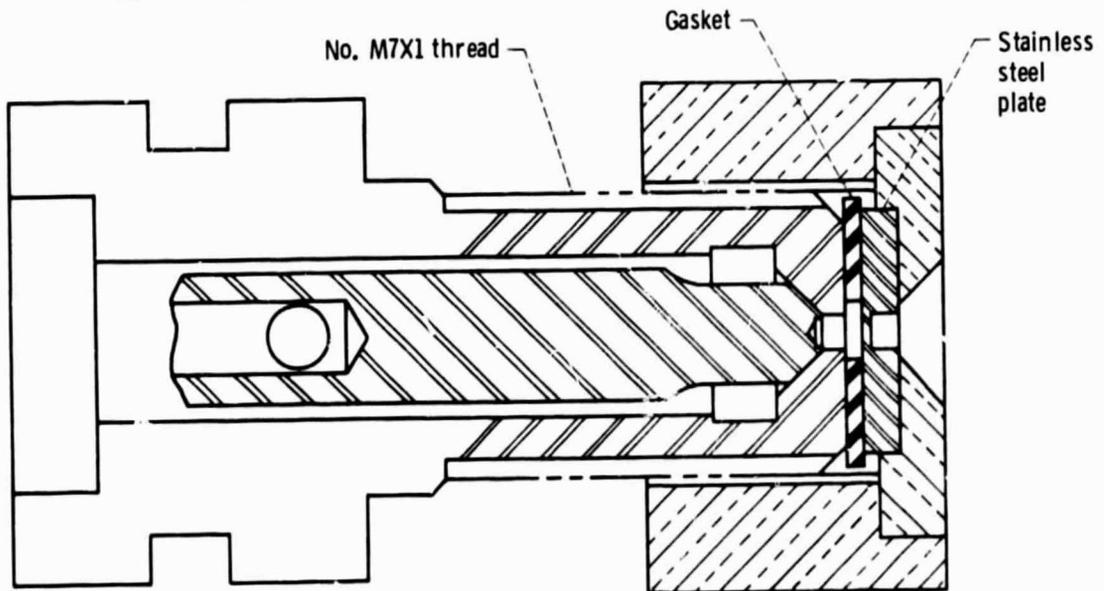


Figure 2. - Modified Bosch L-jetronic injector.

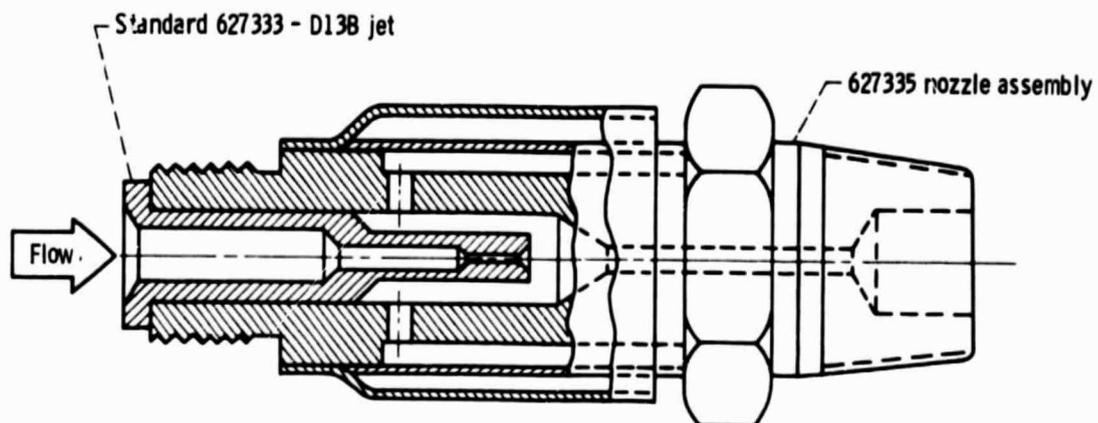


Figure 3. - Standard TCM 627334 injector.

E-7535

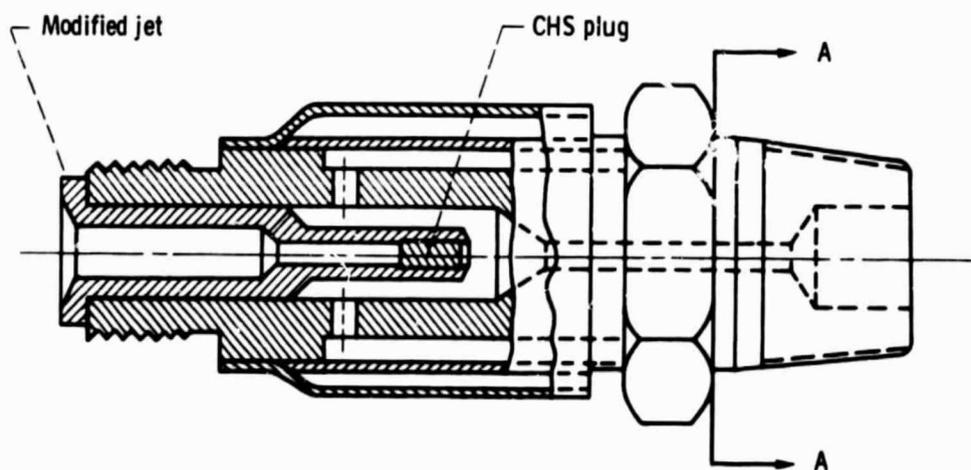


Figure 4. - Modified TCM 627335 injector.

E-7535

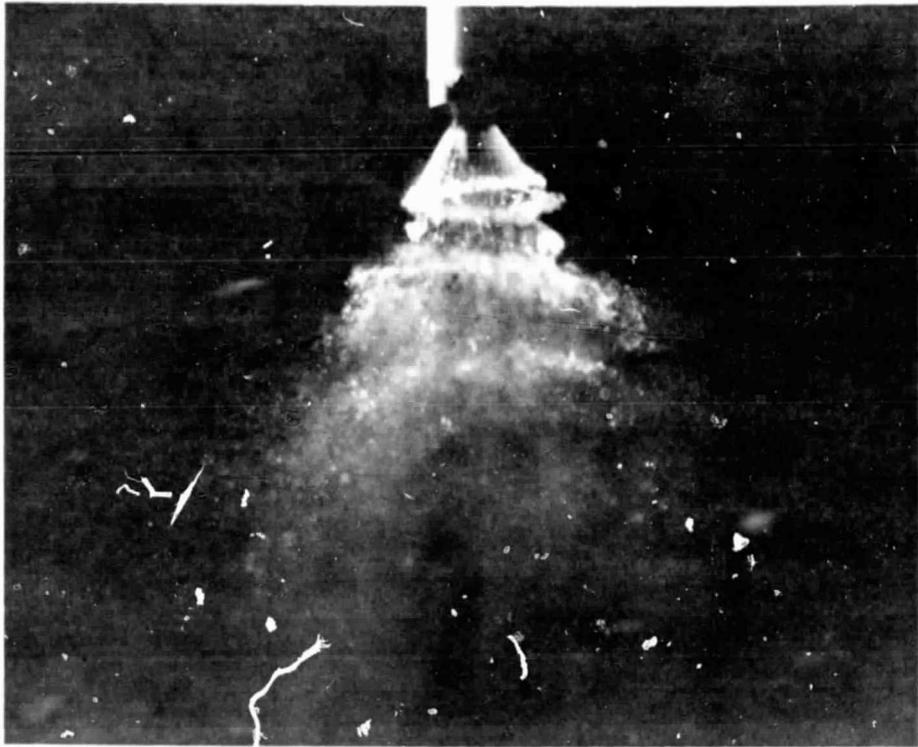


FIGURE 5
SIMMONDS 571341 MECHANICAL IN-
JECTOR FUEL SPRAY, 70 PSIG

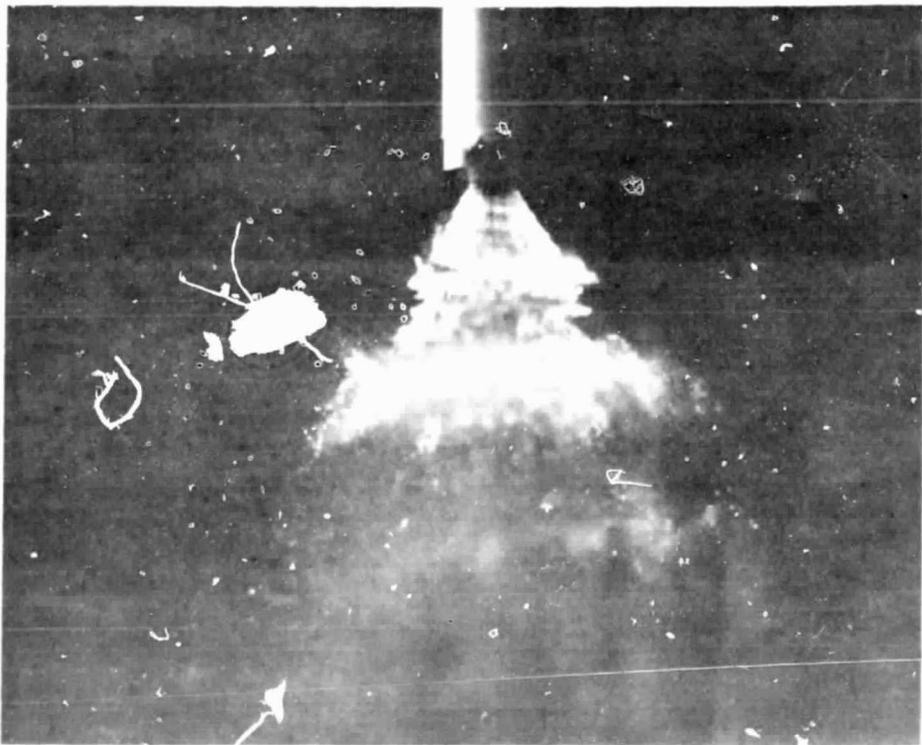


FIGURE 6
SIMMONDS 571341 MECHANICAL IN-
JECTOR FUEL SPRAY, 80 PSIG

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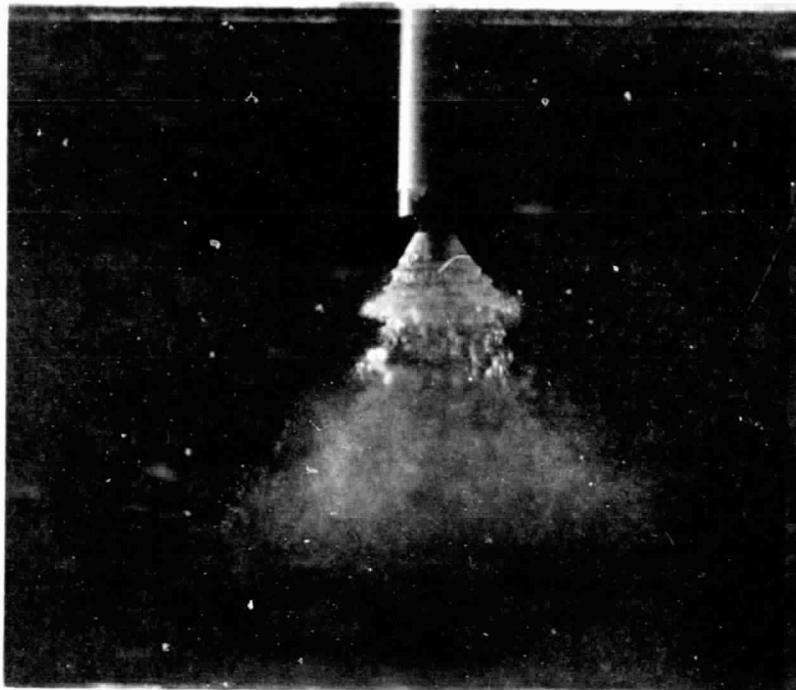


FIGURE 7
SIMMONDS 571341 MECHANICAL IN-
JECTOR FUEL SPRAY, 90 PSIG

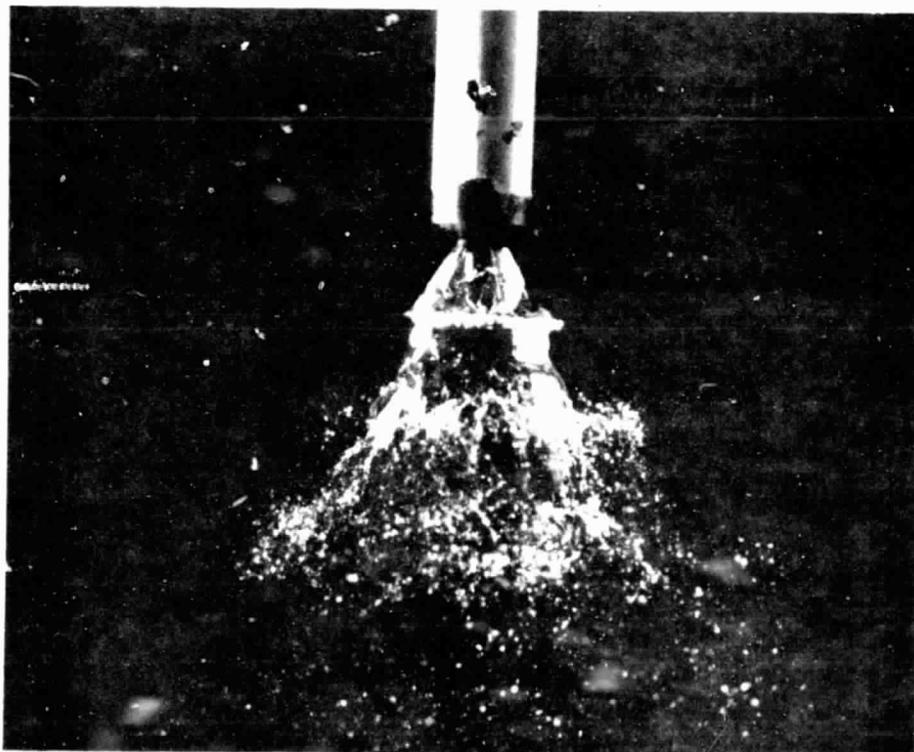


FIGURE 8
SIMMONDS 571341, MECHANICAL IN-
JECTOR WATER SPRAY, 90 PSIG

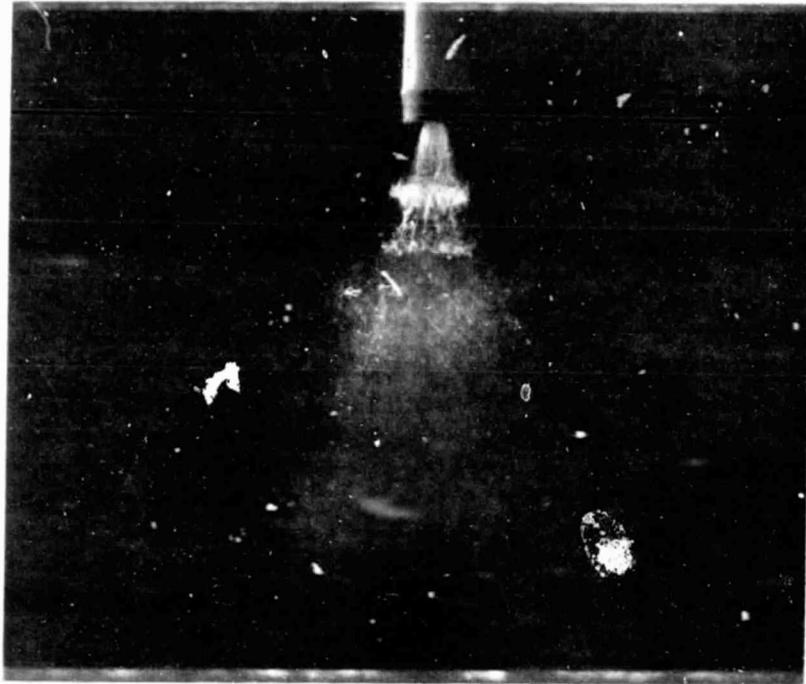


FIGURE 9
BOSCH K-JETRONIC INJECTOR FUEL
SPRAY, 48 PSIG

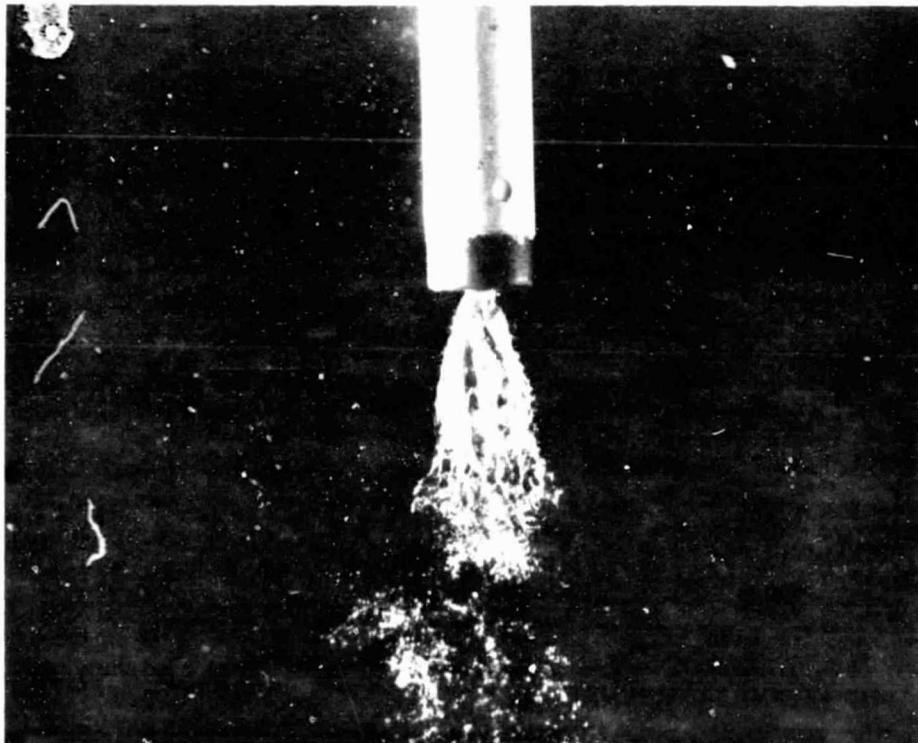


FIGURE 10
BOSCH K-JETRONIC INJECTOR WATER
SPRAY, 48 PSIG

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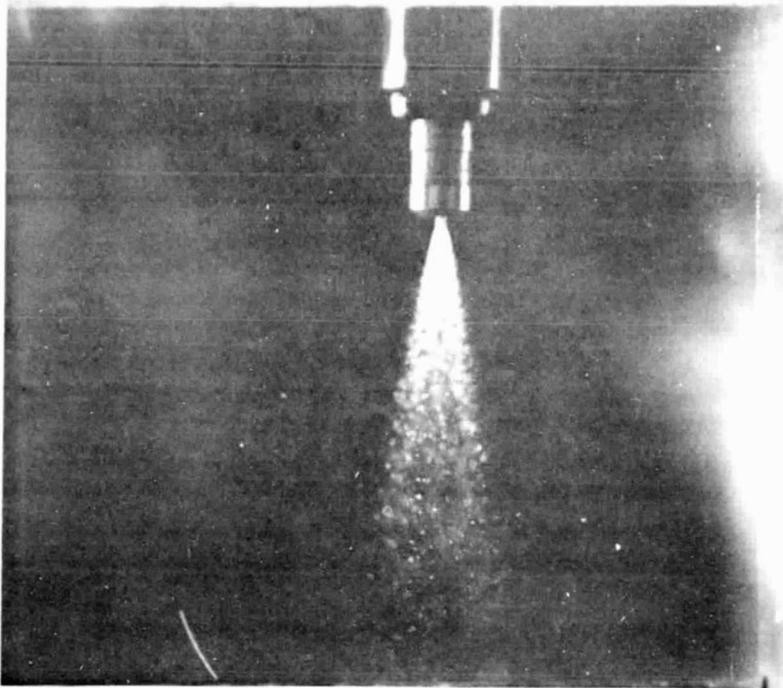


FIGURE 11
LUCAS 073143 ELECTRONIC INJECTOR FUEL SPRAY

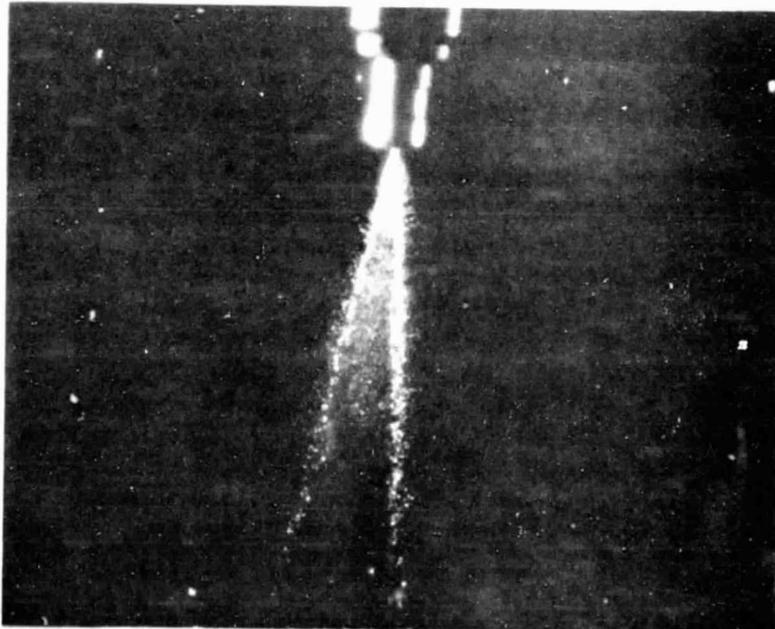


FIGURE 12
BOSCH 0-280-150-151 L-JETRONIC INJECTOR FUEL SPRAY

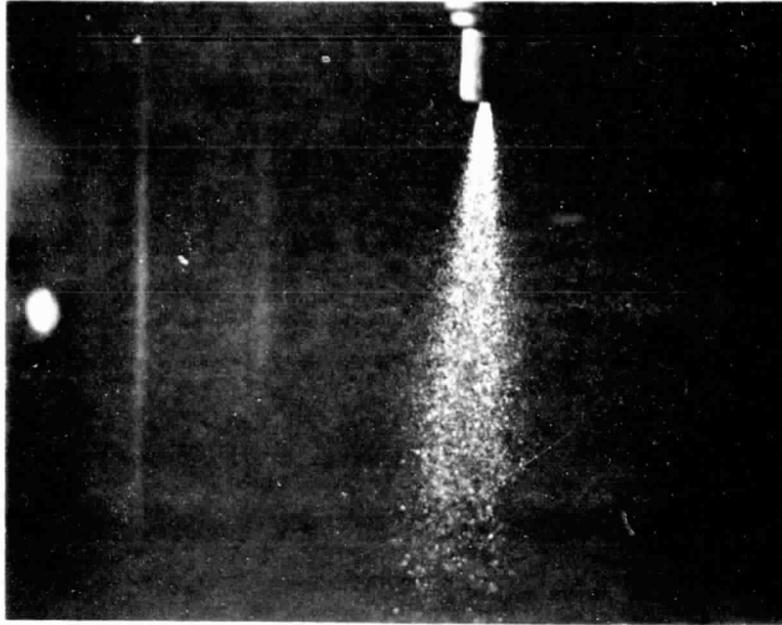


FIGURE 13
GENERAL MOTORS 1607247 ELECTRON-
IC INJECTOR FUEL SPRAY

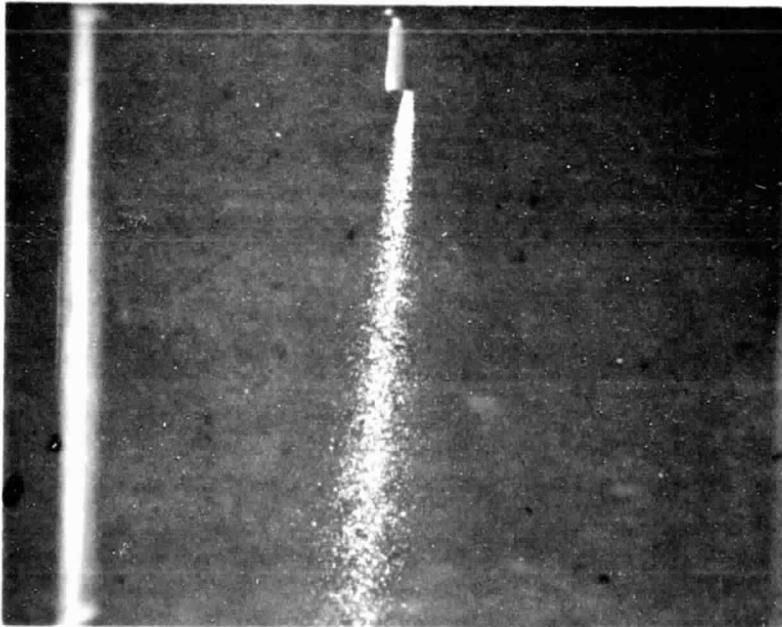


FIGURE 14
GENERAL MOTORS 1606771 ELECTRON-
IC INJECTOR FUEL SPRAY

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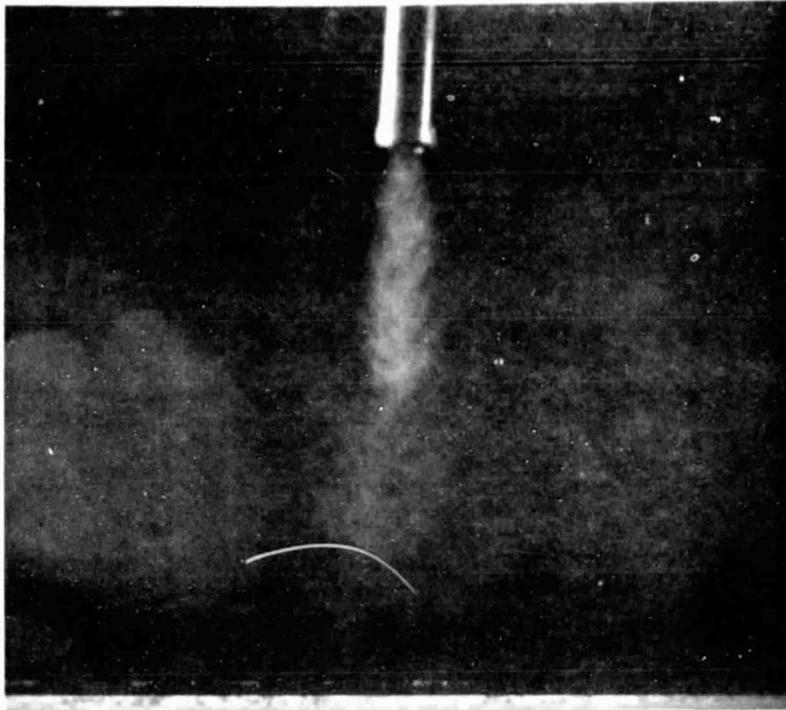


FIGURE 15
TCM 633608-13E INJECTOR FUEL
SPRAY, IDLE MODE

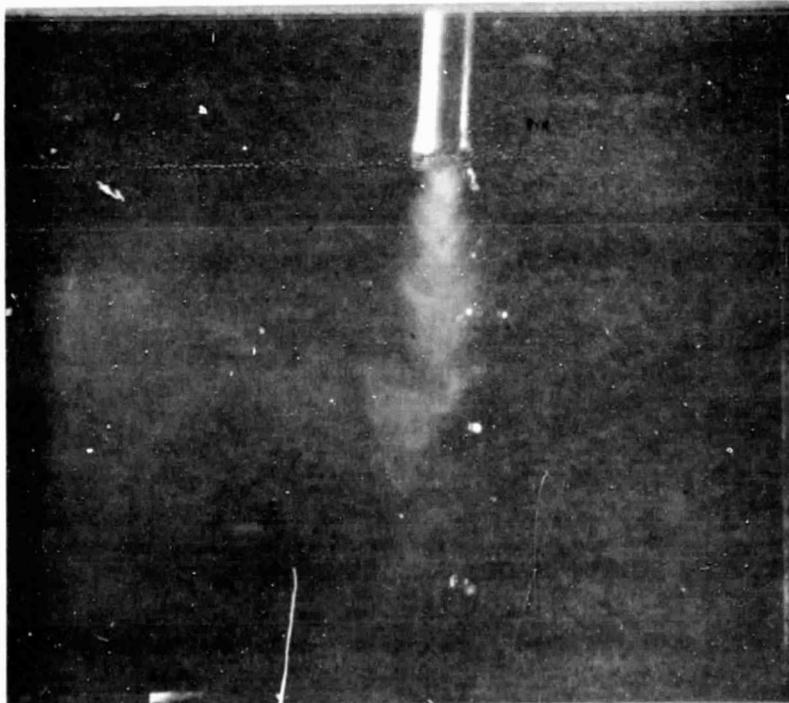


FIGURE 16
TCM 633608-13E INJECTOR FUEL
SPRAY, TAXI MODE

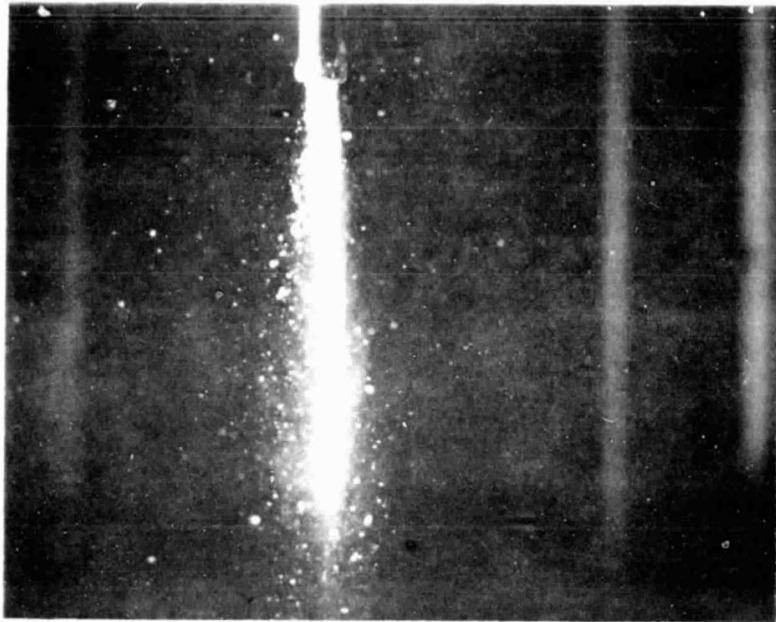


FIGURE 17
TCM 633608-13E INJECTOR FUEL
SPRAY, APPROACH MODE

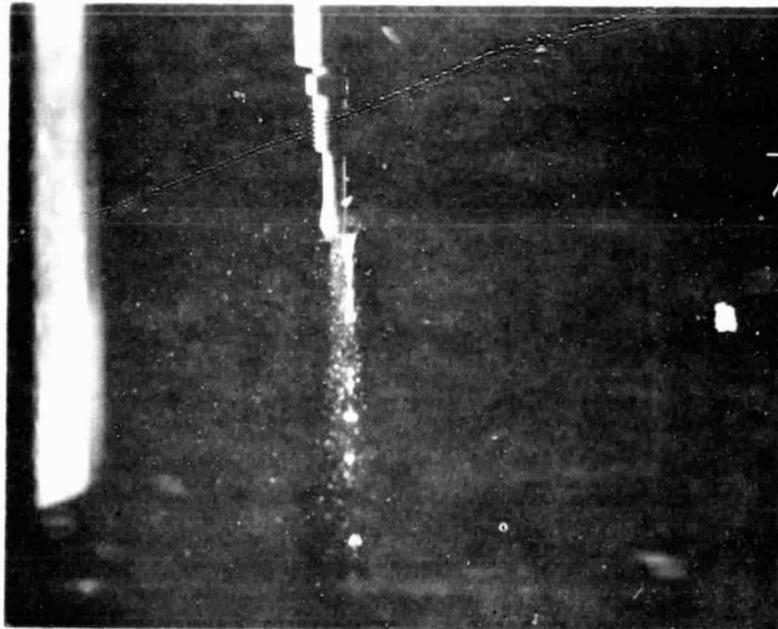


FIGURE 18
TCM 633608-13E INJECTOR FUEL
SPRAY, CRUISE ECONOMY MODE

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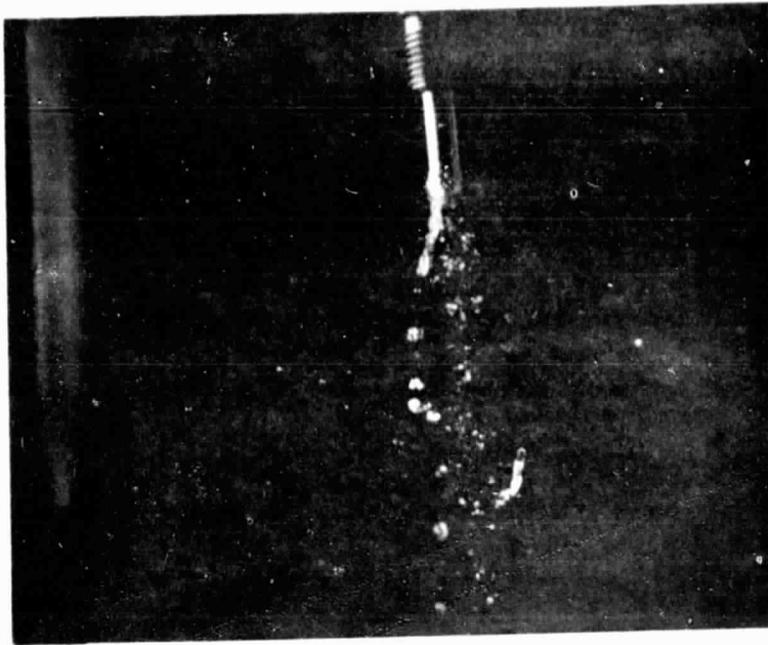


FIGURE 19
TCM 633608-13E INJECTOR FUEL
SPRAY, CRUISE PERFORMANCE MODE

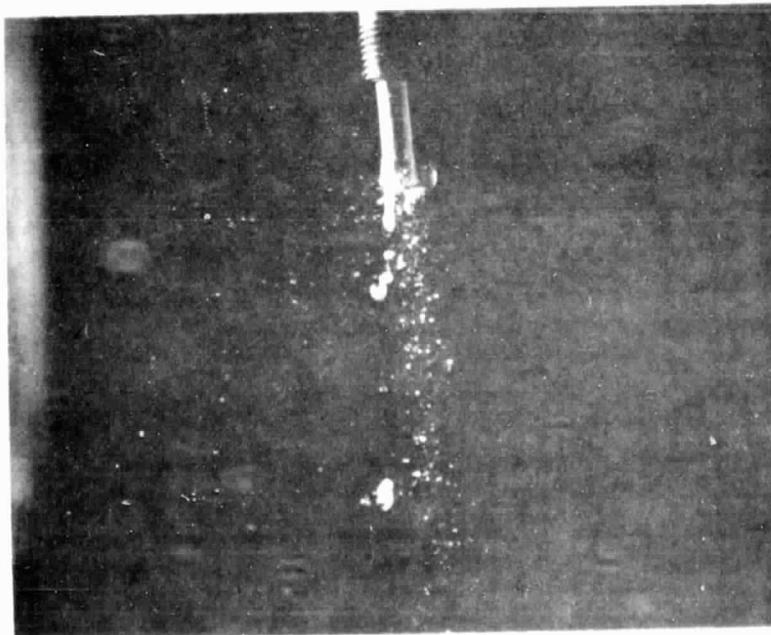


FIGURE 20
TCM 633608-13E INJECTOR FUEL
SPRAY, CRUISE RECOMMENDED MODE

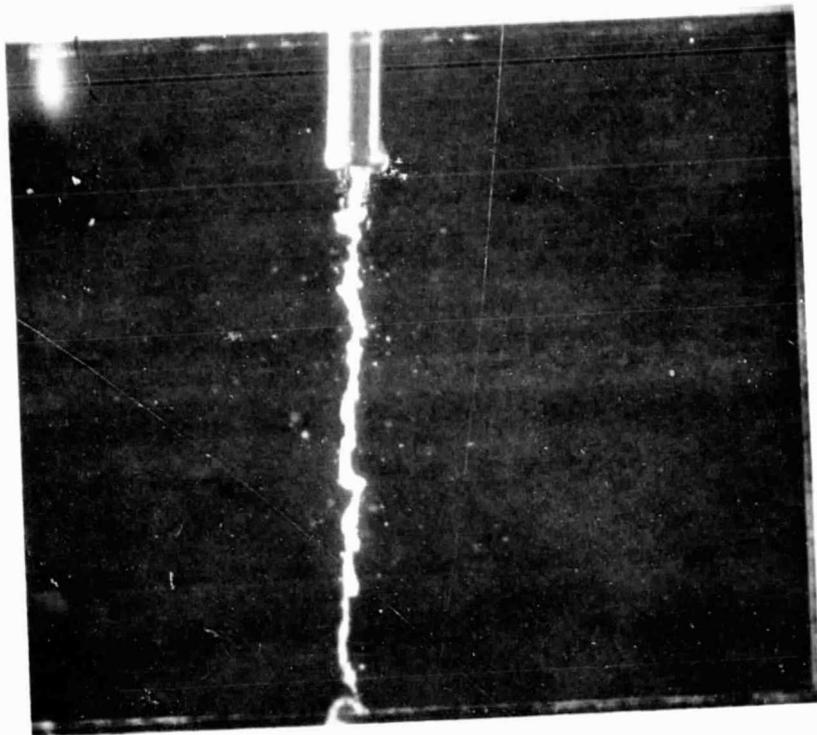


FIGURE 21
TCM 633608-13E INJECTOR FUEL
SPRAY, TAKEOFF MODE

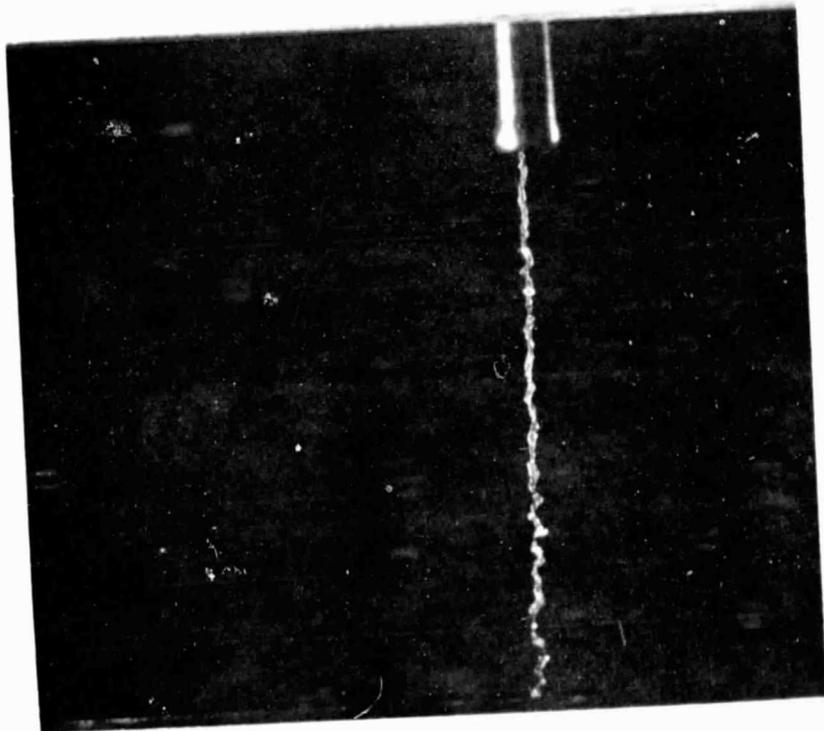


FIGURE 22
TCM 633608-13E INJECTOR FUEL
SPRAY, CLIMB MODE

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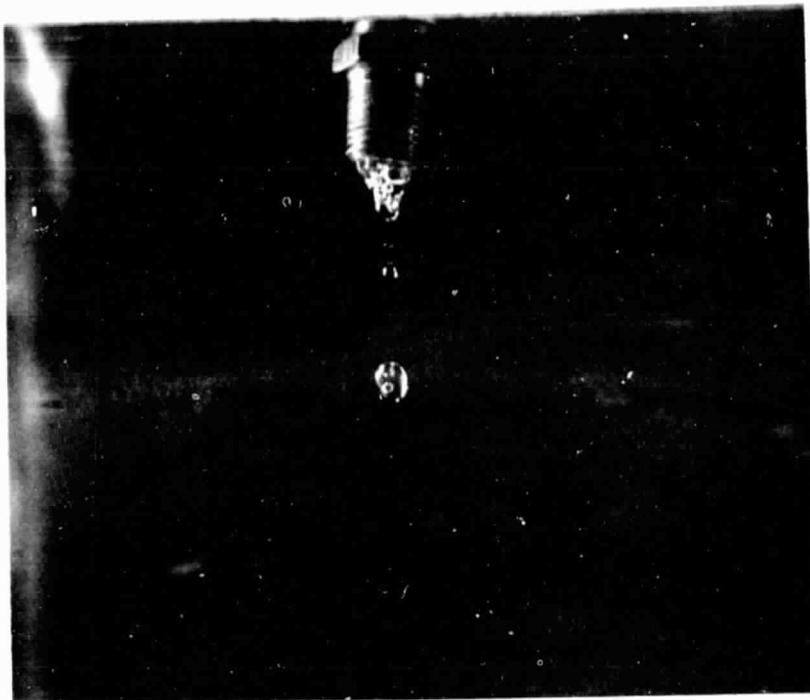


FIGURE 23
BENDIX L74151 INJECTOR FUEL SPRAY,
IDLE MODE

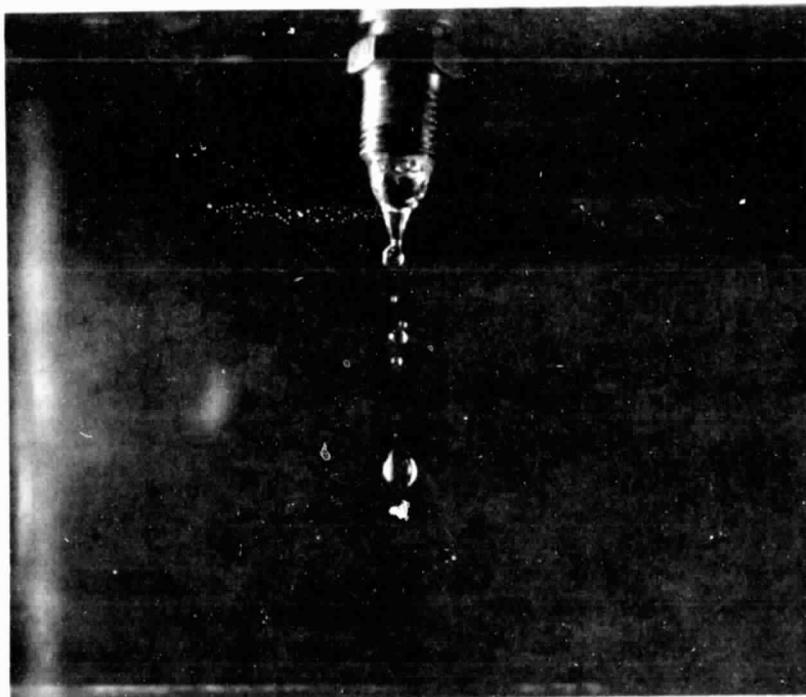


FIGURE 24
BENDIX L74151 INJECTOR FUEL SPRAY,
TAXI MODE

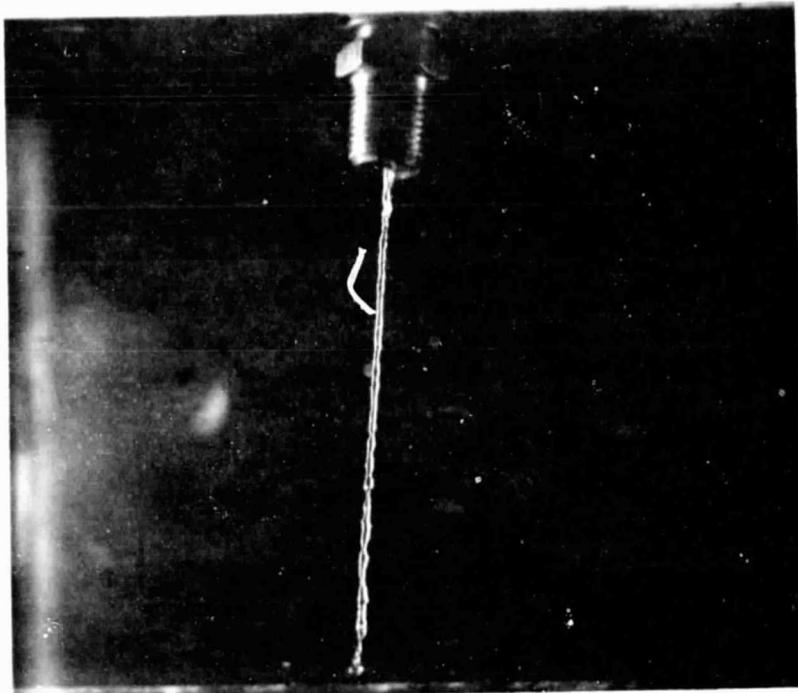


FIGURE 25
BENDIX L74151 INJECTOR FUEL
SPRAY, TAKEOFF MODE

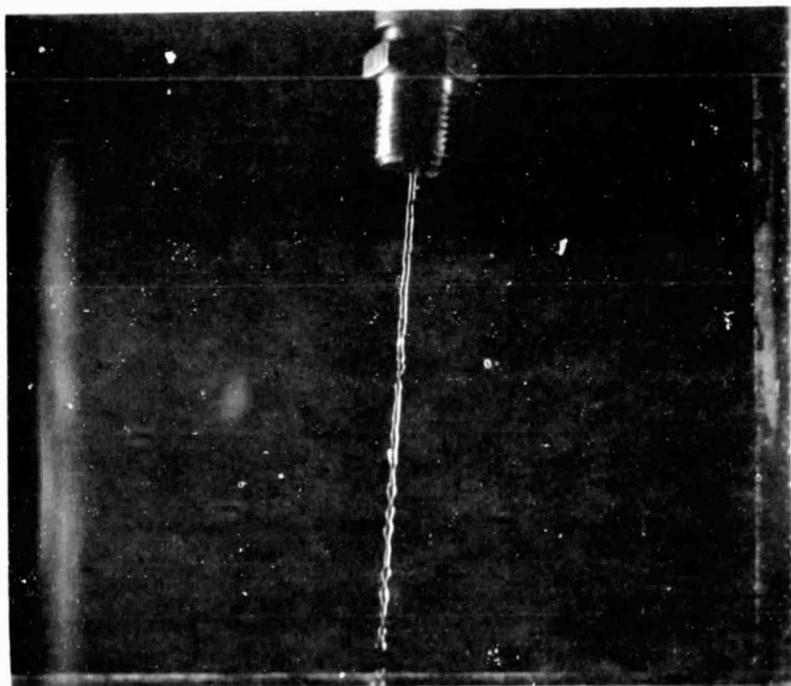


FIGURE 26
BENDIX L74151 INJECTOR FUEL
SPRAY, CLIMB MODE

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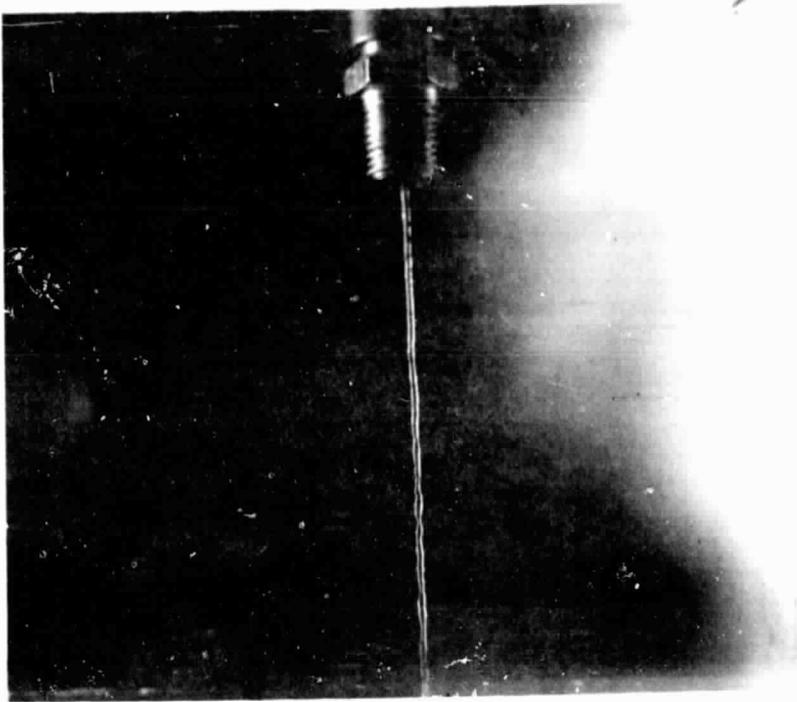


FIGURE 27
BENDIX L74151 INJECTOR FUEL
SPRAY, APPROACH MODE

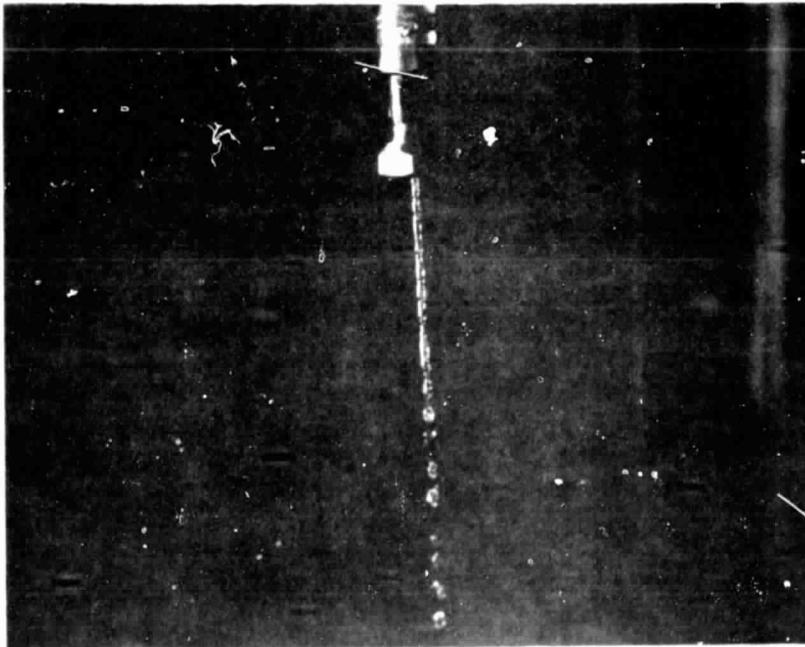


FIGURE 28
TCM 627335 INJECTOR MODIFIED WITH .2033
IN. CHS PLUG, 9.3 LB/HR FUEL FLOW

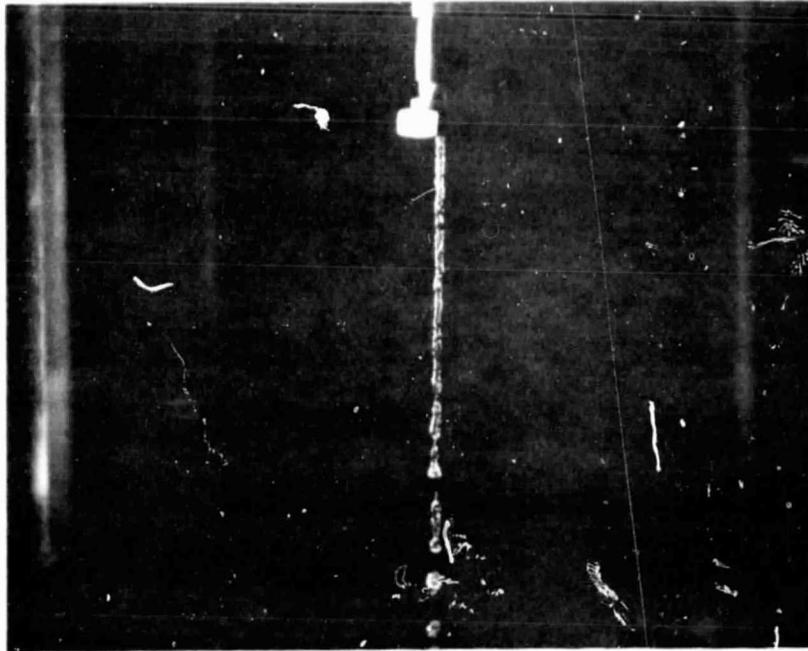


FIGURE 29
TCM 627335 INJECTOR MODIFIED WITH .1536
IN. CHS PLUG, 12.3 LB/HR FUEL FLOW

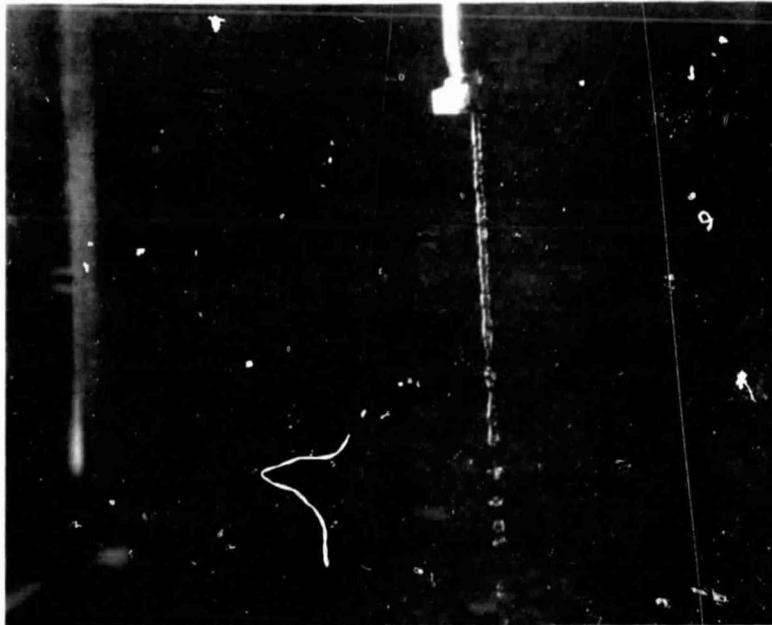


FIGURE 30
TCM 627335 INJECTOR MODIFIED WITH .1026
IN. CHS PLUG, 18.2 LB/HR FUEL FLOW

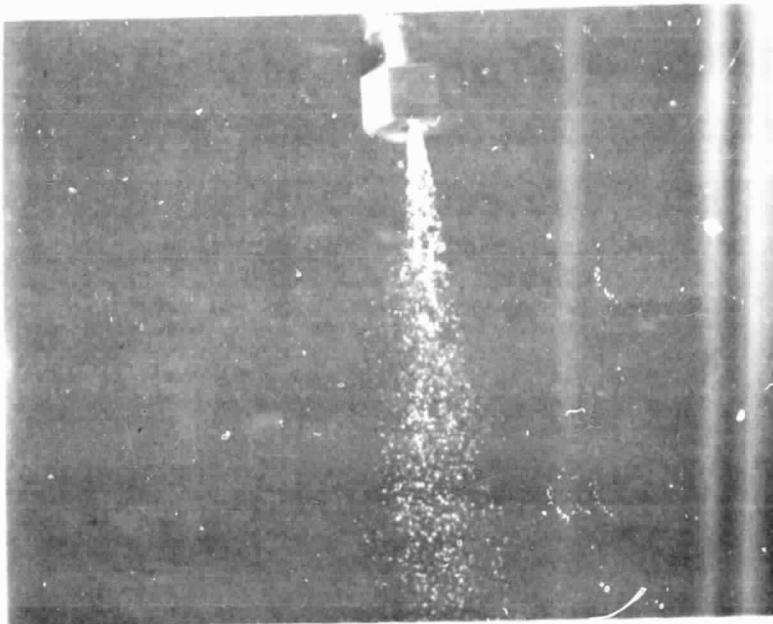


FIGURE 31
MODIFIED BOSCH L-JETRONIC INJECTOR
FUEL SPRAY, 40 PSIG, .010 in. OPENING

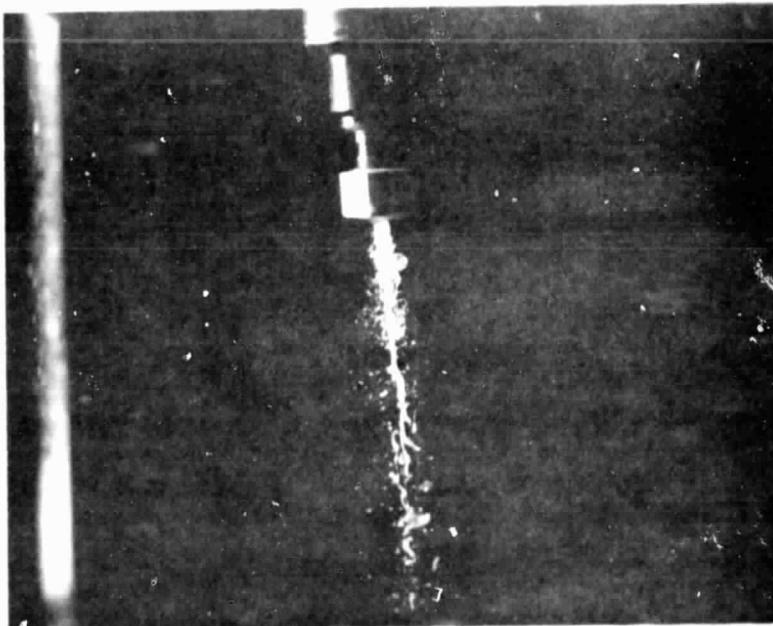


FIGURE 32
MODIFIED BOSCH L-JETRONIC INJECTOR
FUEL SPRAY, 30 PSIG, .040 in. OPENING

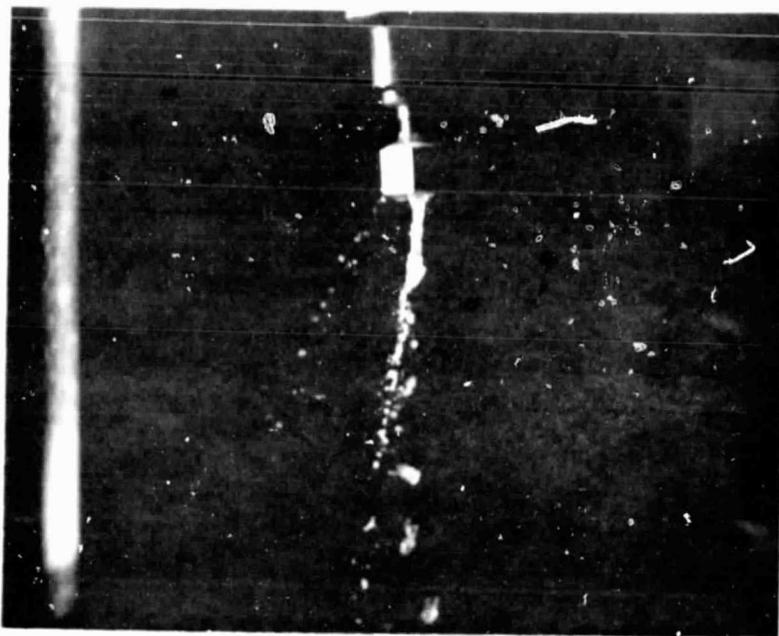


FIGURE 33
MODIFIED BOSCH L-JETRONIC INJECTOR FUEL
SPRAY, 30 PSIG, 33 HOLE GRID @ .002 IN.

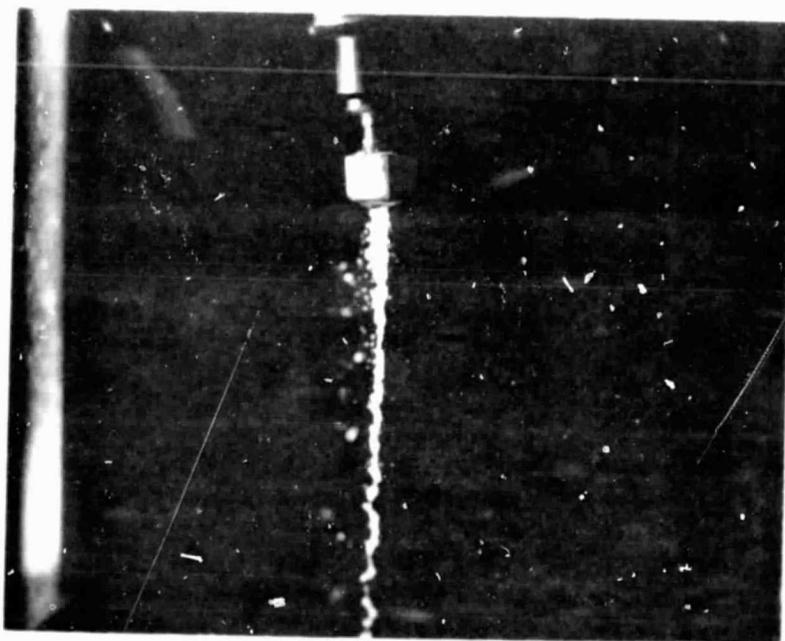


FIGURE 34
MODIFIED BOSCH L-JETRONIC INJECTOR FUEL
SPRAY, 30 PSIG, 21 HOLE GRID @ .004 IN.