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# Effect of Non-Newtonian Antimisting Kerosene on Jet Pump Performance

L.P Bernal  
V. Sarohia

May 1986

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16. Abstract The effect of antimisting kerosene (AMK) on jet pump performance has been determined experimentally. It is shown that the performance of the jet pump is reduced by AMK as much as 50 percent as compared to Jet A under identical operating conditions. Tests with the boost pump driven motive flow showed an improved performance. Low temperature AMK fuel resulted in an additional improvement on performance. Flow visualization and surface pressure measurements indicate suppression of turbulent mixing within the pump to be the cause for the reduced performance. In order to improve the efficiency of jet pumps with AMK, length of the mixing chamber was increased. With increased mixing chamber length, an improvement in mass transferred rate of 15 percent at a 2 psi pressure head was observed. Alternatively, larger size pumps designed to operate with Jet A are also proposed. Scaling parameters are given to dimension the pump using Jet A data. Water ingestion tests showed no precipitate formation prior to the entrance to the pump. As the flow moved through the pump, large amounts of precipitate were formed. This precipitate did not impair the operation of the pump.					
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## TABLE OF CONTENTS

	PAGE
EXECUTIVE SUMMARY	vii
INTRODUCTION	1
APPARATUS AND INSTRUMENTATION	3
RESULTS	14
Jet Pump Performance	14
Surface Pressure and Flow Visualization	19
Water Ingestion	24
Performance Improvement Study	27
DISCUSSION	27
CONCLUDING REMARKS	29
REFERENCES	30

## LIST OF ILLUSTRATIONS

FIGURE		PAGE
1.	Jet Pump Schematic	1
2.	High Pressure Driven Facility Schematic	4
3.	High Pressure Driven Facility. Hardware Elements.	5
4.	Boost Pump Driven Facility Schematic	6
5.	Boost Pump Driven Facility	7
6.	Location of Fuel Samples	8
7.	Water Injection Technique	9
8.	J. C. Carter 60103-5 Jet Pump	10
9.	Diagram Showing The Location of The Surface Pressure Taps	11
10.	Glass Jet Pumps Dimensions	12
11.	Glass Jet Pumps	13
12.	Jet Pump Performance	15
13.	Jet Pump Surface Pressure Distribution	20
14.	Glass Jet Pumps Performance	21
15.	Glass Jet Pump Number 2 with Jet A	22
16.	Glass Jet Pump Number 2 with 0.3 FM9 (RMH 1-240)	23
17.	Jet Pump Performance	25
18.	Improvement in Jet Pump Performance	26

## LIST OF TABLES

TABLE		PAGE
1.	J. C. Carter 60103-5 Performance	16
2.	AMK Degradation Results. High Pressure Driven Primary Flow	17
3.	AMK Degradation Results. Boost Pump Driven Primary Flow	18

## EXECUTIVE SUMMARY

During the past few years, studies by the Federal Aviation Administration (FAA) and other government agencies have shown that the hazards from aircraft crash fires might be significantly decreased if an antimisting kerosene (AMK) fuel could be utilized. The addition of polymeric additive at low concentrations to jet fuels is known to suppress mist formation and ignition of the fuels under circumstances often encountered in survivable aircraft crash landings. An antimisting additive, FM-9<sup>TM</sup> has been developed by Imperial Chemical Industries (ICI) and is available under the trade name AVGARD. This material when dissolved in jet fuels imparts a strong time-dependent threshold type shear-thickening behavior. In case of fuel spillage from a ruptured fuel tank during an aircraft crash, the fuel misting is prevented. Simulated aircraft crash landing fuel spillage tests have indicated that fuel misting can be sufficiently suppressed, and the ignition and the subsequent fireball formation can be greatly reduced or eliminated.

However, this desirable shear-thickening effect of AMK which reduces the postcrash aircraft fires may influence the operation of some of the aircraft components, viz., the jet pump which is the subject of this report. The effects on performance of partial degradation of the motive flow by a boost pump and AMK fuel temperature are documented. Tests were performed to determine the influence of AMK fuel on jet pump priming. Water ingestion tests were also made to determine the effect of precipitate formation on the performance of the pump and on AMK fire protection. Surface pressure measurements and flow visualization were used to determine the effect of AMK fuel on the flow processes inside the jet pumps. Based on these results, hardware modifications to improve the performance of jet pumps were made.

The main results of this investigation are:

1. Jet pump performance with undergraded AMK is significantly reduced compared to Jet A performance. The reduction with AMK was as much as 50 percent as compared to Jet A performance.
2. Partial degradation of the motive flow by a boost pump results in an improved performance.
3. The performance of jet pumps with AMK at low temperature is improved compared with that at room temperature.
4. The suppression of turbulent mixing by AMK is shown to be the cause of reduced performance.
5. Hardware modification to the mixing chamber showed improvement in jet pump performance. This improvement results from increased interaction of primary jet with secondary flow in the mixing chamber. However, optimization of the hardware changes were not made during the course of this investigation.

## INTRODUCTION

This report presents the results of an investigation on the compatibility of antimisting kerosene (AMK) with jet pumps used in aircraft fuel systems. The development of antimisting kerosene to prevent postcrash fires of aircraft has been pursued for a number of years. In its current stage of development, a polymer (FM9<sup>TM</sup> manufactured by Imperial Chemical Industries) and carrier fluids are added to Jet A. The non-Newtonian character of this AMK fuel influences the performance of the low pressure fuel system components. Two requirements that need to be satisfied are: performance of the various components with AMK must be comparable to that found with Jet A fuel, and AMK in the tank must retain its fire protection capability throughout the length of the flight. Jet pumps are extensively used in the low pressure fuel system for scavenging and fuel transfer operations (reference 1). Initial tests, however, showed that jet pumps have significant performance loss with AMK fuel (references 2 and 3) at ambient temperature. Research at JPL was undertaken to determine the mechanism responsible for this loss of performance which will lead to design modifications for acceptable jet pump performance with AMK. Furthermore, how low temperature influences jet pump performance was another goal of this research effort.

A typical jet pump designed for aircraft fuel system operation is shown in figure 1. The pumping action in the induced flow line results from turbulent mixing of the induced flow with the high-speed motive flow and subsequent diffusion of the mixed flow in the divergent portion of the pump. Mixing between the motive and induced flows within the constant area section of the pump directly influences the pressure recovery in this section and results in an improved performance of the diffuser. Typical jet pumps used

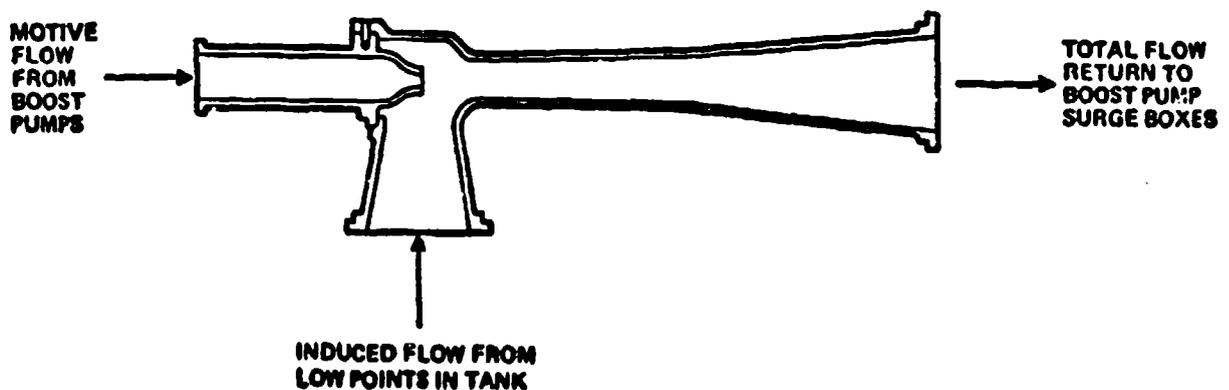


FIGURE 1. JET PUMP SCHEMATIC

in aircraft fuel systems are designed with a mass flow ratio of 3 (induced flow divided by motive flow) and have maximum suction pressure in the range of 5 to 10 psi. Depending on the specific application, jet pumps can encounter priming problems. Priming refers to the ability of the pump to initiate operation when the induced flow line is filled with air. Self-priming pumps are available. They have a reduced efficiency compared to the conventional pumps.

The reported reduced performance of jet pumps with AMK (references 2,3,4,5) is believed to be the result of reduced mixing in the pump. Previous tests reported in references 2,3,4,5 have also shown partial degradation of the AMK delivered by the pump. The configurations used in these tests were typical of aircraft fuel systems. It is therefore difficult to isolate the contribution of the jet pump to the degradation of AMK. Furthermore, the effect of AMK on priming, and the performance of jet pumps with AMK at low temperature were investigated.

In some fuel system tests with AMK, the performance of jet pumps was below acceptable levels. In these cases, because the water scavenge/fuel transfer functions are effected, an improvement of the jet pump performance with AMK may be required or full management design/operational requirements re-evaluated. The jet pump fuel transfer operation is the most critical issue with the use of AMK. If fuel transfer efficiency deteriorates, the fuel feed system could be effected. However, the reduction of water scavenge pump efficiency will not have an effect on engine feed (reference 5), while the requirement for continuous water scavenge with AMK may be eliminated because at the fuel's high affinity for dissolved water (reference 6). It should also be noted that some aircraft manufacturers do not use jet pumps for fuel transfer (reference 5). The following strategies are apparent. On one hand, techniques to improve the efficiency of jet pumps with AMK need to be identified. On the other, the use of larger capacity jet pumps designed to operate with Jet A can eliminate the problem at a reduced efficiency of the overall system. In this case, until a suitable data base becomes available, basic scaling parameters need to be used in order to dimension pumps based on Jet A data.

One of the objectives of the scavenge system is to pick up liquid water from the low points of the tank and to mix it with Jet A as it moves through the jet pump. The water is finely dispersed in Jet A, thus minimizing negative effects of water in the rest of the fuel system. Compatibility studies of AMK with water (reference 6) have shown a tendency of AMK to form a stable precipitate when it comes in contact with water in liquid and vapor state. The water compatibility tests reported in reference 6 show no changes in AMK appearance or quality at low concentration levels, below the solubility limit. However, it is necessary to obtain a better understanding of the interaction between water and/or precipitate with the various fuel system components.

The objectives of this investigation were established as follows. (1) To determine the performance of jet pumps with AMK fuel at ambient and low temperatures. (2) To investigate techniques to improve the performance of jet pumps with AMK fuel. (3) To evaluate the effect of water ingestion by jet pumps on both the physical characteristics of the AMK fuel and on the performance of the pump.

## APPARATUS AND INSTRUMENTATION

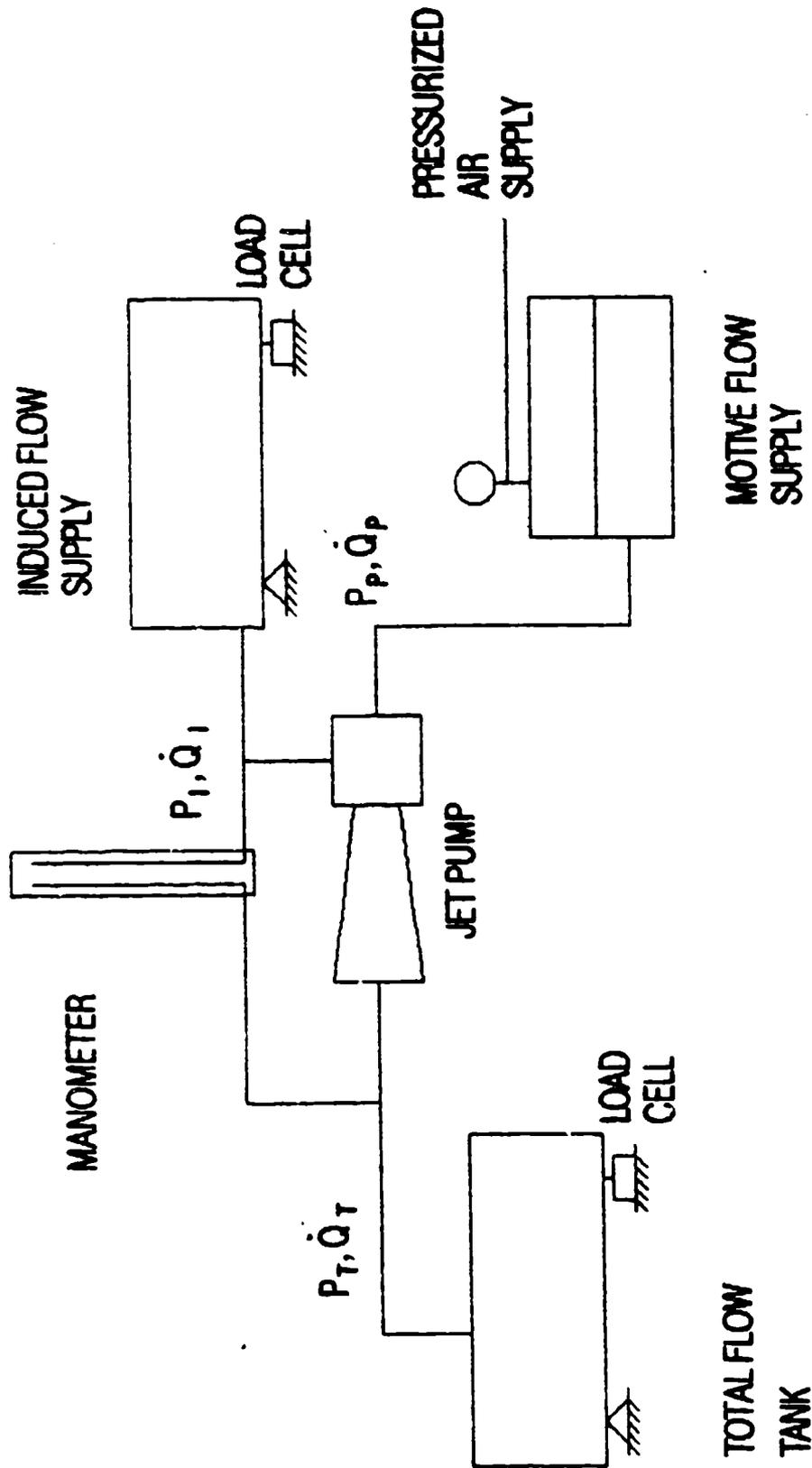
Two different facilities were used to determine the performance of jet pumps with Jet A and AMK fuels. During most of the effort, ICI batch blended AMK was used. Limited tests with inline blended AMK were also performed during a performance improvement study. A high pressure, motive flow facility was designed and assembled. A schematic diagram of this facility is shown in figure 2. A picture of the hardware components is shown in figure 3. The motive flow is supplied from a pressurized tank. The induced flow is drawn from a three-level tank designed to maintain a constant pressure head. The total flow line has a siphon arrangement in order to maintain a constant delivery pressure. The induced flow supply tank and the total flow collecting tank were mounted on load cells in order to measure their respective flow rates. Measurements were also made of the motive flow, tank pressure and the suction pressure ( $P_T - P_I$ ) by means of a strain gauge transducer and a manometer, respectively (see figure 2 and 4 for pressure and mass flow nomenclature). The output of the load cells and motive flow, tank pressure transducer were recorded by a minicomputer based data acquisition system. The minicomputer software was designed to acquire data for one minute and to process the data to give the mean values and rate of change with time of the measured quantities. The suction pressure was recorded manually.

The instrumentation and data acquisition technique in the high pressure, motive flow facility were modified at the initiation of the performance improvement study because the data acquisition computer was not available. In these tests, the suction pressure was measured with a strain gauge transducer. The suction pressure and motive flow pressure were recorded manually. The induced and total flow rates were obtained by means of a strip chart recorder.

Calibration data for the flow rate measurements were obtained prior to each set of tests on both configurations. A 10-second settling time was allowed between the start-up of the facility and the initiation of the data acquisition in order to minimize transient measurement noise.

A second facility was used to determine the jet pump performance at ambient and low fuel temperatures. A schematic diagram of the facility is shown in figure 4. The motive and induced flows were drawn from the same tank. The temperature in the tank could be lowered to  $-50^{\circ}\text{C}$ . A DC-10 boost pump was used to supply the motive flow. After going through the jet pump, the flow was collected in the total flow tank, where a load cell was used to measure the total flow rate. The motive flow pressure and the suction pressure were measured by strain gauge type transducers. The motive, induced, and total flow temperatures were measured with thermocouples. The computer based, data acquisition system was used to control the fuel cooling process in the supply tank. This system was also used for data acquisition and reduction. The typical running time of the facility was one minute. A sketch of the jet pump as installed in this facility is shown in figure 5.

AMK fuel samples were taken at different operating conditions of the jet



- BLOW - DOWN FACILITY; 5 MIN RUN TIME.

- INCORPORATES HEAD CONTROL FOR INDUCED, TOTAL AND MOTIVE FLOW TANKS.

FIGURE 2. HIGH PRESSURE DRIVEN FACILITY SCHEMATIC

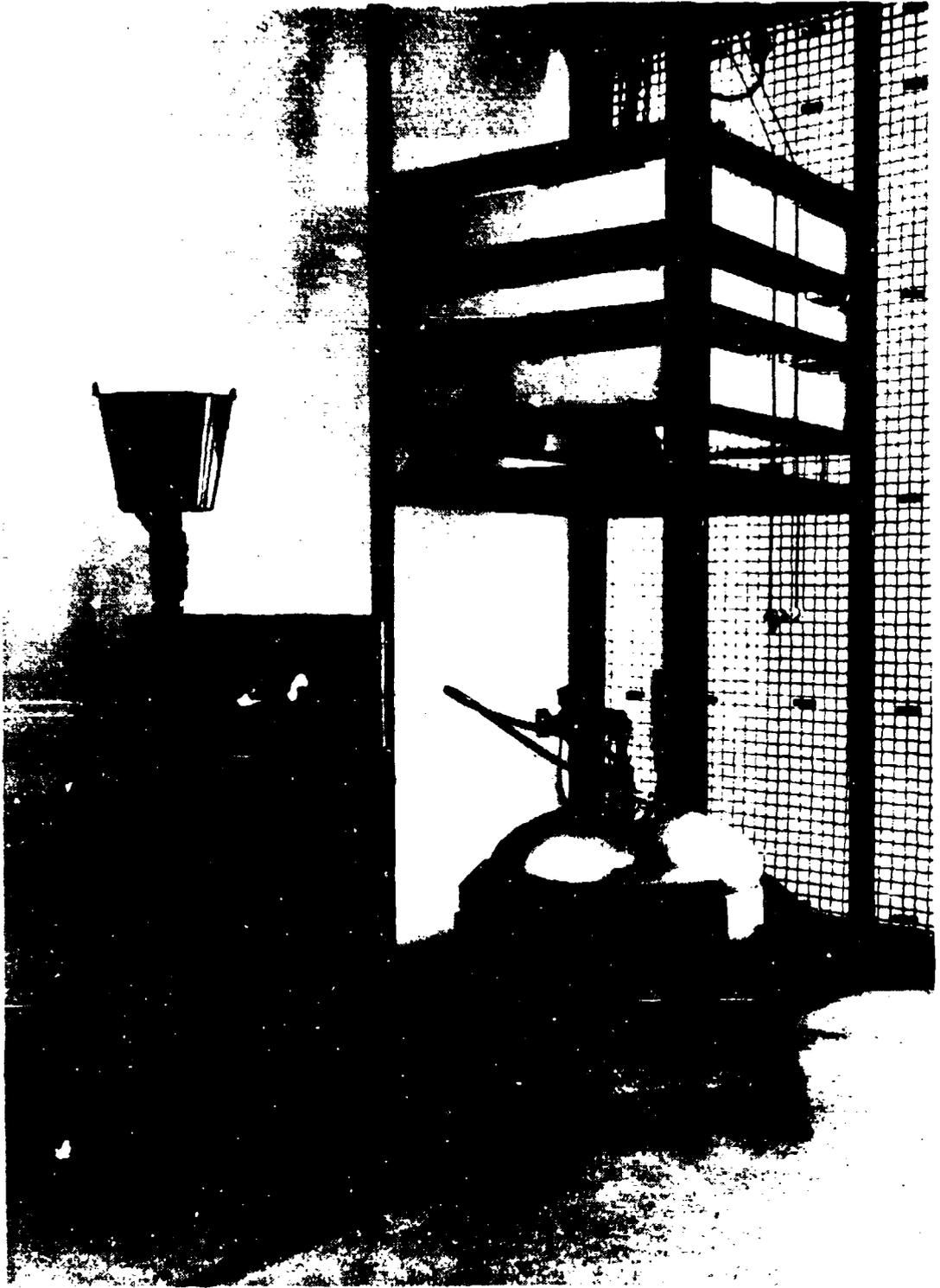
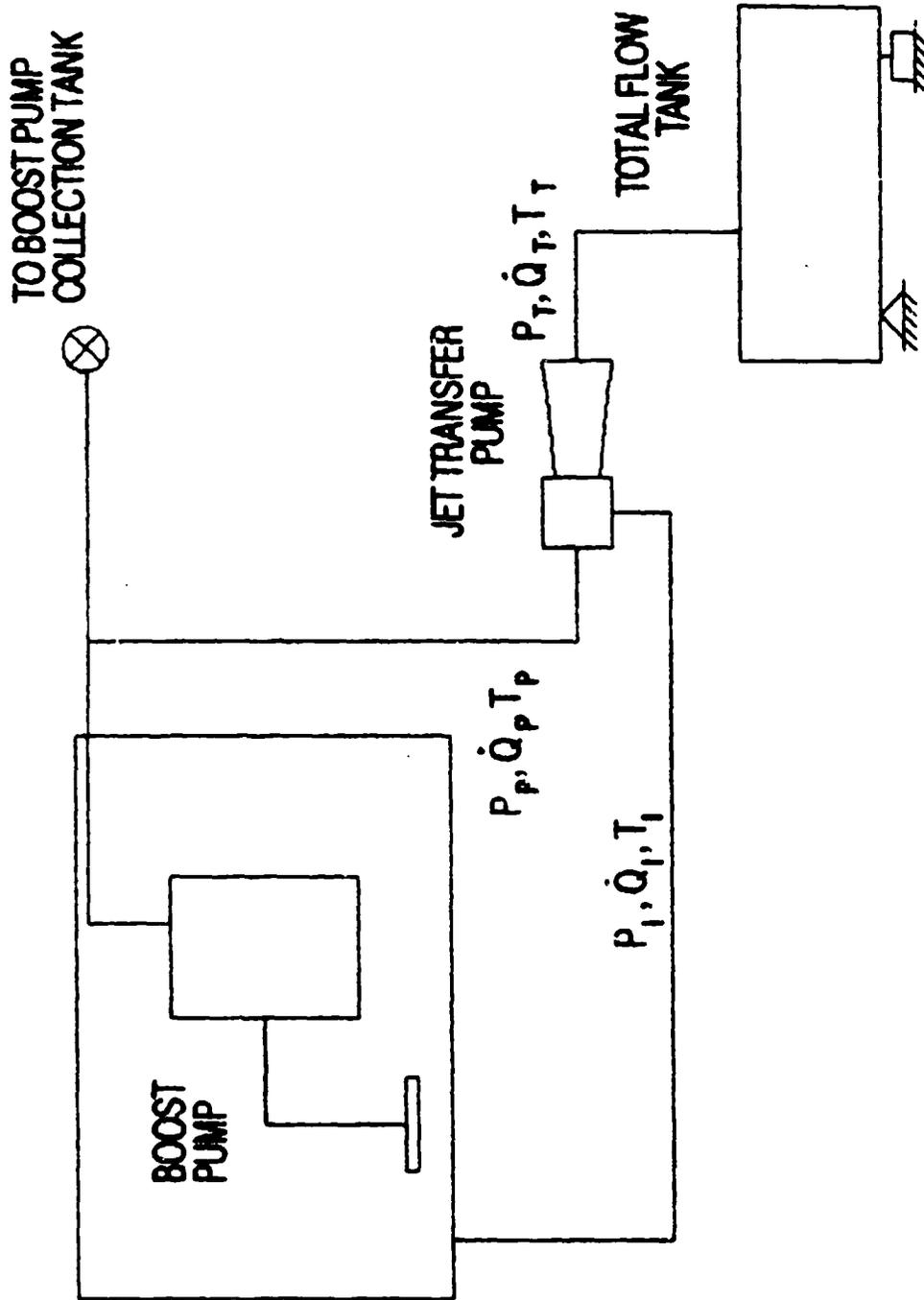


FIGURE 3. HIGH PRESSURE DRIVEN FACILITY. HARDWARE ELEMENTS.



- TYPICAL RUN TIME: 1 MINUTE
- FUEL TEMPERATURE RANGE FROM AMBIENT TO  $-40^{\circ}\text{C}$

FIGURE 4. BOOST PUMP DRIVEN FACILITY SCHEMATIC

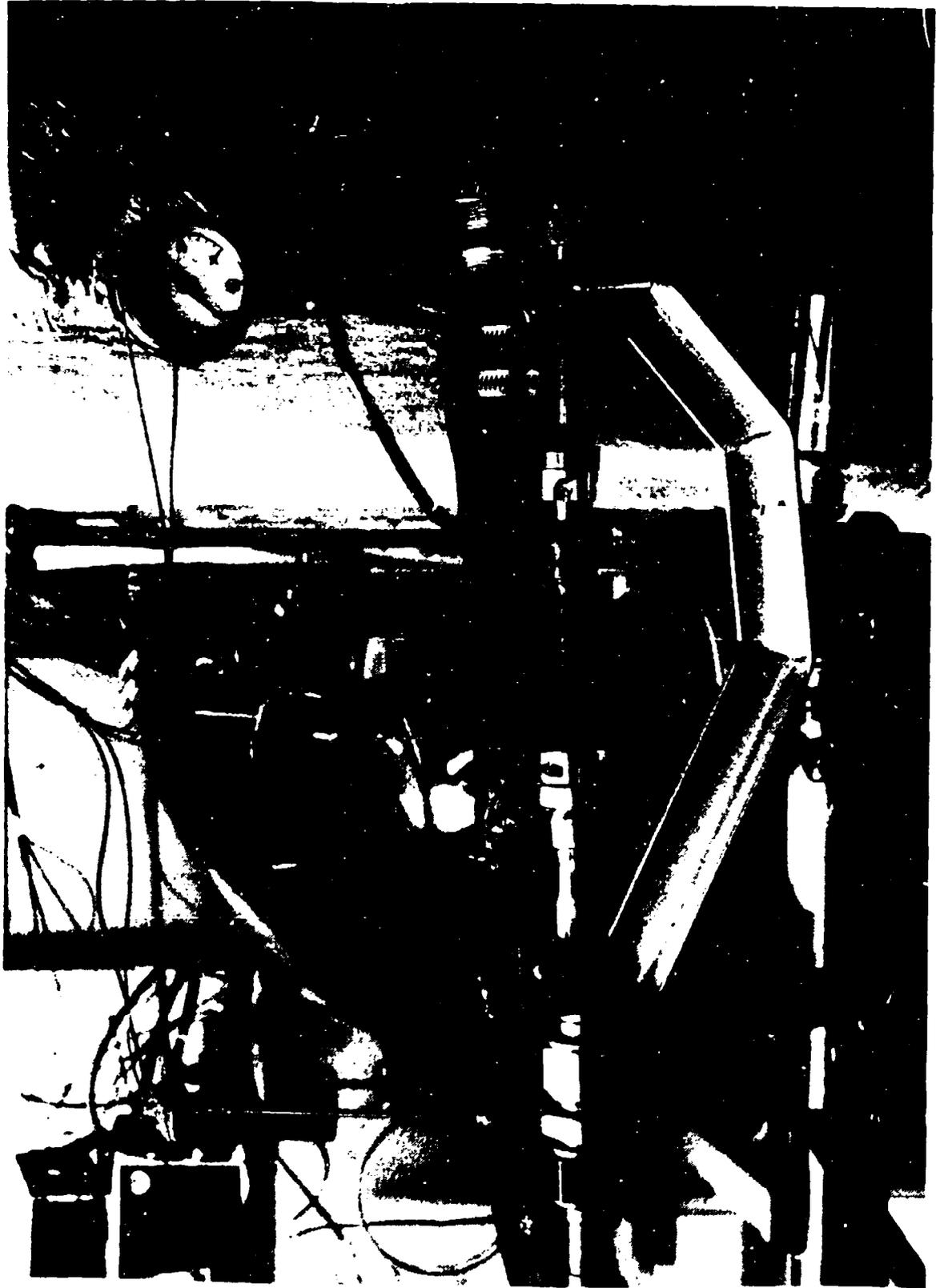


FIGURE 5. BOOST PUMP DRIVEN FACILITY

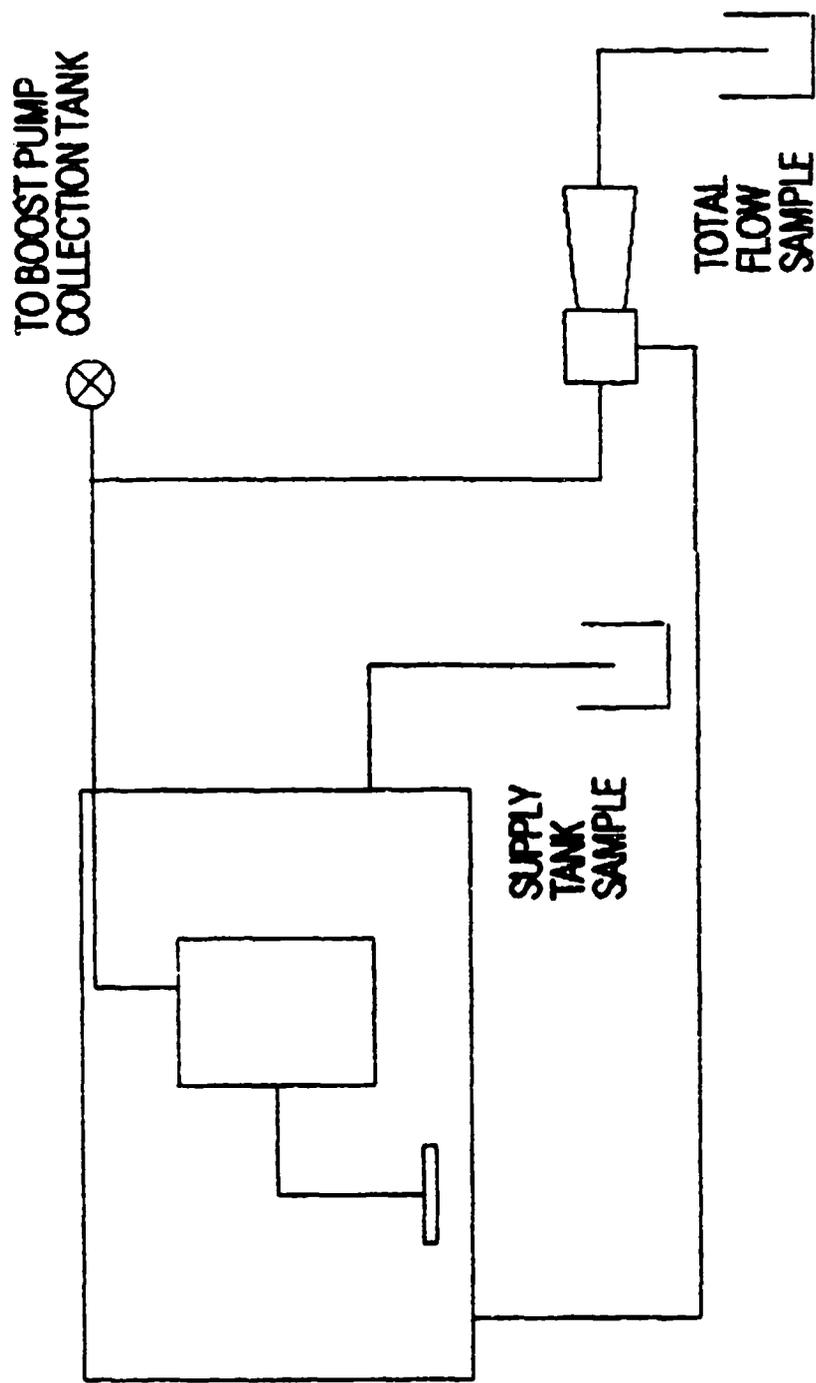
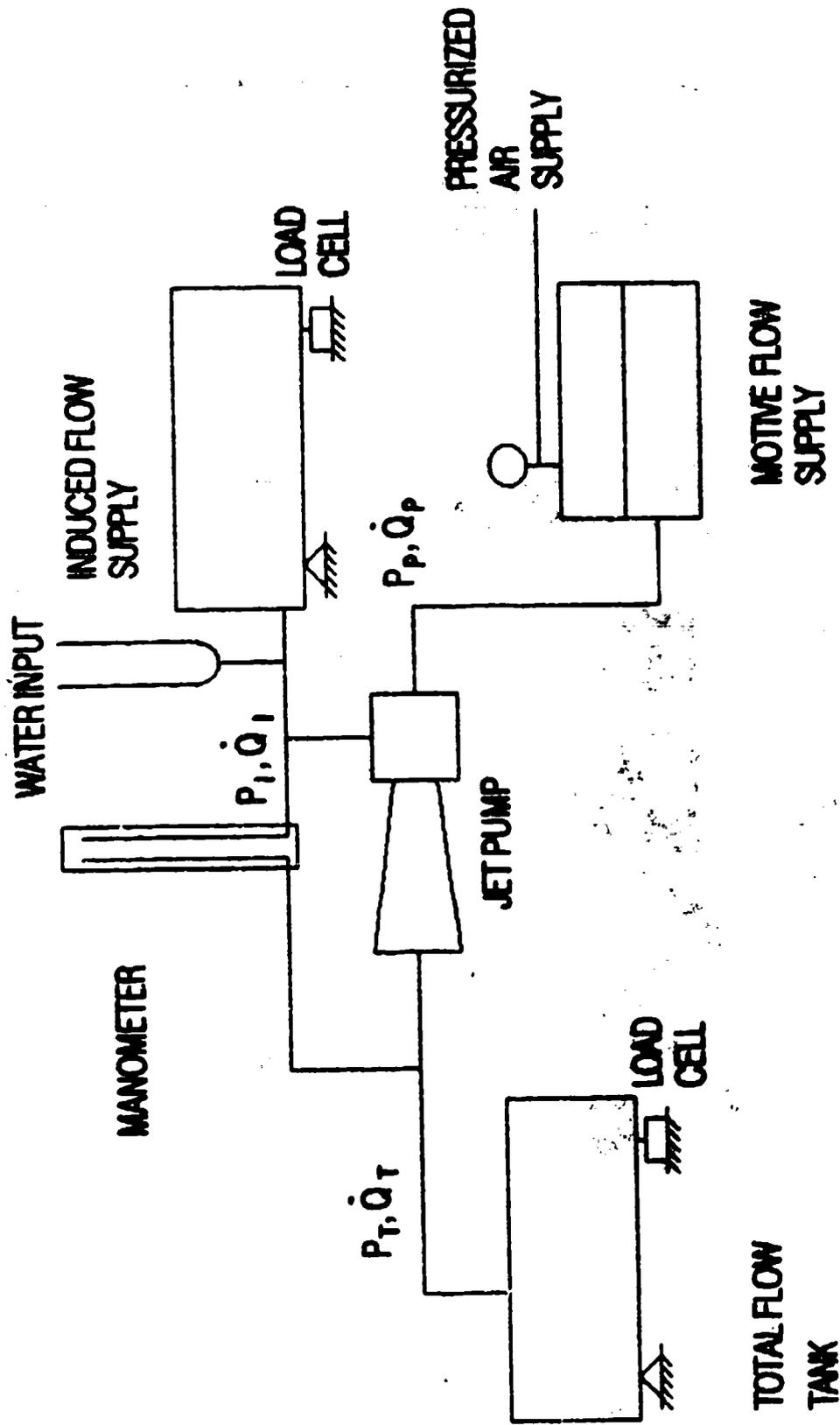


FIGURE 6. LOCATION OF FUEL SAMPLES



- BLOW-DOWN FACILITY; 5 MIN RUN TIME.
- INCORPORATES HEAD CONTROL FOR INDUCED, TOTAL AND MOTIVE FLOW TANKS.

FIGURE 7. WATER INJECTION TECHNIQUE



FIGURE 8. J. C. CARTER 60103-5 JET PUMP

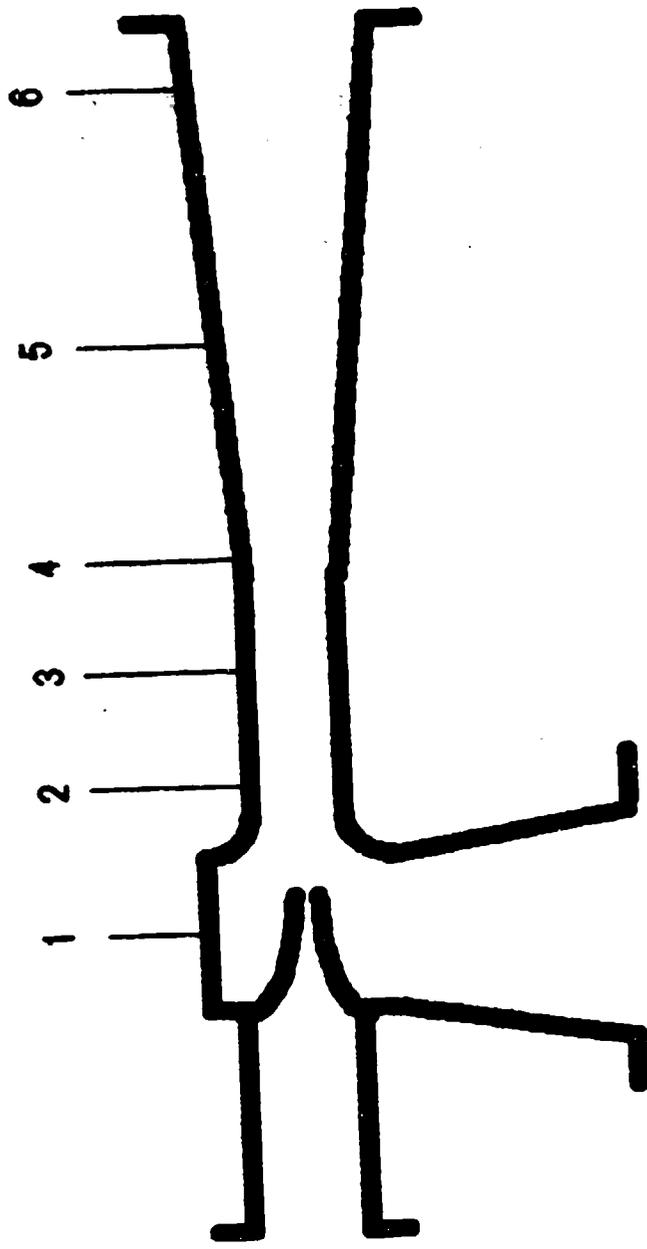


FIGURE 9. DIAGRAM SHOWING THE LOCATION OF THE SURFACE PRESSURE TAPS

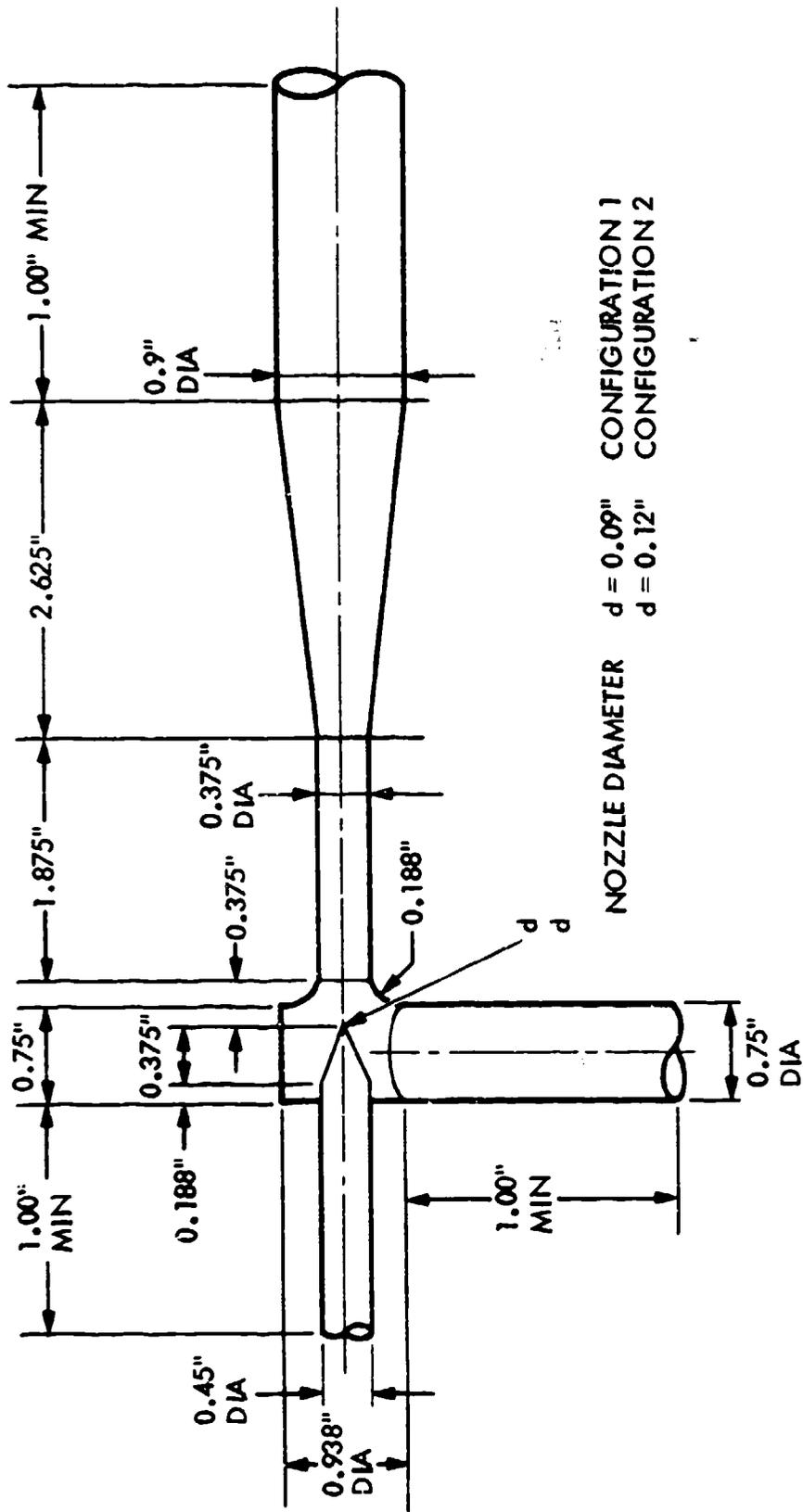


FIGURE 10. GLASS JET PUMPS DIMENSIONS.

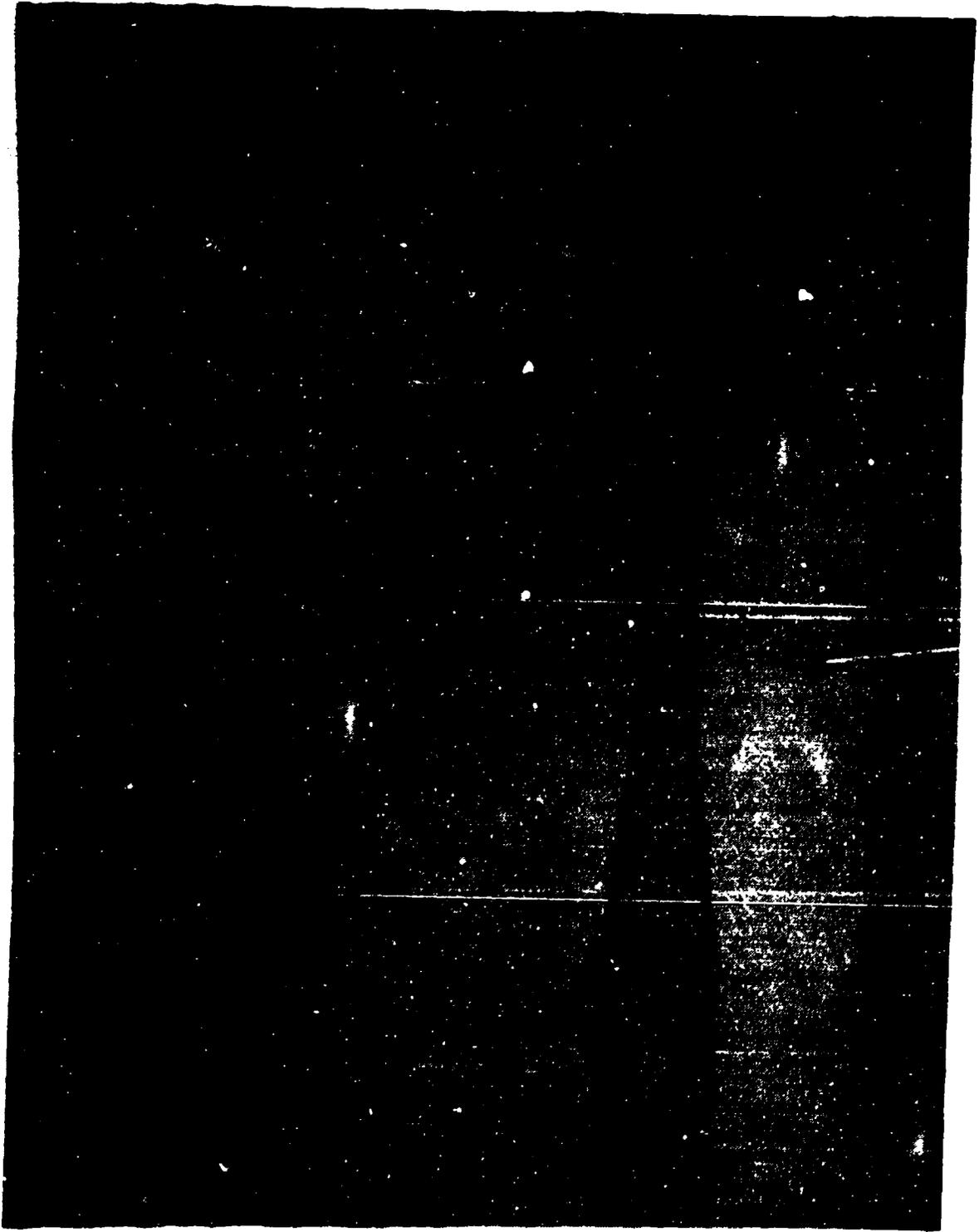


FIGURE 11. GLASS JET PUMPS

pump. In the high-pressure, motive flow facility, the samples were obtained directly from the total flow line. In the boost pump configuration, samples were obtained at the locations shown in figure 6. As indicated in this figure, the AMK fuel quality was monitored in the supply tank. This was necessary because the boost pump cooling flow was allowed to mix with the rest of the fuel in the tank, thus, some degradation was expected.

The water tests were conducted in the high-pressure, motive flow facility. For these tests a small syringe was added to the induced flow line as close to the tank as physically possible, as indicated in figure 7. Approximately 50 cc of water was added to the syringe. The water and fuel pressure head on the induced flow line were as close as possible. The tests were initiated by setting a specified flow condition on the jet pump. After the flow had been established, the water valve was opened, and the physical appearance of the AMK was observed in the induced flow and total flow lines. Samples were obtained of the total flow during these tests.

Most tests were done on J. C. Carter 60103-5 jet pumps as shown in figure 8. These are the jet pumps used in the L1011 aircraft fuel system. Similar pumps have been tested in other investigations (references 4,5). This pump has a priming disc installed at the exit plane for self-priming. The operation of a self-priming jet pump with AMK fuel had not been tested before. The priming disc results in some performance loss with Jet A compared to the performance without the disc. Surface pressure measurements were conducted on this pump. The location of the pressure tap are shown in figure 9. A single pressure transducer was used for these measurements. The different lines were multiplexed manually.

Two other jet pumps were tested during the performance improvement study. Both pumps have the same geometrical dimension except for the motive flow orifice diameter as shown in figure 10. Configuration 1 has 0.09 inch orifice diameter and Configuration 2 has 0.12 inch orifice diameter. Both jet pumps were made out of glass in order to conduct a flow visualization study. A photograph of both glass jet pumps is presented in figure 11.

Limited performance improvement studies were also performed on Allen Aircraft Products Inc. jet pump model 68E108 supplied to JPL by the Boeing Aircraft Company. Both batch and inline blended fuels were used during this investigation.

## RESULTS

### Jet Pump Performance

The measured performance of J. C. Carter 60103-5 pump is presented in figure 12. The results concerning the suction pressure ( $P_T - P_I$ ) as a function of the total volume flow rate are presented in this figure for both Jet A and AMK. The results obtained in both facilities and at low temperature ( $-40^\circ\text{C}$ ) are shown. The motive flow pressure was  $29 \pm 1$  psig and was kept constant throughout these tests. The measured motive flow rate was 0.9 GPM with Jet A and 0.8 GPM with AMK. Thus a reduction of approximately 10 percent was

J. C. CARTER #60103-5

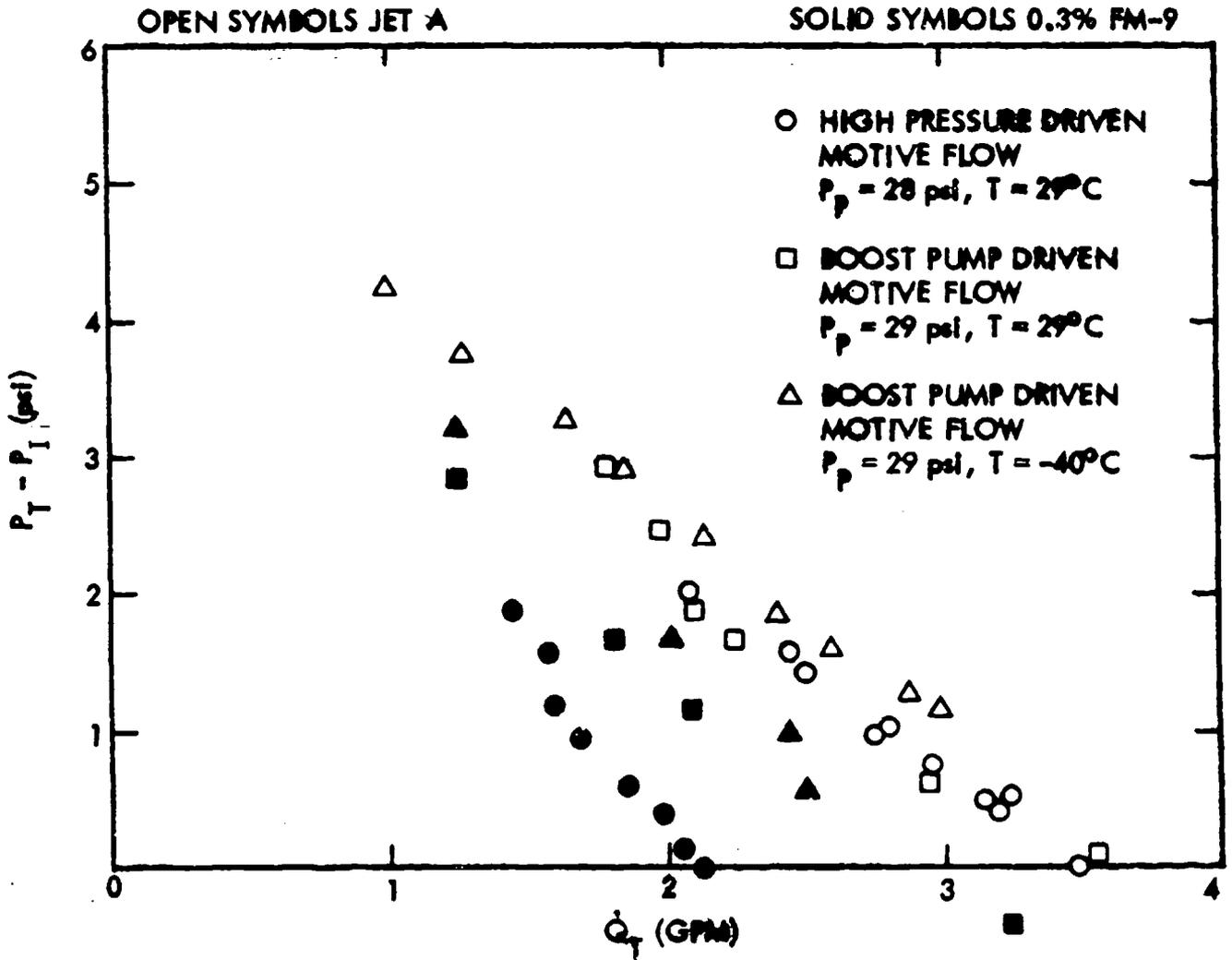


FIGURE 12. J. C. CARTER #60103-5 JET PUMP PERFORMANCE

TABLE 1. J. C. CARTER 60103-5 JET PUMP PERFORMANCE

	Efficiency (percent) @PT-PI = 2 psi		Jet A $\dot{Q}_T$ (gpm)	AMK $\dot{Q}_T$ (gpm)	percent change	Jet A $\dot{Q}_T$ (gpm)	AMK $\dot{Q}_T$ (gpm)	percent change
	Jet A	AMK						
High Pressure Driven Primary Flow $P_p=28$ psi $T=29^\circ\text{C}$	10	5	2.15	1.40	-35	1.25	0.60	-52
Boost Pump Driven Primary Flow $P_p=29$ psi $T=29^\circ\text{C}$	10	7	2.15	1.65	-23	1.25	0.85	-32
Boost Pump Driven Primary Flow $P_p=29$ psi $T=-40^\circ\text{C}$	11	9	2.30	1.85	-20	1.40	1.05	-25

TABLE 2. AMK DEGRADATION RESULTS. HIGH PRESSURE DRIVEN PRIMARY FLOW

FLAMMABILITY

RUN	CONDITIONS	FILTER RATIO	CUP TEST	SPEED*	SPEED**
0	JET A	---	---	365°C	> 1000°C
1	AMK sample storage (0.3% FM-9)	31.8	2.7	0°C	80°C
2	Primary Flow Sample P <sub>T</sub> = 28 psi	24.7	3.0	0°C	20°C
3	Total Flow Sample P <sub>P</sub> = 28 psi Q <sub>T</sub> = 0.567 gpm P <sub>T</sub> - P <sub>I</sub> = 0.960 psi	26.5	2.8	0°C	45°C
4	Total Flow Sample P <sub>P</sub> = 28 psi Q <sub>T</sub> = 0.49 gpm P <sub>T</sub> - P <sub>I</sub> = 1.89 psi	25.1	2.9	0°C	50°C
5	Primary Flow Sample P <sub>P</sub> = 28 psi	23.5	2.9	5°C	70°C

\* Air Velocity 70 m/s, Fuel Flow 9 ml/s

\*\* Air Velocity 70 m/s, Fuel Flow 24 ml/s

TABLE 3. AMK DEGRADATION RESULTS. BOOST PUMP DRIVEN PRIMARY FLOW

SAMPLE	CONDITIONS	LOCATION	FR	TIME ELAPSED
1		SUPPLY TANK	19.4	0
2	$P_P = 29 \text{ psi}$ $P_T - P_S = 2.85 \text{ psi}$ $Q_T = 1.25 \text{ gpm}$	SUPPLY TANK	13.1	10 MIN
		TOTAL FLOW	3.0	
3	$P_P = 29 \text{ psi}$ $P_T - P_S = -0.44$ $Q_T = 3.23$	SUPPLY TANK	8.8	15 MIN
		TOTAL FLOW	1.9	
4	$P_P = 29 \text{ psi}$ PRIMARY FLOW ONLY	SUPPLY TANK	5.6	20 MIN
		TOTAL FLOW	1.5	

measured in the motive flow with AMK as compared with Jet A at the same supply pressure.

The results presented in figure 12 show a significant reduction in the performance with AMK. This reduction can be quantified by the measured total or induced flow rate at a suction pressure of 2 psi. This suction pressure is a typical value encountered by jet pumps during operation (reference 4). These results are presented in table 1. The high pressure driven primary flow gives significantly lower performance with AMK as compared to Jet A. The performance improves in the boost pump driven configuration particularly at low temperature. The results at room temperature are in good agreement with the results of other investigations (references 1,2,4). Low temperature results were not available in the literature.

Antimisting fuel samples were drawn during these tests in order to determine the degradation characteristics of the jet pump. The AMK fuel samples were evaluated by filter ratio, cup, and flammability (FCTA) tests. These tests and these operating procedures are discussed in reference 6. The results for the samples obtained in the high pressure driven primary flow are presented in table 2. It is apparent that no significant degradation of the AMK fuel is caused by the pump. Similar samples were obtained in the boost pump driven primary flow tests. These samples were characterized by filter ratio tests as shown in table 3. These results show significant degradation of the total flow sample as compared to the supply tank sample. Furthermore, the supply tank samples show an increased degradation with time. This degradation can be attributed to the recirculation of the pump cooling fuel in the supply tank. Comparison of the results in the high-pressure driven primary flow test and boost pump driven primary flow tests indicate that the degradation in the latter is entirely due to the boost pump.

Some observations were also made of the priming characteristics of the J. C. Carter 60103-5 jet pump with both Jet A and AMK. The pump successfully started with both fuels. However, pumping with AMK was slow to start with some air bubbles being trapped in the lines. These bubbles did not impair the operation of the pump. This area was not further investigated during the course of this investigation.

#### Surface Pressure and Flow Visualization

Several tests were conducted in order to determine the origin of the decreased performance of jet pumps with AMK as well as to propose design changes in order to improve it. Surface pressure measurements ( $P$ ) were conducted on the J. C. Carter 60103-5 jet pump in the high pressure driven facility. The results are presented in figure 13 for both Jet A and AMK. Location of pressure taps are shown in figure 9. The measurements were obtained at a motive flow pressure of 30 psi and suction pressures ( $P_T - P_I$ ) of 1.45 psi and 1.33 psi for the Jet A and AMK tests, respectively. In the results presented in figure 13, the local pressure has been normalized with the suction pressure. The minimum surface pressure is found at the entrance of the constant area section of the pump. This peak is 50 percent of the suction pressure with Jet A and only 10 percent with AMK. This

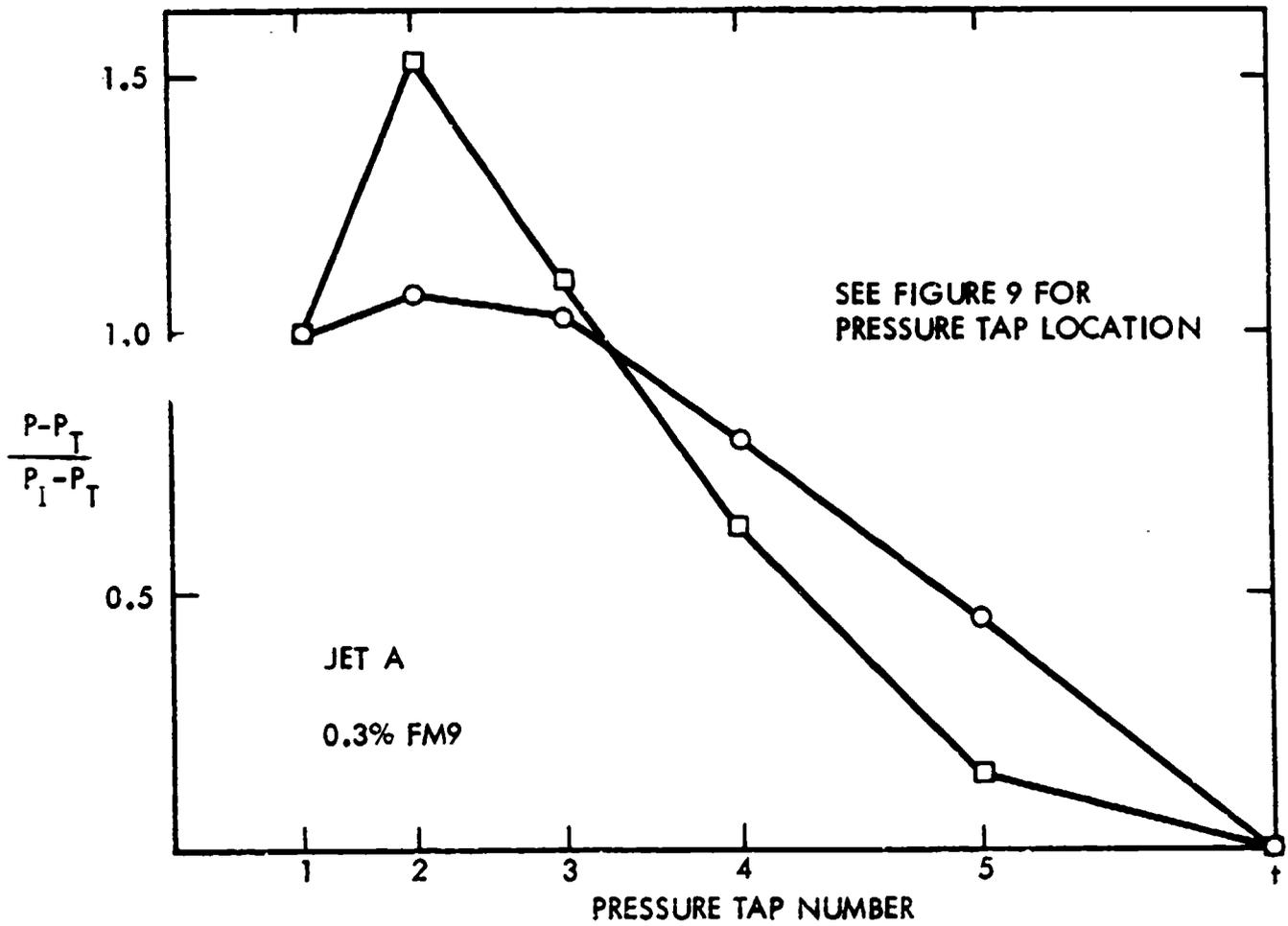


FIGURE 13. JET PUMP SURFACE PRESSURE DISTRIBUTION

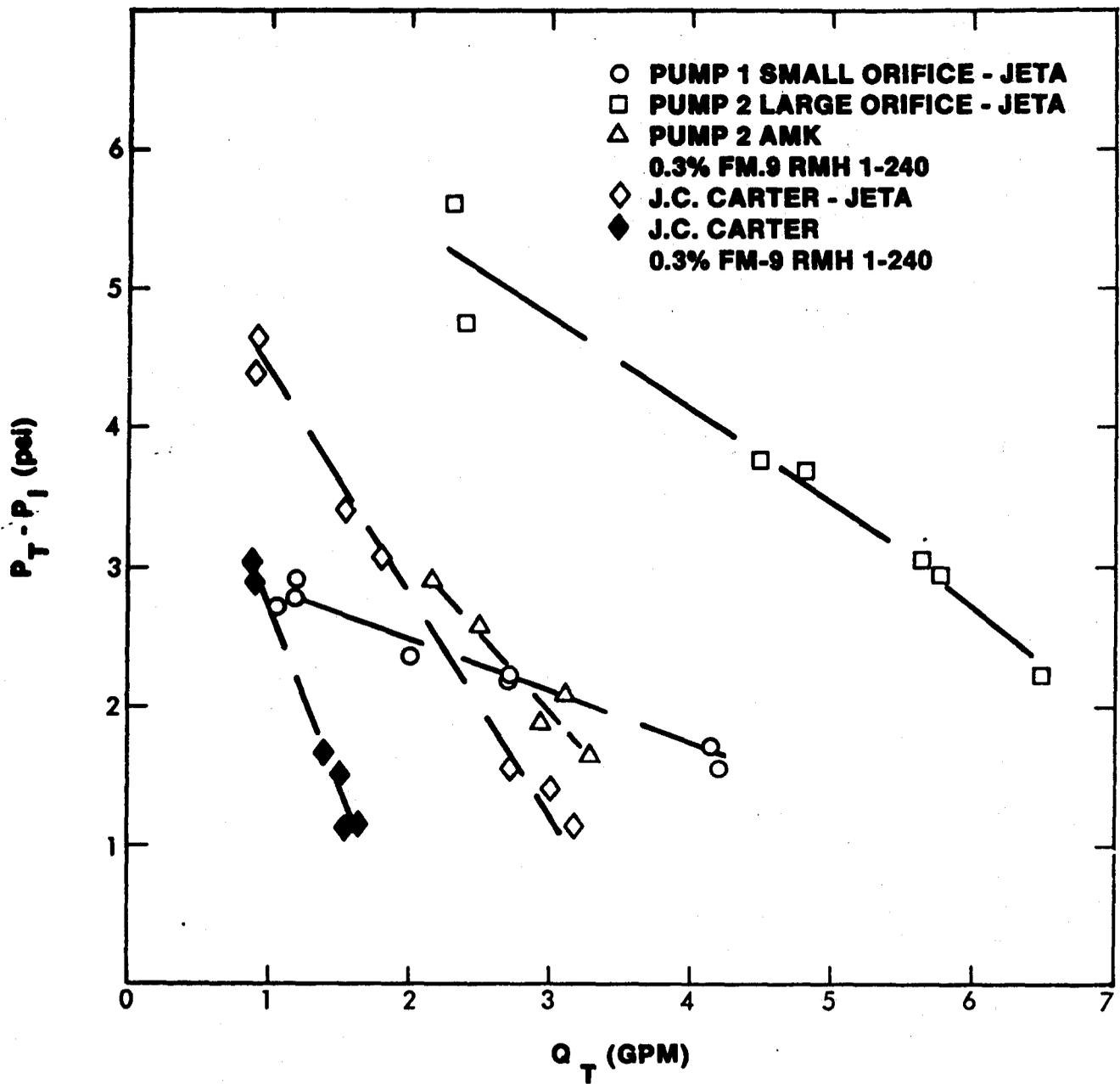


FIGURE 14. GLASS JET PUMPS PERFORMANCE

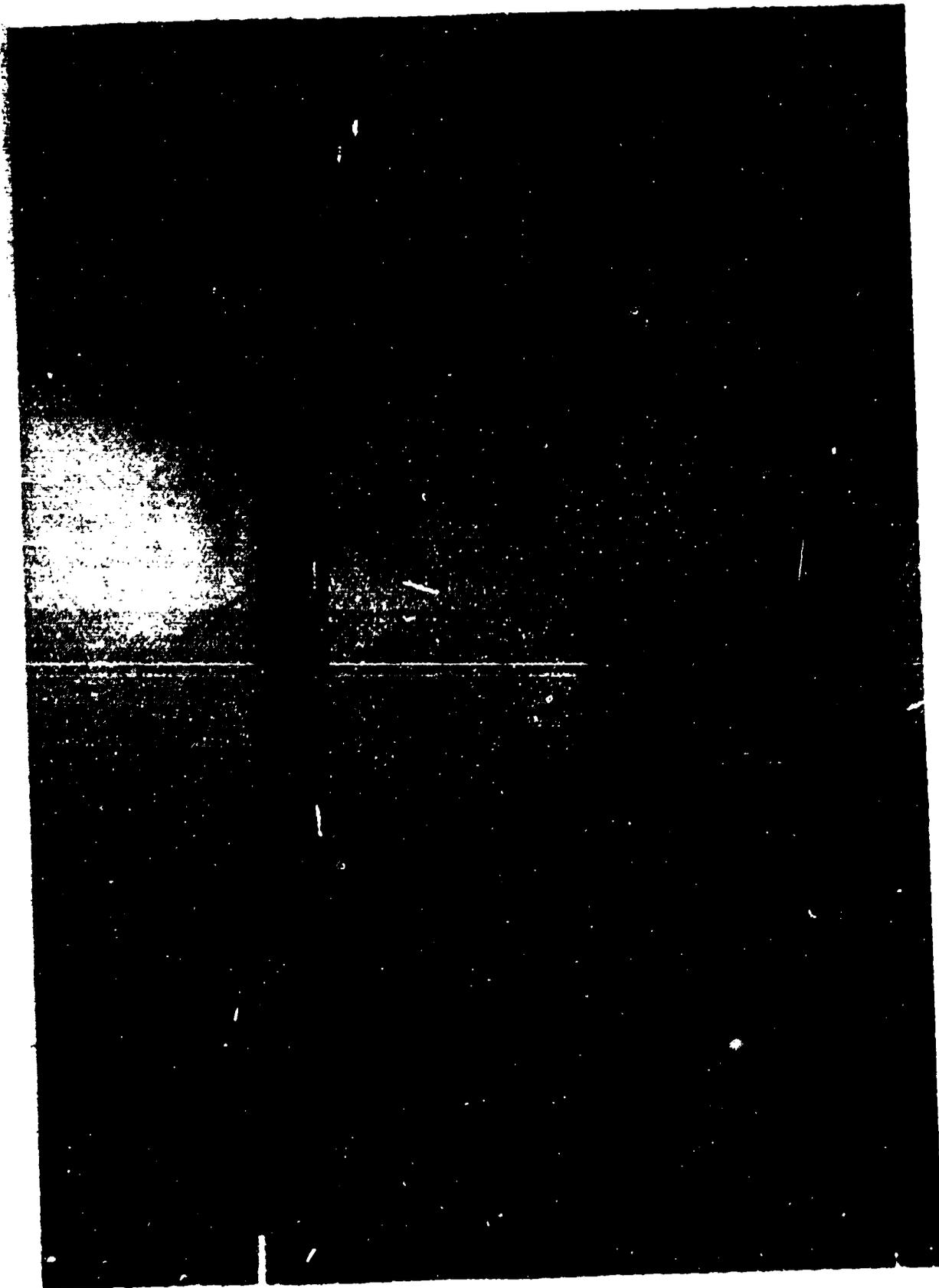


FIGURE 15. GLASS JET PUMP NUMBER 2 WITH JET A

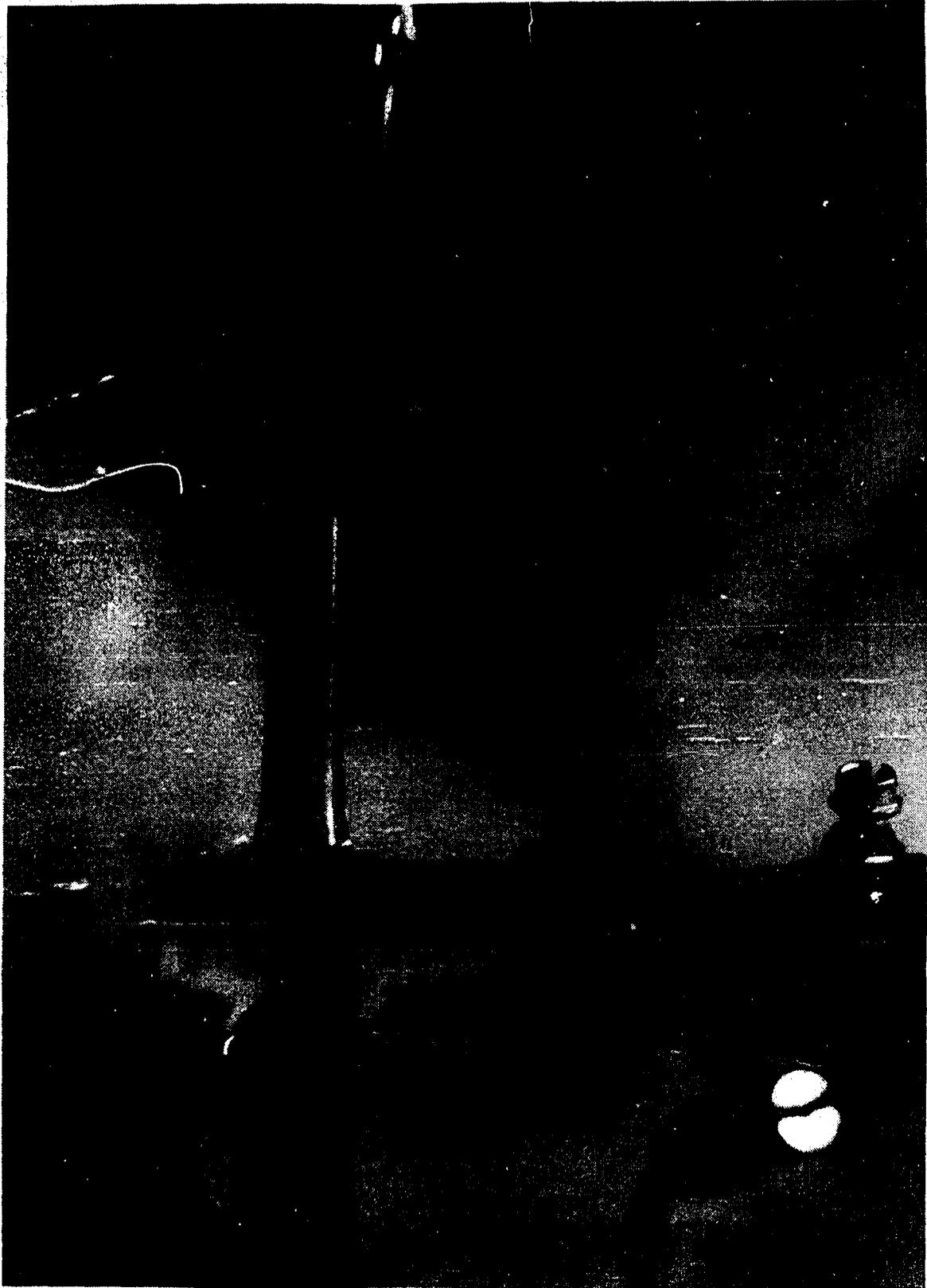


FIGURE 16. GLASS JET PUMP NUMBER 2 WITH 0.3 FM9 (RMH 1-240)

reduction of the minimum pressure with AMK is accompanied by a significantly lower pressure gradient throughout the entire jet pump.

The performance curves of the two glass jet pumps and J. C. Carter 60103-5 are presented in figure 14. The glass jet pump with a 0.09 inch orifice diameter failed to provide any suction with AMK. Comparison of AMK performance curves of J. C. Carter 60103-5 and configuration 2 with orifice diameter of 0.12 inch show a significant increase of the total and induced flow rates. At a delivery pressure of 2 psi, configuration 2 has a 136 percent increased total flow rate and 112 percent increased induced flow. However, these increased flow rates are obtained in part due to a significantly larger motive flow rate (147 percent higher). Both pumps have comparable efficiencies of 2.7 percent and 3.1 percent at a delivery pressure of 2 psi for configuration 2 and J. C. Carter 60103-5 pumps, respectively. The efficiencies of these pumps with Jet A at the same delivery pressure are 11.9 percent for the J. C. Carter pump and 7.1 percent for configuration 2.

To further understand the mixing in a jet pump, flow pictures were obtained with both Jet A and AMK in the glass jet pump (configuration 2). These pictures are presented in figures 15 and 16 for Jet A and AMK, respectively. Careful comparison between these two pictures show that while with Jet A the dyed fluid covers the entire cross-section somewhere in the middle of the constant area section, with AMK the dyed fluid does not fill the entire cross-section within the length of the pump. Turbulent mixing, therefore, is suppressed by the non-Newtonian properties of AMK fuel. This lack of mixing results in a reduced surface pressure gradient as shown in figure 13 and consequently in a reduced suction and induced flow rate for a fixed length pump as indicated in figure 12.

#### Water Ingestion

Water dissolution tests have been completed with batch blended AMK. A known water flow rate was introduced in the induced AMK flow line. Visual observations of the flow-field were conducted as the AMK-water mixture passed through the pump. Filter ratio tests were performed on the AMK fuel prior to the test and on a total flow sample.

For this test the J. C. Carter #60103 pump was operated at an induced flow rate of 0.5 GPM and a total flow rate of 1.5 GPM. The water flow rate was 2 cc/s, which gives water concentrations of 6.3 percent and 2.1 percent on the induced flow and total flow lines, respectively. Even though the concentration in the induced flow line was three times higher than in the total flow line, the water remained in the form of small droplets of a few millimeters in diameter. In the total flow line, however, phase separation was observed (white precipitate). The precipitate did not impair the operation of the pump. It did deposit on the total flow pipe internal surface and was carried into the collecting tank. A sample was drawn from the collecting tank. After the precipitate had settled, a filter ratio of 41.6 was measured on the clear fuel. The pre-test AMK (RMH-1-240) had a filter ratio of 38.5. After the filter ratio test was completed, the filter

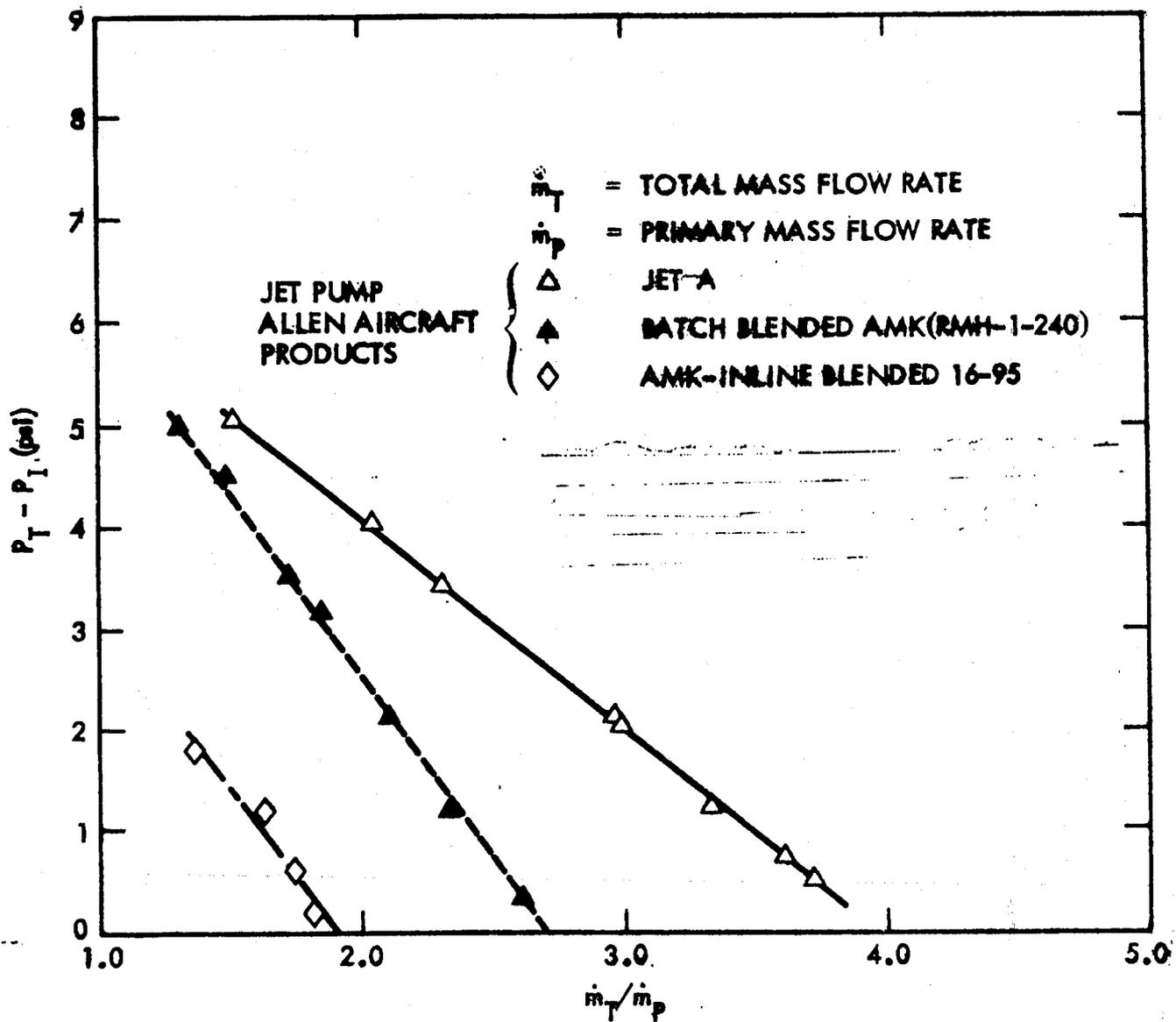


FIGURE 17. JET PUMP PERFORMANCE

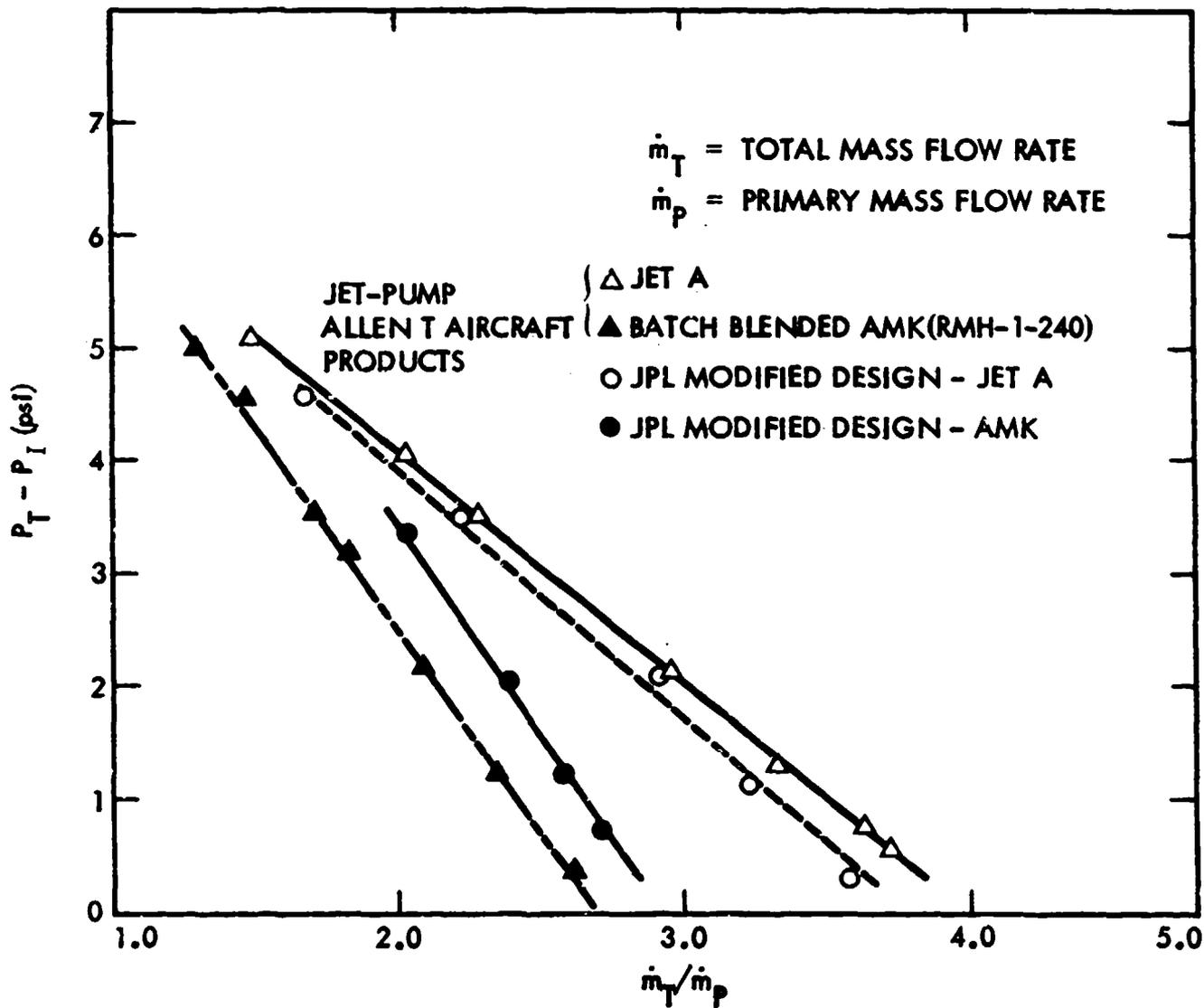


FIGURE 18. IMPROVEMENT IN JET PUMP PERFORMANCE

used was inspected to determine the presence of precipitate. No precipitate was observed.

These observations are in complete agreement with those reported in reference 6. Thus, if pools of water are formed at the low points of an aircraft fuel tank, the jet pumps in the scavenge system will provide the necessary mixing (agitation) for the formation of precipitate. Fire protection of this AMK-water mixture is not reduced as also reported in reference 1 (FR - 41.6). However, as discussed in reference 6, the effect of precipitate on other aircraft fuel system components needs to be determined.

### Performance Improvement Study

As suggested by the jet pump flow visualization study, improvement in turbulent mixing with AMK was attained by increasing the length of constant area mixing chamber. The study was performed on aircraft jet pump manufactured by Allen Aircraft Products Inc. (Model 68E108). Figure 17 shows the induced pressure  $P_T - P_I$  as a function of mass flow ratio  $\dot{m}_T / \dot{m}_p$  for Jet A and AMK where  $\dot{m}_T$  is the total mass flow rate through the jet pump and  $\dot{m}_p$  is the primary motive flow rate which was kept constant throughout this experiment. These tests were performed in the facility shown in figure 3. Both batch blended and inline blended fuel data are shown. Jet pump performance with inline blended fuel using JCK 16-95 slurry was poorer as compared to batch blended material. This was expected because of superior quality of JCK 16-95 blend (i.e., cup = 1.8/filter ratio = 85) as compared to batch blended RMH-1-240 (i.e., cup = 3.2/filter ratio 35). The results obtained with modified mixing chamber to improve jet pump performance are shown in figure 18. The length of the constant area mixing chamber was doubled from 1.0 inch to 2.0 inch without changing the primary nozzle and mixing chamber diffuser geometry. It is evident from results shown in figure 18, a 15 percent improvement in AMK mass flow transfer rate was observed at a suction pressure of 2 psi. During this investigation, however, no effort was made to optimize the geometry to obtain best jet pump performance.

### DISCUSSION

The results of these tests show a significant performance deterioration of typical fuel system jet pumps with AMK fuel as compared with Jet A fuel. The maximum suction pressure, the total flow rate, and induced flow rate are all reduced with AMK. When degradation of the motive flow is avoided, the induced and total flow rate are reduced by 52 percent and 35 percent, respectively. These tests, however, are not realistic in that in an aircraft fuel system the motive flow is obtained from the high pressure output of a pump which results in some degradation of the AMK fuel. Under these conditions the tests show a somewhat better performance. Comparison of the boost pump driven motive flow results between AMK and Jet A show reduction of 32 percent and 23 percent for the induced and total flow, respectively. Furthermore, in a typical flight the fuel temperature is frequently below ambient. Tests show an additional improvement of the pump

performance at low temperature. The performance reduction can be as low as 25 percent and 20 percent at  $-40^{\circ}\text{C}$  in the boost pump driven motive flow configuration for AMK as compared with Jet A.

The performance reduction with AMK fuel is due to the suppression of turbulent mixing within the pump and the reduced motive flow. The flow visualization picture presented in figure 16 clearly shows a typical laminar jet behavior. The implication of this observation is two-fold. On the one hand the fuel does not encounter the high shear rates typical of a turbulent flow. Therefore, little degradation can be expected. On the other hand, the reduced rate of mixing results in a low pressure gradient within the constant area section of the pump as shown by the surface pressure measurements in figure 13. Consequently, for a fixed length pump, the peak pressure in the pump is reduced. An increased length of the pump will therefore result in a performance improvement as confirmed by the results presented in figure 18. The surface pressure distribution results further suggest that in order to achieve a peak pressure with AMK comparable to the value found with Jet A, the length of the constant area section of the pump should be increased by a factor of four. Based on this result, a mixing chamber length-to-diameter ratio of the order of 20 is proposed for undegraded AMK fuel as opposed to the value of 5 to 6 used in current jet pump designs.

However, if the proposed increased length of the jet pump necessary to improve its efficiency is not acceptable from a fuel systems point of view, a second alternative is to continue using current Jet A designs but with larger size in order to upgrade their performance with AMK fuel. This appears to be a better approach since the efficiency of jet pump motive flow with AMK is only 8-10 percent lower than with Jet A under realistic aircraft fuel system conditions and at low temperatures. In considering the actual size increase necessary to satisfy a specific application, Jet A data can be used with the following revisions: (1) the motive rate with AMK is reduced by 10 percent, and (2) the efficiency of the pump with AMK is reduced by 30 percent below Jet A values. These figures are supported by the test reported here as well as those reported in reference 4. They should be used as a first estimate for jet pump sizing and to compute overall system performance loss due to increased motive flow rate.

The priming characteristics of jet pumps with AMK fuel are also deteriorated as compared with Jet A. However, standard techniques used with Jet A are also useful with AMK, for example, a priming disc. As shown by our flow pictures, gel formation with AMK fuel greatly reduces the flow rate back into the induced flow line. Thus, a somewhat slower priming process occurs. Even with Jet A, priming problems can be encountered depending on jet pumps and system design. Somewhat more severe conditions can be expected with AMK. However, similar techniques as used with Jet A can be used to circumvent these problems with AMK fuel.

Water ingestion tests with the jet pump confirmed the findings reported in reference 6. Water droplets in the induced flow line did not result in significant precipitate formation. It is the mixing of those droplets at a small scale that causes the formation of precipitate. The long term

accumulation of precipitate and its effect on other fuel system components may be cause of concern. The operation of the jet pump is not influenced by precipitate formation.

### CONCLUDING REMARKS

1. Jet pump performance with undegraded AMK fuel is significantly reduced as compared with Jet A values. The performance reduction is 52 percent for the induced flow rate and 35 percent for the total flow rate, both at a delivery pressure of 2 psi.
2. Partially degraded motive flow typical of boost pump output results in an improved performance. Comparison with Jet A gives a reduction of 32 percent and 23 percent for the induced and total flow, respectively, at the same delivery pressure.
3. The performance of the pump with AMK at low temperature is better than at room temperature. Comparison with Jet A gives a reduction of 25 percent and 20 percent for the induced and total flow, respectively, at 2 psi and -40°C.
4. Flow visualization and surface pressure measurements showed significantly reduced turbulent mixing with AMK fuel. Based on these measurements, it is estimated that a mixing chamber length to diameter ratio of the order of 20 should be used with AMK instead of the value of 5 to 6 used for pumps designed for Jet A fuel. This value may be reduced if the effect of partially degraded motive flow is taken into account. Preliminary tests showed 15 percent improvement in AMK jet pump transfer rate when the constant area mixing chamber length was doubled.
5. Larger jet pumps designed to operate with Jet A can also be used to compensate for loss of performance with AMK. Performance characteristics obtained for Jet A can be used in sizing the pump by using a 10 percent reduction of the motive flow and a 30 percent reduction of the efficiency. These are typical values based on the results presented here and in reference 4.
6. Priming of jet pumps with AMK fuel is somewhat more sluggish than with Jet A. The techniques used to avoid priming problems with Jet A also apply to AMK fuel.
7. Water compatibility is a challenging aspect of FM-9 AMK fuel. Results show that large amounts of bulk water can be in contact with AMK without formation of precipitate (emulsion). As soon as this mixture moves through the jet pump, large amounts of precipitate are formed. This formation of precipitate does not influence the operation of the pump or reduce the antimisting quality of the fuel.

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