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LIQUID INJECTION THRUST VECTOR CONTROL

by
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ABSTRACT. The technique of obtaining thrust vector control by the injection of a liquid into the supersonic region of a rocket nozzle has been studied. This report presents the experimental results obtained with various liquid injectants together with the effects of some of the more critical physical parameters. Liquids studied were water, Freon-12, Perchloroethylene, nitrogen tetroxide and bromine. In addition, unsymmetrical dimethylhydrazine and inhibited red fuming nitric acid were injected simultaneously to explore the effect of energy release in the nozzle exit cone with bipropellant injection. Data on the relationships of side force to injectant flow rate, the effect of axial location of the injection port, the effect of injection pressure and the effects of injectant properties are presented and discussed.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

16 June 1961

U. S. NAVAL ORDNANCE TEST STATION

AN ACTIVITY OF THE BUREAU OF NAVAL WEAPONS

C. BLENMAN, JR., CAPT., USN — *Commander*
WM. B. MCLEAN, PH.D. — *Technical Director*

FOREWORD

The results of secondary injection tests conducted at the Naval Ordnance Test Station during March and April 1960 are presented in this publication. This program was supported by Special Projects Task Assignment 71402-2.

This report was reviewed for technical accuracy by J. A. Bowen and C. W. Bernard.

JAMES T. BARTLING
Head, Propulsion Development Department

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INTRODUCTION

As the performance of propulsion systems increases, accompanied in most cases by increased combustion temperatures, the problem of satisfactory materials for mechanical thrust vector control devices becomes increasingly critical. With this problem in mind a study of possible techniques of thrust vector control was initiated at the Naval Ordnance Test Station in 1958 (Ref. 1). The technique of injecting a fluid into the expansion cone of a supersonic nozzle (secondary injection) to produce a usable side force or thrust vector force appeared to be the most promising new technique (Fig. 1).

The initial study of the secondary injection technique, using cold-flow (air) equipment, was reported by the United Aircraft Corporation (Ref. 2). Following work was performed by the Naval Air Rocket Test Station (Ref. 3), by United Aircraft Corporation (Ref. 4), and the Naval Ordnance Test Station (Ref. 5 and 6), all with gases as the injected fluids. These studies, in general, indicated that for maximum effectiveness the injected gas should be near the combustion temperature of the main-stream gases. To avoid the high temperature material problems and to meet system requirements the use of liquids as injectants was proposed. The feasibility of using liquids was demonstrated early in 1959 (Ref. 7).

EXPERIMENTAL PROCEDURES

Both liquid and solid propellant motors were used in this experimental program. One injection test was conducted using a quarter-scale SUBROC motor loaded with B. F. Goodrich E-107 polyurethane propellant containing 17.7 percent aluminum by weight. The remainder of the tests were conducted with the liquid propellant applied research motor (LPARM).

LPARM TESTS

The LPARM, Fig. 2, consists of an injector, water-cooled combustion chamber, and the nozzle test section. For the work reported in

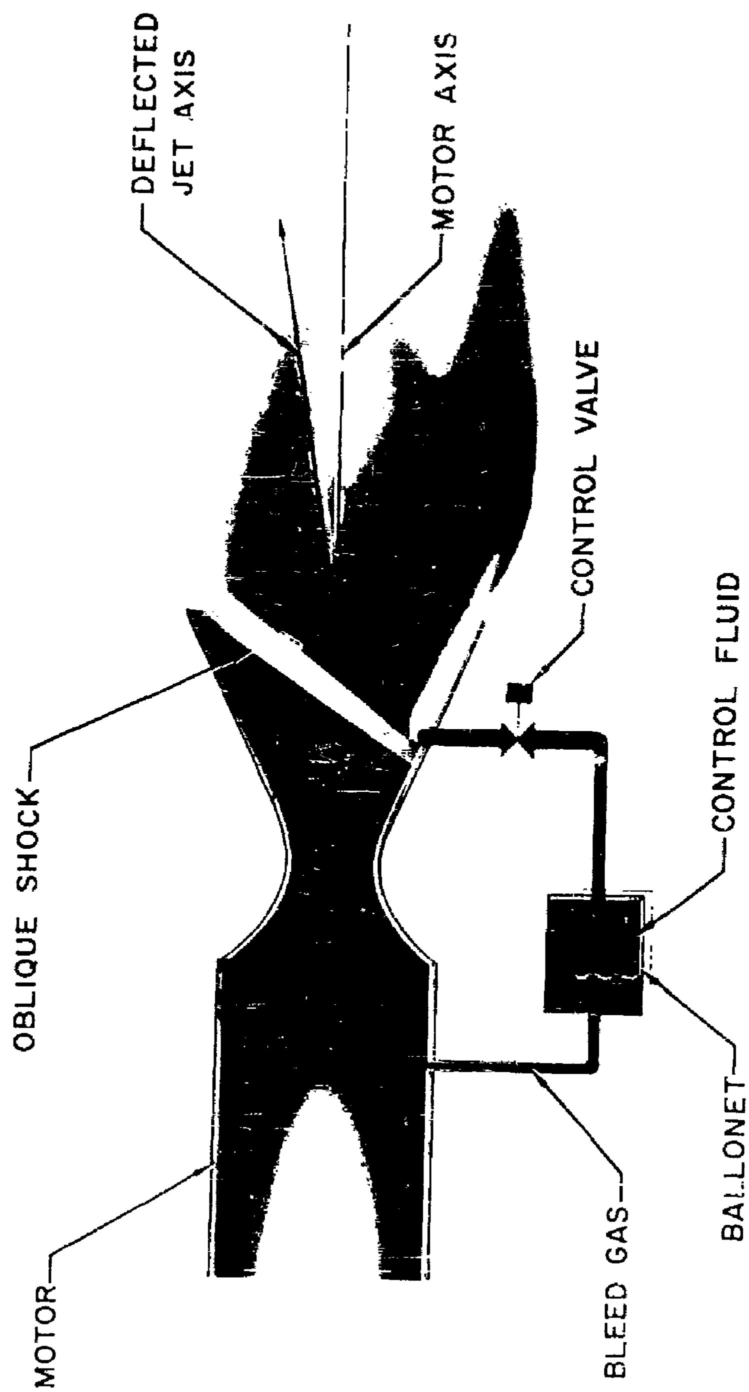

FIG. 1. Thrust Vectoring by Secondary Injection

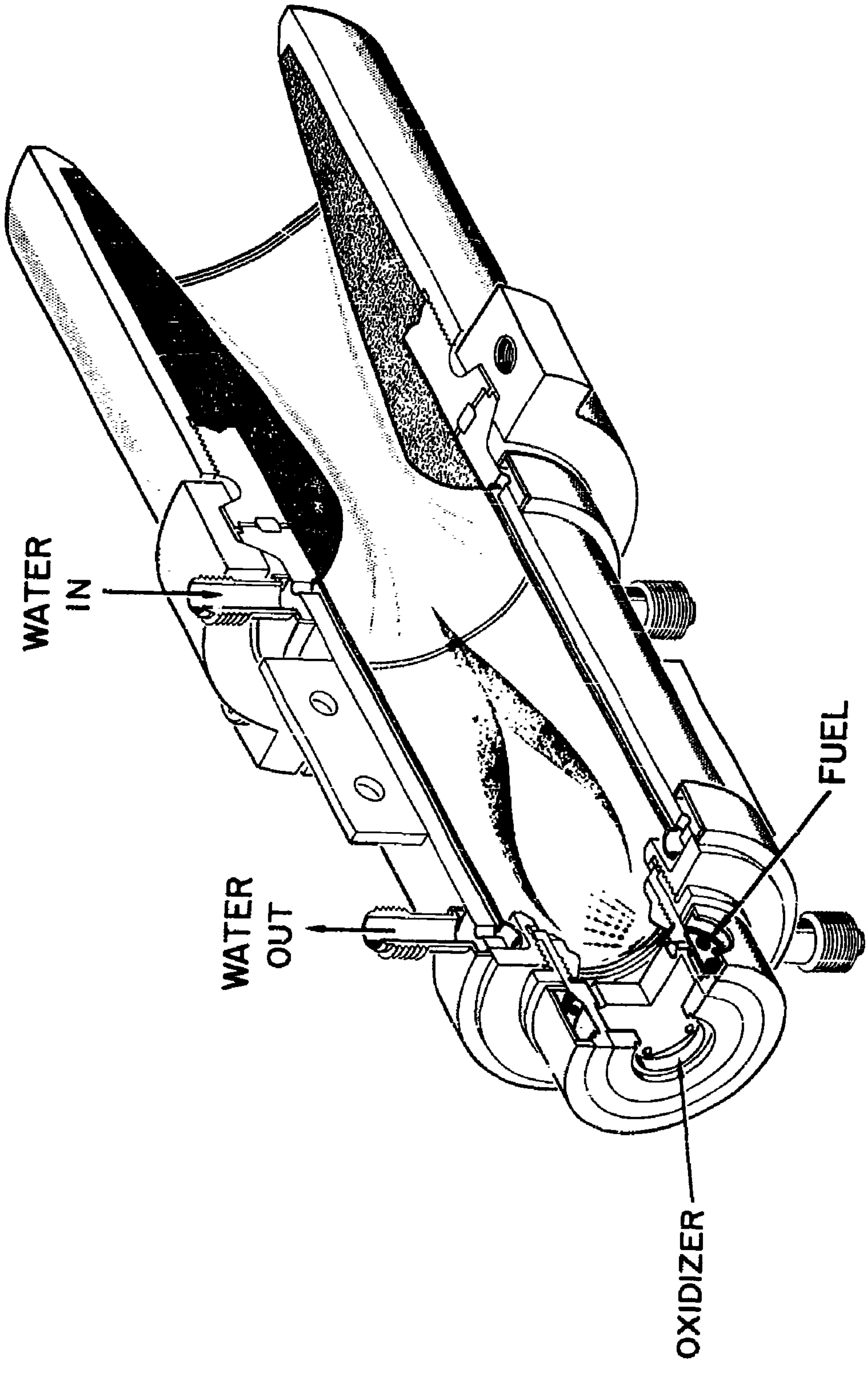

FIG. 2. Liquid Propellant Applied Research Motor

this paper, the LPARM was operated with unsymmetrical dimethylhydrazine and inhibited red fuming nitric acid (UDMH and IRFNA) at the nominal conditions given in Table 1.

Measurements which were recorded during each test were:

1. Main thrust
2. Side thrust
3. Chamber pressure
4. Injection pressure
5. Oxidizer manifold pressure
6. Oxidizer line pressure
7. Fuel manifold pressure
8. Fuel line pressure
9. Oxidizer flow rate
10. Injectant flow rate
11. Fuel flow rate
12. Coolant water flow rate

Four types of secondary injection tests were conducted: single axial position (constant secondary fluid flow rate) (type C, Fig. 3), tests in which injection occurred at four different axial positions (type B, Fig. 4), variable secondary flow rate tests (type A, Fig. 5), and bipropellant injection tests (Fig. 6). Test type A was accomplished through the use of a hydraulically-operated, flow control valve which was opened and closed with water pressure. Opening and closing speed could be adjusted by metering the water to or from the piston-operated valve. Test type B utilized a series of four solenoid valves, which were opened and closed sequentially during the tests.

The test nozzles, Fig. 7 and 8, were uncooled and used graphite throat inserts. These nozzles were adequate for tests of three to four seconds duration. The 16 point nozzle, Fig. 7, was fabricated with four rows of four orifices 90 degrees apart. Each row of orifices was drilled a different diameter. This arrangement permitted the effect of orifice area and axial location of the injection port to be studied. All orifices were round and were drilled perpendicular to the nozzle axis.

For the bipropellant injection tests, the basic nozzle body was modified to permit the insertion of bipropellant injectors, Fig. 8.

Side-force measurements were accomplished through the use of a pivot mount, lever arm, and Wianko force transducer. The side-force assembly was in turn fastened to a flexure mount to permit the measurement of axial thrust, Fig. 9. All side-force measurements reported are resolved to a point on the nozzle 6.42 inches from the throat. Calibration of both side-force and axial thrust was accomplished "in place" through the use of Moorehouse proving rings.

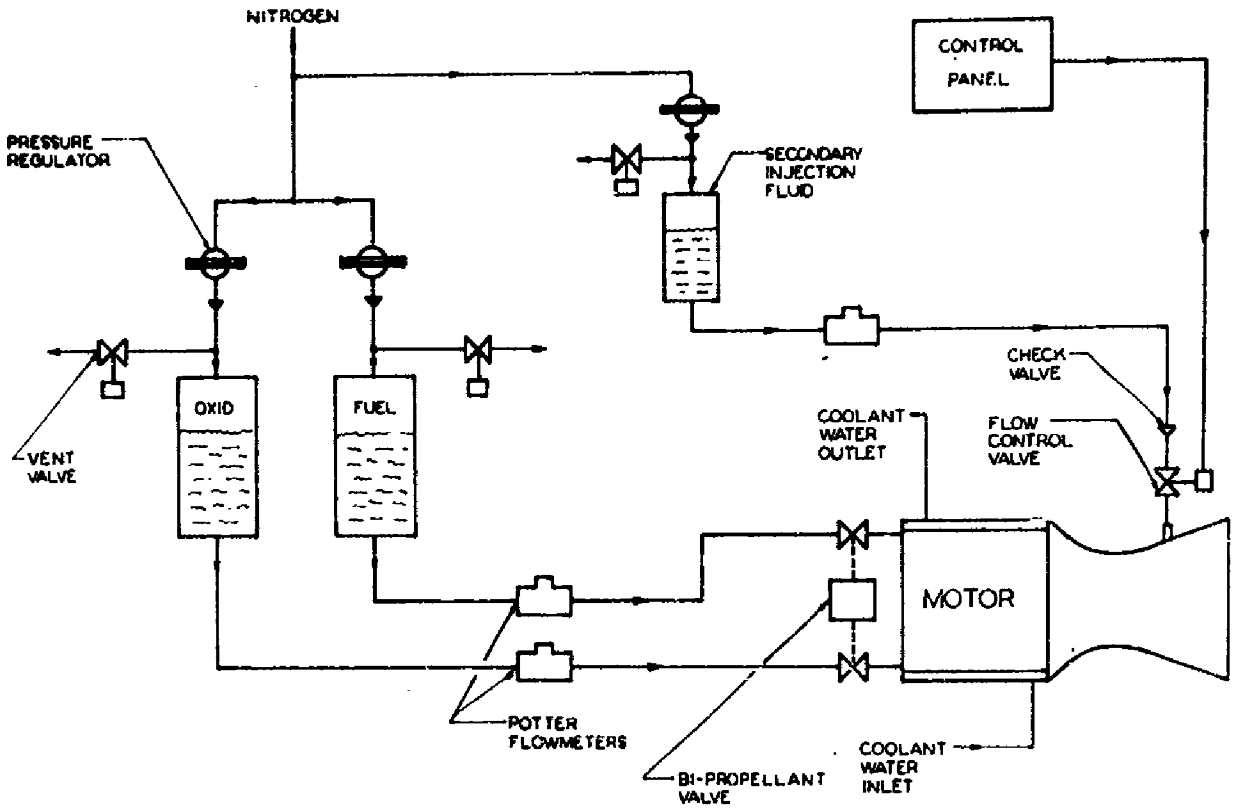

FIG. 3. Schematic of Test Installation for Study of Secondary Injection--Test Type C

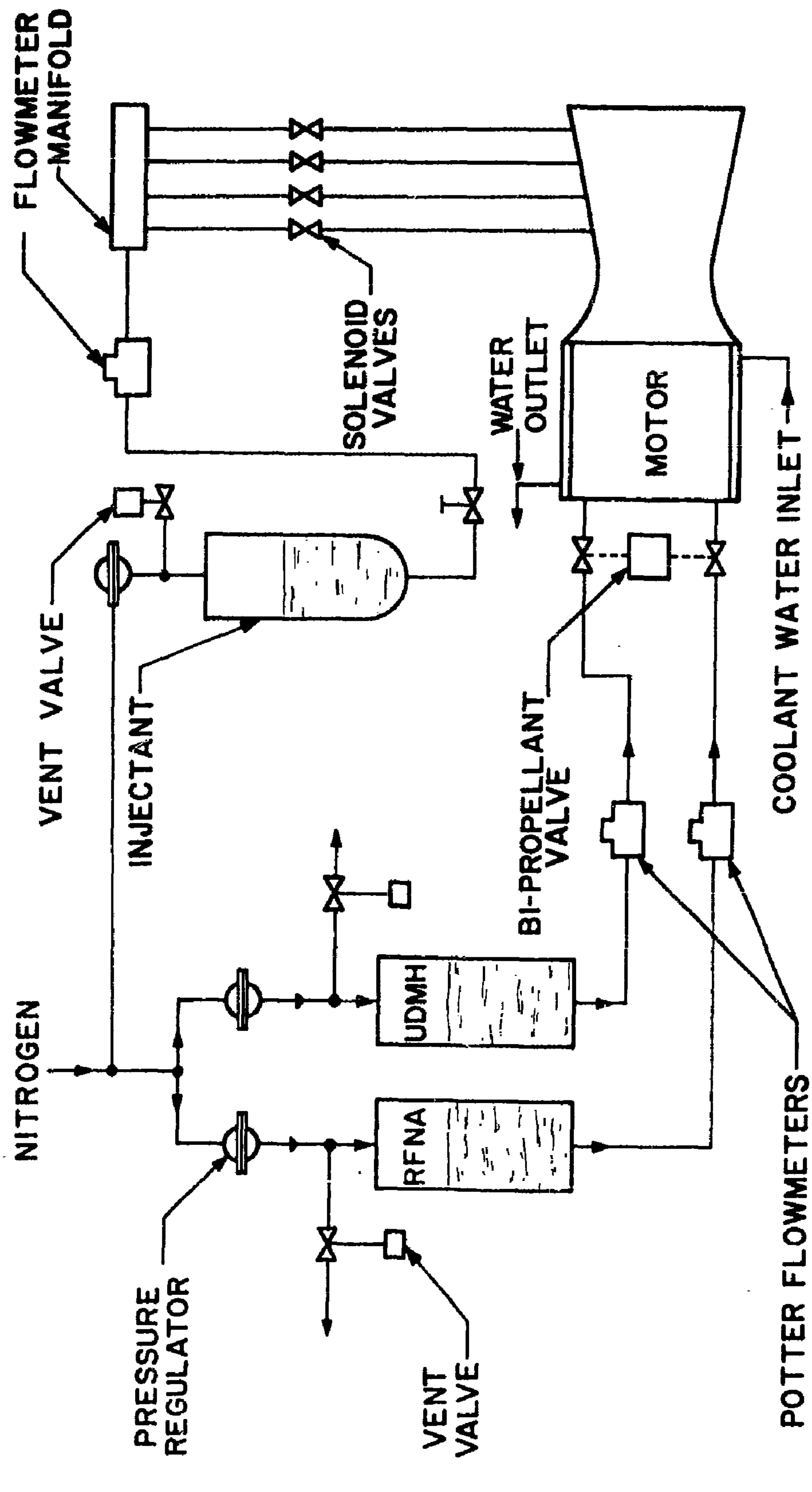

FIG. 4. Schematic of Test Installation for Study of Secondary Injection--Test Type B

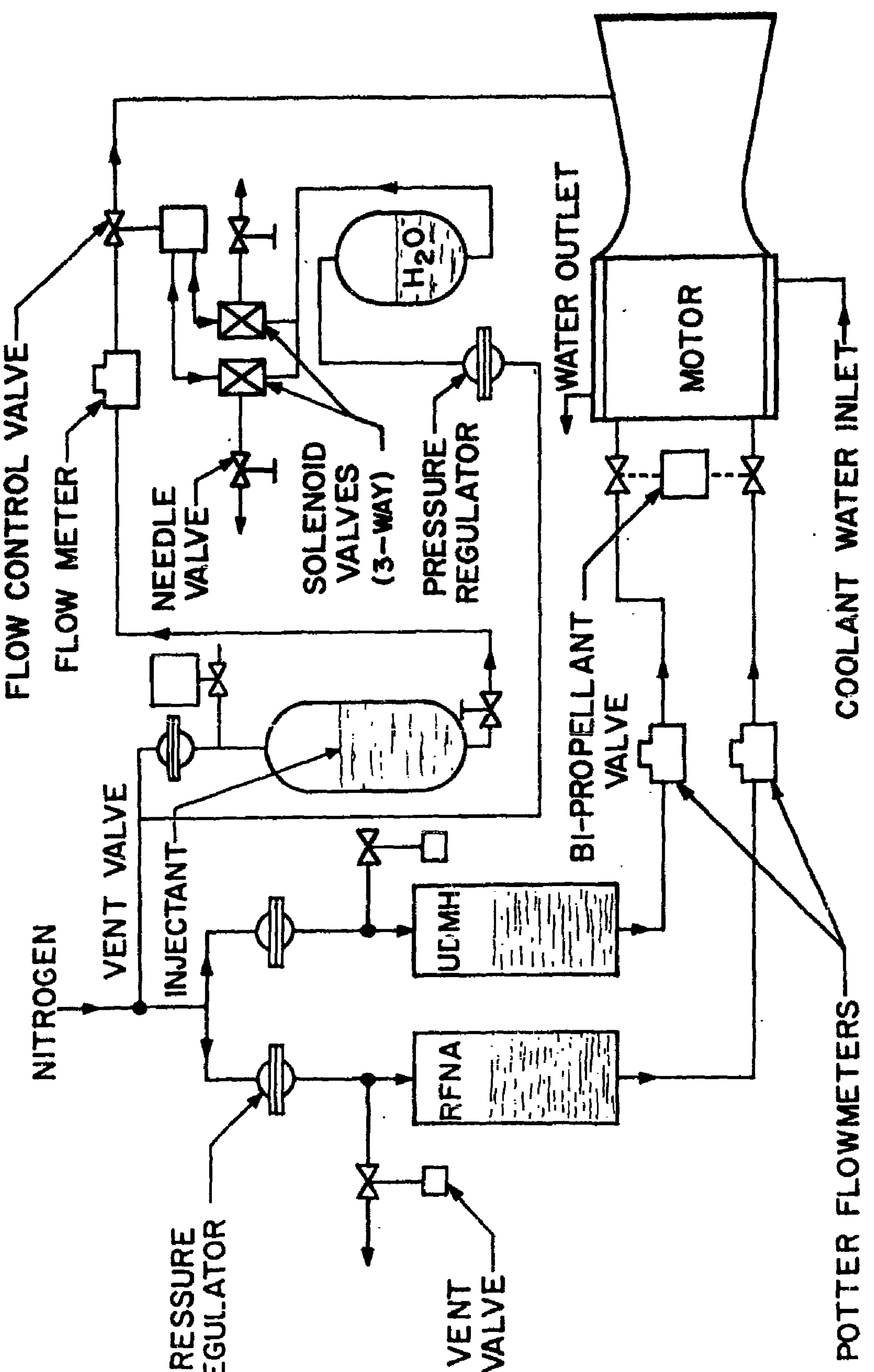

FIG. 5. Schematic of Test Installation for Study of Secondary Injection--Test Type A

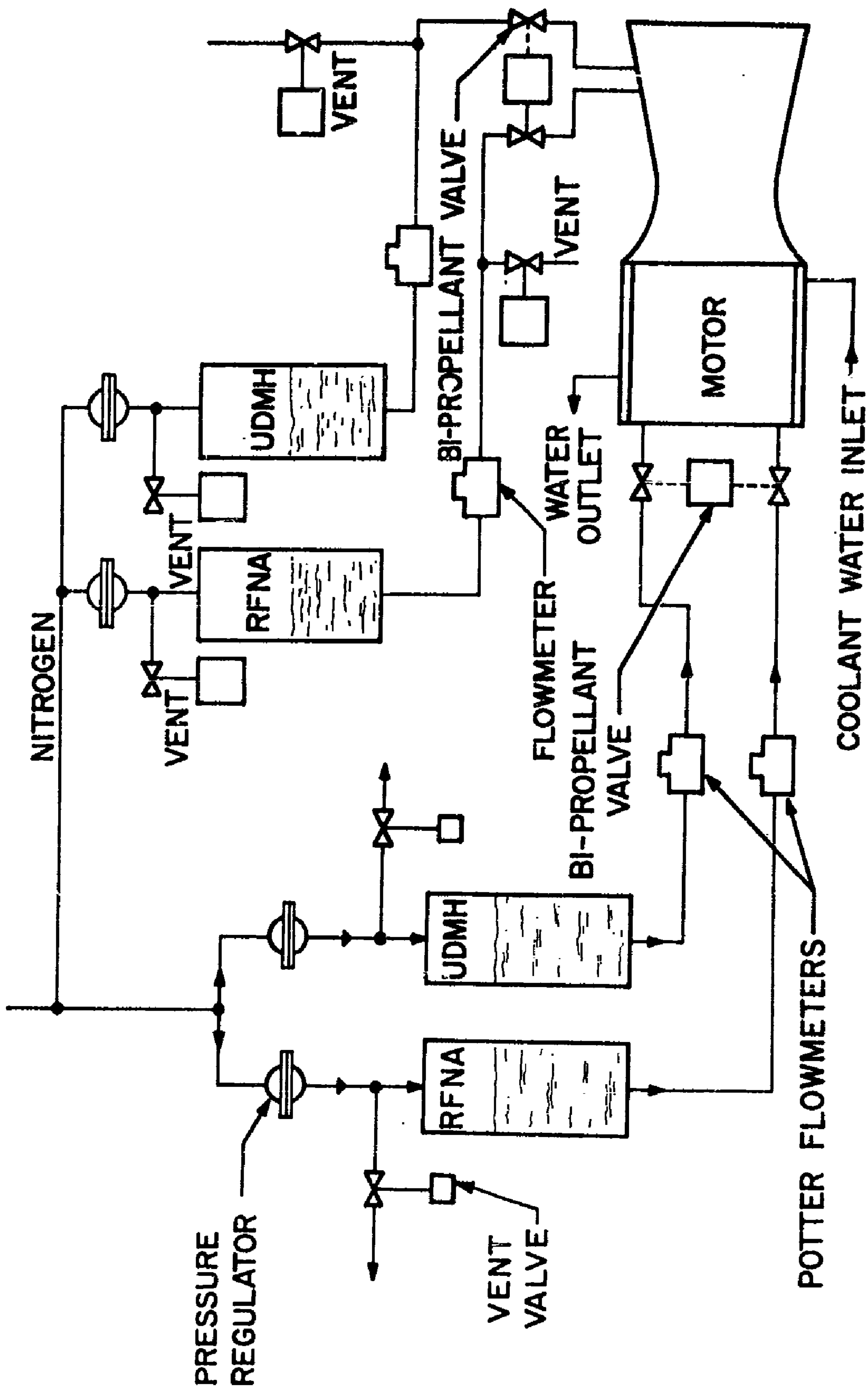

FIG. 6. Bi-propellant Injection Test Installation

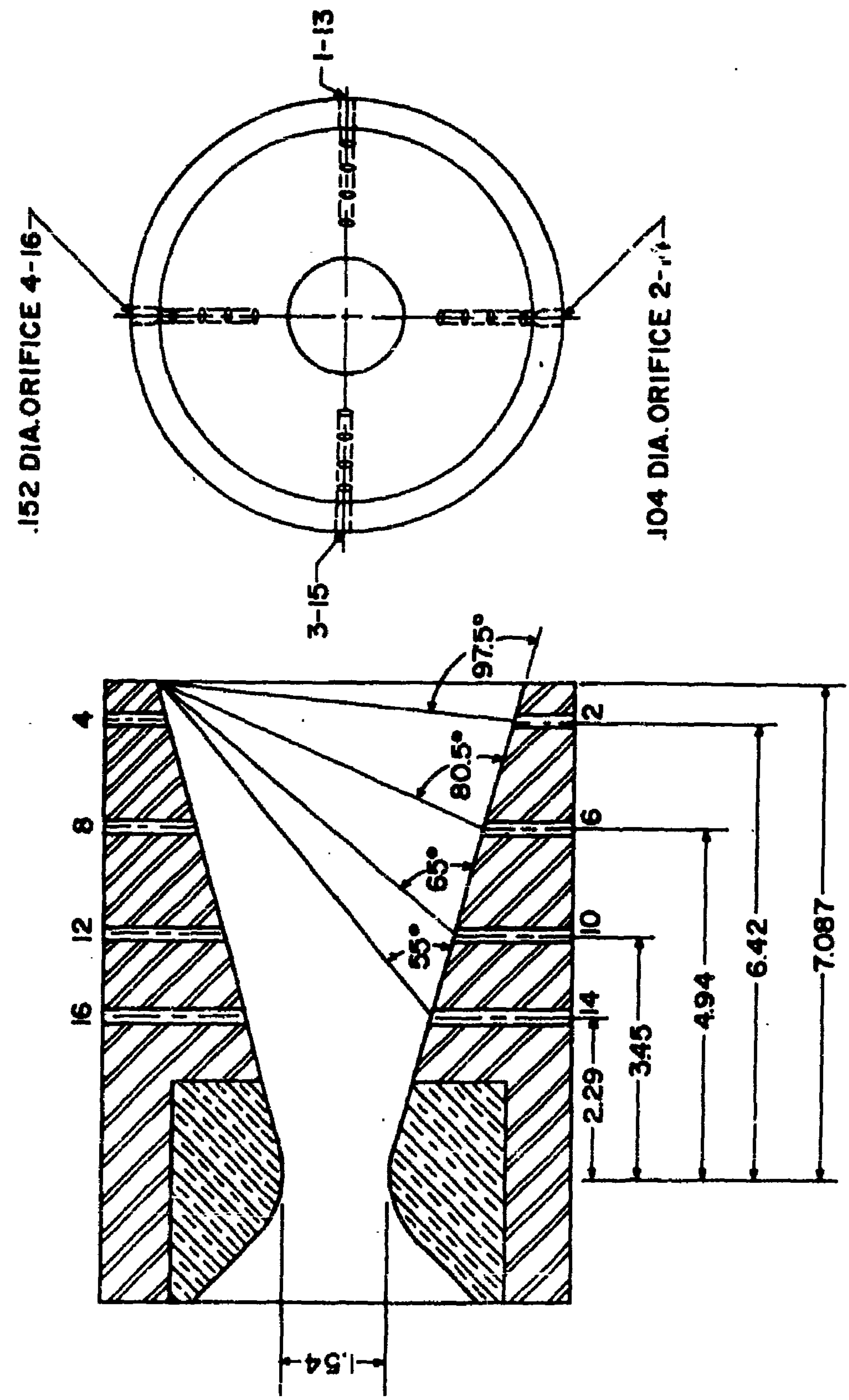

FIG. 7. Sixteen Point Nozzle

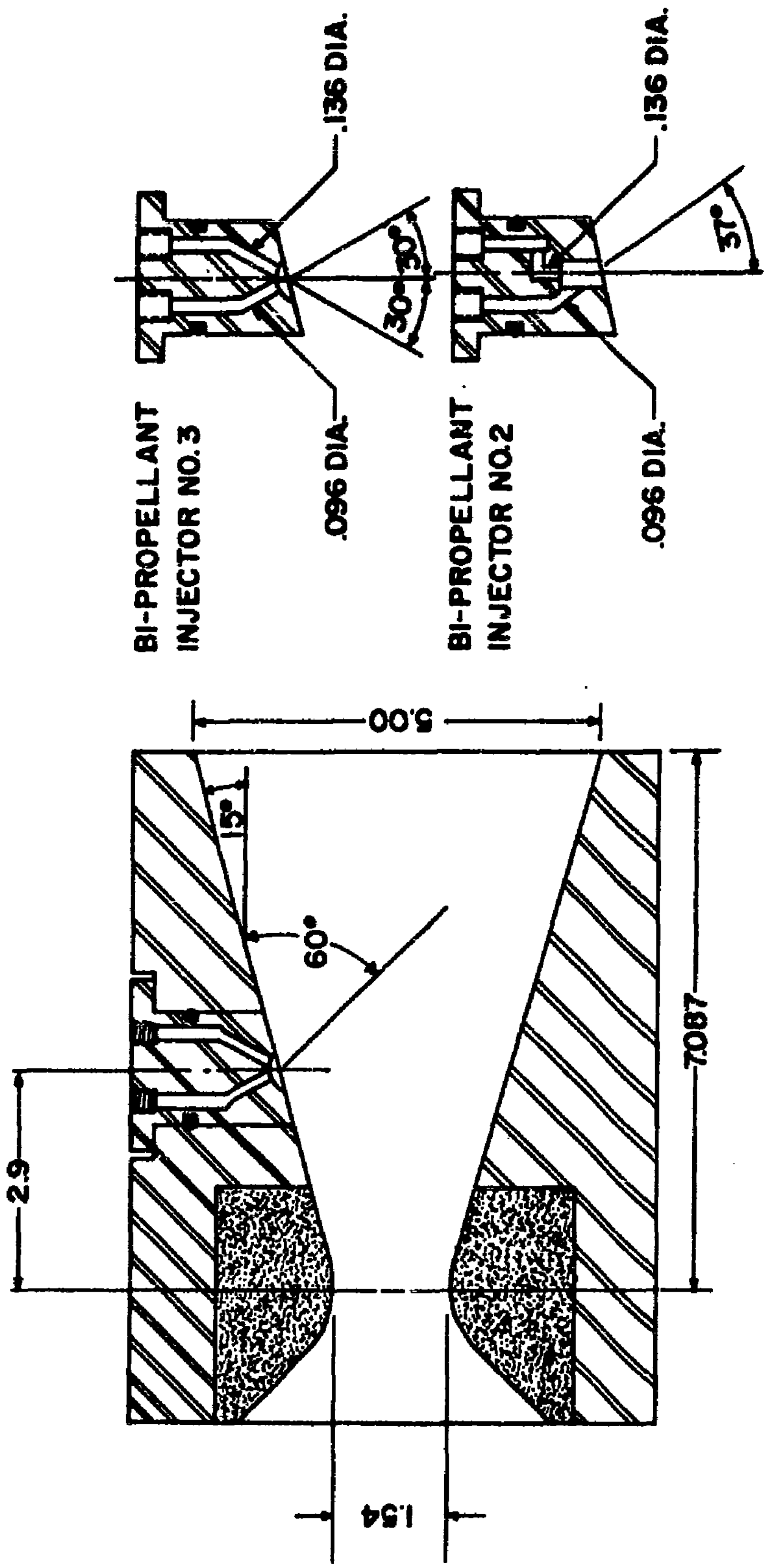

FIG. 8. Bi-propellant Injection Nozzle

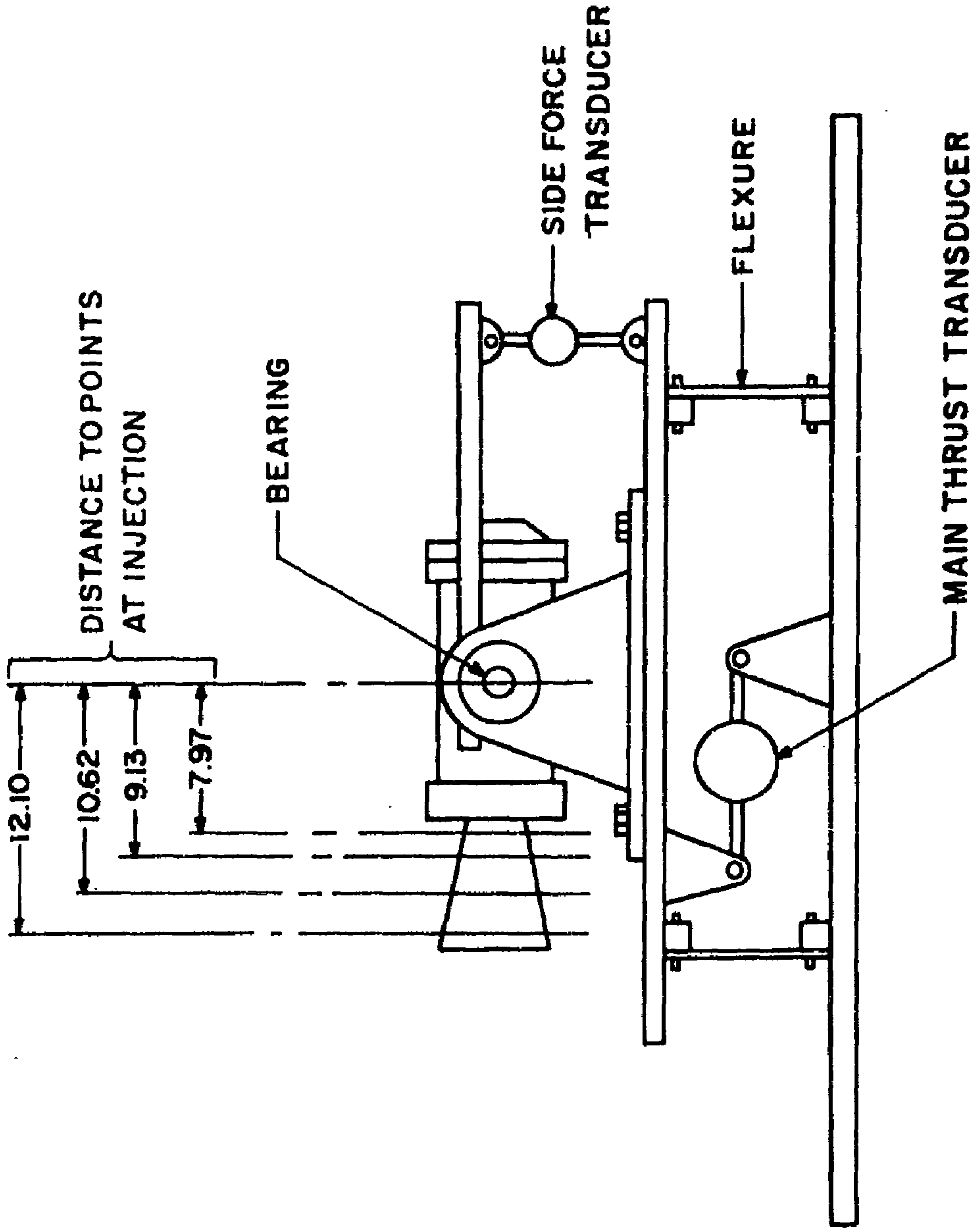

FIG. 9. Schematic of LPARM Motor Mount

In the tests of secondary injection, the motor was allowed to begin operating smoothly before injection was started. This permitted the measurement of side-force as a change in side-force, thus cancelling the effects of any main thrust malalignments and other side-force effects caused by motor operation.

Typical LPARM tests may be seen in Fig. 10 and 11. Figure 10 shows the LPARM operating without secondary injection; Fig. 11 shows operation with secondary injection.

QUARTER-SCALE SUBROC TESTS

The test of secondary injection using a solid propellant motor was conducted primarily for purposes of data comparison. The effects of different motor performances and the aluminized propellant were of particular interest. In addition, three different injection geometries were investigated. Figure 12 depicts the quarter-scale SUBROC nozzle used in this test. The characteristics of the quarter-scale SUBROC motor are given in Table 2. The following measurements were recorded during this test:

1. Axial thrust
2. Chamber pressure
3. Injection pressure
4. Side thrust
5. Injection flow rate

Both Freon-12 and nitrogen tetroxide were used as injectants for this test. Nitrogen tetroxide was injected through a single orifice only, and Freon-12 was injected through both single and multiple orifice configurations.

The fluids were injected in a cyclic fashion during the first 26 seconds of the 35 second motor burning time. An attempt to vary the flow rate of each injectant by the "blow-down" technique was only partially successful due to faulty check valves. Figure 13 shows the test schematic, and Fig. 14 and 15 show the motor in position for firing.

Side-force was measured in two planes 90 degrees apart with Wianko force transducers as shown in Fig. 14. All side-forces are resolved to the nozzle exit plane.

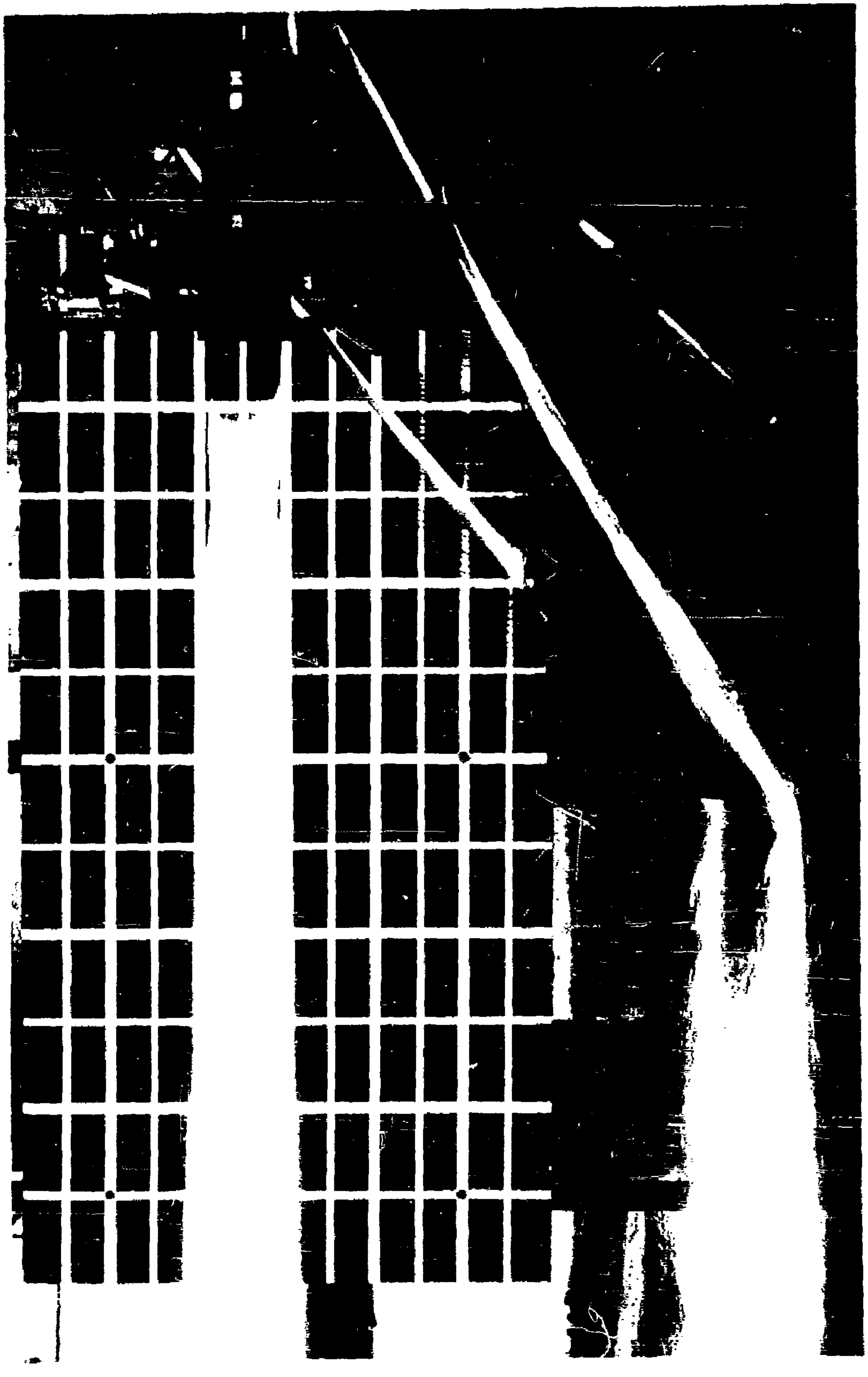

FIG. 10. LPARW Firing Without Secondary Injection

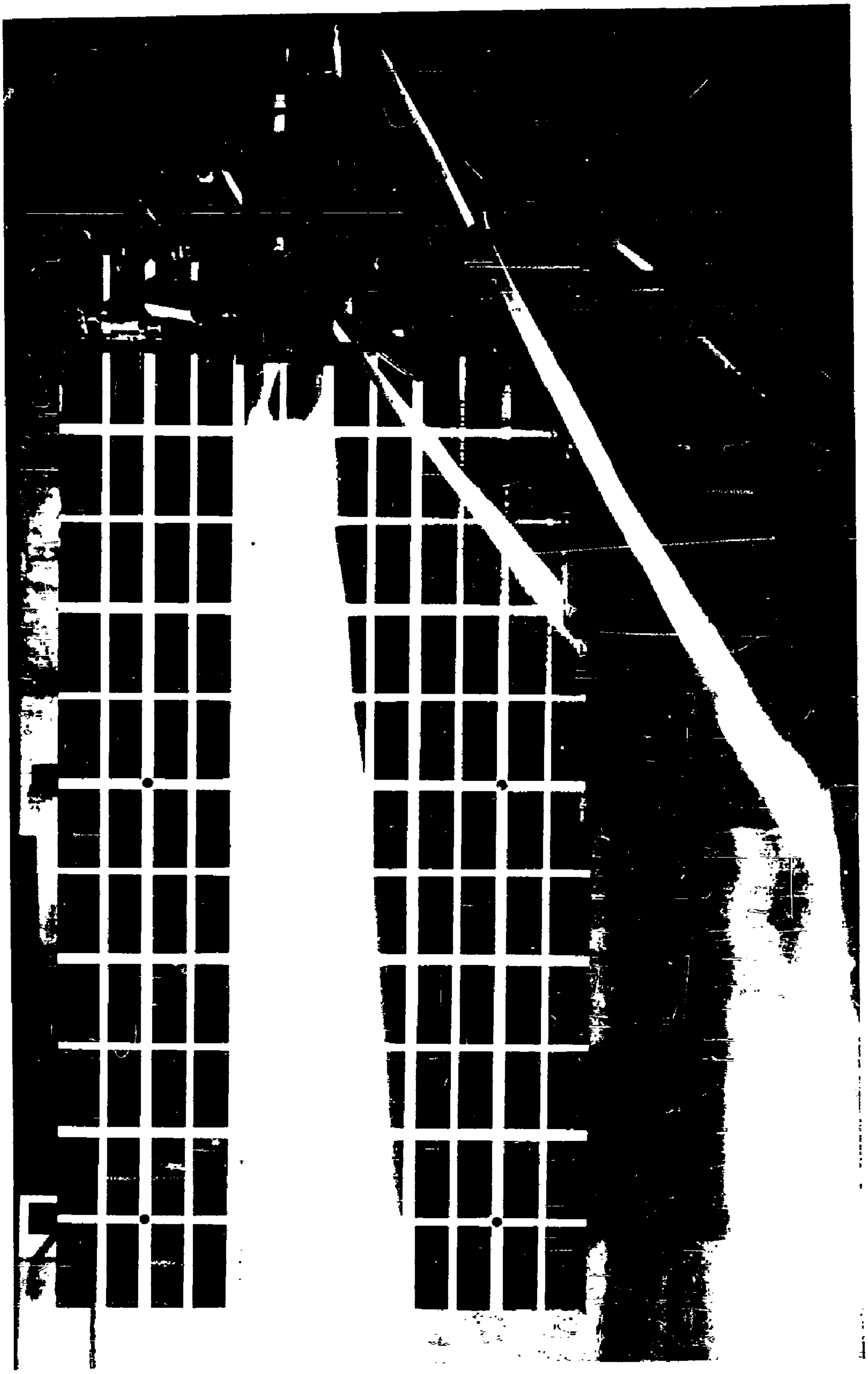

FIG. 11. LPARM Firing With Secondary Injection

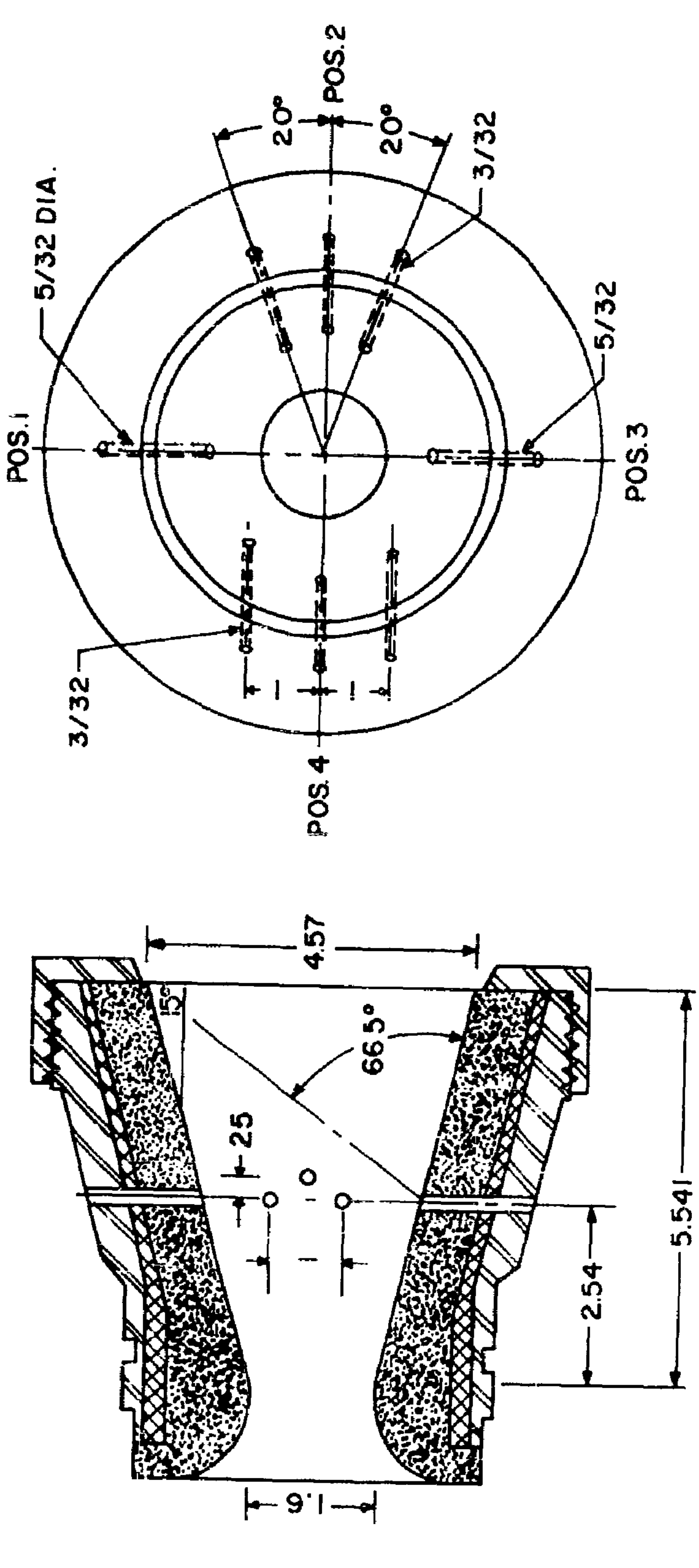

FIG. 12. Quarter-Scale SUBROC Injection Nozzle

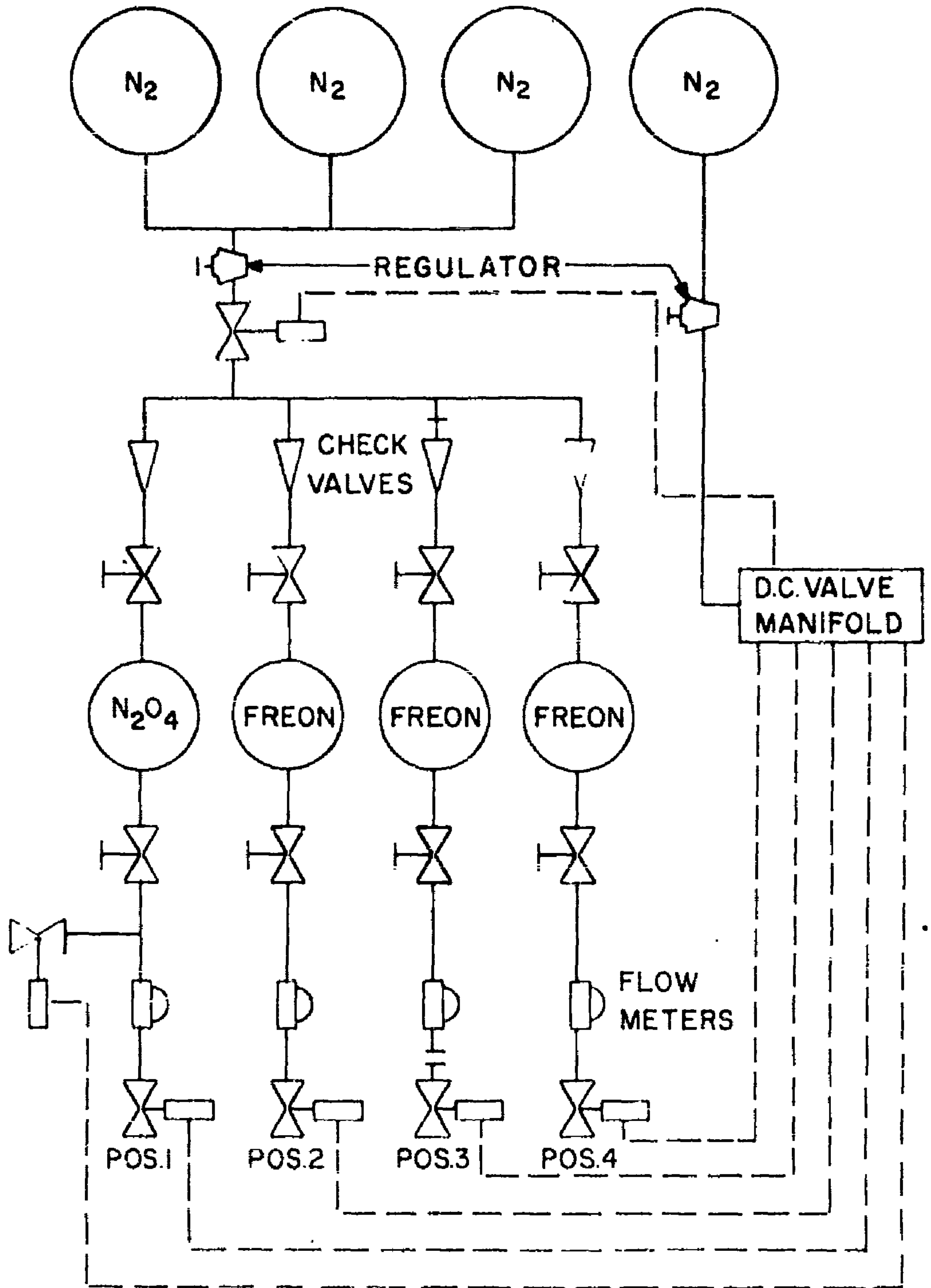

FIG. 13. Quarter-Scale SUBROC Piping Schematic

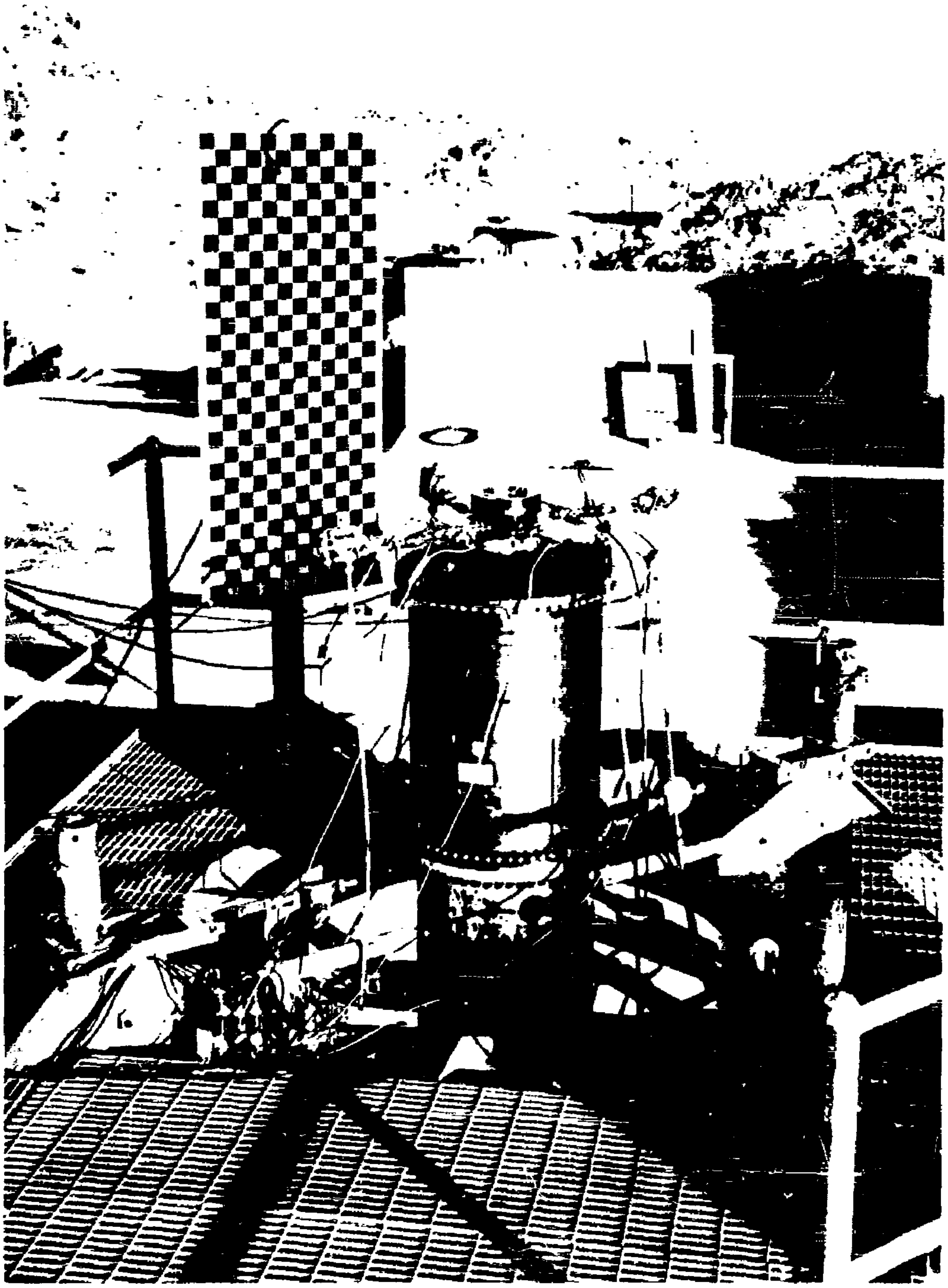

FIG. 14. Quarter-Scale SUBROC Test Set-Up

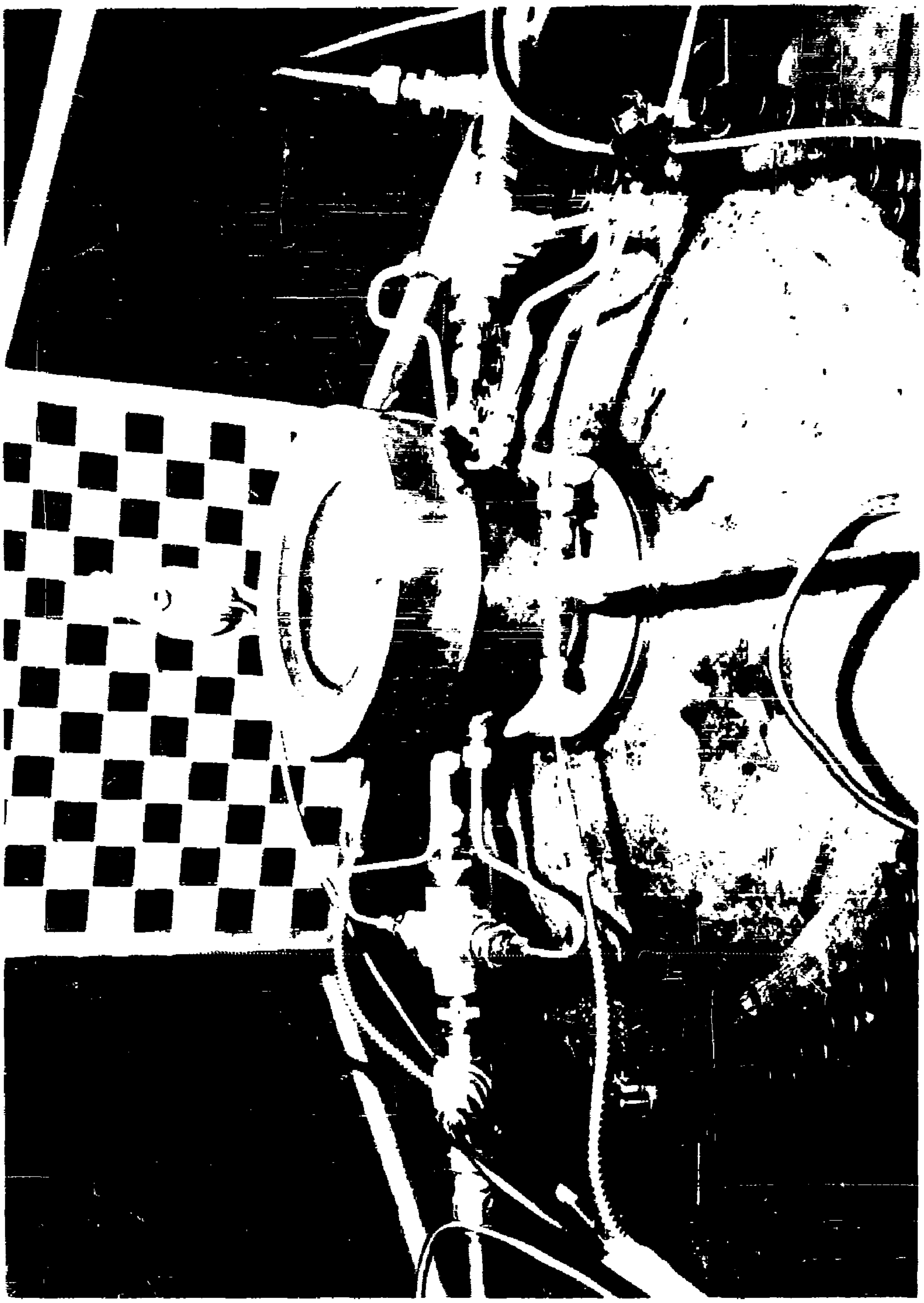

FIG. 15. Quarter-Scale SUBROC Nozzle

RESULTS

Seven fluids, including UDMH and IRFNA, were used as injectants in this experimental program. The five fluids used individually were as follows: Freon-12, perchloroethylene, water, nitrogen tetroxide, and bromine. Tabulated data are presented in Tables 3 and 4 from the LPARM and quarter-scale SUBROC tests respectively.

LPARM DATA

Most data presented graphically in this report are in the form of the ratio of side-force to main thrust versus the ratio of secondary flow rate to main flow rate (F_s/F_m versus $\dot{w}_s/\dot{w}_c$). Consequently, the slope of the line describing the best fit to the data points represents the ratio of the specific impulse of the secondary fluid to the specific impulse of the main stream gases. This slope has been termed the performance ratio. The position number noted on each graph refers to axial location and size of the injection port, Fig. 7.

In some cases, fluids were injected through two orifices located in line axially. Consequently, the notation on the graphs, or in the data tabulation, calls out two position numbers.

The reproducibility of the LPARM side thrust measuring system may be seen in Fig. 16. This figure shows the actual data points obtained from eight different tests of Freon-12 injection.

FREON-12 INJECTION

The family of curves shown in Fig. 17 represents the results obtained by injecting Freon-12 at four different axial locations through orifices 0.152 inch in diameter. These data are shown again in a plot of performance ratio (F_s/F_m versus $\dot{w}_s/\dot{w}_m$) as a function of axial location at injectant flow rates of five, ten, and fifteen percent of the main propellant flow rate, Fig. 18. Both figures show the interdependence of injectant flow rate and axial location upon injectant performance.

Figure 19 shows the result obtained by injecting Freon-12 through 0.104-inch-diameter orifices at two different axial locations. The solid portions of the curve indicate the range in which data were obtained.

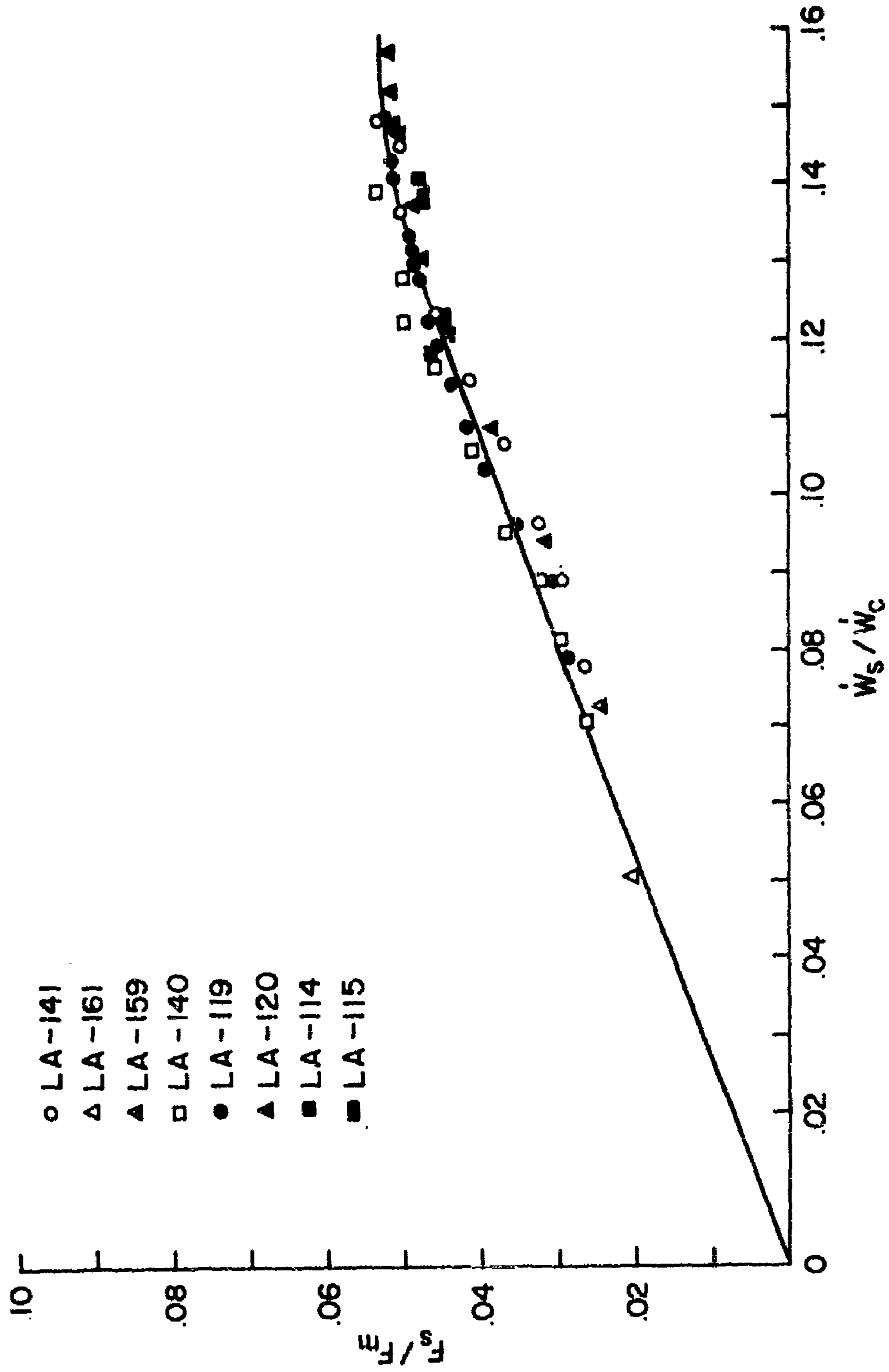

FIG. 16. Freon-12 Data Points

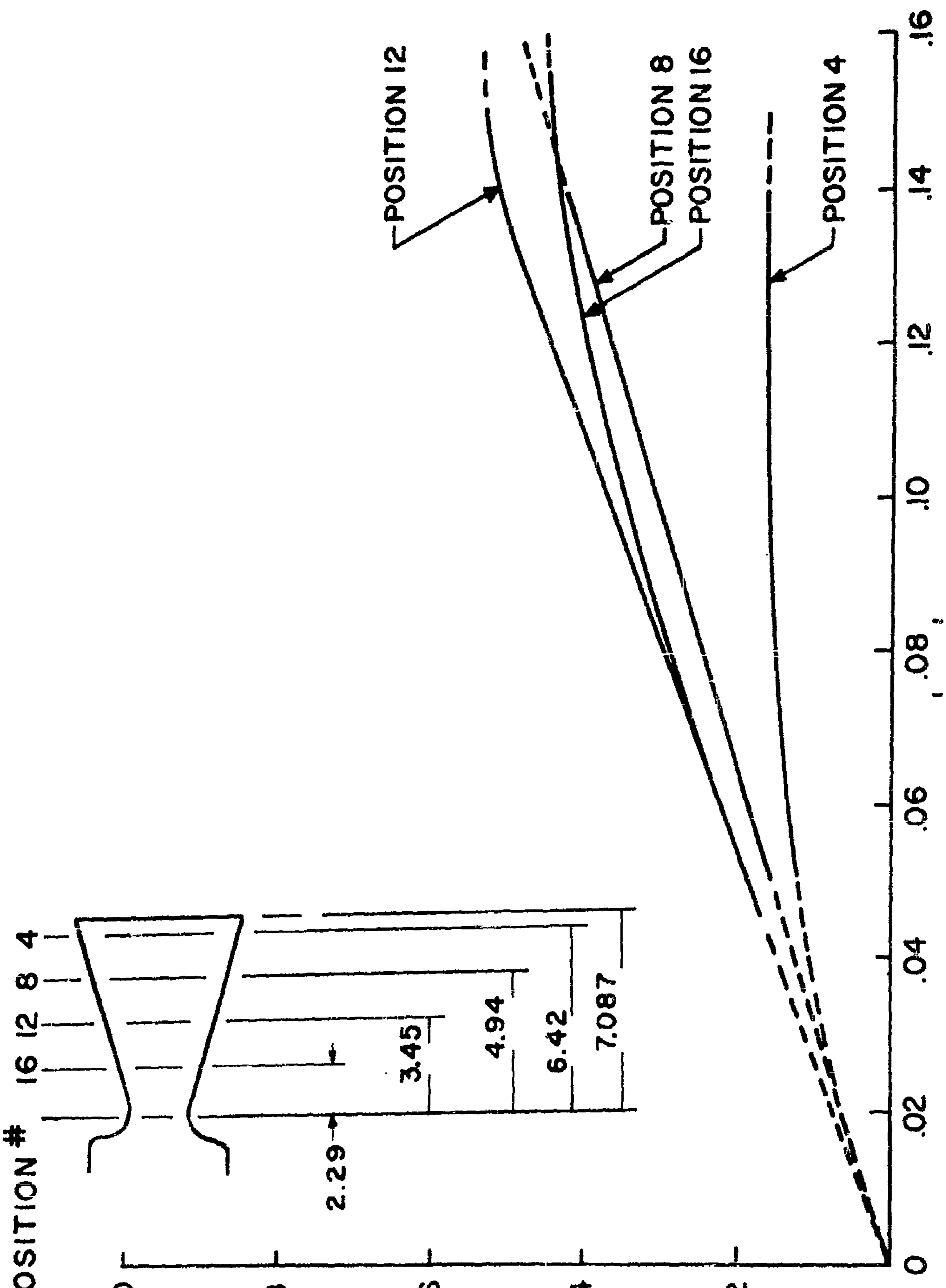

FIG. 17. Freon-12 Injection Data

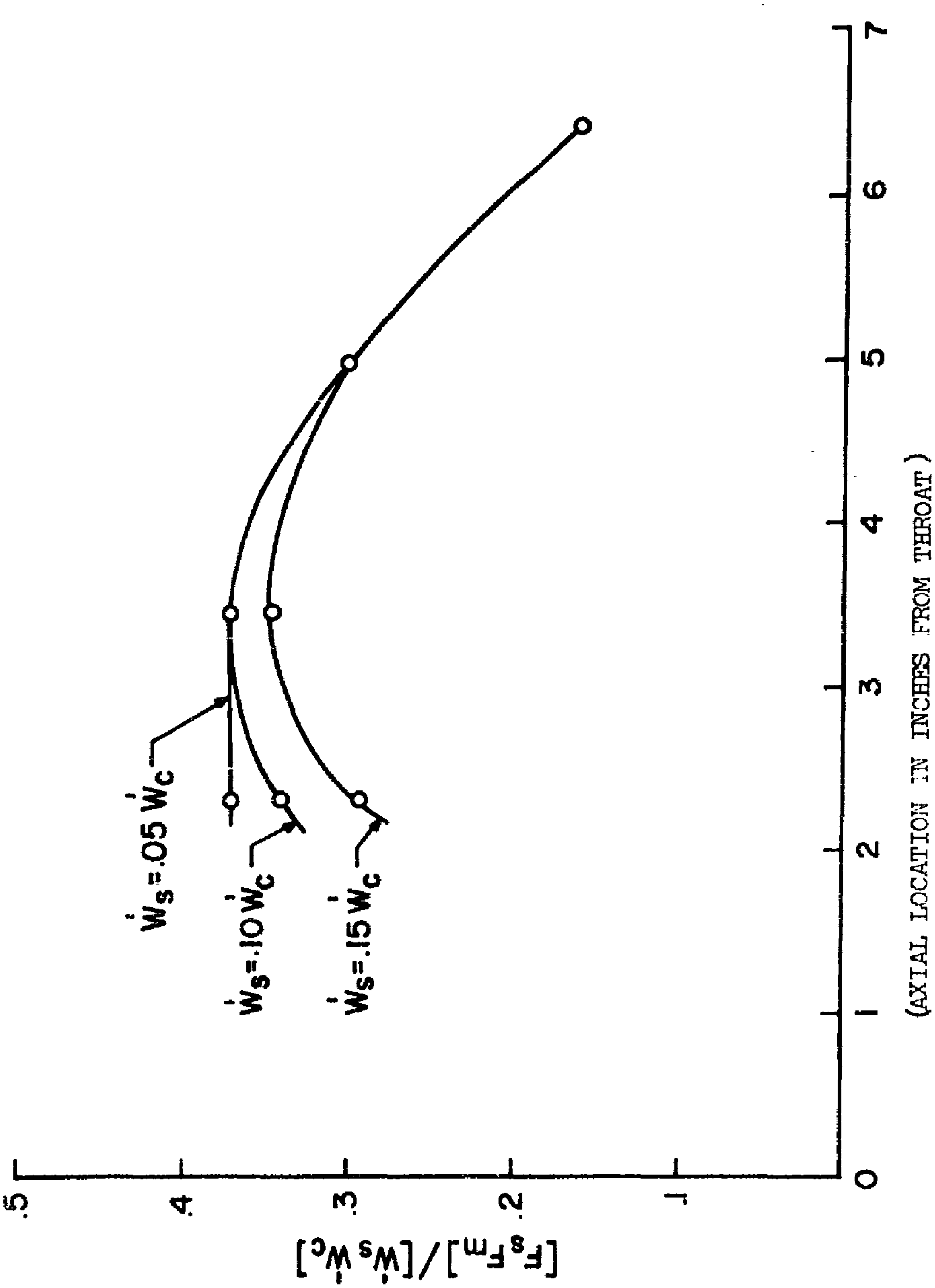

FIG. 18. Effect of Axial Location

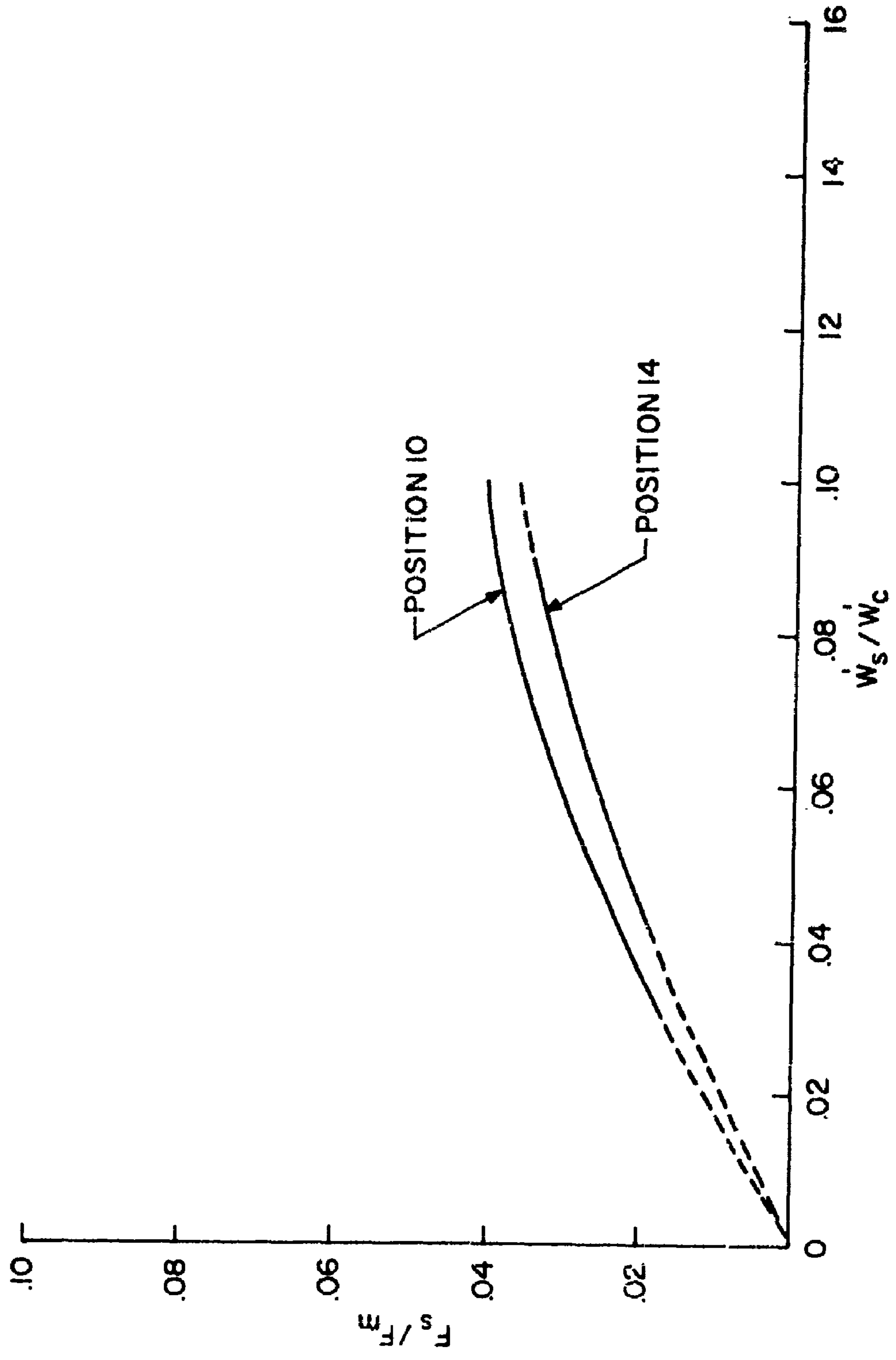

FIG. 19. Freon-12 Injection Data

PERCHLOROETHYLENE INJECTION

Figures 20 and 21 show the results obtained by injecting perchloroethylene through 0.152- and 0.104-inch-diameter orifices at various axial locations. Position 16 (0.152-inch-diameter) corresponds to position 14 (0.104-inch-diameter) in axial location, Fig. 7.

WATER INJECTION

Figure 22 shows the results obtained from water injection through one 0.152-inch-diameter orifice (position 12), and through two 0.152-inch-diameter orifices (position 16 and 12).

BIPROPELLANT INJECTION

Figure 23 shows the results obtained from the simultaneous injection of UDMH and IRFNA. These tests were intended to determine the effects of any exothermic reaction of the injectant within the expansion cone. Two injector designs were used for these tests (Fig. 8); both designs provided approximately the same results. Bipropellant injection provided the highest performance ratio obtained in this test series.

LPARM DATA SUMMARY

Figure 24 compares the results obtained from double orifice injection with Freon-12, perchloroethylene, and water. Figure 25 shows the relative performances obtained with bromine, UDMH and IRFNA, Freon-12, perchloroethylene, and water at similar axial locations.

SUBROC DATA SUMMARY

Figure 26 is a summary of data obtained from the injection tests with the quarter-scale SUBROC motor. Both Freon-12 and nitrogen tetroxide were used as injectants for this test. Nitrogen tetroxide was injected through a single orifice only, and Freon-12 was injected through both single and multiple orifice configurations (Fig. 12). In Fig. 26, "Freon-12 radial" and "Freon-12 parallel" refer to positions 2 and 4 respectively in Fig. 12. Main propellant flow rates were obtained by dividing the main thrust by the propellant specific impulse. The propellant specific impulse was assumed to remain constant over the test duration.

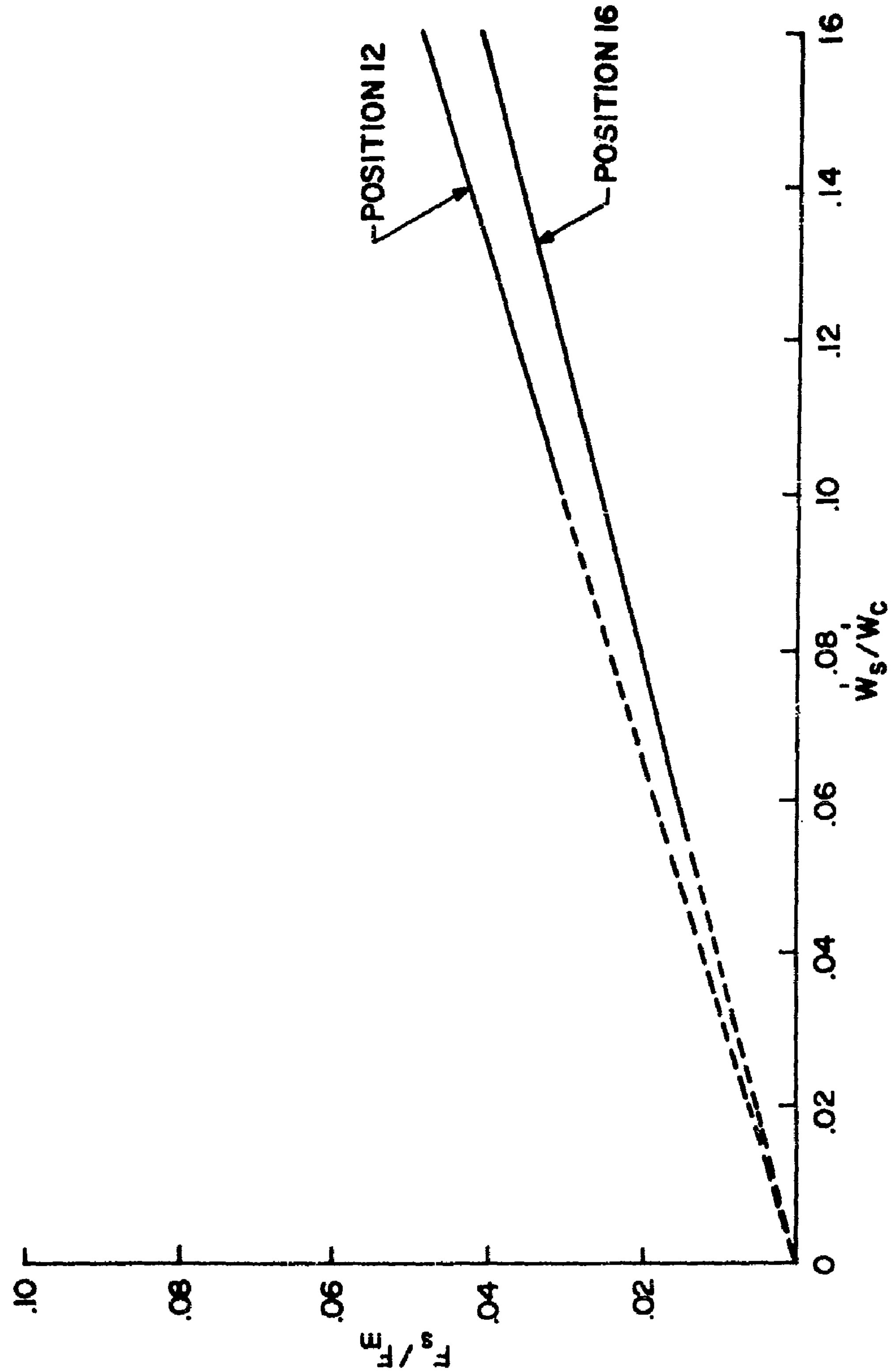

FIG. 20. Perchloroethylene Injection Data

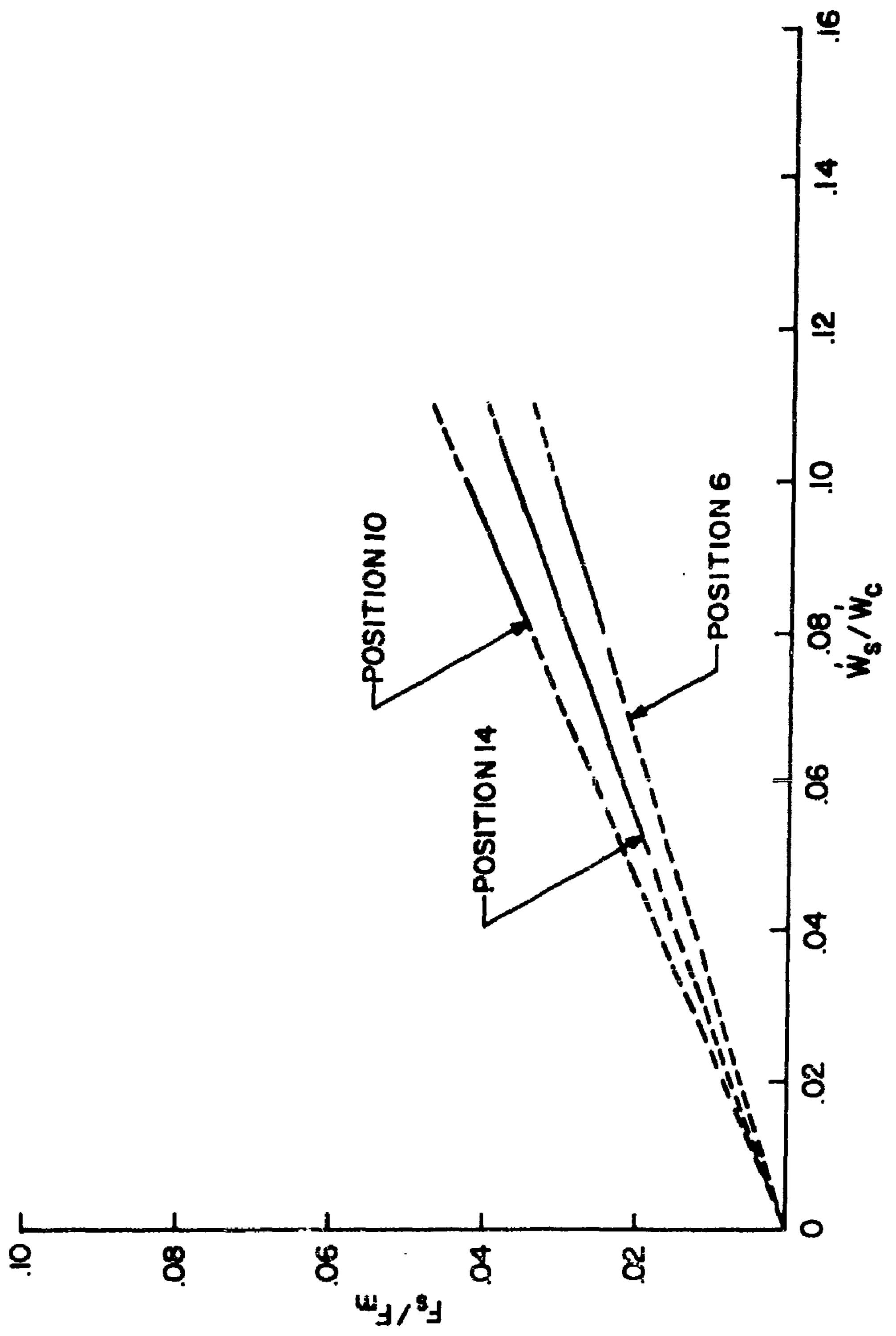

FIG. 21. Perchloroethylene Injection Data

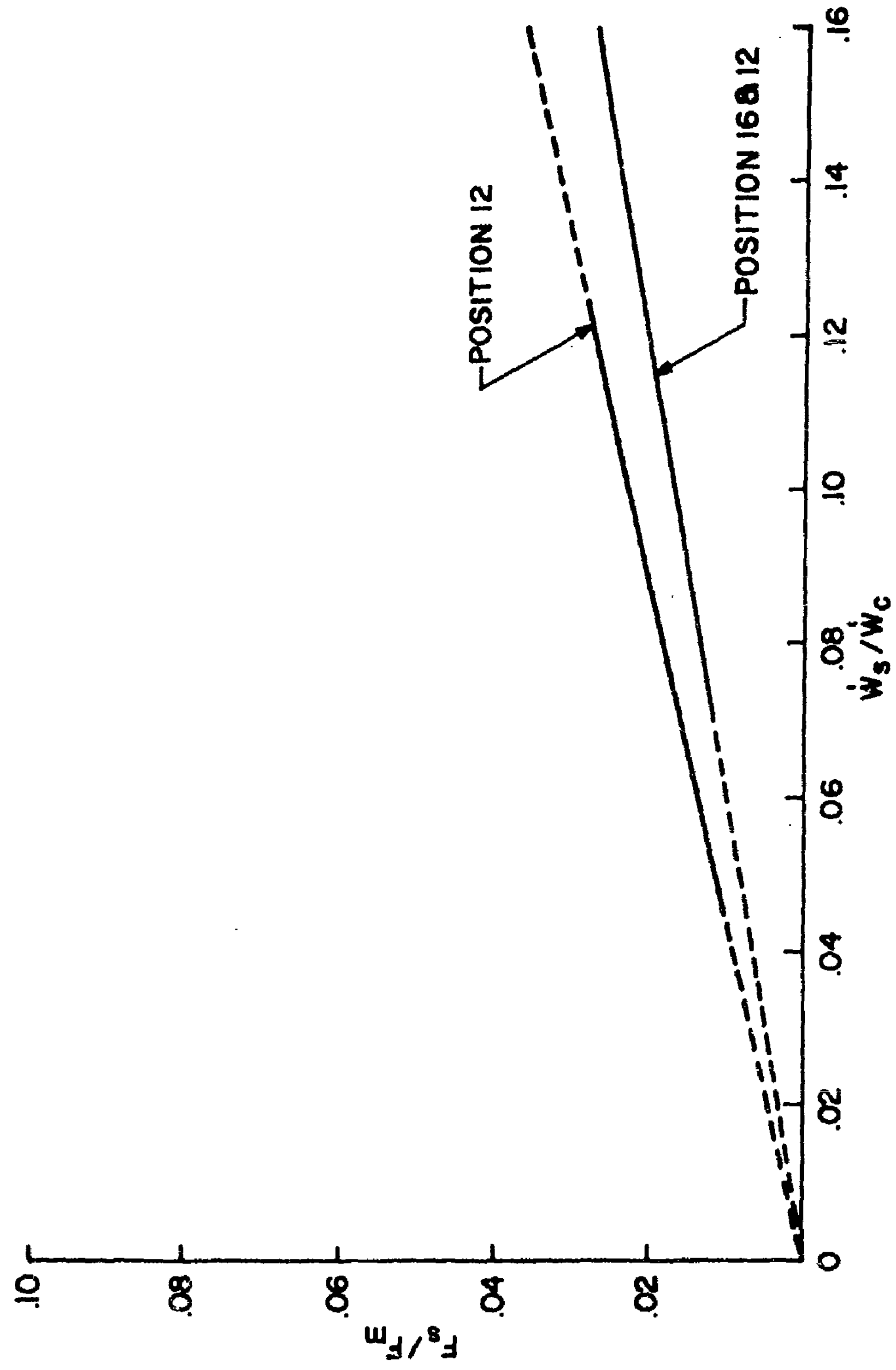

FIG. 22. Water Injection Data

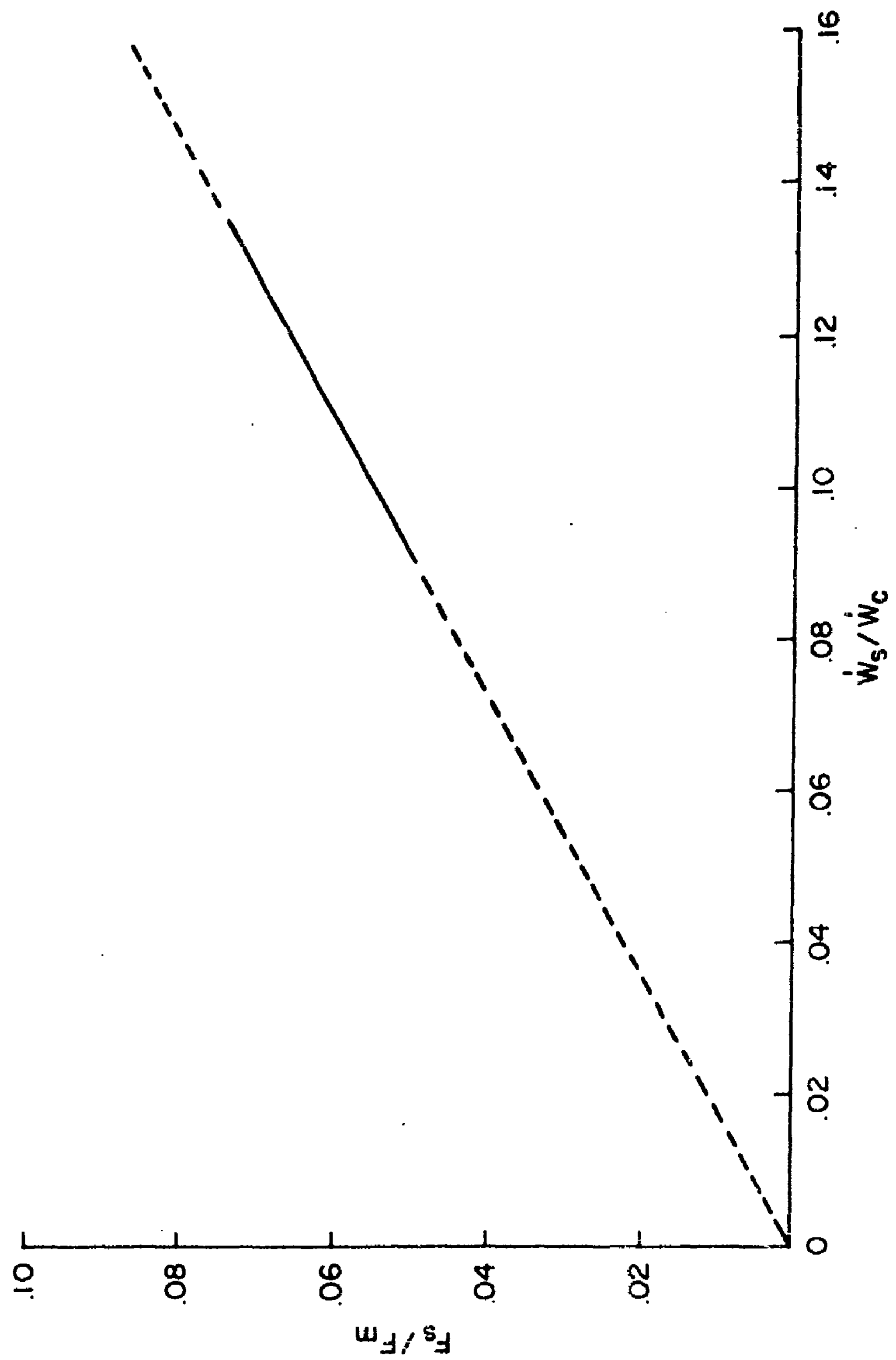

FIG. 23. Bi-propellant Injection Data

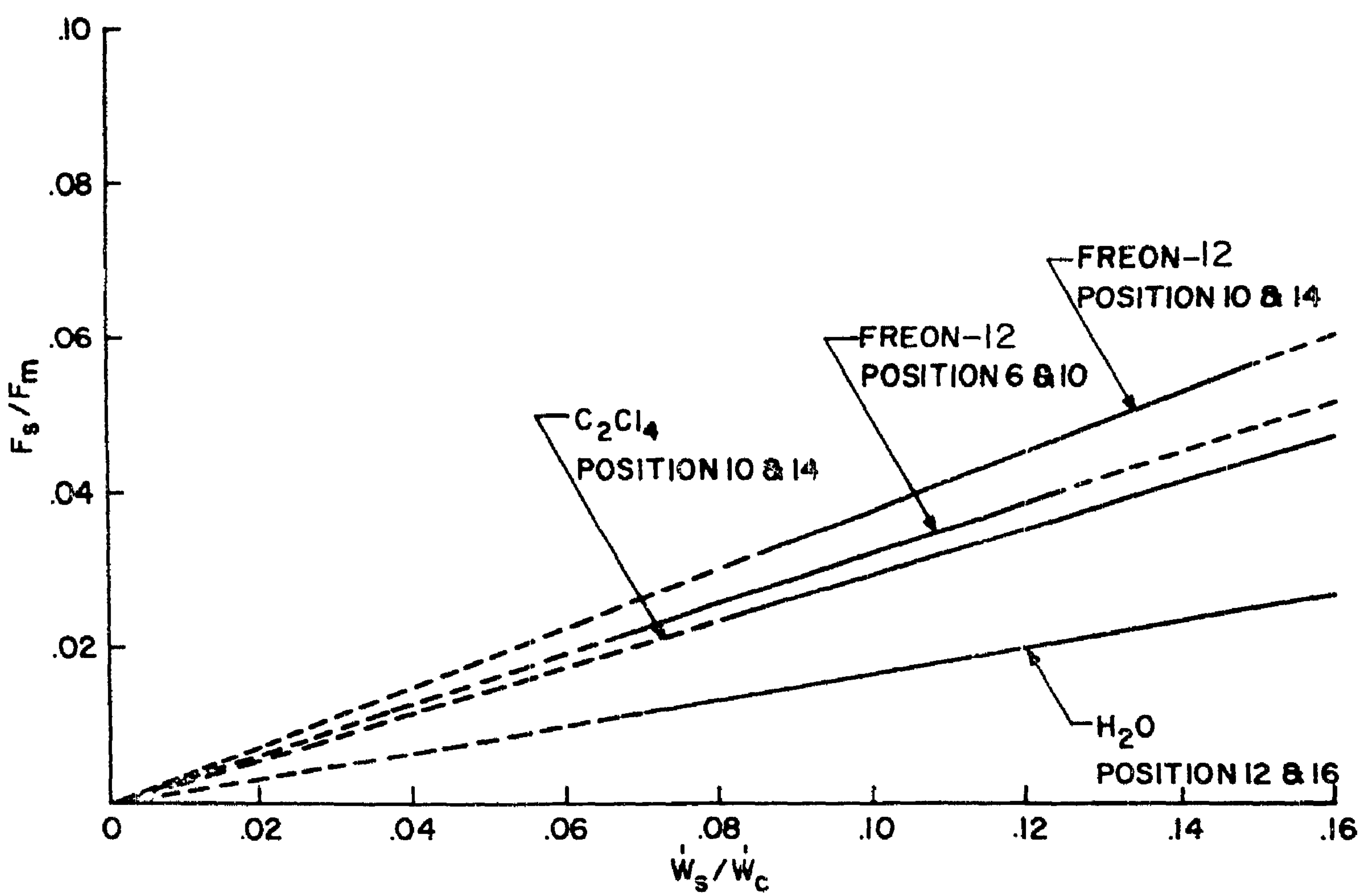

FIG. 24. Double Orifice Injection

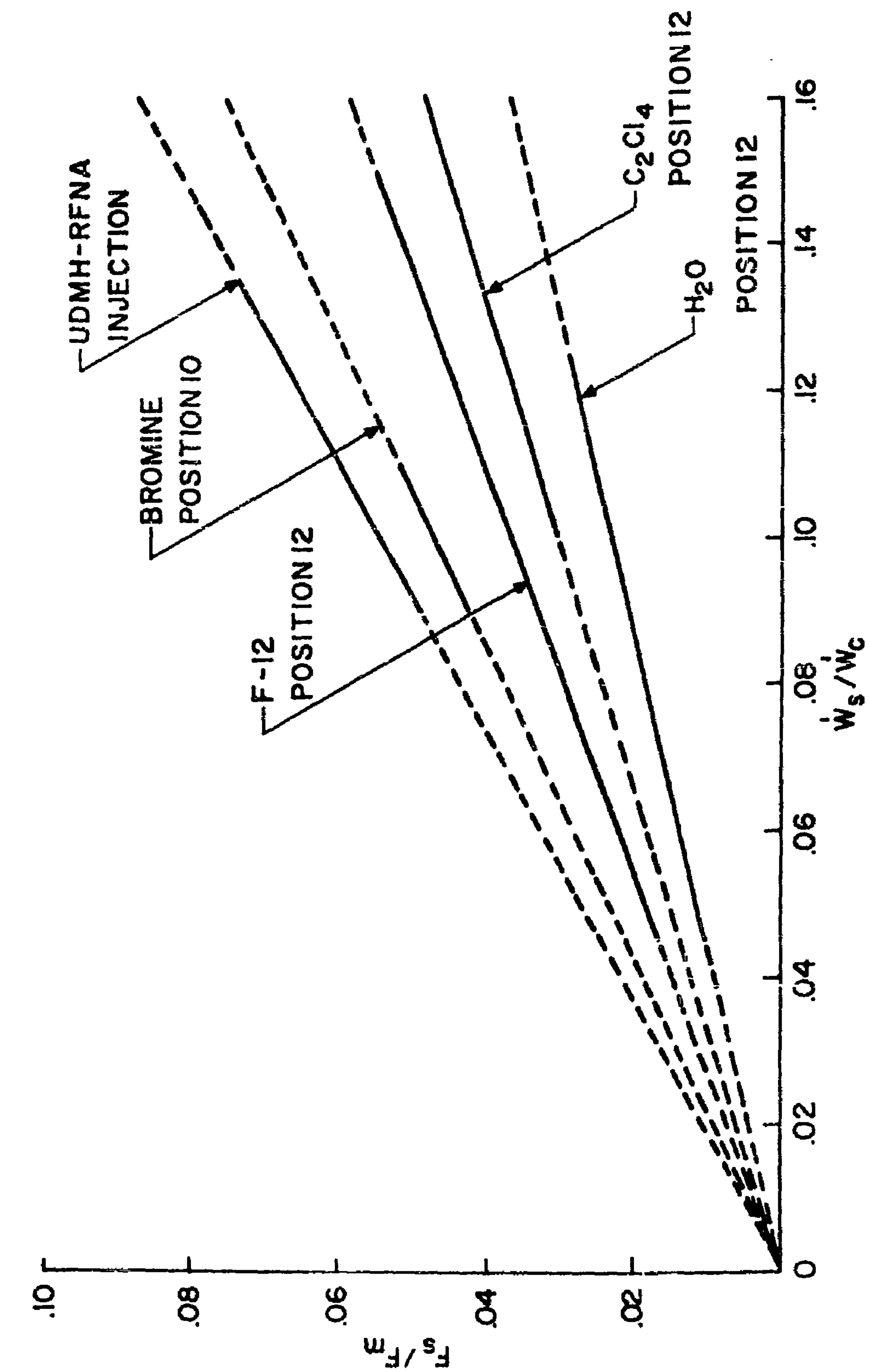

FIG. 25. Performance Summary

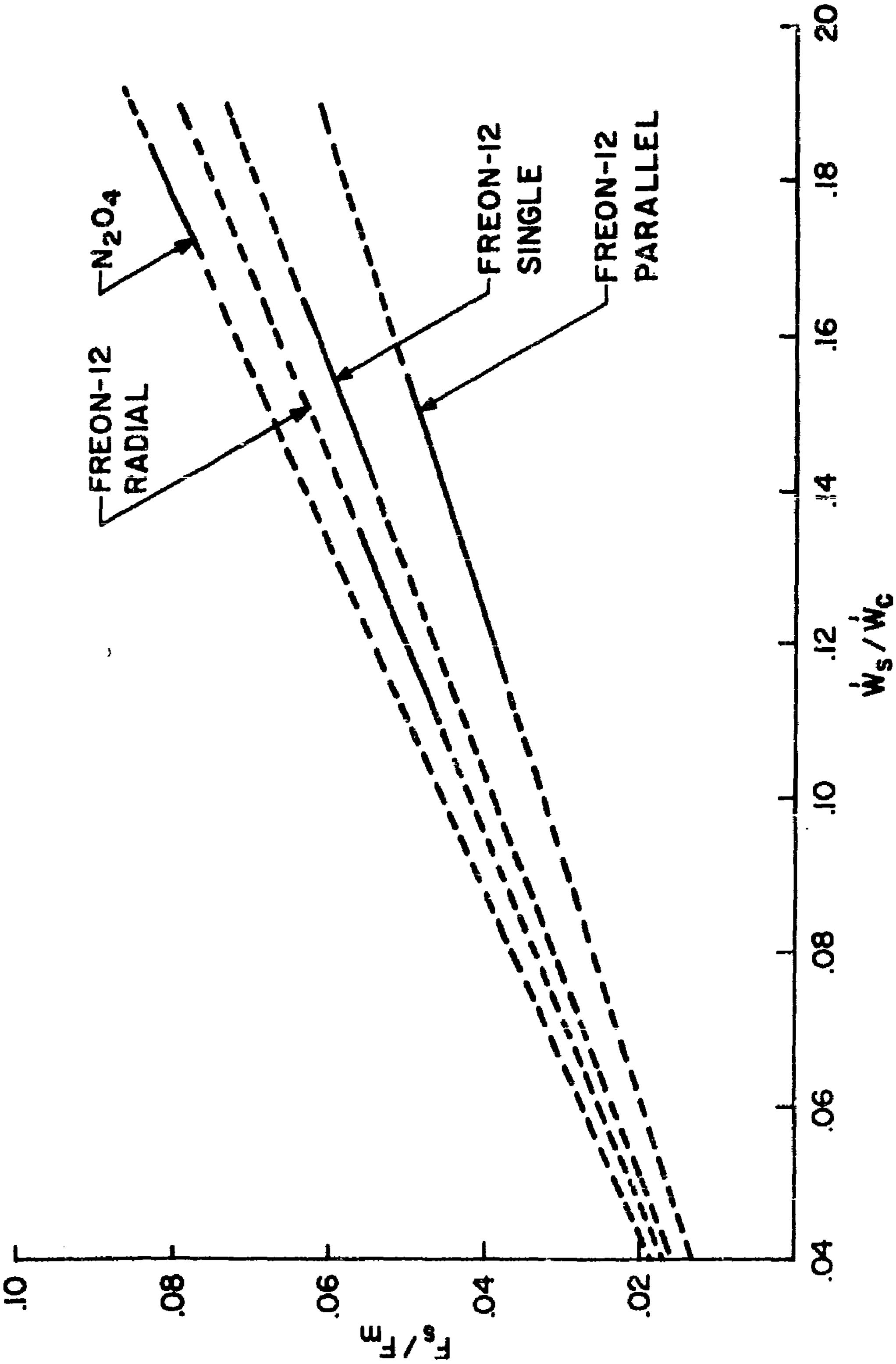

FIG. 26. Quarter-Scale SUBROC Injection Data

DISCUSSION

RELATION OF SIDE THRUST TO INJECTANT FLOW RATE

For a given orifice size and axial location, the variation in side thrust with secondary flow rate was found, in many cases, to be essentially linear; i.e., the injectant specific impulse was found to be constant over the flow range covered in these tests. The performance ratio, or slope of the plot of F_s/F_m versus $\dot{w}_s/\dot{w}_m$, is related to injectant specific impulse in that the performance ratio is equal to the injectant specific impulse divided by the motor specific impulse. The SUBROC data indicate a tendency for the performance ratio of an injectant to remain constant with changes in motor, or rather propellant, performance. Thus, injectant specific impulse may be increased if motor performance, via propellant performance, is increased. However, other factors affect the value of the performance ratio of a particular injectant, such as axial location, injectant momentum, and injection orifice configuration.

EFFECTS OF AXIAL LOCATION

The test data indicate an optimum axial location for maximum injectant performance, which is dependent upon injectant flow rate. The LPARM data indicate that injectant performance increases, for secondary flow rates of five to 15 percent through a 0.152-inch-diameter orifice, as the injection port is moved upstream to a point approximately 3.5 inches from the throat. As secondary flow rates exceed approximately 13 percent of main propellant flow rate at position 12, the performance ratio of Freon-12 appeared to decrease. It is believed that this reduction of the performance ratio of an injectant at high flow rates may be attributed to extreme radial dispersion of the pressure field causing side-force, or reflection of the shock wave off the wall opposite the injection port. In either case, the integration of the radial components of the pressure area forces can yield a decreased component of side-force. Data obtained from the three-port parallel orifice configuration, Fig. 12, indicate a reduction of the performance ratio of the injectant. This reduction was probably due to the radial spread of the pressure field. The three-port radial configuration, on the other hand, showed an increase in the performance ratio over the single-port configuration, indicating that some radial spread may be desired, probably due to the increase in mixing efficiency, and heat transfer.

EFFECT OF INJECTION PRESSURE

Variations in the performance ratio of a single injectant have been noted when the area of the injection port is changed. The data presented in this report indicate a relation between the rate of change of momentum of the injected fluid to the side thrust developed (Fig. 27, 28, and 29). In Fig. 28, the ratio F_s/F_m has been plotted as a function of $(\dot{w}_s/\dot{w}_c \div g/A)^{1/2}$. The square of the main propellant flow rate ($\dot{w}_c^2$) was included in the rate of change of injectant momentum term to take into consideration discrepancies in motor performance and thrust levels, Fig. 27. Thus, $(\dot{w}_s^2/\dot{w}_c^2 \div g/A)^{1/2}$ is essentially a rate of change of momentum ratio, as the rate of change of momentum of the exhaust gases is proportional to $\dot{w}_c^2$. Data on injection through two different sizes of orifices, and even forsimultaneous injection through two orifices in line axially, appear to lie on essentially a single straight line when plotted on log paper. The data for these graphs were obtained from graphs of F_s/F_m versus $\dot{w}_s/\dot{w}_c$ for similar axial locations. Figure 29 shows points of equivalent secondary flow rates through various orifice diameters. From this arrangement of data it may be seen that injection pressure should be as high as possible for a given flow rate. Appreciable increases in the performance ratio of an injectant may be obtained by increasing the injection pressure. The increase in performance may be due to greater injectant penetration of the exhaust gases under these conditions.

From Fig. 29 the following approximate equation describing Freon-12 injection was obtained:

$$F_s/F_m = 0.223\ (w_s^2/w_c^2 \div g/A)^{1/2}$$

Because the data from which this equation was derived covers only a relatively small range of conditions, it is highly approximate. Subsequent testing over a wider range has indicated a tendency of the injectant performance to approximate the curves of Fig. 30. This figure predicts the performance curves of Freon-12 when injected by a variable area, constant pressure technique. These curves were generated through the use of the approximate Freon-12 injection equation.

EFFECT OF INJECTANT CHARACTERISTICS

The total side-force resulting from the injection of a fluid into the expansion cone of a rocket nozzle may be considered to consist of two components: (1) a component of side-force due to the thrust of the fluid upon injection (product of mass flow rate and velocity plus

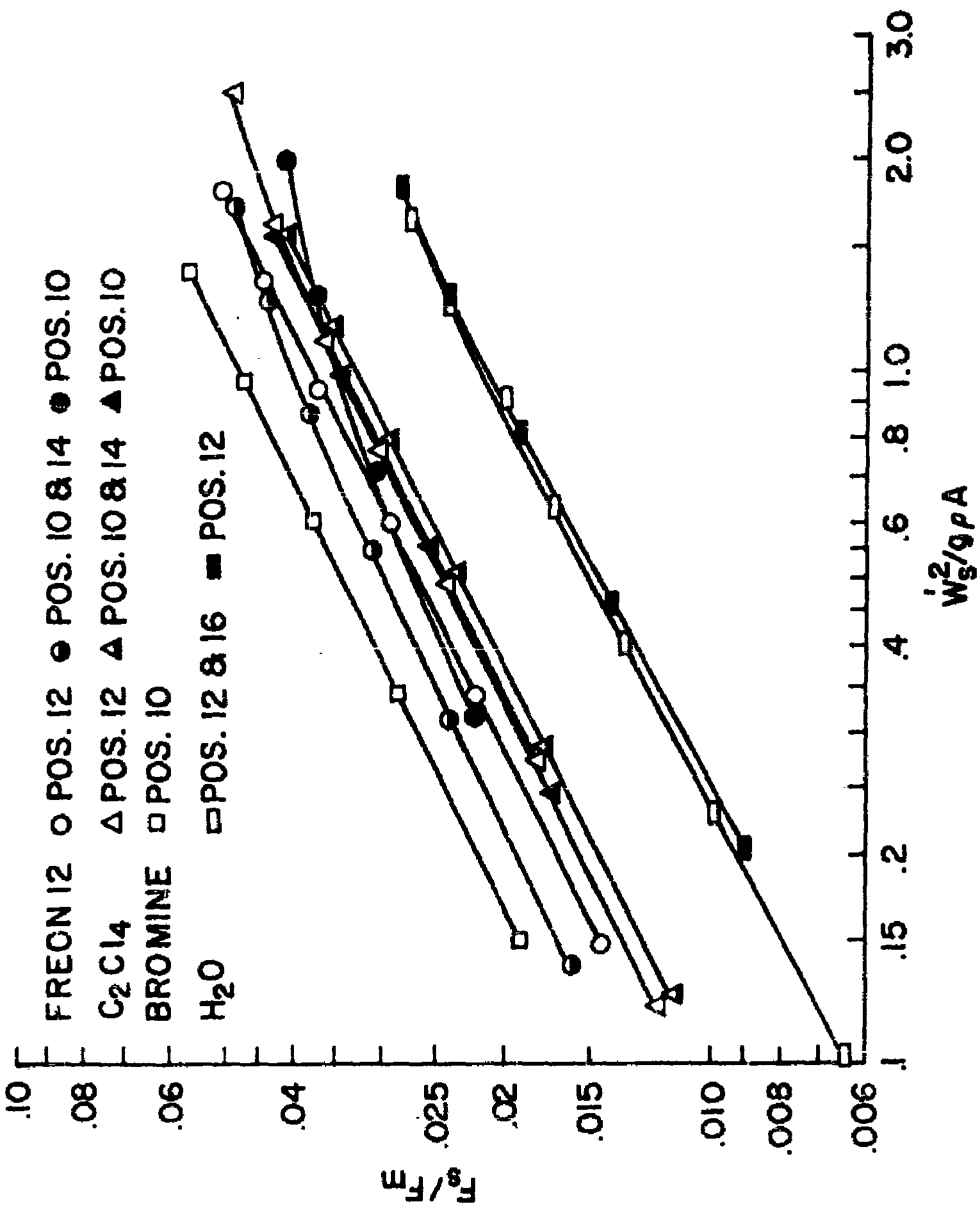

FIG. 27. Momentum of Injection Versus Force Ratio

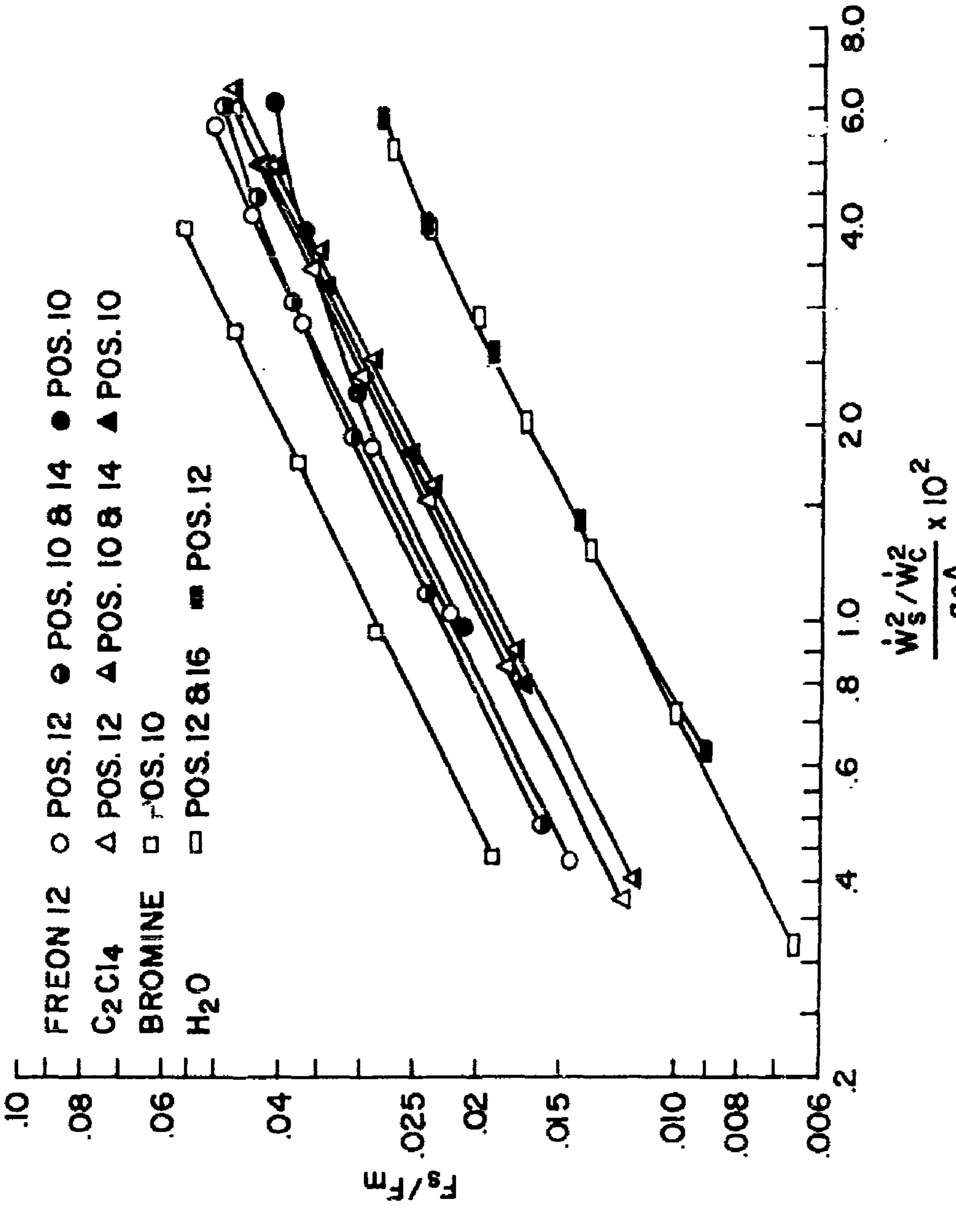

FIG. 28. Momentum of Injection/(Chamber Flow Rate)^2 Versus Force Ratio

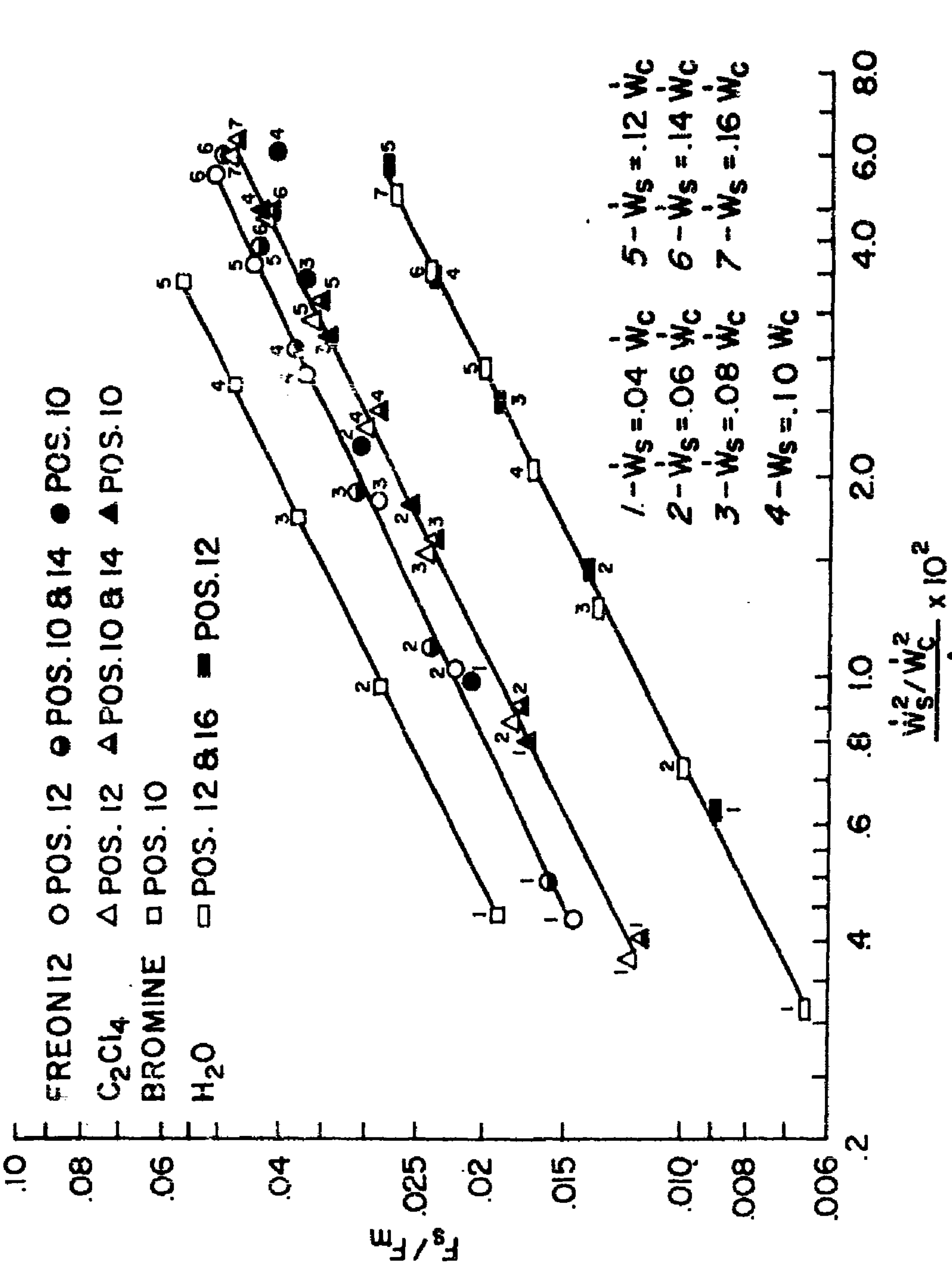

FIG. 29. Momentum of Injection/(Chamber Flow Rate)^2 Versus Force Ratio

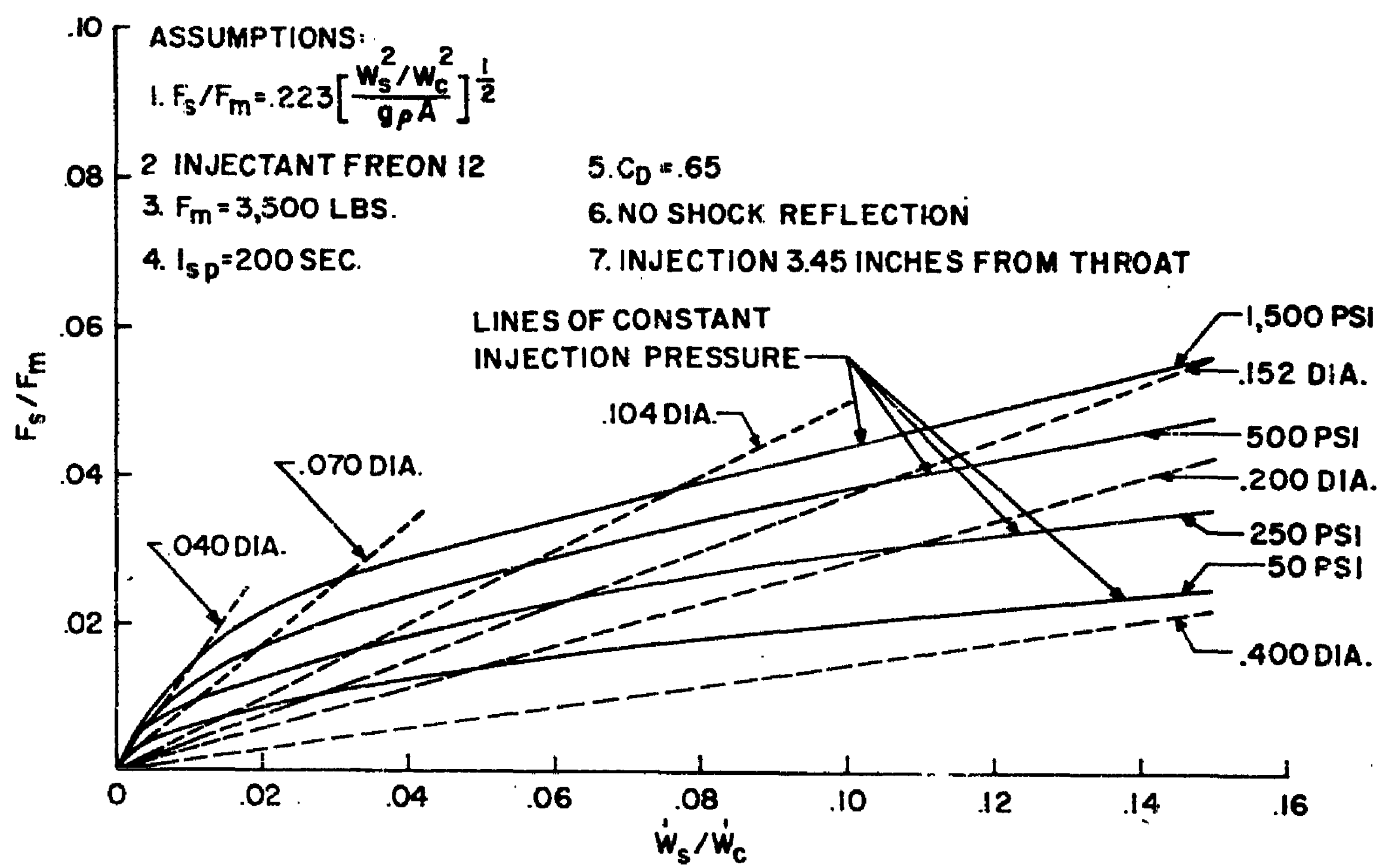

FIG. 30. Effect of Orifice Size and Injection Pressure on Performance

a pressure area term for gas injection), and (2) a component due to the interaction of the injected fluid with the main-stream gases. The second component consists of a static pressure recovery of the main-stream gases acting over an asymmetrical area within the nozzle. The pressure area force resulting from this pressure recovery represents from 80 to 90 percent of the total developed side-force, in the case of liquid injection.

A one-dimensional model of this fluid interaction process has been analyzed (Ref. 8). The results of this analysis indicate that the injectant should provide as large an obstruction as possible to main-stream flow, and should react or decompose with a release of heat or, in the case of an inert fluid, vaporize and/or dissociate with a minimum amount of heat absorption. Consequently, the following, and in some cases conflicting, injectant characteristics are desired:

1. Low specific heat in liquid and vapor phases
2. Low boiling point
3. Low heat of vaporization
4. High heat of reaction or exothermic decomposition
5. Low molecular weights of products of combustion or decomposition
6. High density (from a packaging standpoint)

RECOMMENDATIONS

In view of the demonstrated performance of bipropellant injection, further effort should be directed toward the use of monopropellants and bipropellants as injectants. Various injection techniques which would enhance the occurrence of chemical reation within the nozzle are required to take full advantage of the injectants' heat of reaction or decomposition. Some techniques which could be employed are as follows: (1) short L* premix or decomposition chambers prior to injection, (2) multiport upstream injection to increase heat transfer and injectant residence time, (3) injecting the fluid upstream of an obstruction in the flow to trigger reaction when the fluid passes through the shock generated by the obstruction, and (4) premixing the injectant with some by-passed chamber gases.

Constant pressure injection by means of a variable area orifice may influence system design considerably if only small corrective forces are required for the major portion of the flight time. Figure 30 indicates that large savings in injectant weight could be realized due to the higher performance available during high-velocity, low-flow-rate injection.

Effort should also be directed toward the screening of various storable high density fluids which may perform well as injectants. Fluids should be chosen for testing which look promising in light of the one-dimensional analysis (Ref. 8) and in view of the desirability of high fluid density.

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NOMENCLATURE

A	Injection port area, in.^{2}
F_m	Main thrust, lb.
F_s	Side thrust, lb.
g	Gravitational constant, ft/sec^2
I_{sp}	Specific impulse, sec.
$\dot{w}_c$	Main propellant flow rate, lb/sec.
$\dot{w}_s$	Secondary flow rate, lb/sec.
ρ	Injectant density, lb/ft^3

TABLE 1. Nominal LPARM Operating Conditions

Main Thrust, lb	3,500
Chamber pressure, psi	1,200
Specific impulse, sec	200
Oxidizer to fuel ratio	2.3
Expansion ratio	12:1
Burning time, sec	3 to 4

TABLE 2. Quarter-Scale SUBROC Motor Charteristics

Main thrust, lb	3,635 to 2,835
Chamber pressure, psi	1,115 to 855
Specific impulse, sec	237
Aluminum, %	17.7
Expansion ratio	8.15:1
Burning time, sec	35

TABLE 3. LPARM Data

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
Water Injectant - Position 12									
191	1,200	2.21	3,420	17.87	35	.820		.0459	.0102
191	1,200	2.21	3,420	17.87	53	1.340		.0750	.0155
191	1,200	2.21	3,420	17.87	68	1.560		.0873	.0199
191	1,200	2.21	3,420	17.87	83	1.800		.1007	.0243
191	1,200	2.21	3,420	17.[illegible]	90	1.960		.1097	.0263
191	1,200	2.21	3,420	17.87	93	2.050		.1147	.0272
191	1,200	2.21	3,420	17.87	95	2.230		.1248	.0278
Water Injectant - Positions 12 and 16									
190	1,190	2.21	3,400	17.87	39	1.250		.0699	.0115
190	1,190	2.21	3,400	17.87	46	1.470		.0823	.0135
190	1,190	2.21	3,400	17.87	56	1.920		.1074	.0165
190	1,190	2.21	3,400	17.87	74	2.450		.1371	.0218
190	1,190	2.21	3,400	17.87	80	2.760		.1544	.0235
190	1,190	2.21	3,400	17.87	88	2.850		.1595	.0259
Water Injectant - Positions 12 and 16									
193	1,160	2.20	3,390	17.60	55	1.520		.0864	.0162
193	1,160	2.20	3,390	17.60	59	1.740		.0989	.0174
193	1,160	2.20	3,390	17.60	63	1.960		.1114	.0186
193	1,160	2.20	3,390	17.60	69	2.140		.1216	.0203
193	1,160	2.20	3,390	17.60	72	2.320		.1318	.0212
193	1,160	2.20	3,390	17.60	79	2.470		.1403	.0233
193	1,160	2.20	3,390	17.60	83	2.630		.1494	.0245
193	1,160	2.20	3,390	17.60	89	2.720		.1545	.0263
193	1,160	2.20	3,390	17.60	92	2.850		.1619	.0271
193	1,160	2.20	3,390	17.60	100	3.030		.1722	.0295

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
Perchloroethylene Injectant - Position 14									
203	1,210	2.10	3,435	16.89	70	.860	605	.0509	.0204
203	1,210	2.10	3,435	16.89	90	1.165	930	.0690	.0262
203	1,210	2.10	3,435	16.89	105	1.435	1,305	.0850	.0306
203	1,210	2.10	3,435	16.89	115	1.550	1,465	.0917	.0335
203	1,210	2.10	3,435	16.89	120	1.645	1,650	.0973	.0349
203	1,210	2.10	3,435	16.89	125	1.710	1,765	.1010	.0364
203	1,210	2.10	3,435	16.89	120	1.740	1,825	.1030	.0349
Perchloroethylene Injectant - Position 10									
197.5	1,215	2.16	3,445	17.46	125	1.420	1,320	.0813	.0363
197.5	1,215	2.16	3,445	17.46	130	1.545	1,535	.0885	.0377
197.5	1,215	2.16	3,445	17.46	135	1.610	1,650	.0922	.0392
197.5	1,215	2.16	3,445	17.46	140	1.740	1,895	.0997	.0406
Perchloroethylene Injectant - Position 6									
200	1,200	2.16	3,495	17.46	95	1.405	1,330	.0805	.0272
200	1,200	2.16	3,495	17.46	95	1.505	1,515	.0862	.0272
200	1,200	2.16	3,495	17.46	95	1.580	1,665	.0905	.0272
200	1,200	2.16	3,495	17.46	95	1.620	1,745	.0927	.0272
200	1,200	2.16	3,495	17.46	100	1.650	1,818	.0945	.0286
200	1,200	2.16	3,495	17.46	105	1.660	1,840	.0955	.0300
Perchloroethylene Injectant - Position 14									
190	1,200	2.28	3,415	17.89	105	1.470	1,415	.0822	.0307
190	1,200	2.28	3,415	17.89	110	1.560	1,570	.0872	.0322
190	1,200	2.28	3,415	17.89	115	1.665	1,760	.0930	.0337
190	1,200	2.28	3,415	17.89	120	1.710	1,845	.0955	.0351
190	1,200	2.28	3,415	17.89	120	1.740	1,900	.0972	.0351

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
Perchloroethylene Injectant - Positions 14 and 10									
190	1,190	2.28	3,400	17.89	[illegible]	[illegible]	230	.0676	.0220
190	1,190	2.28	3,400	[illegible]	[illegible]	[illegible]	345	.0889	.0235
190	1,190	2.28	3,400	[illegible]	[illegible]	[illegible]	480	.1012	.0279
190	1,190	2.28	3,400	[illegible]	[illegible]	[illegible]	630	.1224	.0324
190	1,190	2.28	3,400	[illegible]	[illegible]	[illegible]	780	.1308	.0368
190	1,190	2.28	3,400	[illegible]	[illegible]	2.490	890	.1392	.0397
190	1,190	2.28	3,400	17.89	145	2.640	965	.1476	.0426
190	1,190	2.28	3,400	17.89	155	2.790	1,070	.1560	.0456
190	1,190	2.28	3,400	17.89	155	2.870	1,145	.1609	.0456
190	1,190	2.28	3,400	17.89	160	2.870	1,195	.1604	.0470
Perchloroethylene Injectant - Positions 14 and 10									
188	1,195	2.28	3,355	17.89	70	1.130	240	.0632	.0209
188	1,195	2.28	3,355	17.89	90	1.510	360	.0844	.0268
188	1,195	2.28	3,355	17.89	100	1.810	530	.1012	.0298
188	1,195	2.28	3,355	17.89	120	2.040	705	.1140	.0358
188	1,195	2.28	3,355	17.89	130	2.260	840	.1263	.0387
188	1,195	2.28	3,355	17.89	140	2.420	950	.1353	.0417
188	1,195	2.28	3,355	17.89	145	2.490	1,005	.1392	.0432
188	1,195	2.28	3,355	17.89	150	2.640	1,095	.1476	.0447
188	1,195	2.28	3,355	17.89	155	2.640	1,145	.1476	.0462
188	1,195	2.28	3,355	17.89	155	2.720	1,190	.1520	.0462
Perchloroethylene Injectant - Positions 14 and 10									
195	1,200	2.16	3,405	17.46	70	1.210	260	.0693	.0206
195	1,200	2.16	3,405	17.46	80	1.510	320	.0865	.0235
195	1,200	2.16	3,405	17.46	85	1.510	385	.0865	.0250
195	1,200	2.16	3,405	17.46	95	1.810	495	.1037	.0279
195	1,200	2.16	3,405	17.46	105	1.960	565	.1122	.0308
195	1,200	2.16	3,405	17.46	115	1.960	640	.1122	.0338
195	1,200	2.16	3,405	17.46	130	2.260	755	.1294	.0382
195	1,200	2.16	3,405	17.46	135	2.340	900	.1340	.0396
195	1,200	2.16	3,405	17.46	145	2.490	980	.1426	.0426

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
Perchloroethylene Injectant - Positions 14 and 10 (cont'd.)									
195	1,200	2.16	3,405	17.46	150	2.640	1,090	.1512	.0441
195	1,200	2.16	3,405	17.46	155	2.720	1,170	.1558	.0455
195	1,200	2.16	3,405	17.46	160	2.790	1,194	.1598	.0470
Perchloroethylene Injectant - Position 12									
191	1,180	2.23	3,445	18.03	95	1.870	475	.1038	.0276
191	1,180	2.23	3,445	18.03	115	2.185	585	.1210	.0333
191	1,180	2.23	3,445	18.03	135	2.405	670	.1335	.0392
191	1,180	2.23	3,445	18.03	150	2.530	725	.1405	.0435
191	1,180	2.23	3,445	18.03	155	2.630	765	.1460	.0450
191	1,180	2.23	3,445	18.03	155	2.740	820	.1520	.0450
191	1,180	2.23	3,445	18.03	165	2.870	880	.1590	.0479
Perchloroethylene Injectant - Position 16									
198	1,180	2.16	3,455	17.46	70	1.005	285	.0576	.0203
198	1,180	2.16	3,455	17.46	80	1.535	385	.0880	.0232
198	1,180	2.16	3,455	17.46	95	1.925	485	.1100	.0275
198	1,180	2.16	3,455	17.46	100	2.200	570	.1260	.0289
198	1,180	2.16	3,455	17.46	115	2.390	635	.1370	.0333
198	1,180	2.16	3,455	17.46	125	2.610	705	.1495	.0362
198	1,180	2.16	3,455	17.46	135	2.650	735	.1520	.0391
198	1,180	2.16	3,455	17.46	140	2.790	790	.1600	.0405
198	1,180	2.16	3,455	17.46	145	2.870	825	.1645	.0420
198	1,180	2.16	3,455	17.46	145	2.940	855	.1685	.0420
Freon-12 - Position 12									
200	1,190		3,485	17.42	160	2.060	730	.1180	.0460
200	1,190		3,485	17.42	165	2.450	960	.1405	.0470

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
				Freon-12 - Position 12					
200	1,200		3,515	17.57	155	2.150	780	.1225	.0440
200	1,200		3,515	17.57	165	2.410	935	.1375	.0470
200	1,200		3,515	17.57	175	2.580	1,045	.1468	.0498
				Freon-12 - Position 4					
202	1,200	2.18	3,540	17.50	48	1.560	430	.0892	.0136
202	1,200	2.18	3,540	17.50	50	2.140	800	.1225	.0141
202	1,200	2.18	3,540	17.50	52	2.240	880	.1280	.0147
202	1,200	2.18	3,540	17.50	55	2.400	1,010	.1370	.0155
				Freon-12 - Position 8					
200	1,180	2.23	3,550	17.75	110	1.720	530	.0970	.0310
200	1,180	2.23	3,550	17.75	119	1.895	630	.1070	.0335
200	1,180	2.23	3,550	17.75	125	2.020	710	.1140	.0352
200	1,180	2.23	3,550	17.75	128	2.130	780	.1200	.0360
200	1,180	2.23	3,550	17.75	132	2.210	840	.1250	.0372
200	1,180	2.23	3,550	17.75	137	2.360	940	.1330	.0386
200	1,180	2.23	3,550	17.75	140	2.440	1,000	.1380	.0394
				Freon-12 - Position 12					
201	1,200	2.23	3,560	17.75	100	1.400	430	.0788	.0281
201	1,200	2.23	3,560	17.75	110	1.580	500	.0890	.0309
201	1,200	2.23	3,560	17.75	124	1.700	550	.0958	.0348
201	1,200	2.23	3,560	17.75	138	1.835	610	.1035	.0388
201	1,200	2.23	3,560	17.75	148	1.930	660	.1090	.0416
201	1,200	2.23	3,560	17.75	154	2.030	710	.1145	.0432
201	1,200	2.23	3,560	17.75	160	2.120	760	.1195	.0449
201	1,200	2.23	3,560	17.75	164	2.170	790	.1225	.0461
201	1,200	2.23	3,560	17.75	167	2.260	830	.1275	.0469
201	1,200	2.23	3,560	17.75	170	2.300	860	.1295	.0478
201	1,200	2.23	3,560	17.75	171	2.330	890	.1315	.0480

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
Freon-12 - Position 12 (cont'd.)									
201	1,200	2.23	3,560	17.75	173	2.370	910	.1335	.0486
201	1,200	2.23	3,560	17.75	176	2.440	950	.1375	.0494
201	1,200	2.23	3,560	17.75	180	2.500	990	.1410	.0506
201	1,200	2.23	3,560	17.75	180	2.550	1,020	.1435	.0506
201	1,200	2.23	3,560	17.75	180	2.580	1,040	.1450	.0506
201	1,200	2.23	3,560	17.75	183	2.640	1,080	.1487	.0514
Freon-12 - Position 12									
210	1,205	2.15	3,535	16.86	110	1.585	505	.0970	.0311
210	1,205	2.15	3,535	16.86	135	1.830	615	.1085	.0382
210	1,205	2.15	3,535	16.86	155	2.030	720	.1205	.0438
210	1,205	2.15	3,535	16.86	165	2.200	810	.1305	.0470
210	1,205	2.15	3,535	16.86	170	2.320	880	.1375	.0480
210	1,205	2.15	3,535	16.86	175	2.470	975	.1465	.0495
210	1,205	2.15	3,535	16.86	180	2.560	1,035	.1520	.0510
210	1,205	2.15	3,535	16.86	180	2.640	1,090	.1565	.0510
Freon-12 - Position 16									
208	1,200	2.14	3,600	17.25	81	.945	320	.0548	.0225
208	1,200	2.14	3,600	17.25	98	1.310	420	.0760	.0272
208	1,200	2.14	3,600	17.25	113	1.560	510	.0904	.0314
208	1,200	2.14	3,600	17.25	125	1.800	610	.1045	.0347
208	1,200	2.14	3,600	17.25	137	2.010	710	.1165	.0380
208	1,200	2.14	3,600	17.25	146	2.170	790	.1260	.0406
208	1,200	2.14	3,600	17.25	153	2.280	850	.1325	.0425
208	1,200	2.14	3,600	17.25	155	2.390	910	.1385	.0430
208	1,200	2.14	3,600	17.25	155	2.490	970	.1445	.0430
208	1,200	2.14	3,600	17.25	157	2.530	1,000	.1465	.0436
208	1,200	2.14	3,600	17.25	157	2.570	1,030	.1490	.0436
208	1,200	2.14	3,600	17.25	159	2.610	1,050	.1510	.0442
208	1,200	2.14	3,600	17.25	159	2.030	1,060	.1525	.0442

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
				Freon-12 - Position 14					
199	1,185	2.23	3,515	17.67	90	1.10	930	.0622	.0256
199	1,185	2.23	3,515	17.67	105	1.38	1,340	.0781	.0299
199	1,185	2.23	3,515	17.67	105	1.46	1,470	.0826	.0299
				Freon-12 - Position 10					
201	1,160	2.18	3,520	17.50	97	.815	880	.0466	.0276
201	1,160	2.18	3,520	17.50	106	.900	1,030	.0514	.0301
201	1,160	2.18	3,520	17.50	113	.960	1,150	.0549	.0323
				Freon-12 - Positions 6 and 10					
201	1,140	2.16	3,440	17.12	81	1.175	340	.0687	.0240
201	1,140	2.16	3,440	17.12	92	1.375	420	.0804	.0270
201	1,140	2.16	3,440	17.12	97	1.485	470	.0868	.0280
201	1,140	2.16	3,440	17.12	103	1.590	520	.0930	.0300
201	1,140	2.16	3,440	17.12	110	1.670	560	.0975	.0320
201	1,140	2.16	3,440	17.12	114	1.755	610	.1025	.0330
201	1,140	2.16	3,440	17.12	119	1.810	640	.1060	.0350
201	1,140	2.16	3,440	17.12	124	1.880	680	.1100	.0360
201	1,140	2.16	3,440	17.12	127	1.945	720	.1137	.0370
201	1,140	2.16	3,440	17.12	130	1.990	750	.1163	.0380
201	1,140	2.16	3,440	17.12	135	2.100	820	.1227	.0400
				Freon-12 - Positions 14 and 10					
202	1,170	2.13	3,395	16.82	110	1.450	580	.0862	.0324
202	1,170	2.13	3,395	16.82	120	1.590	655	.0945	.0353
202	1,170	2.13	3,395	16.82	130	1.720	740	.1022	.0383
202	1,170	2.13	3,395	16.82	135	1.830	810	.1090	.0398
202	1,170	2.13	3,395	16.82	140	1.930	880	.1150	.0412
202	1,170	2.13	3,395	16.82	150	2.000	930	.1190	.0442
202	1,170	2.13	3,395	16.82	155	2.120	1,020	.1260	.0457
202	1,170	2.13	3,395	16.82	165	2.400	1,255	.1427	.0486
202	1,170	2.13	3,395	16.82	170	2.460	1,310	.1462	.0500

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
				Freon-12 - Position 14					
199	1,290	2.10	3,365	16.89	105	1.330	1,500	.0787	.0312
199	1,290	2.10	3,365	16.89	110	1.435	1,705	.0849	.0327
199	1,290	2.10	3,365	16.89	115	1.480	1,800	.0875	.0342
				Freon-12 - Position 14					
197	1,170	2.22	3,420	17.32	100	1.270	1,365	.0734	.0292
197	1,170	2.22	3,420	17.32	110	1.360	1,535	.0785	.0322
197	1,170	2.22	3,420	17.32	110	1.395	1,600	.0805	.0322
197	1,170	2.22	3,420	17.32	115	1.420	1,650	.0820	.0336
197	1,170	2.22	3,420	17.32	115	1.440	1,690	.0832	.0336
197	1,170	2.22	3,420	17.32	120	1.460	1,740	.0843	.0351
197	1,170	2.22	3,420	17.32	115	1.480	1,775	.0855	.0336
				Freon-12 - Position 12					
185	1,185	2.28	3,435	18.60	90	1.310	385	.0704	.0260
185	1,185	2.28	3,435	18.60	100	1.510	455	.0811	.0290
185	1,185	2.28	3,435	18.60	110	1.650	510	.0888	.0320
185	1,185	2.28	3,435	18.60	125	1.770	560	.0952	.0364
185	1,185	2.28	3,435	18.60	140	1.970	650	.1060	.0408
185	1,185	2.28	3,435	18.60	155	2.170	750	.1165	.0450
185	1,185	2.28	3,435	18.60	170	2.280	815	.1225	.0494
185	1,185	2.28	3,435	18.60	170	2.380	870	.1280	.0494
185	1,185	2.28	3,435	18.60	180	2.590	1,000	.1395	.0524
				Freon-12 - Position 12					
193	1,180	2.23	3,445	17.89	90	1.395	410	.0780	.0260
193	1,180	2.23	3,445	17.89	100	1.590	480	.0888	.0290
193	1,180	2.23	3,445	17.89	115	1.725	545	.965	.0320
193	1,180	2.23	3,445	17.89	130	1.905	610	.1065	.0364
193	1,180	2.23	3,445	17.89	145	2.060	685	.1150	.0408
193	1,180	2.23	3,445	17.89	160	2.210	760	.1235	.0450
193	1,180	2.23	3,445	17.89	170	2.440	895	.1365	.0494

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
Freon-12 - Position 12 (cont'd.)									
193	1,180	2.23	3,445	17.89	180	2.590	980	.1450	.0494
193	1,180	2.23	3,445	17.89	180	2.650	1,020	.1480	.0524
Freon-12									
Position 16									
190	1,160	2.27	3,470	18.29	79	1.263	400	.0690	.0227
Position 12									
190	1,160	2.27	3,470	18.20	83	1.330	400	.0727	.0239
Position 8									
190	1,160	2.27	3,470	18.20	70	1.263	400	.0690	.0202
Position 4									
190	1,160	2.27	3,470	18.20	56	1.280	400	.0700	.0102
Freon-12									
Position 16									
192	1,150	2.21	3,400	17.72	68	.816	225	.0460	.0200
Position 12									
192	1,150	2.21	3,400	17.72	68	.900	225	.0507	.0200
Position 8									
192	1,150	2.21	3,400	17.72	66	.910	225	.0513	.0194
Position 4									
192	1,150	2.21	3,400	17.72	65	.916	225	.0517	.0191
Freon-12									
Position 14									
188		2.26	3,470	18.46	64	.726	400	.0394	.0185
Position 10									
188		2.26	3,470	18.46	67	.745	400	.0403	.0193
Position 6									
188		2.26	3,470	18.46	64	.760	400	.0412	.0193
Position 2									
188		2.26	3,470	18.46	50	.727	400	.0394	.0144

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
Freon-12 - Position 10									
194	1,190	2.17	3,420	17.62	67	.782	350	.0444	.0196
Freon-12 - Position 10									
186	1,190	2.24	3,420	18.36	83	.924	640	.0503	.0243
Freon-12 - Position 10									
191	1,190	2.25	3,480	18.27	91	1.105	660	.0605	.0262
Freon-12 - Position 10									
187.5	1,180	2.28	3,460	18.44	48	.450		.0244	.0139
Bromine Injectant - Position 10									
189	1,190	2.27	3,480	18.47	142	1.630	770	.0885	.0408
Bromine Injectant - Position 10									
184	1,170	2.33	3,460	18.82	178	2.070	1,150	.1100	.0514

TABLE 3. LPARM Data (cont'd.)

I_{sp}	P_c	O/F	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	Sec.O/F	$\dot{W}_s/\dot{W}_c$	F_s/F_m
UDMH and IRFNA - Bi-propellant Injector Number 3									
192.5		2.32	3,580	18.60	230	2.200	2.230	.1185	.0643
UDMH and IRFNA - Bi-propellant Injector Number 3									
192		2.32	3,500	18.37	Early 248	2.300	2.430	.1255	.0709
192		2.32	3,500	18.37	Late 235	2.160	1.900	.1175	.0671
UDMH and IRFNA - Bi-propellant Injector Number 2									
201	1,180	2.15	3,590	17.86	222	2.060	3.800	.1155	.0608
UDMH and IRFNA - Bi-propellant Injector Number 2									
197	1,200	2.21	3,490	17.72	158	1.620	2.520	.0913	.0453
UDMH and IRFNA - Bi-propellant Injector Number 3									
199.5	1,200	2.26	3,620	18.17	227	2.400	1.240	.1320	.0627
199.5	1,200	2.26	3,620	18.17	238	2.380	1.275	.1310	.0658
UDMH and IRFNA - Bi-propellant Injector Number 3									
191	1,140	2.27	3,430	18.00	260	2.420	1.265	.1345	.0758
UDMH and IRFNA - Bi-propellant Injector Number 3									
192		2.28	3,500	18.37	158	1.700	0.975	.0925	.452

TABLE 4. Quarter-Scale SUBROC Data

I_{sp}	P_c	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
Freon-12 Injectant - Three Radial Orifices								
237	1,055 - 855	3,325	14.03	182	1.865	525	.1329	.0547
237	1,055 - 855	3,305	13.95	177	1.825	500	.1308	.0536
237	1,055 - 855	3,305	13.95	174	1.810	495	.1297	.0526
237	1,055 - 855	3,305	13.95	170	1.785	480	.1280	.0514
237	1,055 - 855	3,265	13.78	168	1.765	470	.1281	.0514
237	1,055 - 855	3,265	13.78	159	1.755	465	.1274	.0487
237	1,055 - 855	3,265	13.78	157	1.735	455	.1259	.0481
237	1,055 - 855	3,205	13.52	152	1.710	440	.1265	.0474
237	1,055 - 855	2,960	12.49	145	1.440	450	.1153	.0490
237	1,055 - 855	2,980	12.56	145	1.395	430	.1111	.0487
237	1,055 - 855	2,960	12.49	145	1.375	410	.1101	.0490
237	1,055 - 855	2,900	12.24	142	1.365	395	.1115	.0490
237	1,055 - 855	2,835	11.96	138	1.340	395	.1120	.0487
Freon-12 Injectant - Three Parallel Orifices								
237	1,100 - 950	3,510	14.81	177	2.29	695	.1546	.0504
237	1,100 - 950	3,510	14.81	170	2.24	665	.1512	.0484
237	1,100 - 950	3,470	14.64	165	2.18	635	.1489	.0476
237	1,100 - 950	3,450	14.56	161	2.15	615	.1472	.0467
237	1,100 - 950	3,430	14.47	153	2.12	600	.1465	.0446
237	1,100 - 950	3,390	14.30	148	2.08	585	.1455	.0437
237	1,100 - 950	3,390	14.30	135	2.04	550	.1427	.0398
237	1,100 - 950	3,205	13.52	131	1.82	450	.1198	.0409
237	1,100 - 950	3,145	13.27	125	1.57	430	.1183	.0397
237	1,100 - 950	3,115	13.14	116	1.53	410	.1164	.0372
237	1,100 - 950	3,060	12.91	112	1.51	395	.1170	.0366
237	1,100 - 950	2,980	12.57	109	1.51	395	.1201	.0366

TABLE 4. Quarter-Scale SUBROC Data (cont'd.)

I_{sp}	P_c	F_m	$\dot{W}_c$	F_s	$\dot{W}_s$	P_s	$\dot{W}_s/\dot{W}_c$	F_s/F_m
Freon-12 Injectant - Single Orifice								
237	1,115	3,635	15.34	226	2.48	925	.1617	.0622
237	1,115	3,675	15.50	215	2.35	820	.1516	.0585
237	1,115	3,635	15.34	211	2.23	780	.1454	.0580
237	1,115	3,590	15.15	202	2.23	765	.1472	.0563
237	1,115	3,610	15.23	196	2.17	745	.1425	.0543
237	1,115	3,590	15.15	196	2.17	730	.1432	.0546
N_2O_4 Injectant - Single Orifice								
237	1,115	3,635	15.34	296	2.81	1,005	.1831	.0814
237	1,115	3,635	15.34	289	2.75	925	.1792	.0795
237	1,115	3,600	15.12	284	2.68	885	.1772	.0789
237	1,115	3,570	15.06	280	2.63	845	.1746	.0784
237	1,115	3,570	15.06	280	2.60	815	.1726	.0784

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