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OFFICE OF NAVAL RESEARCH
WASHINGTON, D.C.

3 December 1953
Report No. 763
Special
Copy No.

INVESTIGATION OF THE GASOLINE AND MIXED FLUORINE-OXYGEN PROPELLANT COMBINATION

Contract N7onr - 462
Task Order No. III

SECURITY INFORMATION

3 December 1953

Report No. 763
(Special)

AN INVESTIGATION OF THE GASOLINE AND MIXED FLUORINE-OXYGEN PROPELLANT COMBINATION

Contract N7onr-462

Task Order III

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Period Covered:

1 June through 15 August 1953

AEROJET-GENERAL CORPORATION

Azusa, California

CONTENTS

CONTRACT FULFILLMENT STATEMENT

This special report summarizes the results of one engine test program conducted in partial fulfillment of Contract N7onr-462, Task Order III, Amendment 9.

I. INTRODUCTION

A. Numerous engine test programs have been conducted by contractors and government agencies in an effort to obtain experimental specific-impulse values of more than 270 lb-sec/lb at 300 psia chamber pressure and an exit pressure of 1 atm, but few propellant combinations have yielded such high values. In practically all instances in which such specific impulses have been recorded, it has been found necessary to use liquid fluorine as the oxidizer (the notable exception being the liquid hydrogen—liquid oxygen combination). Fluorine is quite expensive, with no indication of a major reduction in price in the near future.

B. In February 1952, preliminary results were obtained which indicated that high performance could be obtained by burning gasoline in a rocket engine with a mixture of liquid oxygen and liquid fluorine.* It was recognized from qualitative thermodynamic considerations that the use of a hydrocarbon fuel should make it possible to dilute fluorine with oxygen and still achieve high performance, since the fluorine would preferentially combine with the hydrogen, permitting the oxygen to burn the carbon. A substantial reduction in the amount of fluorine needed, and thus in cost of the oxidizer, would be achieved in this way.

II. OBJECT

It was the purpose of the present test program to investigate further the merit of the hydrocarbon and mixed fluorine-oxygen propellant combination, and to attempt to determine the optimum conditions for high specific impulse without entering into an extensive hardware study.

III. RESUME

Tests made earlier (Ref. 1) and results obtained on the program just completed confirm the original theory. Although a very extensive program would be necessary to determine the optimum fluorine-to-oxygen ratio, over-all oxidizer-to-fuel ratio, injector configuration, and minimum characteristic length of the thrust chamber, a sufficient number of tests have now been made to establish the value of the propellant combination in future considerations of high-energy propellants. With an oxidizer consisting of 67 mole % oxygen (63 wt %) and 33 % fluorine, a maximum specific impulse of 272 lb-sec/lb and a characteristic velocity of 6720 ft/sec have been obtained, comparable with results recently published by NACA (Ref. 2) for ammonia burned with 100% fluorine. Because the NACA discovered that engine configuration had a very important bearing on test results, the performance values reported here with the mixed oxidizer are possibly not the maximum obtainable from the system.

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*Equipment under the jurisdiction of this contract was used, but no charges were made to the contract.

IV. CONCLUSIONS AND RECOMMENDATIONS

If costs of \$0.05/lb are set on ammonia, gasoline, and oxygen, and \$10.00/lb for fluorine, the cost of a pound of propellant necessary to obtain the maximum performance measured in the test program would be \$2.61. The cost per pound of propellant in the NACA ammonia-fluorine tests would be \$7.11 at best. Thus, it is possible to obtain comparable experimental specific impulses with a reduction in costs of almost two-thirds when the mixed oxidizer is used. It is therefore recommended that the gasoline--mixed oxygen and fluorine propellant combination be studied further on a small-thrust scale with respect to injector configurations, and that the ideal engine system then be tested at 3000 to 5000-lb thrust.

V. EQUIPMENT AND INSTRUMENTATION

A. PROPELLANTS

Cylinders containing 6 lb of fluorine each at approximately 360 psi were obtained from the Pennsylvania Salt Manufacturing Company. The gas was used without analysis, previous studies having shown that the purity was normally above 98%. Commercial compressed oxygen was used. The fuel used in this program was aviation gasoline; important specifications of the sample used are as follows:

Carbon, wt %	85.13
Hydrogen, wt %	14.85
Empirical formula	$CH_{2.09}$
Specific Gravity, $\frac{60^{\circ}F}{60^{\circ}F}$	0.697
Bromine number	0.3
Aromatics	0.7%
Vapor pressure (Reid)	6.5 psi
Distillation curve	Initial bp = 107°F 10% 154 50% 212 90% 249 Final bp = 324°F

B. FACILITIES

1. The test facilities are essentially those described in a previous report (Ref.3). A view of the engine and associated equipment is shown in Figure 1. The engine produces 100-lb thrust, and during this test series was operated at an L* of 128 in. Fuel and oxidizer displacement is accomplished by means of a piston-cylinder system; on the oxidizer side,

liquid nitrogen within the cylinder displaces the fluorine-oxygen mixture stored within a copper coil surrounded by liquid nitrogen.

2. A single injector was used throughout the series, and because of the widely varying flow conditions it probably was not capable of producing a constant percentage of theoretical performance over the entire range of mixture ratios (fluorine to oxygen, and oxidizer to fuel). The injector was 1 in. in diameter and delivered five pairs of 1:1 impinging fuel and oxidizer streams, the oxidizer being in the center of the chamber. The injector was so designed that the resultant momentum of the impinging streams was axial at a mixture ratio of 4.5 with 50 mole% fluorine. A double coil of 1/4-in. copper tubing (water-cooled) was installed 2 in. from the face of the injector as a turbulence promotor. The main propellants were ignited by means of a starting flame of gaseous hydrogen and oxygen, which also served to bring the thrust chamber nearly to thermal equilibrium before introduction of the test propellants

3. Thrust was measured with a 300-lb force ring (Wiancko Company), the output being recorded on a Consolidated Engineering Corporation multichannel oscillograph. Calibration was accomplished immediately after each test by placing weights on a pulley system connected to the thrust stand. Chamber pressure was measured both by an electrical bourdon gauge (Wiancko Company) and a hydraulic system recording on a Republic pressure recorder. Water-coolant flows were measured by Taylor differential pressure transmitters and recorded on Republic pressure recorders. Propellant flows were measured by calibrated General Electric tachometers attached to the moving pistons by racks and pinions and recorded on Esterline-Angus recorders.

VI. TESTING PROCEDURE

A. PROPELLANT HANDLING

1. Sufficient gasoline for several tests was introduced directly into the fuel cylinder from a storage container which was kept tightly sealed except when a sample was being withdrawn.

2. Mixtures of fluorine and oxygen were made by using a partially empty fluorine cylinder as a mixing chamber. This cylinder was connected by the proper tubing and fittings to a full cylinder of fluorine, which was then opened by remote control until a predetermined pressure of the gas was admitted to the mixing cylinder. After thermal equilibrium was established, the pressure in the mixing cylinder was carefully read. Oxygen was added in a like manner to the mixing cylinder; after thermal equilibrium was reached, the total pressure of the cylinder was carefully read. From these data the mole % of each of the two gases could be calculated. Ideal gas behavior was assumed in the calculations. At least two tests could be made from the same cylinder of mixed oxidizer. The limiting factor in mixing a large quantity of a given percentage of fluorine in oxygen was the pressure safety limit on the fluorine cylinder used for mixing. The mixed fluorine and oxygen gases were permitted to stand for at least 24 hr before being used and often for two or three days to ensure homogeneity.

B. PRE-TEST CONDITIONING

1. Immediately before each test firing, relatively large quantities of the mixed oxidizer were bled through all sections of the motor with which fluorine would come in contact during the run. Bleeding was accomplished by first permitting nitrogen to flow through the system and then slowly adding the mixed oxidizer to this stream, decreasing the amount of nitrogen until the oxidizer alone was flowing. In this manner, any possible contaminants in the lines were slowly burned out. As a further precaution, the thrust chamber and injector components were thoroughly washed in detergent, rinsed with water, and blown dry with nitrogen before this conditioning treatment.

2. After the gaseous mixed oxidizer had been permitted to flow from the storage coil vent (see Figure 1), the vent valve was closed by remote control and liquid nitrogen was introduced into the coolant vessel surrounding the coil. At the same time the oxidizer cylinder on the test engine was filled with liquid nitrogen; the liquefied oxidizer and the liquid nitrogen used for displacement were separated by a valve which was opened only seconds before the opening of the main propellant valve. The mixed oxidizer was permitted to condense until a constant pressure reading was obtained, indicating that the storage coil was full.

C. MOTOR TEST

1. The motor was fired by placing a high-voltage ignition wire in the nozzle, closing the firing switch, and simultaneously opening the gaseous hydrogen and oxygen valves. During this portion of the test run, nitrogen bleeds were automatically maintained through both the fuel and oxidizer sides of the main injector so that no water could condense in the passages. Six to twelve sec after ignition of the hydrogen-oxygen flame, the valve separating the liquid nitrogen from the liquid fluorine was opened. The main propellant valves were then opened simultaneously, permitting the previously pressurized pistons to displace the liquids through the injector. The hydrogen-oxygen flame was shut off as soon as ignition of the test propellants occurred. The run was terminated when all of the mixed oxidizer had been displaced from the coil and liquid nitrogen entered the injector. The fuel valve was then closed, and the chamber was purged with high-pressure nitrogen.

2. The thrust unit was calibrated as soon as any fumes not absorbed by a sodium hydroxide spray tower had been exhausted from the test bay. At this time the diameter of the nozzle was determined, and the absorption tower wash water was examined for unburned carbon.

VII. RESULTS AND DISCUSSION

A. A total of 25 tests were made with oxidizer mixtures containing 0, 33, 50, 67, and 100 mole% fluorine. Maximum performance values were obtained with the 33% mixture; the specific impulse was 272 lb-sec/lb and the characteristic exhaust velocity was 6720 ft/sec. Performance increased from the 0%

to the 33% mixture, decreased from this maximum with the 50% mixture, and then increased somewhat for the 67% mixture. No data were obtained with 100% fluorine because the two tests made with pure fluorine resulted in the only damage to the motor during the series.

B. Complete data for the tests are presented in Table I, and in graphical form in Figures 2,3, and 4. A summary of the results previously obtained (Ref. 1) is shown as Table II. Both uncorrected and corrected values for heat loss to the coolant are presented in Figures 2 and 3, with tie-lines joining the values. Comparison of the two sets of results shows that the maximum performance values were obtained under widely different conditions. It is believed that the difference is due to the injectors used, each having been designed for different flow conditions. Extensive studies of the effect of injector configuration on performance, when fluorine is used as the oxidizer, have been made by NACA (Ref. 2 and 4). It was concluded that despite the high chemical reactivity of fluorine, it is necessary to conduct tests with a variety of injectors in order to obtain maximum performance. Not only do some injectors give a consistently lower percentage of theoretical performance than others, but some actually give relatively high performance over a very narrow range of mixture ratios, the performance then dropping off rapidly on either side of this peak. Such might be the case in the two series of tests made at Aerojet; the fact that the plot of maximum performance of the several mixtures is an "S"-shaped curve (increasing from 0% fluorine to 33%, declining from 33%, to 50%, and then rising to 67%) could also be explained by the assumption that the injector used is capable of producing high performance only under certain restricted conditions of flow. A curve of this shape would be produced if maximum theoretical performance increased with percentage fluorine in the oxidizer (or even dropped off slightly as 100% fluorine is approached) and injector efficiency was low at approximately 50% fluorine, increasing on either side of this point.

In any event, it has been shown that with the proper injector, high values of specific impulse may be obtained when fluorine is diluted as much as two-thirds with oxygen. Even higher values might be possible if an injector study were undertaken.

C. Only two tests resulted in damage to the test engine. Both were tests in which 100% fluorine was used as the oxidizer. The first, Test No. D-45-LF-5, resulted in a fire that destroyed part of the injector oxidizer line and all of the injector face, and damaged the turbulator. The fire started as soon as the main propellant valve was opened, and must be attributed to some contaminant in the injector system. Figure 5 shows the extent of the damage. The second test, No. D-45-LF-25, resulted in more damage in the thrust chamber than did the first, but the primary cause of the fire was not the high reactivity of fluorine. The coolant water for the turbulator is supplied from a tank pressurized to 600 psi; the fact that coolant is flowing is verified before each test. Oscillograph records of the coolant water temperature show that the copper coils were heated far more than normally during the hydrogen-oxygen phase of the test, and that when the main propellants were introduced the water flow was not great enough to cool the turbulator properly. The entire turbulator was consumed, and part of one outside fitting and part of the nozzle was damaged; the injector system was not affected. The coolant filter was examined to determine whether solid particles might have restricted the water flow, but no obstructions could be found. The regulator supplying the high-pressure gas to the coolant supply was also examined to determine whether it might have failed to maintain the necessary pressure during the test, but no evidence of mechanical failure was found.

D. The wash water from the absorption tower for exhaust products was examined after each run for unburned carbon. Each of the tests made at 67% fluorine produced appreciable carbon, and the tests at 50% fluorine yielded much less, though some, carbon. No unburned carbon was found after any of the other tests. The exhaust flame was extremely bright in most of the tests, and bushy in appearance. Shock cones were often visible, but the flame was never sharp enough for the shock cones to be seen throughout the test.

REFERENCES

1. Aerojet Report No. 820-27, 24 March 1952 (Confidential).

2. Research Memorandum E53E08, National Advisory Committee for Aeronautics, 3 July 1953 (Confidential).

3. Aerojet Report No. 527, 31 July 1951 (Confidential).

4. Research Memorandum E52H22, National Advisory Committee for Aeronautics, 29 October 1952 (Confidential).

TABLE I

AEROJET-GENERAL CORPORATION - PROVING GROUNDS
TEST DATA SUMMARY SHEET

PROPELLANT EVALUATION OF MIXED LIQUID FLUORINE AND OXYGEN WITH AVIATION GASOLINE

W.O. -	28010012	Test Series -	D-45-LF
Injector -	AR-20028-Modified	Thrust Chamber -	AR-3395

TEST NUMBER	DATE - 1953	DURATION MAIN PROPELLANTS SECONDS	FUEL	Oxidiser MOLE % F_2	Oxidiser MOLE % O_2	Oxidiser wt % F_2	Oxidiser wt % O_2	THROAT DIAMETER INCHES	L^*	CHAMBER PRESSURE psia	THRUST lbs	$\dot{w}_o$, lb/sec	$\dot{w}_f$, lb/sec	$\dot{w}_p$, lb/sec	MIXTURE RATIO $\dot{w}_o/\dot{w}_f$	c_f, CALCULATED	c^*, CALCULATED	c, CALCULATED	I_{sp}, CALCULATED	c_f, CORRECTED FOR HEAT TRANSFER	c^*, CORRECTED FOR HEAT TRANSFER	c, CORRECTED FOR HEAT TRANSFER	I_{sp}, CORRECTED FOR HEAT TRANSFER	Q, BTU/SEC	AVERAGE HEAT TRANSFER	REMARKS	TEST NUMBER
1	6-2	8.50	Av.Gas	0	100.0	0	100.0	.552	130	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Satisfactory Start and Run - Equilibrium Conditions not Reached.	1
* 2	6-4	9.30	Av.Gas	0	100.0	0	100.0	.550	130	299	105	.3068	.1264	.4332	2.425	1.48	5243	7760	241	1.49	5330	7920	246	133	2.149	Satisfactory Start and Run.	2
* 3	6-5	8.30	Av.Gas	0	100.0	0	100.0	.549	130	288	97	.2931	.1188	.4119	2.470	1.42	5329	7567	235	1.43	5450	7770	241	179	2.500	Satisfactory Start and Run	3
4	6-10	4.50	Av.Gas	0	100.0	0	100.0	.550	130	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Rough Start. Oxidiser Flow Apparently Stopped about the Time H_2O_2 Flameout.	4
5	6-11	4.30	Av.Gas	0	100.0	0	100.0	.550	130	253	82	.2820	.1363	.4183	2.070	1.36	4627	6293	196	1.36	4680	6387	199	78.15	0.915	Satisfactory Start and Run.	5
6	6-24	1.20	Av.Gas	100.0	0	100.0	0	.550	130	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Malfunction of Main Propellant on Start. Apparently Injector Burnt After Malfunction of Oxidiser in Line.	6
7	7-10	13.00	Av.Gas	52.2	47.8	56.5	43.5	.550	130	259	89	.3219	.0643	.3862	5.000	1.35	5130	6930	215	1.35	5459	7380	229	200.68	2.354	Satisfactory Start and Run.	7
**8	7-15	3.50	Av.Gas	50.6	49.4	54.9	45.1	.551	130	-	81	.3237	.0742	.3979	4.352	-	-	-	205	-	-	-	-	-	-	Satisfactory Start. H_2O_2 Flame Out During Run.	8
9	7-16	5.00	Av.Gas	49.6	50.4	54.0	46.0	.550	130	267	86	.3404	.0763	.4167	4.467	1.35	4895	6608	205	1.36	5001	6829	219	122.71	1.440	Satisfactory Start and Run.	9
10	7-17	5.50	Av.Gas	49.6	50.4	54.0	46.0	.550	130	284	85	.3705	.0697	.4402	5.320	1.26	4933	6190	192	1.27	5165	6502	202	109.64	1.286	Satisfactory Start and Run	10
11	7-20	2.70	Av.Gas	32.6	67.4	36.5	63.5	.550	130	338	-	.3481	.0894	.4385	3.893	-	5597	-	-	-	-	-	-	-	-	Satisfactory Start and Run. No Oscillograph Record.	11
12	7-22	5.00	Av.Gas	32.6	67.4	36.5	63.5	.550	130	345	105	.3194	.0937	.4131	3.409	1.28	6389	8178	254	1.31	6720	8760	272	189.31	2.221	Satisfactory Start and Run.	12
13	7-24	5.60	Av.Gas	32.6	67.4	36.5	63.5	.550	130	303	102	.3029	.0948	.3977	3.194	1.42	5829	8277	256	1.43	6045	8649	269	163.71	1.921	Satisfactory Start and Run.	13
14	7-27	4.60	Av.Gas	32.6	67.4	36.5	63.5	.550	130	295	97	.3275	.0872	.4147	3.758	1.38	5442	7532	234	1.39	5543	7683	239	151.82	1.781	Satisfactory Start and Run.	14
15	7-28	5.00	Av.Gas	22.8	77.7	26.0	74.0	.551	130	313	104	.2922	.1112	.4034	2.629	1.39	5956	8279	258	1.39	6070	8460	263	120.77	1.417	Satisfactory Start and Run.	15
16	7-29	5.50	Av.Gas	22.8	77.7	26.0	74.0	.551	130	317	100	.3080	.1024	.4104	3.009	1.32	5929	7826	245	1.33	6237	8303	258	145.00	1.701	Satisfactory Start and Run.	16
17	7-31	-	Av.Gas	65.2	34.8	71.1	28.9	.550	130	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	Malfunction. Oxidiser Valve Failed to Open.	17
18	8-4	5.60	Av.Gas	65.2	34.8	71.1	28.9	.550	130	270	85	.3184	.0599	.3783	5.305	1.32	5460	7207	225	1.35	5759	7850	244	107.83	1.265	Satisfactory Start and Run.	18
19	8-5	4.00	Av.Gas	66.7	33.3	70.4	29.6	.551	130	274	84	.3242	.0643	.3885	5.042	1.29	5396	6961	216	1.32	5574	7335	228	106.79	1.253	Satisfactory Start and Run. Fairly Heavy Carbon Deposits on Chamber and Walls.	19
20	8-6	6.60	Av.Gas	20.0	80.0	22.9	77.1	.550	130	311	94	.3160	.0916	.4076	3.450	1.27	5838	7414	231	1.28	6255	7981	248	163.88	1.923	Satisfactory Start. Hydraulic Pressure Apparently Dropped Off at Midpoint to Give Low Flows. Carbon Deposits on Chamber Walls.	20
21	8-7	3.10	Av.Gas	20.0	80.0	22.9	77.1	.551	130	318	100	.2903	.1199	.4102	2.420	1.32	5951	7855	244	1.33	6257	8326	259	133.76	1.569	Satisfactory Start. Apparent Chugging During Run.	21
22	8-10	3.80	Av.Gas	33.3	66.7	37.2	62.8	.551	130	317	101	.3174	.0872	.4046	3.640	1.34	6014	8059	250	1.35	6264	8430	262	148.98	1.748	Satisfactory Start and Run. Slight Carbon Deposit on Nozzle.	22
23	8-12	3.20	Av.Gas	31.3	66.7	36.5	63.5	.551	130	320	103	.3337	.0818	.4155	4.079	1.35	5917	7981	248	1.36	6148	8336	259	116.79	1.370	Satisfactory Start and Run.	23
24	8-13	5.90	Av.Gas	31.3	66.7	36.5	63.5	.551	130	302	97	.3172	.0850	.4022	3.730	1.35	5764	7781	241	1.37	6035	8260	257	181.52	2.130	Satisfactory Start and Run.	24
**25	8-14	2.30	Av.Gas	100.0	0	100.0	0	.551	130	-	-	.3600	.0506	.4106	7.180	-	-	-	299	-	-	-	-	-	-	Satisfactory Start. Turbulator Burnt Out During Run. Apparently H_2O Flow Reduced.	25

* Heat Transfer Corrections Unreliable.
** Specific Impulse Values Approximate Only.

TABLE II

AVIATION GASOLINE AND MIXTURES OF LIQUID FLUORINE AND LIQUID OXYGEN

SUMMARY OF PERFORMANCE DATA

Test No. PP-15-1-	Fuel	Oxidizer Mol% F_2	Oxidizer Mol% O_2	Oxidizer Wt% F_2	Oxidizer Wt% O_2	Chamber Pressure psia	M.R. (w_{ox}/w_f)	C_F (Corr. for Heat-Trans.)	I_{sp} (Uncorr.) lb-sec/lb	c^*, ft/sec (Corr. for Heat-Trans.)	I_{sp}, lb-sec/lb, (Corr. for Heat-Trans.)	Molar Mixture Ratio
1	Aviation Gasoline	50.7	49.3	55.0	45.0	225	2.57	1.34	192	4708	196	8.29
2		50.7	49.3	55.0	45.0	330	3.62	1.46	244	5541	252	12.32
3		—	100	—	100	241	2.51	1.32	198	5016	206	8.66
4		50.3	49.7	54.6	45.4	319	5.85	1.43	242	5665	252	18.88
5		50.3	49.7	54.6	45.4	322	4.62	1.43	253	5884	261	14.91
6		50.3	49.7	54.6	45.4	316	4.87	1.43	243	5736	255	15.72
7		66.7	33.3	70.4	29.6	321	4.62	1.41	247	5991	262	14.50
8		66.7	33.3	70.4	29.6	305	3.87	1.42	237	5646	249	12.15

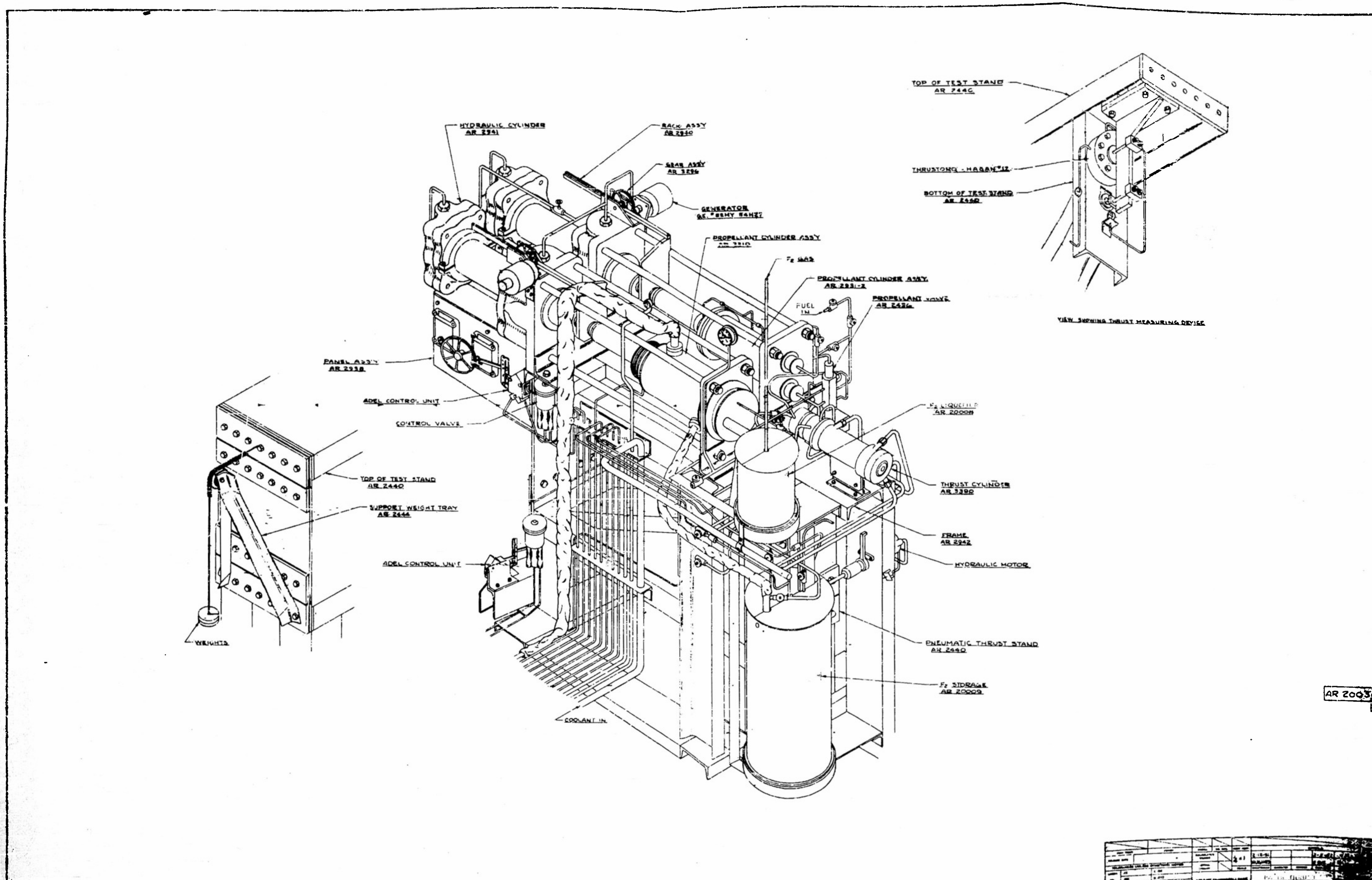

HYDRAULIC CYLINDER AR 2941
RACK ASS'Y AR 2940
GEAR ASS'Y AR 3296
GENERATOR
PROPELLANT CYLINDER ASS'Y
F_2 GAS
PROPELLANT CYLINDER ASS'Y
PROPELLANT VALVE
FUEL IN
PANEL ASS'Y AR 2938
ADEL CONTROL UNIT
CONTROL VALVE
TOP OF TEST STAND AR 2440
SUPPORT WEIGHT TRAY AR 2444
ADEL CONTROL UNIT
WEIGHTS
COOLANT IN
THRUST CYLINDER AR 3390
FRAME AR 2942
HYDRAULIC MOTOR
PNEUMATIC THRUST STAND AR 2440
F_2 STORAGE AR 20009
TOP OF TEST STAND
THRUSTONG - HAGAN
BOTTOM OF TEST STAND
VIEW SHOWING THRUST MEASURING DEVICE
AR 2003

Figure 1.

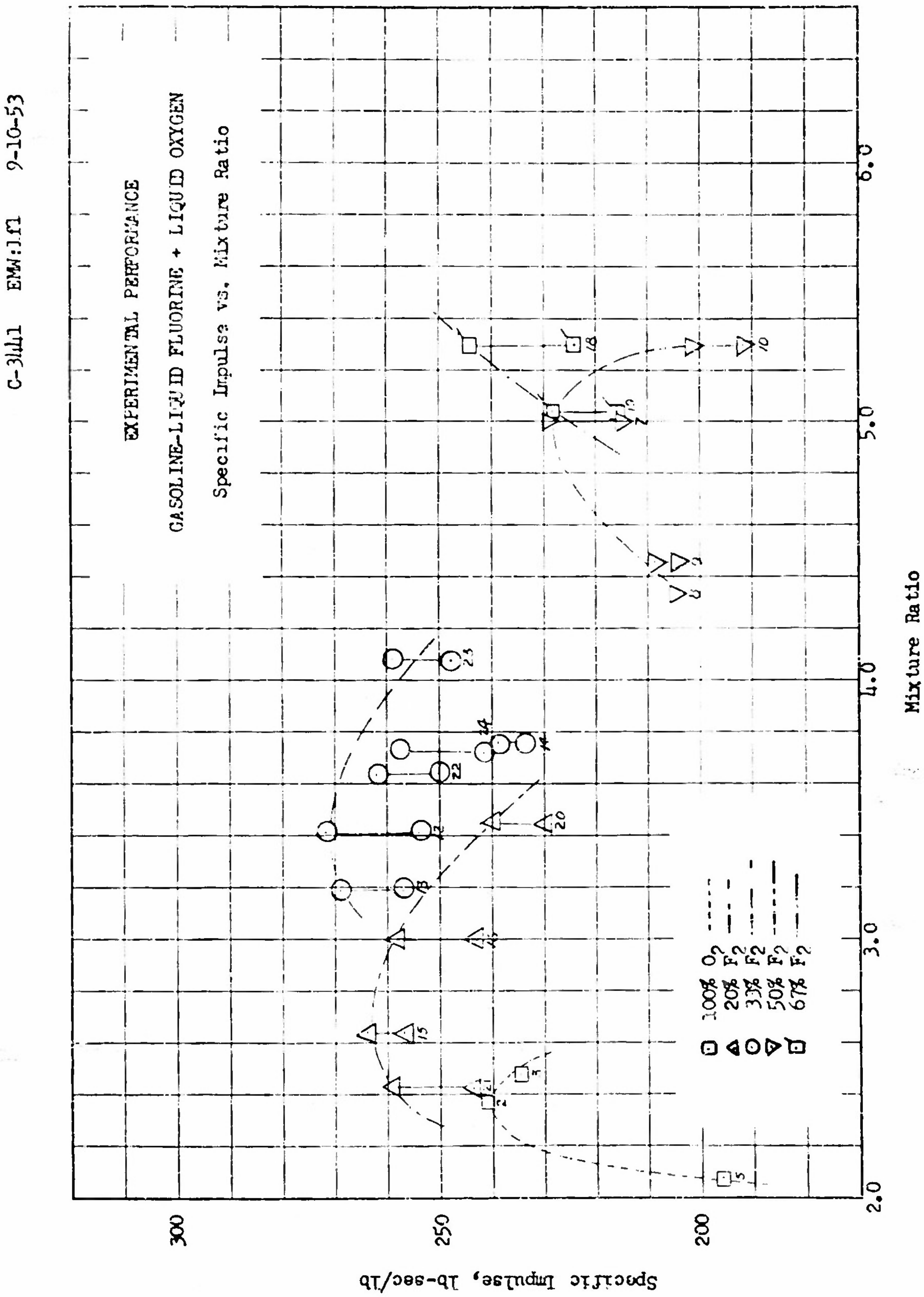

C-3441 EMW:jfl 9-10-53
EXPERIMENTAL PERFORMANCE
GASOLINE-LIQUID FLUORINE + LIQUID OXYGEN
Specific Impulse vs. Mixture Ratio
100% O2
20% F2
33% F2
50% F2
67% F2
Mixture Ratio
Specific Impulse, lb-sec/lb
2.0
3.0
4.0
5.0
6.0
300
250
200

Figure 2

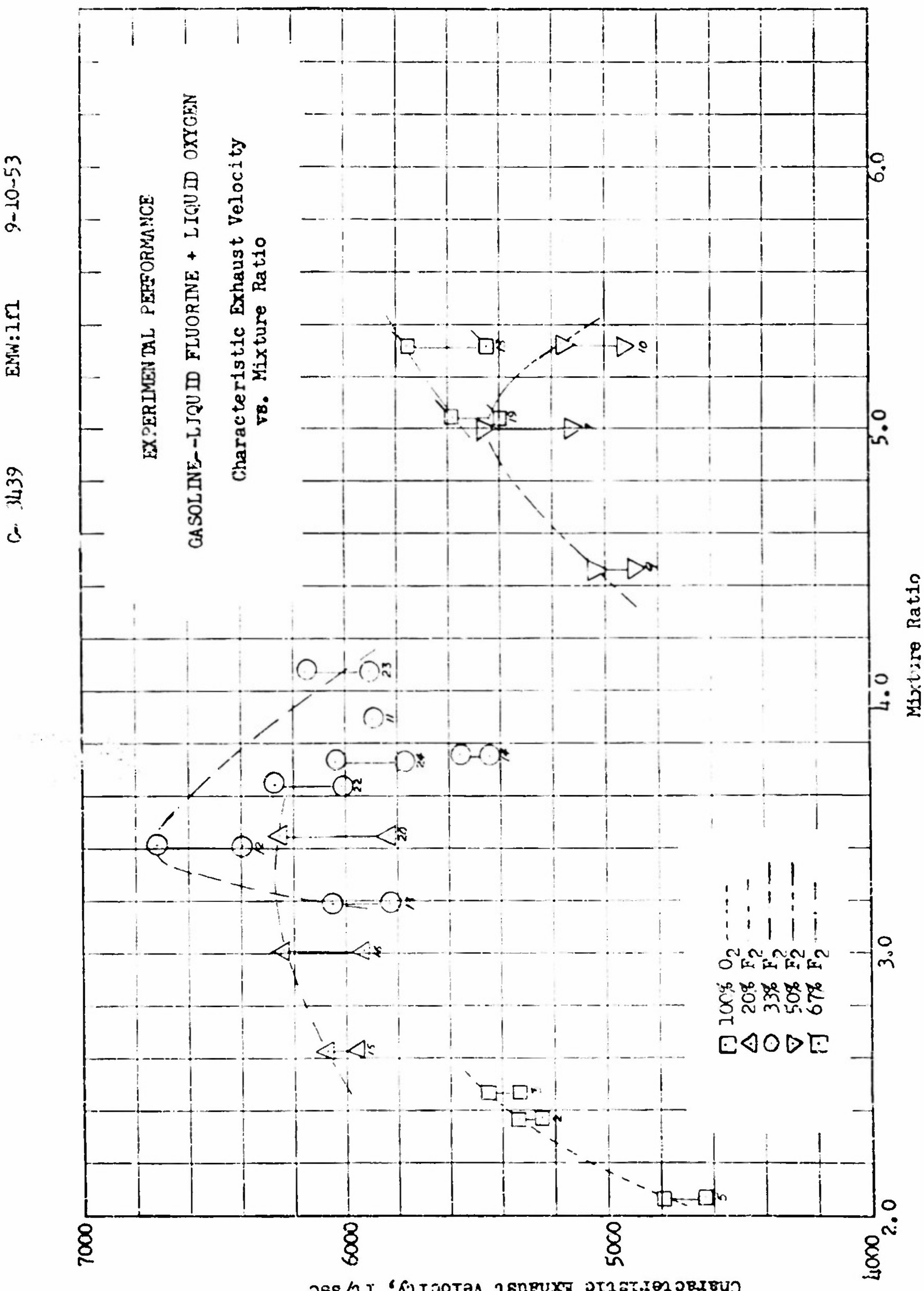

C- 3439
EMW:lfl
9-10-53
EXPERIMENTAL PERFORMANCE
GASOLINE-LIQUID FLUORINE + LIQUID OXYGEN
Characteristic Exhaust Velocity
vs. Mixture Ratio
100% O_2
20% F_2
33% F_2
50% F_2
67% F_2
Mixture Ratio
2.0
3.0
4.0
5.0
6.0
Characteristic Exhaust Velocity, ft/sec
4000
5000
6000
7000

Figure 3

C-3440 EMW:lfl 9-10-53

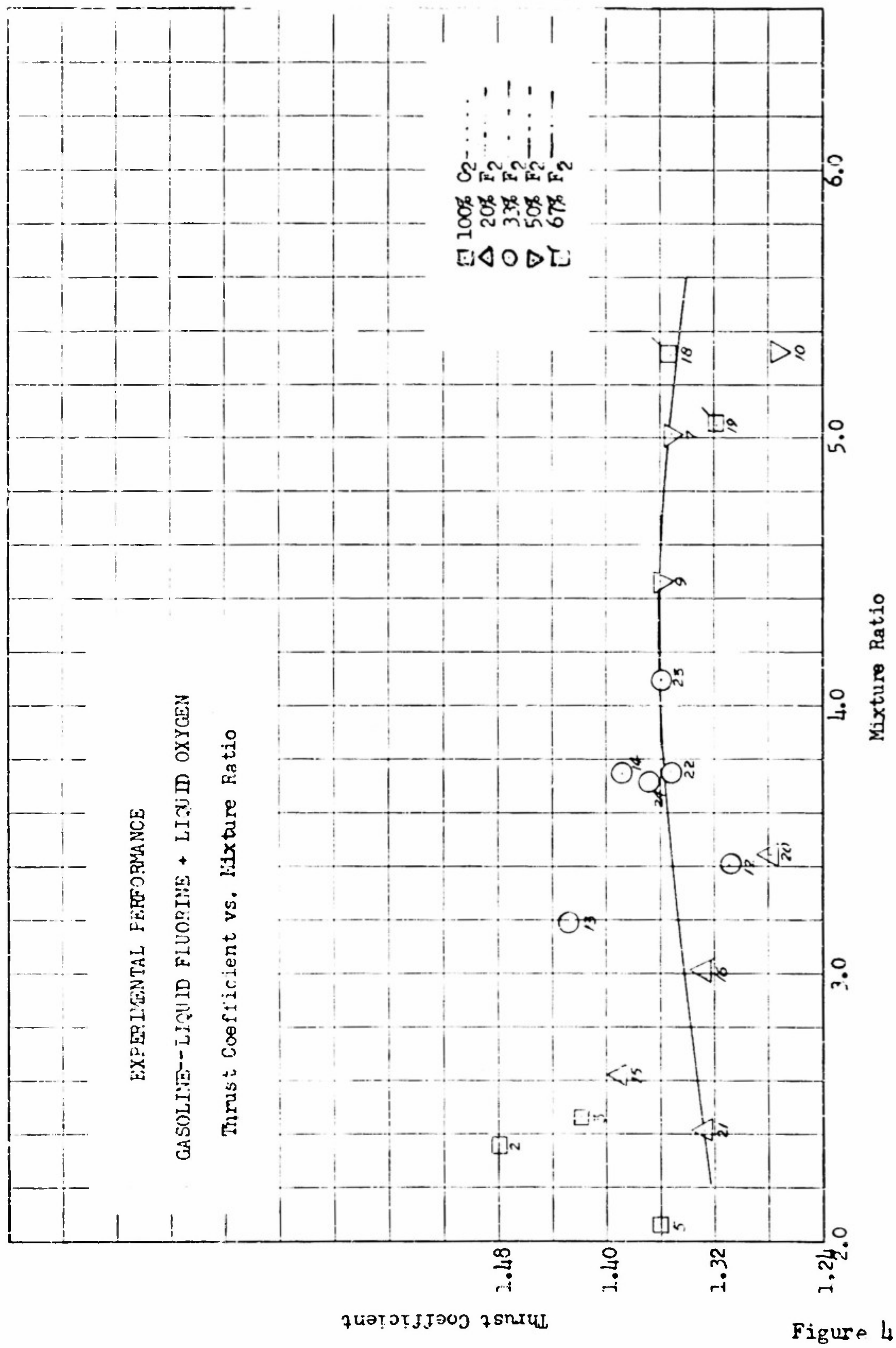
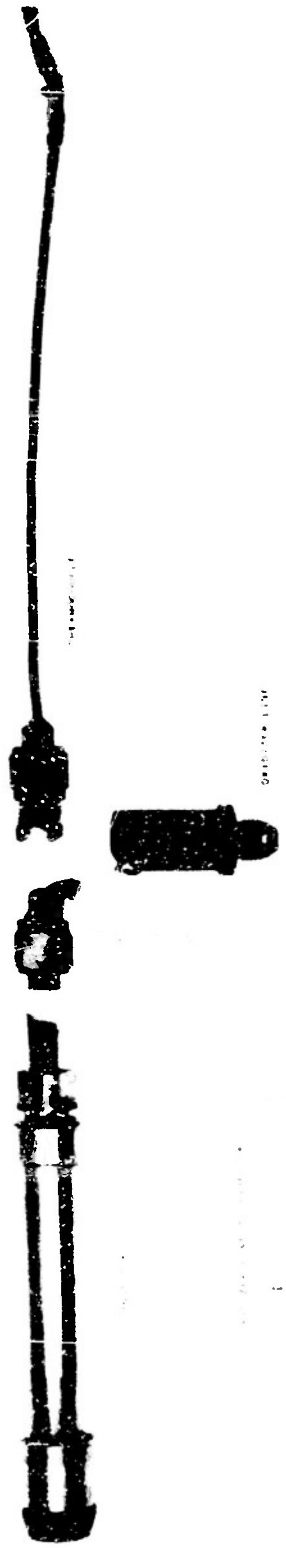


Figure 4



Damage to Injector System During Test D-45-LF-5

0653-610

Figure 5