N 62 14067

NASA TN D-1309

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TECHNICAL NOTE

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IGNITION OF A HYDROGEN-OXYGEN ROCKET ENGINE BY ADDITION OF FLUORINE TO THE OXIDANT

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Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON July 1962

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SUMMARY

The feasibility of using low concentrations of fluorine in the oxidant as a means of obtaining hypergolic ignition of a hydrogen-oxygen rocket system was investigated. A nominal 250-pound-thrust, 300-pound-per-square-inch-absolute-chamber-pressure, uncooled engine was operated at sea-level conditions; the fuel was cold gas and the oxidant was in liquid form initially. The ignition delay was determined as a function of the fluorine concentration in the oxidant, the injector type, and the percentage of fuel in the propellant mixture at ignition.

At least 35 percent fluorine in the oxidant was required to obtain satisfactory ignition (i.e., ignition within 1 sec after the propellants meet in the combustion chamber). A swirl-cup injector required a lower fluorine concentration than did a showerhead injector for obtaining reliable hypergolic ignition. When the swirl-cup injector was used, ignition probability was improved somewhat by increasing the hydrogen temperature.

INTRODUCTION

Extensive use of the high-energy propellant combination, hydrogen and oxygen, in upper-stage rocket propulsion systems is currently being planned. While this combination has a high specific impulse potential it does have the disadvantage of not being spontaneously ignitable and thus requires the development of a reliable ignition system.

Various methods of igniting hydrogen-oxygen rocket engines have been used: spark plugs, glow plugs, pyrotechnic ignitors, and the injection of a third chemical that is hypergolic with one of the propellants (refs. 1 to 4). All these methods introduce the problem of sequencing a third system, which is used only briefly during the engine operations. Also, some of these methods are not readily adaptable to multiple restarts, which are required in many space missions.

A simplified method of ignition would be to cause one of the propellants to be hypergolic with the other by chemical changes or additions. A feasible means of providing spontaneous ignition is the addition of elemental fluorine to the liquid oxygen. Fluorine and oxygen are completely miscible and do not separate even after months of storage (ref. 5). This method of ignition was investigated for the nonhypergolic propellant combination of oxygen and jet fuel (ref. 6); fluorine concentrations in the oxidant as low as 5 percent by weight made this propellant combination hypergolic (at sea level) and also increased the engine performance.

The investigation described herein was conducted to determine the minimum quantity of fluorine required in liquid oxygen to give hypergolic ignition with hydrogen. Ignition characteristics were evaluated by measuring the ignition delays, the propellant flow rates at ignition, and the injector and combustion chamber conditions in a nominal 250-pound-thrust, 300-pound-per-square-inch-absolute-chamber-pressure rocket engine. The two primary variables were the percentage of fluorine in the oxidant and the propellant mixture ratio.

APPARATUS AND PROCEDURE

Test Facility

The experiments were conducted in a test facility capable of supplying hydrogen and oxygen at liquid-nitrogen temperature and at flow rates sufficient for operations at a chamber pressure of 300 pounds per square inch absolute and thrusts up to 300 pounds. All tests were carried out at sea-level conditions.

The propellant flow systems are shown schematically in figure 1. The gaseous hydrogen was supplied from high-pressure gas cylinders. The flow rate was controlled by a pressure regulator. For most of the tests, the ambient-temperature gas was cooled by means of a liquid-nitrogen heat exchanger to a minimum of 140° R in order to provide more severe ignition conditions. Although this temperature is still about 100° R above liquid-hydrogen temperatures and, hence, is not as severe as when direct liquid injection is used, it does fall in the range of injection temperatures for a regeneratively cooled rocket engine.

The oxidant system consisted of a propellant tank, a flowmeter, and a fire valve; all were submerged in liquid nitrogen. The system had a connection to gaseous-fluorine and liquid-oxygen sources. The tank was suspended from a weighing device, which was used when oxidant mixtures were prepared from the fluorine and the oxygen.

Propellants

The three propellants - hydrogen, oxygen, and fluorine - used in this investigation were obtained from commercial sources. The hydrogen and the oxygen were drawn from large daily shipments, analysis of which indicated purity of 98 percent or more. The fluorine was condensed from commercial gas cylinders; the manufacturer's guarantee of 97 percent or higher purity was assumed to be correct.

Engines

The rocket engines used for this investigation consisted of an injector, a cylindrical combustion chamber, and a converging nozzle. The three pieces were externally bolted together and mounted vertically on the test stand. The first injector used was a showerhead design with a dished face that formed a converging spray (fig. 2). It was previously used in another ignition study (ref. 1). The injection pattern consisted of nine oxidant jets, in a three by three grid pattern, and 24 fuel jets, so positioned that each oxidant jet was surrounded by four fuel jets. The second injector used provided superior mixing characteristics. In this injector the propellants were injected tangentially into the bottom of a swirl cup located in the center of the injector face (fig. 2(a)).

The combustion chamber was an 8-inch length of 2-inch steel pipe. The uncooled chamber walls limited the duration of each test run to a few seconds. The nozzle was a copper ring with the inner surface contoured to the desired throat diameter (fig. 2(c)).

Instrumentation

The facility instrumentation and controls were located in a blastproof room adjacent to the test cell.

Pressures were measured with strain-gage pressure transducers and temperatures by copper-constantan thermocouples. Oxidant tank weight, fuel and oxidant pressures, and chamber pressures were recorded on self-balancing potentiometer strip charts. The chamber-pressure instrument had a low- and a high-pressure cutoff switch for test abort purposes. A multichannel, variable-speed, recording oscillograph provided a permanent record of the chamber pressure, flowmeter pressure differentials, and the injection temperatures and pressures. Figure 3 is a copy of one such test record. The ignition delay was determined as the time interval between the contacting of the fuel and oxidant in the combustion chamber and the sudden increase in chamber pressure that denoted combustion had occurred. Most tests were made with an oxidant lead and the time of contact was determined as the time of hydrogen injection, which was readily seen in the chamber-pressure record as a sudden small rise in pressure.

Data Accuracy

The accuracy of the pressure transducers was approximately ±1 percent and the frequency response of the static-pressure pickups was 1000 cycles per second or better; the differential pressure pickups were capable of following 500 cycles per second. The estimated maximum error in temperature measurements was ±3 percent. The accuracy of measuring the ignition delay was ±0.005 second with a recorder speed of 10 inches of record per second.

The accuracy of the oxidant tank weighing system was about ±1/4 pound. Since the oxidant mixtures were prepared by first condensing most of the contents of an approximately 6-pound-capacity fluorine cylinder and then adding the necessary amount of oxygen to obtain the desired fluorine-oxygen ratio, the greatest error occurred when the least amount of oxygen was added. For example, at 50 percent fluorine concentration the error was about $\pm 2\frac{1}{2}$ percent.

Test Procedure

The use of fluorine required that the oxidant system be carefully cleaned, preconditioned with a small amount of fluorine, and pressure checked before the introduction of the fluorine. Prior to loading the fluorine, the oxidant supply tank was submerged in liquid nitrogen and the weighing apparatus calibrated. The gaseous fluorine was then admitted into the system, and it condensed in the oxidant tank. The weight of the condensed fluorine was determined, and enough liquid oxygen was introduced to obtain the desired oxygen-fluorine ratio. The two oxidants were mixed by blowing helium through the system.

The hydrogen gas cylinders were connected to the fuel system, and the system was pressurized, evacuated, and then repressurized with the hydrogen. The pressure regulators in both propellant systems were then set to provide the desired flow rates.

Some tests were conducted with gaseous hydrogen that had passed through flow lines and a cooling coil submerged in liquid nitrogen, which provided a hydrogen temperature of about 140° R. Neither the injector nor its feed manifold, however, were precooled; therefore, the initial ignition temperatures of the fuel (and oxidant) were considerably above this value, as can be seen in figure 3. Since data for each of the tests were recorded in the first second of flow at the ignition point, most of the injection temperatures in tables I and II(a) are still higher than that of liquid nitrogen.

Data from tests in which the hydrogen was precooled to liquid-nitrogen temperatures are denoted as "cold" test data. Data from tests in which the hydrogen was kept at ambient temperatures are denoted as "warm" test data.

RESULTS AND DISCUSSION

The results of the test program using a showerhead injector with cold hydrogen and various fluorine-oxygen combinations are presented in table I. The ignition delays using this injector are shown in figure 4 as a function of the fluorine concentration and the percentage of fuel in the total propellant flow. The data points represent ignition delays of greater than and less than 1 second.

Swirl-cup injector test data are presented in table II. The data of table II(a) were obtained with cold hydrogen, and the data of table II(b), with warm hydrogen gas. Figures 5(a) and (b) show, respectively, the ignition delays greater and less than 1 second, for the cold and warm hydrogen gas.

The principal objective of this investigation was the determination of ignition-delay characteristics of various fluorine-oxygen mixtures with hydrogen. With fluorine concentrations of greater than 50 to 60 percent, rapid and repeatable ignition was possible with either the showerhead or the swirl-cup injector. When the amount of fluorine in the oxidant was below 15 percent, the results were fairly consistent: no ignition. In the fluorine percentage range between these two points, it was impossible to obtain consistent and repeatable data. In this region, for identical fluorine concentrations and at a given percentage of fuel, the ignition delay varied from test to test. The reason (or reasons) for this variation were not apparent; because of this, no definite relation could be established between the ignition delay and the percentage of fuel at a given fluorine concentration.

In order to establish overall trends in ignition delay, the experimental data was analyzed on the basis of being either "satisfactory" or "unsatisfactory," which are defined as the occurrence of ignition in less than or more than 1 second, respectively. This analysis suggested the trends discussed in the following sections.

Effect of Fluorine Concentration on Ignition Delay

As might be expected, as the percentage of fluorine in the oxidant was reduced, igniting the engine within a given period of time became more difficult. As the fluorine concentration was gradually decreased, however, the ignition delay was expected to increase gradually; instead, the change from high to low ignition reliability was very abrupt. For example, with the showerhead injector all mixtures ignited within 1 second at 56 percent fluorine concentration; less than half the mixtures ignited within 1 second at 49 percent fluorine; and none of the mixtures ignited within 1 second at fluorine concentrations less than 45 percent (fig. 4). The reduction in ignition reliability is not as abrupt for the swirl-cup injector under identical conditions (fig. 5(a)) and is even more gradual when warm hydrogen is used with the swirl-cup injector (fig. 5(b)).

Effect of Engine Injector Design on Ignition Delay

Two injector designs were tested in this program: a showerhead type and a swirl-cup type. A comparison of their probability to obtain ignition within 1 second for any given oxygen-fluorine mixture is shown in figure 6. This probability is represented as the percentage of total tests in which ignition delays of less than 1 second were observed. The showerhead injector had a 100 percent probability of ignition to about 55 percent fluorine; then, as the fluorine concentration was decreased to 40 percent, the probability of ignition went to zero. The swirl-cup injector had the ability to ignite within 1 second down to about 35 percent fluorine in the oxidant; ignition probability then decreased with a decrease in fluorine concentration.

The swirl-cup injector design promoted more rapid and complete mixing of the propellants and may also have promoted increased atomization and vaporization. Rapid mixing, atomization, and vaporization with the swirl-cup injector is evidenced by the high steady-state combustion performance observed with this injector in previous investigations (ref. 7). It is probable also that this design provided higher fluorine concentrations in close proximity to the hydrogen; hence, it promoted rapid ignition.

Effect of Propellant Temperature on Ignition Delay

Many papers on ignition (refs. 8 to 10) state that for various propellant combinations the ignition delay is adversely affected by decreasing propellant injection temperatures. In order to determine the effect of hydrogen temperature, one series of tests was conducted with the swirl-cup injector using ambient-temperature (480° to 500° R) hydrogen gas and compared with similar tests using cold gas. The data for this test series are given in table II(b), and the ignition-delay data are plotted as a function of the fluorine concentration and percentage of fuel in figure 5. Comparison of figures 5(a) (cold hydrogen) and 5(b) (warm hydrogen) show that the increased hydrogen temperatures increased the probability of ignition, especially at the low fluorine concentrations. This technique of warming either or both the propellants decreases the ignition delay, but there are obvious limitations to its use in practical applications.

CONCLUSIONS

This investigation of the hypergolic ignition characteristics of a rocket engine system employing gaseous-hydrogen and liquid-oxygen-fluorine oxidant mixtures at a combustion chamber pressure of 300 pounds per square inch resulted in the following conclusions:

1. Hydrogen gas fuel requires three to six times as much fluorine in the oxidant to obtain hypergolic ignition as does JP-4 fuel (NACA RM E53J20).

2. The injector design is an important factor in obtaining hypergolic ignition with the minimum quantity of fluorine in the oxidant.

3. To a lesser degree the hydrogen temperature and its percentage of the total propellant flow affect the probability of hypergolic ignition.

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National Aeronautics and Space Administration
Cleveland, Ohio, March 2, 1962

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TABLE I. - IGNITION DELAY DATA FROM SHOWERHEAD INJECTOR WITH COLD HYDROGEN AND FLUORINE-OXYGEN OXIDANT MIXTURES

Fluorine in oxidant, percent	Oxidant flow rate, lb/sec	Oxidant injection temperature at ignition, $^{\circ}R$	Hydrogen injection temperature at ignition, $^{\circ}R$	Hydrogen flow rate, lb/sec	Total flow rate, lb/sec	Fuel in total flow, percent	Ignition delay, sec
56.5	0.236	420	205	0.079	0.314	25.0	0.32
	.223	460	250	.075	.298	25.1	.05
	.235	465	250	.076	.311	24.5	.05
	.245	460	255	.071	.315	22.4	.05
	.249	---	---	.069	.318	21.8	----
48.8	0.306	455	260	0.068	0.374	18.3	0.05
	.309	440	235	.066	.375	17.5	.12
	.341	430	225	.061	.402	15.2	.19
	.359	465	255	.051	.411	12.5	.05
	.399	448	238	.050	.449	11.2	.12
	.408	450	240	.046	.454	10.0	.11
	.079	435	233	.072	.151	47.4	.15
37.9	0.365	~175	~175	0.096	0.461	20.8	1.40+
	.408			.095	.503	18.8	
	.433			.095	.528	18.0	
	.433			.095	.528	18.0	
	.447			.083	.530	15.7	
	.439			.083	.522	15.9	
	.454			.083	.537	15.4	
	.421			.092	.513	17.9	
	.418			.092	.510	18.0	
	.429			.092	.521	17.7	
	.412			.092	.504	18.3	
	.434			.083	.517	16.1	
	.452			.083	.535	15.5	
	.444			.083	.527	15.8	
	.452			.083	.535	15.5	
	.489			.066	.555	11.9	
	.478			.066	.544	12.1	
	.492			.059	.551	10.7	
	.395			.084	.479	17.6	
	.414			.083	.497	16.7	
	.392			.096	.488	19.7	
	.367			.097	.464	20.9	
	.341			.097	.438	22.1	
	.343			.096	.439	21.9	
	.418			.083	.501	16.6	
45.2	0.358	~175	~175	0.096	0.454	21.1	1.40+
	.390			.095	.485	19.6	
	.388			.092	.480	19.2	
	.353			.098	.451	21.7	
	.442			.097	.539	18.0	
	.394			.096	.490	19.6	
	.400			.096	.496	19.3	
	.444			.065	.509	12.8	
	.390			.099	.489	20.2	
	.396			.094	.490	19.2	
	.347			.096	.443	21.7	
	.426			.082	.508	16.1	
48.8	~0.30	~175	~175	~0.092	0.392	23.5	1.40+
	~.25			~.092	.342	27	1.40+
	~.25			~.083	.333	25	.94
	~.25			~.088	.338	26	1.40+
	~.25			~.083	.333	25	
	~.23			~.071	.301	23.5	
	~.23			~.071	.301	23.5	
	~.23			~.066	.396	16.5	
	~.23			~.066	.396	16.5	
	~.25			~.071	.321	22	
	~.22			~.065	.285	23	
	~.22			~.065	.285	23	
	~.20			~.065	.265	24.5	
	~.21			~.082	.292	28	
	~.21			~.055	.265	21	
	~.20			~.055	.255	21.5	
	~.20			~.066	.266	25	
	~.20			~.055	.255	21.5	
	~.20			~.080	.280	28.5	
	~.12			~.056	.176	32	
	~.12			~.046	.166	28	
	~.22			~.046	.266	17	

TABLE II. - IGNITION DELAY DATA FROM SWIRL-CUP INJECTOR WITH HYDROGEN AND FLUORINE-OXYGEN OXIDANT MIXTURES

(a) Cold mixtures

Fluorine in oxidant, percent	Oxidant flow rate, lb/sec	Oxidant injection temperature at ignition, ^{o}R	Hydrogen injection temperature at ignition, ^{o}R	Hydrogen flow rate, lb/sec	Total flow rate, lb/sec	Fuel in total flow, percent	Ignition delay, sec
49.4	0.37	380	220	0.088	0.458	19.0	0.30
	.39	395	190	.086	.476	18.0	.37
	.33	340	190	.073	.403	18.0	.43
	.35	390	190	.066	.416	16.0	.52
	.28	385	220	.059	.339	18.0	.38
	.34	180	175	.055	.395	14.0	.93
44.8	0.40	400	205	0.082	0.482	16.0	0.25
	.35	410	175	.077	.427	21.0	.32
	.37	440	180	.070	.440	16.0	.37
	.38	435	215	.062	.442	14.0	.25
	.35	300	220	.061	.411	14.0	.18
	.33	380	198	.056	.386	15.0	.37
	.32	410	190	.062	.382	16.0	.38
	.33	400	170	.062	.392	15.5	.48
36.9	0.30	440	225	0.065	0.365	18.0	0.17
	.33	215	190	.056	.386	15.0	.61
	.34	330	180	.056	.396	14.0	.46
	.32	285	170	.069	.389	17.5	.51
	.30	220	165	.069	.369	19.0	.62
	.30	190	180	.069	.369	19.0	.56
	.37	330	175	.085	.455	19.0	.50
	.29	220	160	.084	.374	22.5	.58
	.29	190	168	.082	.372	23.0	.70
	.31	260	225	.054	.364	15.0	.25
	.39	410	203	.054	.444	12.5	.32
	.34	180	170	.053	.393	13.5	.92
34.4	0.38	380	170	0.074	0.454	16.5	0.58
	.33	180	170	.068	.398	17.5	.80
	.37	210	170	.067	.437	15.0	.67
	.39	310	180	.063	.453	14.0	.48
	.34	180	175	.059	.399	15.0	.73
34.3	0.37	170	175	0.050	0.420	12.0	1.20+
	.34	170	175	.049	.389	13.0	1.04
	.39	390	195	.050	.440	11.5	.39
	.39	400	200	.056	.446	13.0	.40
	.32	180	170	.056	.376	14.5	.98
27.5	0.38	460	180	0.068	0.448	15.5	0.38
	.37	420	170	.084	.454	20.0	.64
	.37	385	195	.062	.432	14.5	.32
	.32	175	165	.064	.384	16.5	1.30+
	~.33	180	165	~.062	.392	15.7	1.30+
	~.33	175	170	~.062	.392	15.7	1.30+
	.37	180	170	.056	.426	13.5	1.30+
	.34	175	175	.062	.402	15.5	1.12
	.33	500	200	.061	.391	16.0	.32
	.32	370	200	.060	.380	16.0	.28
	.33	180	180	.058	.388	15.0	.62
23.5	~0.29	415	203	~0.087	0.377	23	0.30
	~.29	~175	~175	~.087	.377	23	1.20+
	~.28			~.087	.367	23.5	1.20+
	~.285			~.087	.372	23	1.20+
	~.31			~.081	.391	20.5	1.20+
	~.31			~.081	.391	20.5	1.20+
	~.32			~.068	.388	17.5	1.10+
	~.32			~.068	.388	17.5	1.20+
	~.33			~.054	.384	14	1.20+
	~.34			~.054	.394	14	1.20+
	~.35			~.046	.396	11.5	1.20+
	.34			.049	.389	12.5	1.20+
	~.35			~.046	.391	11.5	1.20+
	~.32			~.046	.366	12.5	1.20+
	~.32			~.046	.366	12.5	1.10+

TABLE II. - Continued. IGNITION DELAY DATA FROM SWIRL-CUP INJECTOR WITH HYDROGEN AND FLUORINE-OXYGEN OXIDANT MIXTURES

(a) Concluded. Cold mixtures

Fluorine in oxidant, percent	Oxidant flow rate, lb/sec	Oxidant injection temperature at ignition, °R	Hydrogen injection temperature at ignition, °R	Hydrogen flow rate, lb/sec	Total flow rate, lb/sec	Fuel in total flow, percent	Ignition delay, sec
23.5	~0.29	~175	~175	~0.047	0.337	14	1.30+
	~.29			~.047	.337	14	1.20+
	.33			.095	.425	22.5	1.20+
	~.29			~.095	.385	25	1.20+
	~.33			~.095	.425	22.5	1.20+
	~.34			~.095	.335	22	1.20+
	.37			.094	.464	20	1.10+
	~.36			~.081	.441	18	1.20+
	~.28			~.081	.361	23	1.10+
	~.28			~.081	.361	23	1.20+
	~.27			~.042	.312	13.5	1.20+
	.29			.044	.334	13.5	1.10+
100	0.26	210	168	0.075	0.335	22.5	0.65
	.27	240	171	.076	.346	21.5	.57
	.30	330	186	.056	.356	16.0	.45
	.31	315	182	.058	.368	16.0	.48
	.32	360	193	.046	.366	12.5	.40
	.33	360	193	.045	.375	12.0	.40
31.4	0.25	440	233	0.084	0.334	25.5	0.15
	.37	240	171	.084	.454	18.0	.57
	.38	240	170	.084	.464	18.0	.56
	.30	235	170	.045	.345	13.0	.58
	.33	238	171	.046	.376	12.0	.57
	.33	310	183	.044	.374	11.5	.48
	.37	390	200	.063	.433	16.0	.35
	.37	380	198	.062	.432	14.5	.37
	.37	350	191	.062	.432	14.5	.42
	.34	225	170	.062	.402	15.5	.60
	.31	210	168	.062	.372	16.5	.64
	.31	215	168	.062	.372	16.5	.62
	.36	440	228	.062	.423	15.0	.18
24.9	0.27	275	175	0.106	0.376	28.0	0.53
	.31	330	185	.105	.415	26.0	.46
	.30	440	232	.106	.406	26.0	.16
	.34	430	220	.108	.448	28.0	.22
	.30	425	213	.088	.388	22.0	.26
	.35	390	200	.089	.439	20.5	.35
	.31	435	224	.076	.386	20.5	.20
	.29	405	202	.072	.362	19.5	.33
	.38	445	238	.065	.445	14.0	.12
	.34	435	224	.063	.403	16.0	.20
	.32	430	216	.066	.386	17.5	.24
	.29	420	209	.065	.355	18.5	.28
18.9	~0.28	300	180	~0.084	0.364	23	0.50
	~.28	~175	~175	~.084	.364	23	1.20+
	~.28			~.084	.364	23	
	.25			.086	.336	25.5	
	~.31			~.084	.394	21	
	~.33			~.084	.414	20	
	.33			.085	.415	21.0	
	~.35			~.070	.420	16.5	
	~.35			~.056	.406	14	
	.33			.046	.376	12.5	
	~.33			~.042	.372	11.5	
	~.31			~.042	.352	12	
	~.28			~.042	.322	13	
	.25			.045	.295	15.5	
	~.25			~.056	.306	18	
	~.25			~.070	.320	22	
	~.25			~.085	.335	25	
	.25	185	168	.110	.360	30.5	.72
	.25	175	172	.110	.360	30.5	1.30+
	~.25	175	175	~.110	.360	30	1.20+

TABLE II. - Continued. IGNITION DELAY DATA FROM SWIRL-CUP INJECTOR

WITH HYDROGEN AND FLUORINE-OXYGEN OXIDANT MIXTURES

(b) Warm mixtures

Fluorine in oxidant, percent	Oxidant flow rate, lb/sec	Oxidant injection temperature at ignition, °R	Hydrogen injection temperature at ignition, °R	Hydrogen flow rate, lb/sec	Total flow rate lb/sec	Fuel in total flow, percent	Ignition delay, sec
28.2	0.345	200	475	0.061	0.406	15.0	0.67
	.35	260	480	.061	.411	14.5	.55
	.30	380	492	.061	.361	17.0	.38
	.29	170	470	.060	.350	17.0	1.12
	.33	185	465	.074	.404	18.5	.72
	.35	200	465	.074	.424	18.0	.67
	.28	185	470	.072	.352	21.0	.75
	.34	170	---	.056	.396	14.0	1.03
	.33	195	465	.057	.387	15.5	.68
	~.34	175	470	~.056	.396	14	.88
	.32	440	490	.050	.370	13.5	.10
	.32	220	473	.049	.369	13.0	.60
	~.36	365	481	~.048	.408	11.5	.40
24.0	0.33	445	489	0.075	0.405	18.5	0.10
	.26	415	474	.075	.335	22.5	.29
	.27	195	488	.075	.345	21.5	.67
	.28	180	475	.062	.342	18.0	.80
	.29	182	---	.060	.350	17.0	.77
	.33	220	---	.060	.390	15.5	.60
	.29	288	---	.060	.350	16.5	.51
	.34	395	480	.057	.397	14.0	.34
	.32	212	---	.055	.375	14.5	.63
	.30	175	491	.055	.355	16.0	1.30
	~.36	170	493	~.048	.408	11.5	1.02
	.35	175	490	.049	.399	12.5	1.40+
	.34	175	491	.048	.388	12.5	1.50+
	.35	170	---	.047	.397	12.5	1.08
27.0	0.28	170	476	0.077	0.357	21.0	0.98
	.29	178	---	.077	.367	20.5	.84
	.32	190	480	.078	.398	19.5	.68
	.34	175	491	.047	.387	12.0	1.20+
	.34	---	492	.047	.387	12.0	1.20+
	~.34	---	---	~.056	.396	14	1.20+
	.33	280	470	.064	.394	16.0	.52
	.34	170	495	.065	.395	16.5	1.16
	.32	---	500	.063	.383	16.5	1.01
	.32	178	483	.059	.379	16.0	.86
	.34	170	497	.059	.399	14.5	.97
	.32	188	475	.055	.385	14.0	.71
	.30	170	498	.055	.355	15.0	1.16
	.30	305	472	.051	.351	14.5	.49
	.35	180	487	.047	.397	12.0	.80
	~.36	177	489	~.048	.408	11.5	.85
	.34	160	470	.048	.388	12.5	1.40+
	.35	300	475	.047	.397	12.0	.38
19.2	0.28	420	482	0.073	0.353	20.5	0.27
	.34	190	473	.074	.414	18.5	.69
	~.32	175	471	.068	.388	17.5	1.20+
	.34	---	---	.063	.403	15.5	1.20+
	.34	---	---	.073	.413	17.5	1.20+
	~.31	---	473	~.073	.383	19	1.20+
	.35	183	482	.074	.424	17.5	.77
	.33	193	481	.072	.402	18.0	.70
	.35	200	480	.077	.427	18.0	.67
	.32	170	476	.081	.401	20.5	1.02
	~.30	175	477	~.073	.373	19.5	1.30+
	.31	---	476	.073	.383	19.5	1.20
	.31	---	475	.074	.384	19.0	1.20+
	.32	---	---	.072	.392	19.0	1.30+
	.33	---	---	.088	.418	21.0	1.20+
	~.30	170	470	~.088	.388	22.5	1.28
	.33	195	483	.074	.404	18.5	.70
	.32	175	468	.072	.392	18.0	1.40+
	.30	178	480	.073	.373	19.5	.83
	.33	172	475	.065	.395	16.5	1.00
	.23	170	471	.054	.284	20.5	1.35
	.31	365	495	.058	.368	15.5	.40
	.31	365	495	.048	.358	13.5	.40
	.35	170	470	.046	.417	12.0	1.30+
	.36	---	---	.055	.429	13.0	1.20+
	.36	380	498	.064	.424	15.0	.37
	.37	172	472	.073	.443	16.5	.93

TABLE II. - Continued. IGNITION DELAY DATA FROM SWIRL-CUP INJECTOR WITH HYDROGEN AND FLUORINE-OXYGEN OXIDANT MIXTURES

(b) Continued. Warm mixtures

Fluorine in oxidant, percent	Oxidant flow rate, lb/sec	Oxidant injection temperature at ignition, $^{\circ}R$	Hydrogen injection temperature at ignition, $^{\circ}R$	Hydrogen flow rate, lb/sec	Total flow rate, lb/sec	Fuel in total flow, percent	Ignition delay, sec
19.6	0.27	178	473	0.077	0.347	22.5	0.82
	.30	345	488	.075	.375	20.5	.43
	.29	182	484	.074	.364	21.0	.76
	.33	173	477	.072	.402	18.0	.92
	.33	180	485	.072	.402	18.0	.78
	.31	~170	468	.062	.372	16.5	1.30+
	.32		---	.067	.387	17.5	1.30+
	.28		470	.071	.351	19.5	1.28
	.32		477	.075	.395	19.0	.98
	.33		476	.072	.402	18.0	.94
	.36	205	487	.071	.431	16.5	.65
	.34	378	493	.063	.403	15.5	.38
	.35	440	502	.062	.412	14.5	.10
	.32	~170	~470	.054	.374	14.5	1.30+
	~.33			~.061	.391	15.5	1.30+
	.32			.058	.378	15.5	1.40+
	~.35			~.065	.415	15.5	1.30+
	~.35			~.067	.417	16	1.30+
	.34			.072	.412	17.5	1.30+
	.31	210	483	.072	.382	19.0	.64
	.33	290	490	.072	.402	18.0	.50
15.2	0.26	195	487	0.078	0.338	23.5	0.69
	.24	180	477	.071	.311	23.5	.78
	.25	200	481	.067	.317	21.9	.67
	.28	183	472	.067	.347	19.5	.76
	.27	212	481	.067	.337	20.0	.62
	.30	198	485	.066	.366	18.5	.67
	.29	405	498	.067	.357	19.5	.33
	~.31	~170	~465	~.067	.377	17.5	1.30+
	~.31			~.071	.381	18.5	1.30+
	~.31			~.075	.385	19.5	1.30+
	~.31			~.080	.390	20.5	1.30+
	.34			.083	.423	19.5	1.20+
	~.30			~.083	.383	21.5	1.30+
	~.29			~.083	.373	22	1.25
	~.29			~.083	.373	22	1.23
	.31			.082	.392	21.0	1.30+
	.28			.083	.363	23.0	1.18
	~.26			~.074	.334	22	1.30+
	~.26			~.074	.334	22	1.30+
	~.28			~.075	.355	21	1.30+
	~.28			~.075	.355	21	1.30+
	.34	220	477	.077	.417	18.5	.62
	~.29	~170	~465	~.077	.367	21	1.30+
	~.29			~.083	.373	22	1.30+
	~.29			~.072	.362	20	1.30+
	~.33			~.077	.407	19	1.30+
	.31			.068	.378	18.0	1.20+
	~.28			~.068	.348	19.5	1.30+
	~.28			~.072	.352	20.5	1.30+

TABLE II. - Concluded. IGNITION DELAY DATA FROM SWIRL-CUP INJECTOR

WITH HYDROGEN AND FLUORINE-OXYGEN OXIDANT MIXTURES

(b) Concluded. Warm mixtures

Fluorine in oxidant, percent	Oxidant flow rate, lb/sec	Oxidant injection temperature at ignition, ^{o}R	Hydrogen injection temperature at ignition, ^{o}R	Hydrogen flow rate, lb/sec	Total flow rate, lb/sec	Fuel in total flow, percent	Ignition delay, sec
16.1	~0.29	~170	~475	~0.073	0.363	20	1.30+
	~.29			~.073	.363	20	1.37
	.29			.073	.363	20.5	1.20
	.28			.074	.354	21.0	1.07
	.30			.073	.373	20.0	1.30+
	~.26			~.073	.333	22	
	~.26			~.073	.333	22	
	~.29			~.073	.363	20	
	~.29			~.073	.363	20	
	~.31			~.073	.383	19	
	~.26			~.073	.333	22	
	.33			.048	.378	11.5	
	~.26			~.060	.320	19	1.38
	~.26			~.060	.320	19	1.30+
	~.28			~.060	.340	17.5	
	~.31			~.060	.370	16	
	~.34			~.060	.400	15	
	~.27			~.065	.335	19.5	
	~.29			~.065	.355	18	
	~.31			~.065	.375	17.5	
	.36	175	481	.065	.425	15.0	.85
	.35	170	475	.065	.415	15.5	1.30+
	~.34	---	---	~.065	.405	16	1.25
	.36	180	487	.065	.425	15.5	.78
	.32	170	475	.067	.387	17.5	1.40+
	.35			.067	.417	16.0	1.30+
	~.31			~.073	.383	19	
	~.34			~.073	.413	17.5	
	~.36			~.073	.433	17	
	~.38			~.073	.453	16	
	.39	180	477	.067	.457	14.5	.78
	~0.38	170	475	~0.070	0.450	15.5	1.30+
	.36			.067	.427	15.5	
	~.38			~.064	.444	14.5	
	~.38			~.061	.441	14	
	~.38			~.053	.433	12	
	~.38			~.084	.464	18	
	~.36			~.084	.444	19	
	.35	355	505	.084	.434	19.0	.38
	.36	170	475	.084	.444	19.0	1.20+
	.36			.084	.444	19.0	1.20+
	~.31			~.084	.394	21	1.30+
	.33	173	481	.084	.414	20.5	.96
	.32	170	477	.084	.404	20.0	1.10+
	.34	208	490	.082	.422	20.0	.63

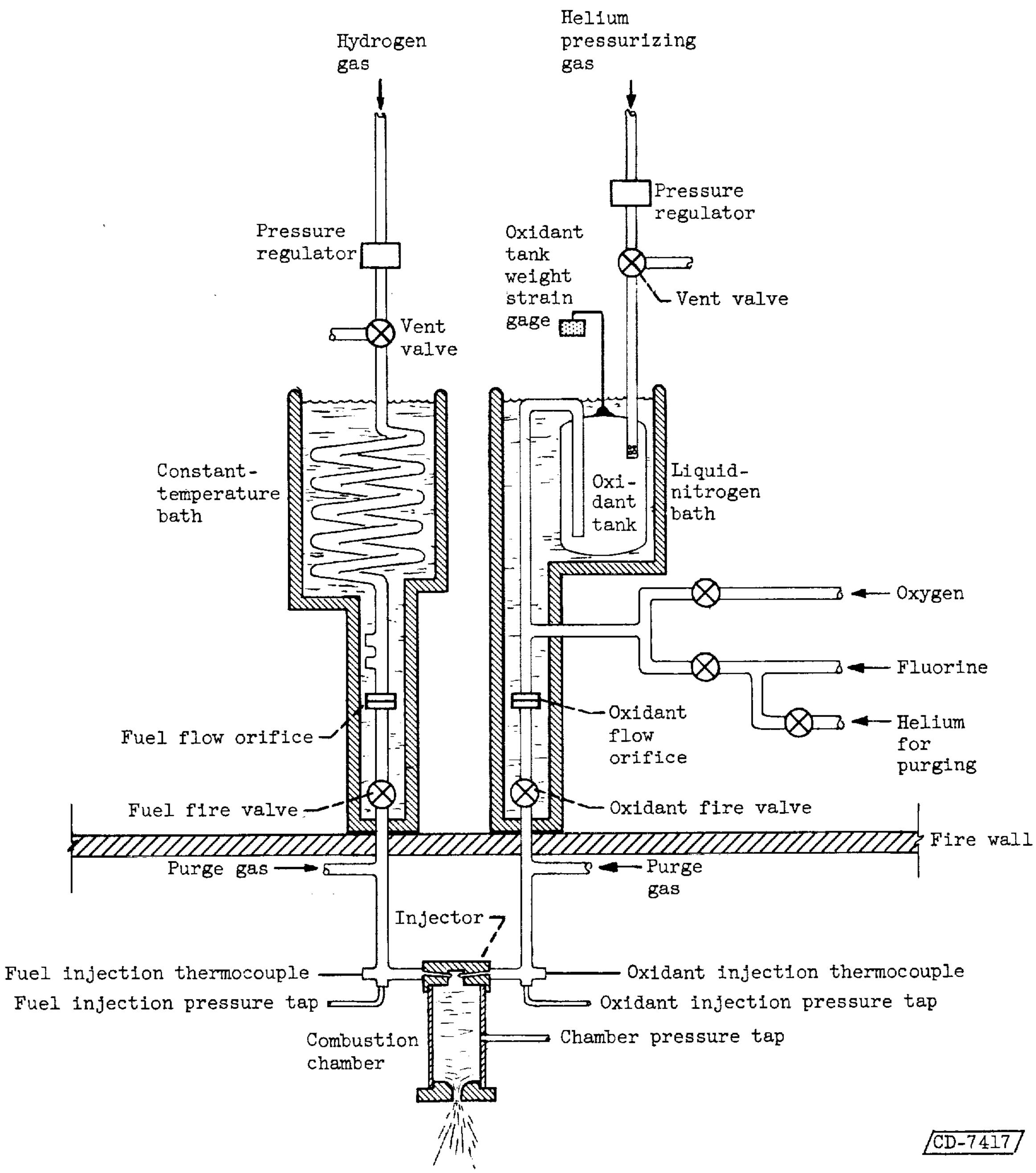
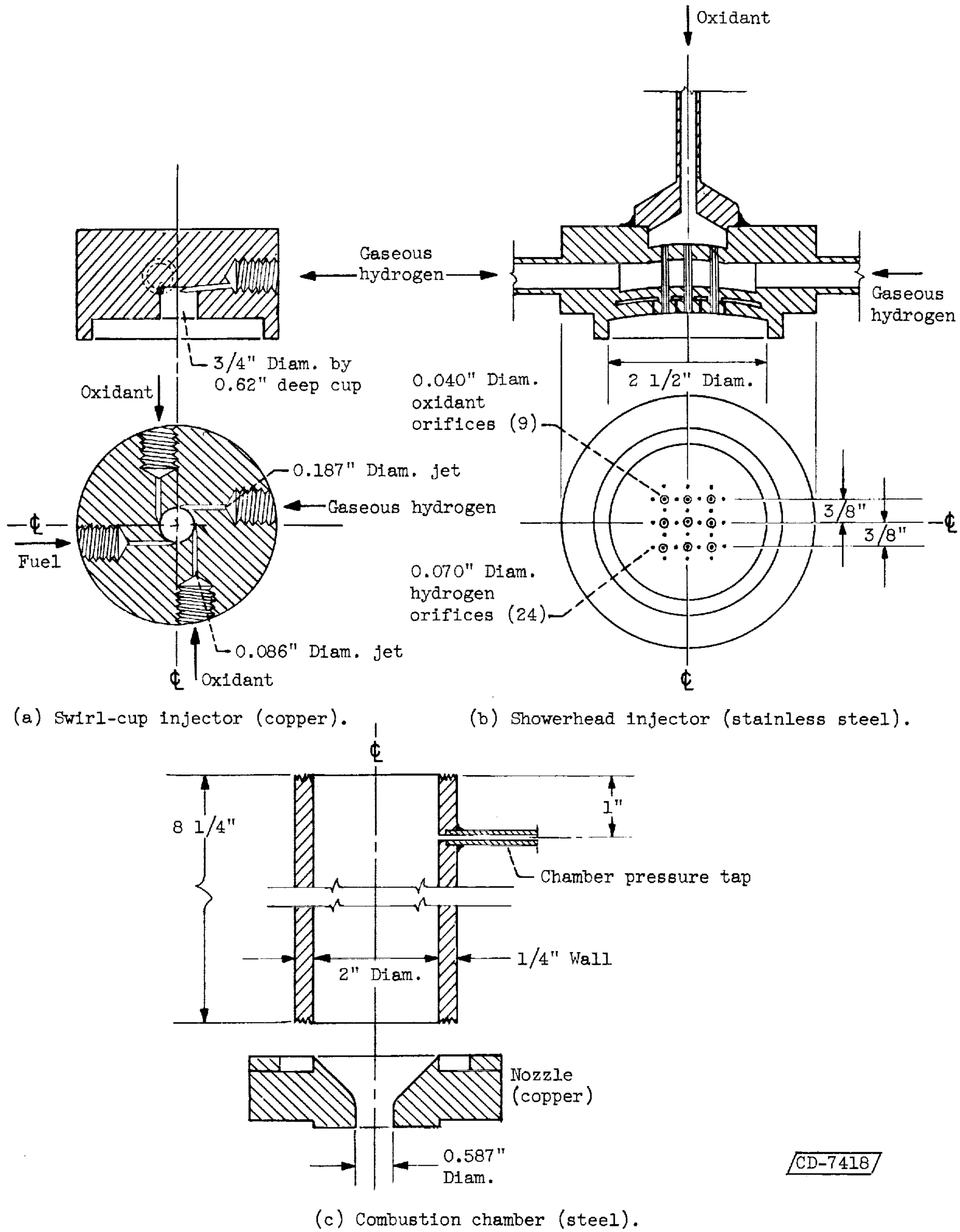


Figure 1. - Gaseous hydrogen - liquid oxidant propellant flow systems.



(a) Swirl-cup injector (copper). (b) Showerhead injector (stainless steel).

(c) Combustion chamber (steel).

Figure 2. - Nominal-200-pound-thrust chamber assembly.

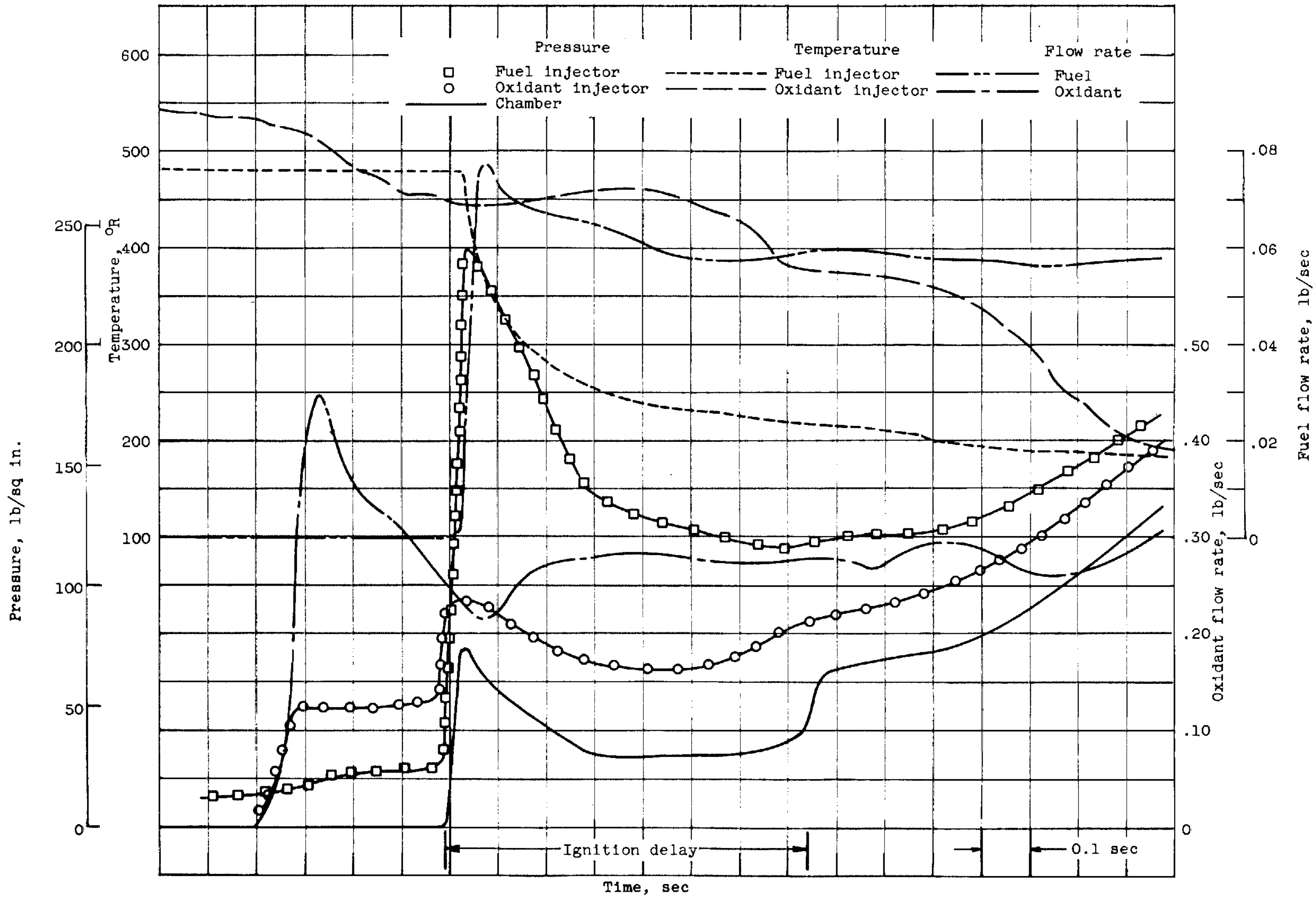


Figure 3. - Typical transient ignition data. Oxidant contained 49.4 percent fluorine.

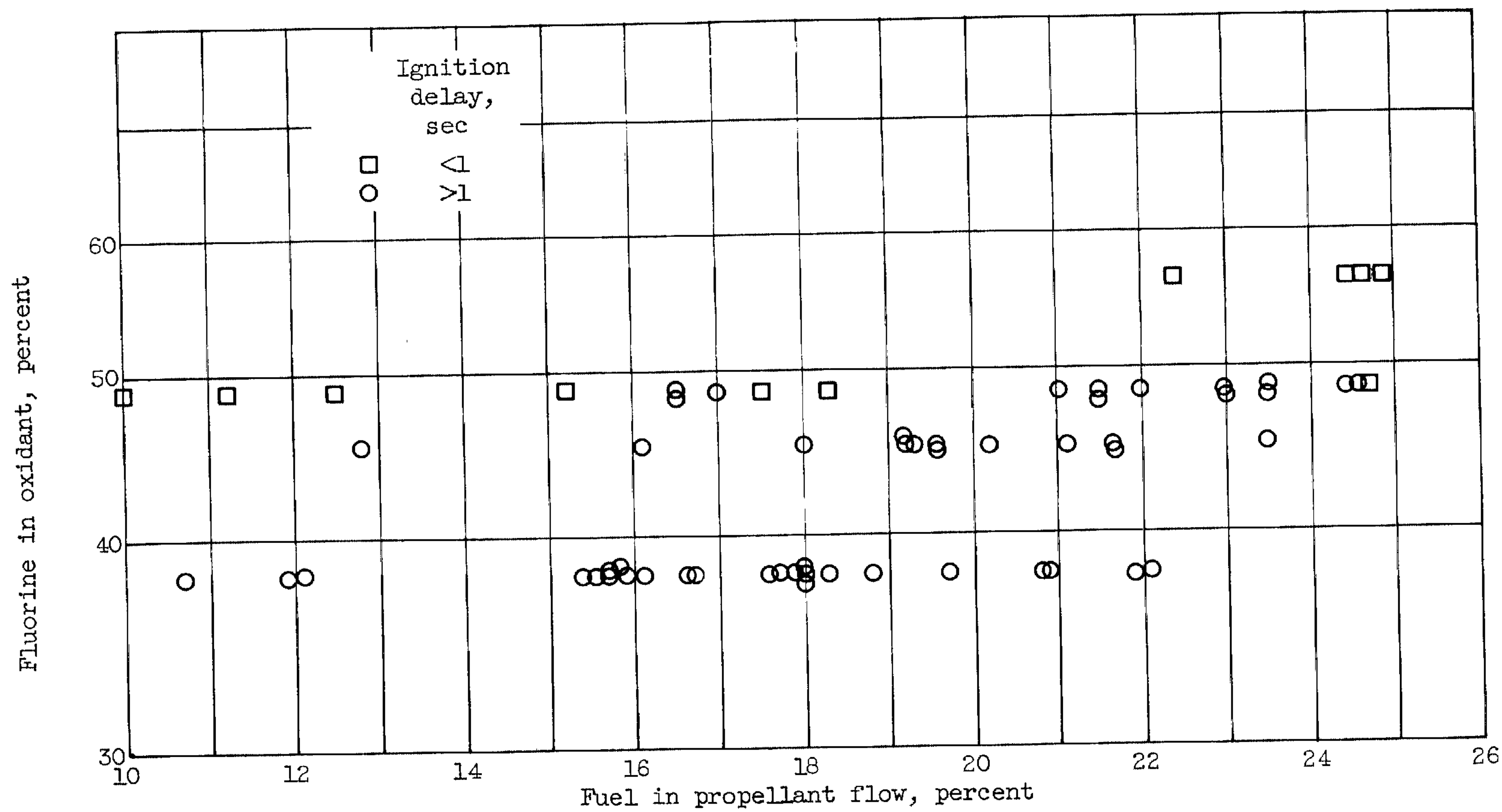
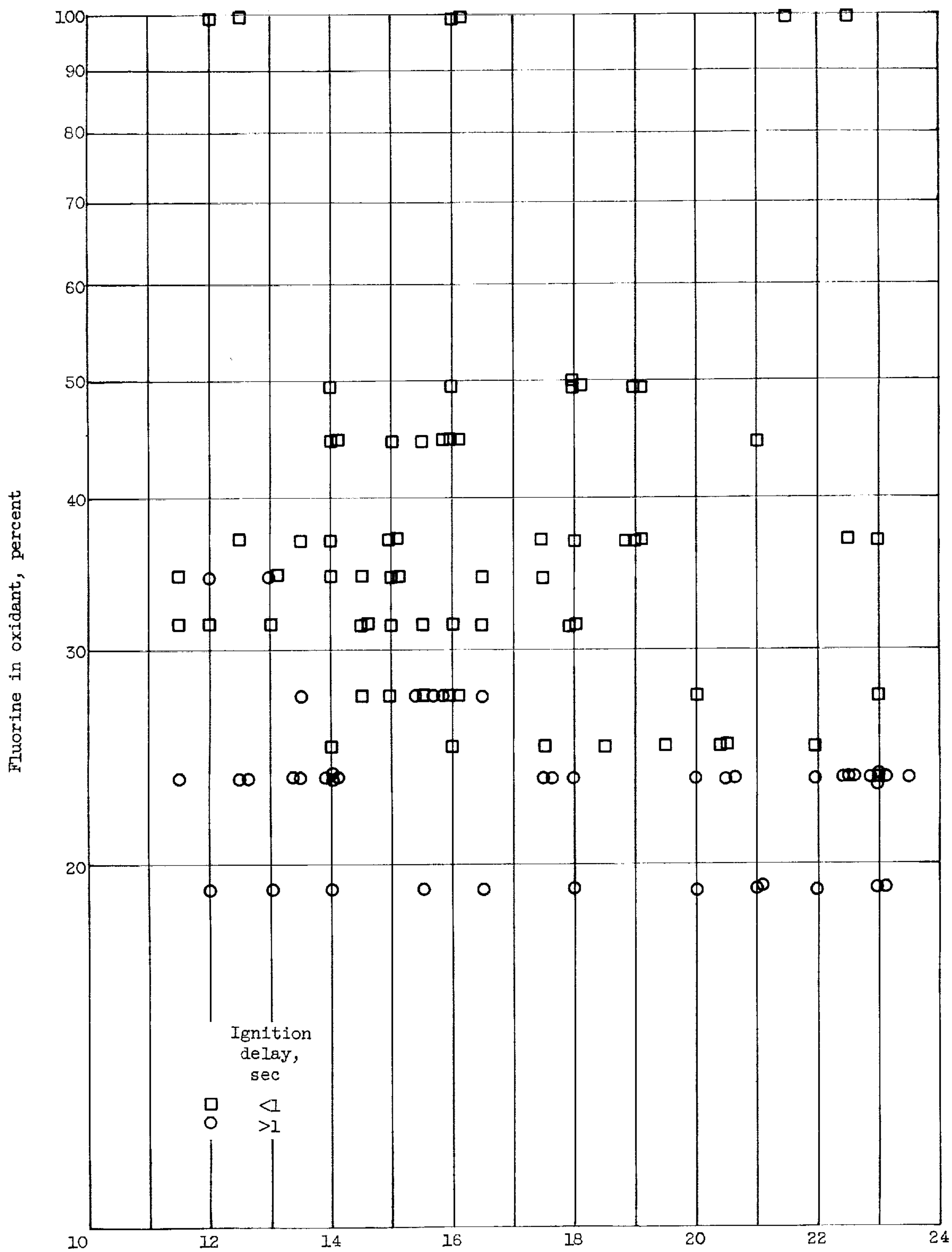
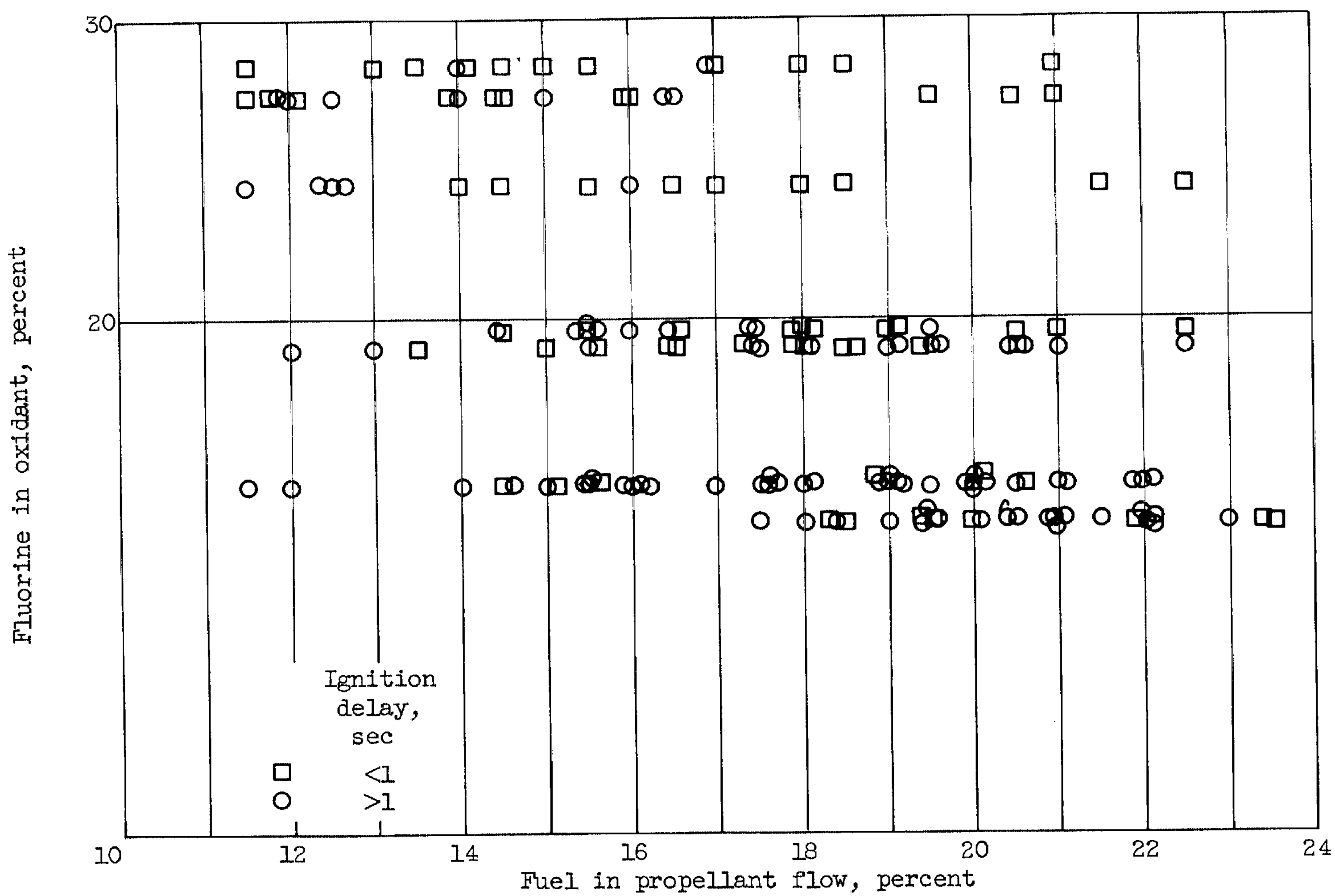


Figure 4. - Ignition characteristics of showerhead injector using cold hydrogen.



(a) Cold hydrogen.

Figure 5. - Ignition characteristics of swirl-cup injector.



(b) Warm hydrogen.

Figure 5. - Concluded. Ignition characteristics of swirl-cup injector.

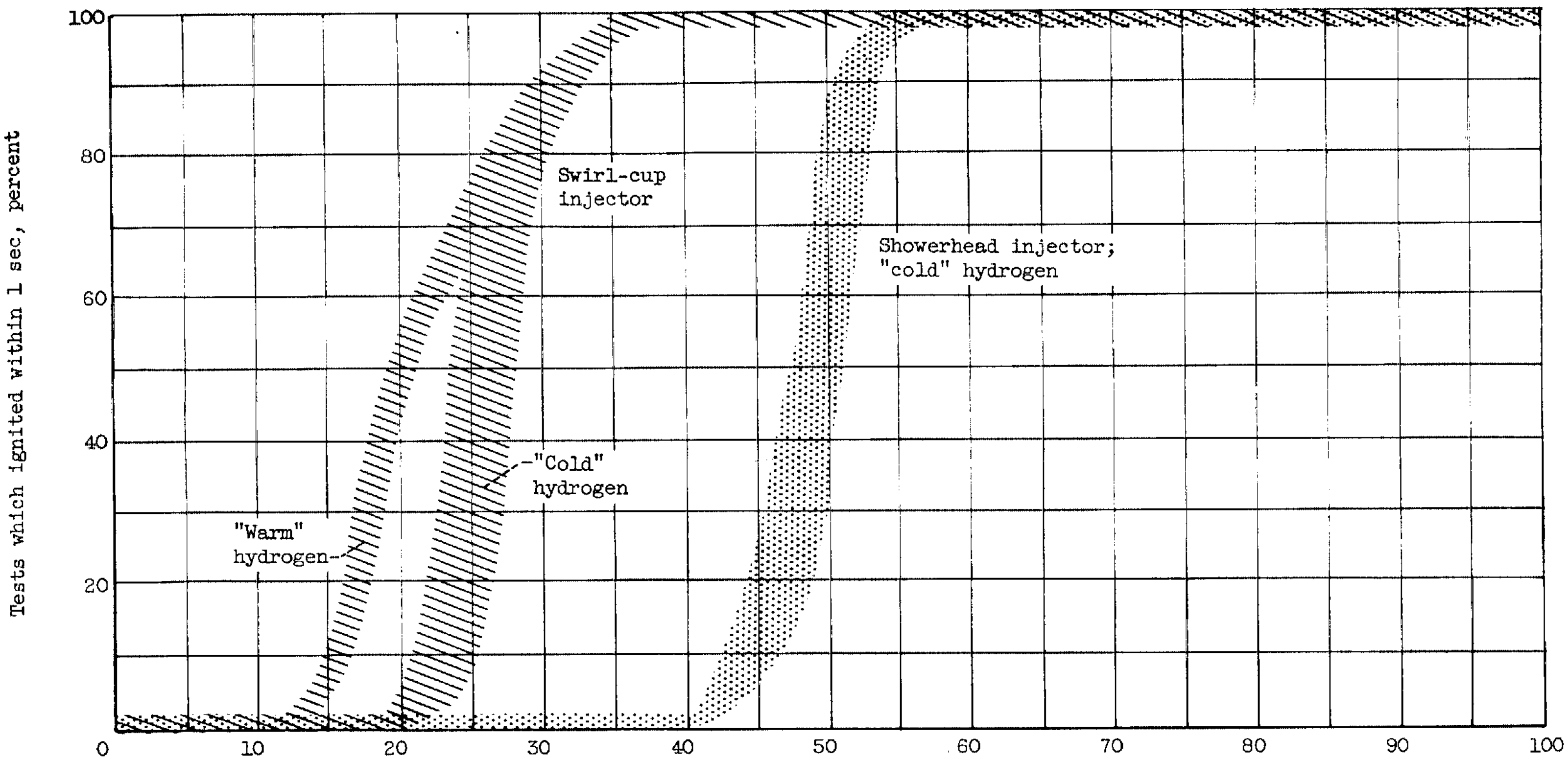


Figure 6. - Probability of hypergolic ignition between gaseous hydrogen and fluorine-oxygen mixtures with showerhead and swirl-cup injectors.

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Ignition delay of the propellant combination cold hydrogen gas and an oxidant mixture of liquid oxygen and liquid fluorine was determined as a function of the fluorine concentration in the oxidant, the injector type, and the percentage of hydrogen in the total propellant flow. It was found that at least 50 percent of the oxidant had to be fluorine to obtain hypergolic ignition delays of less than 1 sec with a shower-head injector, whereas a swirl-cup injector required only 35 percent fluorine concentrations to obtain the same results. The fuel-injection temperature and fuel-oxidant ratio had only slight effect on the hypergolic ignition characteristics.

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