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Photographic Combustion Characterization Of LOX/Hydrocarbon Type Propellants

Contract NAS 9-15724
Phase I Data Dump Report DM-113T-1
27 July 1979

Prepared For:
National Aeronautics And Space Administration
Lyndon B. Johnson Space Center
Houston, Texas 77058

By: D. C. Judd

(NASA-CR-160318) PHOTOGRAPHIC COMBUSTION CHARACTERIZATION OF LOX/HYDROCARBON TYPE PROPELLANTS (Aerojet Liquid Rocket Co.) 84 p HC A05/MF A01 CSCL 21I

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Aerojet Liquid Rocket Company

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Prepared By:

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Program Manager

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Houston, Texas

FOREWORD

This data dump describes the experimental work and the data collected during Phase I of the "Photographic Combustion Characterization of LOX/HC Type Propellants" Program. The activity was performed by Aerojet Liquid Rocket Company on contract NAS 9-15724, under the direction of Mr. M. F. Lausten, NASA-JSC Project Manager. Aerojet personnel included Mr. J. W. Salmon, Program Manager; Mr. B. R. Lawver, Project Manager, and Mr. D. C. Judd, Project Engineer. The following individuals also contributed to the program:

Gene Hron	Fabrication
Arnold Keller	Test Engineering
Lee Lang	Injector Design
Norm Rowett	Test Instrumentation

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I. INTRODUCTION AND SUMMARY

A. INTRODUCTION

The objectives of this program are two-fold. The first objective (Phase I) is to experimentally demonstrate the advantages and limitations of using high speed photography to identify and characterize potential anomalies (i.e., pops, fuel freezing, thermal decomposition, and reactive stream separation) in the combustion of liquid oxygen (LOX)/Hydrocarbon (HC) type propellants while operating with different element concepts. The second objective (Phase II) is to develop a combustion evaluation criteria based on the above mentioned testing and use it to evaluate, characterize, and screen promising low cost LOX/HC type propellants for long life reusable propulsion systems. The basic injector element combustion data generated in this effort will provide much of the needed experimental data necessary to rationally select the most promising propellant combination(s) and injector elements for future engine technology efforts and engine development programs. Without this experimental data, compromises will have to be made between risk and the present state-of-the-art data base. This could result in either significant development cost and/or operational costs being incurred unnecessarily.

B. SUMMARY

The development work undertaken during Phase I resulted in the design and testing of three single element injectors and two fuels with the aim of photographically characterizing observed combustion phenomena. The three injectors tested were the O-F-O triplet, the Transverse Like on Like (TLOL), and the Rectangular Unlike Doublet (RUD). The fuels tested were RP-1 and Propane.

The hot firings were conducted in a specifically constructed chamber fitted with quartz windows for photographically viewing the impingement spray field.

I, B, Summary (cont.)

Test results from Phase I main chamber element testing show that the appearance of LO_2/Hydrocarbon combustion is markedly different from storable propellant combustion observed on previous blowapart tests (Contract NAS 9-14186, Ref. 1). However, the pressure effects on combustion show similar trends. All LOX/HC testing demonstrated coking with the RP-1 fuel leaving far more soot than the Propane fuel. No fuel freezing or popping was experienced under the test conditions evaluated during Phase I. Carbon particle emission and combustion lightbrilliance increased with Pc for both fuels although RP-1 was far more energetic in this respect. RSS phenomena appear to be present in the high Pc tests as evidenced by striations in the spray pattern and by separate fuel rich and oxidizer rich areas.

The RUD element was also tested as a fuel rich gas generator element by switching the propellant circuits. Excessive sooting occurred at this low mixture ratio (0.55), precluding photographic data.

Testing to date has increased our knowledge of LOX/HC combustion phenomena and has shown that some of the anticipated problems (i.e., fuel freezing, flash vaporization, etc.) are not likely to occur at the test conditions being examined. Further testing with new elements and fuels will be necessary to characterize the above mentioned combustion phenomena more precisely. This testing will be preformed during Phase II of this program.

II. RESULTS AND CONCLUSIONS

A. RESULTS

A summary of the most important findings from Phase I testing is shown below:

Fuel Freezing or Pops - No occurrence of fuel freezing or popping was noted with the use of LOX/RP-1 in three Phase I injectors (OFO triplet, TLOL, and RUD). Although this is a significant finding, it is not conclusive evidence that freezing and popping will not occur with other injectors and propellants (e.g., LOX/NH_3). The use of larger orifices than those in this program (.030 in.) may also promote fuel freezing. Larger streams would receive proportionally less heat from recirculation gases because of their reduced surface area to volume ratio.

Coking - Coking was influenced by type of fuel, mixture ratio, and injector element. RP-1 definitely deposited more soot than Propane for a given injector. Lower mixture ratios resulted in coking which coated the chamber and windows precluding photography. The RUD with its coherent jet impingement resulted in greater soot formation than the TLOL with its spray fan impingement. The TLOL appeared to atomize, mix, and burn more completely.

Reactive Stream Separation (RSS) - There appears to be an RSS type of phenomena as evidenced by striations in the spray pattern and by separate areas of fuel and oxidizer rich propellants. There does seem to be a Pc dependence with better mixing and less combustion light emission at the lower pressures. Higher pressure seems to promote the apparent separation and greatly enhance the light emission. Light intensity increases during RSS because of the carbon formation resulting from poor mixing and incomplete combustion. Verification of RSS and correlations between RSS and velocity, mixture ratio, orifice diameter, injector type, or propellants will be a major goal of Phase II of this program.

II, A, Results (cont.)

Super Critical Pressure Operation - No occurrence of flahs vaporization leading to resurge phenomena has been experienced at sub-critical or super-critical pressure operation. As mentioned previously there is an increase of light emission and apparent separation with an increase in Pc. This increase, however, is gradual and continuous and seems to bear no relationship to the critical pressure.

Fuel Type - RP-1 produces a brilliant combustion flame which is surrounded by turbulent, dark, recirculation gas flows. The fuel fan (TLOL) is black as it exits the injector and the oxidizer fan is a light gray color. Combustion light increases with chamber pressure and coking is always present.

Propane has a lower rate of carbon particle emission and therefore produces a much less brillian combustion flame. The fuel fan is a grayish-brown color as it exits the injector and the oxidizer fan is a light gray color. Combustion light also increases with chamber pressure, but to a lesser degree than with LOX/RP-1. A brownish vapor is visible in the low pressure tests, resulting from Propane's high vapor pressure. Propane demonstrates far less carbon deposition or sooting than RP-1.

Main Chamber vs Gas Chamber - All of the above findings are in reference to main chamber operating conditions. The RUD injector element was fired with LOX/C_3H_8 at Pc = 850 psia and MR = .55 to examine fuel rich gas generator effects. The injector burned smoothly but yielded no photographic data because of excessive sooting. The windows and chamber are completely covered with soot and allowed no penetration of light.

B. ADVANTAGES AND LIMITATIONS OF USING HIGH SPEED PHOTOGRAPHY TO CHARACTERIZE ANOMALIES ON LOX/HC COMBUSTION

1. Advantages

Phase I high speed photography of single element, LOX/HC injectors has been effective in showing the existence of coking and an apparent RSS phenomena and in demonstrating the absence of fuel freezing, as described in the previous section. Each injector/fuel combination tested to date has yielded different results as discussed in Section II,A. Physical processes such as fuel decomposition, mixing, atomization, vaporization, and apparent separation are visible in varying degrees of clarity in each test. Being able to see and interpret these occurrences has resulted in a better general understanding of the LOX/HC combustion process.

2. Limitations

In Phase I testing, emphasis was directed toward obtaining information about a concept or method that could be used to provide data necessary to screen and evaluate various fuels and injector elements. The advantages listed above are important, but for the most part are qualitative. Certain physical processes have been seen to occur as expected (such as coking, extreme brightness, an apparent RSS type of phenomena), but the ability to develop empirical correlations between test conditions and combustion phenomena is still in question. Although testing has been limited to date (44 tests, three injectors, and two fuels), the LOX/HC photographic results are more vague and difficult to obtain than the photos from the N_2O_4/Amine program. Testing to date indicates that some injector/fuel combinations will never give good photographic results regardless of the technique used (e.g., the RUD fuel rich gas generator). It is believed that the photographic technique now in use is the most flexible and efficient to be utilized, but is compromised by soot and fog formation under many design and operating conditions. Testing with Methane and Ammonia in Phase II may alleviate these sooting and clouding problems somewhat and aid in developing empirical correlations for these two fuels. The possibility of adding a dye to Propane to aid in film interpretation may also facilitate a greater understanding of the combustion process. For this reason it is felt that Phase II photography is worth pursuing using the methods developed during Phase I.

The question naturally arises as to whether photographic observations alone will suffice or whether other methods of confirming the existence of RSS and other phenomena should be employed. The use of larger, multiple element injectors would allow the accurate measurement of Isp and C* which would in turn reflect the occurrence of RSS. It is felt that multiple element testing will be a necessary part of the injector and fuel evaluation and will serve to answer questions perhaps not addressed by single element photographic testing.

C. CONCLUSIONS

The most significant conclusions drawn from the work in Phase I are:

1. RSS appears to occur with non-hypergolic fuels (RP-1 and Propane), and shows a tendency to increase with chamber pressure.

2. Fuel freezing and popping is not observed with the injector elements and operating conditions tested to date (.030 in. jets with RP-1 and Propane).

3. Operation at supercritical pressure is not noticeably different than operation at subcritical pressure, even though the LOX is observed to vaporize more rapidly as chamber pressure is increased.

4. Thermal decomposition and sooting increase as the hdyrogen-to-carbon ratio decreases. The type of injector element also influences coking with the coherent jet unlike doublet depositing far more soot than the TLOL or OFO.

5. Photographic characterization of a fuel rich gas generator will be very difficult because of the excessive sooting.

III. RECOMMENDATIONS

A recommendation (along with all supporting rationale) as to the propellants, elements, and operating conditions to be considered in Phase II was prepared and submitted to NASA-JSC for review and approval (Ref. 2). A summary of these recommendations is shown below:

1. Further testing of six elements (four main chamber and two gas generator), and three fuels (Propane, Methane, and Ammonia) are recommended to aid in characterizing LOX/HC combustion phenomena.

2. Efforts should be made to develop empirical correlations between test conditions and LOX/HC combustion phenomena so that future LOX/HC engines can be designed more efficiently.

IV. TECHNICAL DISCUSSION

A. EXPERIMENTAL HARDWARE AND TEST SETUP

1. Test Apparatus

The test apparatus consists of a test chamber equipped with transparent viewing ports, a LOX/H_2 igniter, removable injectors, and nozzles as shown in Figure 1. The test chamber was designed during the Task III "Blowapart" program (Ref. 1) and was modified slightly for use during this program. Of the three injectors fired during Phase I, one of them (O-F-O triplet) was residual hardware from the "Storables Blowapart" program (Contract NAS 9-14186) and two of them (Transverse Like on Like and Rectangular Unlike Doublet) were designed and fabricated during Phase I.

a. Test Chamber

The test chamber was machined from a 4-inch square x 6-inch long block of 304 CRES. The combustion chamber section is 4 inches (10.16 cm) long, to which a 2 in. (5.08 cm) L* spacer is bolted to increase the combustion zone length to 6 inches (15.2 cm). The block was bored to provide a 2.75 inch (6.99 cm) diameter combustion chamber. Four circular quartz windows were provided to facilitate photography and to allow flexibility in photographic lighting of the combustion process. The windows are 1/2 inch (1.27 cm) thick to provide a safety margin for 1000 psia (6.89×10^5 N/m^2) operation. The flat quartz windows are sandwiched between durabula gaskets for cushioning against ignition shocks and uneven loading. A silicon "O" ring provides sealing on the window periphery. Quartz windows are used to provide good propellant compatibility and well defined optical properties. Thin quartz disc inserts are also employed to protect the 1/2" pressure bearing windows from high heat flux and window damage.

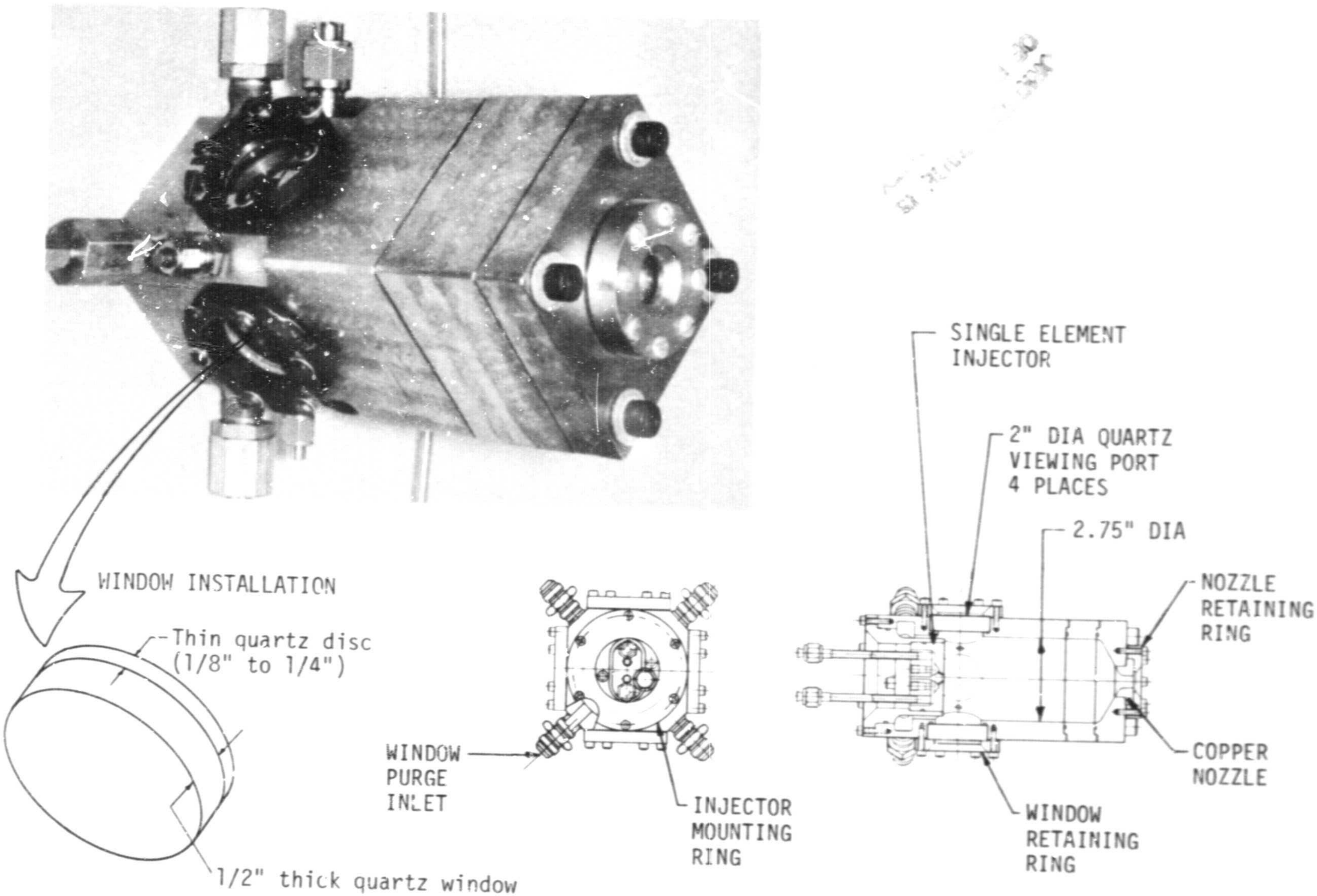


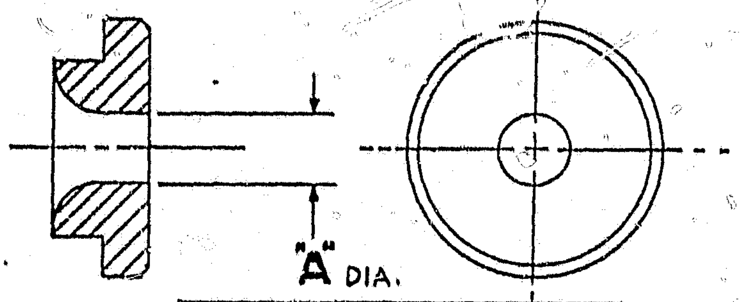
Figure 1. Test Chamber Assembly

The chamber was designed to provide an inert gas (GN_2) film purge to prevent obscuring the view of propellant spray impingement on the windows. The gas purge flow is injected through four inlets into an annular manifold. The gas is directed from the manifold through an annular gap and made to flow around the periphery of the chamber wall. The gas passages were sized such that the GN_2 is injected into the chamber at 50 ft/sec (15.2 m/sec) at 300 psia (2.07×10^6 N/m^2) chamber pressure to minimize mixing with the propellant spray and combustion gas. Storable propellant "Blowapart" testing (Ref. 1) showed that the cold GN_2 purge gas causes poor spray field visibility due to the density gradient created between it and the hot combustion gas. Therefore all subsequent storable propellant tests were run without purging during hotfire. However, it was necessary to re-activate the purge circuit for LOX/HC testing. A helium, in place of GN_2, purge is used to protect the windows from the LOX spray during the start transient and from carbon deposits during shutdown. It automatically shuts off during steady state operation.

Provisions were made for mounting both high and low frequency response pressure transducers and thermocouples. The nozzles consist of removable copper inserts drilled to provide the desired operating pressures. The nozzle configuration and exiting sizes are shown in Figure 2.

b. Igniter

The igniter shown in Figure 3 operates on gaseous hydrogen and oxygen which are ignited by a spark plug. This assembly is an existing igniter that has been used on many high pressure programs proving extremely reliable. The igniter is mounted in a port drilled into the L* spacer section by means of an adapter (see Figure 4). The igniter operates at a mixture ratio of 2.0 and a chamber pressure of 250 psia during hotfire testing.



"A" Diameter	
.089	.257"
.1"	.269"
.113	.281
.125	.297
.129	.328
.140	.332
.150	.370
.166	.413
.173	.435
.189	.465
.196	.500
.213	.567
.234	.600
.250	.75 "

Figure 2. Heatsink Copper Nozzles

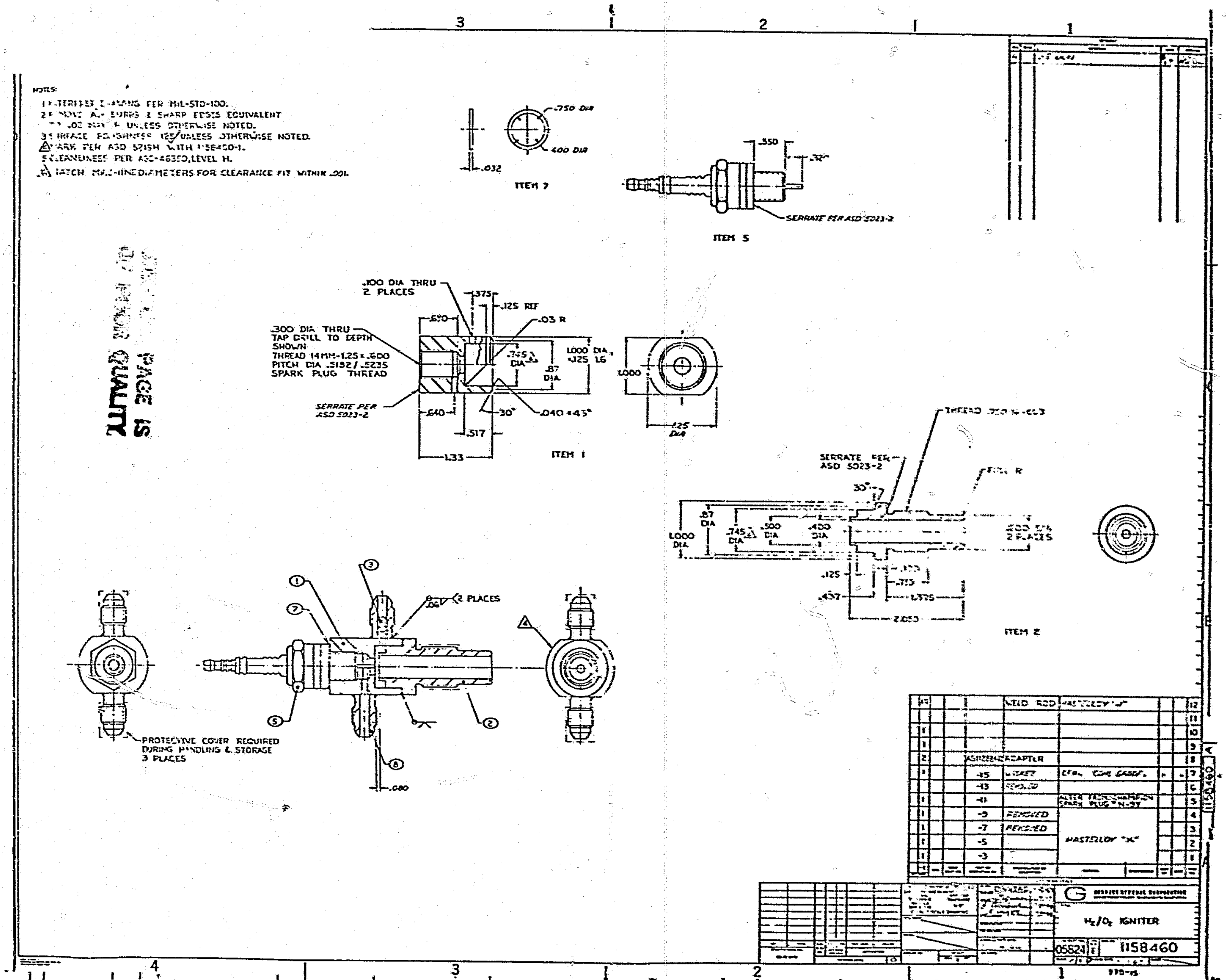


Figure 3. GO_2/GH_2 Torch Igniter

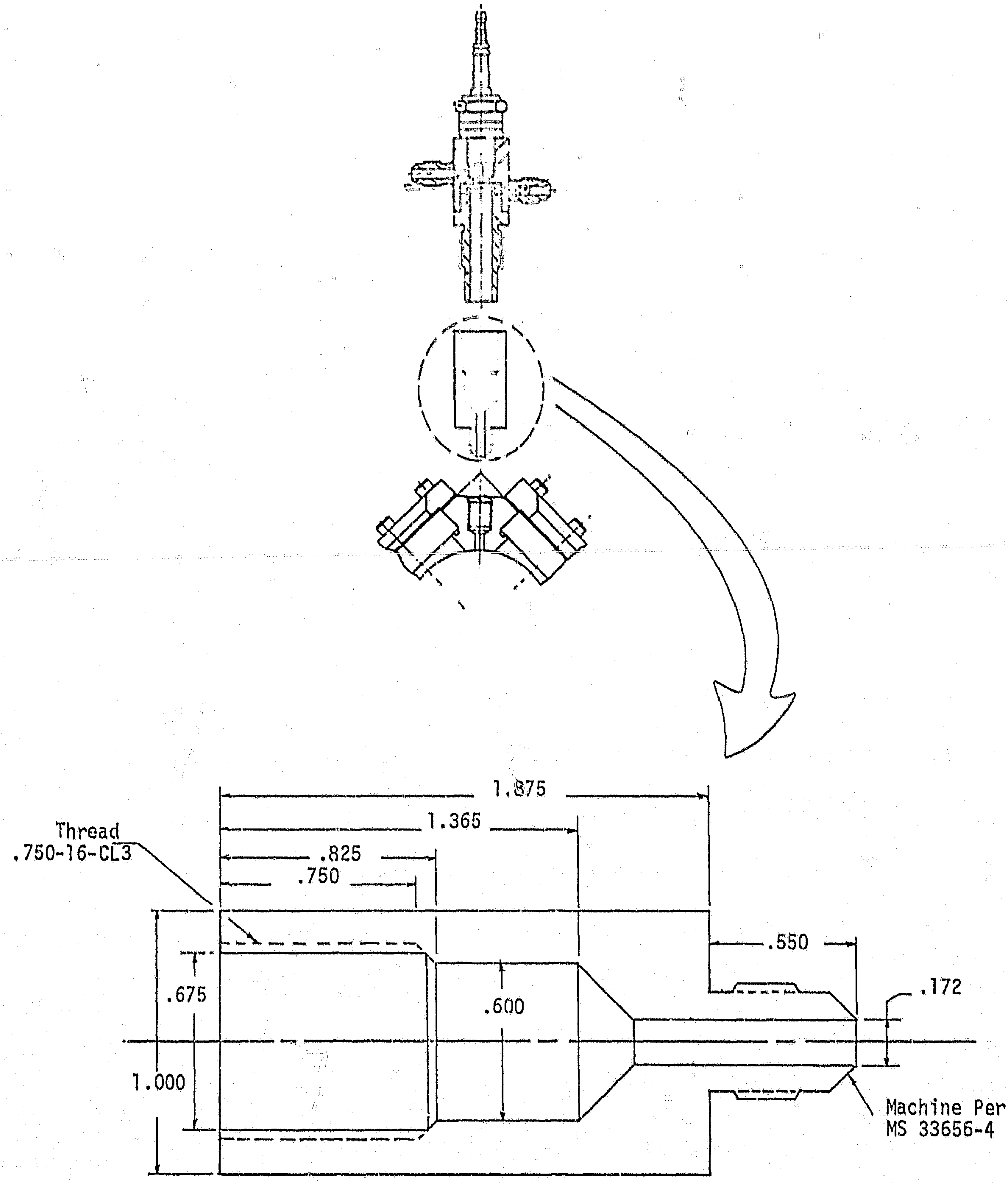


Figure 4. Igniter Mounting Adapter

c. Injectors

Three injectors; the OFO Triplet, Transverse Like-on-Like (TLOL) and Rectangular Unlike Doublet (RUD) were tested during Phase I. All of the injectors were made in a cylindrical "piston" shape to fit into the chamber purge ring located at the forward end of the chamber. The injector is held in the purge ring by allen head screws. A silicon rubber O-ring seals the injector to the purge ring.

(1) O-F-O Triplet

The OFO triplet shown in Figure 5 is residual hardware from Contract NAS 9-14186. It was designed for testing with LOX/Propane propellants but was not tested at that time due to a program redirection.

The OFO arrangement was selected to maximize the oxidizer to fuel interface to maximize the potential for fuel freezing. The fuel is injected axially and the oxidizer is fed from the inlet tube to a torus which feeds two orifices 180° apart. The impingement half angle is 30°. The .030 in. diameter orifices are EDM'ed in the torus cover which is EB welded to the body.

(2) TLOL

The TLOL (Figure 6) is a photoetched platelet injector which was selected for the following reasons:

(a) Like impingement and self-atomizing injectors are predicted to inhibit fuel freezing.

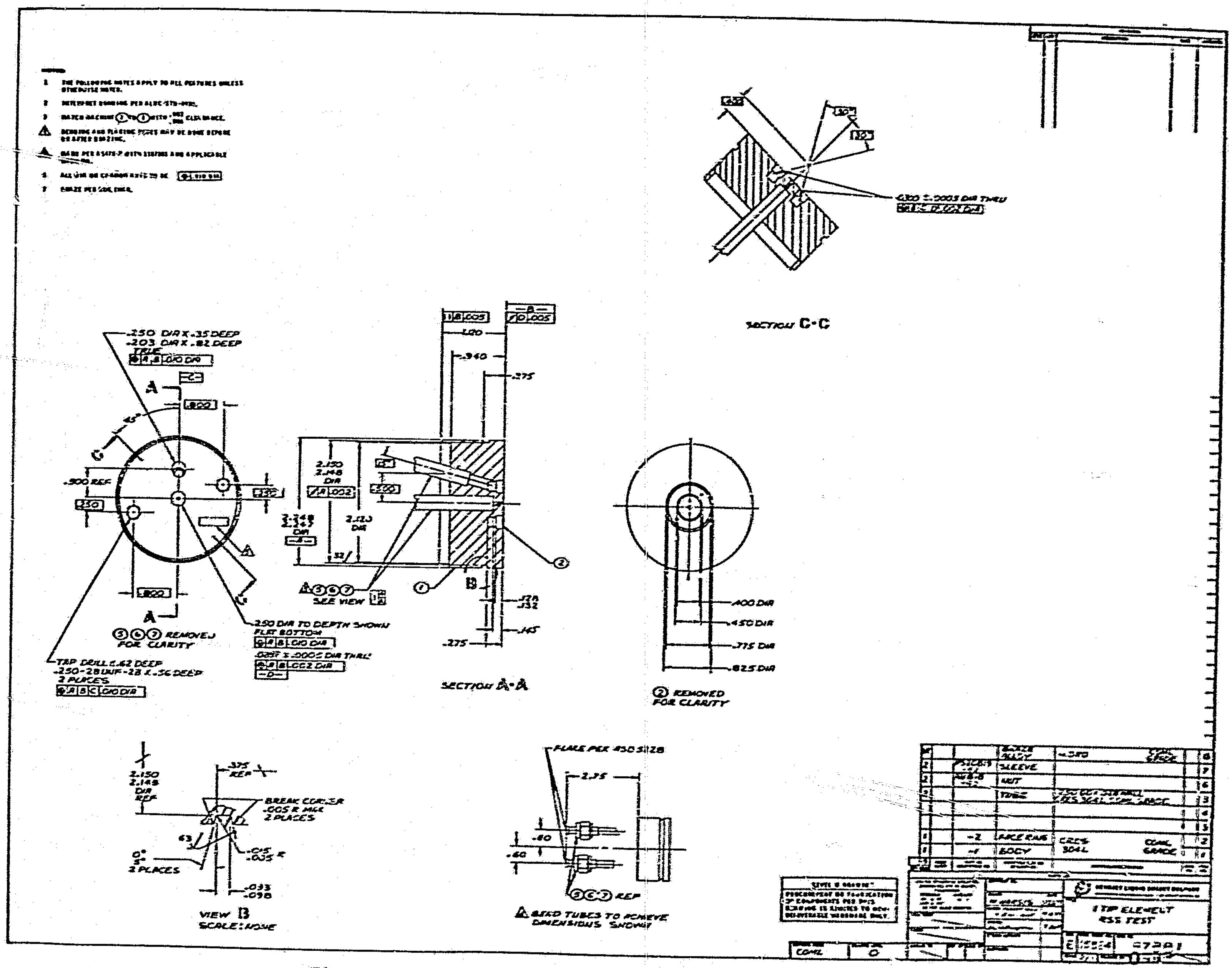


Figure 5. O-F-O Triplet Injector

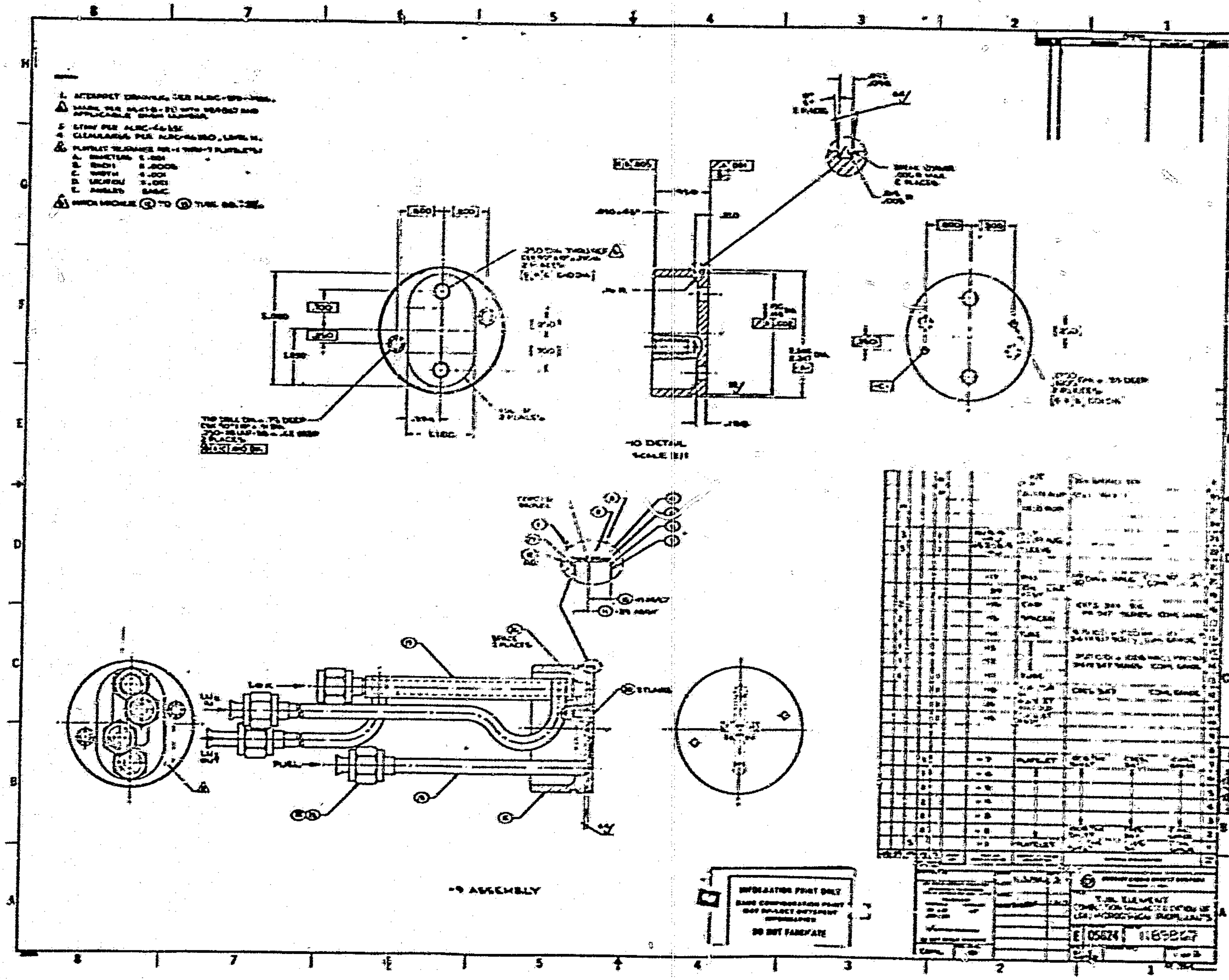


Figure 6. TLOL Element Injector (Sheet 1 of 3)

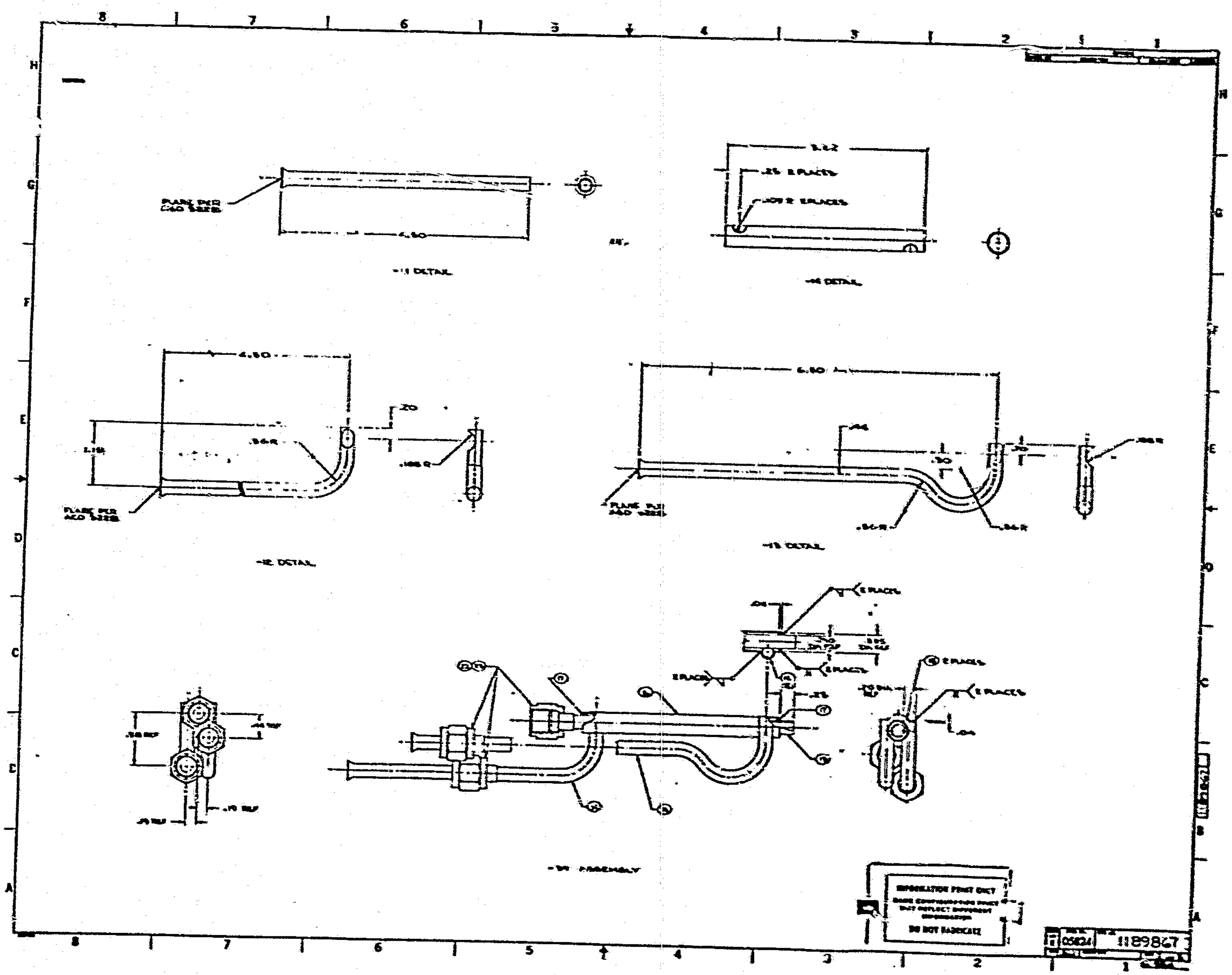


Figure 6. TLOL Element Injector (Sheet 2 of 3)

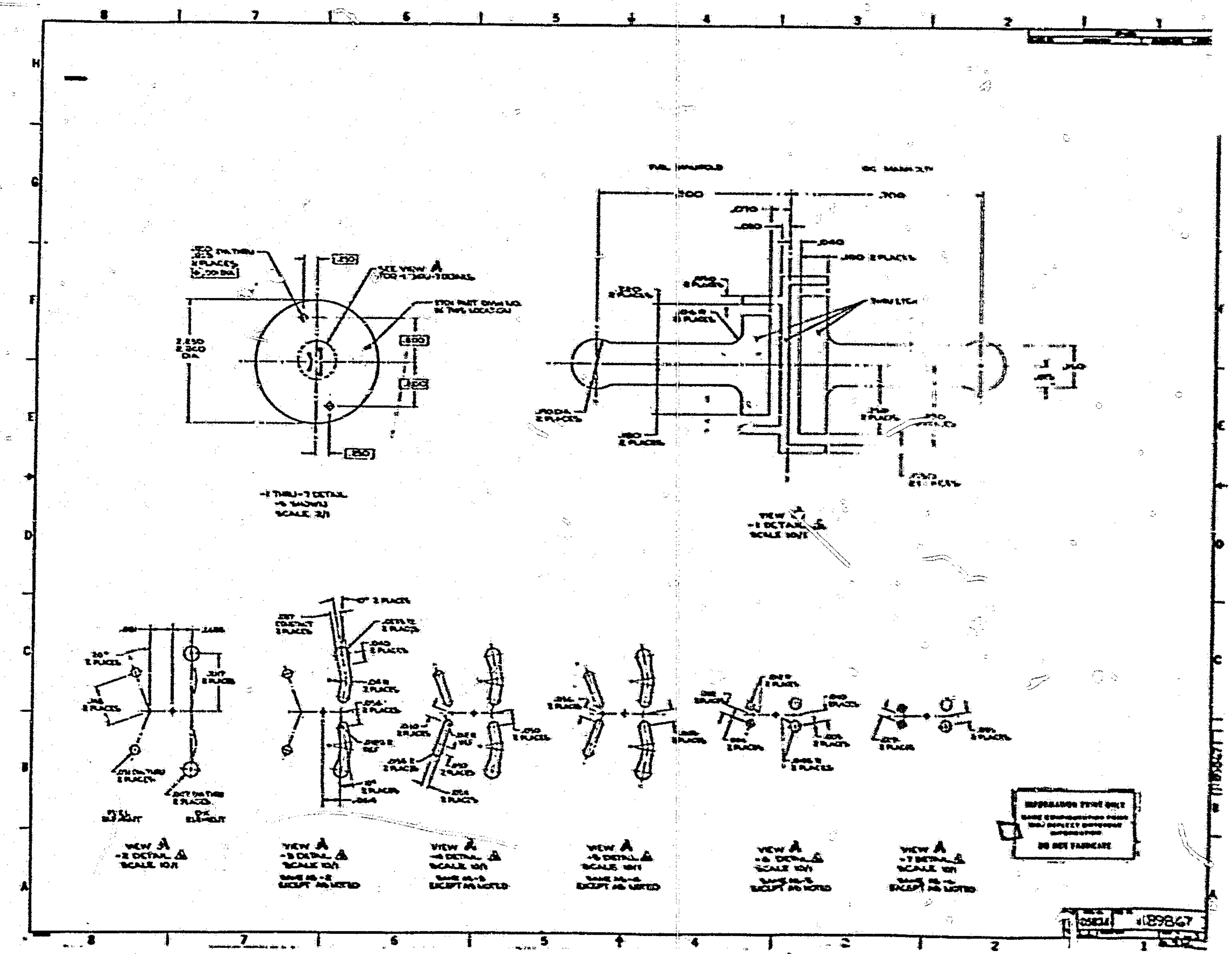


Figure 6. TLOL Element Injector (Sheet 3 of 3)

(b) Self-atomizing injectors promote RSS.

(c) Like impinging doublets can be operated over a wide range of MR, Pc, and T_f with little effect on resultant spray angle.

(d) This element is well characterized and is predicted to produce acceptable combustion stability and performance characteristics.

The single element TLOL was designed for the following nominal operating conditions: (1) F = 50 lbF, (2) MR = 2.8 with RP-1 and MR = 3.0 with propane, (3) Pc = 1000 psia, (4) $\Delta P_{OX} = \Delta P_f = 250$ psi.

The TLOL consists of a body, inlet lines, a manifold platelet stack, and an element platelet stack. The manifold stack shown in Figure 7 provides propellant routing and thermal isolation. The element stack (Figure 8) contains the transverse inertance channel to the injection orifice. The platelet stacks are diffusion bonded and then brazed to the body.

(3) RUD

The RUD (Figures 9 through 11) is an EM'd injector fed directly from inlet tubes. The injector face is machined so that the propellants are injected in streams normal to the face. A rectangular orifice configuration was selected to avoid the large diameter mismatch associated with LOX/HC circular orifices. The circular orifice diameter mismatch produces a "banana" shaped spray distribution which is difficult to interpret photographically. The RUD is complimentary to the TLOL for the following reasons:

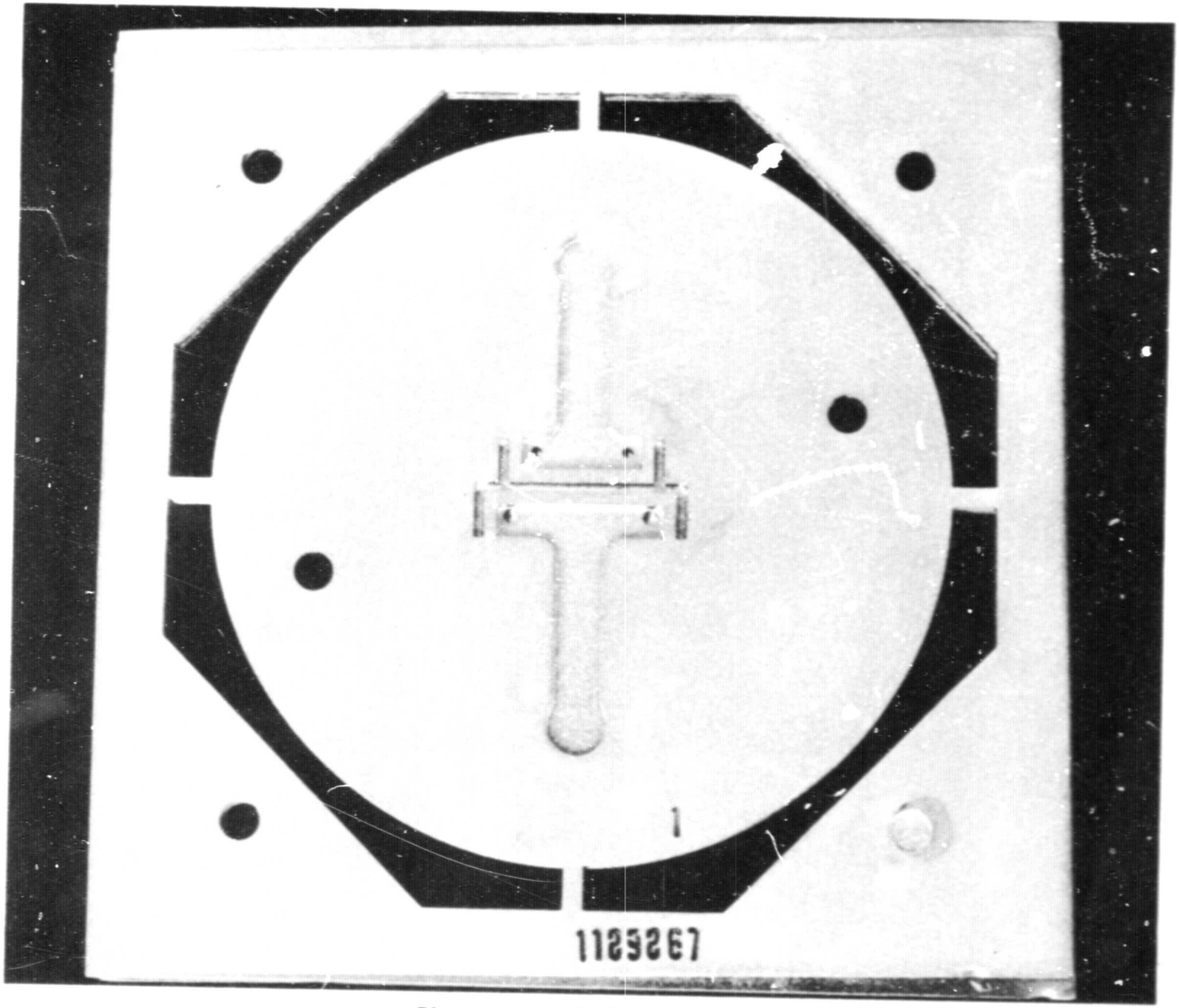


Figure 7. TLOL Manifold Stack

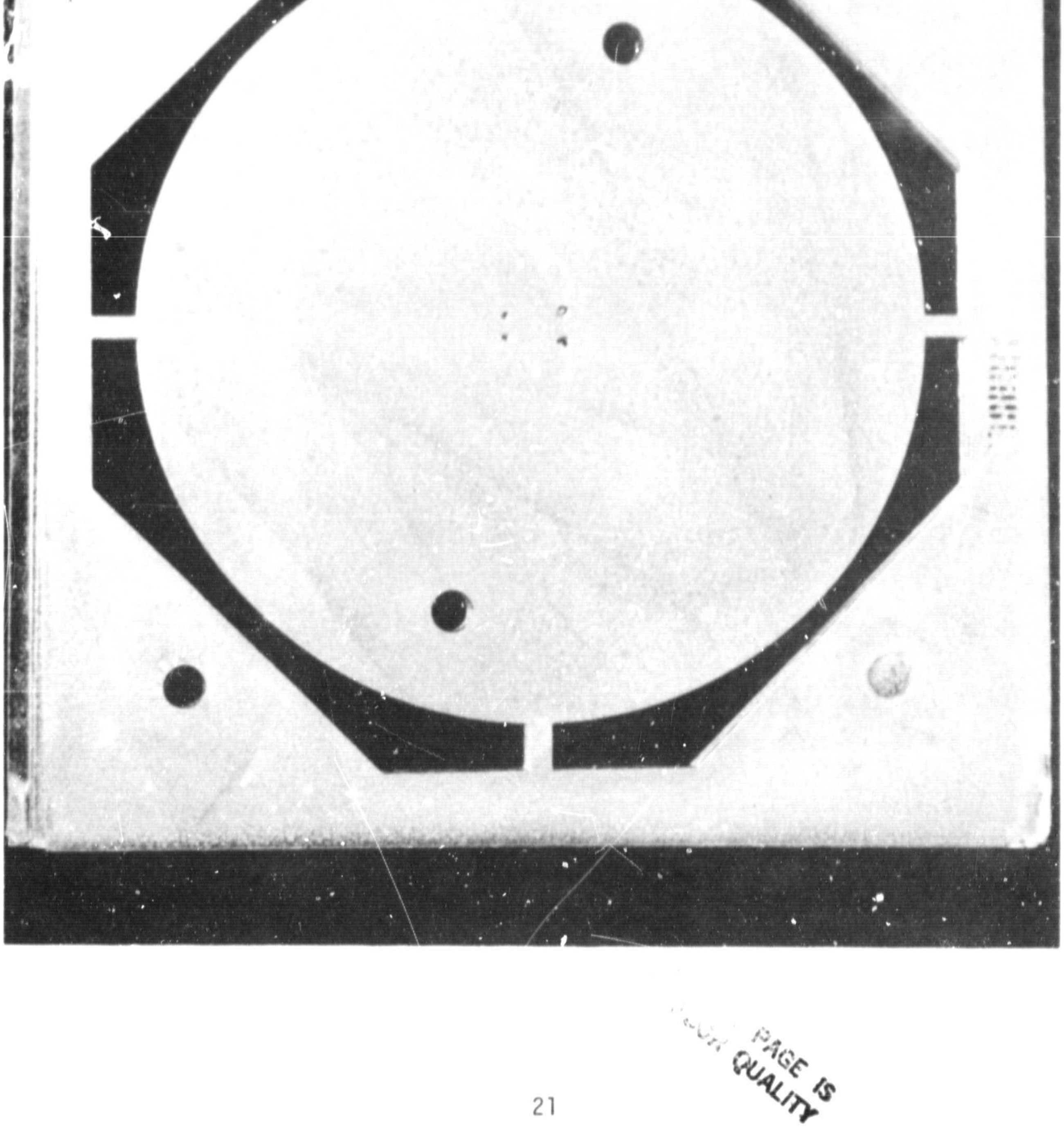


Figure 8. TLOL Element Stack

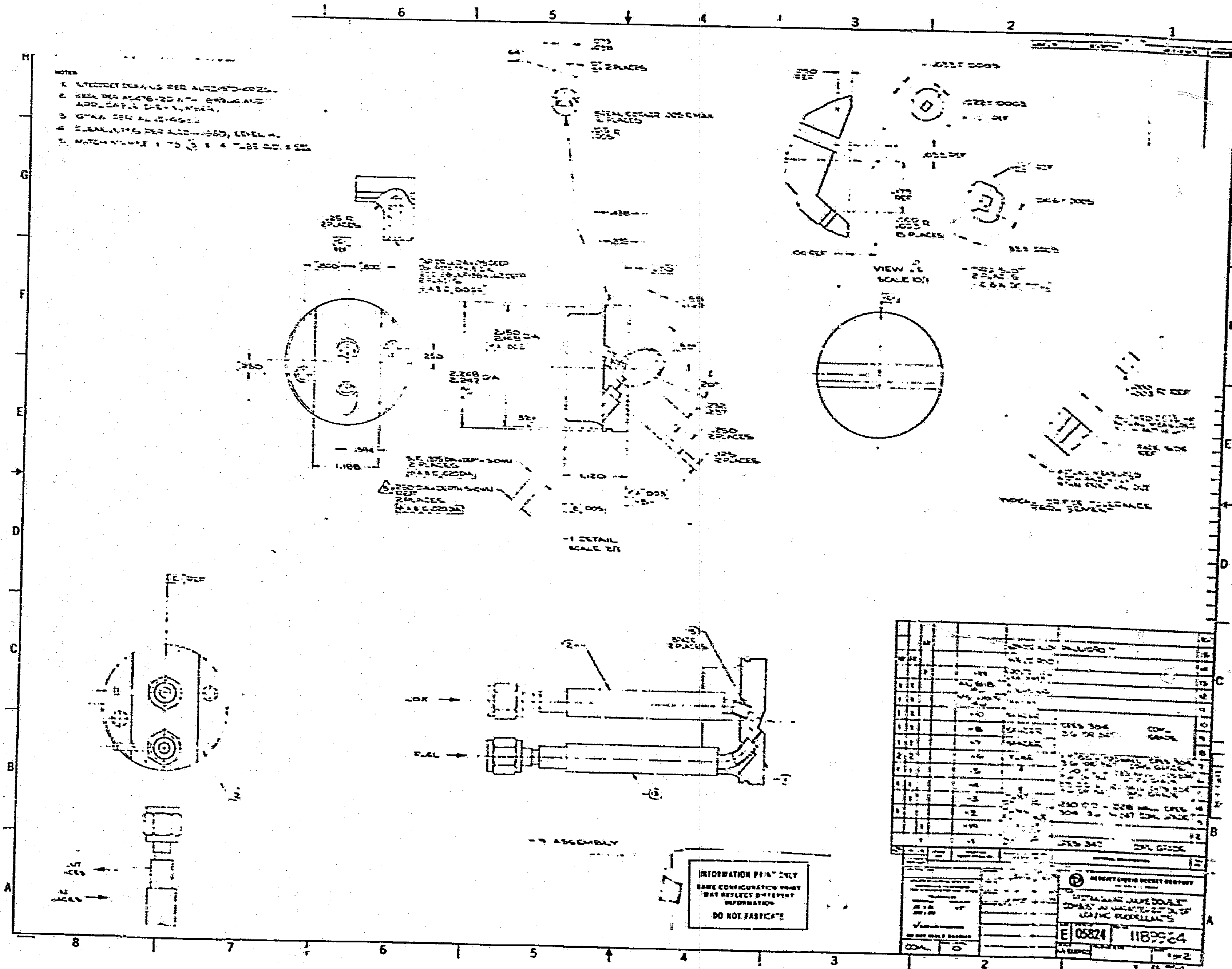


Figure 9. Rectangular Unlike Doublet Combustion Characterization of LOX/HC Propellants (Sheet 1 of 2)

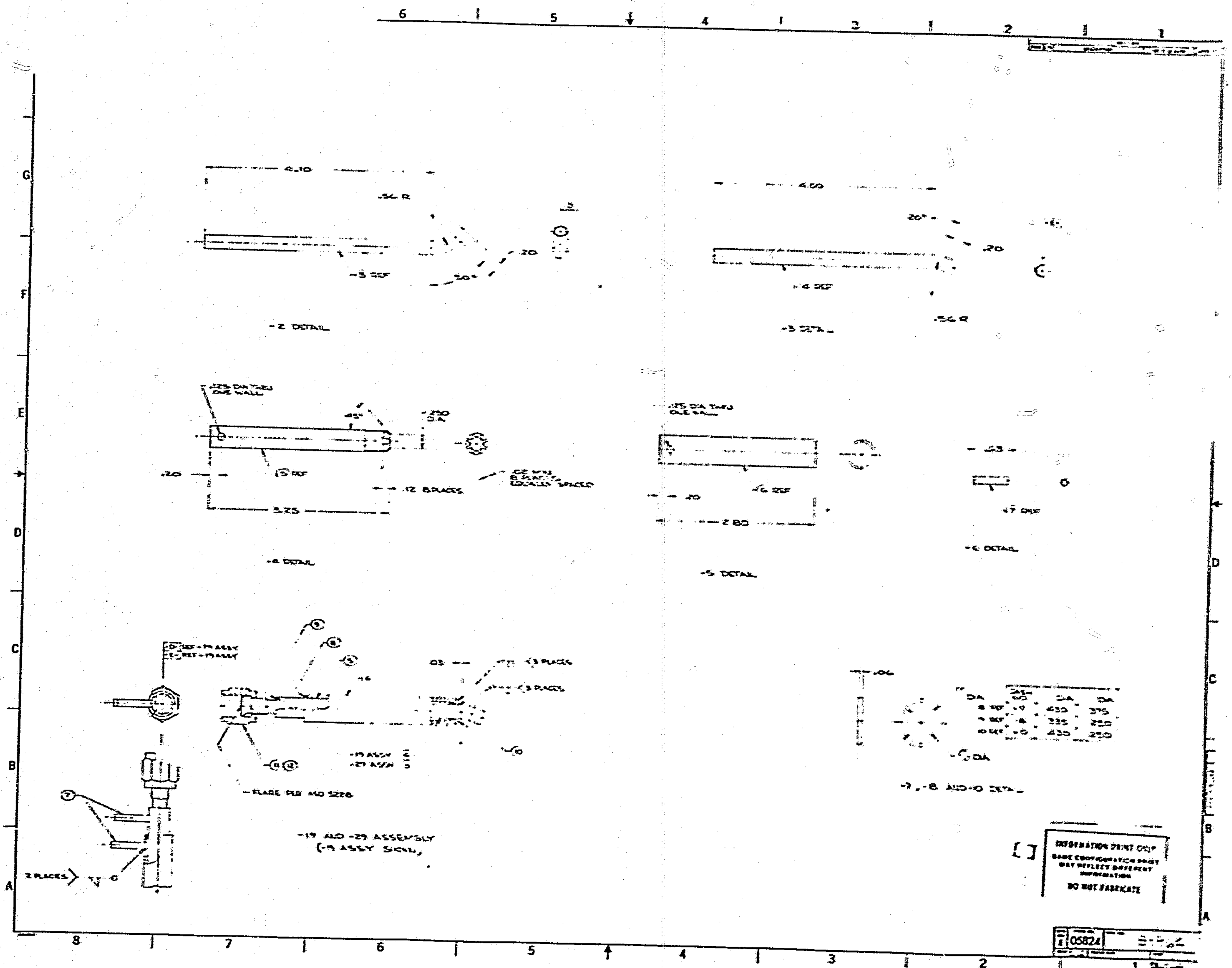


Figure 9. Rectangular Unlike Doublet Combustion Characterization of LOX/HC Propellants (Sheet 2 of 2)

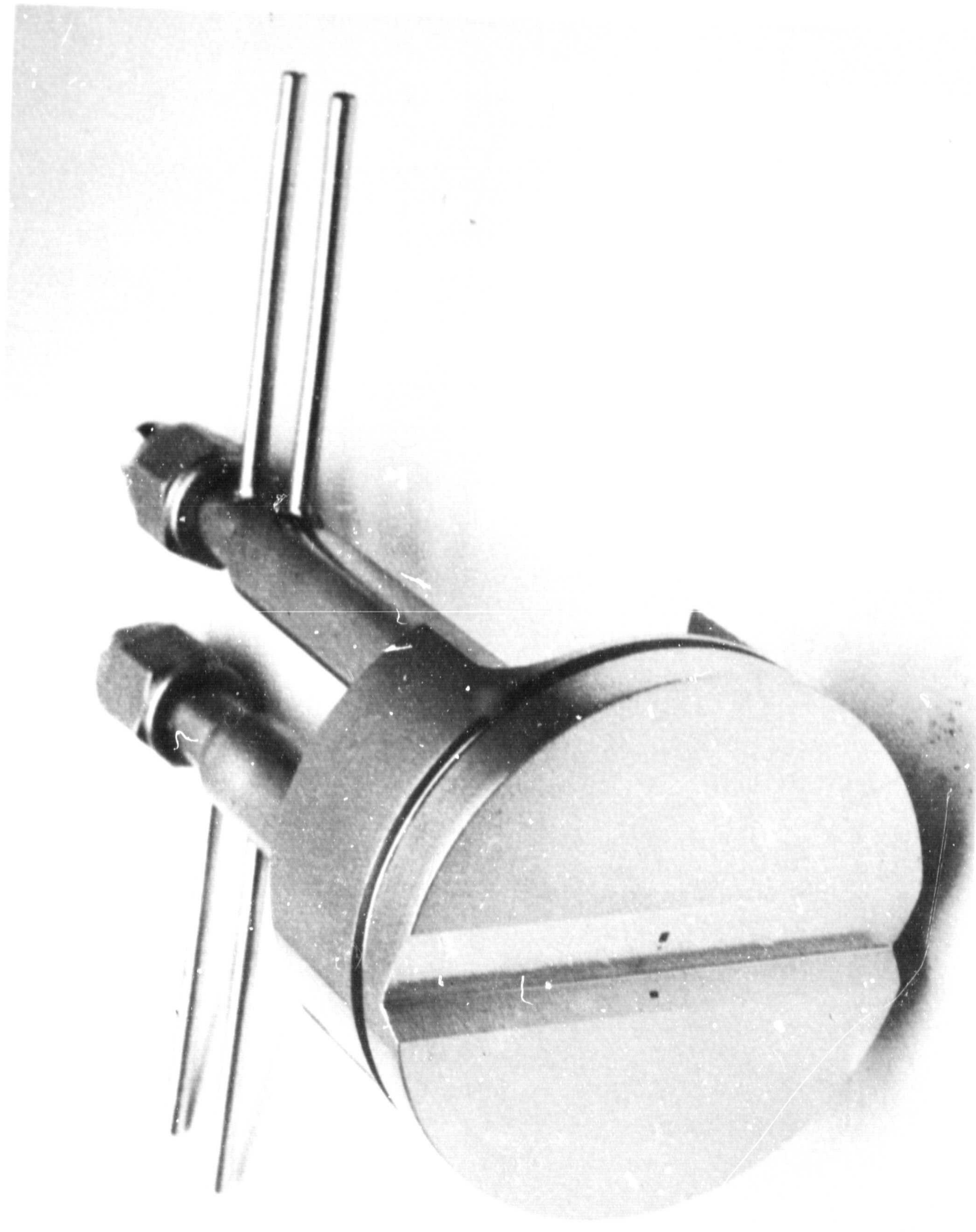


Figure 10. Rectangular Unlike Doublet

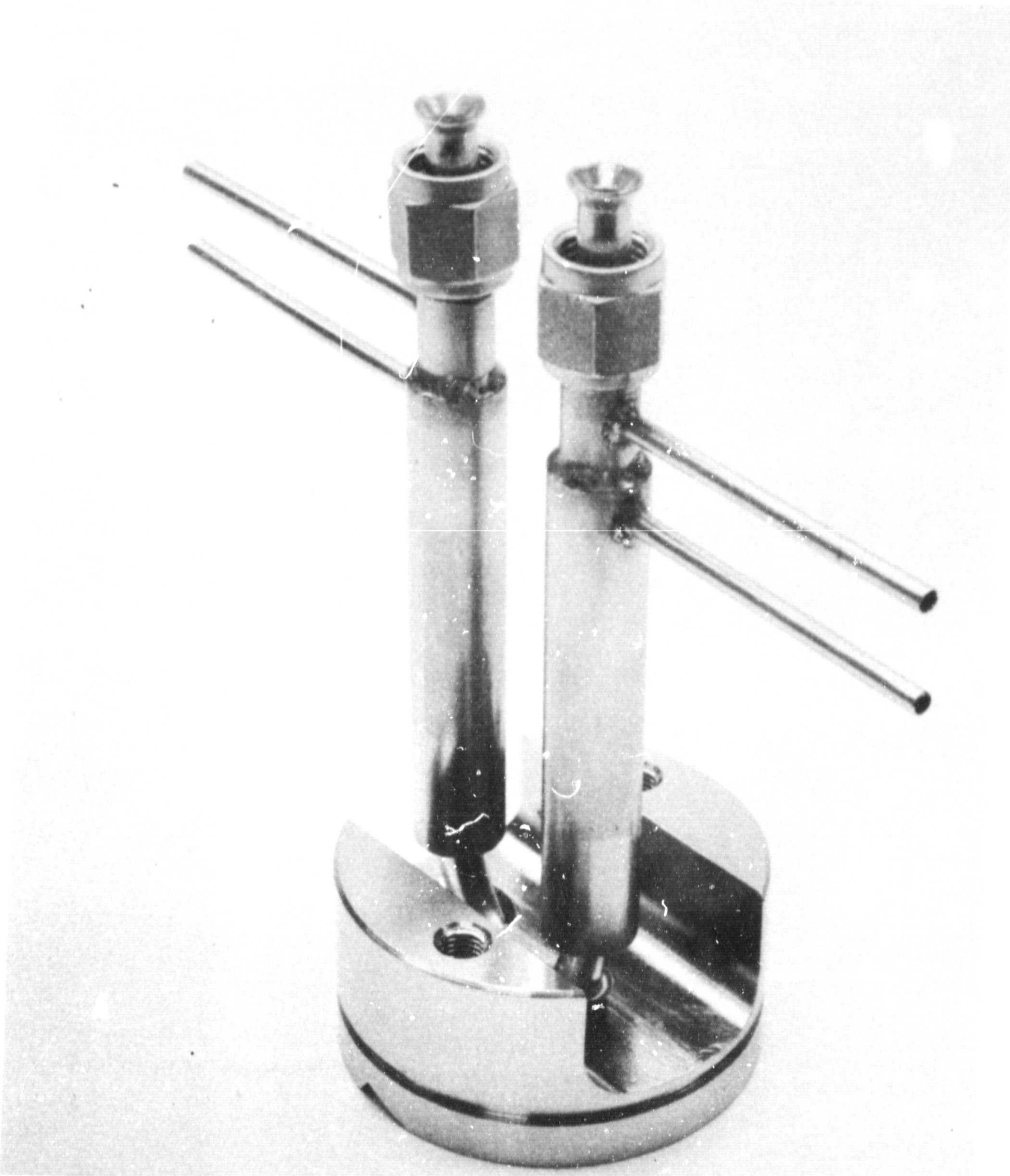


Figure 11. Rectangular Unlike Doublet

(a) Unlike impingement of coherent jets is predicted to encourage freezing with LOX/RP-1 propellants.

(b) Coherent jets have less interfacial surface area and are not as active in promoting RSS.

(c) Spray angle and mixture ratio distributions will most likely vary with MR, Pc, and T_f.

The RUD injector was designed for the same operating conditions and propellants as the TLOL. The injection angles of 50° for the fuel and 20° for the LOX were selected so that the resultant spray fan would parallel the centerline of the chamber at nominal mixture ratio. Aspect ratios were chosen to keep orifice area and surface tension to a minimum, thus helping to avoid the change in free stream cross section from rectangular to circular. The L/D ratio for both orifices is greater than 6 in order to facilitate flowing fully attached (Ref. 3).

The inlet lines are fitted with "two-pass" coolant jackets to allow for switching propellant circuits. This switching flexibility allows the RUD to be used as a fuel rich gas generator element.

2. Hotfire Test Facility Setup

The test apparatus was setup in Test Bay 3 of the ALRC Research Physics Lab as shown in Figure 12. A schematic of the propellant system used is shown in Figure 13. Propellant was stored in one-gallon, 3000 psi run vessels. Gaseous pressurization of these systems was used to provide controlled run conditions over a wide range of chamber presssures. Gaseous heliuim was used to pressurize the LOX and gaseous nitrogen for the RP-1 and C_3H_8.

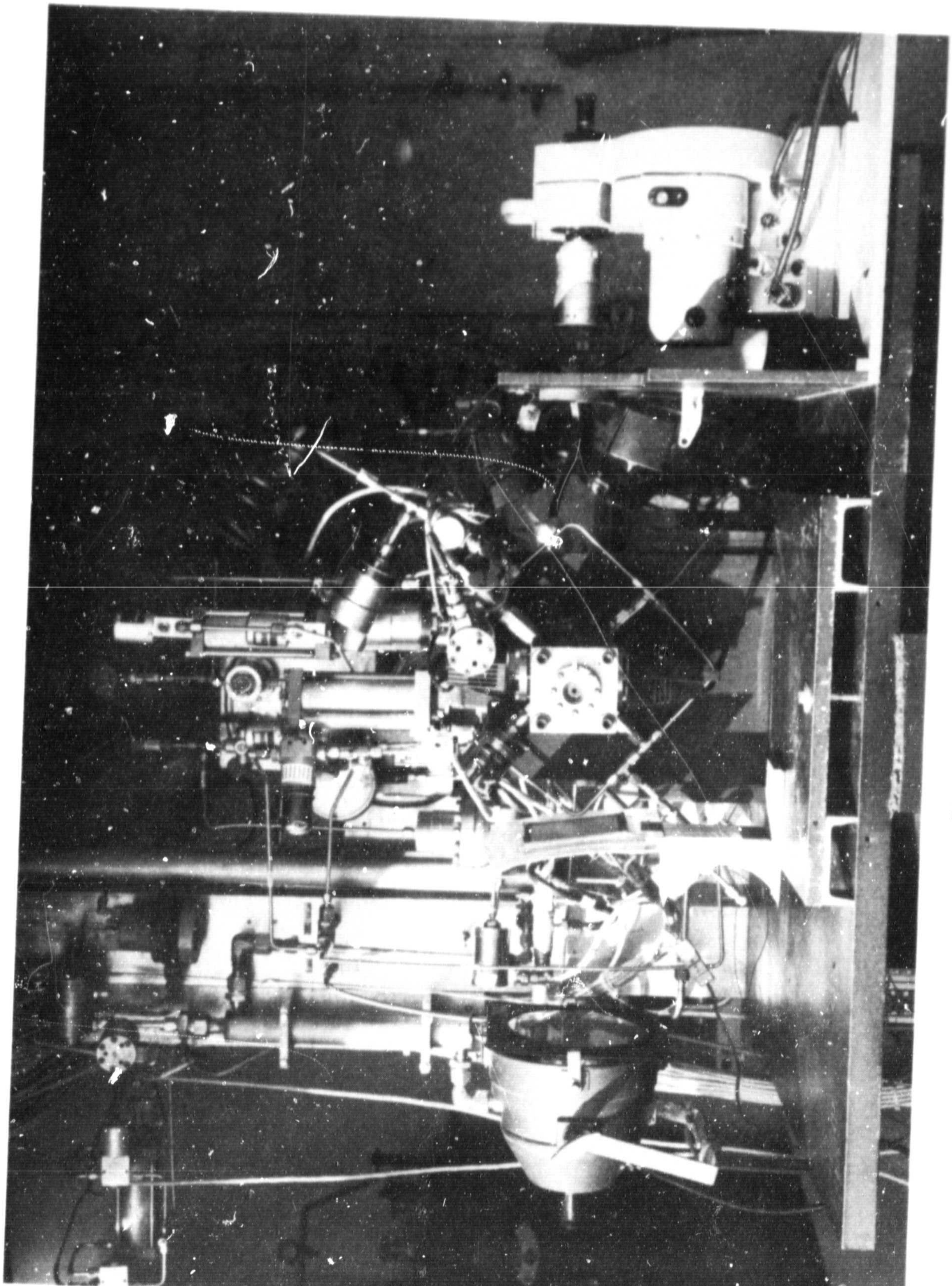


Figure 12. Test Setup

PRESSURE

TEMPERATURE

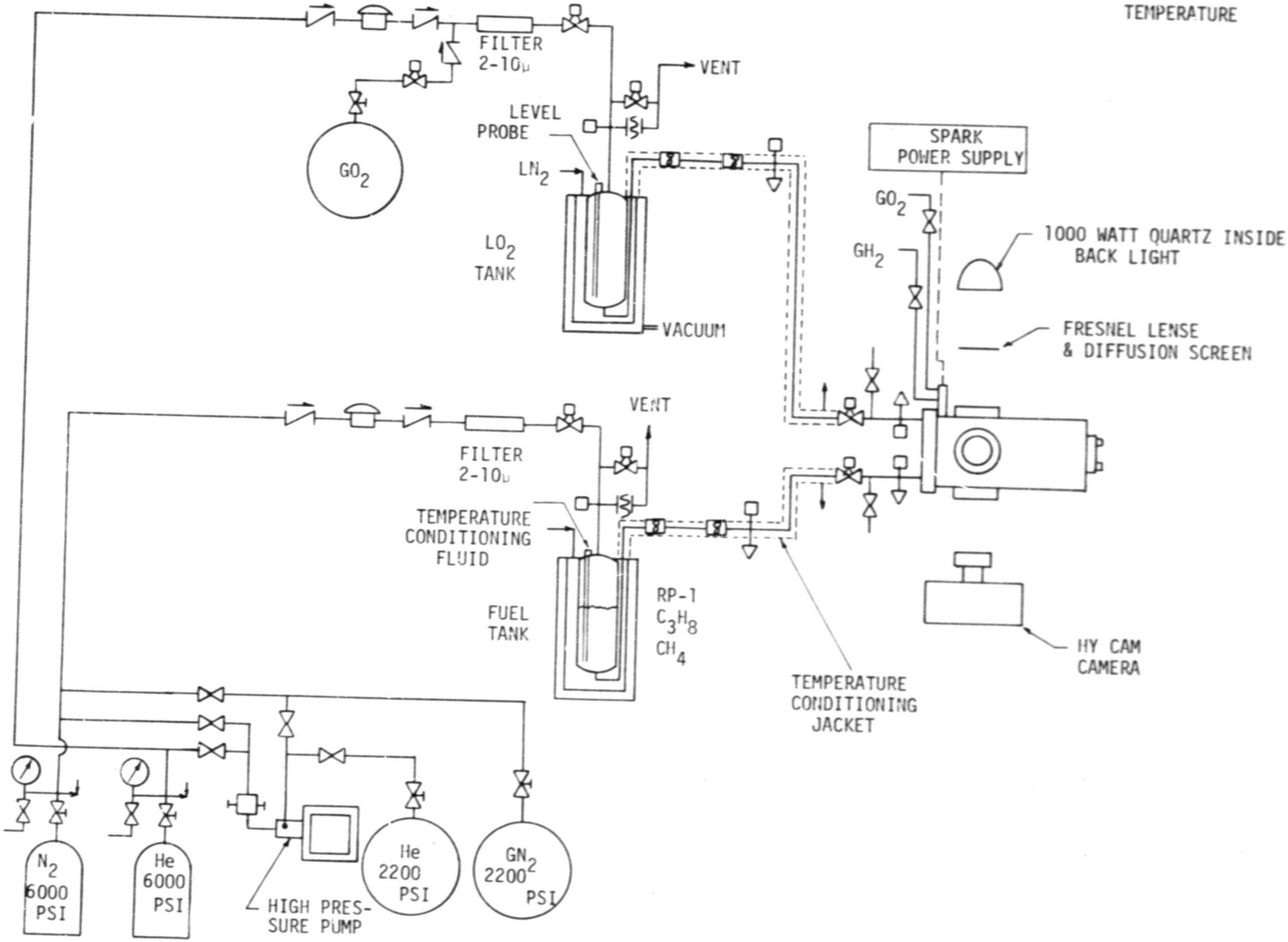


Figure 13. Propellant Flow System Schematic

LOX temperature conditioning was provided by means of the following: (1) LN_2 coolant jacket surrounding the LOX inlet line, (2) addition of a LOX bypass circuit to increase mass flow and keep LOX temperature low, and (3) chilling of the LOX thrust chamber valve with an LN_2 jacket. Both RP-1 and Propane were fired at ambient temperature conditions.

Four separate purges were employed during testing as follows: (1) a helium trickle purge was connected to the oxidizer circuit to prevent contamination or propellant migration, (2) a nitrogen purge was connected to the fuel circuit for the same reason, (3) a separately regulated GH_3 purge was used to provide chamber back pressure as well as provide window purge for the chamber viewports during the start and shutdown transients, (4) a separately regulated GN_2 supply was used to purge the test chamber after shutdown.

3. Cold Flow Test Setup

The cold flow tests were also conducted in the ALRC Research Physics Laboratory. Filtered, de-ionized water was used as the test fluid on most tests. Pressure measurements were made using Heise pressure gages and flow rate was measured using a time/volume technique, with run times of from 60 to 200 seconds. Strobe light photographs were taken of some of the injector flow tests to better evaluate propellant stream properties (see Section IV,C for photos).

4. Hot Fire Instrumentation

The high frequency and low frequency instrumentation listed in Tables I and II were used in the locations shown in the schematic of

TABLE I

HIGH FREQUENCY RESPONSE INSTRUMENTATION

Test Parameter	Symbol	Instrument Make	Instrument Model	Range	Accuracy
Oxidizer Manifold Pressure	POJHF	Kistler	601	0-3000 psi (P-P)	± 0.5%
Fuel Manifold Pressure	PFJHF	Kistler	601	0-3000 psi (P-P)	± 0.5%
Chamber Pressure	PCHF	Kistler	601	0-3000 psi (P-P)	± 0.5%

TABLE II

LOW FREQUENCY RESPONSE INSTRUMENTATION

Test Parameter	Symbol	Range	Units	Recorder "O" Graph	Recorder Tape	Recorder Digital
Ox Tank Pressure	POT	0-2000	PSIA	X		
Fuel Tank Pressure	PFT	0-2000	PSIA	X		
Ox Injector Pressure	POJ	0-2000	PSIA	X		X
Fuel Injector Pressure	PFJ	0-2000	PSIA	X		X
Chamber Pressure	PC	0-1500	PSIA	X		X
Igniter Chamber Pressure	PCI	0-1500	PSIA	X		X
Ox Flowrate	WO	0-0.2	LB/SEC	X		X
Fuel Flowrate	WF	0-0.2	LB/SEC	X		X
Ox Flowmeter Temp	TOFM	-300-100	°F	X		X
Fuel Flowmeter Temp	TFFM	0-500	°F	X		X
Ox Injector Temp	TOJ	-300-100	°F	X		
Fuel Injector Temp	TFJ	0-500	°F	X		
Ox Valve Voltage	VOV			X		
Fuel Valve Voltage	VFV			X		
Camera Voltage	VCAM				X	
Injector Purge Valve Voltage	VIPV			X		
Igniter Ox Valve Voltage	VOVI			X		
Igniter Fuel Valve Voltage	VFVI			X		

Figure 14. Low frequency response test parameters were recorded on a Consolidated Electrodynamics Corporation's direct writing oscillograph. High frequency response data were recorded on a Sangamo Model 3564 analog tape recorder.

Propellant flowrates were measured both by flowmeter and by using injector cold flow Kw's and the measured injection pressure drops. The pressure drops were electronically determined from the POJ, PFJ, and Pc transducers. Transducer bias and zero offsets were accounted for by pretest calibration.

The test operating point data were digitized and processed in an on-line HP 2100A computer. The Physics Lab data reduction program for the N_2O_4/Amine test program was modified for use with LOX/HC type propellants (see Appendix A). Curve fits for various LOX/HC properties such as viscosity, surface tension, density, etc. have been incorporated over the range of anticipated temperatures and pressures (see Appendix B). Figure 15 shows the input to the program and the formulas for the calculations to be made.

B. PHOTOGRAPHIC EQUIPMENT AND TECHNIQUES

The method of photographic characterization initially used was that found to be successful on the N_2O_4/MMH "Blowapart" program. Color high speed photographs of the spray field were taken at a rate of 800 pictures per second and an exposure time of 25μ sec with a Hycam Model 41-0004 high speed camera (Figure 16). Ecktachrome EF No. 7242 film (400 ft rolls) was used. The spray volume was illuminated with one 1000-watt quartz iodine lamp for back lighting and four 750 watt lamps for sidelighting.

Subsequent testing showed that this method was not capable of

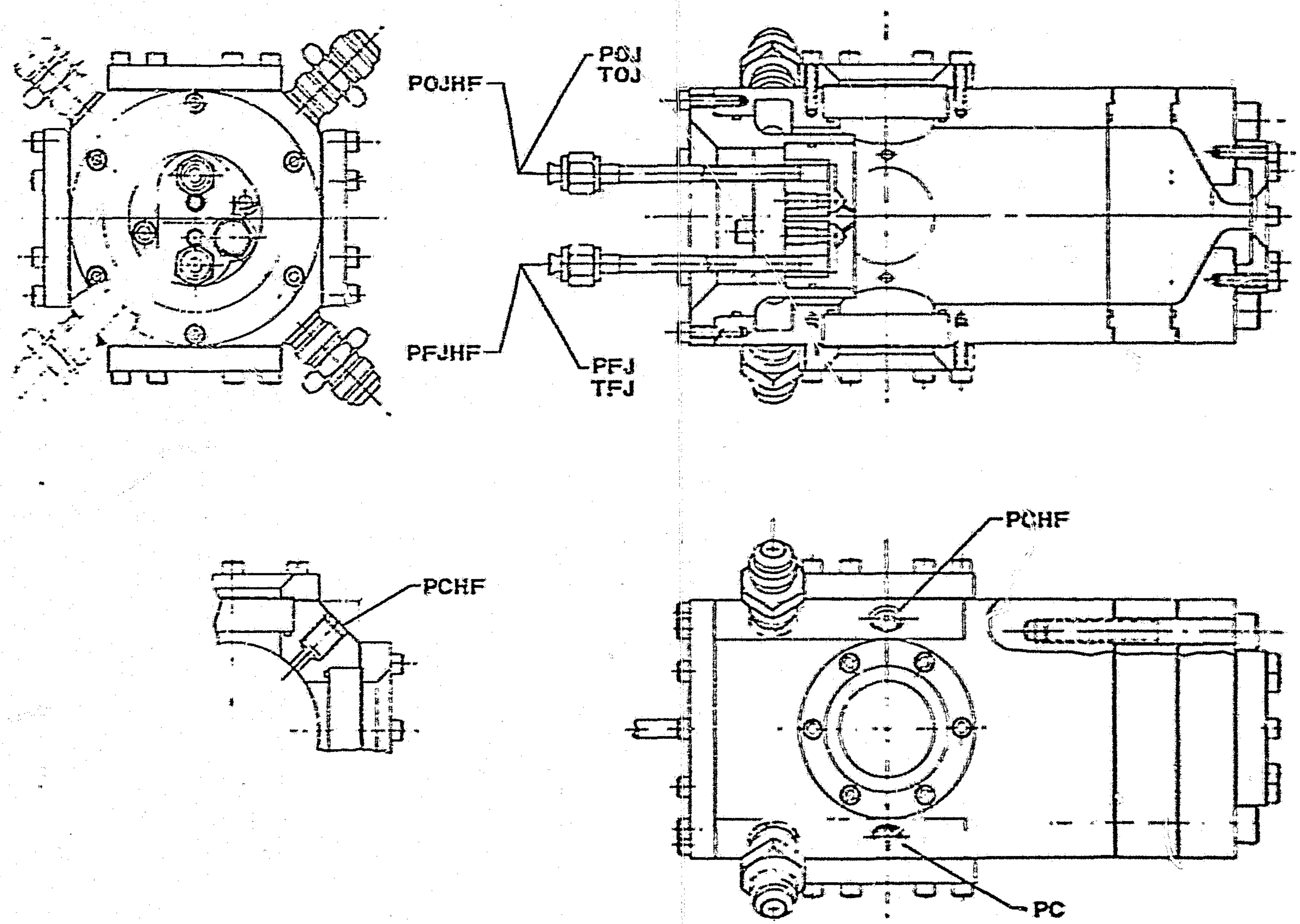


Figure 14. Instrumentation Schematic

Given: D_f (in), D_{ox} (in), D_T (in), $K_{W_{ox}}$, K_{W_f}, Inj Type,

Fuel = RP-1, Propane or Methane; Oxidizer = LOX

ρ (lb/ft^3), μ(lbm/ft-sec), σ(lbf/ft), T = 5000°R

Input from Instrumentation: Pc (psia), TOJ (deg F), TFJ (deg F),

$\dot{W}_f$ (lbm/sec), $\dot{W}_{ox}$ (lbm/sec), POT (psia), PFT (psia)

POJ (psia), PFJ (psia), PCI (psia), TOFM (°F)

TFFM (°F)

Calculations

1. $\Delta P = P_{injection} - Pc$ (psi)

2. $\dot{W} = K_W \sqrt{\Delta P \, \delta}$ $\quad \delta$ = Specific gravity at TOJ or TFJ

3. $A_{orif} = \frac{\pi D^2}{4}$ (in^2)

4. $V = \frac{\dot{W}\,(144)}{\rho \, A_{orif}}$ (ft/sec) $\quad \rho = \delta$ (62.4) lbm/ft^3

5. $Re = \frac{\rho \, V \, D}{\mu \, (12)}$

6. $R = 1545/MW_{combustion}$ $\quad MW_{comb}$ = 24 for RP-1; 23.5 for Propane; and 22 for Methane

7. $WEF = \frac{Pc\,(12)\,V^2\,(D)}{RT\,g\,\sigma}$

8. $CSTAR = \frac{Pc\,A_T\,(.98)\,g_c}{\dot{W}_T}$ $\quad A_T = in^2$

μ = viscosity
ρ = density
σ = surface tension
MW = molecular weight
WEF = Fuel Weber Number

Figure 15. Computer Data Reduction Calculations

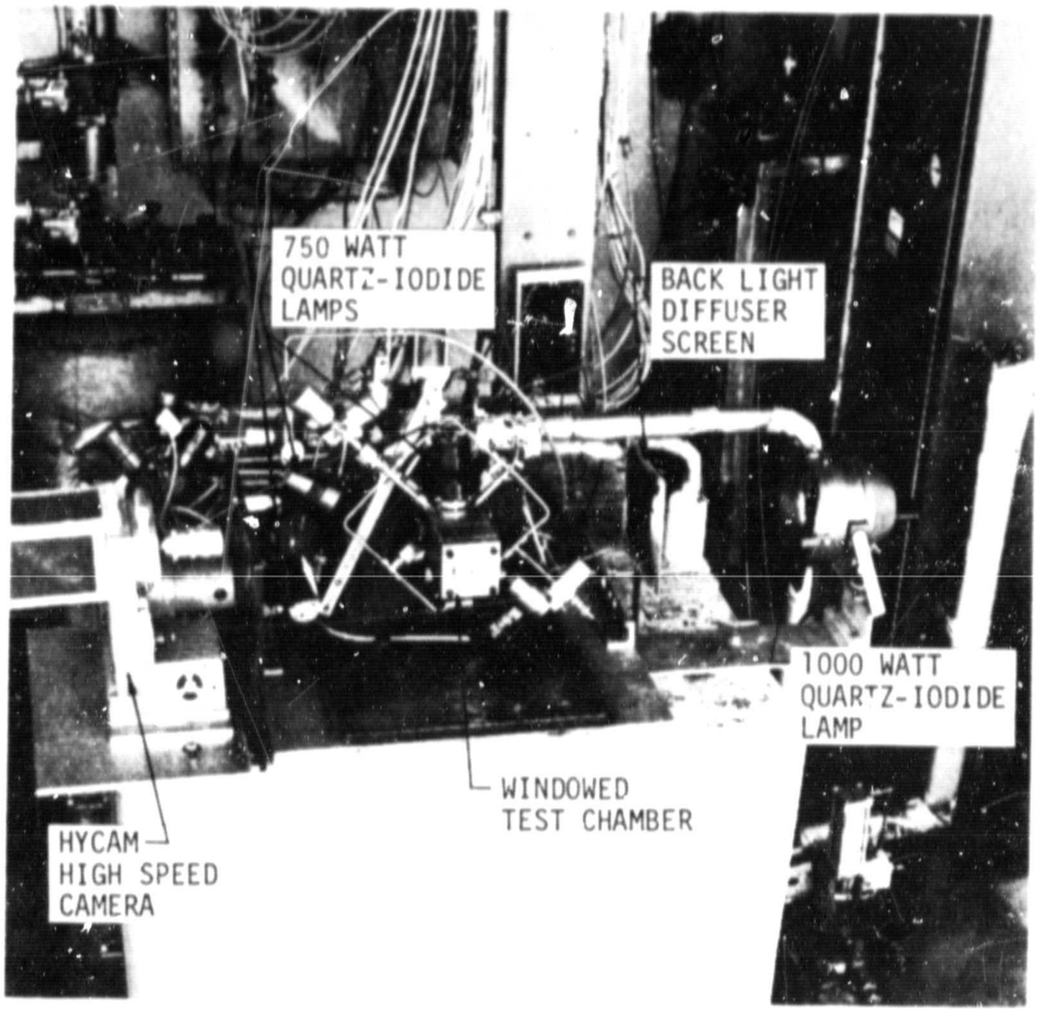


Figure 16. Photographic Equipment Setup

"masking" the bright LOX/HC combustion light and "seeing" into the atomization and mixing process. It was soon discovered that one successful light setting would not be possible for each of the test conditions, as was the case during the Storable Propellant Blowapart program. Instead it was necessary to vary the f-stop, camera speed, and external lighting intensity depending on the chamber pressure, fuel type, and mixture ratio. Consequently a new flashbulb lighting technique was employed which proved much more effective in taking clear, discernible photographs. Each of the incandescent photo-floods was replaced with a large flashbulb (6 megalumen on the two front lights and 2 megalumen for the top, bottom, and back lights). The flashbulbs were triggered during steady state combustion just before shutdown and provided 25 ms of extremely bright light at a film speed of 3200 fps and an f-stop of 16. This technique proved to be much more effective in masking combustion light and seeing into the mixing process than the previous lighting arrangement.

C. TEST RESULTS

A total of 44 hotfire tests of three injectors (OFO, TLOL and RUD), and two fuels (RP-1 and Propane) were conducted between 1 March 1979 and 13 June 1979. Cold flow tests were also conducted to determine the injector element hydraulic resistances and to characterize non-reactive impingement phenomena.

1. Cold Flow Test Results

Each of the injectors were cold flow tested to determine their hydraulic resistance and to verify impingement accuracy. The cold flow tests were conducted in the Research Physics Laboratory. Filtered, de-ionized water was used as the test fluid on most tests. Pressure measurements were made using Heiss pressure gages and flow rate was calculated using a time/volume technique, with run times of from 60 to 200 seconds. Strobe light photographs were taken of the elements to evaluate propellant stream properties.

The hydraulic resistances were determined for each of the elements from plots of flowrate versus pressure drop as shown in Figures 17

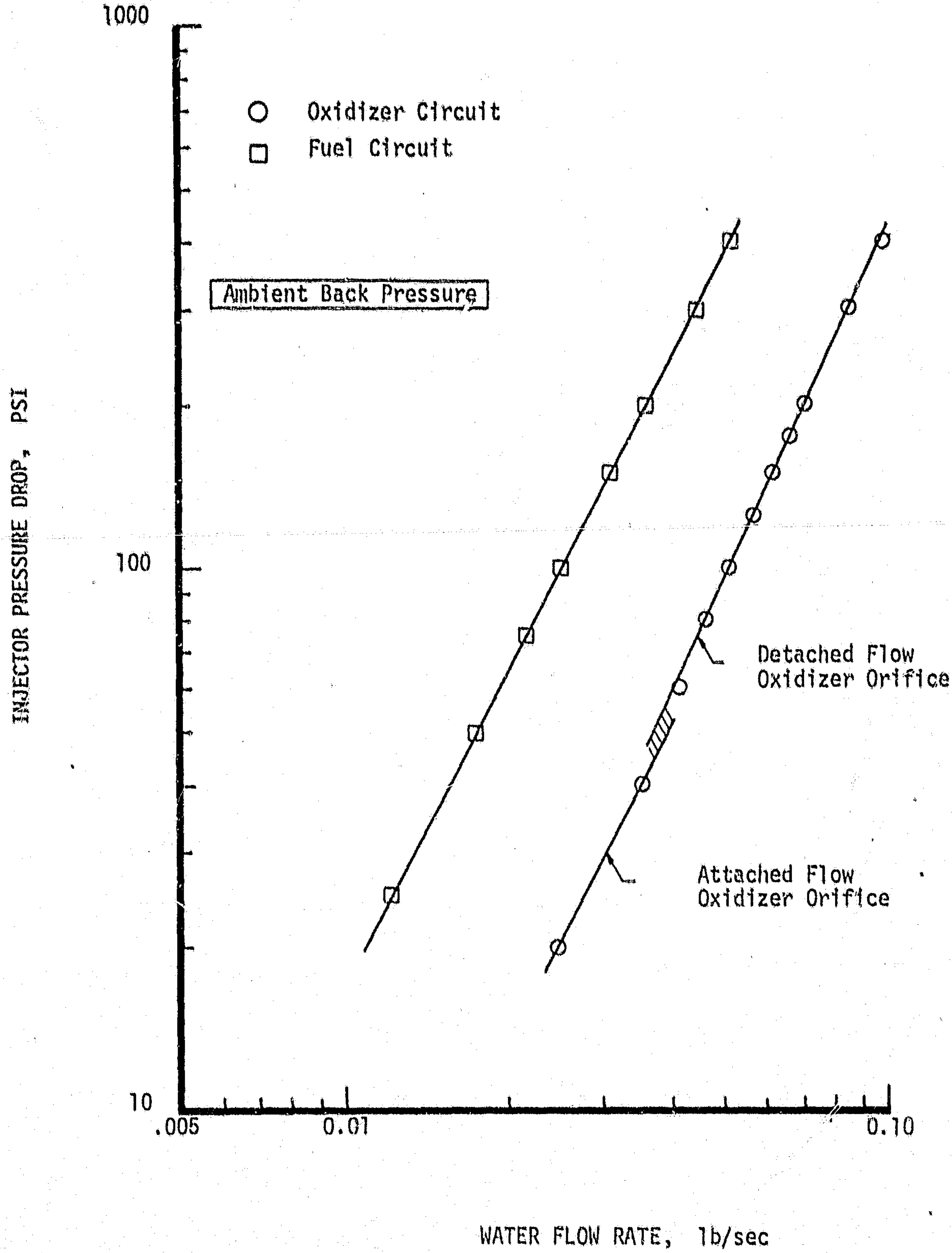


Figure 17. Pressure Drop Characteristics of the OFO Triplet

through 19. Since the RUD injector element was damaged and repaired it was re-cold flowed. A plot of flowrate vs pressure drop for the repaired RUD element is superimposed on Figure 19. The resistance values for the three injectors are shown in Tables III through V.

The OFO triplet was residual hardware from Contract NAS 9-14186 and was shelved for a year after its original cold flow in January 1978. It was re-cold flowed in January 1979 (Figure 17) and yielded results which agreed within approximately 11% of the previous results. In both cases the fuel orifice flowed detached (due to cavitation) at pressure drops above 60 psi. This detachment phenomena did not occur during hotfire because of the increased back pressure. One of the oxidizer jets misimpinged very slightly during cold flow, but the spray fan still appeared to be well mixed.

The TLOL injector element was flowed both as a platelet stack and as a complete injector assembly with similar results. Figure 20 shows the unlike fan impingement of the TLOL at a pressure drop of 40 psi.

The RUD injector element was cold flowed twice because of damage sustained during hotfire testing (see Figures 21 and 22). After being repaired the RUD demonstrated Kw values and mixing qualities very similar to those obtained with the original injector. Figure 23 illustrates the coherent, rectangular jets and the well mixed spray fan obtained from the RUD during cold flow.

2. Hot Fire Test Results

A total of 44 hot fire tests of three injectors (OFO, TLOL, and RUD), and two fuels (RP-1 and Propane) were conducted between 1 March 1979 and 13 June 1979. The original OFO test matrix from Ref. 4 and the

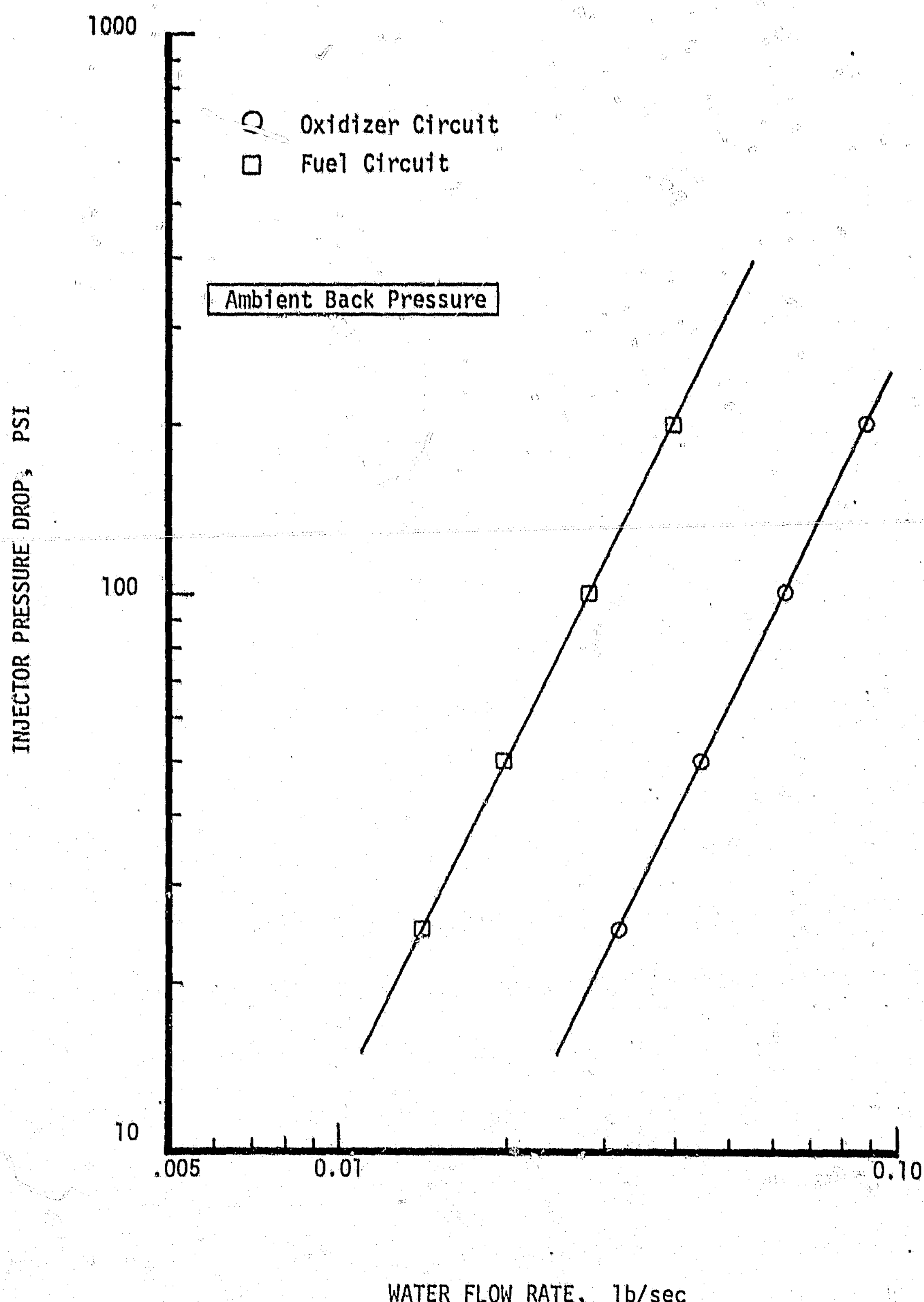


Figure 18. Pressure Drop Characteristics of the TLOL

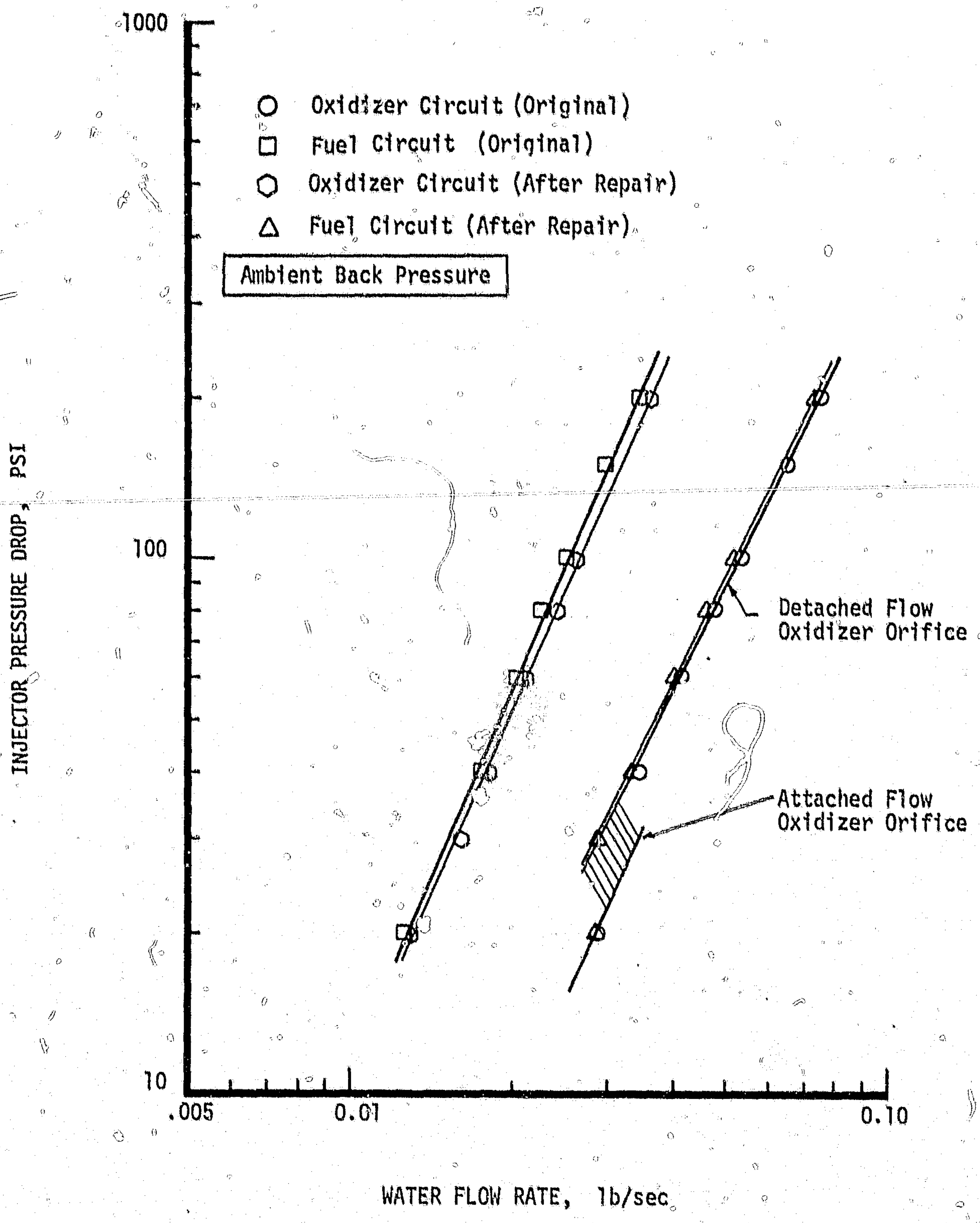


Figure 19. Pressure Drop Characteristics of the RUD Injector

TABLE III

Kw VALUES FOR O-F-O TRIPLET*

January 10, 1978				January 26, 1979			
ΔP_{ox}	$K_{w_{ox}}$	ΔP_f	K_{w_f}	ΔP_{ox}	$K_{w_{ox}}$	ΔP_f	K_{w_f}
20	.005577	25	.002433	20	.005712	20	.002820
40	.00558	50	.002467	40	.005577	40	.002824
60	.005365	75	.002489	60	.005351	60	.002812
80	.005186			80	.005190	80	.002805
100	.005103	100	.002478	100	.005165	100	.002734
200	.004967	200	.002530	250	.004964	250	.002747
400	.004919	400	.002582	500	.004841	500	.002805
				750	.004862	750	.002834

*Values used during hotfire: $Kw_f = .0028$, $Kw_{ox} = .0055$

TABLE IV

Kw VALUES FOR TLOL PLATELET STACK* AND FOR TLOL INJECTOR ASSEMBLY

TLOL PLATELET STACK (3-6-79)

Oxidizer		Fuel	
ΔP_{ox}	Kw_{ox}	ΔP_f	Kw_f
20	.006358	20	.002777
40	.006327	40	.002786
60	.006258	60	.002758
80	.006215	80	.002770
100	.006351	100	.002775
200	.006140	200	.002738
300	.006202	300	.002745

TLOL INJECTOR ASSEMBLY (3-17-79)

Oxidizer		Fuel	
ΔP_{ox}	Kw_{ox}	ΔP_f	Kw_f
25	.00634	25	.00282
50	.00630	50	.00279
100	.00628	100	.00280
200	.00621	200	.00280

*Values used during hotfire: $Kw_f = .0028$, $Kw_{ox} = .00628$

TABLE V

Kw VALUES FOR RUD INJECTOR ASSEMBLY*

Original Cold Flow
(4-6-79)

Oxidizer		Fuel	
ΔP_{Ox}	$K_{W_{ox}}$	ΔP_F	K_{W_F}
20	.006473	20	..2807
40	.005433	40	.002786
60	.005332	60	.002645
80	.005336	80	.002537
100	.005320	100	.002533
150	.005323	150	.002433
200	.005296	200	.002430

After Repair
(5-21-79)

Oxidizer		Fuel	
ΔP_{Ox}	$K_{W_{ox}}$	ΔP_F	K_{W_F}
20	.006354	20	.002881
40	.005224	40	.002891
60	.005166	60	.002758
80	.005130	80	.002709
100	.005176	100	.002643
200	.005179	200	.002570

*Values used during hotfire: Kw_f = .002886, Kw_{ox} = .006354

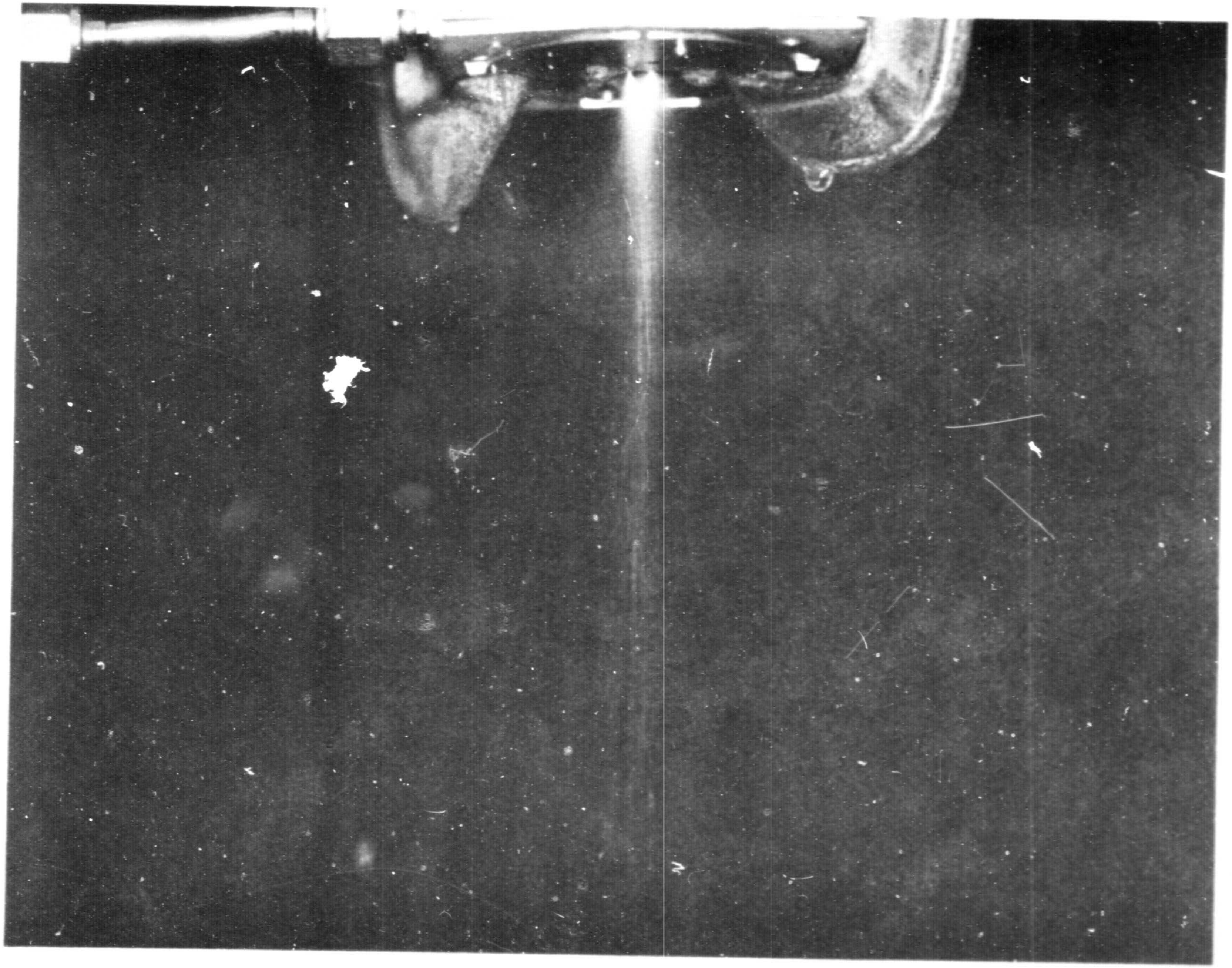


Figure 20. Unlike Fan Impingement of TLOL at ΔP = 40 Psi (Water Flow)

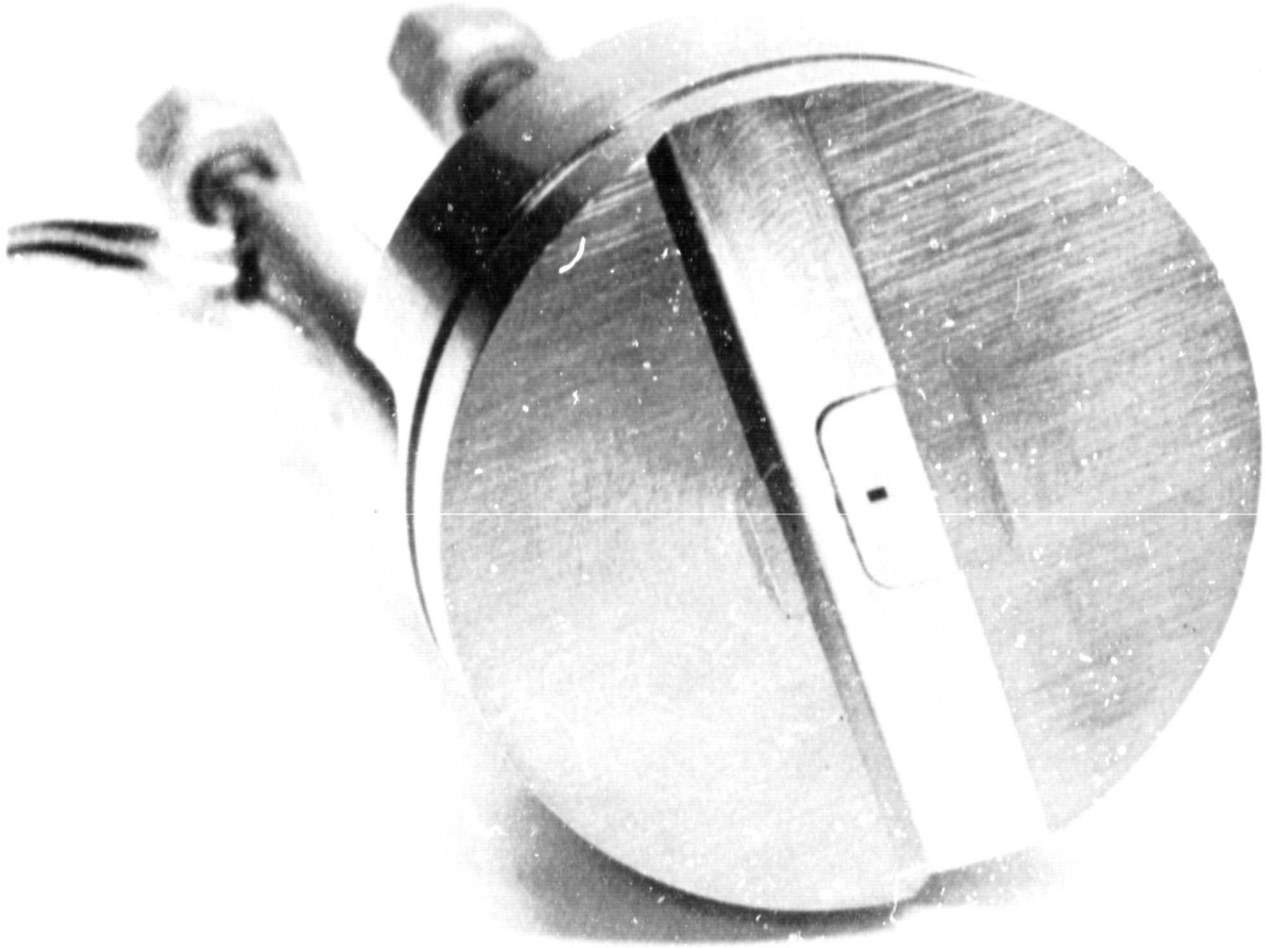


Figure 21. Rectangular Unlike Doublet Injector, Repaired

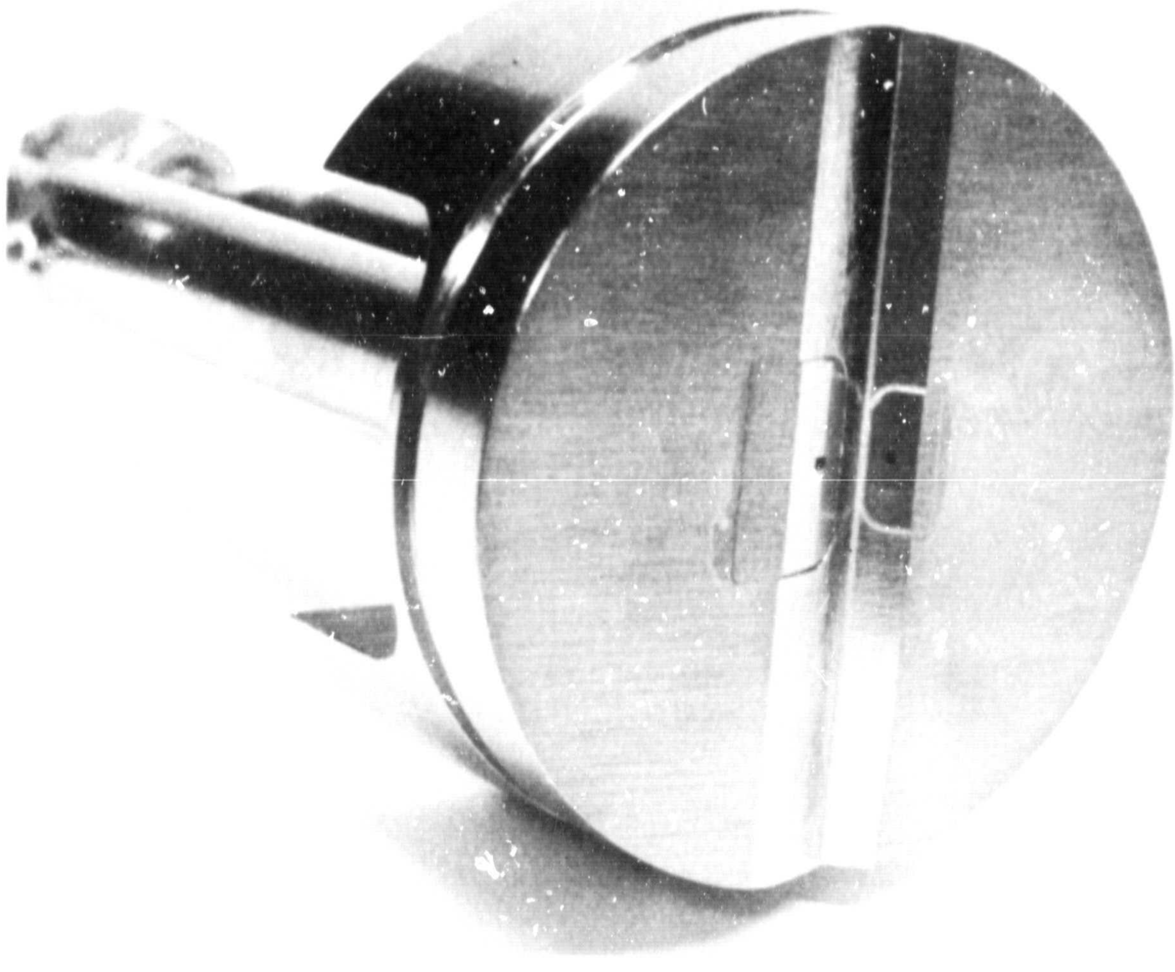
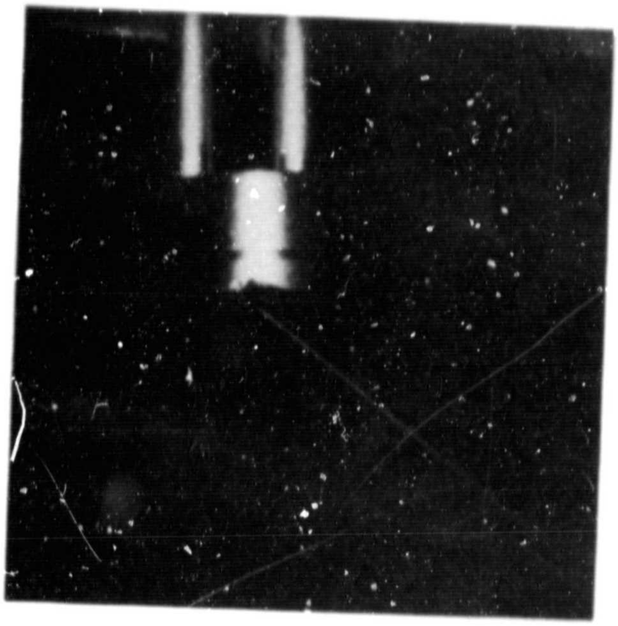
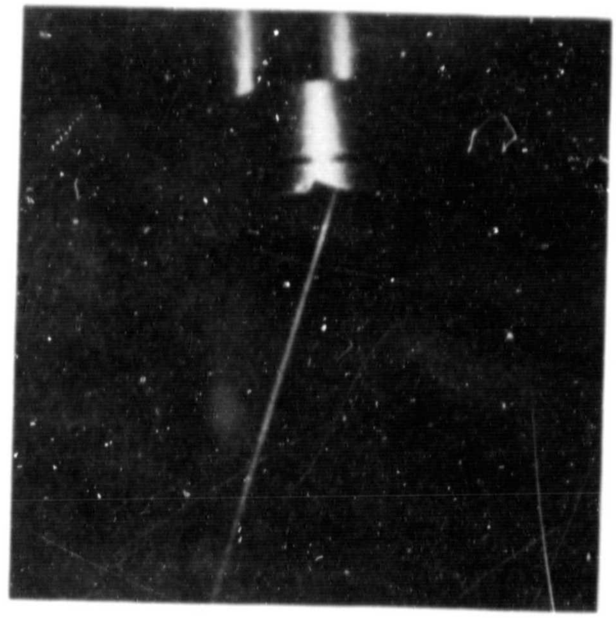


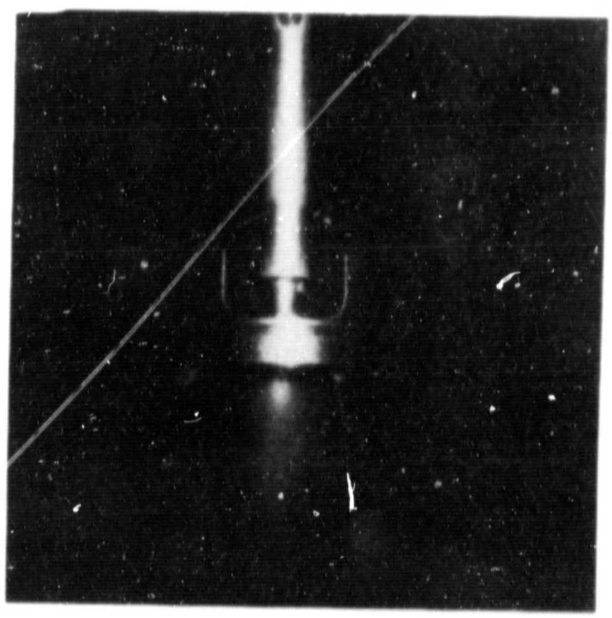
Figure 22. Rectangular Unlike Doublet Injector, Repaired



Fuel Circuit - 20 psig



Oxidizer Circuit - 20 psig



Spray Fan - 20 psig

Figure 23. Cold Flow of RUD Injector Assembly

original test matrix for the TLOL and the RUD from Ref., 5 are shown in Tables VI and VII respectively. The test results along with pertinent comments are summarized in Table VIII. Included in Table VIII is a description of the chamber pressure, type of element, mixture ratio, injection velocities, propellant temperatures, and a list of symbols. Photographs taken from selected tests are shown in Figure 24 (13 pages). These photos are blowups of the high speed 16 mm movie film and will be of assistance in understanding the discussion which follows.

A total of sixteen tests were conducted with the OFO triplet using RP-1 as fuel. The chamber pressure was varied from 450 psia to 1505 psia while the mixture ratio varied from 1.7 to 2.8. These tests were dedicated to checking out the facility and photographic equipment and firming up a successful photographic technique.

Test results showed a very overexposed, turbulent combustion with an extremely bright central flame. There was far too much combustion light to see any droplet details using the baseline camera settings (ASA 125 film, shutter = 1/50, 800 pps, f4). After some test stand and light setting changes the movies showed greater detail, but showed a need for increased external light. The bright central flame which was white in earlier films appeared as a yellow flame interspersed with brownish areas which likely represent decomposing RP-1 and carbon formation. There appeared to be an RSS type of phenomena as evidenced by striations in the spray.

The final OFO tests during early April indicated that the light settings in use represented the optimum to be obtained from conventional photo-flood lighting. Test 114, at 1000 psia and MR = 2.35, appears as a bright central yellow flame interspersed with decomposing RP-1 and carbon formation. Test 116, at 1500 psia and MR = 2.6, differs from Test 114 only in its greater brillance.

TABLE VI

TEST CONDITIONS O-F-O TRIPLET

TEST CONDITION NO.	TEST OBJECTIVE	FUEL	PC (PSIA)	MR	ΔP_f (PSI)	V_f [2] (FT/SEC)	ΔP_{ox} (PSI)	V_{ox} (FT/SEC)
1	System Checkout Tests	RP-1	300	2.9	75	87	93	81
2	System Checkout Tests		500	2.9	125	112	155	105
3	System Checkout Tests		1000	2.9	250	158	310	148
4	System Checkout Tests		1500 [1]	2.9	375	194	465	181
5	Photographic Improvement		500	2.9	125	112	155	105
6	Photographic Improvement		650	2.9	125	112	155	105
7	Evaluate Pc Influence		800	2.9	250	158	310	148
8	Evaluate Pc Influence		1000	2.9	250	158	310	148
9	Evaluate Pc Influence		1200	2.9	250	158	310	148
10	Evaluate Vel. Influence		500	2.9	50	71	62	66
11	Evaluate Vel. Influence		500	2.9	100	100	124	94
12	Evaluate Vel. Influence		500	2.9	500	224	620	209
13	Evaluate MR Influence		500	4.0	125	112	155	105

(1) In the interest of protecting the camera from potential damage during this first test at Pc = 1500 psia, the camera will be removed from the stand.

(2) Assumes $C_{D_f} = 0.735$

$C_{D_{ox}} = 0.737$

TABLE VII

TEST CONDITIONS FOR PHASE I TESTING

Test No.	Injector	Fuel*	Pc (psia)	MR	ΔP_f (psi)	V_f (ft/sec)	ΔP_{ox} (psi)	V_{ox} (ft/sec)	Test Objective
14	TLOL	RP-1	100	2.8	125	87	136	73	Balance and Checkout, and Pc Influence
15	TLOL	RP-1	650	2.8	125	87	136	73	Pc Influence
16	TLOL	RP-1	800	2.8	125	87	136	73	Pc Influence
17	TLOL	RP-1	1500	2.8	125	87	136	73	Pc Influence
18	TLOL	RP-1	650	1.5	125	87	39	39	MR Influence
19	TLOL	RP-1	650	5.0	125	87	435	130	MR Influence
20	TLOL	RP-1	1000	2.8	250	123	273	103	Velocity Influence
21	TLOL	RP-1	1000	2.8	1000	246	1091	206	Velocity Influence
22	RUD	RP-1	100	2.8	125	114	150	105	Balance and Checkout, and Pc Influence
23	RUD	RP-1	1500	2.8	125	114	150	105	Pc Influence
24	RUD	RP-1	650	1.5	125	114	43	56	MR Influence
25	RUD	RP-1	650	2.0	125	114	76	75	MR Influence
26	RUD	RP-1	650	4.0	125	114	305	149	MR Influence
27	RUD	RP-1	650	5.0	125	114	477	187	MR Influence
28	RUD	RP-1	1000	2.8	250	161	185	116	Velocity Influence
29	RUD	RP-1	1000	2.8	1000	321	740	233	Velocity Influence
30	TLOL	C_3H_8	100	3.0	125	111	97	61	Balance and Checkout with Pc Influence
31	TLOL	C_3H_8	650	3.0	125	111	97	61	Pc Influence
32	TLOL	C_3H_8	800	3.0	125	111	97	61	Pc Influence
33	TLOL	C_3H_8	1500	3.0	125	111	97	61	Pc Influence
34	TLOL	C_3H_8	650	1.5	125	111	24	61	MR Influence
35	TLOL	C_3H_8	650	5.0	125	111	269	102	MR Influence
36	TLOL	C_3H_8	1000	3.0	250	157	194	87	Velocity Influence
37	TLOL	C_3H_8	1000	3.0	1000	313	775	173	Velocity Influence
38	RUD	C_3H_8	100	3.0	125	144	106	88	Balance and Checkout
39	RUD	C_3H_8	1500	3.0	125	144	106	88	Pc Influence
40	RUD	C_3H_8	650	1.5	125	144	27	44	MR Influence
41	RUD	C_3H_8	650	2.0	125	144	47	59	MR Influence
42	RUD	C_3H_8	650	4.0	125	144	189	118	MR Influence
43	RUD	C_3H_8	650	5.0	125	144	295	147	MR Influence
44	RUD	C_3H_8	1000	3.0	250	204	212	125	Velocity Influence
45	RUD	C_3H_8	1000	3.0	1000	408	850	250	Velocity Influence

*Fuel at Ambient Temperature

TABLE VIII

SUMMARY OF INJECTOR ELEMENT TEST RESULTS

LIST OF SYMBOLS

DESCRIPTION OF HEADINGS FOR TABLE

Pc	Chamber Pressure (psia)
O/F	Mixture Ratio
T_f	Fuel Temperature (°F)
Noz	Nozzle (Throat) Diameter (in.)
D_F	Fuel Orifice Diameter (in.)
POT	Oxidizer Tank Pressure (psia)
PFT	Fuel Tank Pressure (psia)
ΔP_f	Fuel Circuit Injector Pressure Drop (psi,
V_f	Fuel Injection Velocity (ft/sec)
Rey. No.	Fuel Reynolds Number Based on Diameter
Weber No.	Fuel Weber Number

TABLE VIII (cont.)

TEST CONDITION SUMMARY

Date	Test No.	D_f	Fuel	Pc	MR	T_f	T_o	ΔP_f	Noz	POT (psig)	PFT (psig)	f-Stop	Frame Rate (PPS)	Shutter	Inj. Element	Remarks
3-1-79	101	.0287"	RP-1	460	2.4	50°	-215°	150	.196	634	618	4	800	1/50	OFO	Ox Orifice plugged. Re-cold flow
3-7-79	102	.0287	RP-1	135	-	66°	-	501	.196	633	626	4	800	1/50	OFO	Couldn't get Liq oxygen.
3-7-79	103	.0287	RP-1	467	-	66°	-	137	.196	641	625	4	800	1/50	OFO	0.700 sec. oxid lead to get liq. Pc Spike broke windows
3-14-79	104	.0287	RP-1	462	2.5	60°	-252°	162	.196	635	623	-	-	-	OFO	No camera to evaluate ox rich shutdown & new igniter location. Copper coil LN_2 jacket on oxid inlet line.
3-14-79	105	.0287	RP-1	480	2.78	50°	-275°	134	.196	641	618	8	800	1/50	OFO	ASA 400. Cold flow LOX just prior to FS-1 to cool inj. Broke 2 inserts.
3-14-79	106	.0287	RP-1	488	2.75	50°	-275°	134	.196	645	623	11	800	1/50	OFO	Too hot. Melting parts of chamber. Broke 2 quartz windows.
3-14-79	107	.0287	RP-1	875	2.6	70°	-260°	365	.166	1275	1246	11	800	1/50	OFO	Duration=0.8 sec Still too hot & broke windows.
3-28-79	108	.0287	RP-1	450	1.7	70°	-230°	60	.129	490	513	8	3200	1/50	OFO	Ox FM wouldn't turn. Helium purge used to protect windows. P_{He}=400 psi at check valve.
3-28-79	109	.0287	RP-1	470	2.3	65°	-260°	85	.166	560	560	8	3200	1/50	OFO	Windows still look good. He purge seems to be helping with shutdown.
3-28-79	110	.0287	RP-1	No Digital Data			-258°	-	.234	-	-	11	3200	1/50	OFO	Lost digital data. Analog data looks good. Windows look good.

TABLE VIII (cont.)

Date	Test No.	D_f	Fuel	Pc	MR	T_f	T_o	P_f	Noz	POT (psig)	PFT (psig)	f-Stop	Frame Rate (PPS)	Shutter	Inj. Element	Remarks
3-28-79	111	.0287	RP-1	480	2.7	67°	-255°	275	.234	809	756	16	3200	1/50	OFO	Repeat of 110 except for F-stop. No inserts on side windows and they were slightly cracked.
3-28-79	112	.0287	RP-1	900	2.5	72°	-258	142	.113	1067	1054	11	3200	1/50	OFO	Pc spike of 1750 broke 2 windows. Igniter didn't fire.
3-30-79	113	.0287	RP-1	375	2.5	52°	-280°	666	.113	1021	1055	11	3200	1/50	OFO	Spark plug did-not work. No ignition.
3-30-79	114	.0287	RP-1	970	2.35	66°	-238°	104	.113	1071	1069	11	3200	1/50	OFO	Repeat of Test 113. Windows look good.

TABLE VIII (cont.)

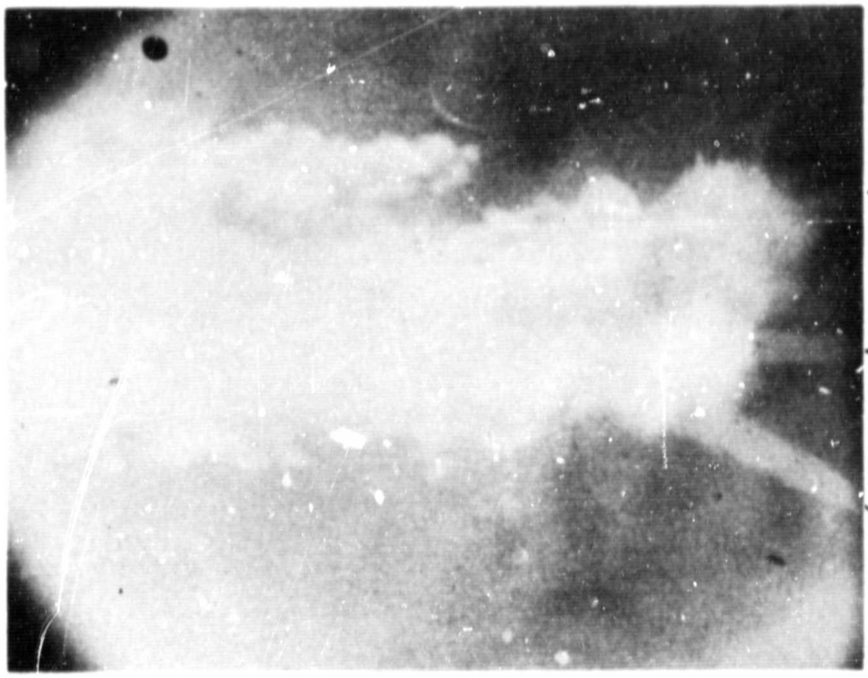
Date	Test No.	Fuel	Inj. Element	Pc	O/F	T_f	Noz.	D_f	POT (psia)	PFT (psia)	ΔP_f	ΔV_f	Rey.No. Fuel	Weber No. Fuel	F-Stop	Frame Rate (FPS)	Shutter	Remarks
4-3-79	115	RP-1	OFO	450	2.6	51°	.10	.0287	1608	1602	1130	335	29048	916	11	3200	1/50	No Spark or Ignition-Cold Flow Test
4-3-79	116	RP-1	OFO	1505	2.6	51°	.10	.0287	1630	1610	101	100	8470	271	11	3200	1/50	Repeat of 115 at lower igniter inlet pressures, windows look good.
4-27-79	117	RP-1	RUD	130	2.6	15°	.281	.0266	165	161	34	57	2498	6.49	11	3200	1/50	Difficulty in flowing liquid oxygen Duration = 1.8 sec.
4-27-79	118	RP-1	RUD	854	2.9	71°	.166	.0266	965	932	72	84	9151	107	11	3200	1/50	Igniter fuel valve hung up. Chamber over-pressure and injector damage resulted during start.

TABLE VIII (cont.)

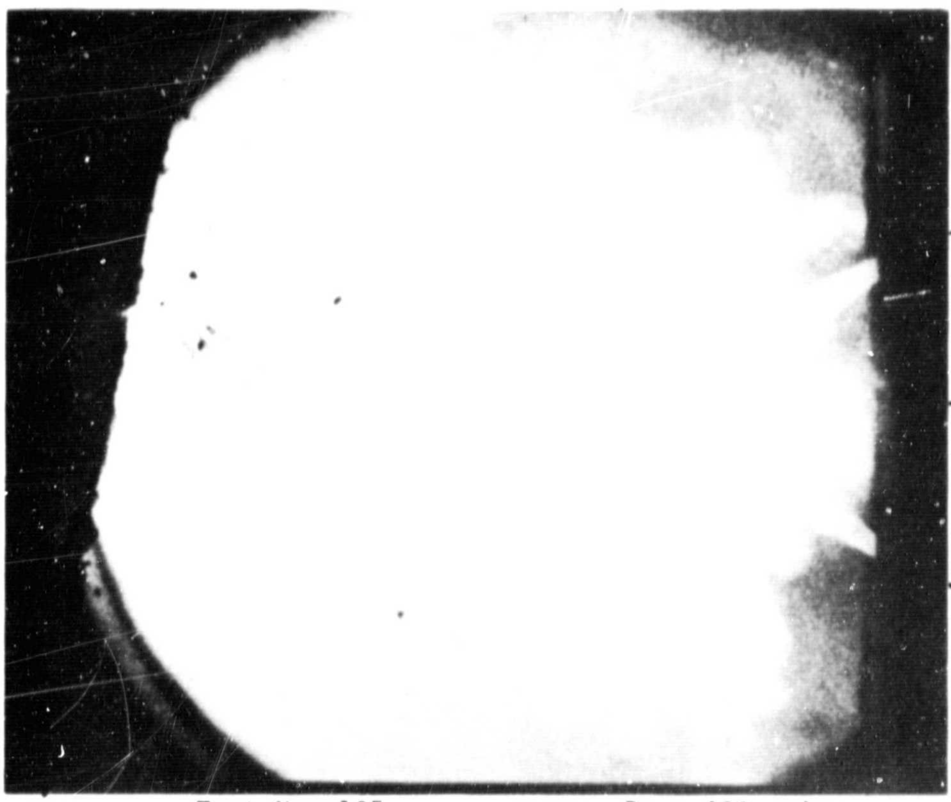
Date	Test No.	Fuel	Inj. Element	Pc	O/F	T_f	Noz.	D_f	POT (psia)	PFT (psia)	ΔP_f	V_f	Rey No. Fuel	Weber No. Fuel	f-Stop	Frame Rate (fps)	Shutter	Remarks
5-2-79	119	RP-1	TLOL	140	Very Erratic	7°	.281	.024	213	192	17	32	1196	2.11	11	3200	1/50	Facility Kill. Difficulty flowing liquid.
5-2-79	120	RP-1	TLOL	136	2.4	41°	.281	.024	180	192	55	59	3840	6.95	11	3200	1/50	Repeat of 119. Dur = 2.0 sec.
5-2-79	121	RP-1	TLOL	310	2.8	38°	.213	.024	362	354	45	53	3140	12.73	11	3200	1/50	Looks Good. Dur = 1.5 sec.
5-2-79	122	RP-1	TLOL	785	2.7	40°	.166	.024	976	934	144	95	6014	105	11	3200	1/50	Looks Good. Dur = 0.8 sec.
5-2-79	123	RP-1	TLOL	475	2.65	36°	.189	.024	604	582	106	82	4705	46.3	16	3200	1/50	With 5 flash bulbs. Dur = 0.8 sec. Looks good.
5-2-79	124	RP-1	TLOL	475	2.65	35°	.189	.024	607	587	110	83	4797	48	22	3200	1/50	Repeat of 123 at new light setting.
5-2-79	125	RP-1	TLOL	472	2.5	35°	.189	.024	597	587	110	83	4776	48	22	6000	1/50	Repeat of 123 at new light setting.
5-11-79	126	RP-1	TLOL	130	Very Erratic	30°	.25	.024	170	174	35	47	2000	4.24	16	3200	1/50	Trouble flowing liquid. Four megalumen flashbulbs used.
5-11-79	127	RP-1	TLOL	250	2.85	30°	.213	.024	305	291	37	48	2495	8.45	16	3200	1/50	Good test. Dur = 2.0 sec.
5-11-79	128	RP-1	TLOL	400	3.1	39°	.196	.024	496	466	63	63	3426	23.15	16	3200	1/50	Good test. Dur = 2.0 sec.
5-11-79	129	RP-1	TLOL	800	2.8	45°	.166	.024	964	944	134	92	5847	99.67	16	3200	1/50	Good test. Five megalumen flashbulbs used. Dur = 1.5 sec.
5-22-79	130	C_3H_8	TLOL	134	2.5	45°	.234	.024	156	175	40	63	41607	24	16	3200	1/50	With LOX by-pass circuit. Still trouble flowing liquid.
5-22-79	131	C_3H_8	TLOL	290	2.65	44°	.189	.024	331	352	59	76	49666	76	16	3200	1/50	Looks good.
5-22-79	132	C_3H_8	TLOL	540	3.0	44°	.166	.024	627	636	100	98	64458	235	16	3200	1/50	Looks good.
5-22-79	133	C_3H_8	TLOL	785	2.8	45°	.150	.024	910	935	146	120	78710	516	16	3200	1/50	Looks good.
5-30-79	134	C_3H_8	RUD	-	-	55°	.150	.0266	909	929	863	377	290,000	434	8	3200	1/50	LOX Valve hung up for 0.4 sec. overpressure broke windows.

TABLE VIII (cont.)

Date	Test No.	Fuel	Inj Element	Pc	O/F	T_f	Noz.	D_f	POT (psia)	PFT (psia)	P_f	V_f	Rey. No. Fuel	Weber No. Fuel	f-stop	Frame Rate (FPS)	Shutter	Remarks
6-8-79	135	C_3H_8	RUD	771	2.8	68°	.150	.0264	906	935	164	166	137,923	1294	8	3200	1/50	Shutdown because of calib. problem. No flash.
6-8-79	136	C_3H_8	RUD	785	2.75	57°	.150	.0264	898	935	150	158	121,770	1086	8	3200	1/50	Repeat of 135.Dur=.8 sec. 2 mega. Flashbulbs
6-8-79	137	C_3H_8	RUD	790	2.6	54°	.100	.0264	812	821	28	68	51,148	197	8	3200	1/50	Dur.= .8 sec. 2 mega bulbs
6-8-79	138	C_3H_8	RUD	-	-	54°	.166	.0264	622	642	-	-	-	-	-	-	-	Igniter Pc Auto-Kill
6-8-79	139	C_3H_8	RUD	545	2.9	54°	.166	.0264	622	642	101	129	96,293	476	8	3200	1/50	Repeat of 138,Dur.=.8 Chamber looks good.
6-8-79	140	C_3H_8	RUD	294	2.9	54°	.189	.0264	340	355	59	98	74,006	153	5.6	3200	1/50	Dur.=1.5 sec., Two 5 mega. bulbs on Front lights
6-8-79	141	C_3H_8	RUD	150	3.1	52°	.213	.0264	167	178	24	63	47,125	32	4	3200	1/50	Dur.=1.5 sec. One 5 Mega. and One 6 mega bulb on front lights.
6-13-79	142	C_3H_8	RUD-GG	-	-	60°	.089	.03911	914	934	-	-	-	-	3.3	3200	1/50	LOX TCV Shutdown
6-13-79	143	C_3H_8	RUD-GG	860	.51	60°	.089	.03911	914	934	72	110	128,737	886	3.3	3200	1/50	Dur.=1.8 sec. Two 6 mega. bulbs on front. Excessive sooting.
6-13-79	144	C_3H_8	RUD-GG	850	.50	60°	.089	.03911	902	934	80	116	133,986	556	3.3	800	1/50	Repeat of 143 with Photo-Floods. Broke insert. Sooting

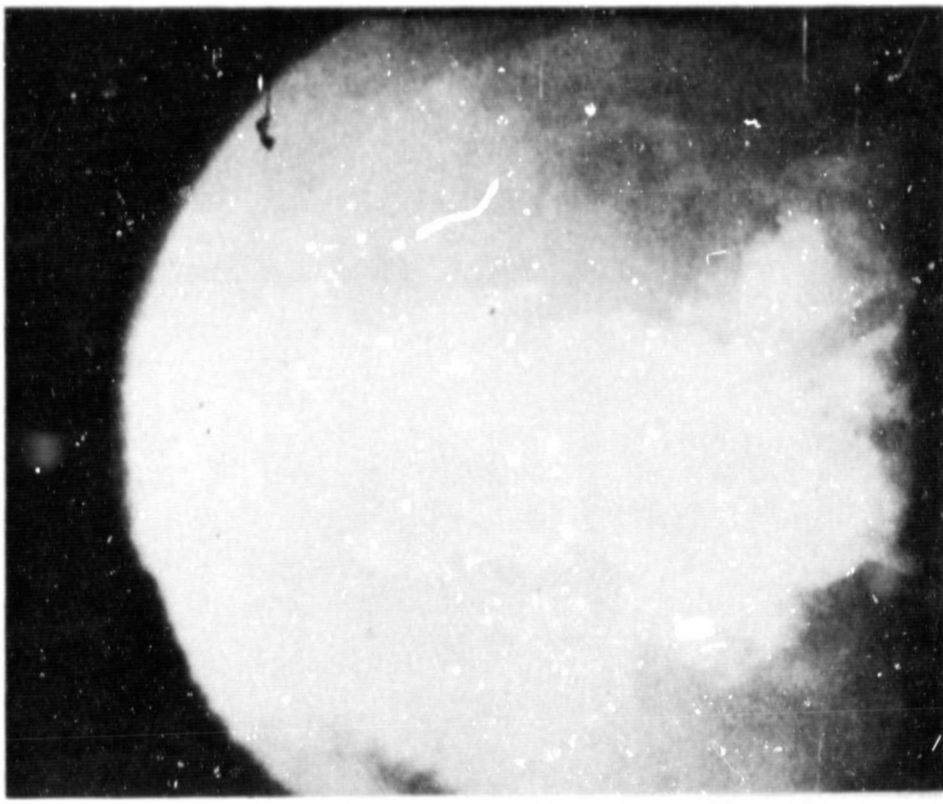


Test No. 101 Pc = 460 psia
Fuel Type: RP-1 O/F = 2.40
Injector Element: OFO



Test No. 105 Pc = 480 psia
Fuel Type: RP-1 O/F = 2.78
Injector Element: OFO

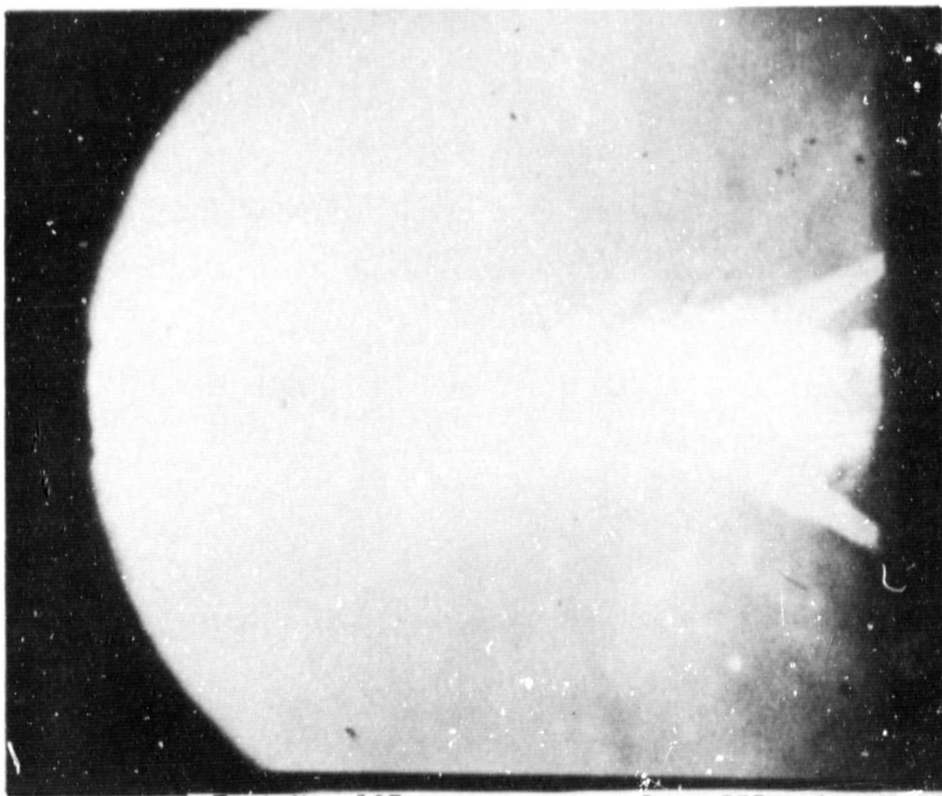
Figure 24. Single Element LOX/HC Combustion (Sheet 1 of 13)



Test No. 106 Pc = 488 psia

Fuel Type: RP-1 O/F = 2.75

Injector Element: OFO

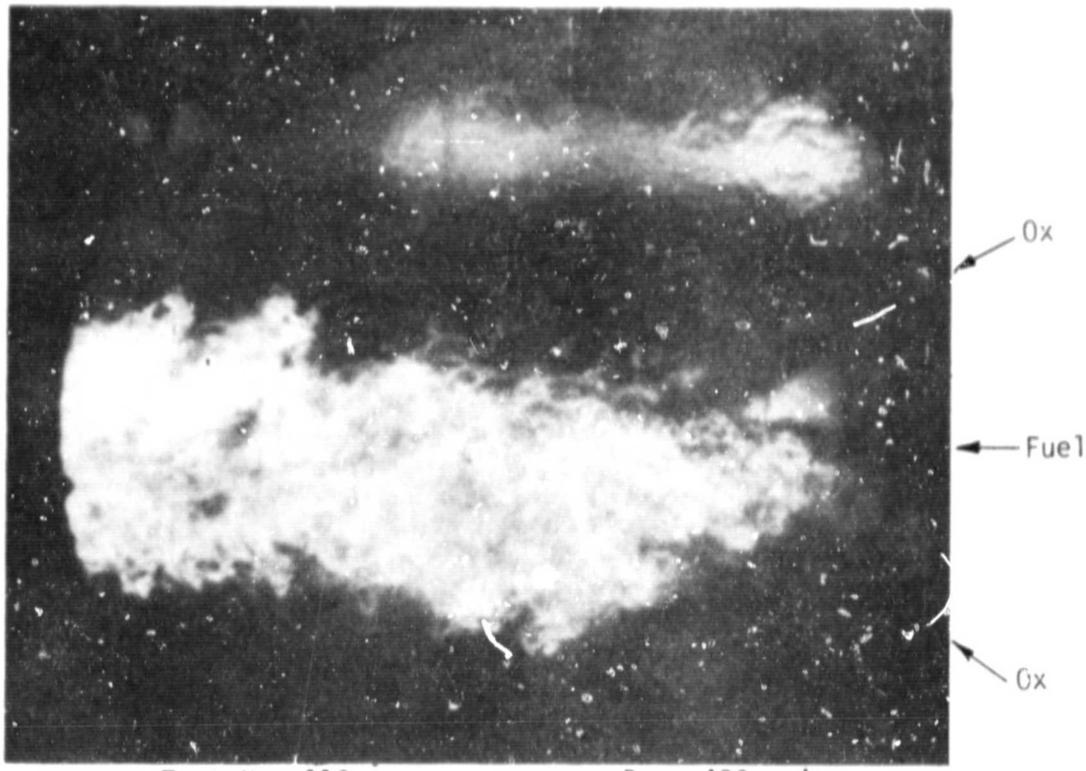


Test No. 107 Pc = 875 psia

Fuel Type: RP-1 O/F = 2.60

Injector Element: OFO

Figure 24. Single Element LOX/HC Combustion (Sheet 2 of 13)



Test No. 110 Pc = 480 psia

Fuel Type: RP-1 O/F = 2.7

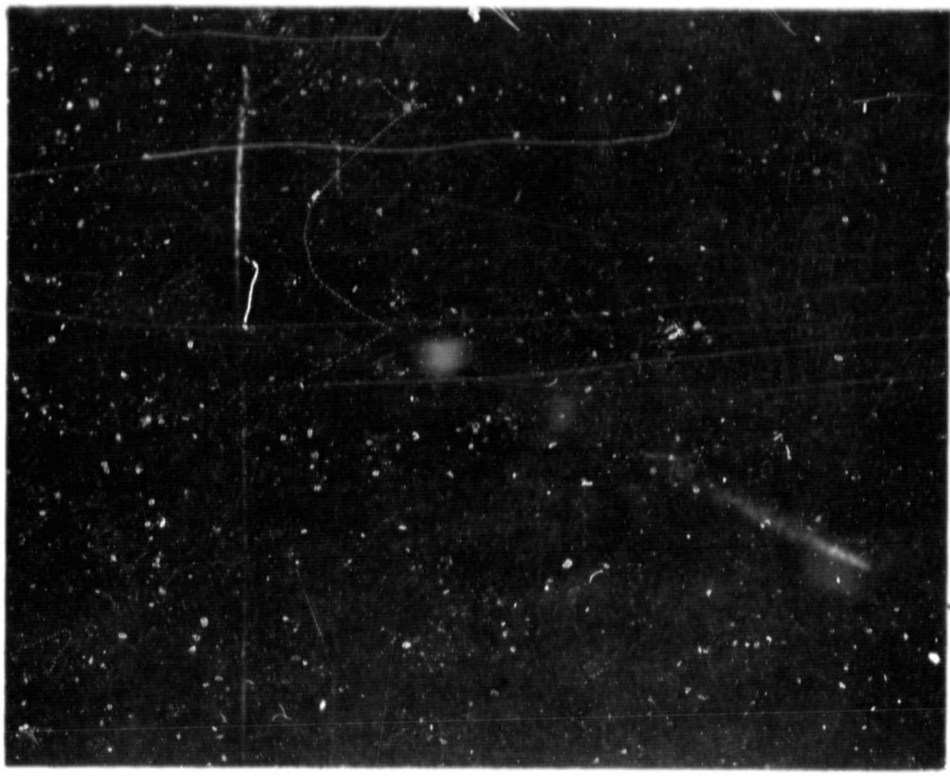
Injector Element: OFO

Test No. 114 Pc = 970 psia

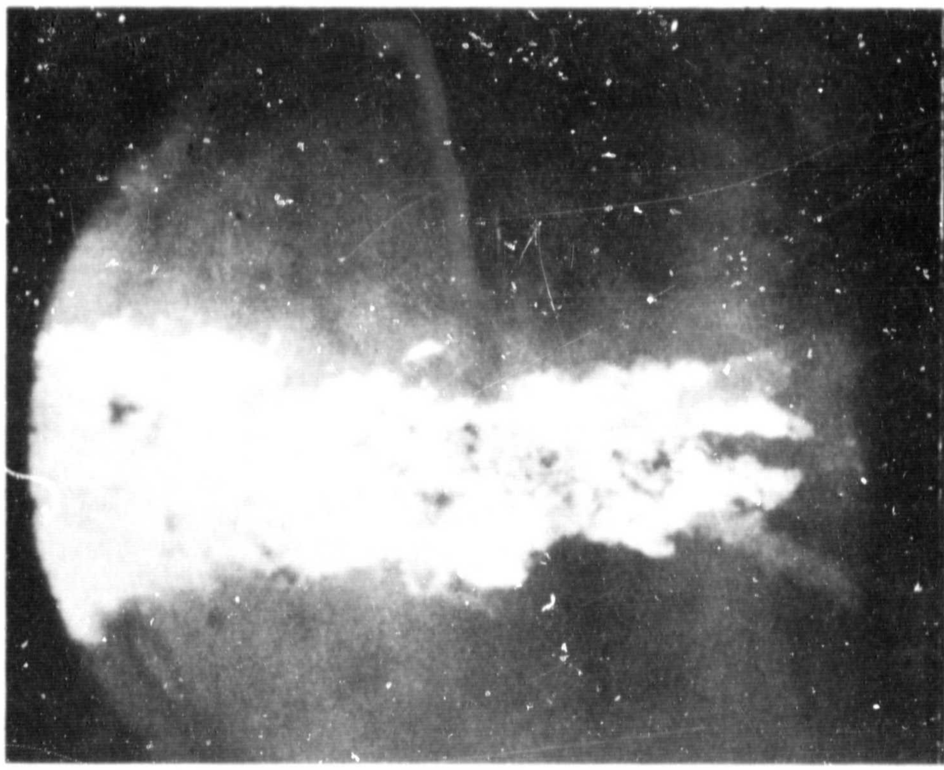
Fuel Type: RP-1 O/F = 2.35

Injector Element: OFO

Figure 24. Single Element LOX/HC Combustion (Sheet 3 of 13)

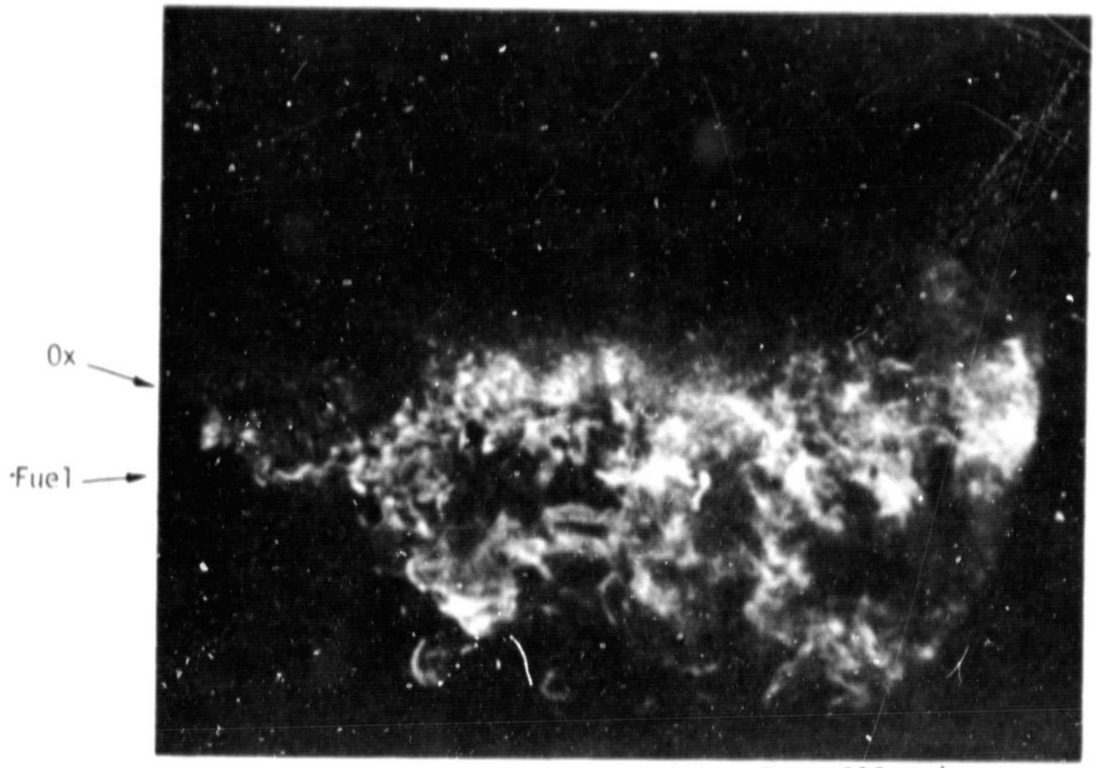


Test No. 115 Pc = — psia
Fuel Type: RP-1 O/F = —
Injector Element: OFO Lox Cold Flow



Test No. 116 Pc = 1505 psia
Fuel Type: RP-1 O/F = 2.60
Injector Element: OFO

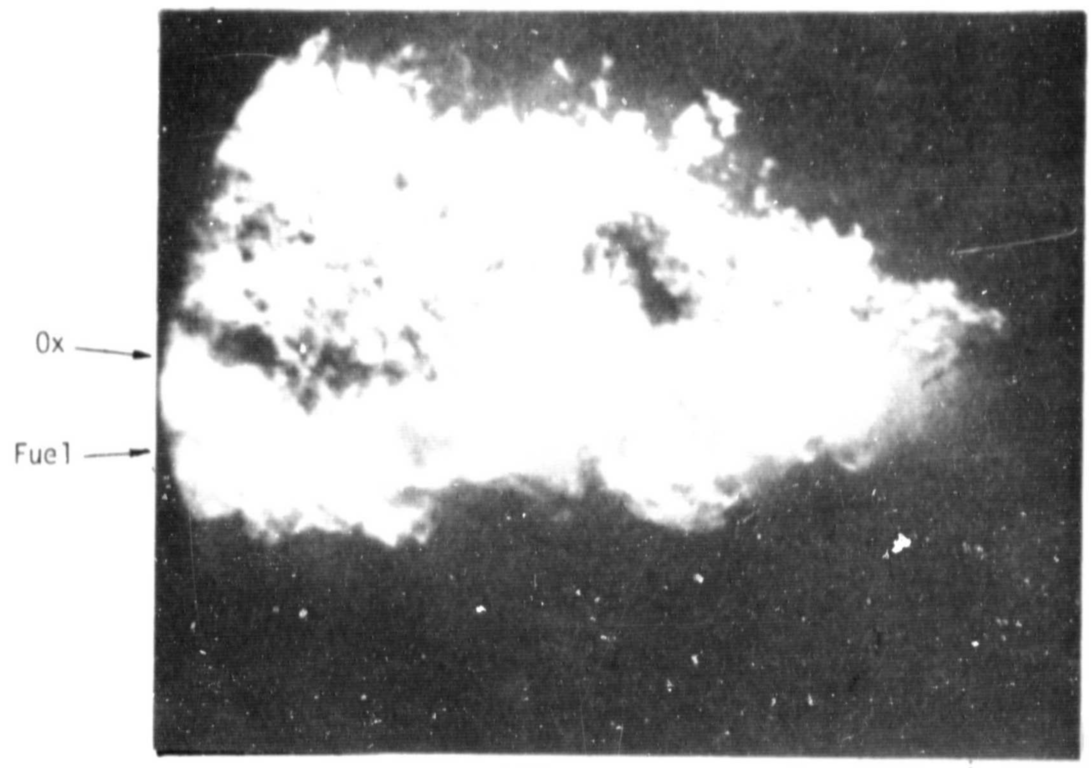
Figure 24. Single Element LOX/HC Combustion (Sheet 4 of 13)



Test No. 121 | Pc = 310 psia

Fuel Type: RP-1 | O/F = 280

Injector Element: TLOL

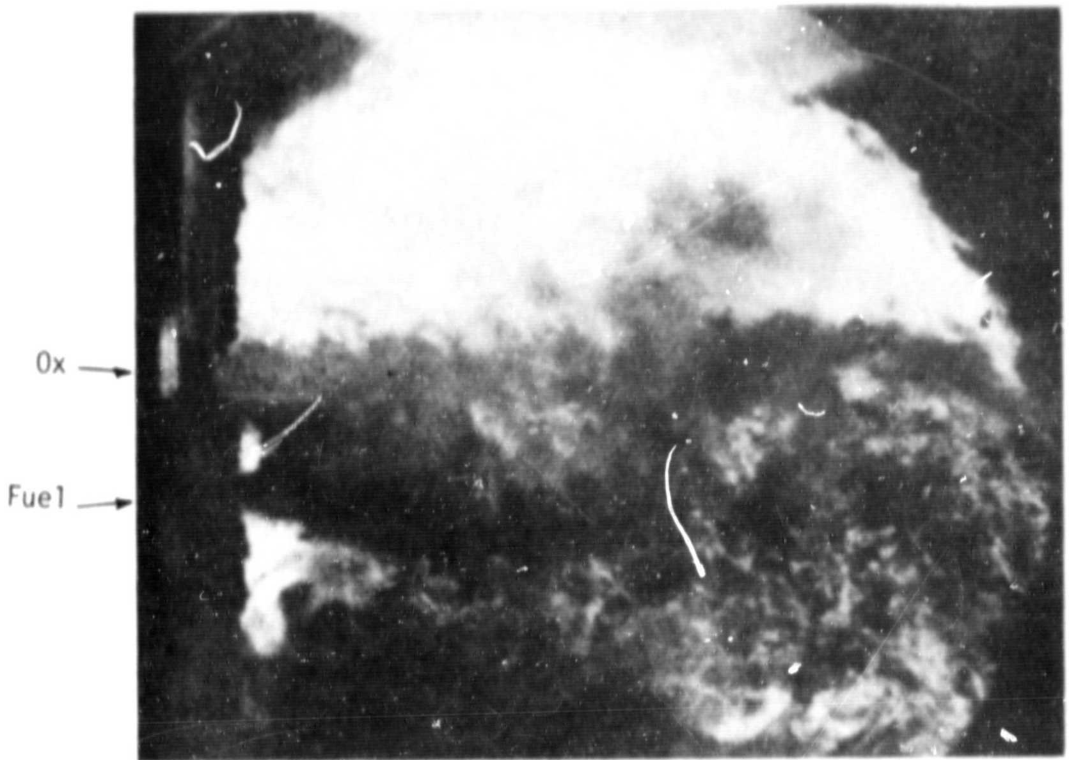


Test No. 122 | Pc = 785 psia

Fuel Type: RP-1 | O/F = 2.70

Injector Element: TLOL

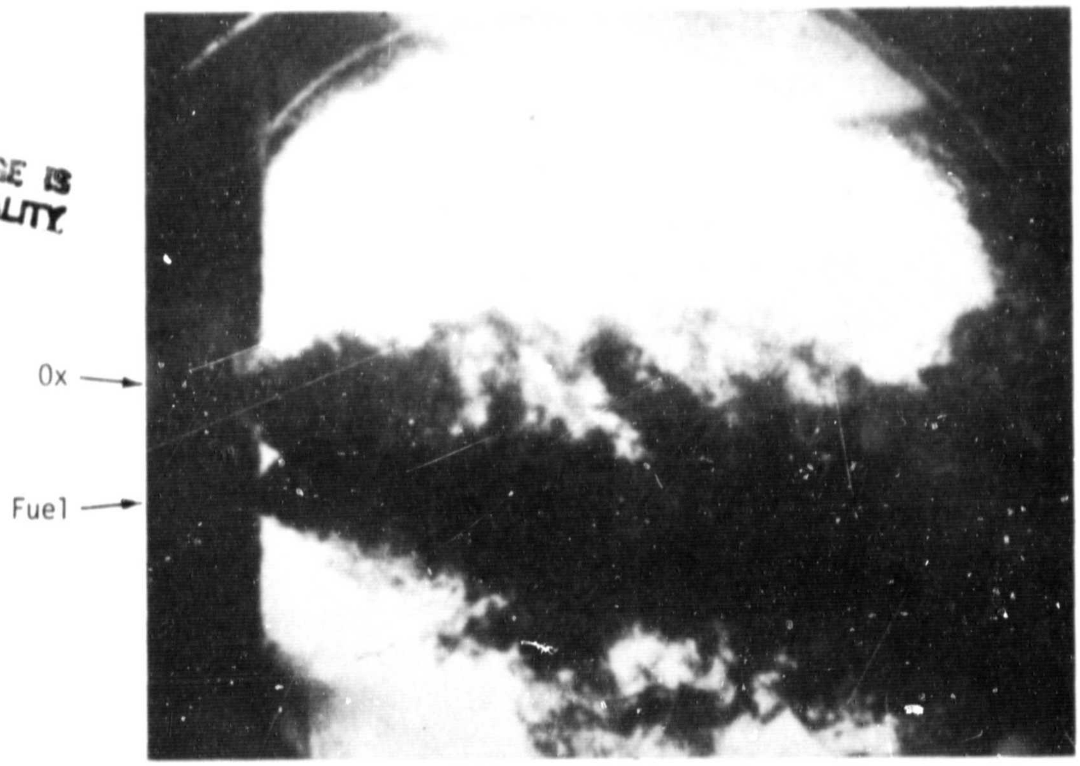
Figure 24. Single Element LOX/HC Combustion (Sheet 5 of 13)



Test No. 123 Pc = 475 psia

Fuel Type: RP-1 O/F = 2.65

Injector Element: TLOL

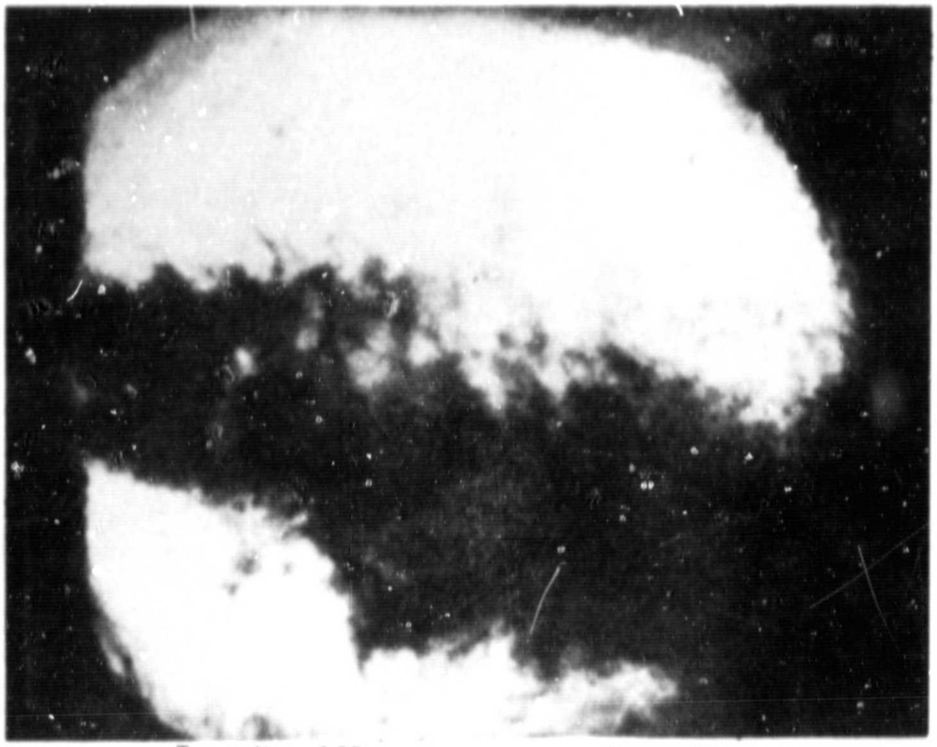


Test No. 124 Pc = 475 psia

Fuel Type: RP-1 O/F = 2.65

Injector Element: TLOL

Figure 24. Single Element LOX/HC Combustion (Sheet 6 of 13)



Test No. 125 Pc = 472 psia

Fuel Type: RP-1 O/F = 2.50

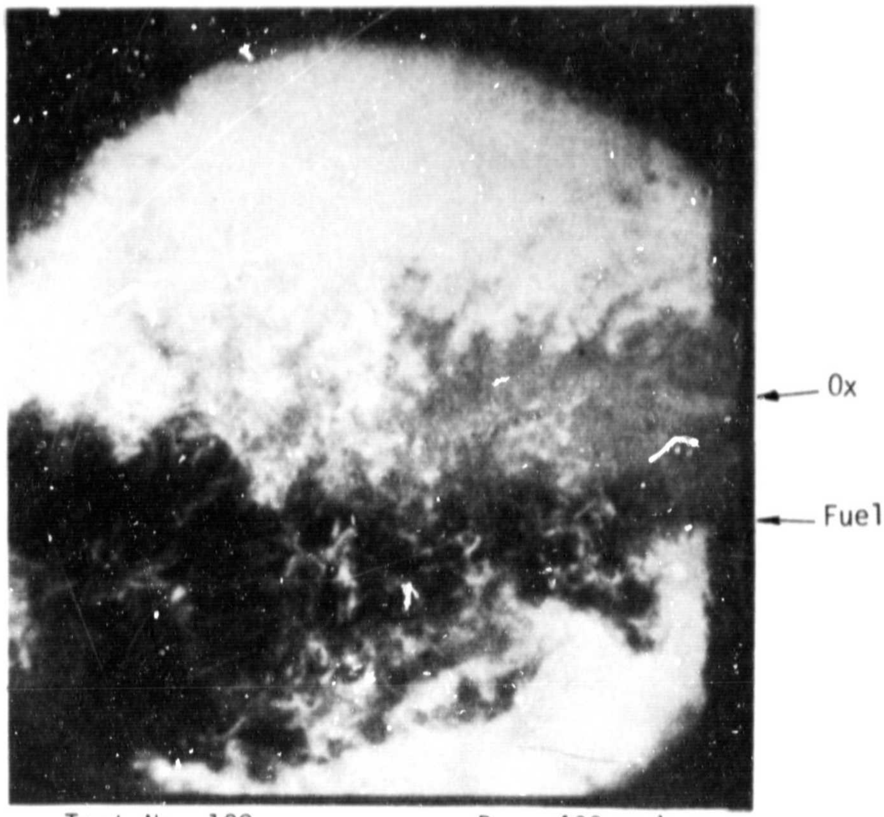
Injector Element: TLOL

Test No. 127 Pc = 250 psia

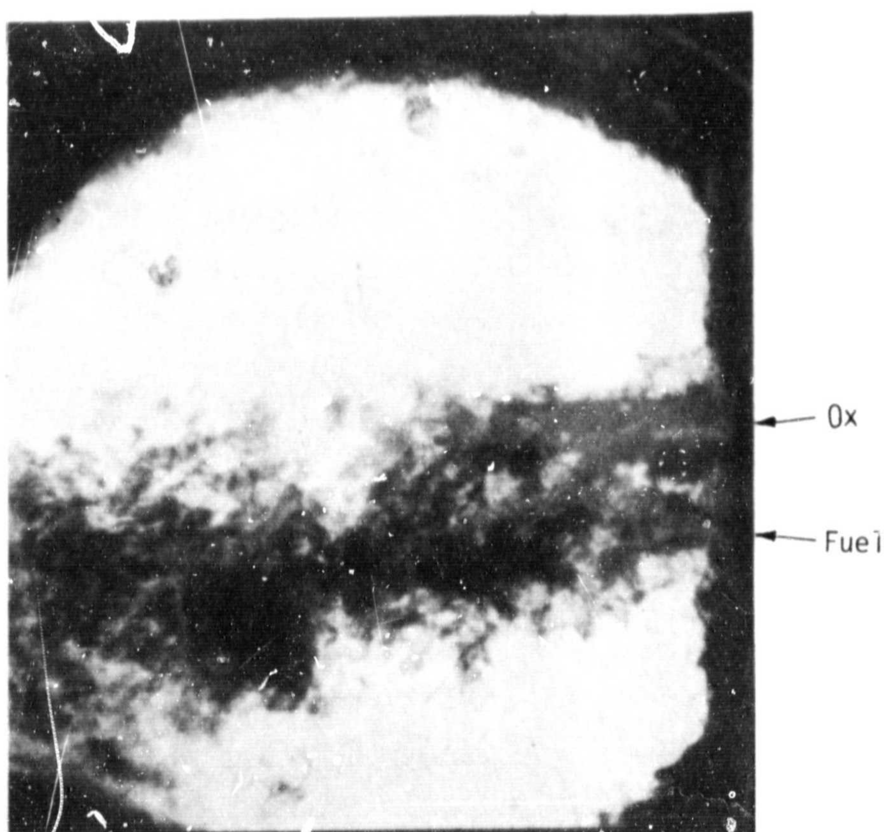
Fuel Type: RP-1 O/F = 2.85

Injector Element: TLOL

Figure 24. Single Element LOX/HC Combustion (Sheet 7 of 13)

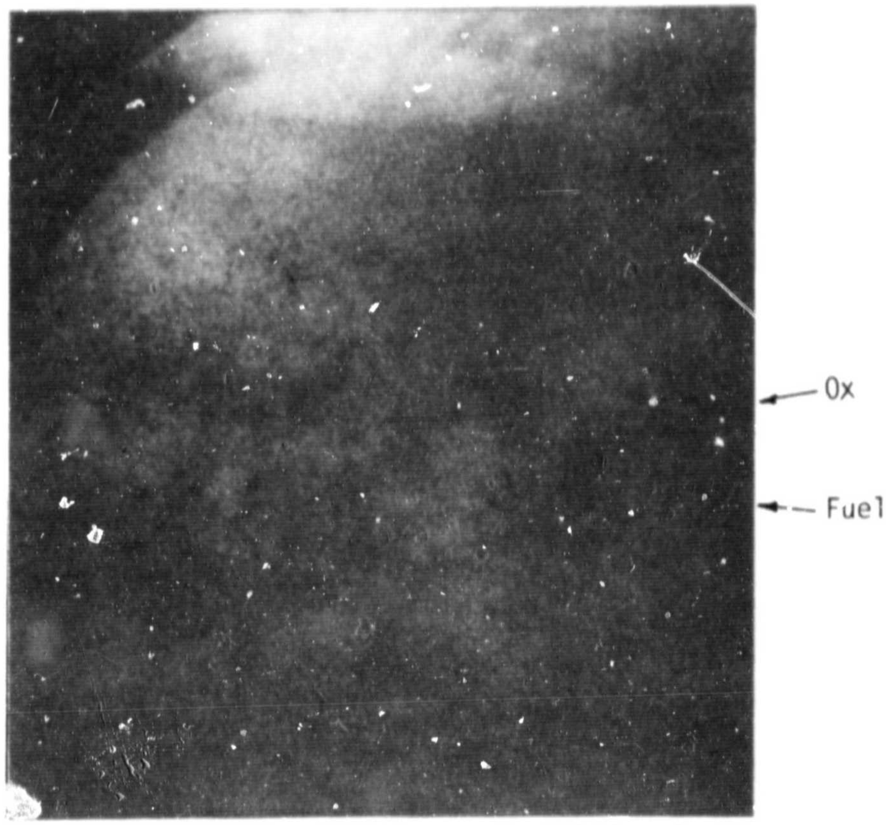


Test No. 128 Pc = 400 psia
Fuel Type: RP-1 O/F = 3.10
Injector Element: TLOL



Test No. 129 Pc = 800 psia
Fuel Type: RP-1 O/F = 2.8
Injector Element: TLOL

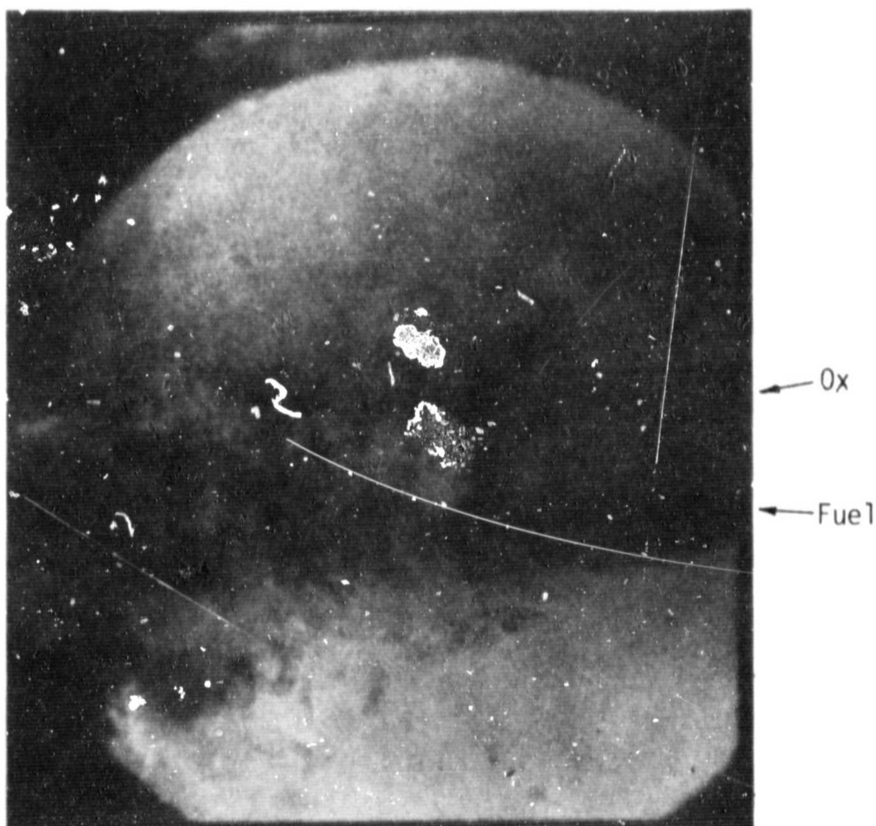
Figure 24. Single Element LOX/HC Combustion (Sheet 8 of 13)



Test No. 130 Pc = 134 psia

Fuel Type: C_3H_8 O/F = 2.50

Injector Element: TLOL

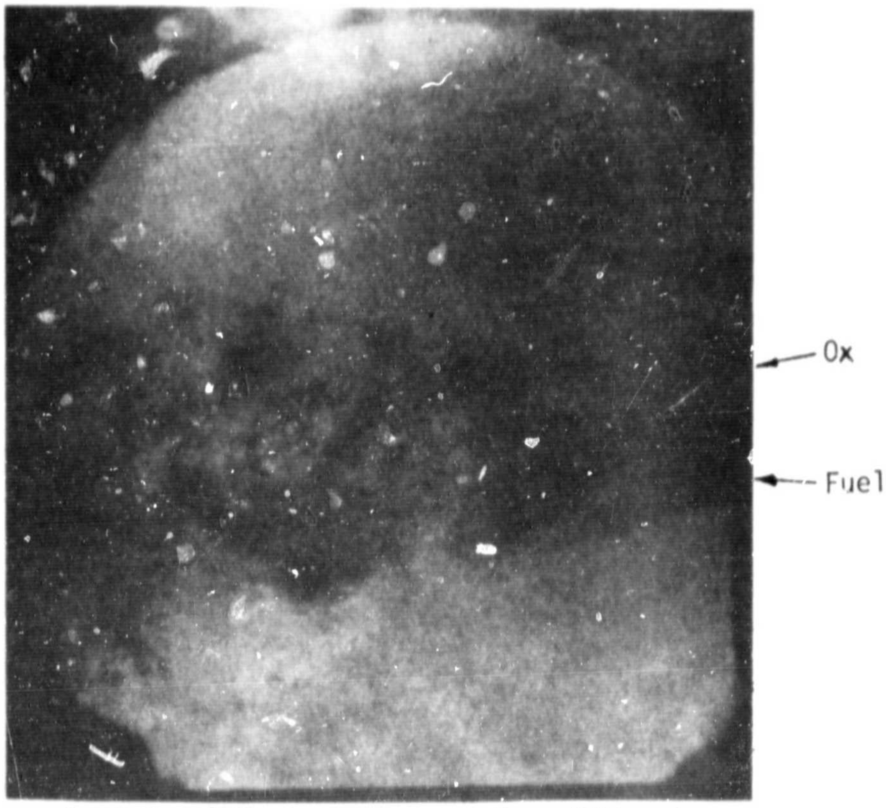


Test No. 131 Pc = 290 psia

Fuel Type: C_3H_8 O/F = 2.65

Injector Element: TLOL

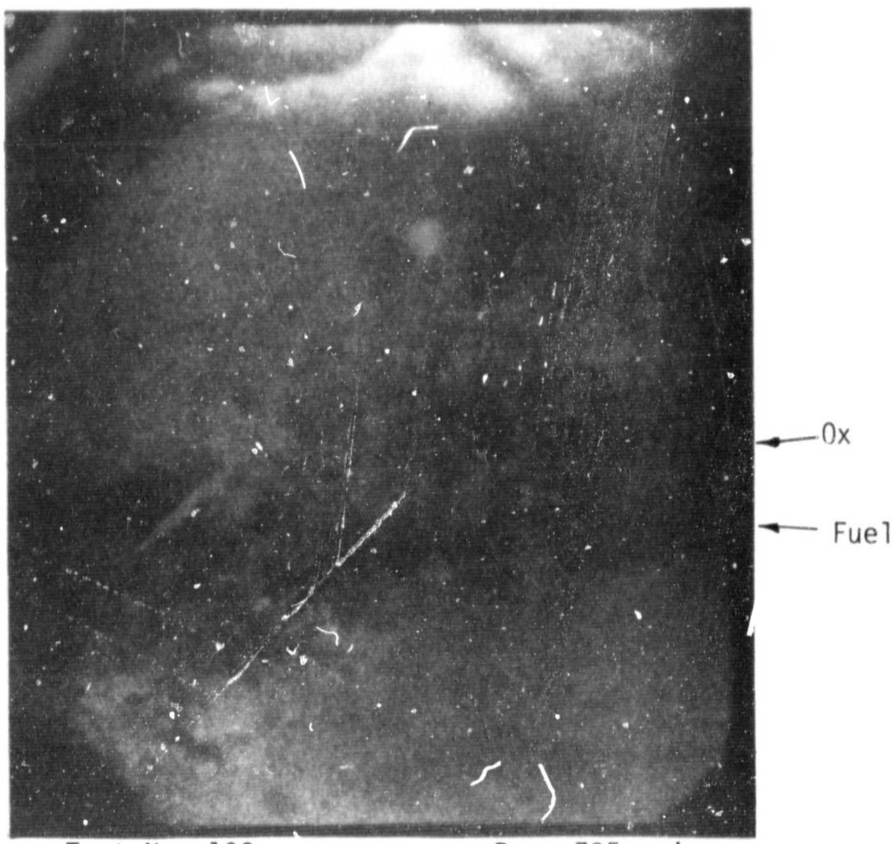
Figure 24. Single Element LOX/HC Combustion (Sheet 9 of 13)



Test No. 132 Pc = 540 psia

Fuel Type: C_3H_8 O/F = 3.00

Injector Element: TLOL



Test No. 133 Pc = 785 psia

Fuel Type: C_3H_8 O/F = 2.80

Injector Element: TLOL

Figure 24. Single Element LOX/HC Combustion (Sheet 10 of 13)

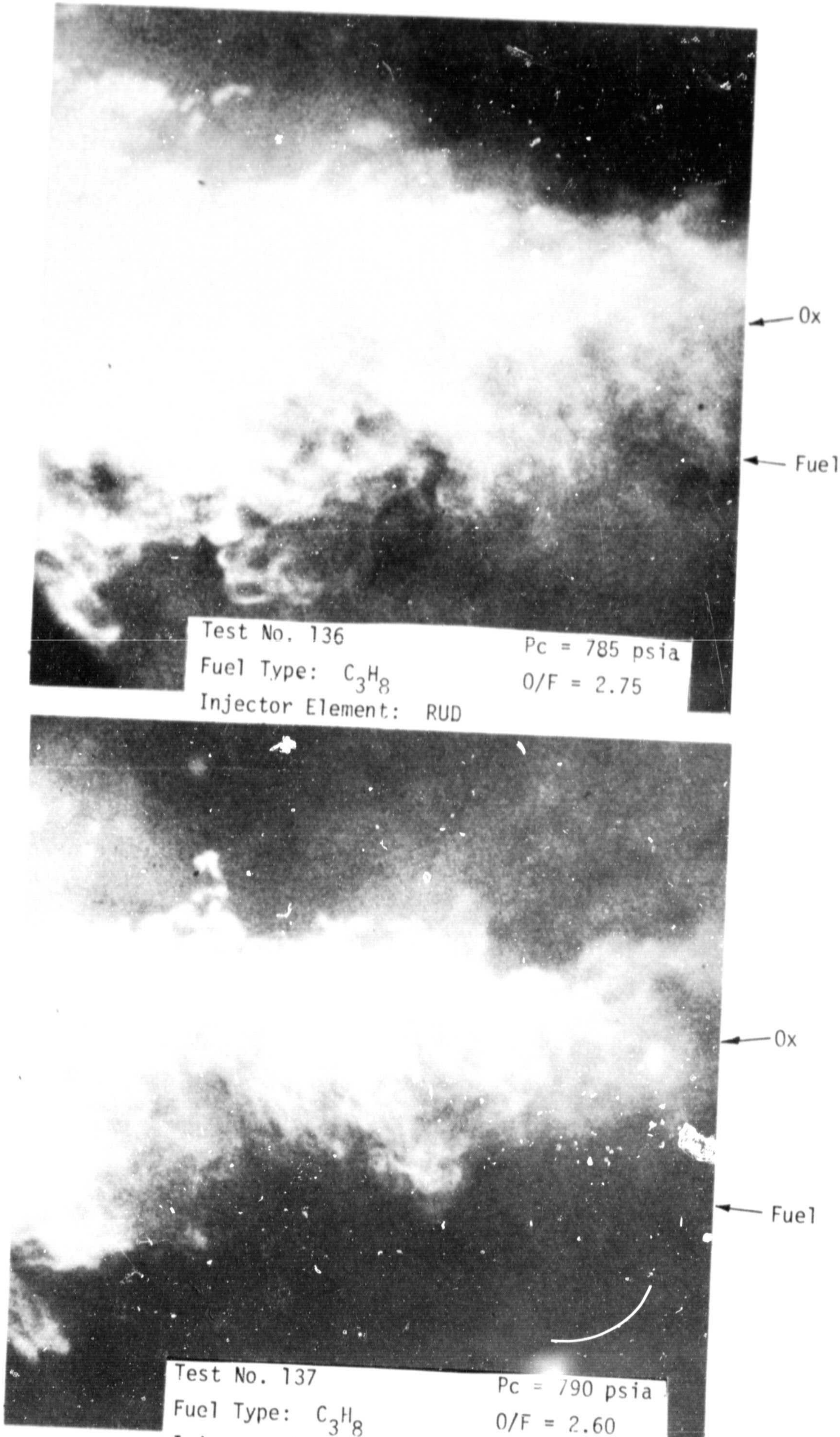
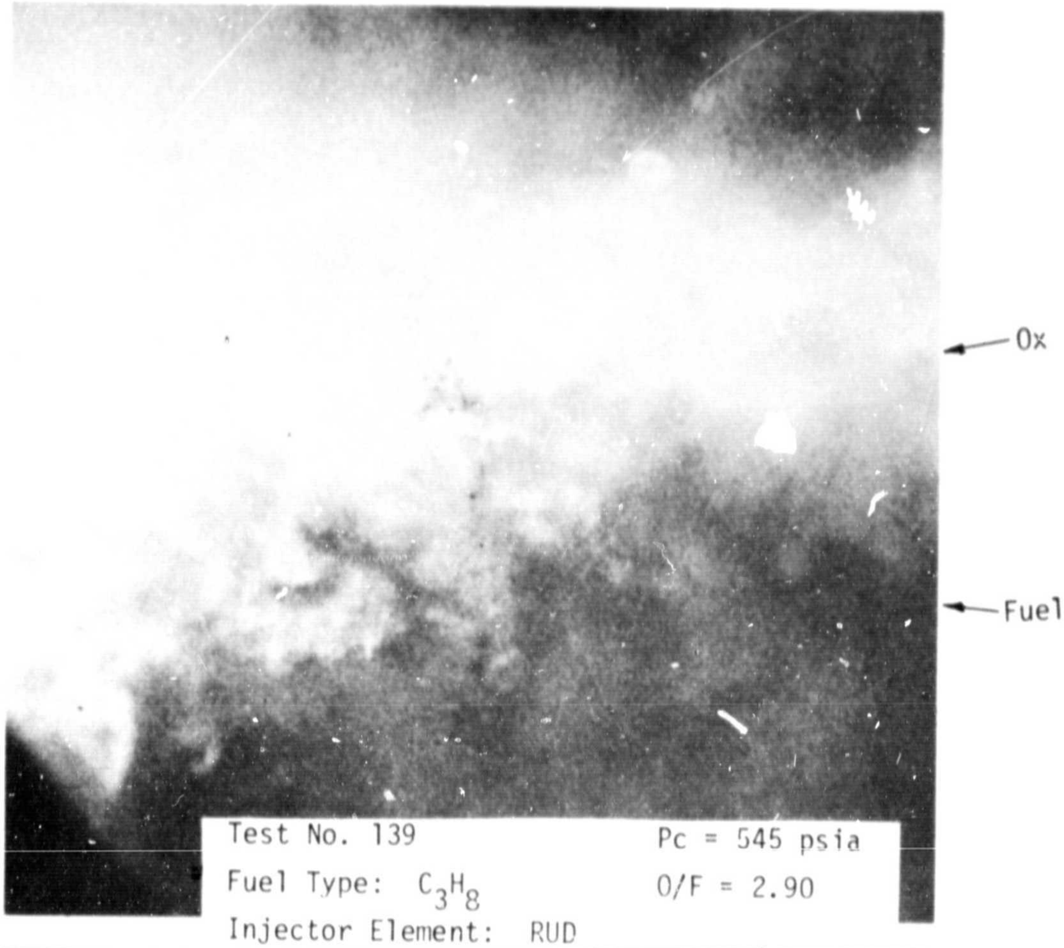


Figure 24. Single Element LOX/HC Combustion (Sheet 11 of 13)



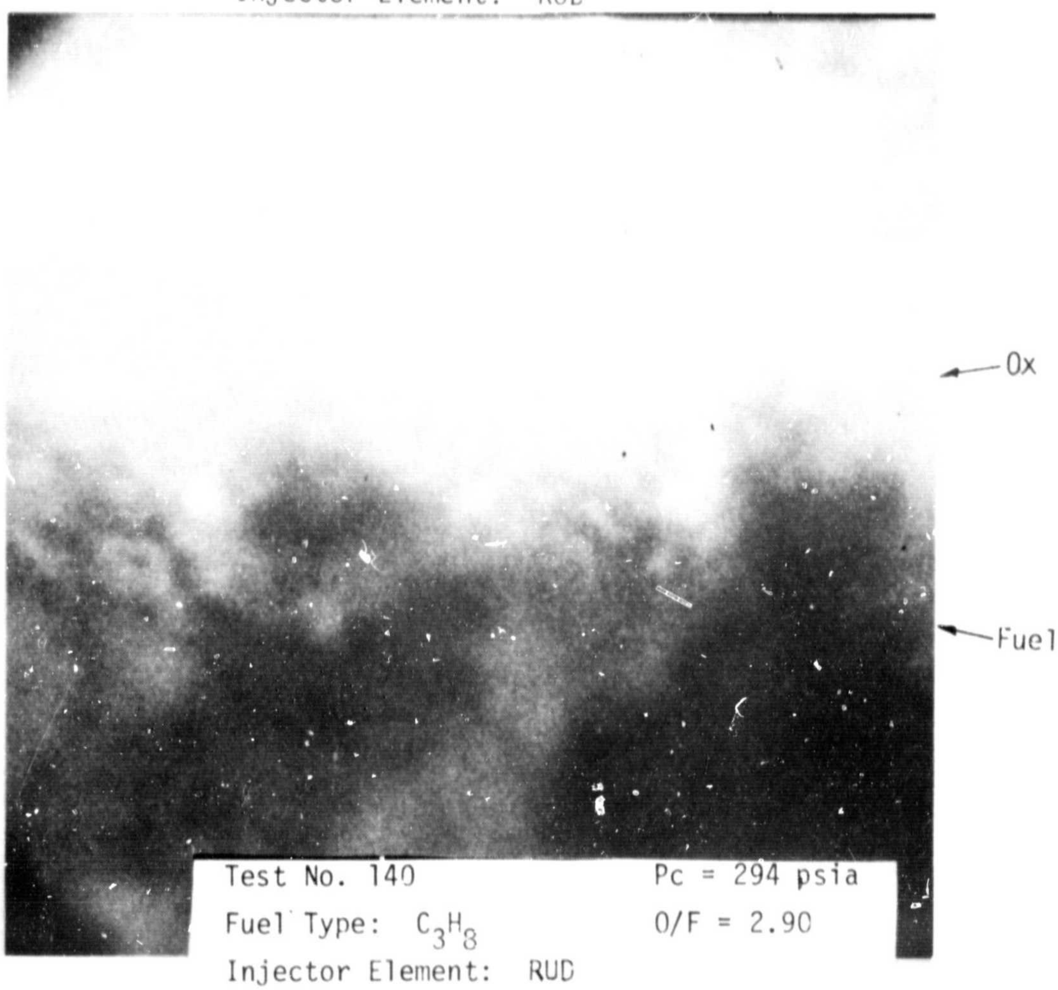
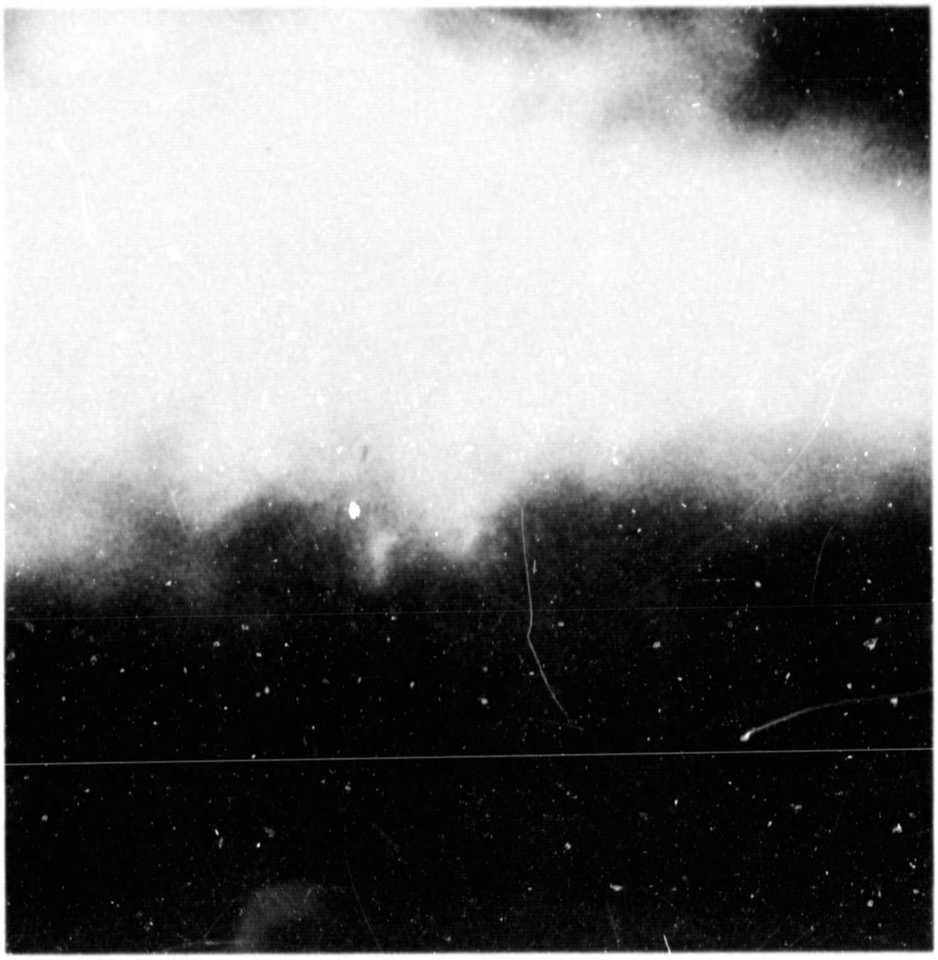


Figure 24. Single Element LOX/HC Combustion (Sheet 12 of 13)



Test No. 141 Pc = 150 psia

Fuel Type: C_3H_8 O/F = 3.10

Injector Element: RUD

Figure 24. Single Element LOX/HC Combustion (Sheet 13 of 13)

IV, C, Test Results (cont.)

A total of fifteen tests were conducted with the TLOL injector element using both RP-1 and Propane as fuel. TLOL testing utilized the flashbulb lighting technique described in Section IVB which greatly improved picture quality.

The TLOL combustion using RP-1 as fuel was similar to that of the OFO triplet with regards to: (1) coking, (2) lack of freezing or popping, (3) increasing brilliance with increasing chamber pressure, and (4) recirculation gas flow patterns. Dissimilarities in the spray field uniformity were observed due to differences in mixing characteristics. Both type of elements appear to exhibit RSS. The fuel fan was a brownish-black color even before unlike impingement, indicating thermal decomposition due to propellant stream heating. The LOX fans were a white-gray color and vaporized more rapidly with increasing chamber pressure.

The TLOL was then tested with Propane in order to gain an early comparison with the LOX/RP-1 data. The movies showed a much less brilliant combustion flame which produced much less carbon-particle emission than the LO_2/RP-1 combustion. The fuel fans were a grayish-brown color before unlike impingement indicating less thermal decomposition than the RP-1. Combustion light also increased with chamber pressure, but to a lesser degree than with LOX/RP-1. A brownish vapor is visible in the low pressure tests, resulting from propane's high vapor pressure. In comparison with the RP-1 tests carbon decomposition or sooting in the chamber was negligible.

The RUD injector element was scheduled to be tested with both RP-1 and propane, but facility problems arose which only left time for propane testing. Seven tests were fired with the RUD operating as a main chamber element. These tests covered a chamber pressure range from 150 psia to 800 psia and were markedly different from the TLOL LOX/C_3H_8 tests. These movies were darker than the TLOL LOX/C_3H_8 tests even though the lens was opened two stops. Much less mixing and combustion was in evidence near the injector face than with the TLOL or the OFO triplet. Swirling dark clouds near the injector face obscured the impingement interaction. The external lighting did not yield the same quality of picture as with the TLOL and OFO triplet, because the vapor and unburned combustion intermediates formed a sort of opaque mixture which wouldn't allow the penetration of external light. This lighting problem is due to the low vapor pressure of propane and RSS effects which modify the mixing characteristics of the RUD injector. A description of the degree of RSS demonstrated by the RUD element is difficult because the impingement is obscured and the chamber is filled with dark clouds.

The fuel and oxidizer circuits were then switched on the RUD so that it would be tested at fuel rich gas generator conditions. The first valid test (No. 143) fired for 2 seconds at Pc = 860 psia and MR = 0.55. Excessive sooting was experienced and the window inserts needed to be replaced (carbon deposits were cooked onto the glass and couldn't be removed). The windows were completely black and no photographic data was gained. Test 144 was a repeat of test 143 using conventional lighting for a comparison. After ignition the chamber filled with soot immediately and nothing more could be seen.

REFERENCES

1. Lawver, B.R., "High Performance N_2O_4/Amine Elements Blowapart, Final Report", Contract NAS 9-14186, Report No. 14186-DRL, 15 Nov. 1978.

2. Judd, D.C., "Phase II Propellants, Injectors, and Test Condition Recommendations", Contract NAS 9-15724, July 1979.

3. Lawver, B.R., "High Performance N_2O_4/Amine Elements Blowapart, Injector Element Design Criteria", Contract NAS 9-14186, 15 Nov. 1978.

4. Judd, D.C. and Lawver, B.R., "Photographic Combustion Characterization of LOX/HC Type Propellants, Phase I Test Plan (-1)", Contract NAS 9-15724, 22 Dec. 1978.

5. Judd, D.C., "Photographic Combustion Characterization of LOX/HC Type Propellants, Phase I Test Plan (-2)", Contract NAS 9-15724, 8 Jan. 1979.

APPENDIX A

DATA REDUCTION COMPUTER PROGRAM

```
TN,L,T,C
      SUBROUTINE EUSER(C,D,S,TIME)
      DIMENSION D(256), C(60), S(32)

      DOUBLE PRECISION TIME

      INTEGER S
     WHEN COMPILING PROGRAM, LOADER MUST CALL %OXY
     %EUCNV,%RAMLD

   ARRAY 'D' CONTAINS WEFF DATA IN ENGINEERING UNITS.

   ARRAY 'C' CONTAINS CONSTANTS AS INPUT TO THE 'CALDK' FILE.

  PERFORM CALCULATIONS USING DATA IN ARRAY 'D' INDEXED BY CONSTANTS
   IN ARRAY 'S' AND STORE RESULTS IN ARRAY 'D' IN LOCATION SELECTED
   BY INPUT TO THE 'CALDK' FILE.

   PROVIDE F500 CARDS FOR THE CHANNELS IN ARRAY 'D' WHICH WILL CONTAIN
   CALCULATED PARAMETERS.

      C ARRAY CONTAINS L CARD LOCATIONS
       C(2) CONTAINS FUEL PROPELLANT PROPERTIES LOGIC, 1=RP1
       2=METHANE, 3=PROPANE
       C(3) CONTAINS LOX PROPELLANT PROPERTIES LOGIC, 4=LOX
       C(4) CONTAINS WO=1 DELETION LOGIC
       C(5) CONTAINS WO=2 DELETION LOGIC
       C(6) CONTAINS WF=1 DELETION LOGIC
       C(7) CONTAINS WF=2 DELETION LOGIC
       C(8) CONTAINS FUEL KW
       C(9) CONTAINS AT
       C(10) CONTAINS OX KW
       C(11) CONTAINS FUEL ORFICE AREA
       C(12) CONTAINS OX ORFICE AREA
       C(13) CONTAINS FUEL ORFICE DIAMETER
       C(14) CONTAINS OX ORFICE DIAMETER
       C(15) CONTAINS FUEL  REYNOLDS #SEQ.#LOCATION FOR EULST.
       C(16) CONTAINS OX  REYNOLDS #SEQ.#LOCATION FOR EULST.
       C(17) CONTAINS FUEL WEBER #SEQ. # LOCATION FOR EULST.

       WO1=D(S(1))
       WO2=D(S(2))
       WF1=D(S(3))
       WF2=D(S(4))
       POFM=D(S(5))
       PFFM=D(S(6))
       POJ= D(S(7))
       PFJ= D(S(8))
       PC=  D(S(9))
       TOFM=D(S(12))
       TFFM=D(S(13))
       TOJ= D(S(14))
       TFJ= D(S(15))

       CONVERT FLOWMETER DATA TO #/SEC OF PROPELLANT
       CALCULATE FUEL DENSITY

      CALL PROPT(C(2),TFFM,SGF,DUM1,DUM2)
```

```
      CALCULATE OX DENSITY

      CALL OXY(POFM,TOFM,SGO)

      CALCULATE WOXAVG (IF 1 INLOCATION C(4)WO=2 ONLY
      IF 1 IN C(5) WO=1 ONLY

      IF(C(4).NE.1.) GOTO10
      WO1=WO2
   10 IF(C(5).NE.1.)GOTO 20
      WO2=WO1
   20 WOAVG=(WO1+WO2)*SGO/2

      CALULATE WFAVG(IF 1 IN LOCATION C(6) WF=2 ONLY
      IF 1 IN LOCATION C(7) THEN WF=1 ONLY

      IF(C(6).NE.1.) GOTO 30
      WF1=WF2
   30 IF(C(7).NE.1.)GOTO 40
      WF2=WF1
   40 WFAVG=(WF1+WF2)*SGF/2
      EMR=WOAVG/WFAVG

      CALCULATE FUEL PROPERTIES FOR INJECTOR FLOWRATE

      CALL PROPT(C(2),TFJ,SGFJ,SRFTF,VISCF)

      CALCULATE OX PROPERTIES FOR INJECTOR FLOWRATE

      CALL OXY(POJ,TOJ,SGOJ)
      CALL PROPT(C(3),TOJ,SGOJ,SRFTO,VISCO)

      CALCULATE FUEL MOLECULAR WEIGHT

      C=C(2)
      IF(C.EQ.1.)GO TO 50
      IF(C.EQ.2.)GO TO 60
      IF(C.EQ.3.)GO TO 70
      RMW=0.
      GO TO 80
   50 RMW=1545./24.
      GO TO 80
   60 RMW=1545./22.
      GO TO 80
   70 RMW=1545./23.5

            CALULATE INJECTOR DELTA PRESSURE

   80 DPOX=POJ-PC
      DPF=PFJ-PC
      WFINJ=0.0
      X=DPF*SGFJ
      IF(X.GT.0.0)WFINJ=C(8)*X**0.5
      WOINJ=0.0
```

```
      Y=DPOX*SGOJ
      IF(Y.GT.0.0)WOINJ=C(10)*Y**.5
C     CALULATE INJECTOR KW'S
      OXKW=0.0
      X=DPOX*SGOJ
      IF(X.GT.0.0)OXKW=WOAVG/X**0.5
      FKW=0.0
      X=DPF*SGFJ
      IF(X.GT.0.0)FKW=WFAVG/X**0.5
C     CALULATE CSTAR    (C(9) CONTAINS AT
      AT=WOINJ+WFINJ
      VOX=WOINJ*144./(C(12)*SGOJ*62.4)
      VF=WFINJ*144./(C(11)*SGFJ*62.4)
      CSTAR=.98*PC*C(9)*32.17/(WOINJ+WFINJ)
C     CALCULATE INJECTOR FLOWRATE MIXTURE RATIO
      CMR=0.0
      Z=WOINJ
      IF(Z.GT.0.0)CMR=WOINJ/WFINJ
C     CALCULATE REYNOLDS NUMBER
      REF=62.4*SGFJ*VF*C(13)/(VISCF*12.)
      REO=0.0
      Z=VISCO
      IF(Z.LT.888.)REO=62.4*SGOJ*VOX*C(14)/(VISCO*12.)
C     CALCULATE WEBER NUMBER
      WEF=0.0
      Z=SRFTF
      IF(Z.GT.0.0)WEF=PC*12.*(VF)**2*C(13)/(RMR*32.17*5000.*SRFTF)
      D(S(10))=VF
      D(S(11))=VOX
      D(S(17))=SGO
      D(S(18))=SGF
      D(S(19))=WOAVG
      D(S(20))=WFAVG
      D(S(21))=AT
      D(S(22))=EMR
      D(S(23))=WOINJ
      D(S(24))=DPOX
      D(S(25))=DPF
      D(S(26))=OXKW
      D(S(27))=FKW
      D(S(28))=CSTAR
      D(S(29))=WFINJ
      D(S(30))=SGFJ
      D(S(31))=SGOJ
      D(S(32))=CMR
      D(C(15))=REF
      D(C(16))=REO
      D(C(17))=WEF
      RETURN
      END
      END$
```

APPENDIX B

EQUATIONS FOR SPECIFIC GRAVITY, VISCOSITY,
AND SURFACE TENSION

```
TN,L,T,C
      SUBROUTINE PROPT (E,P,TF,SG,ST,VS)

         THIS SUBROUTINE COMPUTES SPECIFIC GRAVITY, VISCOSITY, AND
         SURFACE TENSION FOR SOME STANDARD ROCKET PROPELLANTS
         THE TEMPERATURE MUST BE PROVIDED IN DEGREES FAHRENHEIT.
         OUT-OF-RANGE SPECIFIC GRAVITY OR VISCOSITY IS RETURNED
         AS A VALUE OF 88888.  OUT-OF-RANGE SURFACE TENSION IS
         RETURNED AS A NEGATIVE REAL NUMBER OR ZERO.

      SG=88888.
      VS=88888.
      TR=TF+459.7
      TK=TR/1.8
      GO TO (10,20,30,40,50) E

         COMPUTE SG,ST,VS FOR RP-1

   10 SG=-.000388*TF+.82828
      ST=1.-TK/679.25
      IF(ST.GT.0.) ST=ST**1.2671*53.5055*6.85195E-5
      Z=(TF-68.)/97.
      IF(ABS(Z).GT.1.) GO TO 100
      VS=((((-1.956135E-4*Z+7.86782E-4)*Z-1.303092E-3)*Z+1.322725E-3)
     1    *Z-1.255994E-3)*Z+1.144314E-3
      GO TO 100

         COMPUTE SG,ST,VS FOR METHANE

   20 ST=1.-TK/190.555
      IF(ST.GT.0.) ST=ST**1.23625*40.322*6.85195E-5
      Z=(TR-252.632)/89.388
      IF(ABS(Z).GE.1.) GO TO 100
      VS=((((((-7.190261E-2*Z+2.45455E-2)*Z+0.1088466)*Z-1.784053E-2)
     1    *Z-8.52951E-2)*Z+3.547601E-2)*Z-4.333652E-2)*Z+7.088399E-2
      VS=VS/1.4881639
      SG=((((((-6.849984E-2*Z-5.252717E-2)*Z+7.200876E-2)*Z+3.821812E-2)
     1    *Z-3.900402E-2)*Z-3.324897E-2)*Z-8.740642E-2)*Z+.3773215
      GO TO 100

         COMPUTE SG,ST,VS FOR PROPANE

   30 ST=1.-TK/369.8
      IF(ST.GT.0.) ST=ST**1.24821*51.492*6.85195E-5
      Z=(TR-422.84)/242.82
      IF(ABS(Z).GE.1.) GO TO 34
      VS=((((((-3.516625*Z+3.172092)*Z+3.215512)*Z-2.325508)
     1    *Z-1.378224)*Z+0.8517147)*Z-0.1949874)*Z+0.1816328
      VS=VS*.001/1.4881639
   34 Z=(TR-405.4430)/251.577
      IF(ABU(Z).GE.1.) GO TO 100
      SG=((((((-7.27397E-2*Z-5.84529E-2)*Z+7.127882E-2)*Z+3.560425E-2)
     1    *Z-4.879066E-2)*Z-3.866206E-2)*Z-0.1573468)*Z+0.5883114
      GO TO 100

         COMPUTE ST,VS FOR OXYGEN

   40 CALL OXY (P,TF,SG)
      ST=1.-TK/154.576
      IF(ST.GT.0.) ST=ST**1.22222*38.461*6.85195E-5




      Z=(SG-.9790199)/.3275971
      IF(ABS(Z).GE.1.) GO TO 100
      VS=((((((8.694109E-6*Z+3.157964E-5)*Z+3.500642E-5)*Z+4.602466E-5)
     1    *Z+8.467757E-5)*Z+8.153158E-5)*Z+6.243964E-5)*Z+6.625252E-5
      GO TO 100

         COMPUTE ST,VS,SG FOR AMMONIA

   50 ST=0.0020787-8.9888E-6*TF
      VS=1.E-5/(0.072471+0.00044197*TF)
      TSAT=(((-7.3826E-10*P+1.5323,?-6)*P-1.29498E-3)*P+0.675)*P+1.90664
      IF((TSAT-TF).LT.1.) GO TO 100
      SG=0.6621185-(1.132834E-6*TF+6.937453E-4-5.336631E-8*P)*TF
     1    +2.473552E-6*P
  100 RETURN
      END
      END$
```