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PHOTOGRAPHIC COMBUSTION CHARACTERIZATION OF LOX/HYDROCARBON TYPE PROPELLANTS

Final Summary Report

By

D. C. Judd

AEROJET LIQUID ROCKET COMPANY

Prepared For

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PHOTOGRAPHIC COMBUSTION CHARACTERIZATION OF LOX/HYDROCARBON TYPE PROPELLANTS

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Final Summary Report MA-262T

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Prepared by:
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FOREWORD

This final summary report describes the analytical and experimental work conducted to develop techniques for photographing Liquid Oxygen/Hydrocarbon (LOX/HC) phenomena and to identify and characterize potential anomalies (e.g.. reactive stream separation [RSS], carbon formation, fuel freezing) in the combustion of LOX/HC propellants operating with a variety of injector elements. 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 success of the program:

Gene Hron	Fabrication
Arnold Keller	Test Engineering
Norm Rowett	Test Instrumentation
Duane Robertson	Test Instrumentation
Lee Lang	Injector Design
Jim Duey	Data Analysis
Anne Johnson	Data Analysis

ABSTRACT

An experimental and analytical program was conducted to determine if previously developed high-speed photography techniques could be utilized to increase the analytical understanding of LOX/HC type propellant combustion. The program was conducted in two phases. The objective of Phase I was to demonstrate the advantages and limitations of using high-speed photography to identify potential combustion anomalies (e.g., pops, fuel freezing, reactive stream separation [RSS], carbon formation). The objective of Phase II, and the primary program end product, was to develop combustion evaluation criteria for evaluating, characterizing, and screening promising low-cost propellant combination(s) and injector elaments(s) for long-life, reusable engine systems.

Carbon formation and RSS mechanisms and trends were identified by using high-speed color photography at speeds up to 6000 frames/sec. Complete color photography coverage of the test program is provided in the program final report (Ref. 1). Single element injectors were tested with LOX/RP-1, LOX/Propane, LOX/Methane and LOX/Ammonia propellants. Tests were conducted using seven separate injector elements. Five different conventionally machined elements were tested: OFO Triplet; Rectangular Unlike Doublet (RUD); Unlike Doublet (UD); Like-on-Like Doublet (LOL-EDM); and Slit Triplet. The RUD and Slit Triplet had rectangular orifices; the others were circular. Two platelet injectors were tested: the Transverse Like-on-Like Doublet (TLOL) and the Pre-Atomized Triplet (PAT). Platelet injectors are fabricated by diffusion-bonding a stack of thin metal sheets which have etched flow passages. All seven injectors were fired at main engine conditions. The RUD and LOL-EDM were also fired at gas generator mixture ratios. One hundred and twenty-seven (127) tests were conducted over a chamber pressure range of 125-1500 psia, a fuel temperature range of -245°F to 158°F, and a fuel velocity range of 48-707 ft/sec.

Combustion evaluation criteria were developed at the initiation of Phase II to guide selection of the fuels, injector elements, and operating conditions for testing. Separate criteria were developed for fuel and injector element selection and evaluation.

ABSTRACT (cont.)

The fuel selection criteria were divided into two categories: system and test. The system criteria are 1) Specific Impulse, 2) Regenerative Chamber Cooling Capability, 3) Bulk Density, 4) Cost, 5) Toxicity, and 6) Corrosiveness. The selected test criteria are 1) Fuel Freezing, 2) Pops, 3) Carbon Formation, 4) Reactive Stream Separation (RSS), and 5) Supercritical Pressure Operation.

The injector element selection criteria were 1) Atomization, 2) Mixing (i.e., RSS), 3) Injector Face Compatibility, 4) Chamber Wall Compatibility, 5) Chug Stability, 6) High Frequency Combustion Stability, 7) Injector Momentum Balance, 8) Fuel Freezing, and 9) Meaningful Photographic Results. After Phase II testing, two additional criteria were added: Carbon Formation and Fabrication Complexity.

The Phase II testing provided data for assessment of two of the fuel evaluation criteria: Carbon Formation and RSS. The gas-side carbon formation criteria proved to be accurate. As the fuel hydrogen/carbon ratio decreased (CH_4 = 4.0, C_3H_8 = 2.67, RP-1 = 2.0), carbon formation increased. The fuel type also influences the fuel vaporization rate, which plays a significant role in carbon formation. As the fuel vaporization rate increases in the injector face near-zone, carbon formation decreases. Mixing limited combustion (i.e., RSS) proved to be sensitive to all parameters that influence fuel vaporization rate. For any operating point, the fuel yielding the more rapid near-zone fuel vaporization generally will increase the degree of RSS.

The Phase II testing resulted in definitive data on four of the previously described injection element evaluation criteria: Mixing (i.e., RSS), Injector Momentum Balance, Fuel Freezing, and Carbon Formation. Two factors control mixing: 1) the fuel vaporization rate and 2) degree of injection orifice or spray fan cant towards the unlike propellant. Unlike spray fan impingement elements (i.e., TLOL, PAT and EDM-LOL) increase the fuel vaporization rate and promote RSS. The testing confirmed the pretest criteria for injector momentum balance. No incidences of fuel freezing

ABSTRACT (cont.)

occurred. Fuel freezing is not an important design criteria for injectors in the low thrust per element design range (approximately 1-50 lbF/element). The photographic test results indicated conclusively that injector element type and design directly influence carbon formation. Unlike spray fan impingement elements reduce carbon formation because they induce a relatively rapid near-zone fuel vaporization rate. Coherent jet impingement elements, on the other hand, exhibit increased carbon formation.

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I. INTRODUCTION AND SUMMARY

A. INTRODUCTION

Studies to date indicate that two of the major keys to achieving low space transportation costs are minimizing engine development and operational costs. Therefore, major reductions in future space transportation costs will be achieved with highly reusable systems that utilize low-cost propellants. Since the selection of the propellants will have a major impact on the cost of future space transportation, it is imperative that a comprehensive evaluation be conducted prior to the selection of the final propellant combination(s).

The use of high-speed single element photography has been found to be an economical and successful method for evaluating and characterizing hypergolic propellants (Ref. 2). The results have been successfully applied in the following programs: Space Shuttle Orbital Maneuvering Engine Technology; Space Shuttle Orbital Maneuvering Engine Development; Air Force ITIP (Improved Transtage Injector Program); Air Force 5 lbF N_2O_4/MMH; Improved Aerobee; and the Post-Boost Propulsion System for the Air Force MX Program. In this study, a number of low-cost propellants (LOX/Hydrocarbon and LOX/Ammonia), iniectors, and operating conditions were characterized and screened with a minimum of funding by using a modification of these photographic techniques.

The program had two primary objectives. The first objective, Phase I, was to experimentally demonstrate the advantages and limitations of using high-speed photography to identify and characterize potential anomalies (e.g., pops, fuel freezing, thermal decomposition, and reactive stream separation [RSS]) in the combustion of liquid oxygen/hydrocarbon (LOX/HC) type propellants operating with a variety of injector elements. The second objective, Phase II, was to develop combustion evaluation criteria based on the test results for evaluating, characterizing, and screening promising low-cost LOX/HC type propellants for

I, A, Introduction (cont.)

long-life reusable propulsion systems. The seven injectors and four propellant combinations tested in this program provide much of the needed experimental data necessary to rationally select the most promising propellent combination(s) and injector element(s) for future engine technology efforts and development programs.

The program was incrementally funded, as indicated in Figure 1. Figure 2 shows the program schedule and the detailed breakdown of Phase I and Phase II events. Testing with single element injectors in this manner was proven to be a cost-effective, and successful way to develop an understanding of LOX/HC combustion.

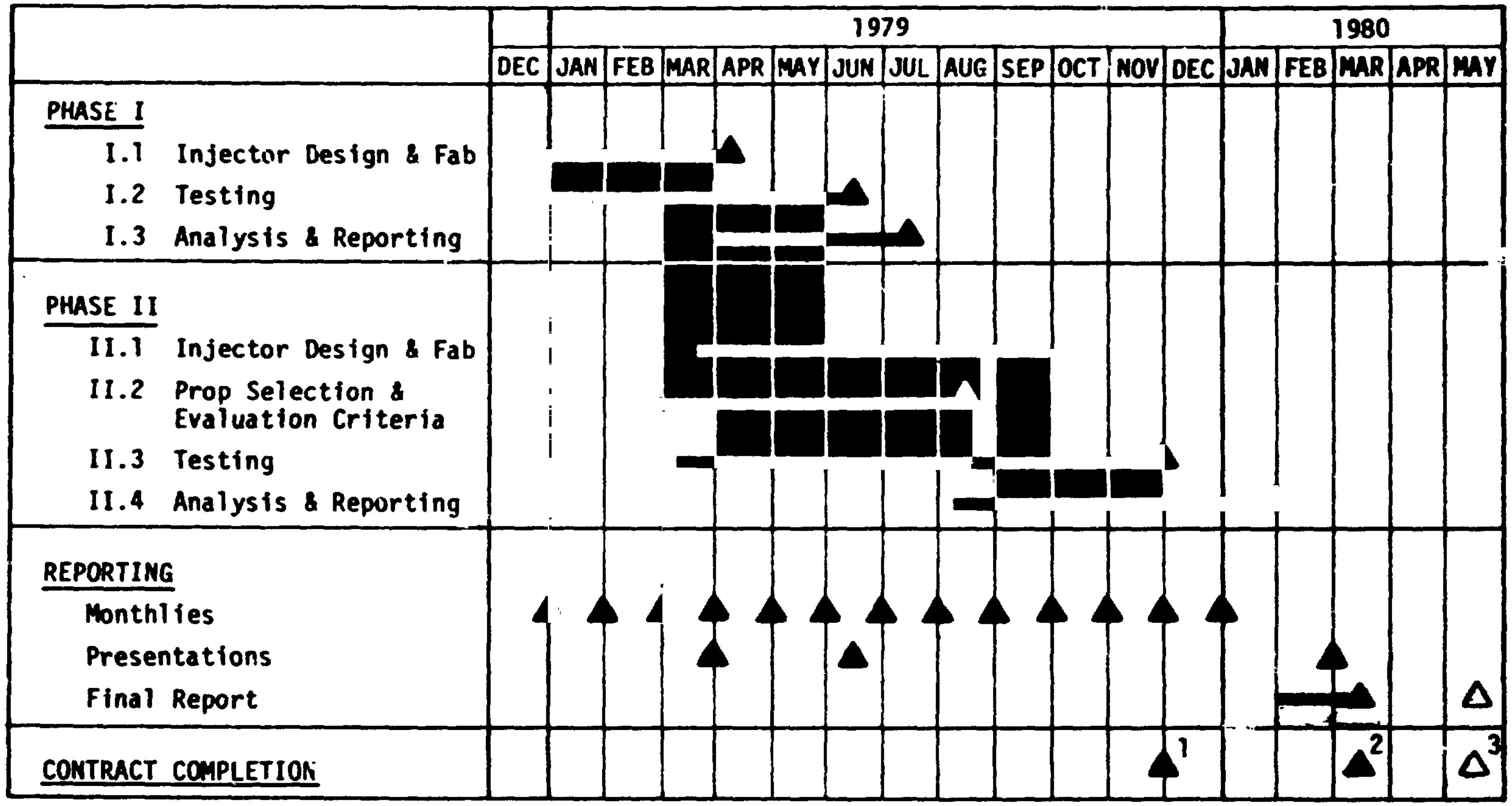
B. SUMMARY

The work undertaken in this program resulted in the design and testing of seven single-element injectors and four fuels, with the aim of photographically characterizing observed combustion phenomena. The seven injectors tested were the OFO Triplet, the Platelet Transverse Like-on-Like Doublet (TLOL), the Rectangular Unlike Doublet (RUD), the Unlike Doublet (UD), the Like-on-Like Doublet Electrical Discharge Machined (LOL-EDM), the Platelet Pre-Atomized Triplet (PAT), and the EDM Slit Triplet. The OFO triplet consists of three inline circular orifices. The outside two orifices flow with oxidizer and are canted inboard to impinge the axially directed fuel orifice. Except for the two platelet elements, all of the elements utilize coherent jet impingement. These elements mechanically atomize the propellant prior to impingement. The fuels tested were RP-1, Propane (C_3H_8), Methane (CH_4) and Ammonia NH_3. The hotfirings were conducted in a specifically constructed chamber fitted with quartz windows for photographically viewing the impingement spray field (see Figure 3).

Test photographic results showed that the appearance of LOX/HC combustion is markedly different from previously observed storable propellant

	ORIGINAL CONTRACT	MODIFIED CONTRACT	ACTUALS PLUS COST-TO-COMPLETE (2-15-80)
PHASE I	$ 68.4K	$ 68.4K	$ 97.5K
PHASE II	$ 71.4K	$160.6K	$129.6K
TOTAL COST	$139.8K	$227.1K	$227.1K

Figure 1. Program Funding



1 - Original Contract

2 - Add-on Scope for Phase II

3 - Recommended End Date, Data Analysis Stretch

Figure 2. Photographic Characterization of LOX/HC Type Propellants - Program Schedule

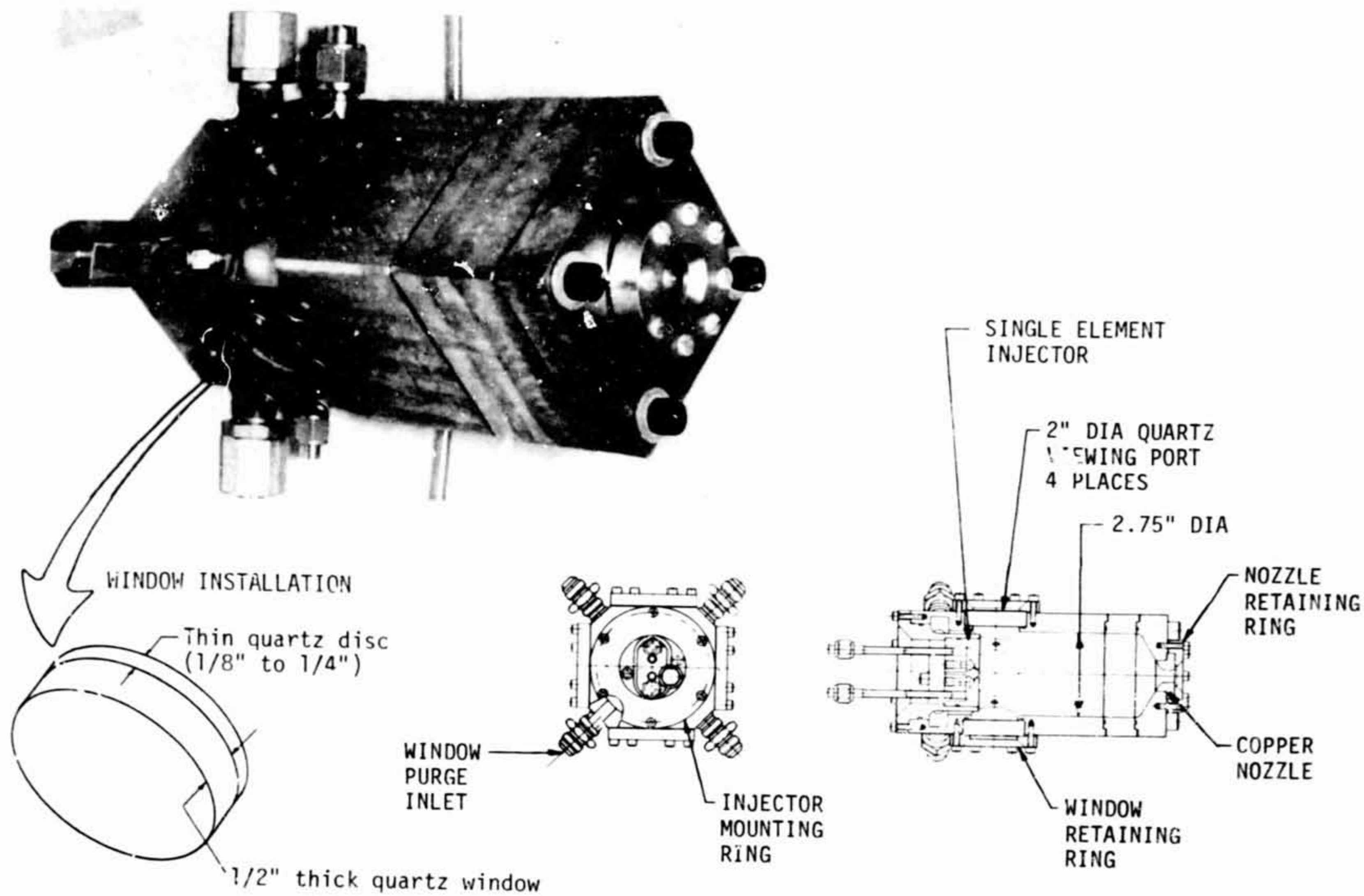


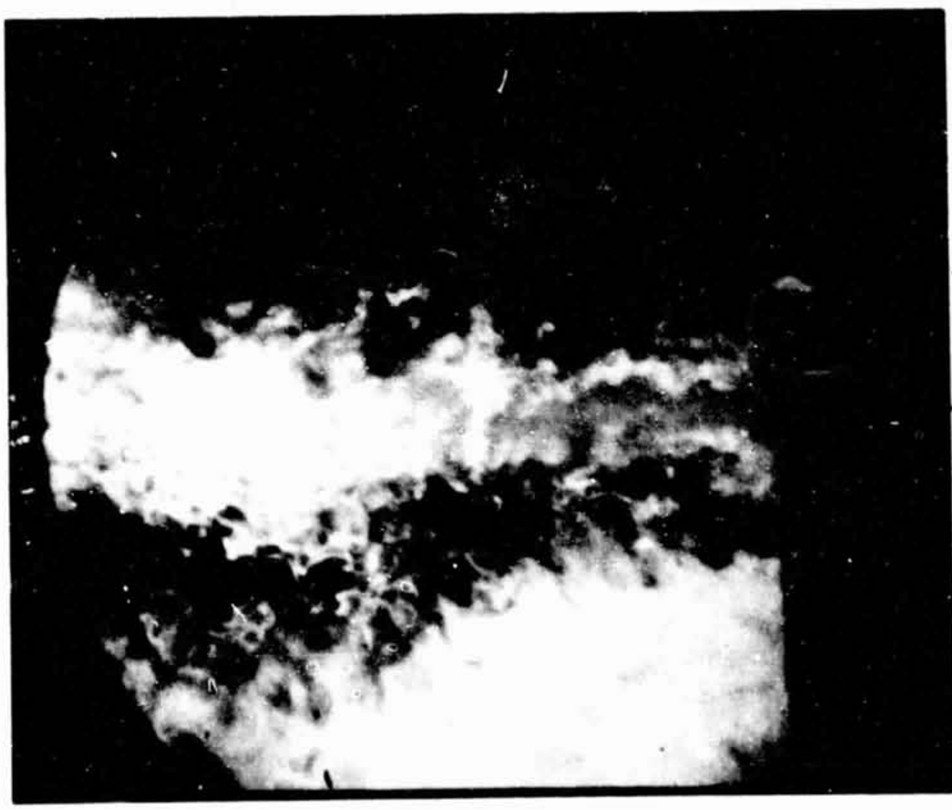
Figure 3. Test Chamber Assembly

combustion (Ref. 2). Figure 4 displays typical photographic results from the program. In the top photograph, black clouds are clearly visible downstream of the impingement zone. The occurrence of these clouds was assumed to indicate the formation of free carbon during the combustion process. The bottom photograph shows striated oxidizer and fuel fans, which indicates relatively poor bipropellant mixing. Carbon formation and mixing were the two combustion processes most thoroughly characterized as a result of the photographic testing.

Injectors and conditions tested are summarized in Table I. The Phase I test program consisted of 44 tests. The following main chamber injector/fuel combinations were tested: 1) OFO Triplet/RP-1 Fuel; 2) RUD/RP-1 Fuel; 3) TLOL/RP-1 Fuel; 4) TLOL/Propane Fuel; and 5) RUD/Propane Fuel. The RUD was also tested with propane at gas generator conditions. The Phase I testing resulted in the establishment of a baseline photographic technique for main chamber conditions. The testing indicated that carbon formation and RSS (i.e., mixing) trends could be established by using high-speed photography. The major limitation to proper assessment of high-speed gas generator combustion characterization was caused by dense black clouds obscuring the combustion flow field during testing.

The Phase II test program consisted of 83 tests. The fuels, injection elements, and operating conditions were selected with the Phase II combustion evaluation criteria (described below). The following main chamber injector/fuel combinations were tested: 1) UD/Ammonia Fuel; 2) LOL-EDM Propane Fuel; 3) PAT/Propane Fuel; and, 4) Slit Triplet/Gaseous Methane Fuel. Two gas generator injector/fuel conbinations were tested: 1) LOL-EDM Propane Fuel and 2) LOL-EDM/Liquid Methane Fuel. The Phase II testing yielded important insights leading to preliminary model formulations for carbon formation and RSS.

Test No. 172 — Pc = 610 psia
Fuel Type: C_3H_8 — O/F = 2.95
Injector Element: Like-on-Like EDM



Test No. 187 — Pc = 800 psia
Fuel Type: C_3H_8 — O/F = 2.90
Injector Element: Pre-Atomized Triplet

Figure 4. High-Speed Photography Shows Carbon Formation and Mixing Trends for Hydrocarbon Fuels

TABLE I

SUMMARY OF INJECTORS AND TEST CONDITIONS

INJECTOR ELEMENT	FUEL	CHAMBER PRESSURE (psia)	MR	FUEL VELOCITY (ft/sec)	FUEL TEMPERATURE (°F)	NO. OF TESTS	
OFO Triplet	RP-1	450-1500	1.7-2.8	76-200	50-72	16	Phase I
RUD (Main Engine)	RP-1	130	2.8	57	15	2	
RUD (Main Engine)	C_3H_8	150-790	2.6-3.15	63-166	52-68	8	
RUD (Gas Gen)	C_3H_8	850-860	0.46-0.5	110-116	59-61	3	
TLOL	RP-1	135-800	2.1-3.1	48-95	30-45	11	
TLOL	C_3H_8	135-790	2.5-3.0	63-120	43-45	4	
UD	NH_3	150-505	1.1-1.67	73-150	45-65	12	Phase II
LOL-EDM (Main Engine)	C_3H_8	150-800	2.2-4.1	56-165	29-158	20	
LOL-EDM (Gas Gen)	C_3H_8	510-810	0.72-0.73	88-113	75-79	2	
LOL-EDM (Gas Gen)	ℓCH_4	485-805	0.82-0.44	113-157	-206-245	6	
PAT	C_3H_8	150-805	2.2-3.5	69-178	43-120	21	
Slit Triplet	gCH_4	125-810	2.75-4.7	174-707	38-73	22	
						127	

I, B, Summary (cont.)

Carbon formation within the injector spray field was found to be directly related to fuel temperature (T_f), fuel type, chamber pressure (Pc), and injector type. Each test was rated according to the degree of carbon formation observed, as shown in Figure 5. Distinct regions of carbon formation were identified and correlated with three plots of "Pc-VS-T_f". Each of the data points is a symbol which represents a certain degree of photographic clarity assumed to be indicative of carbon formation (Figure 6). The data indicate that the carbon formation may be related to a flame-quenching or a partial reaction mechanism. Development of a physically mechanistic model will require more experimental work. Testing with methane at both main engine and fuel-rich gas generator mixture ratios showed that methane can burn with very little or no carbon deposition.

For the purposes of this report, RSS is defined as any degradation of change in the hot-fire spray mixing characteristics as compared to those observed in cold-flow mixing. Some degree of RSS was observed to occur with all of the fuels except ammonia. One hypothesis for its occurrence is vaporization-controlled combustion at the impingement interface. Interface combustion is a function of fuel ignition delay time, chamber pressure, fuel temperature, and fuel type. Impingement angle was also observed to have an influence on HC RSS. A second hypothesis is that the change in mixing characteristics with chamber pressure and temperature is dependent on gas dynamic effects correlated by the Weber Number. The Weber Number effect at higher chamber pressures may cause faster breakup which changes mixing patterns. Further testing is required to clarify the RSS mechanism. The schematic in Figure 7 illustrates the effect of RSS at low and high pressure observed with the PAT injector.

No fuel "freezing" or popping was experienced under any of the test conditions evaluated in this program (orifice diameters from .024 to .045 inches). It is possible, however, that the use of large orifices (e.g., booster engine applications) could promote fuel freezing because of their reduced surface area to volume ratio (i.e., combustion gases would heat larger orifice jets more slowly).

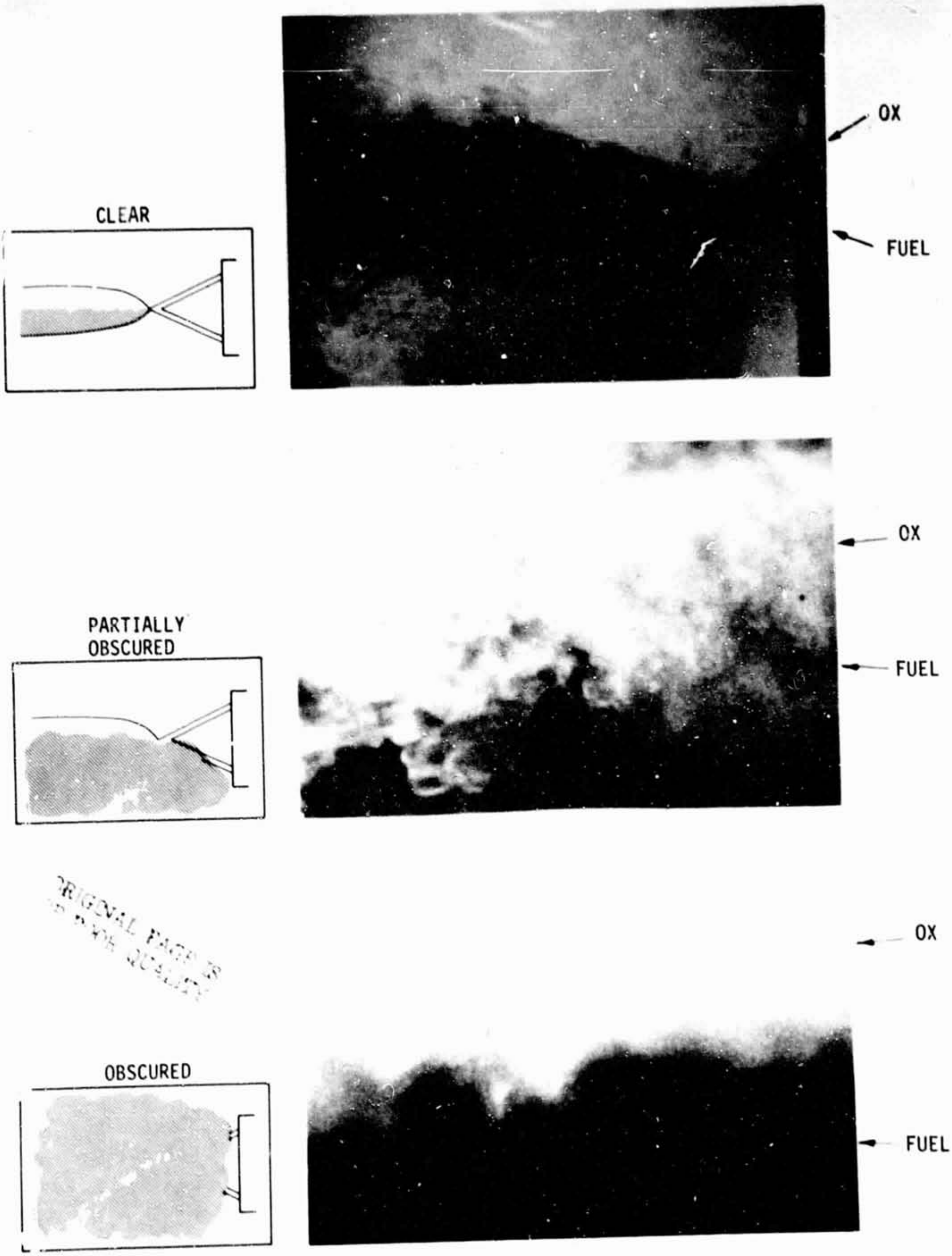


Figure 5. Modes of Carbon Formation

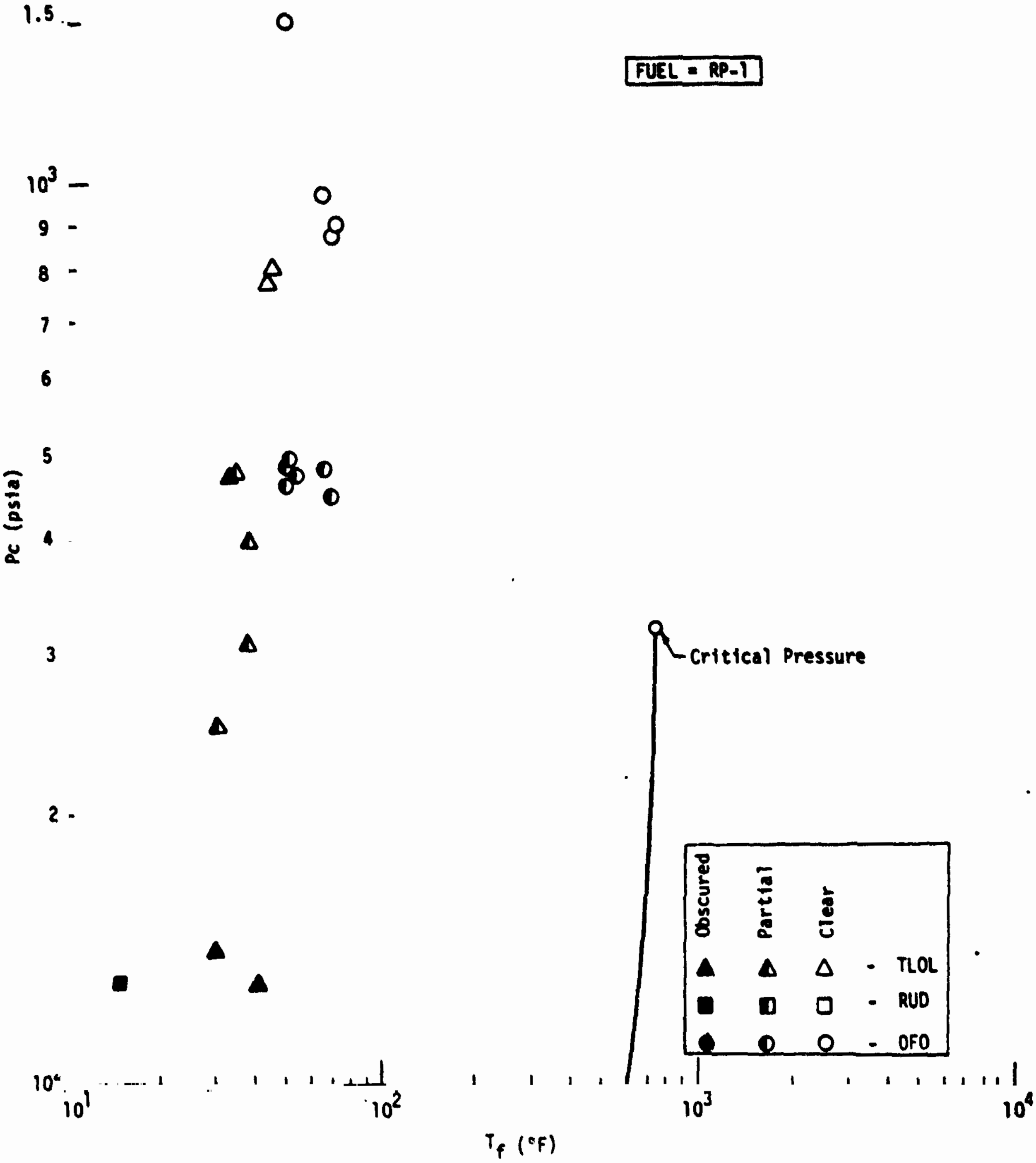


Figure 6. Carbon Formation is Correlated with Chamber Pressure, Fuel Temperature, Fuel Type, and Injector Type (Sheet 1 of 3)

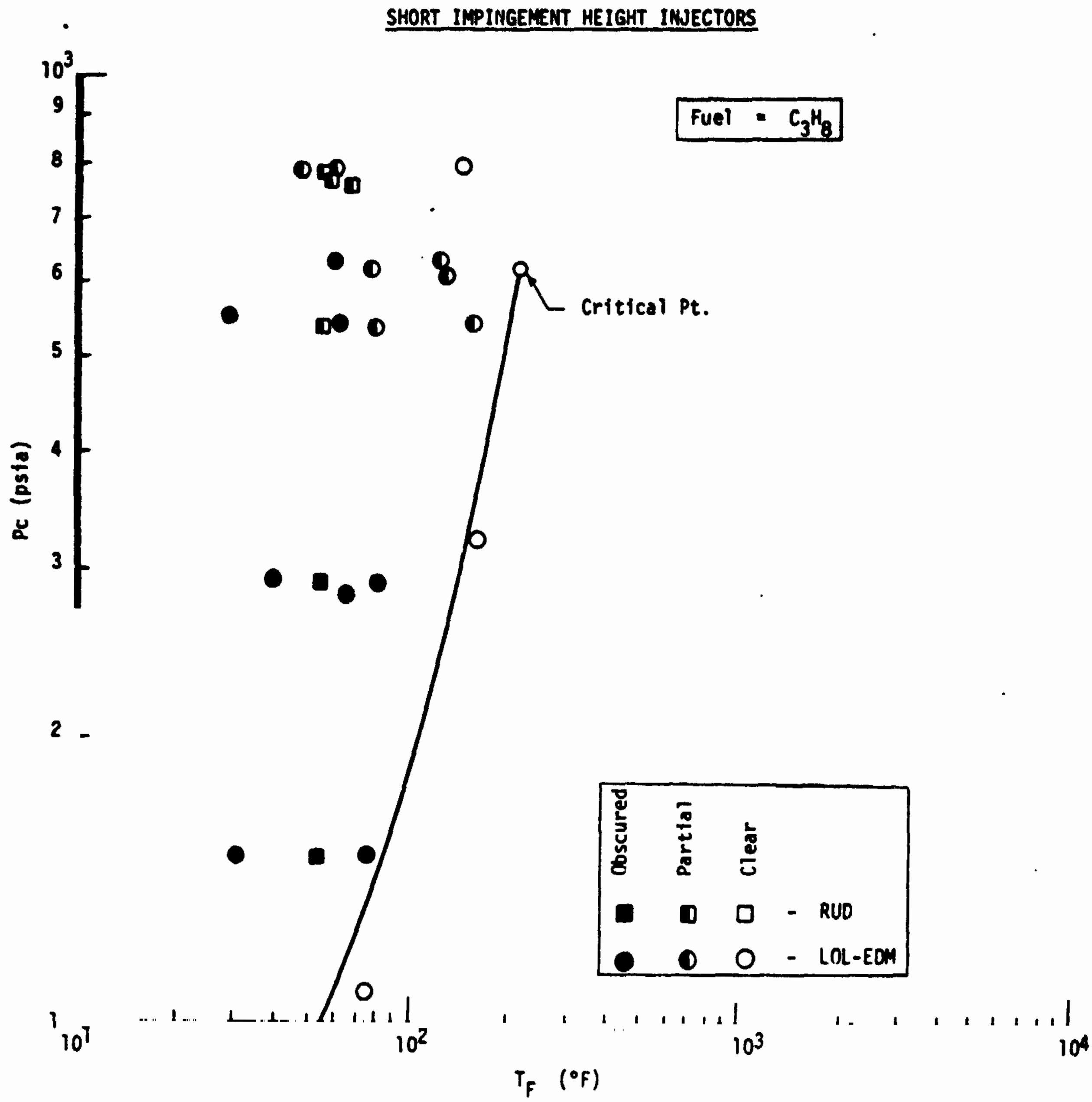


Figure 6. Carbon Formation is Correlated with Chamber Pressure, Fuel Temperature, Fuel Type, and Injector Type (Sheet 2 of 3)

LONG IMPINGEMENT HEIGHT ELEMENTS

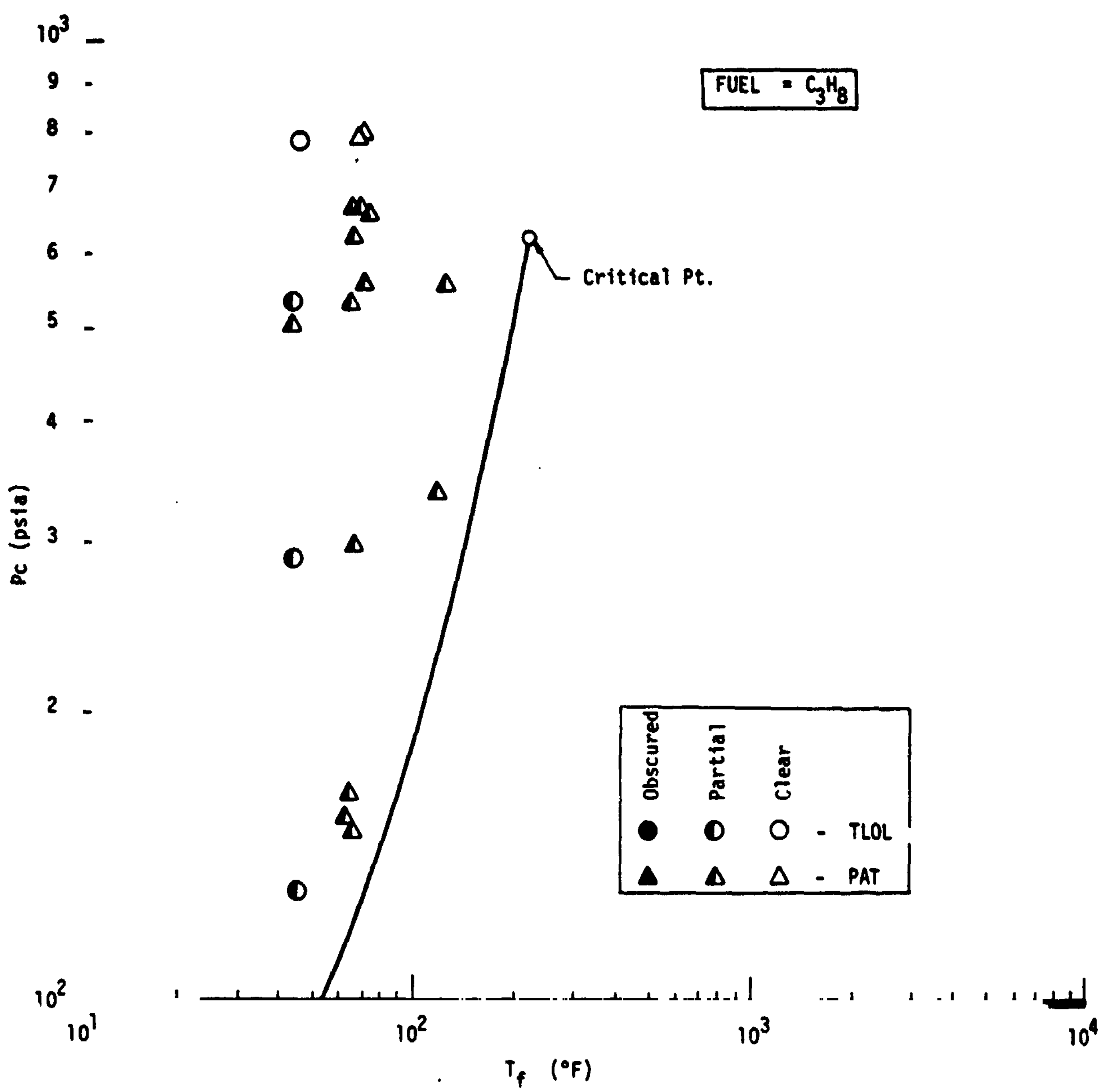


Figure 6. Carbon Formation is Correlated with Chamber Pressure, Fuel Temperature, Fuel Type, and Injector Type (Sheet 3 of 3)

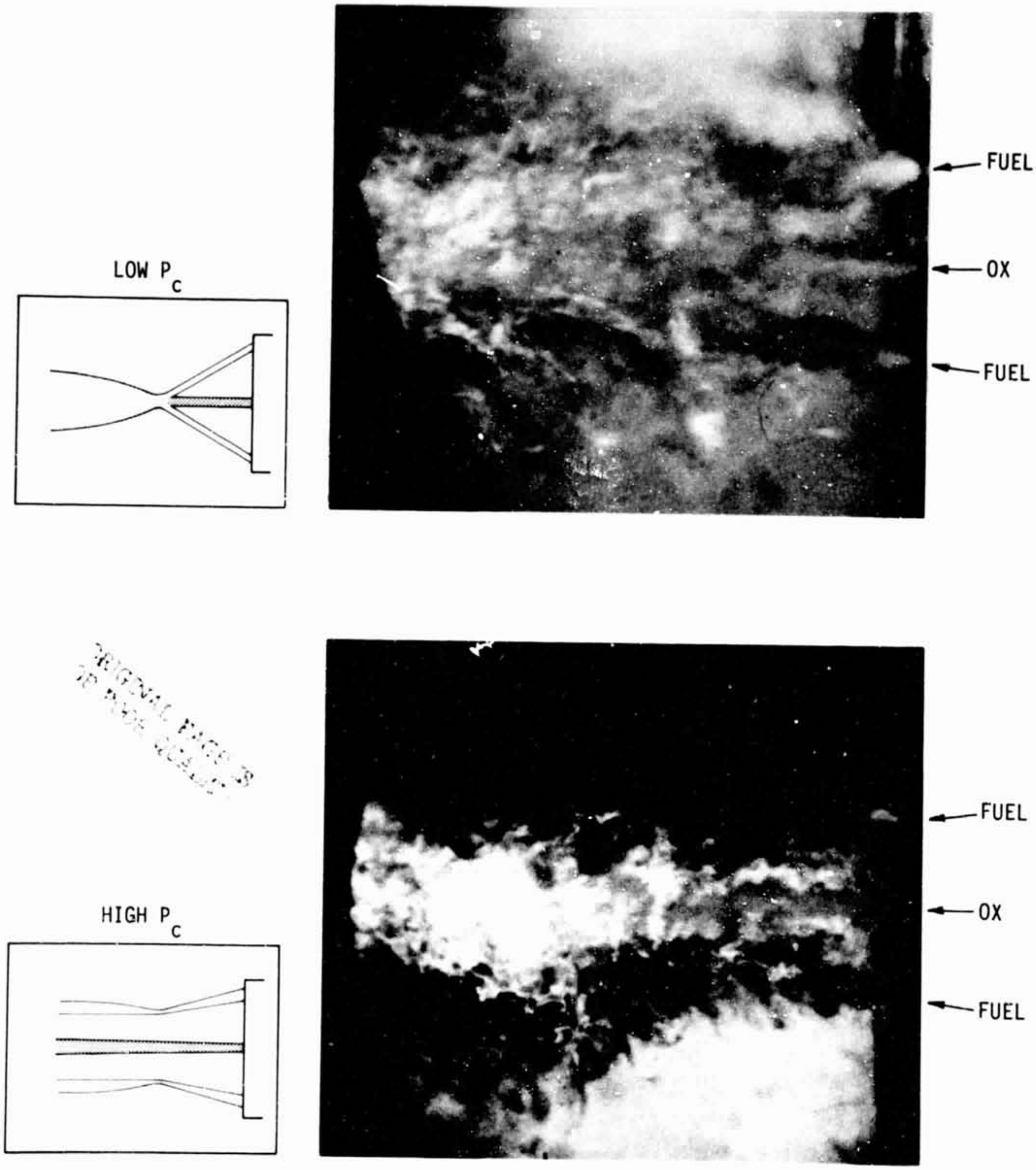


Figure 7. Stream Separation in the Spray Field at High Chamber Pressure

I, B, Summary (cont.)

Combustion evaluation criteria were developed at the initiation of Phase II to guide selection of the fuels, injector elements, and operating conditions for testing. The basic sources of data for development of the criteria were recently conducted LOX/HC technology programs, the N_2O_4/Amine fuels "Blowapart" program (Ref. 1), and the Phase I test results. Separate criteria were developed for fuel and injector element selection and evaluation.

The fuel selection criteria were divided into two categories: system and test. The system criteria are 1) Specific Impulse, 2) Regenerative Chamber Cooling Capability, 3) Bulk Density, 4) Cost, 5) Toxicity, and 6) Corrosiveness. The system criteria were used for fuel selection but were not evaluated during the test program. The selected test criteria are 1) Fuel Freezing, 2) Pops, 3) Carbon Formation, 4) Reactive Stream Separation, and 5) Supercritical Pressure Operation.

The injector element selection criteria were: 1) Atomization, 2) Mixing (i.e., RSS), 3) Injector Face Compatibility, 4) Chamber Wall Compatibility, 4) Chug Stability, 6) High Frequency Combustion Stability, 7) Injector Momentum Balance, 8) Fuel Freezing, and 9) Meaningful Photographic Results.

The fuel and injector element criteria were used to select the fuel and injection elements for Phase II testing. For the most part, qualitative judgments were used to rate the candidate fuels and elements. Based on the criteria, three fuels (propane, methane (gaseous and liquid), and ammonia) and six injector element configurations (LOL-EDM, PAT, UD, Slit Triplet, RUD Gas Generator, and LOL-EDM Gas Generator) were selected.

The Phase II testing provided data for assessment of two of the fuel evaluation criteria: carbon formation and RSS. The gas-side carbon formation criteria proved to be accurate. As the fuel hydrogen/carbon ratio decreased (CH_4 = 4.0, C_3H_8 = 2.67, RP-1 = 2.0), carbon formation increased.

The fuel type also influences the fuel vaporization rate, which plays a significant role in carbon formation. As the fuel vaporization rate increases in the injector face near-zone carbon formation decreases. Mixing limited combustion (i.e., RSS) proved to be sensitive to all parameters that influence fuel vaporization rate. For any operating point, the fuel yielding the more rapid near-zone fuel vaporization generally will increase the degree of RSS.

The Phase II testing resulted in definitive data on four of the previously described injection element evaluation criteria: Mixing (i.e., RSS), Injector Momentum Balance, Fuel Freezing, and Meaningful Photographic Results. As a result of the testing and a reanalysis of the important considerations pertaining to injector selection, two additional criteria were also added: Carbon Formation and Fabrication Complexity. Two factors control mixing: 1) the fuel vaporization rate and 2) the degree of injection orifice or spray fan cant towards the unlike propellant. Unlike spray fan impingement elements (i.e., TLOL, PAT and EDM-LOL) increase the fuel vaporization rate and promote RSS. The testing confirmed the pretest criteria for injector momentum balance. No incidences of fuel freezing occurred. Fuel freezing is not an important design criteria for injectors in the low-thrust per element design range (approximately 1-50 lbF/element). The photographic test results indicated conclusively that injector element type and design directly influence carbon formation. Unlike spray fan impingement elements reduce carbon formation because they induce a relatively rapid near-zone fuel vaporization rate. Coherent jet impingement elements, on the other hand, exhibit increased carbon formation.

Testing to date has increased knowledge of LOX/HC combustion phenomena and has provided much of the necessary data. However, the suggested fuel and injection element selection criteria are still qualitative. Carbon formation and RSS trends and influences are understood. However, mechanistic analytical modeling must still be conducted in order to obtain quantitatively accurate evaluation criteria as well.

II. OBJECTIVES AND APPROACH

A. OBJECTIVES

The objective of this program was to identify and characterize potential LOX/HC combustion anomalies with various low-cost fuels and injectors to rationally select the most promising combinations for future engine technology and development efforts. This objective was accomplished through high-speed photography and analysis of seven single-element injectors and four low-cost propellants (see Table I). The injectors, fuels, and test conditions are representative of advanced OMS and RCS engine applications at both main engine and fuel-rich gas generator conditions.

The Task I objectives were to conduct all the design, fabrication, testing, and analysis necessary to demonstrate the advantages and limitations of using high-speed photography to identify and characterize potential anomalies (e.g., pops, fuel freezing, stream separation, carbon formation, etc.) in the combustion of LOC/HC type propellants while operating with various injector elements.

The Task II objectives were 1) to develop combustion evaluation criteria based on pretest analysis and Phase I hot-fire testing and 2) to evaluate, characterize, and screen several LOX/HC propellants with different injector elements on the basis of the evaluation criteria.

B. APPROACH

The Phase I work included the following: preparation of a detailed test plan (Ref. 3 and 4); design of an unlike jet impinging injector (Rectangular Unlike Doublet-RUD); design of an unlike spray impinging injector (Transverse Like-on-Like-TLOL); experimental testing and photographic coverage of the RUD and TLOL with RP-1 and propane at main engine conditions; experimental testing and photographic coverage of an existing OFO Triplet injector with RP-1 at main engine conditions; and experimental testing and photographic coverage of the RUD with propane at fuel-rich gas generator conditions.

II, B, Approach (cont.)

Phase II emphasis was directed towards providing data to aid in the rational selection of the most promising propellant combination(s) and injector element(s) for future engine technology and development efforts. Task II work included the following: 1) preparation of a "Propellant, Injector, and Test Conditions Recommendation" for Phase II testing (Ref. 5), which included the combustion evaluation criteria that had served as a screening guide for fuel and injector selection and 2) design and testing of the following injector and fuel combinations:

a) Unlike Doublet - LOX/NH_3 as a main engine element.

b) LOL-EDM - LOX/C_3H_8 as a main engine and gas generator element.

c) LOL-EDM - $LOX/\ell CH_4$ as a gas generator element.

d) PAT - LOX/C_3H_8 as a main engine element.

e) Slit Triplet - LOX/gCH_4 as a main engine element.

Task II also included 1) an evaluation and comparison of the test results as per the combustion evaluation criteria, along with pertinent data correlations aiding in the characterization of LOX/HC combustion anomalies (included herein) and 2) a discussion of the unexpected program results/benefits, combined with recommendations for further efforts (included herein).

III. RESULTS

The significant results of this program are presented below in terms of the specific Phase I and Phase II objectives described in the previous section. A, Photographic Techniques, relates the Phase I high-speed photography results. B, Combustion Evaluation Criteria, describes the Phase II development of the criteria. C, Test Results Evaluation, shows how the criteria were applied to analysis of the test results. D, Data Correlations, details the development of an understanding of the two most important observed combustion phenomena, Carbon Formation and Reactive Stream Separation (RSS).

A. PHOTOGRAPHIC TECHNIQUES

The intent of photographic characterization of injector element combustion phenomena is to provide an understanding of the physico-chemical processes that are operative at engine operating conditions. This necessitates the ability to "look" through the flame to observe the liquid propellant streams and resultant sprays in order to determine relative spray mass and mixture ratio distributions by observing the liquid propellant colors.

It was found that there are two major problems associated with photographing LOX/HC combustion flow fields. The first was that the combustion flame light emission was so intense that it masked the reflected light necessary to see the propellant streams (see Figure 8). The best technique found for overcoming the intense combustion light was to reduce the film exposure time to where the film, in effect, didn't "see" the flame light and then to provide high-intensity external lighting for viewing of the propellant streams. It was found that use of back lighting alone will not provide the lighting balance required to properly interpret the film, since the external lighting must be provided from the back, top, bottom, and front to obtain a balance between reflected and absorbed light.

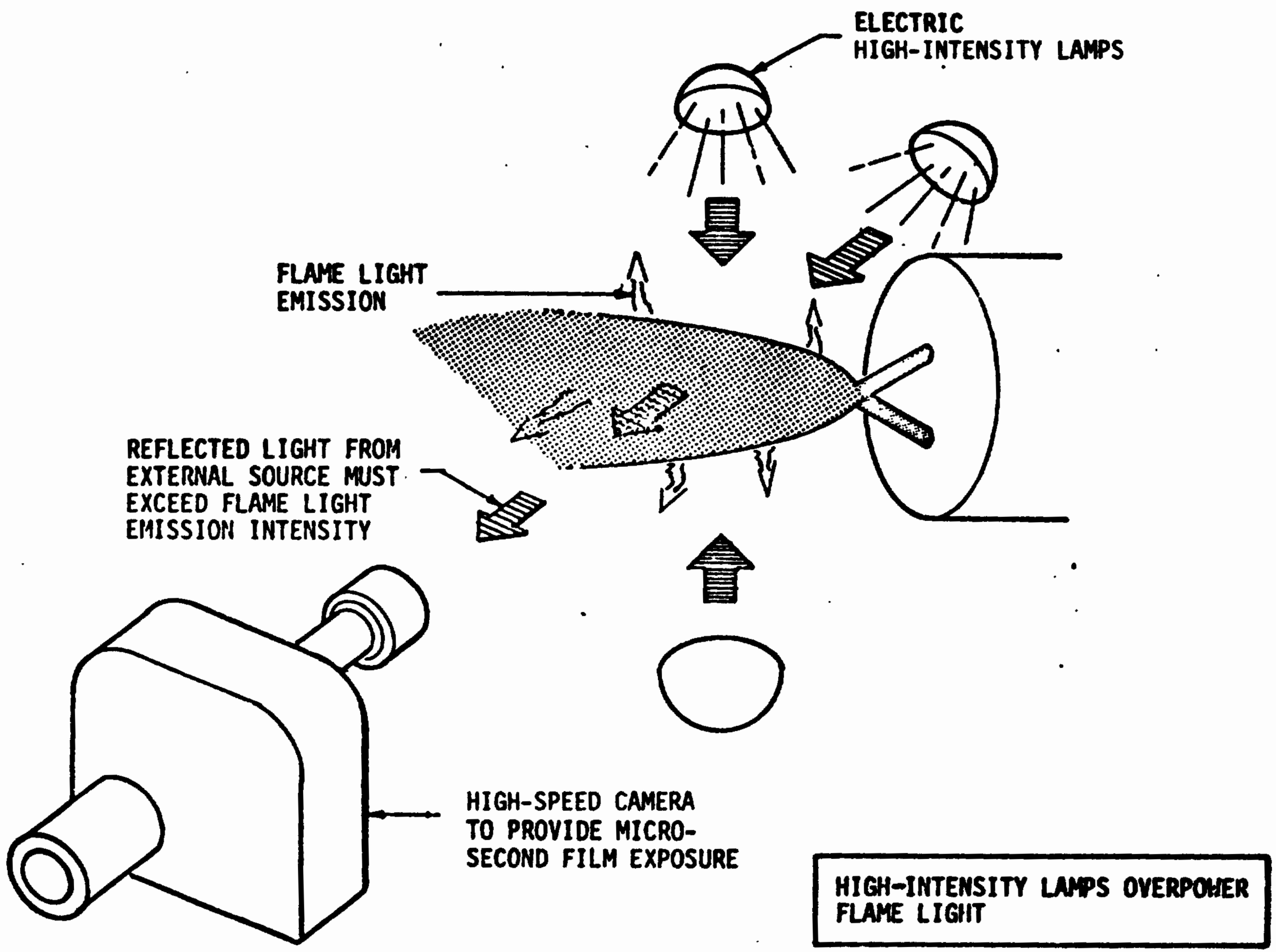


Figure 8. High-Intensity Lamps Overpower Flame Light Emission

The second problem concerned obtaining useful photographic data when the chamber was filled with dark, swirling clouds or when the windows became coated with carbon. This problem was alleviated in a limited sense by providing oxidizer-rich transients as well as window purges to protect windows from carbon deposits. Notwithstanding all of the efforts to get good movies, the field of view was almost always obscured at pressures below 300 psia with RP-1 and C_3H_8.

The photographic combustion characterization was accomplished by using the equipment shown in Figure 9. The photographic equipment is centered around a Hycam (Model 41-0004) rotating prism, high-speed movie camera. This unique camera has the capability of varying the frame exposure time independent of the film frame rate through a replaceable rotating shutter. The shutter is mounted to the prism shaft and rotates at the same speed as the prism. The light exposure at a given frame rate is controlled by changing the shutter ratio of open time to close time. This is done with interchangeable shutters. The available shutter ratios are:

1/2.5, 1/10, 1/20, 1/50, and 1/100.

The light exposure time is determined by the product of the shutter ratio and the reciprocal of the frame rate:

Exposure time = Shutter ratio x 1/pps (pictures per second).

Thus it is possible to obtain exposures of a few microseconds at relatively low frame rates.

The method of photographic characterization initially used was the one found to be successful in 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. Ektachrome EF No. 7242 film (400 ft rolls) was used. The spray volume was illuminated with one 1000-watt quartz

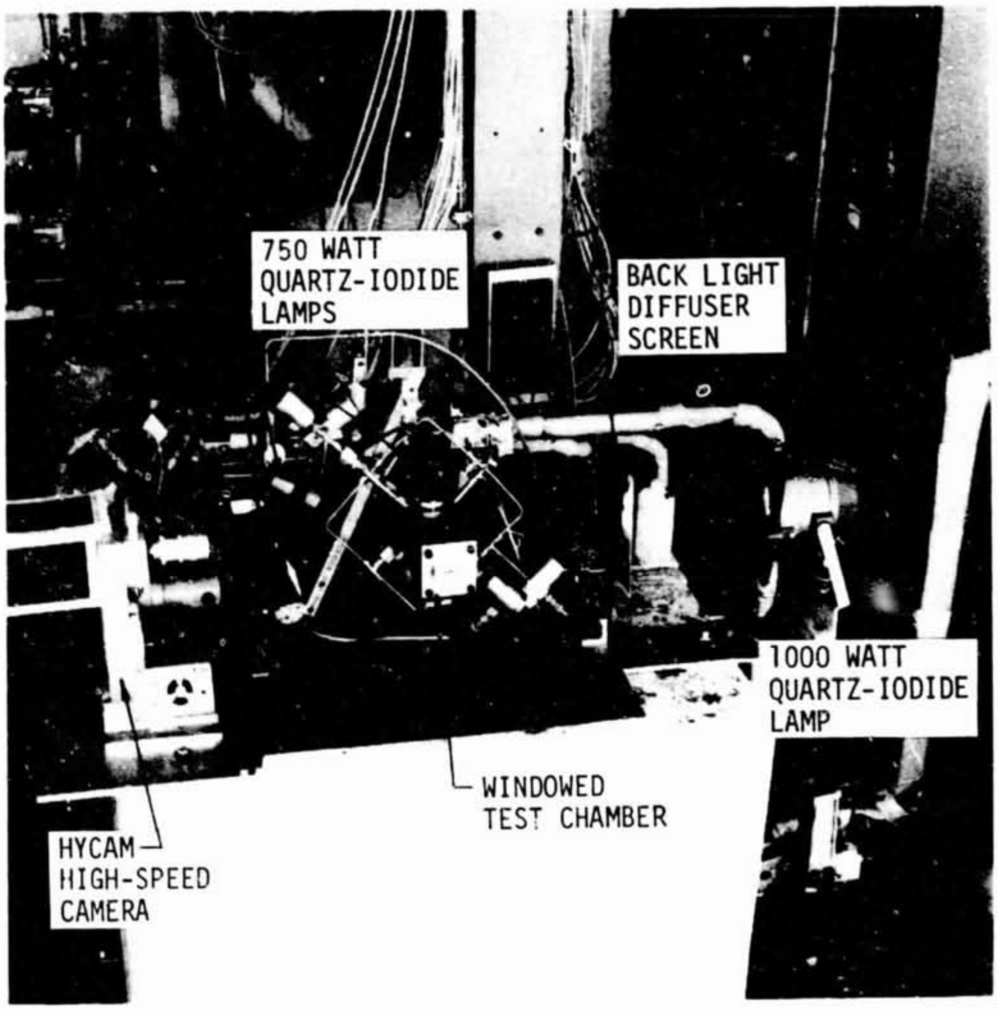


Figure 9. Photographic Equipment Setup

iodine lamp for back lighting and four 750 watt lamps for side, top, and bottom lighting.

Subsequent testing showed that this method was incapable of "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 had been the case during the storable propellant "Blowapart" program. Instead, the f-stop, camera speed, and external lighting intensity would have to be varied in correspondence to the chamber pressure, fuel type, and mixture ratio. As a result, 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 (5 megalumen on the two front lights and 2 megalumen for the top, bottom, and backlights). 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 lightning arrangement with RP-1 and C_3H_8. Tests using CH_4 and NH_3 as fuels gave off far less combustion light and were easily photographed using only photoflood lighting at 800 pps and an f-stop of 4.

Phase I testing resulted in a meaningful photographic display of LOX/HC combustion phenomena. The Phase I results were used to generate combustion evaluation criteria and recommendations for the Phase II test program, as described in the following paragraphs.

B. COMBUSTION EVALUATION CRITERIA

A major objective of Task II was to develop combustion evaluation criteria based on analysis and testing, and to use it to evaluate, select and characterize test results with several combinations of LOX/HC propellants, injector elements, and operating conditions. Complete criteria development and Phase II selection results are given in Ref. 5.

The basic sources of data for development of the criteria are recently conducted LOX/HC techno.ogy programs, the N_2O_4/Amine fuels "Blowapart" program (Ref. 2), and the results from the program Phase I testing. The criteria were separately developed for 1) fuel and 2) injector element selection and evaluation.

1. Fuel Evaluation

The primary factors considered for selection of propellants for long-life reusable engine application were subdivided into two major categories: (1) System and (2) Test. System considerations are those which describe the performance and operational characteristics of a fuel in a given system. Test considerations describe the effect of numerous combustion-related phenomena which may affect engine operation.

Six criteria were selected for system evaluation. These criteria, along with the characteristics which would be considered desirable for each criterion, are as follows:

(1) Isp - High specific impulse is desired.

(2) Regenerative Chamber Cooling Capability - High thermal conductivity and high heat capacity are desired. Capability of withstanding high termperatures without thermal decomposition.

(3) Bulk Density - High bulk density is desired to maximize vehicle payload and minimize vehicle gross lift-off weight.

(4) Cost - Low-cost propellants are required for economical, long life, reusable engine systems.

(5) Toxicity - Toxicity is an important operations and maintenance issue for reusable engine systems.

(6) Corrosiveness - Corrosiveness affects propellant storability.

Five criteria were selected for test evaluation. These criteria, along with the characteristics which would be considered desirable for each criterion, are as follows:

(1) Fuel Freezing - Fuel freezing should be avoided to preclude spray explosions and unsteady combustion simular to pops.

(2) Pops - It is desirable to operate with steady combustion and no pops.

(3) Carbon Formation - Control of gas-side carbon formation is desirable. It is undesirable at gas-generator conditions. It may be advantageous as a chamber wall insulator at main chamber conditions. Also, its impact on main chamber performance is not well understood.

(4) Reactive Stream Separation - It is desirable to predict the range of operating conditions and injector types which result in RSS so that injectors can be designed to operate entirely in either a separated mode or a mixing mode. Shifting between these two modes is undesirable.

2. <u>Injector Element Evaluation</u>

Nine criteria were selected for injector element evaluation. These criteria, along with the characteristics which would be considered desirable for each criterion, are as follows:

(1) Atomization - Small drop size is desired.

(2) Mixing - Uniform mixing is desired for high efficiency and complete combustion.

(3) Injector Face Compatibility - A low heat flux is necessary to preclude damage to the injector face.

(4) Chamber Wall Compatibility - The element must produce a uniform, well-mixed combustion zone to preclude local hot spots or chamber streak.

(5) Chug Stability - Short combustion time lags are desirable to preclude chugging.

(6) High Frequency Combustion Stability - Uniform atomization distribution is desired to facilitate damping device design.

(7) Injector Momentum Balance - A resultant axial momentum is desirable at all operating conditions. Elements insensitive to mixture ratio changes are desired.

(8) Fuel Freezing - Fuel freezing should be avoided to preclude spray explosions and popping.

(9) Meaningful Photographic Results - The injector must be capable of demonstrating combustion phenomena in a manner that can be photographed and analyzed.

C. TEST RESULTS EVALUATION

Application of the combustion evaluation criteria to the Phase II test results is described in the following two subsections: 1) Operating Conditions Selection and 2) Test Results.

1. Operating Conditions Selection

a. Fuel Selection

Seven fuels were considered for Phase II test evaluation: 1) Methane (CH_4); 2) Ethane (C_2H_6); 3) Propane (C_3H_8); 4) Butane (C_4H_{10}) 5) Heptane (C_7H_{16}); 6) RP-1; 7) Ammonia (NH_3). Numerical values were assigned to the various evaluation criteria for each fuel. These numerical values reflected the rating of a specific fuel with respect to those criteria. All criteria were given equal weight to make the evaluation as general as possible. Weighting factors could be used when detailed system requirements had been defined.

Methane and Propane rated the highest scores as per the criteria. This would indicate that both are highly suited for use in future LOX/HC engines and that the superiority of one over the other could be more clearly determined when detailed system requirements are defined. (As an example, the need for a clean burning fuel with highest possible Isp would indicate a need for methane, whereas the need for greater bulk density - where coking and Isp are not so critical - would indicate propane to be more suitable.) Propane and methane were the two hydrocarbons selected for Phase II testing. Ammonia was selected as the third test fuel for primarily two reasons. First, it contains no carbon and thus would provide an excellent base for photographic comparison. Secondly, in addition to being extremely low cost, it is a good coolant, indicating two significant advantages for a long-life, reusable engine design.

b. Injector Element Selection

Thirteen injector elements were considered for the Phase II evaluation and selection. These injectors were divided into two categories: main chamber and fuel-rich gas generator. Numerical values were assigned to the various evaluation criteria for each element. These numerical values reflected the rating of a specific injector with respect to those criteria.

The results indicated that many of the candidate elements could be successfully used for Phase II testing. Schedule and budgetary restraints, however, required that certain hardware items (already fabricated) and certain injectors be used for both main chamber and gas generator applications. The injectors which best met the above mentioned criteria and were recommended for Phase II testing are described below. Reasons for each of the selections are included.

LOL-EDM - This element provides spray-on-spray unlike impingement for good mixing and has historically been used successfully with LOX/HC propellants. Data from the LOL-EDM testing would also be very complementary to data gained from the Transverse Like-on-Like (TLOL) injector in Phase I testing.

Pre-Atomized Triplet (PAT) - The PAT consists of two fuel splash plate elements which impinge on one centrally located oxidizer x-doublet (XDT) element. Both of these platelet element concepts are analytically well characterized at ALRC for performance efficiency, combustion stability, and thermal compatibility with storable propellants. The intent of pre-atomization of the propellants prior to impingement is to promote propellant heating and mixing. This should prevent possible fuel freezing associated with coherent stream impingement. PAT Phase II testing would also provide a basis for comparison with the Phase I OFO Triplet combustion data.

Unlike Doublet (Using NH_3) - The main reason for the selection of this element is the fact that it was residual hardware from Contract NAS 9-14186 and was readily adaptable to firing with LOX/NH_3. While the unlike doublet may not be the optimum selection from a performance, heat transfer, or compatibility standpoint, it certainly does provide the opportunity to economically explore LOX/NH_3 combustion phenomena. The unlike doublet also provides the best view of the impingement interaction. External lighting problems encountered with LOX/HC propellants (Phase I testing) were not anticipated to occur during these tests due to the lack of carbon particle emission.

Slit Triplet - The slit triplet was recommended as a main engine injector to be used with LOX and gaseous methane. This design features a centrally located rectangular LOX orifice (high aspect ratio) which would be impinged upon by gaseous methane exiting from two outside rectangular orifices. The interaction between the methane and the sheet of LOX should produce good atomization, mixing, compatibility, and stability. The Slit Triplet is similar in function to a coaxial swirler element, but is expected to yield better photographic results due to the impingement away from the injector face. Since this element is easily photographed, it should yield new insights into the mixing and combustion of impinging gas and liquid streams.

Rectangular Unlike Doublet (Gas Generator) - The Rectangular Unlike Doublet (RUD) injector from Phase I testing could be utilized as a fuel-rich (C_3H_8) gas generator by switching the oxidizer and fuel circuits. The fact that both of the inlet lines are LN_2 jacketed makes this "switching" possible. Utilization of the existing RUD as a gas generator affords an economical, quick look at the advantages and limitations of high-speed photography at low mixture ratio.

LOL-EDM (Gas Generator) - The switching option mentioned above could also be employed with the LOL-EDM element. Of the five injectors previously described, the LOL-EDM should have the least problems converting to a fuel-rich gas generator. The LOL-EDM could be tested with both Propane and Methane to provide a basis for comparing fuel-related sooting characteristics.

2. Test Results

The following comments regarding application of the combustion evaluation criteria are made on the basis of the Phase II test results.

a. Fuel Evaluation

The criteria selected for test evaluation are commented on below.

(1) Fuel Freezing

No fuel freezing was encountered during Phase I or Phase II testing. This was true even for the highest freezing point fuels (RP-1 and NH_3) with the use of direct impingement, coherent jet injectors. It is possible, however, that the use of large orifices (e.g., booster engine applications) could promote fuel freezing because of their reduced surface area to volume ratio (i.e., combustion gases would heat larger orifice jets more slowly).

(2) Pops

No unsteady combustion was experienced during any of the program testing. The testing provided no conclusive information regarding any aspect of combustion stability.

(3) Carbon Formation

The gas-side carbon formation criteria for fuel evaluation proved to be accurate. As the fuel hydrogen/carbon ratio decreases (CH_4 = 4.0, C_3H_8 = 2.67, RP-1 = 2.0), carbon formation increases for any given injector element and operating point. The injector type and operating point also significantly influenced carbon formation. As a result of these findings, carbon formation was added to the injector element selection criteria.

(4) Reactive Stream Separation

Propellant mixing limited combustion (i.e., RSS) is sensitive to all parameters that influence fuel vaporization rate. For any operating point, the fuel yielding more rapid fuel vaporization generally will increase the degree of RSS. Existing drop size and vaporization models must be utilized to determine the actual vaporization rate for candidate fuels for any application.

(5) Supercritical Pressure Operation

Exceeding the critical pressure did not in itself significantly change the atomization, vaporization, or combustion process for any of the fuels tested. When the fuel injection temperature exceeded the saturation temperature at any pressure, carbon formation was essentially eliminated. This indicates that fuel vaporization rate is the key to carbon formation and that reaching the critical pressure does not create a discontinuity in the fuel vaporization process.

b. Injection Element Evaluation

The Phase II testing resulted in definitive data on four of the previously described injection element selection criteria. As a result of the testing and a subsequent analysis of the important considerations guiding injector selection, two additional criteria were also added.

(1) Mixing

Bipropellant mixing limited combustion (synonymous with RSS in this report) was displayed quite vividly during the Phase II testing. The visual data and subsequent correlations indicate that two factors control mixing: 1) the fuel vaporization rate and 2) the degree of injection orifice or spray fan cant towards the unlike propellant. The most important conclusion was that unlike spray fan impingement elements (i.e., TLOL, PAT and EDM-LOL) promote RSS. With unlike spray fan impingement elements, significant vaporization occurs before unlike propellant contact. This gas generation prohibits mixing. When coherent unlike jet impingement occurs, mixing improves. It should be noted that of the unlike spray fan impingement elements tested, only the EDM-LOL had near optimum spray fan cant angles. The TLOL and PAT elements had too shallow an unlike impingement angle, which undoubtedly promoted RSS. The results agree with this conclusion. The EDM-LOL showed a higher degree of mixing than the PAT and TLOL. As a result, it was concluded that PAT and TLOL mixing could have been improved with increased unlike impingement angles.

(2) Injector Momentum Balance

The photographic results confirmed the pretest conclusions regarding momentum balance. Symmetric unlike jet elements (e.g., FOF triplets, OFO triplets, slit triplets, pentads, etc.) are totally insensitive to mixture ratio. Asymmetrical unlike jet elements (e.g., unlike doublets) exhibit the most unfavorable characteristics with respect to axial momentum balance. Unlike spray fan impingement elements (e.g., EDM-LOL, TLOL, PAT) fall in between the above extremes.

(3) Fuel Freezing

It seems reasonable to assume that unlike coherent jet impingement would promote fuel freezing because of intimate contact. However, no incidences of fuel freezing occurred during the testing. As a result of this testing, it was concluded that fuel freezing is not an important design consideration for injectors in the low thrust per element design range (approximately 1-50 lbF/element).

(4) Meaningful Photographic Results

The testing confirmed that excellent photographic results could be achieved for those elements where unlike jet or spray fan impingement occurred in a plane normal to the plane of view.

(5) Carbon Formation

The photographic test results indicated conclusively that the injector element type directly influences carbon formation. Unlike spray fan impingement elements reduce carbon formation because they induce a relatively rapid fuel vaporization rate. Coherent jet impingement elements, in contrast, exhibit increased carbon formation.

(6) Fabrication Complexity

Pre-atomized (i.e., platelet or swirler) elements are inherently more insensitive than coherent jet orifices to orifice size and alignment tolerances. This factor should be considered during injector element selection.

D. DATA CORRELATIONS

Carbon formation and RSS were found to be the most prominent observable combustion phenomena with LO_2/HC propellants. The objective of the data analysis effort was to develop an understanding of these processes. The data analysis involved literature review, study of high-speed color movies of single-element firings, and analytical modeling. The 1) data trends, 2) carbon formation correlations, and 3) RSS correlations are discussed below.

III, D, Data Correlations (cont.)

1. Summary of Data Trends

Subsequent discussion centers around characterizing and correlating carbon formation and RSS mechanisms. Data trends evident dᵘ ing testing are summarized in Figure 10, and discussed below.

a. Carbon Formation Trends

The hydrocarbon fuels tested showed increasing carbon formation in the following order: CH_4, C_3H_8, RP-1. As the C concentration of the H/C molecule increases, decomposition results in increased C_2 species that initiate the ploymerization process. In an associated manner, it follows that as the mixture ratio is decreased (increased carbon species concentration), the carbon formation rate increases.

The coherent jet impingement injector elements (RUD, LOL-EDM, OFO) showed increased carbon formation. It can be assumed that fuel droplet heating is delayed because of increased atomization time lag and increased mixing with the cryogenic oxidizer (resulting in fuel chilling). The delay in fuel droplet heating results in delayed fuel vaporization. The pre-atomized triplet element (PAT) caused the least amount of carbon formation. What is noteworthy is that the PAT was the least mixed of all the injectors. This finding agrees with the theory that more rapid fuel atomization and vaporization minimizes carbon formation. The carbon formation trend curves for fuel temperature and chamber pressure also agree with this theory. As fuel temperature is decreased, the vaporization rate decreases and carbon formation increases. The vaporization rate also decreases with decreasing chamber pressure.

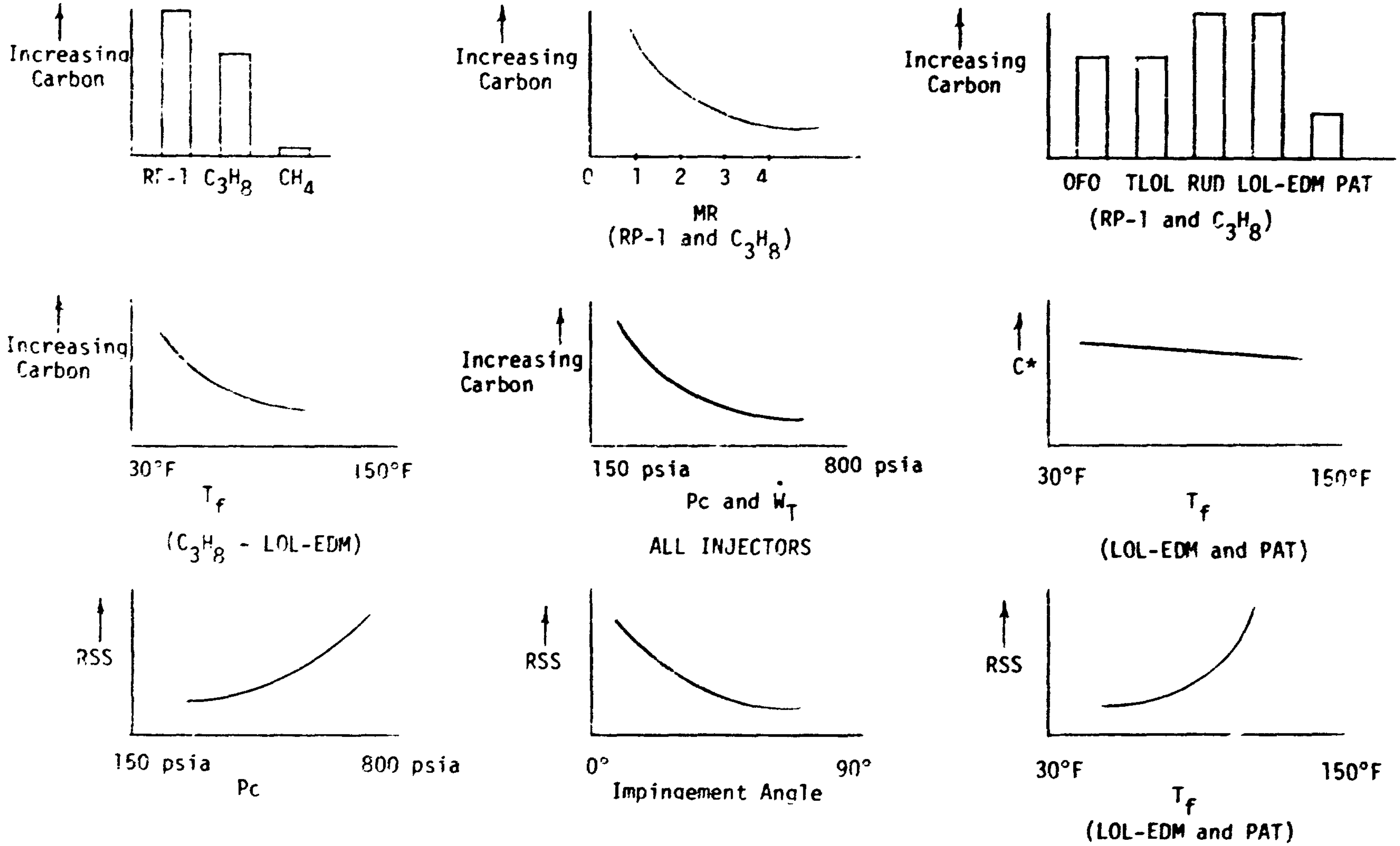


Figure 10. Data Trends

b. RSS Trends

Increasing incidence of RSS (i.e., decreased mixing) occurs as the fuel vaporization rate increases. This can be seen from the chamber pressure and fuel temperature trend curves. Fuel vaporization increases with increasing pressure and fuel temperature, resulting in more severe RSS. RSS increases as the unlike impingement angle decreases because of a decreased tangential momentum ratio (i.e., the fuel and oxidizer fans become more parallel).

2. Carbon Formation

A good deal of information about the carbon formation mechanism was gained during this study. All of the testing pointed toward the theory that carbon formation is directly related to fuel vaporization. Vaporization, in turn, is primarily affected by chamber pressure, fuel temperature, mixture ratio, fuel type, and injector element. Carbon formation will result if the fuel vaporization and combustion are slowed for whatever reason (intimate contact with LOX, short free-stream length, low chamber pressure and heat flux, coherent jet versus spray fan with large surface area, low fuel temperature, etc.). The low temperature carbon formation may be related to the coking or gumming observed with hydrocarbon fuels in heated tube testing (see Figure 11) or to some flame-quenching reaction. Further study is required to define the physico-chemical mechanisms. Each test was previously rated according to the degree of carbon formation observed. Figure 6 illustrated how ratings of "Clear," "Partialiy Obscured," and "Obscured" appear with a simple unlike doublet injector element.

In an attempt to characterize the carbon formation mechanism, twelve combustion correlations for each of the twelve injector/propellant combinations were plotted from the data. Each of the data points was a symbol

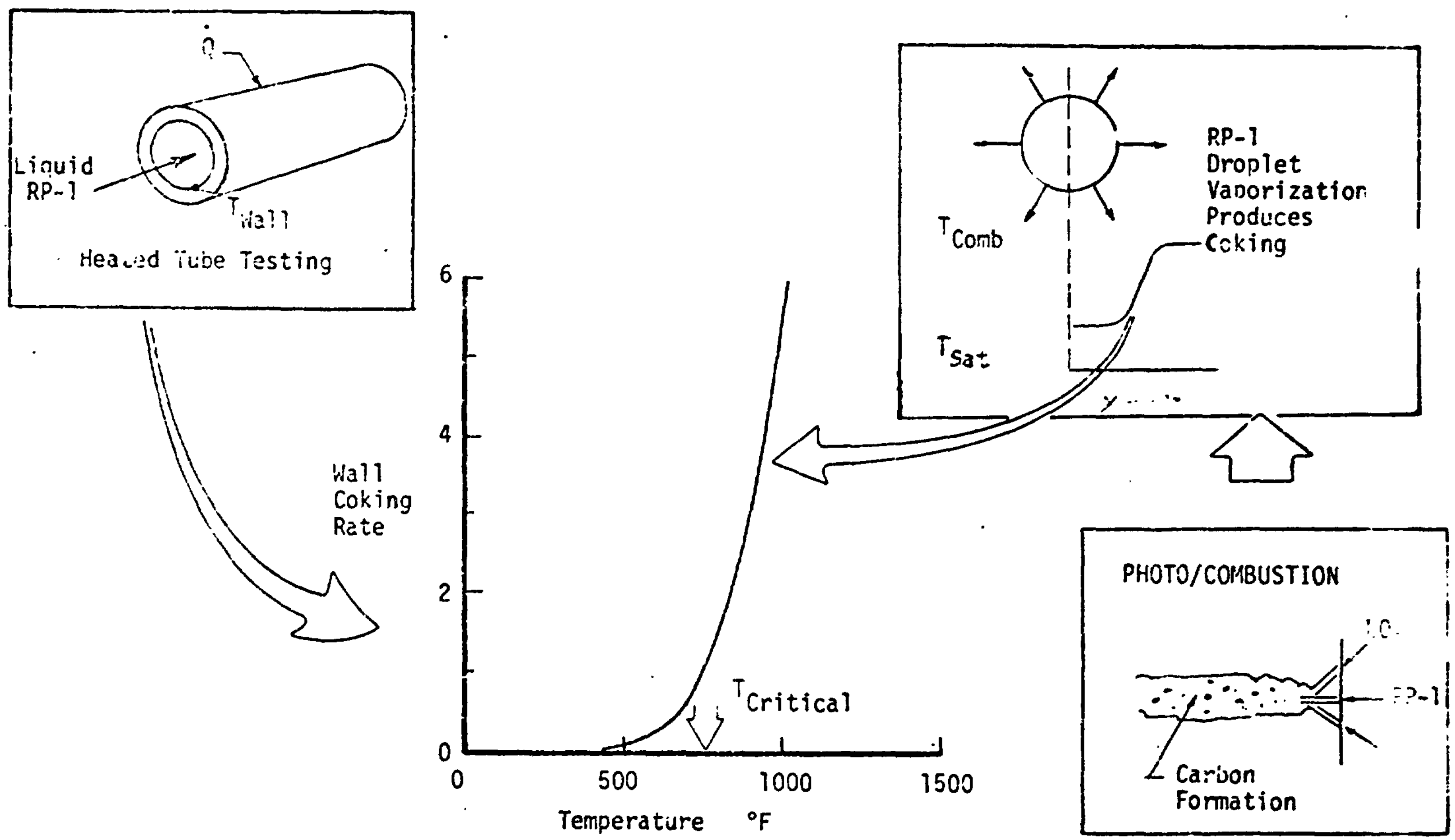


Figure 11. Carbon Formation Mechanism

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representing a certain degree of carbon formation, thereby making carbon formation trends easier to identify. A study of these correlations shows that a plot of "Pc -vs- T_f" gives the best correlation for the twelve injector/propellant combinations. Further study revealed that these twelve plots can be reduced to only three on the basis of carbon formation similarities between fuels and injector spray patterns.

Figure 6 (Sheet 1) correlates carbon formation for all of the injectors fired with LOX/RP-1. Chamber pressure is seen to be the dominant force in the change from excessive carbon formation to fairly clean combustion. Jet surface area and free-stream length were not found to be important factors in the carbon formation at the conditions tested. Most RP-1 tests were fired with fuel temperatures near ambient, so the effect of fuel heating could not be observed.

Figure 6 (Sheet 2) correlates carbon formation for the short impingement height injectors (RUD and LOL-EDM) fired with LOX/C_3H_8. Both chamber pressure and temperature are seen to influence carbon formation, thus reinforcing the vaporization theory. The two tests fired at temperatures above the saturation temperature were clear even though they were conducted at relatively low pressures. However, this occurred because the fuel was already in the vapor state and ready to burn.

Figure 6 (Sheet 3) correlates carbon formation for the long impingement height injectors (TLOL and PAT) fired with LOX/C_3H_8. Both chamber pressure and fuel temperature are seen to influence carbon formation. These injectors, however, show a definite tendency to remain more clear at low pressures than did the short impinging injectors. This is believed to be due to the increased vaporization of the pre-atomized, long fuel free stream before impingement.

There were no carbon formation correlations for the UD injector since it was fired only with NH_3.

Carbon formation in the LOX/C_3H_8 fuel-rich gas generators was excessive mainly because of the low mixture ratio (0.4 to 0.7) in addition to the above-mentioned reasons.

No carbon formation was experienced with the use of either gaseous or liquid methane. Propane decomposition and reaction result in a higher C_2 species concentration than methane. The C_2 species are very active and, through a process of polymerization, build up into particulate matter. Full-scale, multi-element methane gas generators may produce small amounts of carbon, but the quantity would be minuscule in comparison to the carbon production of a propane gas generator.

3. Reactive Stream Separation (RSS)

Previous analysis and testing with storable propellants have shown RSS to be controlled by a vaporization-controlled combustion mechanism (Ref. 2). Data correlations for the storable propellants showed that regimes of RSS could be correlated with chamber pressure and fuel Reynolds number, with chamber pressure exhibiting the strongest influence on RSS. Since vaporization is the controlling mechanism for the storable propellants, it is reasonable to assume that non-hypergolic impingement may also experience RSS. With these facts in mind, two hypotheses were postulated to explain RSS observed with LOX/HC propellants.

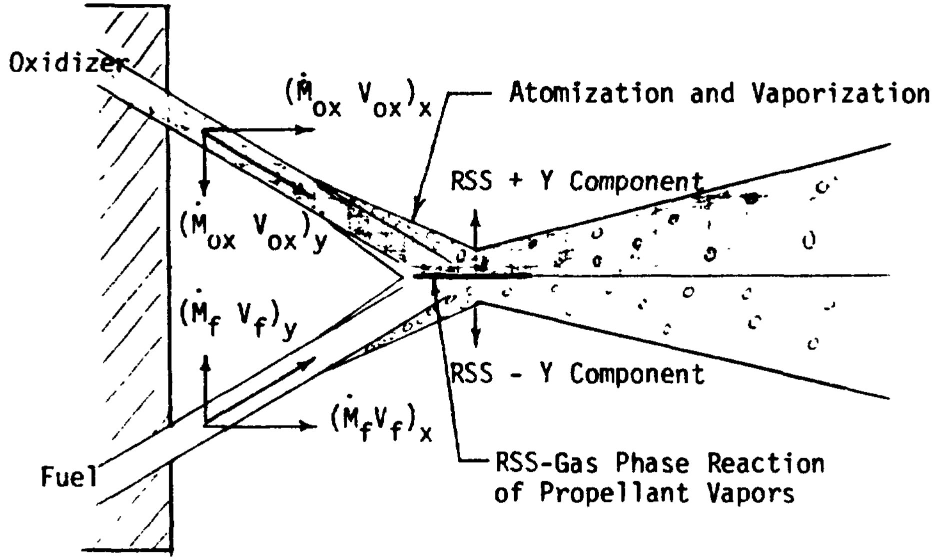
a. The first hypothesis is that LOX/HC RSS is also caused by vaporization-controlled combustion at the impingement interface. An attempt at correlating the hydrocarbon data with the storable fuel parameters

(Pc -vs- fuel Reynolds number) was unsuccessful. There was a definite Pc dependence, but the Reynolds number influence is less for the following reasons:

(1) Storable propellants are hypergolic and are not dependent on reaching an ignition temperature for combustion to occur.

(2) Hypergolic propellants are forced toward RSS by increasing velocity. Increased velocity causes increased interfacial surface area, which leads to a greater evaporation rate and more combustion. This, however, is only a second-order effect with LOX/HC propellants as the increased interfacial surface area means greater contact between the ambient temperature fuel and the cryogenic oxidizer. Since cooling of the fuel slows vaporization and combustion, RSS is likely to occur.

(3) Evaporation of the surface of the fuel stream by hot gas recirculation heating plays a major role in causing RSS with hydrocarbon propellants. Not only it is necessary that some minimum amount of fuel be vaporized before impingement, but also that it is heated to its autoignition temperature for RSS to occur. The amount vaporized is a function of fuel free-stream length, chamber pressure, fuel velocity, fuel temperature, and type of fuel (see Figure 12). In this respect, one can see the similarity between the influence of chamber pressure on RSS in storable and hydrocarbon propellants alike. Mathematically, this concept can be described as shown below:



COMBUSTION GAS GENERATION

$\dot{W}_g = (P_c, \tau_{ign}, \tau_r, T_f, \text{Fuel Type})$

W_g = Combustion Gas Generation

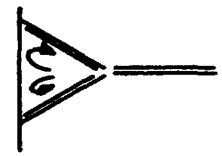
P_c = Chamber Pressure

τ_{ign} = Ignition Delay Time

T_f = Fuel Temperature

τ_r = Residence Time

- Highly Dependent on Chamber Pressure and Hot Gas Recirculation Heating to Vaporize Fuel Stream Surface.
- Not as Dependent on Fuel Reynolds Number Because Increasing Velocity Increases the Surface Area, Chilling the Fuel and Retarding RSS.
- Dependent on Fuel Ignition Delay Time and Fuel Type

 $\tau_{ign} \leq \tau_r$

- Sufficiently Large Impingement Angles Can Retard RSS when Flow Components $[(\dot{M}_f\ V_f)_y$ and $(\dot{M}_{ox}\ V_{ox})_y]$, Are Greater than RSS Components.

Figure 12. Vaporization Controlled Hydrocarbon RSS

$$\dot{W}_v = f\ (Pc,\ \tau_r,\ \tau_{ign},\ T_f,\ \text{Fuel Type})$$

where

$\dot{W}_v$ = evaporation rate

Pc = chamber pressure

τ_r = time between injection and impingement (residence time)

T_f = fuel temperature

τ_{ign} = ignition delay time.

High chamber pressure and long residence time obviously increase heat input to the fuel stream and promote evaporation and RSS. If the fuel is preheated, it serves to lessen the amount of time and pressure necessary to cause RSS. The type of fuel is an important factor because of heat of vaporization and autoignition temperatures (see below):

Fuel	Heat of Vaporization (cal/gr)	Autoignition Temperature (°C)
Ammonia	328.3	651.1
RP-1	69.5	250
Propane	101.7	504.4
Methane	121.7	632.2

Both the heat of vaporization and the spontaneous ignition temperature of ammonia are greater than the respective values for RP-1, Propane, and Methane. RSS was seen to occur with all of the hydrocarbon fuels but not with ammonia. The fact that ammonia seems far less reactive from an RSS standpoint than the hydrocarbons fits in well with the theory that vaporization-controlled combustion causes separation.

There is also evidence that when fuel residence times (τ) are short (as in the case of the two Like-on-Like injectors), the impingement angle has an influence on whether or not the streams will separate. The LOL-EDM (32° included) always seemed mixed, while the TLOL (15° included) always fired in the separated mode at the same test conditions and with same fuel. The hydrocarbon RSS combustion is apparently weak in comparison to its more reactive hypergolic counterpart, and it can be negated or overcome by propellant flow components which forcefully counteract the RSS vector. This line of reasoning indicates that the PAT injector, which operated in the separated regime at high pressures, could take on better hot-fire mixing characteristics if the included angle of impingement were increased and its free length were reduced.

b. The second RSS mechanism theory postulated states that the change in mixing characteristics with chamber pressure and fuel temperature is dependent on gas dynamic effects related to the Weber number. The Weber number effect at higher chamber pressures may cause faster spray breakup and atomization, which changes the mixing patterns.

Most of the test movies showed a trend away from RSS into a well-mixed regime occurring at chamber pressures between 100-300 psia for the fuels exhibiting RSS. The major exception to this rule was the LOL-EDM, which had a free-stream length of only 0.1 in. before fan impingement and an included angle of 32° (cooling the propellant and retarding RSS). Very limited testing was performed between 100-300 psia because the heavy carbon formation precluded photography. At the lower pressures, the better mixing and lower heat flux maintained a cooler fuel temperature and encouraged carbon formation. Although RSS trends were observable, and although possible mechanisms for its occurrence could be postulated, more testing at lower pressure, different impingement angles, and varied fuel temperatures is necessary to formulate correlations and design curves.

IV. APPLICATION OF RESULTS

The primary result of this program is the development of an understanding of the combustion phenomena, primarily RSS and carbon formation, associated with LOX/HC combustion. This understanding will be used to aid the design, test, and analysis of multi-element LOX/HC injectors aimed at gaining data for the development of full-scale engines. The results are currently being used to aid injector selection and design in the Combustion Performance and Heat Transfer Characterization of LOX/HC Type Propellants Program (NAS 9-15958).

It is currently envisioned that these photographic techniques could be applied successfully to future LOX/HC and LOX/H_2 technology programs. Based on current NASA five-year planning, the following three specific applications come to mind:

1. OTV Advanced Expander Cycle Barrier Element. It is desired to enhance heat transfer to the hydrogen regenerative coolant. These techniques can be used to develop a well-mixed element that will maximize the gas-side heat transfer coefficient.

2. LOX Hydrocarbon Engine Gas-Side Carbon Deposition. Carbon deposition on the chamber gas-side can significantly reduce heat load to the chamber coolant, thereby increasing coolant design margin. An understanding of how to control this process would be advantageous for design purposes.

3. LOX Hydrocarbon Ignition Technology. Bipropellant igniters must be developed for advanced LOX/HC engines. These techniques can aid the understanding of igniter combustion chamber design requirements.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The following conclusions are drawn from this work.

1. Single element photography has been successfully used to characterize LOX/HC combustion.
2. Qualitative trends are understood for control of carbon formation. Chamber pressure, fuel type, fuel temperature, and injector design influences have been observed. Carbon formation increased for the fuels tested in the following order: ammonia, methane, propane, RP-1.
3. Methane shows significant promise as a non-carbon generating hydrocarbon fuel for gas generators and preburners.
4. Ammonia displayed relatively benign combustion that resulted in a well-mixed bipropellant spray fans over a wide operating range.
5. Qualitative trends are understood for control of LOX/HC combustion mixing. Chamber pressure, fuel type, fuel temperature and injector design influences have been observed.
6. Preliminary modeling approaches for carbon formation and RSS have been suggested, but physically mechanistic models are not yet developed.
7. The program carbon deposition data could be used to develop models for gas-side carbon deposition for high-pressure LOX/HC thrust chambers.
8. The program RSS data could be used to develop models for injector element mass and mixture ratio distribution control for all advanced engines.

V, Conclusions and Recommendations (cont.)

B. RECOMMENDATIONS

The following recommendations are made on the basis of the program results:

1. Continued single-element, cold-flow, and hot-fire photographic testing is recommended.

    a. Testing of heated propane and RP-1 at gas generator operating conditions is necessary to characterize carbon formation dependence on fuel temperature.

    b. The carbon formation trends should be used as a guide to update the fuel-rich combustion model developed on Contract NAS 3-21753.

    c. High-pressure cold-flow testing should be performed to allow differentiation between gas dynamic (Weber number) and combustion (RSS) effects.

    d. Further testing at low pressures (100-300 psia) is necessary to determine the influence of the fuel type and injector element design parameters on the occurrence of RSS.

2. The results of the Task I cooling analysis of the Combustion Performance and Heat Transfer Characterization of LOX/HC Type Propellants Program (NAS 9-15958) should be reviewed to ensure that all potential thrust chamber assembly operating points have been characterized at single-element conditions.

3. Scaling studies should be conducted to determine the applicability of the current data base to high-pressure LOX/HC liquid rocket booster designs.

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