High Performance N2O4/AMINE Elements "BLOWAPART"

NASA CR-160272

Final Summary

March 1979

(NASA-CR-160272) HIGH PERFORMANCE N2O4/AMINE ELEMENTS BLOWAPART Final Summary Report (Aerojet Liquid Rocket Co.) 50 p HC A03/MF A01 CSCL 21I G3/28

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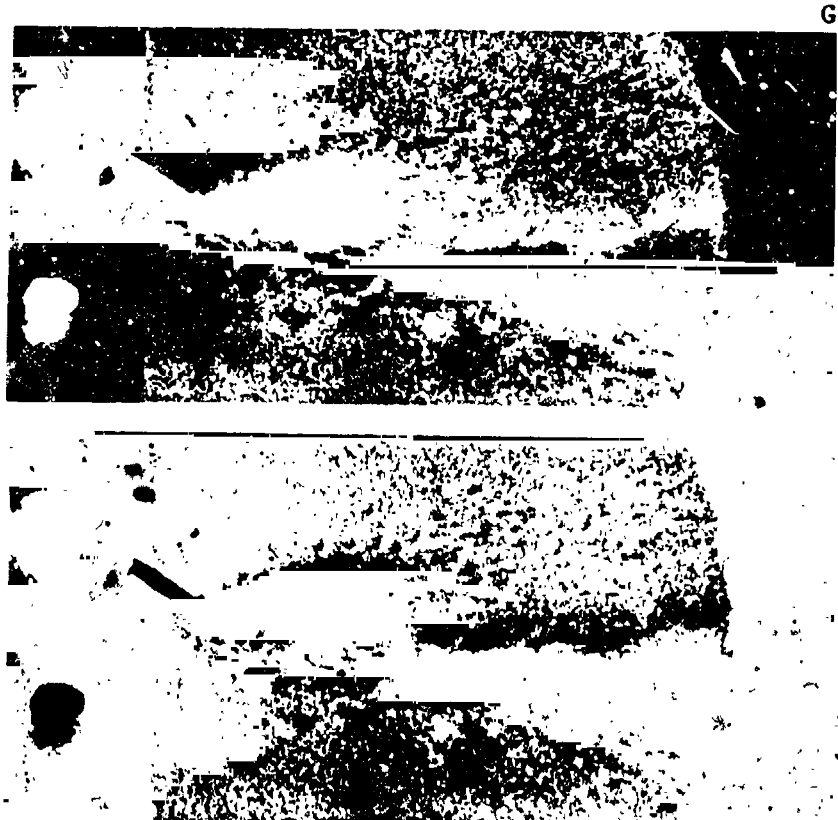

Contract NAS 9-14186

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ORIGINAL CONTAINS COLOR ILLUSTRATIONS

AEROJET LIQUID ROCKET COMPANY

FOREWORD

This summary report describes analytical and experimental work conducted to identify the mechanisms governing Reactive Stream Separation (RSS) and to develop techniques for predicting its occurrence. RSS is a combustion induced phenomenon that results in striation of hypergolic propellant oxidizer and fuel sprays fans. This reduced intra-element mixing (compared to the well-mixed distribution developed in a non-reacting cold flow case) can influence thrust chamber performance, heat transfer, and stability. The activity was performed by Aerojet Liquid Rocket Company (ALRC) on Contract NAS 9-14186, under the direction of Merlyn Lausten, NASA/JSC Project Manager. Aerojet personnel included L. B. Bassham, Program Manager, D. L. Kors, Project Manager and B. R. Lawver, Project Engineer. J. W. Salmon also served as ALRC Program Manager, commencing in January of 1978. The following individuals contributed significantly to the success of the program:

Paul Lloyd	Test Engineering
Arnold Keller	Test Engineering
Duane Robertson	Test Instrumentation
Cliff Thompson	Combustor Design
Lee Lang	Combustor Design
Gene Hron	Fabrication
Judy Schneider	Data Analysis
Dick Walker	Data Analysis.

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ABSTRACT

An experimental and analytical program was conducted to develop an understanding of the mechanisms controlling hypergolic propellant reactive stream separation (RSS). RSS is a combustion induced phenomenon that results in striation of hypergolic propellant oxidizer and fuel sprays fans. This reduced intra-element mixing (compared to the well-mixed distribution developed in a non-reacting cold flow case) can influence thrust chamber performance, heat transfer, and stability. The program end product was development of design criteria for coping with RSS to allow the design of high performing,stable injectors. RSS mechanisms were identified using high speed color photography to observe reactive stream mixing of single element injectors tested with N_2O_4/MMH, N_2O_4/A-50, and N_2O_4/N_2H_4 propellants. Three hundred and fifty six tests were run over a chamber pressure range of 60-1000 psia, a fuel temperature range of 55°F-300°F, and a fuel velocity range of 30-200 ft/sec. This wide parametric characterization included modeling of the Space Shuttle Orbital Manuevering System (OMS) and Reaction Control System (RCS) engine injectors.

Tests were conducted using five different conventionally machined unlike doublet elements and two triplet elements. Also, three platelet elements were tested. Platelet injectors are fabricated by bonding together a stack of thin metal sheets which have etched flow passages. A simulation of the Space Shuttle/RCS engine injector element was included in the unlike doublets and a simulation of the Space Shuttle/OMS engine platelet like-on-like doublet injector element was included in the platelet injectors.

The single element firings were conducted in a specially constructed chamber fitted with quartz windows for photographically viewing the impingement spray field. Analysis of the film identified the occurence of reactive stream separation as evidenced by non-uniform spray fields.

ABSTRACT (cont.)

Distinct regions of mixing and separation were identified and correlated for each of the injectors tested. Color photographs of the combustion phenomena are included. Finally, a working model was developed that correlates RSS as a function of a fuel vaporization rate control parameter.

The most important design criteria derived from this work states that: "the element should be designed to avoid transition between mixed and separated modes within the engine operational envelope".

I. INTRODUCTION AND SUMMARY

Hypergolic earth-storeable N_2O_4/Amine propellants have been historically used for a vast number of liquid rocket propulsion system applications. They have been used on the Titan II and Titan III first, second, and third stage engines. Also, they have been the near exclusive choice for reaction control and orbital maneuvering systems with low to moderate ΔV requirements (e.g., Apollo and Space Shuttle). These propellants are highly reactive and can experience reactive stream separation (RSS) (i.e., blowapart) which can inhibit intra-element mixing. RSS is a combustion induced phenomenon that results in striation of hypergolic propellant oxidizer and fuel sprays fans. This reduced intraelement mixing (compared to the well-mixed distribution developed in a non-reacting cold flow case) can influence thrust chamber performance, heat transfer, and stability. Modifications of the spray field uniformity can result in lowered combustion efficiency, altered gas side heat transfer conditions, and reduced stability. It is imperative that the RSS phenomena be understood so that the designer of today's high efficiency engines can cope with its effects. The identified modes of RSS are shown in Figure 1.

Several studies (References 1-17) have been conducted over the past decade in an effort to understand the RSS phenomena, identify operational limits of RSS, and develop design criteria for its avoidance. However, none were totally successful. Several RSS models were postulated but none were able to correlate all the experimental data.

The objective of this program was to develop an understanding of the mechanisms controlling hypergolic propellant RSS. Design criteria for coping with RSS, to allow the design of high performing stable injectors, would be developed with that understanding. The approach taken was to clarify some of the previous studies, to provide a consistent set of data for the identification of mechanisms responsible for RSS, and to map RSS regimes for a wide range of injector elements that included Space Shuttle

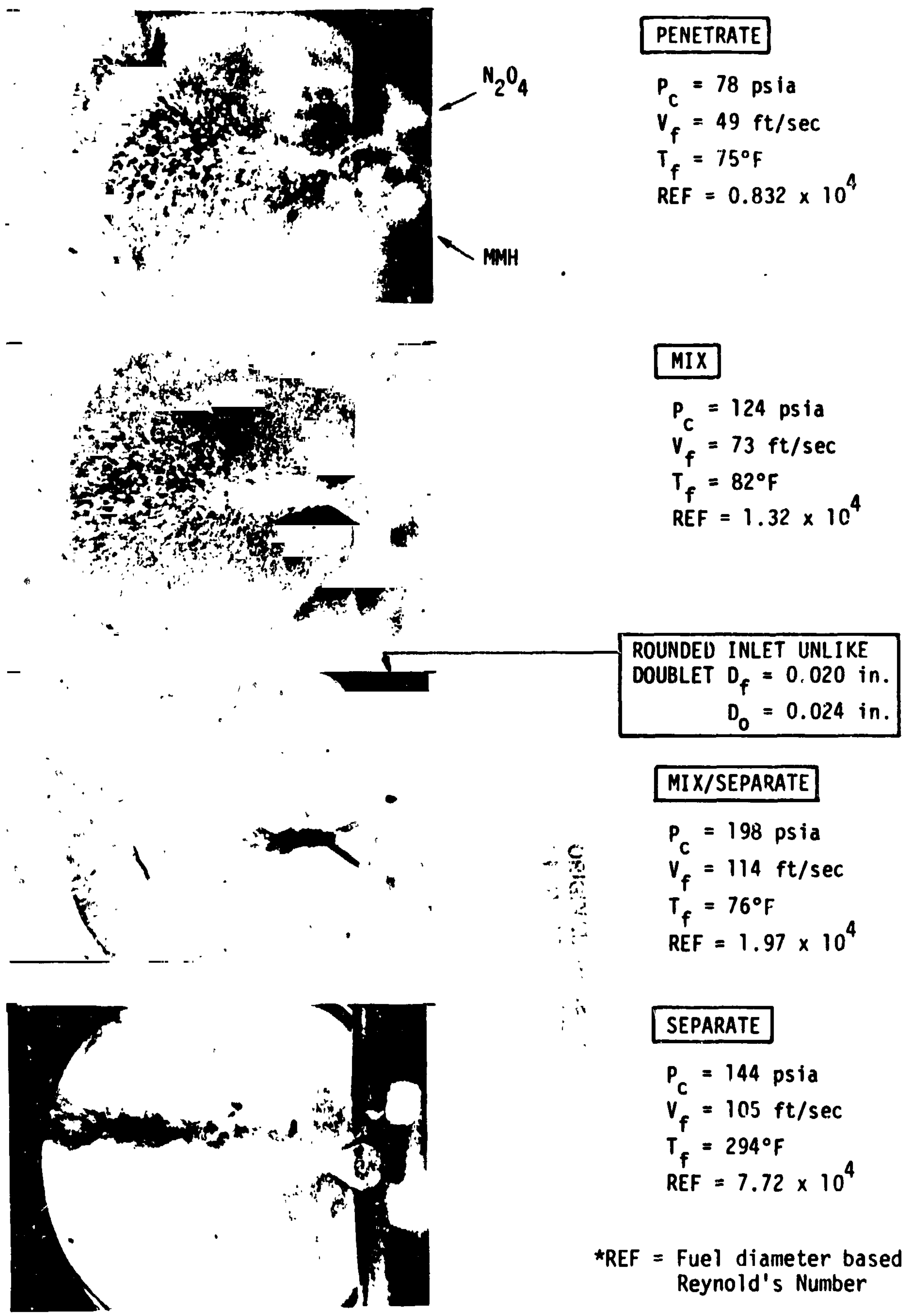


Figure 1. High Speed Photography Defines Four Modes of Reactive Stream Impingement

engine applications. Clarification of the previous studies was accomplished through an evaluation of the data and RSS models found in the literature. These results were used to initiate an iterative model development/test program as shown in Figure 2.

The program was incrementally funded as indicated in Figure 3. Spreading the funding over a four year period has proven to be a cost effective way to develop this technology. Sufficient time was available to thoroughly assess the data, apply the results to engine development problems, and get feedback for program direction, as illustrated in Figure 2.

Understanding of RSS mechanisms was accomplished through the development of high speed color photography techniques to observe single element injector combustion using N_2O_4/MMH, N_2O_4/A-50, and N_2O_4/N_2H_4 propellants. Injectors and conditions tested are summarized in Table I and include the Space Shuttle Orbit Maneuvering System (SS/OMS) engine and Space Shuttle Reaction Control (SS/RCS) engine applications. Tests were conducted using four different unlike doublet injectors, two triplet injectors, and three platelet injectors. Platelet injectors are fabricated by bonding together a stack of thin metal sheets that have etched flow passages. A simulation of the SS/RCS injector was included in the unlike doublets and a simulation of the SS/OMS engine transverse platelet like-on-like doublet (TLOL) injector was included in the platelet injectors. Tests were run over a chamber pressure range of 60-1000 psia, a fuel temperature range of 55°F-300°F, and a fuel velocity range of 30-200 ft/sec.

The hot firings were conducted in the specially constructed photographic chamber shown in Figure 4. High speed color movie film identified the occurrence of reactive stream separation as shown in Figure 1.

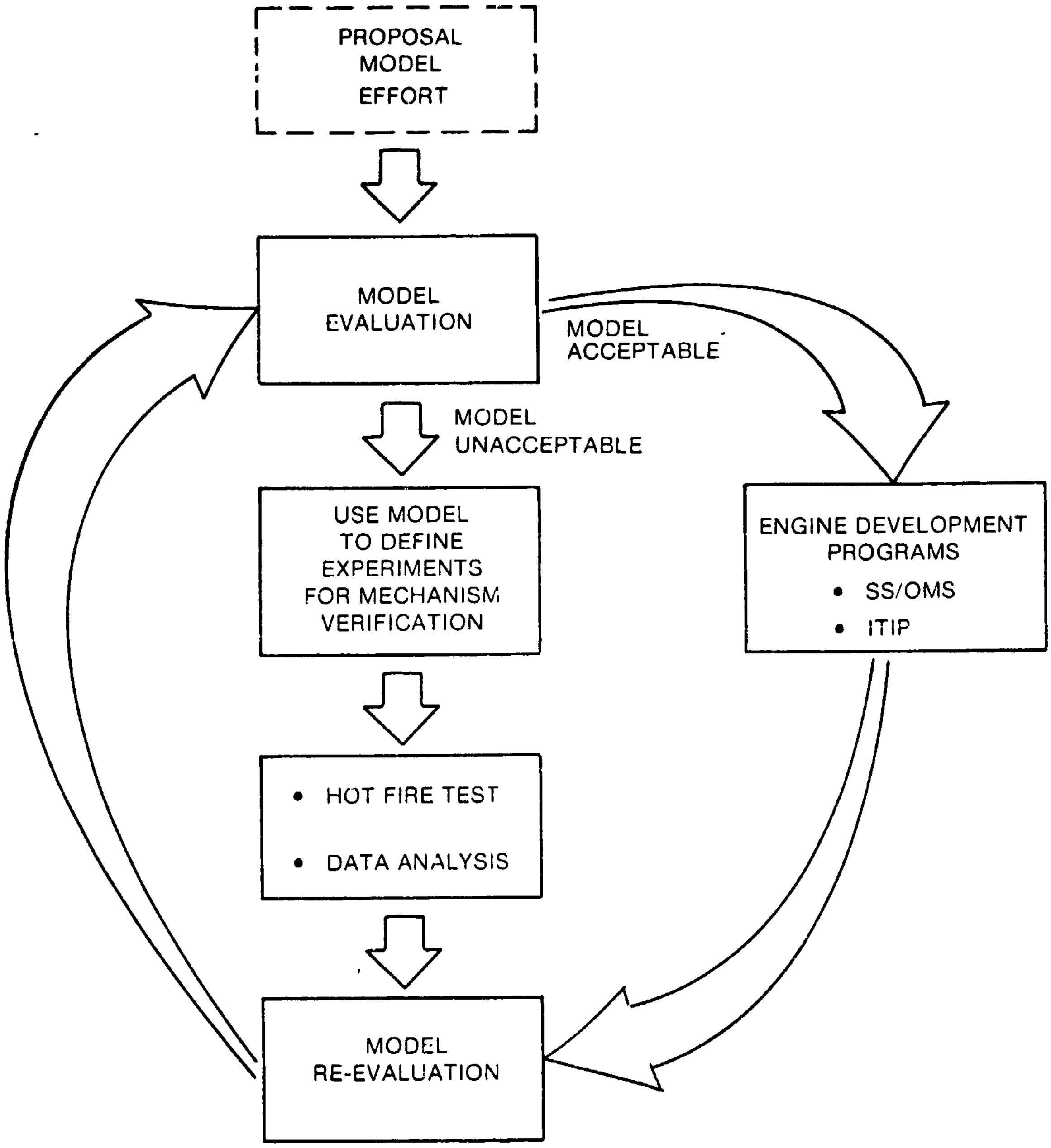


Figure 2. RSS Model Development Approach

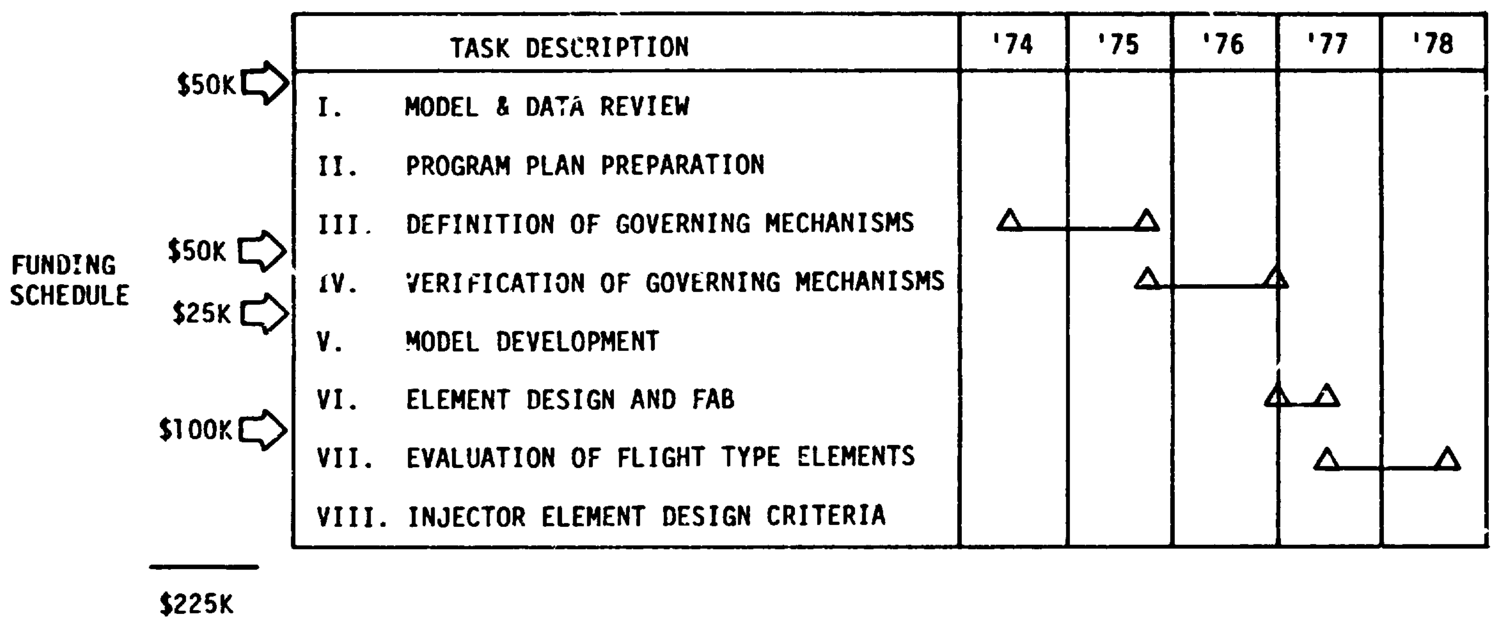


Figure 3. Blowapart Technology Program Approach

TABLE I

SUMMARY OF INJECTOR ELEMENTS AND TEST CONDITIONS

Fuel	Injector* Elements	P_c (psia)	V_f (ft/sec)	T_f (°F)	MR
MMH	1,2,3,4,5 6,7,8,9,10,11	40-1000	30-220	50-300	1.4-3.2
A-50	1	90-1000	50-160	60-85	1.6-1.7
N_2H_4	1,5,6,9	60-400	30-175	60-90	1.4-2.0

*Injector Element Code

1. Rounded Inlet Unlike Doublet, D_f = 0.020 Long Impingement (0.160")
2. Rounded Inlet Unlike Doublet, D_f = 0.020 Short Impingement (0.040")
3. Small F-O-F Triplet D_f = 0.020
4. Large F-O-F Triplet D_f = 0.029
5. Small Sharp Edged Unlike Doublet, D_f = 0.020
6. Large Sharp Edged Unlike Doublet, D_f = 0.030
7. Space Shuttle/RCS Unlike Doublet, D_f = 0.023
8. Space Shuttle/RCS Unlike Doublet, Offset Impingement, D_f = 0.023
9. Space Shuttle/OMS TLOL Platelet Injector D_f = 0.028
10. XDT Platelet, D_f = 0.021
11. Splashplate Platelet, D_f = 0.021

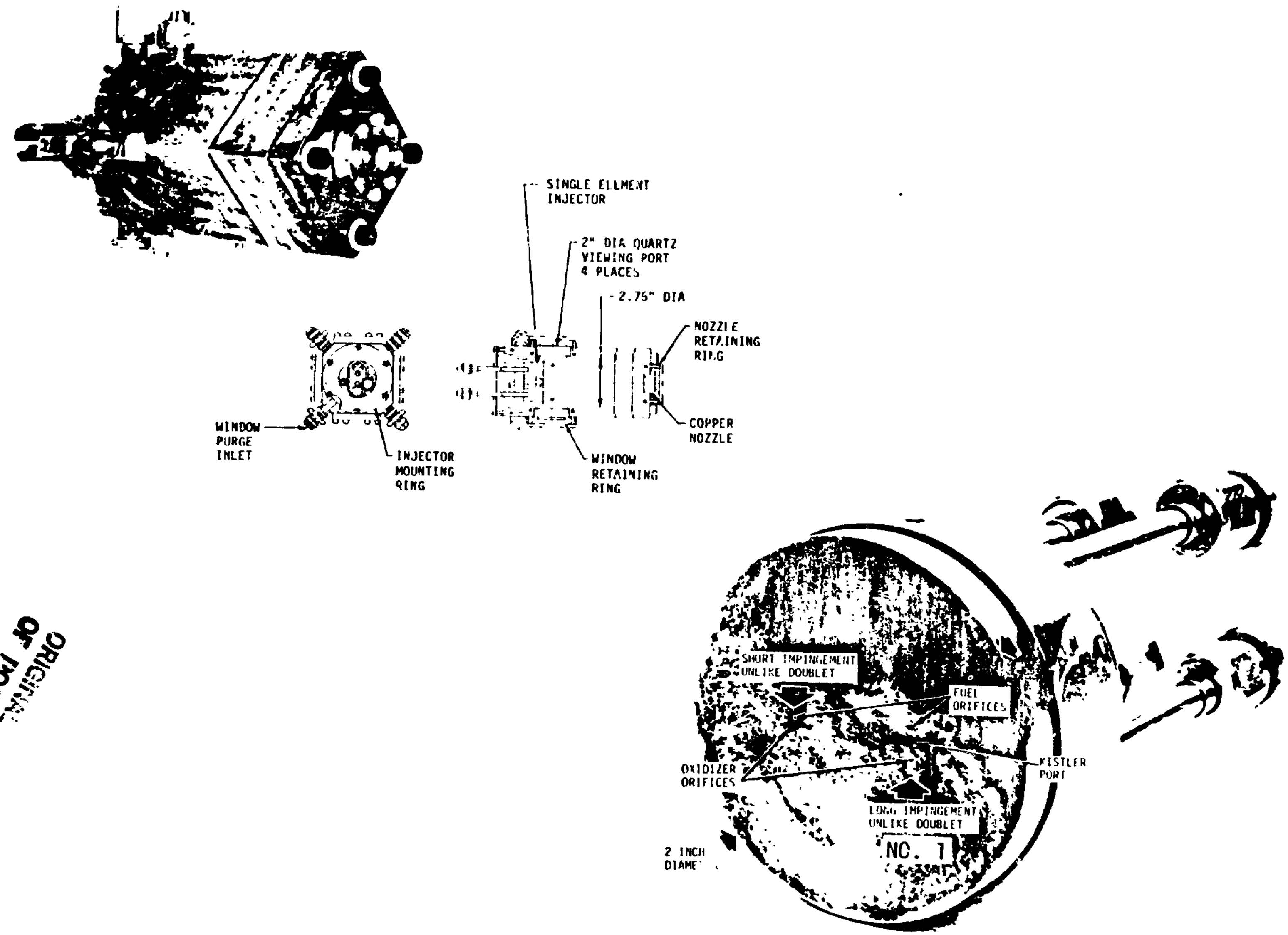


Figure 4. Photographic Test Chamber and Single Element Injector

Fuel vaporization rate controlled combustion was identified as the RSS controlling mechanism for the operating conditions and elements listed in Table I. These elements include both coherent stream and atomized impingement injector types. Data correlations made on the basis of a fuel vaporization controlled RSS model show that regimes of RSS are correlated for both types of injector elements. The model independent variables are chamber pressure and the fuel orifice Reynolds Number (REF), as shown in Figures 5 and 6. Figure 6 includes some single element data obtained during the OMS subscale development program (Ref. 18). This data is also reported in the Interim Report, (Ref. 19). The chamber pressure exhibits the strongest influence on RSS. Increasing chamber pressure promotes RSS. Orifice diameter, injection velocity and propellant temperature effects are correlated with the fuel orifice Reynolds Number. Increasing anyone of these promotes RSS.

Injector design criteria were developed and are published as an appendix to the program final report (Ref. 20). The primary element design criteria states that the elements should be designed to avoid transitions between mixed and separated modes within the engine operating Pc-MR range. The element design guide provides the design data required to meet this criteria.

The technology developed on this program has been used to aid the development of both the Space Shuttle/OMS engine and the Improved Transtage Injector Program (ITIP) engine as well as characterize the Space Shuttle/RCS engine injector element. This work was especially instrumental in the development of the highly successful Space Shuttle/OMS engine platelet injector. Substantial program development time and funding were saved by using single element testing to select injector elements to solve an engine stability problem. The element selected was found to be insensitive to engine operating point which permits more accurate prediction of performance, heat transfer and stability. These photographic techniques are currently being used to develop an understanding of combustion phenomena associated with hydrocarbon fuels and injectors.

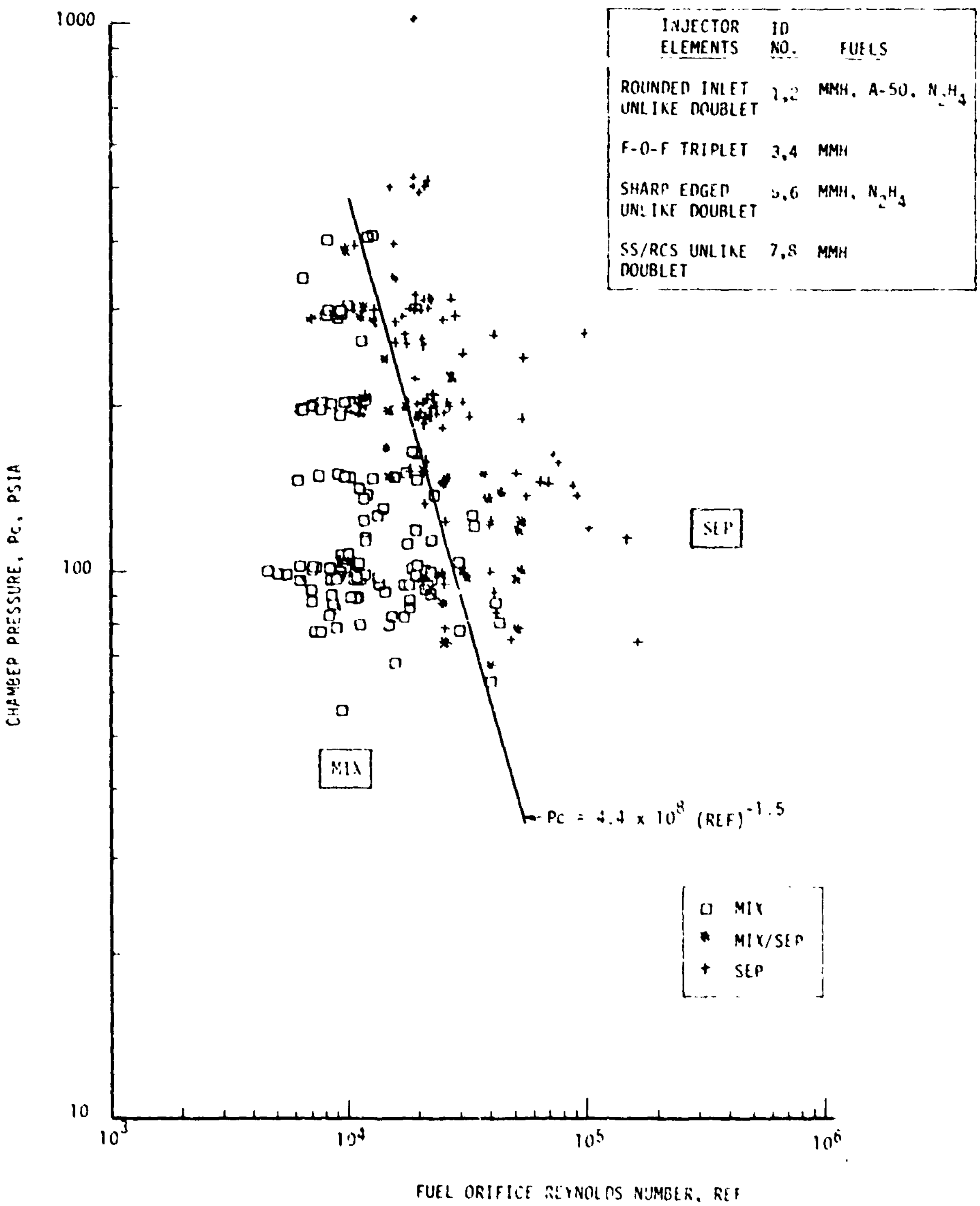


Figure 5. Vaporization Model Correlates RSS for Coherent Stream Impingement Injector Elements

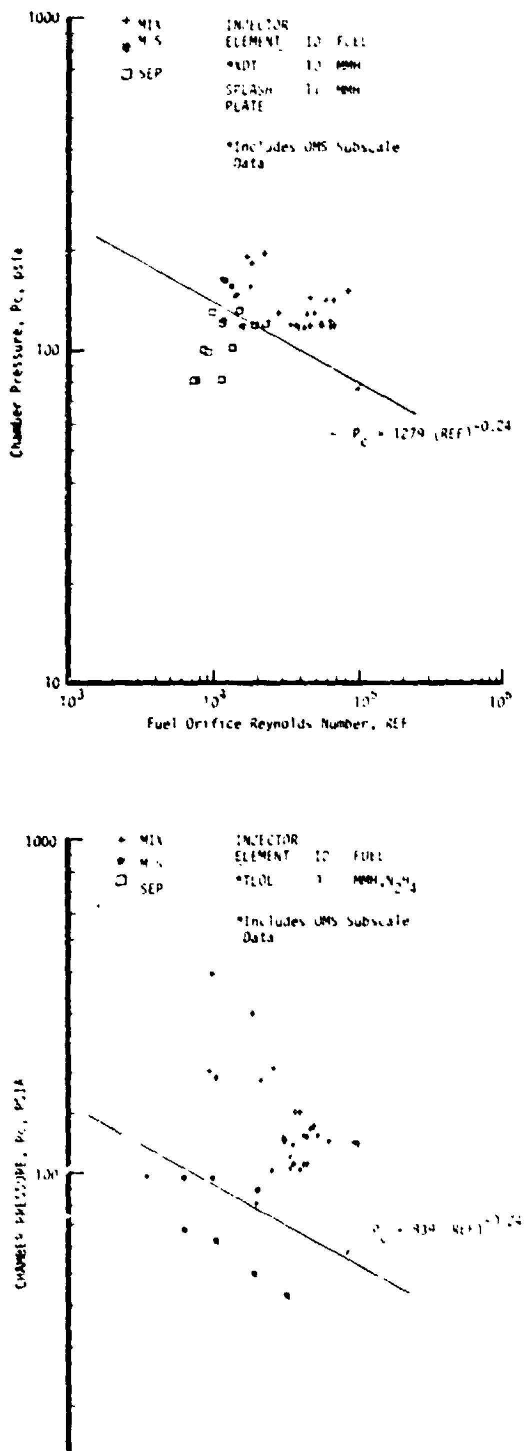


Figure 6. Vaporization Model Correlates RSS for Atomized Spray Impingement Injector Elements

II. PROBLEM DESCRIPTION AND TECHNICAL APPROACH

A. PROBLEM DESCRIPTION

Injector element selection is key to successful engine development since the element design exhibits a first order impact on thrust chamber performance, stability and thermal compatibility. Historically, rocket injector designs have had to rely on analysis and single element cold flow evaluation for element selection criteria. Experience has shown that these design tools do not adequately account for combustion effects which can exhibit controlling influences on these performance parameters. The classic example is the Reactive Stream Separation (RSS) (i.e., "blowapart") phenomena associated with the N_2O_4/Amine fuel propellant combinations. Reactive stream separation was observed to reduce performance of an unlike doublet injector during the Space Shuttle/OMS engine predevelopment phase. It was later found to impact the stability of an OMS platelet XDT injector. RSS related performance, stability and thermal compatibility problems were also encountered during the Space Shuttle/RCS engine development. RSS effects were also observed on the Apollo SPS engine. During its development the SPS engine experienced "pops" which were attributed to orifice hydraulic flip. Selected orifices were counterbored to prevent hydraulic flips which resulted in a reduction in "pops". A subsequent analysis (Ref. 1) of the problem revealed that counterboring of the orifice resulted in "bushy" streams which operate in the RSS mode as opposed to the mix mode associated with the coherent streams before counterboring. The resultant effect was to induce RSS which inhibited intra-element mixing and popping since mixing is a prerequisite for popping (Ref. 1).

Like most high performance injectors, both the SS/OMS and SS/RCS injectors depend on unlike impingement momentum exchange mixing to achieve uniform propellant spray distributions. RSS is a combustion phenomena which modifies the momentum exchange mixing process, and hence effects the engine performance, stability and thermal compatibility.

RSS is the consequence of vigorous reaction within the impingement interface which produces combustion gases in sufficient quantities to inhibit the stream or spray momentum exchange.

B. APPROACH

The approach taken to develop an understanding of the RSS mechanisms involved literature review, model evaluation, development of high speed color photography techniques, testing of single element injectors, and analytical modeling. A mechanistic approach which involves examination of the physico-chemical processes was taken since successful modeling requires that the basic processes be understood. Previous work had shown that RSS is difficult to quantify on the basis of normal engine performance measurements. This is because mixing between adjacent elements "masks" the influence of combustion on intra-element mixing. Therefore, it was decided to use photographic techniques to observe the RSS phenomena. Single element injectors as shown in Figure 4 were selected for testing to provide a clear view of the impingement zone. The use of single element injectors also saves fabrication and testing costs. Further fabrication cost savings were attained by putting two elements in each injector body. Only one element is fired at a time.

The single element injectors were fired in the photographic test chamber shown in Figure 4. The chamber is fitted with viewing ports for lighting and viewing the combustion process. The chamber has replaceable nozzles for controlling the chamber pressure independent of propellant flowrate or injection velocity. Testing with the single element injectors also allowed testing over a wider range of operating conditions than could be done within normal engine operating constraints. The wide range of parameters tested allowed the true parameter influences to be determined.

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

The major problem associated with photographing combustion flow fields is that the combustion flame light emission is so intense that it masks the reflected light necessary to see the propellant streams as illustrated in Figure 7. The technique used to overcome the intense combustion light was to reduce the film exposure time such that the film in effect doesn't "see" the flame light and to provide high intensity external lighting for viewing of the propellant streams. The external lighting was provided from the back, top, bottom, and front to obtain a balance between reflected and absorbed light. It was found that use of back lighting alone will not provide the lighting balance required to properly interpret the film.

The photographic equipment was centered around a Hycam model 41-0004 rotating prism high speed movie camera. The best pictures were obtained at 400 pictures per second with a 1/100 shutter. A 35mm telephoto lense was used to provide magnification of the spray field. Lighting of the spray field was accomplished with one 1000-watt quartz iodine lamp to backlight the spray area with three small 750 watt lamps to light the top, bottom, and front. The small lamps were placed within one inch of the top and bottom windows to maximize the illumination. The net effect was to provide a balance between the front lighting and the back lighting.

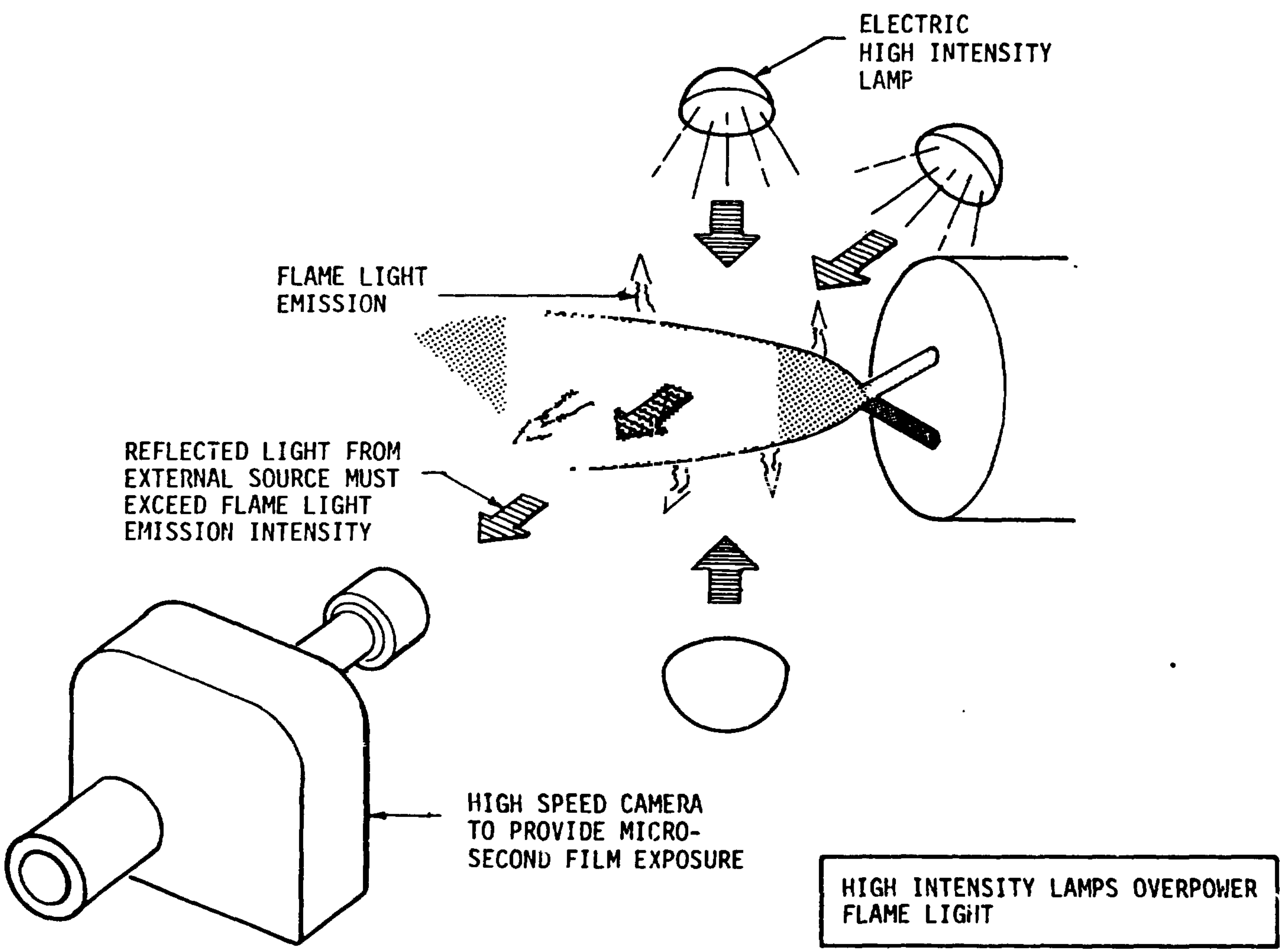


Figure 7. High Intensity Lamps Overpower Flame Light Emission

The program was structured to consist of eight tasks as shown in Figure 3. The inter-relationship of each task toward development of the program final vaporization controlled RSS model is shown in Figure 8. The Task I objectives were to; critique all existing models relating to RSS, review and summarize all associated RSS data, and formulate an updated RSS model based on existing data. The results of this work were used to guide the Task III testing.

The Task II objective was to prepare a detailed program plan, i.e., to formulate a detailed method of approach to be taken for model testing and verification in subsequent tasks. This work is documented in Reference 21.

The Task III objectives were to define the mechanisms governing RSS, establish limits for RSS and to define appropriate models. The work included; design, fabrication and testing of two single element unlike doublet injectors, incorporation of high speed photographic techniques for visual propellant stream characterization, and correlation of RSS with various independent test variables. The results of the Task III work were used to evaluate and update the Task I models and to define further testing.

The Task IV objectives were to; establish operating limits for RSS for other injector types, and verify mechanisms governing RSS and the appropriate physical models resulting from the Task III work. The Task IV effort inlcuded the design, fabrication and testing of triplet and atomized spray impingement platelet injectors. The term "atomized spray" as used here means that a single propellant provides the atomization, either by self impingement or by impingement with a surface. The results of this work showed that the primary factors controlling RSS are the chamber pressure, the fuel velocity and the fuel temperature. Correlations involving the chamber pressure, the fuel Weber number, and the fuel Reynolds number were developed.

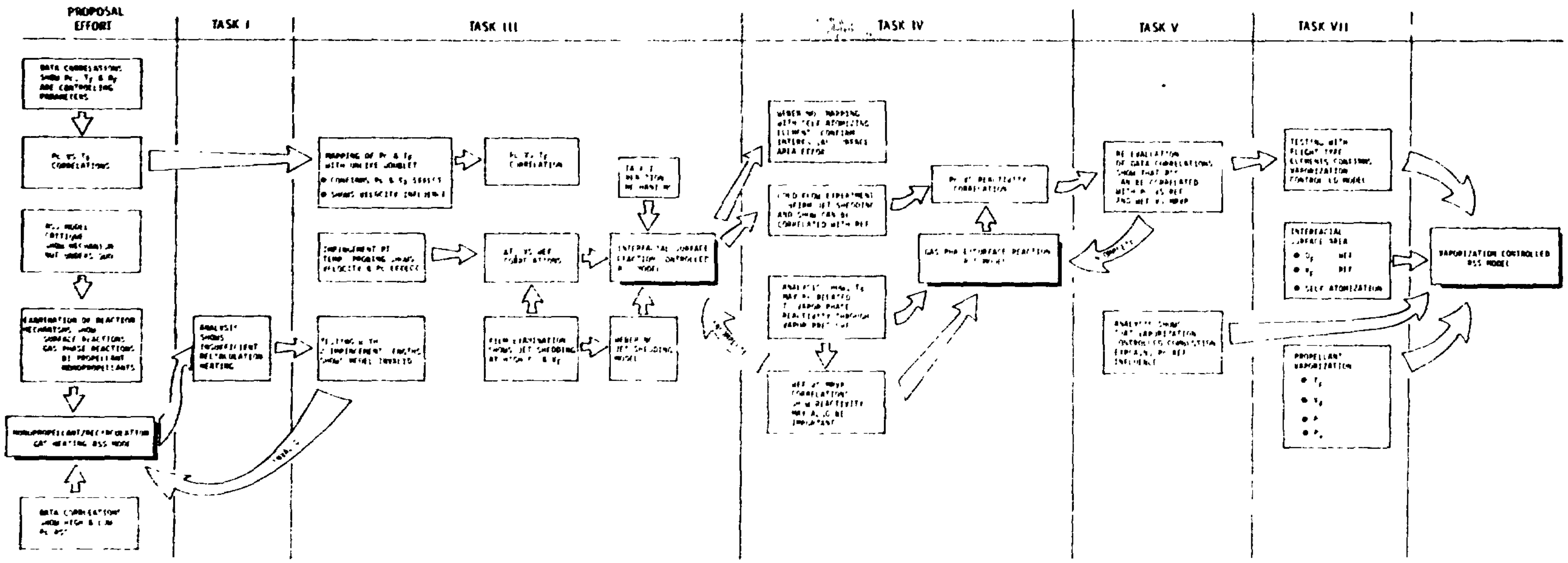


Figure 8. RSS Model Development Chronology

II, B, Approach (cont.)

The objective of Task V was to review all available reactive stream separation data and develop a more comprehensive RSS model. This model effort was directed toward definition of mixed and separated zones which can be related to injector element design and operating parameters. A vaporization controlled gas phase combustion RSS model was developed as a result of this work. The correlations developed on this task were used to select operating conditions to be tested in Task VII, the final model verification tests.

The objective of Task VI was to design and fabricate two flight type injectors for testing in Task VII. The intent was to verify the RSS mechanisms with flight type injector elements. A sharp-edged unlike doublet and the Space Shuttle/RCS unlike doublet element were selected. Each of the injectors incorporated independently manifolded elements so that two different single element designs were built within each of the injector bodies. In addition, a previously designed and fabricated platelet like doublet element (TLOL), which duplicates the Space Shuttle Orbit Maneuvering Engine core element design was made available for Task VII testing.

The Task VII objectives were to define regimes of RSS for the flight type injector elements fabricated in Task VI and to verify the vaporization RSS model. Testing included the sharp-edged unlike doublet, the Space Shuttle/RCS unlike doublet, the Space Shuttle/OMS platelet TLOL, and the rounded inlet unlike doublet. Both MMH and N_2H_4 fuels were tested. The results of this work confirm the vaporization RSS model and show that MMH, A-50, and N_2H_4 fuels exhibit the same RSS limits.

The Task VIII objective was to prepare an element design criteria for coping with the effects of RSS. The design criteria are published as an appendix to the program final report (Ref. 20).

III. RESULTS

The significant results of this program are: A, development of an improved photographic technique for viewing combustion processes under rocket engine operating conditions; B, identification of regimes of RSS for a wide range of injector elements and operating conditions; C, identification of mechanisms controlling RSS and development of an RSS model; D, identification of non-reactive factors influencing intra-element mixing; and E, publication of an RSS element design criteria.

A. IMPROVED PHOTOGRAPHIC TECHNIQUE

The improved photographic technique developed on this program is based on the use of high intensity external lighting to illuminate the combustion field as shown in Figure 7. The flame light is overpowered by the high intensity lamps so that the film doesn't "see" it. It was found that the light must be balanced to provide uniform lighting from front, back, bottom, and top to get high quality film like that shown in Figure 4. It was also found that the use of cold gas purges on the inside of the window must be avoided. The cold purge gas creates density gradients that are visible on the film. The effect is like viewing through a film of turbulent water which obscures the view. Development of these improved photographic techniques early in the program was essential to the success of this program. RSS mechanisms could not have been identified without them.

B. RSS REGIMES

Regimes of RSS were identified for the ten different injector elements tested. They include both coherent jet and atomized spray impingement type injector elements.

Coherent Steam Elements

- Unlike Doublet
    - Rounded inlet long L/D (L/D = 12)
    - Sharp Edged Short L/D (L/D = 5)
    - SS/RCS (L/D = 10)
- Fuel-Oxidizer-Fuel Triplet

Atomized Spray Impingement Elements

- X-Doublet Platelet
- Splash plate platelet
- SS/OMS like-on-like platelet

The detailed element configurations are shown in Figure 9. High speed color photography was used to identify the RSS operating modes. Four modes of impingement were identified from the film as illustrated in Figure 1. Penetration occurs at low injection velocity (less than 50 ft/sec), low fuel temperatures (below 70°F), and low chamber pressure (less than 100 psia) and is evidenced by "shoot-through" of the fuel and oxidizer. Penetration has been reported in earlier cold flow work and was also observed on this program using propellant simulants as well as reactive streams. Penetration is a consequence of the non-reactive momentum exchange mixing process. Mixing is observed at moderate injection velocities (50-100 ft/sec), moderate fuel temperatures (70-90°F), and moderate chamber pressures (100-200 psia). It is evidenced by a highly uniform spray field which looks similar to a non-reactive spray field. Mix/Separate occurs at the onset of RSS. It is evidenced by a slightly non-uniform spray field. Separation is observed at higher injection velocities (greater than 100 ft/sec), higher fuel temperature (greater than 90°F), and higher chamber pressures (greater than 200 psia). It is evidenced by highly non-uniform spray fields in which distinct regions of unmixed fuel and oxidizer exist.

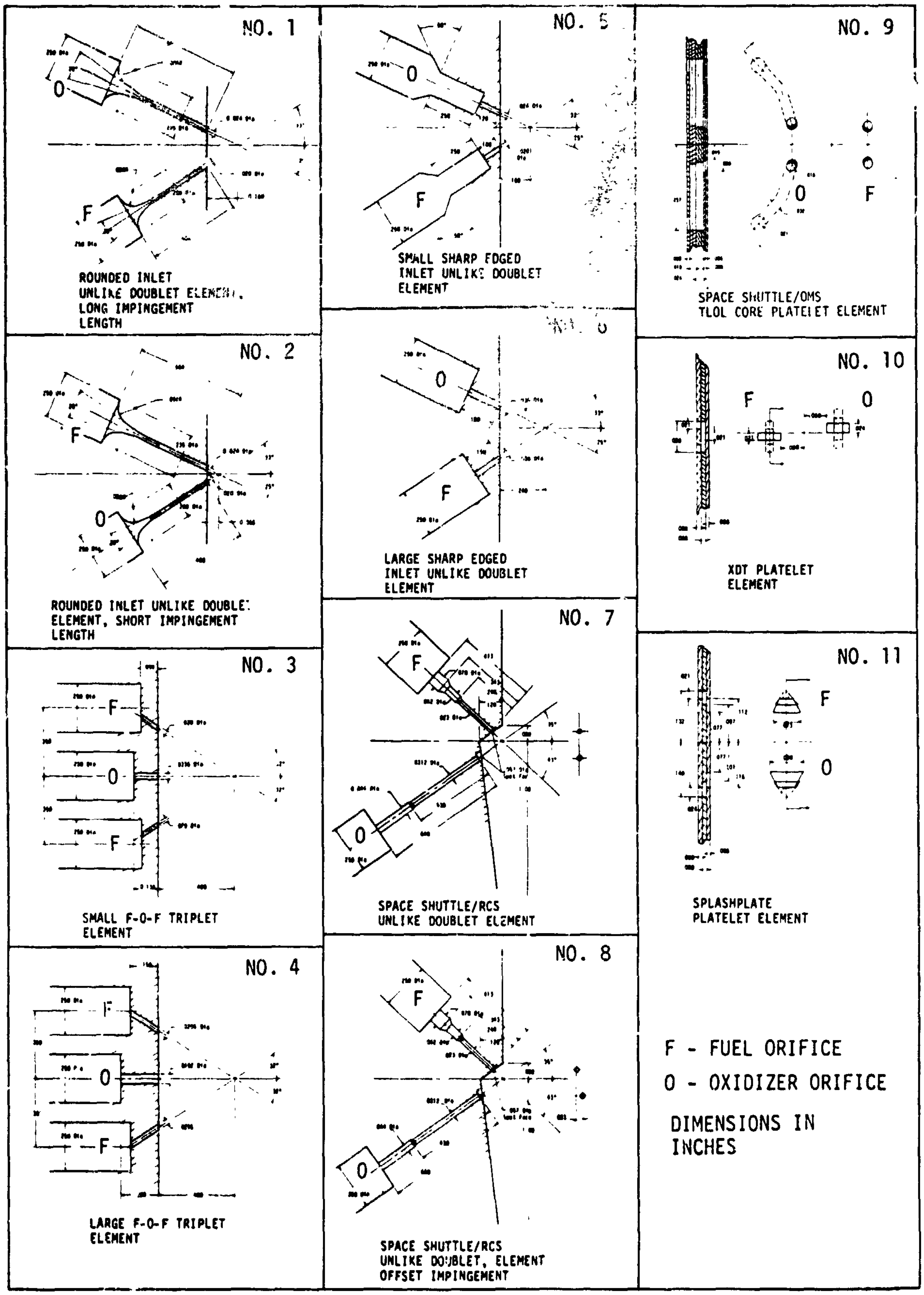


Figure 9. Injector Element Orifice Configurations

Distinct regions of mixing and separation were identified and correlated for each of the injectors tested. It was found that regimes of RSS with the coherent stream types of injector elements (i.e., the unlike doublets and triplets) are all correlated by the equation:

$$Pc = 4.4 \times 10^{8} \, (REF)^{-1.5} \qquad (1)$$

where:

REF = Fuel Orifice Reynolds Number.

Mixing occurs at chamber pressures less than that specified by Equation (1) and separation occurs at greater chamber pressures. Regimes of RSS with the atomized spray impingement platelet types of injectors are correlated by:

$$Pc = 1272 \, (REF)^{-0.24} \quad \text{(XDT \& Splash Ptate)} \qquad (2)$$

$$Pc = 839 \, (REF)^{-0.24} \quad \text{(TLOL)}. \qquad (3)$$

Again mixing occurs at chamber pressures below this value and separation occurs at pressures greater than this.

Examples of mixed and separated regimes are shown in Figures 10 through 17 for each type of injector element and fuel. It was found that both A-50 and N_2H_4 fuel exhibit the same RSS limit as MMH fuel as shown in Figures 10 and 11.

The RSS characteristics of all of the coherent stream elements (i.e., rounded inlet unlike doublet, triplet, sharp-edged unlike doublet, and RSS/RCS unlike doublet) were found to be similar and are correlated with the same correlation equation. The similarity in behavior for the

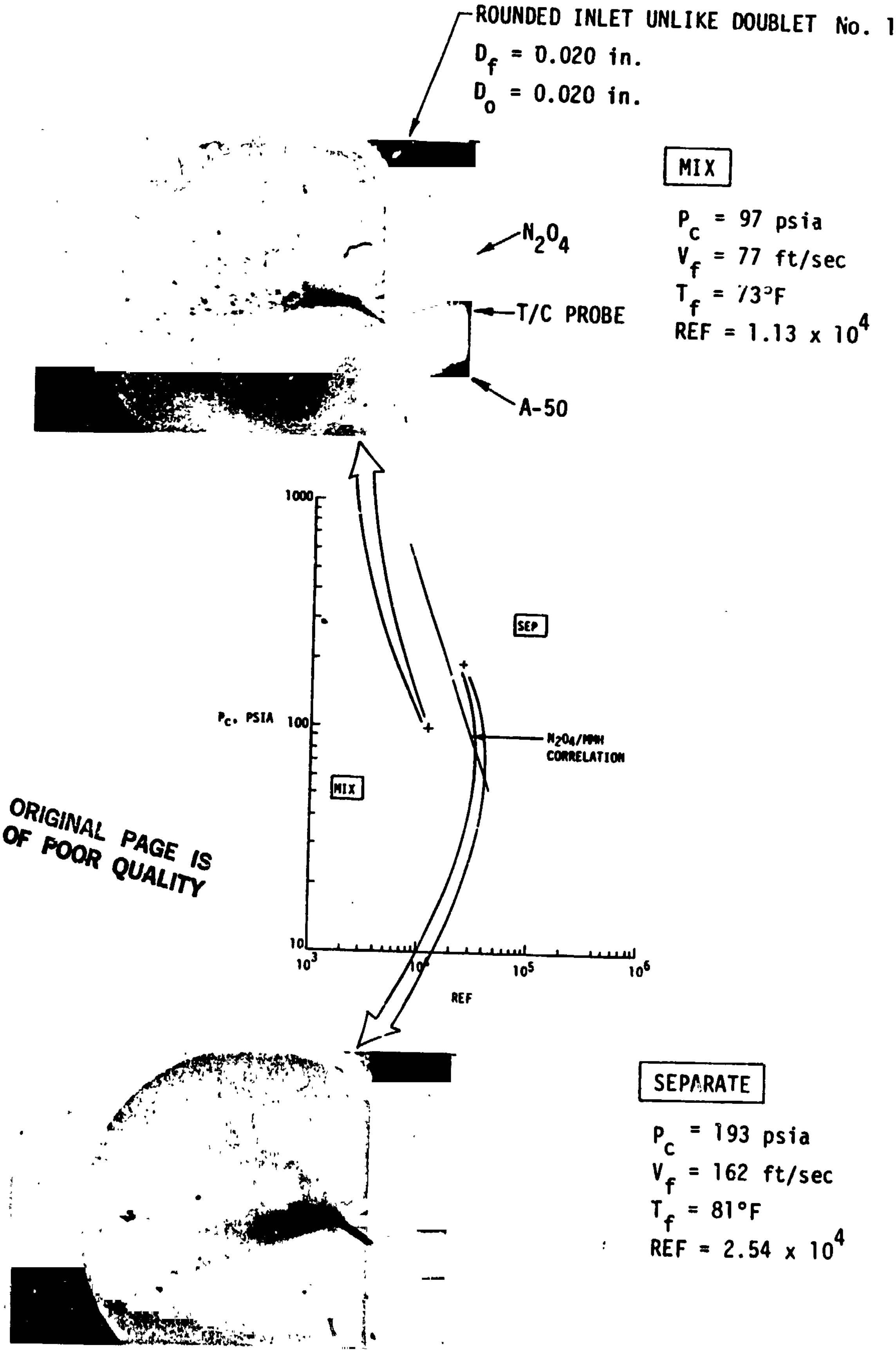


Figure 10. A-50 Fuel Behaves Like MMH Fuel

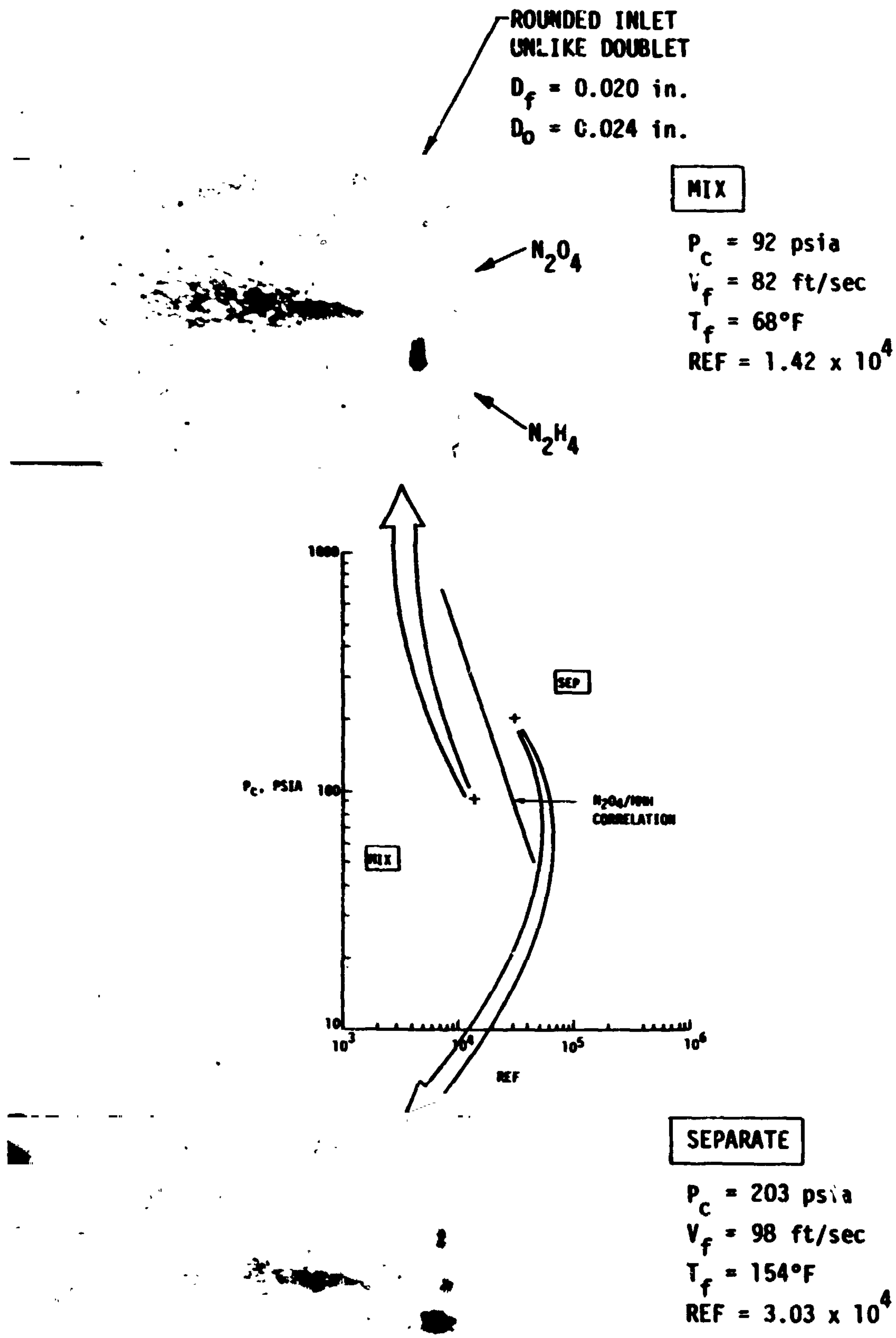


Figure 11. N_2H_4 Fuel Exhibits the Same RSS Limits as MMH Fuel

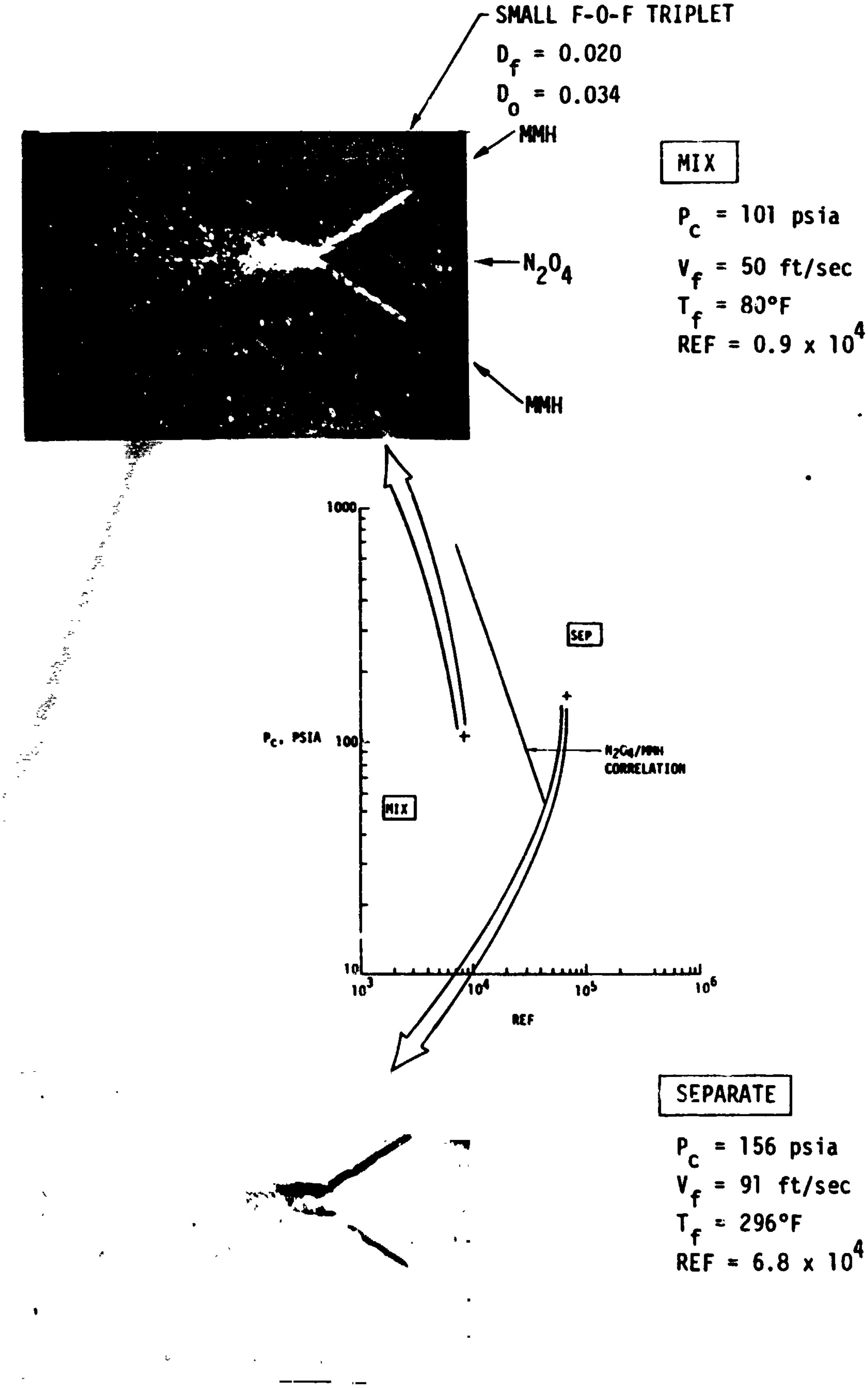


Figure 12. Reactive Stream Impingement with the Small F-O-F Triplet Element No. 3

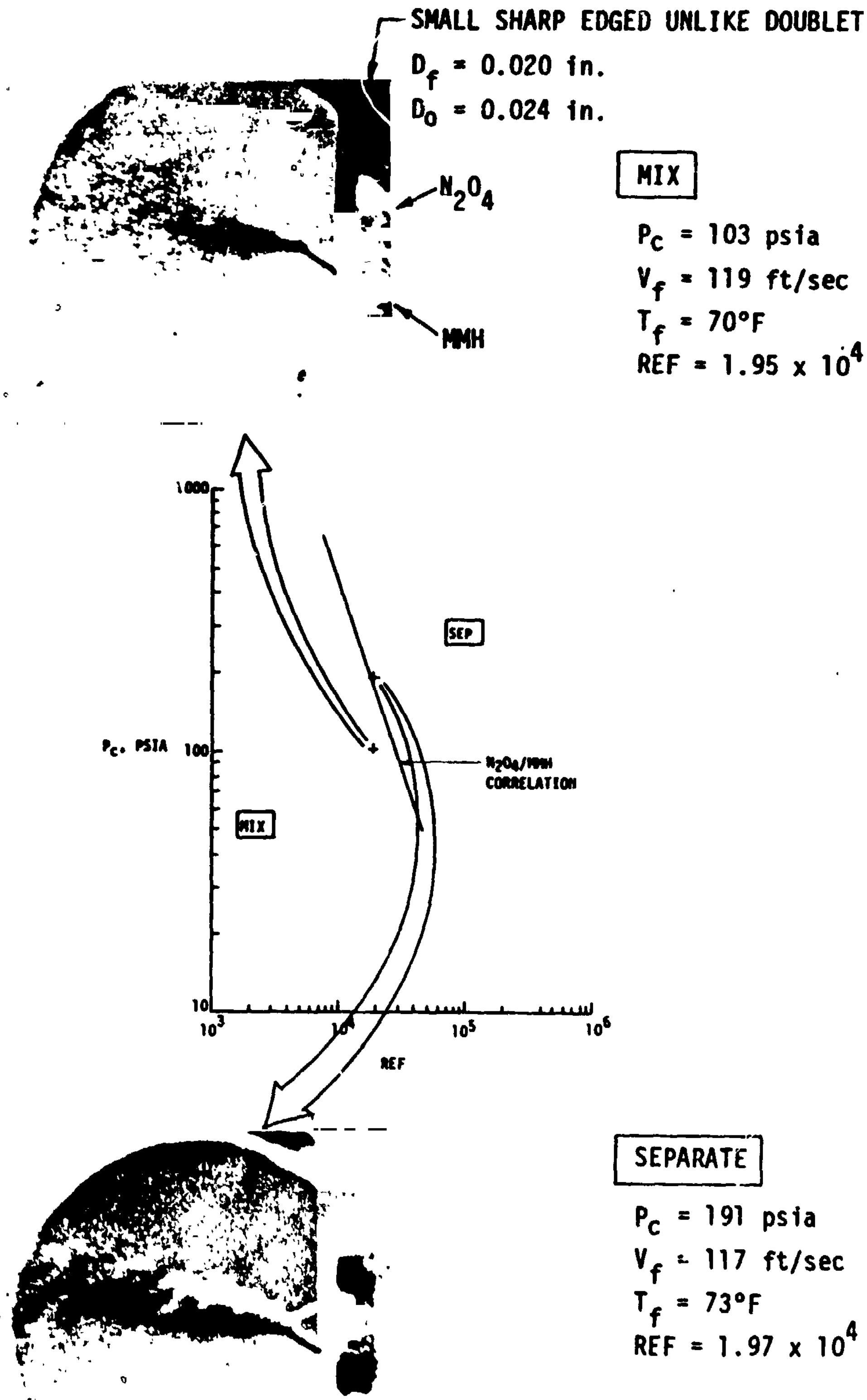


Figure 13. Reactive Stream Impingement with the Small Sharp Edged Unlike Doublet No. 5

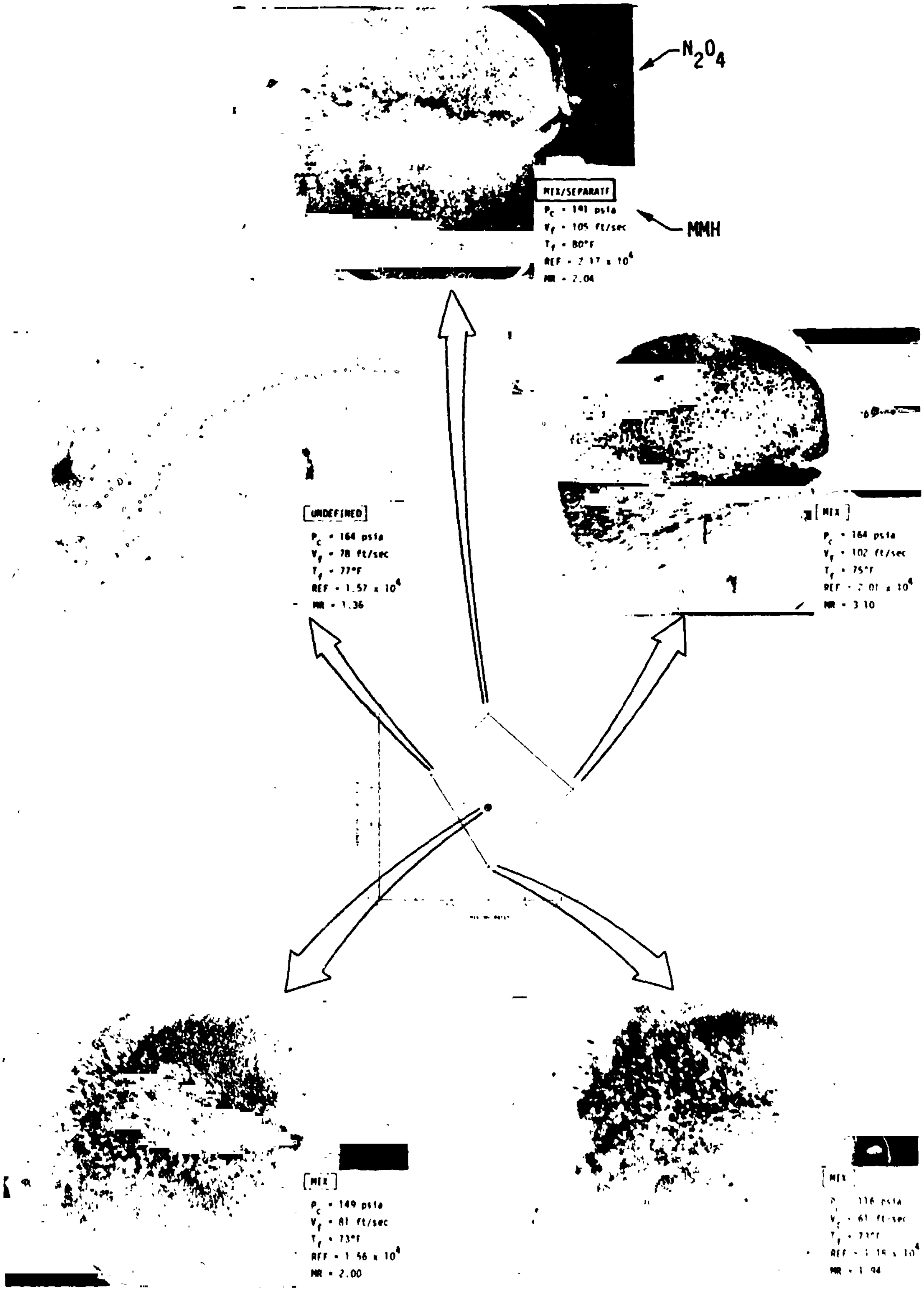


Figure 14. Reactive Stream Impingement with the Space Shuttle Unlike Doublet No. 7

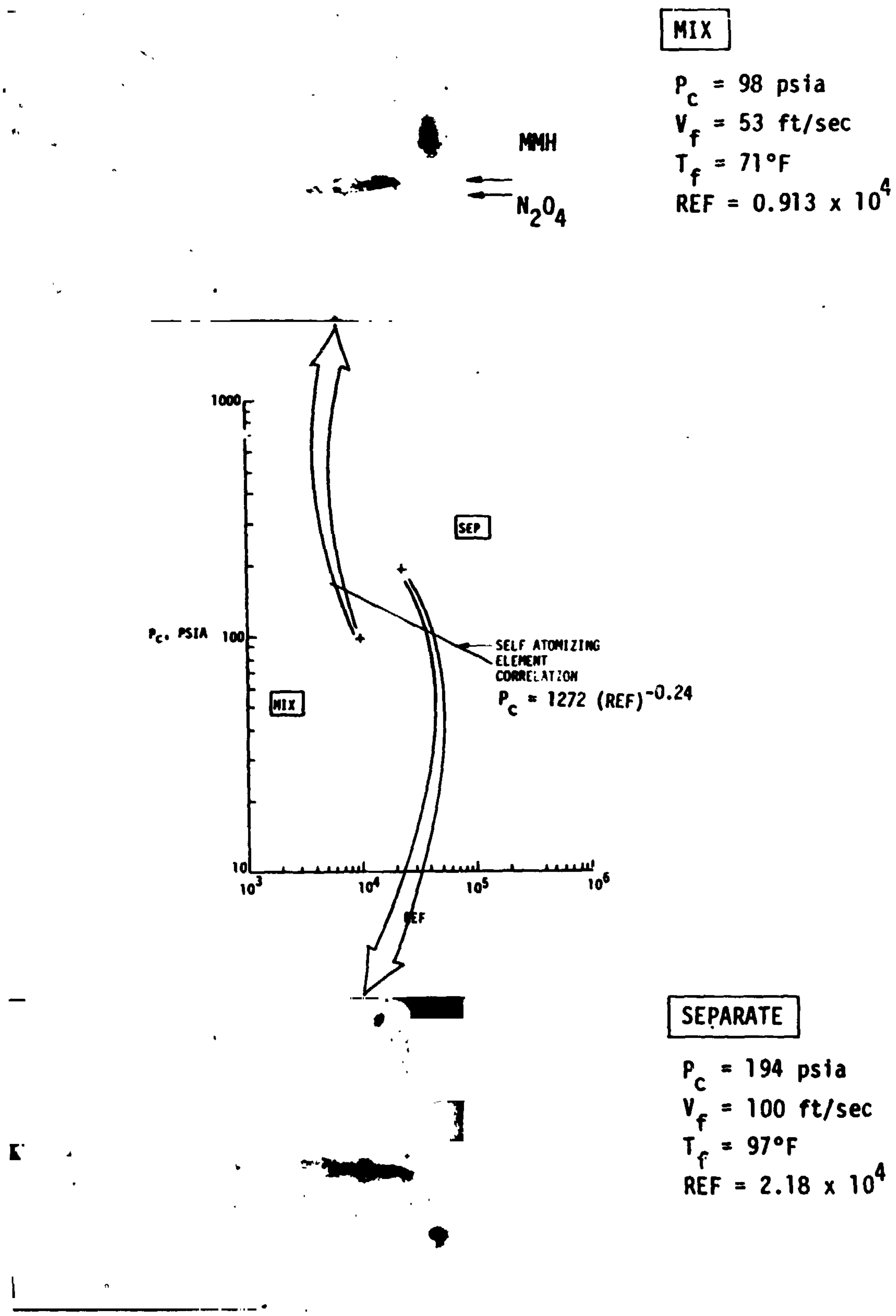


Figure 15. Reactive Stream Impingement with the XDT Platelet Element No. 10

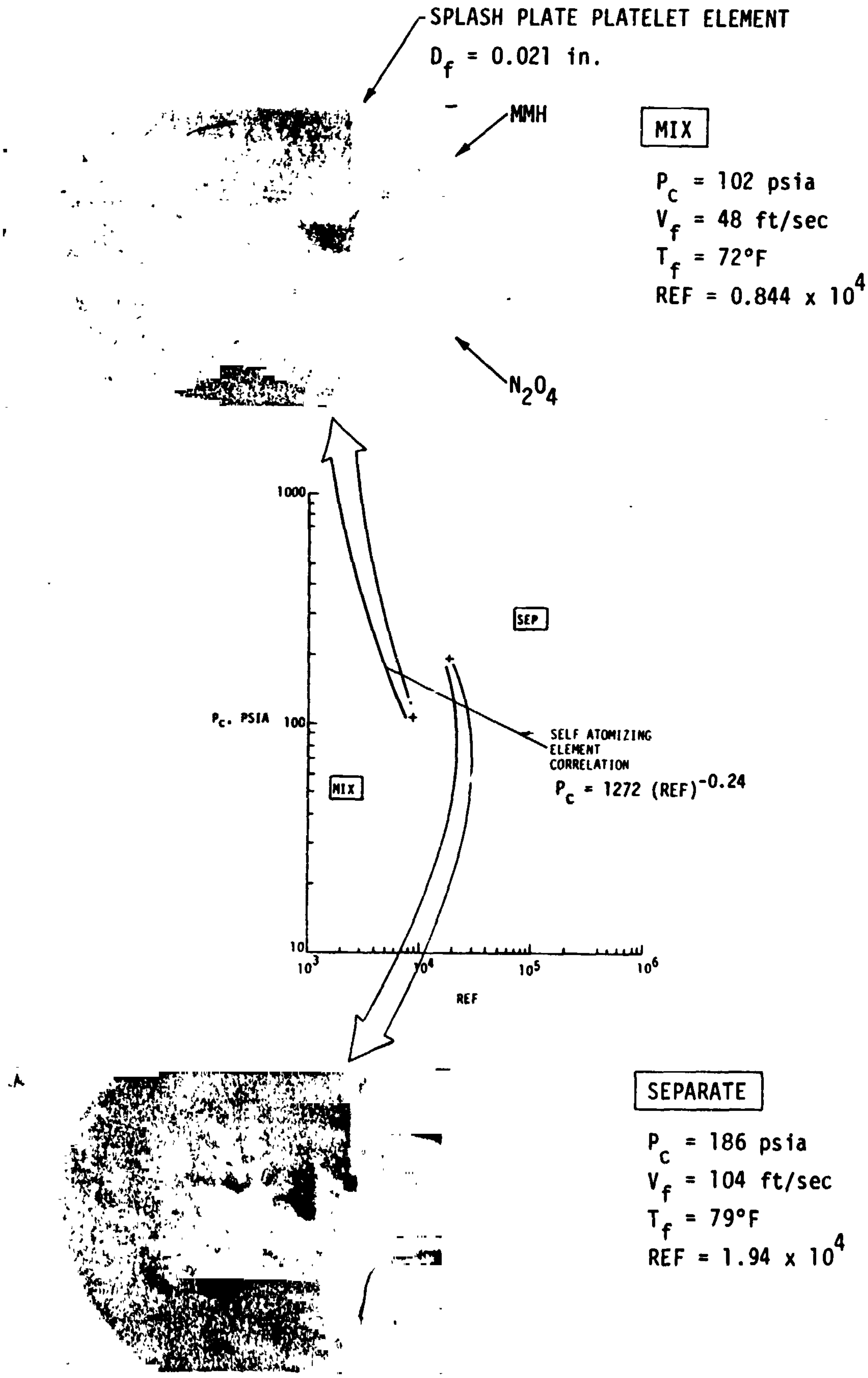


Figure 16. Reactive Stream Impingement with the Splash Plate Element No. 11

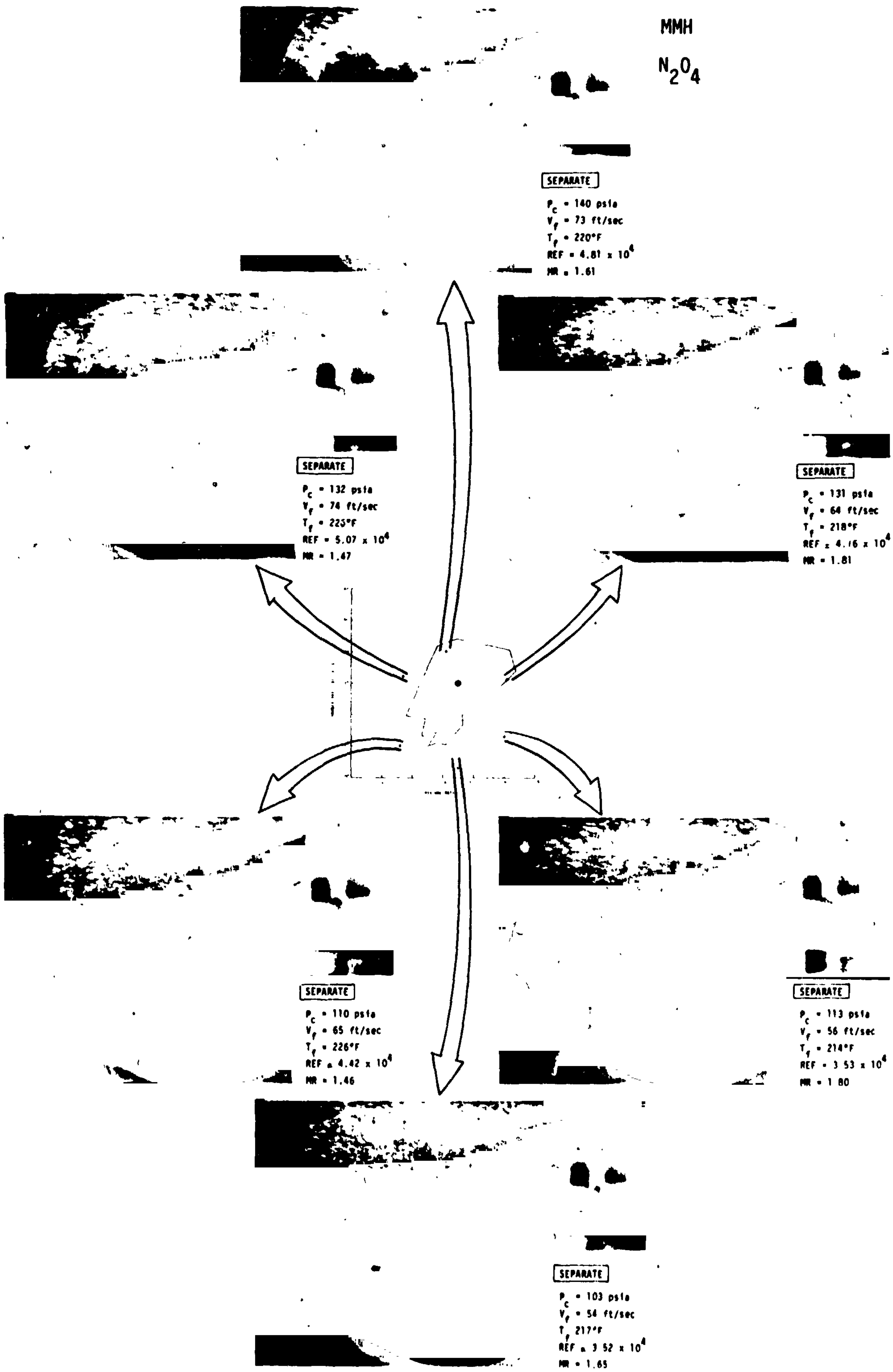


Figure 17. Reactive Stream Impingement with the Space Shuttle/OMS TLOL Platelet Element No. 9

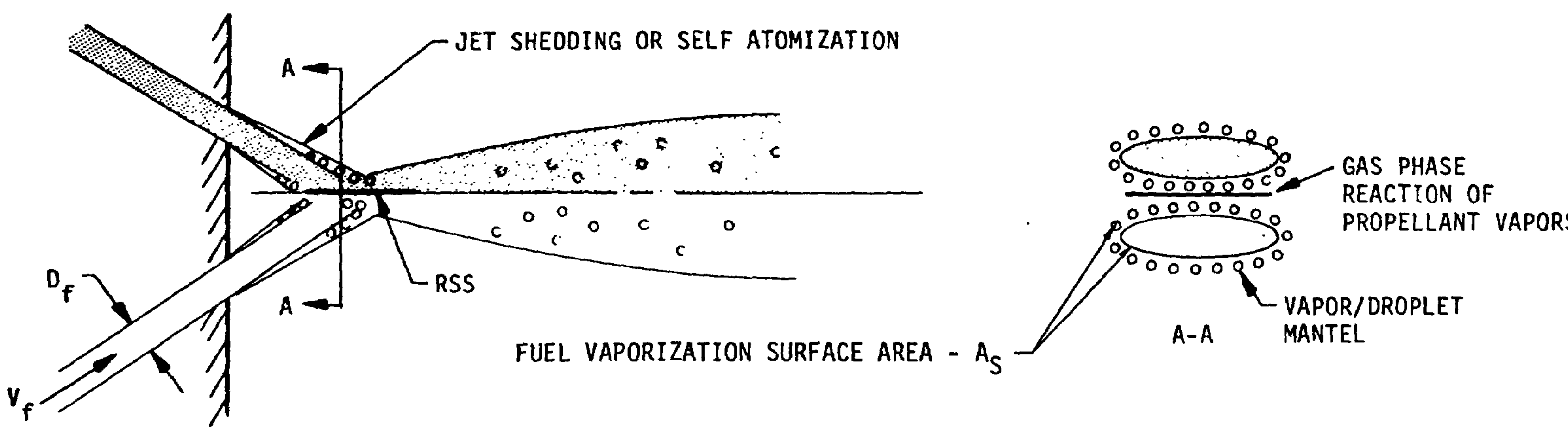
small triplet and small unlike doublet is shown in Figures 12 and 13. The behavior of the SS/RCS unlike doublet is illustrated in Figure 14 which shows the element behavior over its whole Pc-MR operating range. The impingement mode and operating condition is indicated next to each photo.

The RSS Characteristics of the XDT, the splashplate and the SS/OMS TLOL self-atomizing elements were found to differ from the coherent stream elements in that RSS occurs at lower chamber pressures than for the coherent stream elements. The RSS characteristics of the XDT and the splashplate elements are illustrated in Figures 15 and 16. The SS/OMS TLOL platelet element is an example of an element that operates in a separated mode over its entire operating range as illustrated in Figure 17. The detailed test data are given in the final report (Ref. 20).

C. RSS CONTROLLING MECHANISM & RSS MODEL

Fuel vaporization rate controlled combustion was identified as the mechanism controlling RSS with both coherent and atomized spray impingement injector elements and the operating conditions tested in this program. Data correlations for coherent stream elements made on the basis of a fuel vaporization controlled RSS model show that regimes of RSS are correlated with chamber pressure and the fuel orifice Reynolds Number as shown in Figure 5. The chamber pressure exhibits the strongest influence on RSS, increasing chamber pressure promotes RSS. Orifice diameter, injection velocity and propellant temperature effects are correlated with the fuel orifice Reynolds Number. Increasing any one of these promotes RSS. Atomized spray impingement elements promote RSS although they show less of a pressure influence than the coherent stream elements as shown in Figure 6.

The fuel vaporization RSS model is described in Figure 18. The model is based on the following assumptions:



VAPORIZATION RATE:

$\dot{W}_V = A_S K_V P_{VS} = A_S K_V P_c$

$\dot{W}_V$ = VAPORIZATION RATE

A_S = EVAPORATION SURFACE AREA

K_V = MASS TRANSFER COEFFICIENT

P_{VS} = FUEL VAPOR PRESSURE EVALUATED AT T_{SAT}

P_c = CHAMBER PRESSURE

MASS TRANSFER COEFFICIENT:

$Nu_m = D_S R^- K_V / \mathcal{D} = 2.0 + 0.6\, Sc^{1/3} Re^{1/2}$

D_S = DROPLET DIAMETER

R = GAS CONSTANT

T = FILM TEMPERATURE

$\mathcal{D}$ = DIFFUSION COEFFICIENT

ASSUMPTIONS:

- COMBUSTION GAS GENERATION RATE MUST EXCEED SOME MINIMUM RATE FOR RSS TO OCCUR
- COMBUSTION GAS GENERATION OCCURS THROUGH GAS PHASE REACTION ONLY
- COMBUSTION GAS GENERATION RATE IS LIMITED BY VAPORIZATION RATE FROM FUEL VAPORIZATION SURFACE AREA
- FUEL FILM IS HEATED TO SATURATION TEMPERATURE

JET IMPINGEMENT: $P_c \propto Re^{-3/2}$

$A_S \propto Re$

SELF ATOMIZING IMPINGEMENT: $P_c \propto Re^{-1/2}$

$A_S \neq f(Re)$

Figure 18. Fuel Vaporization Controlled RSS Model

1. The combustion gas generation rate prior to and at the impingement interface must exceed some minimum rate for RSS to occur.

2. Combustion gas generation occurs through gas phase reaction only.

3. Combustion gas generation rate is limited by the fuel vaporization rate since it is the more difficult propellant to vaporize.

4. The vapor in the film surrounding the stream is rapidly heated to the saturation temperature.

The following functional relationships result as a consequence of these assumptions:

Coherent Stream Elements $P_{c_{Critical}} \propto REF^{-3/2}$ Equation (3)

where: $A_s \propto REF$

A_s = Fuel vaporization surface area

The fuel vaporization surface area includes all fuel vaporizing surfaces aheaa of impingement. This includes the jet surface and droplet surfaces as shown in Figure 18.

Atomized Spray Impingement Elements $P_{c_{Critical}} \propto REF^{-1/2}$ Equation (4)

where: $A_s \neq f\,(REF)$

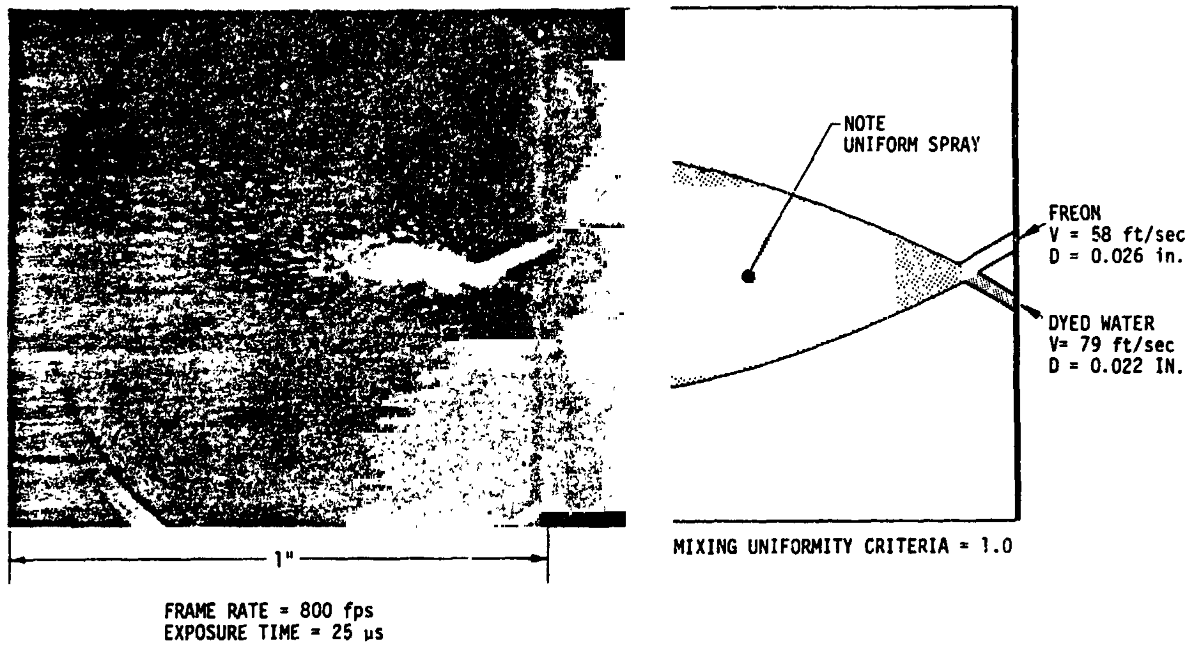
This model shows good agreement with the coherent stream experimental data in that the measured exponent on REF is -3/2. The exponent on REF is found to be -0.24 rather than -0.5 for the atomized spray impingement elements. However, the agreement with the experimental data is sufficient to conclude that RSS is controlled primarily by fuel vaporization rate controlled combustion.

D. NON-REACTIVE MIXING INFLUENCES

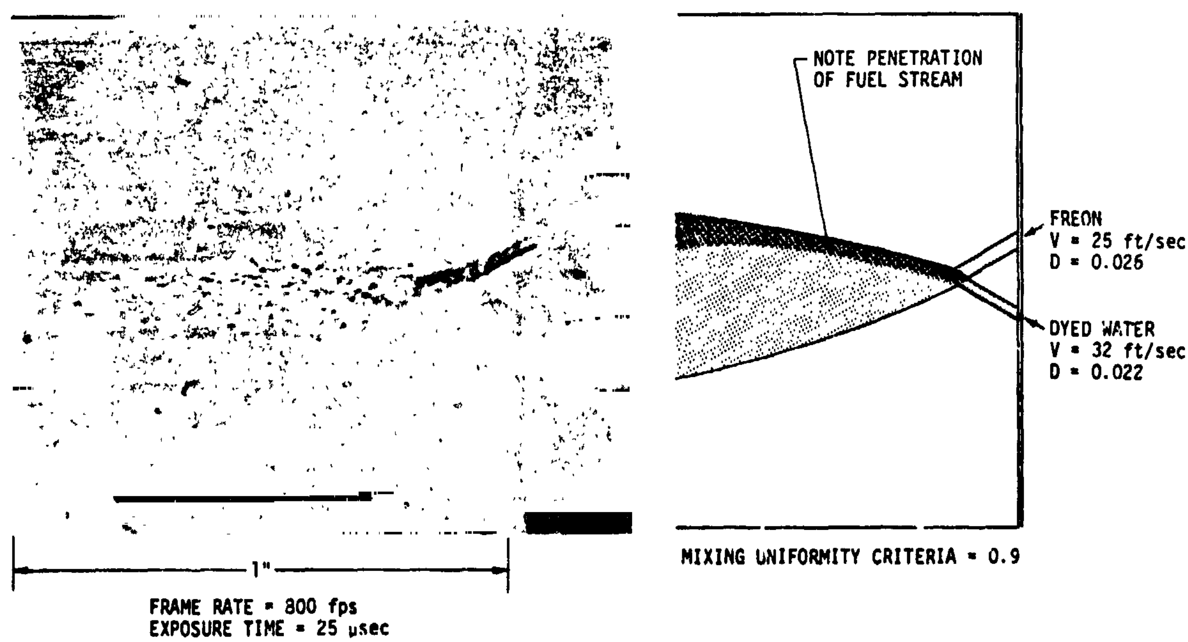
Cold flow tests were conducted with some of the unlike doublet element injectors to characterize non-reactive stream impingement. The following factors were identified as controlling influences on intra-element mixing and need to be considered irrespective of RSS.

1. Stream Momentum Balance
2. Orifice Diameter Mismatch
3. Orifice Diameter Misalignment

The ideal mixing condition specified by Rupe's Uniformity Criteria for unlike doublet is illustrated in Figure 19. This photograph is an enlargement of a 16mm high speed movie film. The propellant simulants are dyed water (the blue stream) for fuel and freon (the clear stream) for oxidizer. The momentum ratio condition is for best mixing according to the Rupe criteria. The spray uniformity attained at the optimum stream momentum ratio condition is clearly evident. The propellant "shoot-through" (i.e., penetration) phenomena reported by Rupe is also observed with lower stream momentum as shown in Figure 19.



a. Rupe's Mixing Uniformity Criteria Define for Uniform Spary Non-reactive Impingement



b. Low Stream Momentum Produces Penetration Phenomena for Non-reactive Impingement

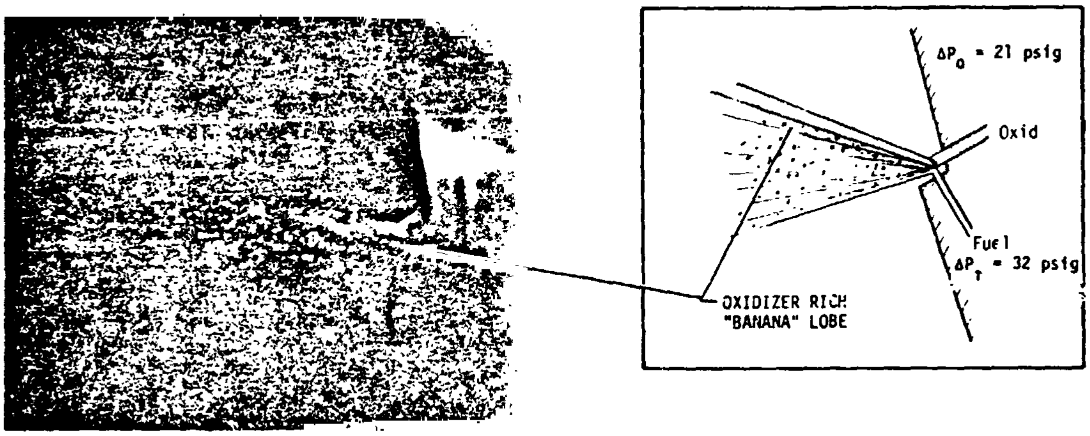
Figure 19. Rounded Inlet Unlike Doublet Non-Reactive Impingement

The "mixing" and "penetration" impingement modes are observed in hot firing and look a great deal like these cold flow photos, except for the propellant color differences.

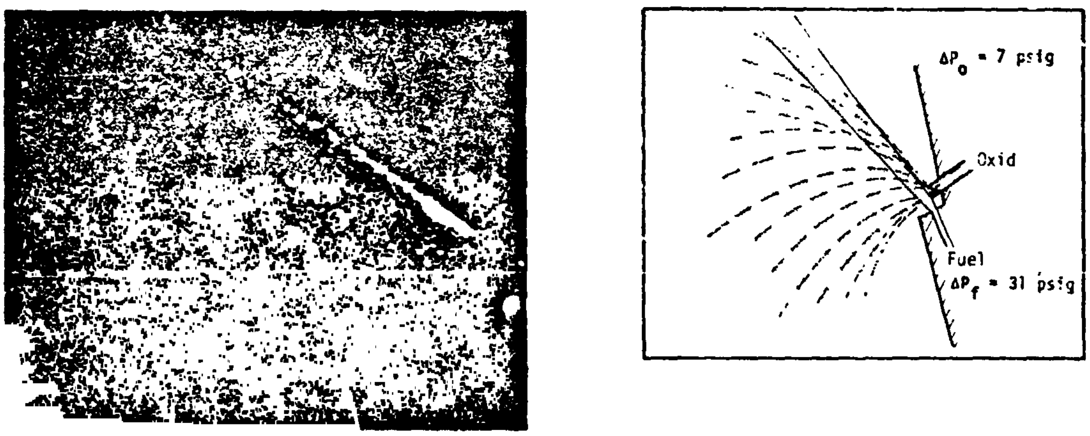
The effect of off-design momentum ratio on the spray distributions is illustrated in Figure 20. Operation at the fuel rich off-momentum condition is shown in the second photo. The low oxidizer momentum and diameter mismatch case the oxidizer stream to "umbrella" around the fuel stream resulting in poor mixing. The hot fire results show that these effects coupled with RSS can result in poor performance, stability, and compatibility. Further reduction in mixing efficiency results when the fuel and oxidizer orifices are mismatched or are misaligned. The cold flow tests show these to be important factors in designing high performance injectors.

E. ELEMENT DESIGN CRITERIA

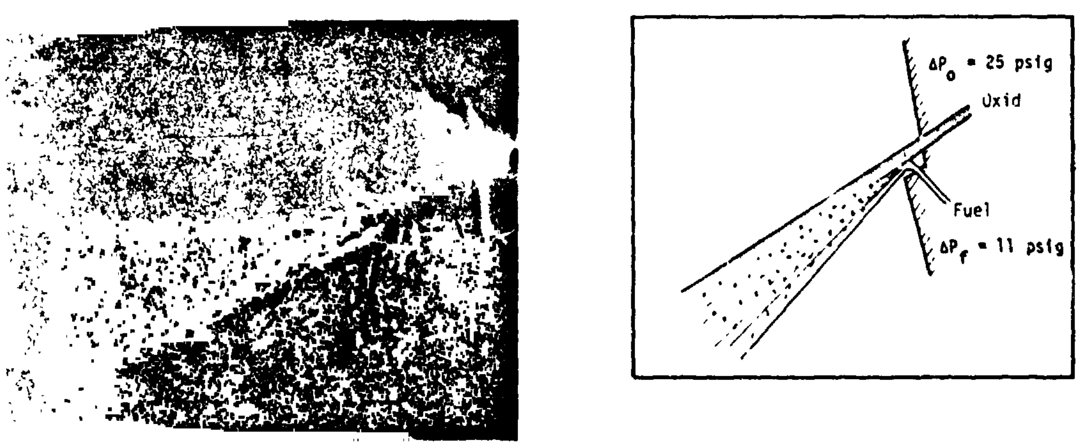
This work is culminated in a set of injector element design criteria published as an appendix to Ref. 20. The design criteria include non-reactive and reactive criteria for hypergolic propellant injector elements.



a. Orifice Diameter Mismatch Produces Non-Uniform Spray



b. Fuel Rich Momentum Condition Causes Oxidizer Stream to "Umbrella" Around Fuel Stream



c. Oxidizer Rich Momentum Condition Produces Good Mixing

Figure 20. Space Shuttle/RCS Unlike Doublet Non-Reactive Impingement

IV. APPLICATION OF RESULTS

The application of the results of this program can be grouped under three headings, A) development of RSS design criteria and high speed color photography techniques for hypergolic propellants, B) applications of these techniques on current hypergolic propellant technology and development programs, and C) application of these techniques to advanced systems utilizing other propellant combinations.

A. HYPERGOLIC PROPELLANT RSS MODELS AND TECHNIQUES

The primary results of this program are the development of design criteria for coping with RSS experienced with hypergolic N_2O_4/Amine propellants. These design criteria provide guidelines for the design of high performing stable injectors. Criteria for both coherent stream and atomized spray impingement type of injector elements are included.

A secondary but important result of this program is the development of high speed color photography techniques for observing single element injector combustion. RSS design criteria could not have been developed without these techniques. The high speed color photography is applicable to both single and multiple element injector combustion tests.

B. APPLICATION TO CURRENT PROGRAMS

The photographic techniques were used on the Acoustic Cavity Technology for High Performance Injector Program (Ref. 22), Contract NAS 9-14232, to observe cavity/injector pattern interactions. The understanding gained has aided the development of stability prediction models at ALRC.

The technology and techniques developed on this program were used on the Space Shuttle/OMS engine injector development program (Ref. 18) to solve an injector related "resurge" stability problem. Analysis of OMS and OME technology test results indicated that the "resurge" instability involved chamber acoustics, injector hydraulics, and the combustion process. The first order stability influencing parameters were found to be the injector element design, the injector ring manifold and orifice hydraulics and the chamber acoustic cavity configuration.

ALRC combustion stability models were used to evaluate injector designs to predict differences in their stability characteristics. Their predicted stability behavior were then compared to the experimentally known behavior to identify the probable mechanisms and appropriate design parameters which might account for the stability differences. The following parameters were identified as stability influences and consequently selected for element design criteria;

- Element hydraulic inertance
- Unlike impingement height
- Atomization
- Element and pattern mixing rate
- Energy Release Efficiency (ERE) vs chamber length profile.

Understanding of these combustion parameters was accomplished through the use of uni-element and multi-element subscale injectors. Uni-element injector cold flow tests were conducted to characterize the element and spray hydraulics to determine the spray fan geometry, the unlike impingement height, the relative atomization distribution, and the element pressure drop. The more promising uni-element designs were hot fire tested in the photographic chamber designed and fabricated on this program to compare element spray combustion rates and sensitivity. Hot fire characterization was achieved through:

(1) Analysis of high speed movies using techniques developed on this contract to identify the influence of design parameters and operating conditions on relative spray mixing and "blowapart".

(2) Measurement of C* performance used to quantify spray mixing influences.

(3) Perturbation of the element sprays with a shock tube to measure their high frequency combustion pressure response.

The fundamental understanding of the combustion process gained from the subscale tests was used to synthesize three fullscale platelet injector patterns for dynamic combustion stability demonstration. No evidence of "resurge" instability was encountered on any of the three full scale platelet injectors. Furthermore, all delivered acceptable performance and demonstrated that it is not necessary to sacrifice performance to improve stability characteristics. Good chamber thermal compatibility was also achieved.

The transverse like-on-like (TLOL) platelet injector element was selected for the OMS engine as a result of the subscale program. The spray mass and mixture ratio distributions produced by this element were found to be insensitive to engine operating point which permits greater predictability of performance, compatibility and stability. The TLOL platelet element OMS injector pattern design has in fact demonstrated good performance, excellent combustion stability and excellent chamber thermal compatibility. The OMS engine is the first manrated engine to be flight qualified to the CPIA 247 stability specification.

The Space Shuttle/RCS engine injector element was also photographically characterized over its full chamber pressure/mixture ratio operating range. This element was observed to be extremely sensitive to operating condition not only from an RSS standpoint but also from a stream momentum balance standpoint. These photos have aided understanding of the SS/RCS engine performance and compatibility.

C. APPLICATION TO FUTURE SYSTEMS

The photographic techniques developed on this program can be used to establish an understanding of combustion phenomena associated with any fuels and injectors. The fuel vaporization rate controlled RSS model developed during the program is currently being extended to hydrocarbon fuels on the Photographic Combustion Characterization of LOX/Hydrocarbon Type Propellants Program, Contract NAS 9-15724. This investigation will also utilize single element photography to gain understanding of combustion processes.

V. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn from this work.

1. The single element hot fire investigation technique has provided an effective, low-cost approach for understanding the earth-storable hypergolic propellant combustion process.

2. Photographic coverage of single element combustion has been verified as a valuable technique for understanding combustion processes.

3. RSS is a consequence of fuel vaporization controlled combustion at the impingement interface.

4. RSS regimes are defined by the chamber pressure and fuel orifice Reynolds number for a wide range of injector elements.

5. Operation in RSS transition regimes should be avoided if the spray mass and mixture ratio distributions are to be controlled.

6. RSS technology has benefitted hypergolic storable engine development.

7. Non-hypergolic impinging propellants may experience RSS since vaporization is the controlling mechanism.

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

1. The RSS criteria should be incorporated into the JANNAF standardized performance computer programs to warn the designer of operation within RSS regimes.

2. The photographic techniques should be used to define combustion mechanisms with advanced fuels for new engine systems.

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