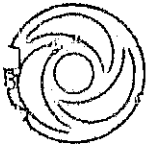


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Analysis Of Rocket Engine Injection Combustion Processes

Final Report 31531F-2
Contract NAS 8-31531

February 1977

Prepared For:
NASA

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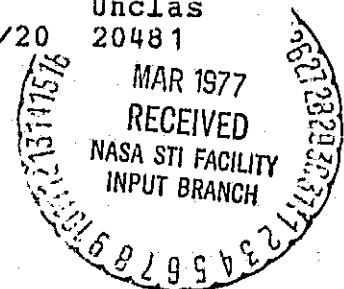
(NASA-CR-150200) ANALYSIS OF ROCKET ENGINE
INJECTION COMBUSTION PROCESSES Final Report
(Aerojet Liquid Rocket Co.) 43 p
HC A03/MF A01

CSCL 21H

N77-19163

G3/20

Unclas
20481



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FINAL REPORT

ANALYSIS OF ROCKET ENGINE INJECTION
COMBUSTION PROCESSES

FEBRUARY 1977

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GEORGE C. MARSHALL SPACE FLIGHT CENTER
CONTRACT NAS 8-31531
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FOREWORD

This report was prepared for the NASA George C. Marshall Space Flight Center under Contract NAS 8-31531, by Aerojet Liquid Rocket Company (ALRC), Sacramento, California. The NASA Contracting Officer Representative was Mr. K. W. Gross. The subject study constituted the second (or add-on) phase of a two phase program, the purpose of which was to identify and improve technical shortcomings of the JANNAF DER and CICM combustion analysis computer models. The primary objective of this program phase was to gain insight into combustion mixing and to improve the mixing methodologies of the aforementioned models. The total program period of performance was from July 1975 through January 1977. Phase II was initiated in September of 1976. Results of the Phase I work are reported in Ref. 1.

The ALRC Project Manager for this study was Mr. David L. Kors, Manager, Analytical Design Section, Design and Analysis Department. Mr. Larry B. Bassham was the Program Manager responsible for all fiscal and contracting functions. Mr. Jeffery W. Salmon served as Project Engineer and was co-author of this program final report. Mr. David Saltzman was Principal Investigator during this program phase and also co-author of the final.

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I SUMMARY

The main objective of this program was to accomplish mixing methodology improvement for the JANNAF DER and CIGM injection/combustion analysis computer programs. There were two end product objectives. First, ZOM plane prediction model development work initiated under the first phase of this program (Ref. 1) would be improved for installation into the new standardized DER computer program (Contract FO4-611-75-C-0055) or an alternate model approach would be recommended. Secondly, following a literature review, an intra-element mixing model development approach would be recommended for gas/liquid coaxial injection elements for possible future incorporation into the CIGM computer program. A three task program was scoped to result in attainment of the stated objectives; Task I - ZOM Plane Identification, Task II - CIGM Intra-Element Mixing Model, and Task III - Documentation.

Task I consisted of a continuation of the work reported in Section V of Ref. 1. The major conclusion of the Phase I work was that the influence of reactive stream separation (RSS or "blowpart") combustion forces on spray fan mass distribution should be included in the originally formulated gas acceleration effects ZOM prediction model. A three part task was scoped for this Phase II effort, based on the Phase I "blowpart" modeling recommendation. (1) The gas acceleration effects ZOM model would be tested with subscale injector data unaffected by "blowpart" combustion forces in order to verify the original model formulation. (2) The model would be expanded to account for the influence of "blowpart" on spray fan mass distribution. The resultant new model would be verified through correlation of the established OMS subscale quadlet injector data base utilized during the Phase I model correlation work. (3) Based on the results of the data correlation effort incorporation of the model into the "standardized" DER program would begin or an alternate model approach would be proposed.

The results of the first subtask described above substantiated previous conclusions regarding the need for characterization of RSS combustion effects in any mass distribution model designed for incorporation into DER. The Improved Transtage Injector Program (ITIP) subscale data correlated during this Phase II effort are predicted to be influenced by RSS; contrary to the original assumption that this data was developed entirely in the "mixed" operating regime.

I Summary (cont.)

Indeed, for NTO/Amine fuel propellant combinations it appears that most "real" operating points will be influenced by RSS. Since RSS again clouded the correlation effort with the gas acceleration effects ZOM model, the basic model formulation could not be verified, as was originally intended. Results of recent RSS studies were examined during the second subtask described above. It was concluded that models developed during these studies indicate conditions required for the presence of RSS, but no physical characterizations are presented which could be utilized to evaluate chamber mixing performance. Development of an applicable RSS analytical model was far beyond the scope of this program effort. In addition to the RSS influences cited, correlation of the ITIP subscale data also resulted in the conclusion that turbulent mixing effects due to increasing chamber length significantly influence chamber mixing efficiency. The gas acceleration effects model is limited in application to the injector face near zone (up to 2-4 inches from the face plane). The results of this effort also cite the need for a turbulent mixing model in DER. The total implication is that the mixing problem is divisible into two regions; first, the near zone which is dominated by combustion influences and, secondly, the downstream chamber segment where turbulent mixing is significant.

Task II had as its objective development of a comprehensive plan for incorporation of an intra-element gas/liquid coaxial mixing model into CICM. Documented gas/liquid and gas/gas coaxial mixing studies were reviewed and critiqued. It was concluded that relevant gas/liquid mixing work was limited to an interrelated series of studies conducted to characterize circular coaxial mixing for the FLOX (l)/methane (g) propellant combination. An additional conclusion of the literature review was that one study, in particular, resulted in an analytically formulated, empirically correlated gas/gas model far superior to others in terms of applicability to the rocket engine coaxial injector design problem. The mixing model review results guided the development of two proposed modeling approaches. The first would entail adapting the identified and available gas/gas mixing model to the current CICM calculation scheme. The major limitation of this method is uncertainty concerning the influence of combustion on the radial distribution of vaporized but unmixed oxidizer vapor from the element core.

I Summary (cont.)

The second suggested approach consists of a comprehensive test, data analysis, and model development program that would be based on direct measurement of gas/liquid coaxial element mass distributions. This would be a more expensive and prolonged development effort, however, model accuracy and generality would be improved.

Task III of the program resulted in two monthly status letters and this final report containing recommendations for improvement of the mixing methodologies of the JANNAF DER and CICM combustion computer models. The English system of units has been exclusively employed in this report since SI units have yet to be adapted to the JANNAF system of computer programs. The program COR has concurred with and approved this choice.

II INTRODUCTION

Two primary tasks were completed during the recent first phase of the Injection Processes program, that preceded the Phase II effort documented in this report. Task I, Computer Program Review and Operation, resulted in comprehensive critiques of DER and CICM. These reviews are documented as complete appendices in the first phase final report (Ref. 1). Task II, Analysis and Data Correlations, had the original objective of providing information on the present prediction capabilities of the DER and CICM through the correlation of well documented hot fire data bases. The CICM analysis of the 500,000 lbf (at 500 psia chamber pressure) M-1 engine was completed as planned. The analysis verified the CICM model for high performing thrust chambers with negligible intra-element mixing losses. However, a primary weakness of CICM was identified; that of having no capability for general calculation of intra-element or inter-element (manifold induced) mixing losses. The model currently depends on user input of cold flow mass distribution data for calculation of these losses.

The DER analysis phase of Task II was not conducted. After a careful evaluation of the Task I DER Computer Program Review, it was concluded that the DER subcritical K-Prime version contained inadequacies in the analytical formulations that could produce invalid data when applied, as originally planned, to the ALRC Space Shuttle OMS engine data base. It was decided that this task segment should rather concentrate on the removal of detected technical shortcomings of the model.

Improvement of the LISP ZOM plane mass distribution methodology was selected as the alternate Phase I Task II DER goal for three reasons*. First, the "standardized" DER (SDER) development program (Contract FO 4611-75-C-0055), conducted concurrently with Phase I of the Injection Processes Program, concentrated on improvement of the DER vaporization modeling, but not on mass distribution and mixing modeling. Secondly, the ZOM plane location is known to be a key DER input parameter which significantly influences the calculated

* ZOM is the axial location of the plane at which the cold flow mass distribution for hot fire mixing efficiency calculation is characterized.

II Introduction (cont.)

chamber mixing performance efficiency. Lastly, recent empirical investigations had led to formulation of a model for calculation of the ZOM plane location on an a priori basis.

The resulting Phase I program initial development of an analytical ZOM prediction model for DER, that allows for gas acceleration effects on spray fan formulation and mixing, resulted in the following important conclusions.

- The OMS subscale test program has resulted in an excellent data base for the investigation of near-zone combustion and mixing phenomena.
- The formulated ZOM prediction model should be tested with a data set that is void of significant "blowpart" forces.
- The ZOM model calculated ZOM values on the level of those required to accurately predict injector mixing performance. Therefore, the model probably accurately accounts for near zone injection and gas acceleration momentum forces.
- Combustion reactive forces due to the mechanism termed "blowpart" strongly alter droplet inertial forces.
- A physically accurate, mechanistic near-zone model that will predict the ZOM location must account for both gas acceleration and reactive stream forces on droplet spray fan formation and mixing.

Based on the initial ZOM prediction model conclusions listed above and the identified CICM mixing model limitation, two primary objectives were identified for the Phase II program effort described in this report. First, the ZOM model work would be brought to fruition; resulting in either model installation into the new "standardized" DER program or recommendation of an alternate model approach, including an assessment of its potential success.

II Introduction (cont.)

The second objective was to design a plan for development of an intra-element gas/liquid coaxial mixing model for CICM including required analytical assumptions, empirical correlations, and any specific test data to verify the model.

III ZOM PLANE IDENTIFICATION

The objective of this program task was to bring the ZOM gas acceleration effects model work initiated during the first program phase to fruition; resulting in either model installation into the new "standardized" DER program or a recommendation of an alternate model approach, including an assessment of its potential success.

The OMS subscale injector data correlations originally accomplished with the ZOM model are documented in the program Phase I final report (Ref. 1). The major conclusion of the initial work was that a physically mechanistic model that will predict the ZOM location must account for both gas acceleration and reactive stream separation (RSS or "blowpart") forces on droplet spray fan formation and mixing.

A three part task, based on the "blowpart" modeling recommendation, was scoped to continue the original ZOM plane identification work during the Phase II program. (1) The gas acceleration effects ZOM model would be tested with subscale injector data unaffected by "blowpart" combustion forces in order to verify the original model formulation. (2) The model would be expanded to account for the influence of "blowpart" on spray fan mass distribution. The resultant new model would be verified through correlation of the established OMS subscale quadlet injector data base utilized during the Phase I model correlation work. (3) Based on the results of the data correlation effort incorporation of the model into the "standardized" DER program would begin or an alternate model approach would be proposed.

The results of the first subtask described above substantiated previous conclusions regarding the need for characterization of RSS combustion effects in any mass distribution model designed for incorporation into DER. The Improved Transtage Injector Program (ITIP) subscale data correlated during this Phase II effort is predicted to be influenced by RSS; contrary to the original assumption that this data was developed entirely in the "mixed" operating regime. Indeed, for NTO/Amine fuel propellant combinations it appears that most "real" operating points will be influenced by RSS. Since RSS again clouded the correlation effort with the gas acceleration effects ZOM model, the basic model formu-

III ZOM Plane Identification (cont.)

lation could not be verified, as was originally intended.

Results of recent RSS studies were examined during the second subtask described above. It was concluded that models developed during these studies indicate conditions required for the presence of RSS, but no physical characterizations are presented which could be utilized to evaluate chamber mixing performance. Development of an applicable RSS analytical model was far beyond the scope of this program effort.

In addition to the RSS influences cited, correlation of the ITIP sub-scale data also resulted in the conclusion that turbulent mixing effects due to increasing chamber length significantly influence chamber mixing efficiency. The gas acceleration effects model is limited in application to the injector face near zone (up to 2-4 inches from the face plane). The results of this effort also cite the need for a turbulent mixing model in DER. The total implication is that the mixing problem is divisible into two regions; first, the near zone which is dominated by combustion influences and, secondly, the downstream chamber segment where turbulent mixing is significant.

A. Recommendation

The ZOM model development effort accomplished during the Injection Processes Program was initiated based on an empirical observation that high relative near-injector zone combustion gas velocities correlated with a relative lowering of thrust chamber C^* efficiency. Subsequent data correlation with an originally formulated combustion gas acceleration effects model has led to two important discoveries. First, combustion Reactive Stream Separation (RSS or "blowpart") forces strongly influence spray fan mass distribution and resulting injector performance. Turbulent mixing mass distribution improvement with increasing chamber length (downstream of the near-injector zone primary mixing area) must also be accounted for in a physically mechanistic mixing model. Available analytical models that are directly applicable to

III ZOM Plane Identification (cont.)

computer solution of these two mechanisms appear to be virtually non-existent. It is recommended that advancement through conductance of empirical programs to generate applicable data in these two areas be initiated. There appears to be little possibility of significant improvement of the DER/ZOM cold flow based mixing technique without the performance of such work.

B. ITIP Subscale Injector/Chamber Data Correlation

The first goal of this continuation of the ZOM work was to determine if the model could be used to correlate data that was unaffected by "blowpart" combustion forces. Another subscale injector investigation was conducted recently at ALRC during the Improved Transtage Injector Program (ITIP). One thousand (1K) lbf thrust injectors were tested in a 19 inch chamber intensively instrumented with static pressure transducers to determine axial combustion energy release profiles. Three like doublet pair injectors (36, 60, and 90 element designs) were tested. The previously correlated OMS subscale tests utilized a 6 element (130 lbf) like doublet pair injector. The 60 element ITIP 1K like doublet pair injector is pictured in Figure 1. The 19 inch test combustion chamber design is shown in Figure 2.

The 36 element injector tests were selected for model analysis because their lower performance afforded more data "sensitivity". It was believed the tests would be valuable because the low ITIP injector design pressure drops (about 30 psia at a design P_c of 105 psia) would result in "mixed" (no RSS) combustion spray fans, according to the Ref. 2 RSS model. The 36 element injector tests are listed below in Table I.

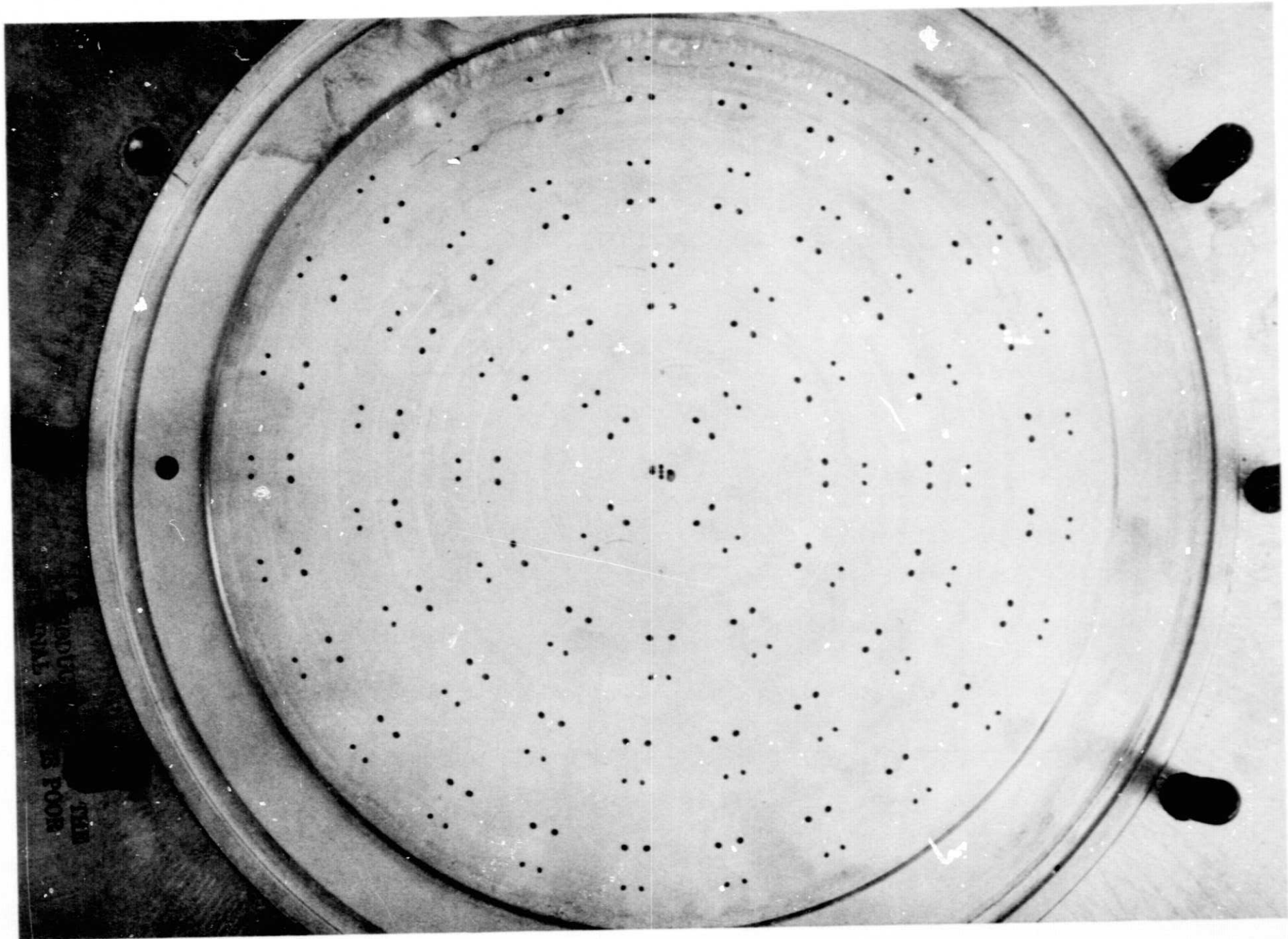


FIGURE 1. ITIP 60 ELEMENT 1K LB_F LIKE DOUBLET PAIR INJECTOR

TABLE I
ITIP 36 ELEMENT LIKE DOUBLET PAIR TEST SUMMARY

<u>Test</u>	<u>O/F</u>	<u>P_c</u> <u>(psia)</u>	<u>T_o</u> <u>(°F)</u>	<u>T_f</u> <u>(°F)</u>	<u>η_{C*}</u> <u>(%)</u>
117	2.09	97.8	89	80	.948
119	1.84	99.5	91	83	.943
120	2.10	99.9	89	84	.951
121	2.05	121.0	88	84	.950
122	2.13	89.0	88	85	.950
123	2.19	119.6	71	72	.950
124	1.84	122.0	74	75	.940
125*	1.98	99.2	82	80	.930

*13 Inch Chamber Test

The test C* efficiencies are plotted versus chamber pressure in Figure 3. All the tests were conducted with ambient temperature propellants (70-90°F) near a mixture ratio of 2:1.

The characterization of RSS for the OMS and ITIP subscale injectors is shown in Figure 4. The ITIP propellants are NTO/A-50, while the OMS propellants are NTO/MMH. The higher A-50 value of vapor pressure (P_f) (A-50 vapor pressure is 2.3 psia and MMH vapor pressure is 0.8 psia at 70°F) actually overrides the influence of low design pressure drop (i.e., the lower injection velocity lowers the fuel Reynold's number in the term plotted as the abscissa in Figure 4). Therefore, the ITIP data is also predicted to be influenced by RSS forces. The slightly decreasing trend of C* efficiency with increasing chamber pressure, shown in Figure 3, tends to agree with this conclusion. In general, it appears, for the like doublet pair injectors that have been analyzed, that non-separated operation for a reasonable injector design (i.e., high enough injection pressure drops to avoid low frequency stability problems) is out of the question. This indicates the severity of the need for a model that can predict the effect of RSS on injector mixing performance.

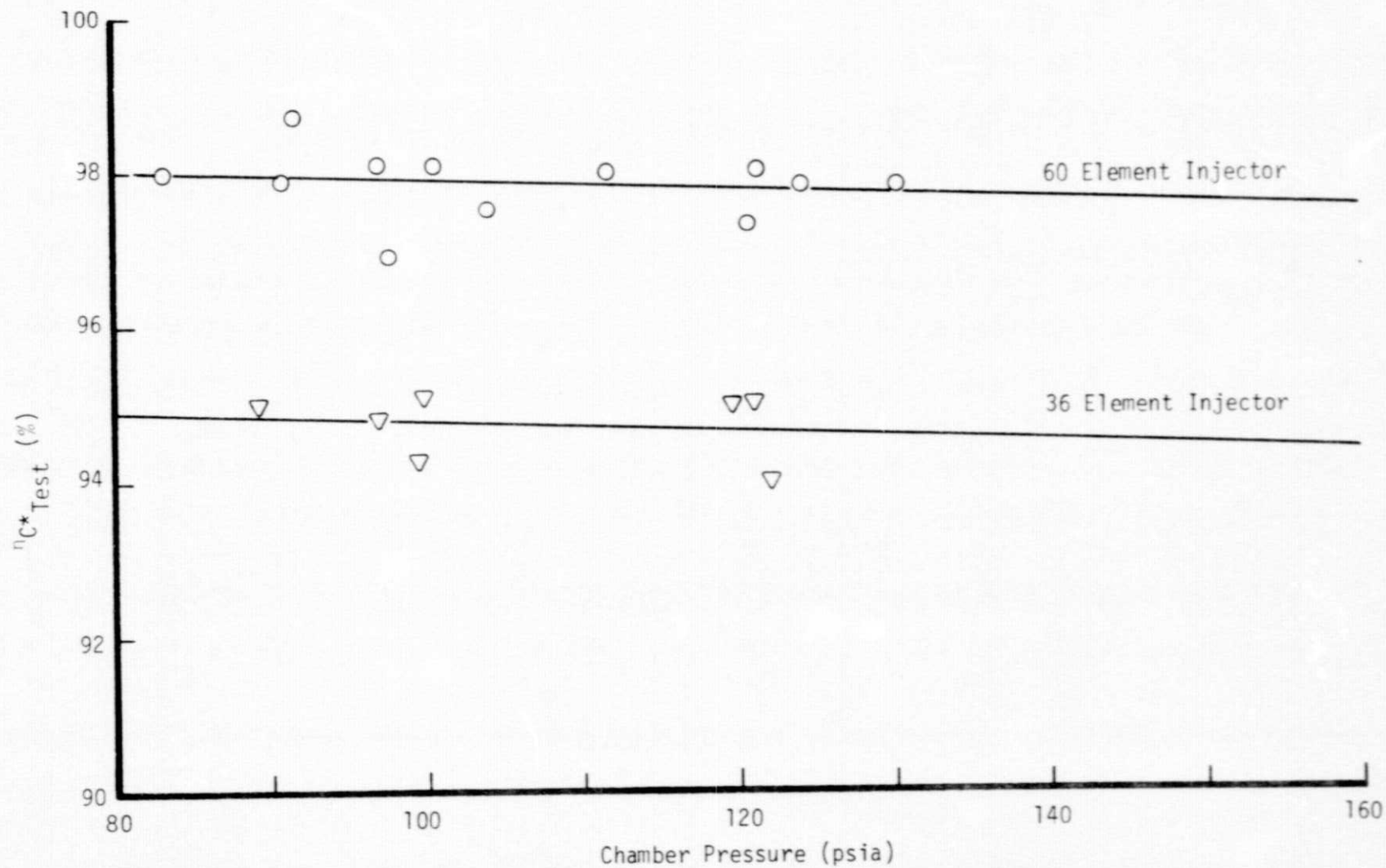


FIGURE 3. ITIP SUBSCALE MEASURED C* EFFICIENCY VERSUS CHAMBER PRESSURE

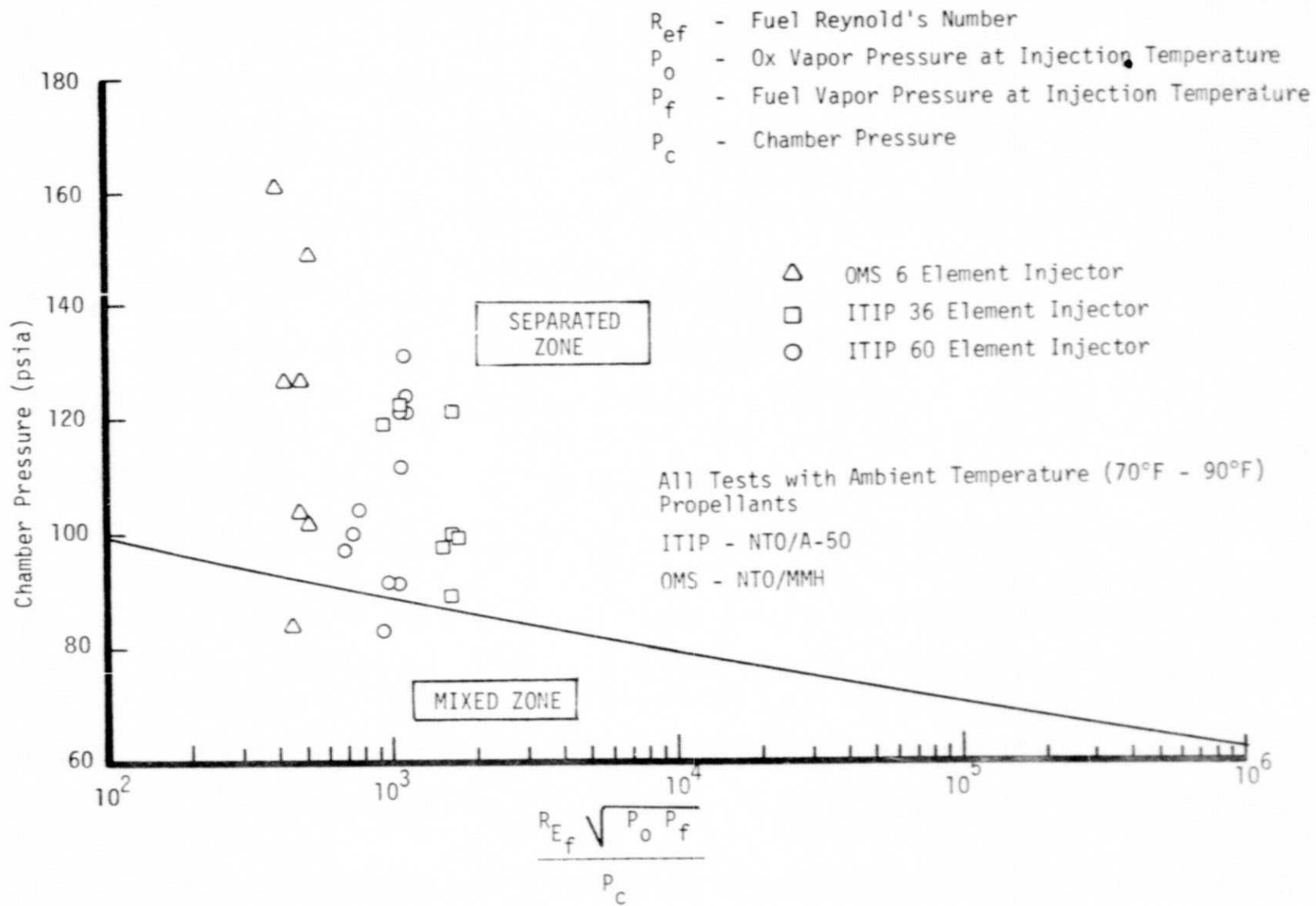


FIGURE 4. SUBSCALE INJECTOR RSS CHARACTERIZATION

III ZOM Plane Identification (cont.)

The ITIP 36 element data was correlated with the ZOM model (even though RSS is concluded to be a performance factor) to determine if the results would compare with the previous OMS injector correlation. Typical test deduced gas velocity profiles for a low and high chamber pressure test are shown in Figure 5. Consistent with the OMS correlation experience, the high chamber pressure tests performs higher near the injector face (more rapid immediate vaporization results in higher near injector zone gas velocities) but is lower performing at the combustion chamber throat plane. The original ZOM model was formulated based on the assumption that the higher initial gas velocity would more rapidly reduce radial velocity forces that induce mixing, thereby reducing mixing efficiency and lowering overall injector performance. The stronger influence of increased liquid injection velocity with increased operating pressure on the model calculation was not initially anticipated. Gas velocities similar to those shown in Figure 5 were input to the ZOM model for the 36 element injector tests listed in Table I.

The test data was also used to "back out" the correct ZOM plane value to compare to the model prediction.

$$\eta_{C^* \text{ Mix}}^{\text{Test}} = \eta_{C^* \text{ Test}} / \eta_{C^* \text{ Vap}}^{\text{Test}}$$

$$\text{ZOM} = f(\eta_{C^* \text{ mix}}), \text{ from Figure 7.}$$

Vaporization efficiency ($\eta_{C^* \text{ Vap}}$) predictions for the ITIP injectors are shown in Figure 6. The calculation was made with a "two flame" modified version of the Priem L-General model (Ref. 3). The "backed out" mixing efficiency ($\eta_{C^* \text{ Mix}}$) for each test was calculated by dividing test C* efficiency by the calculated vaporization efficiency. The test ZOM value was then determined from Figure 7.

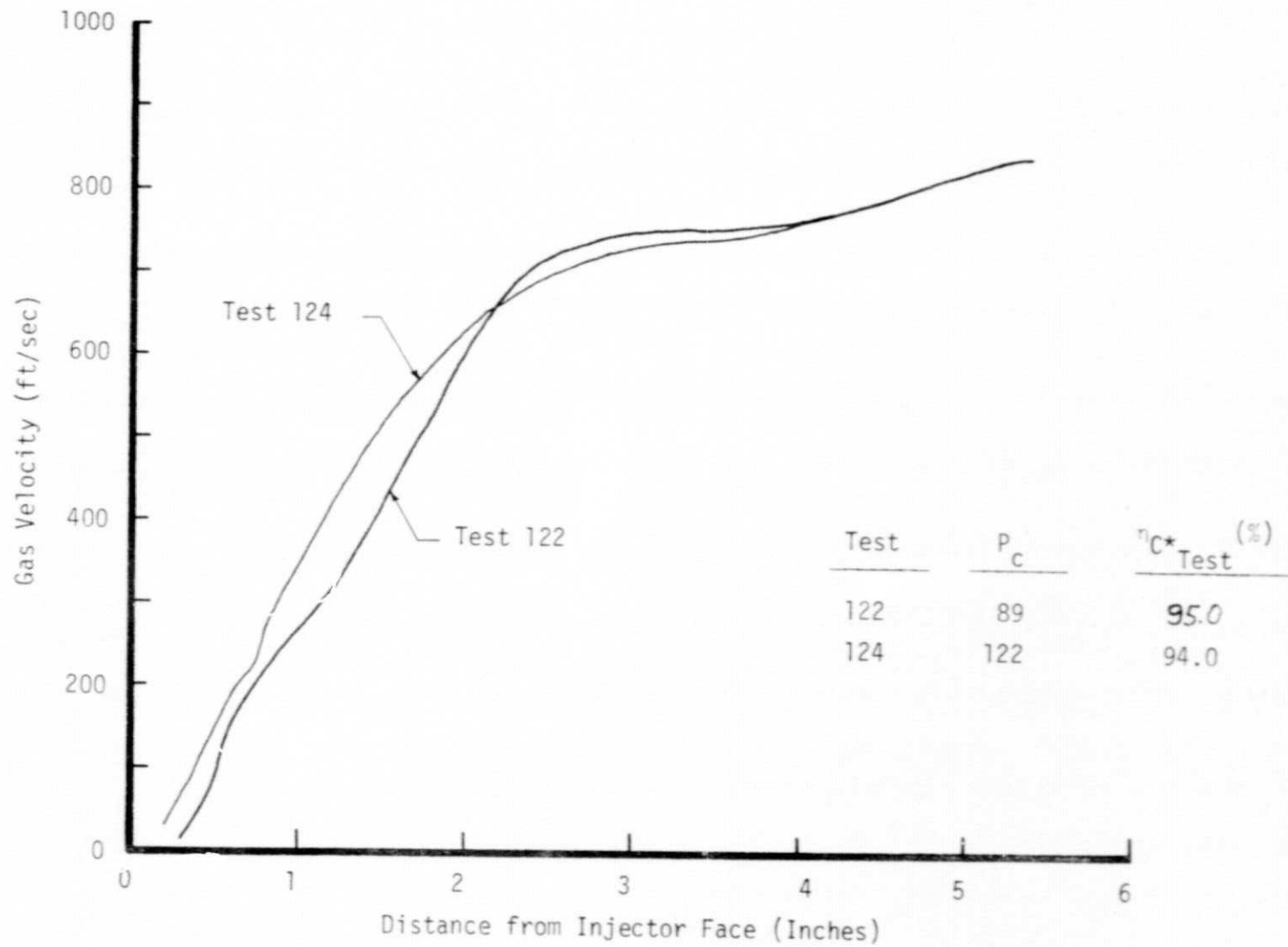


FIGURE 5. GAS VELOCITY PROFILES FOR LOW AND HIGH CHAMBER PRESSURE TESTS

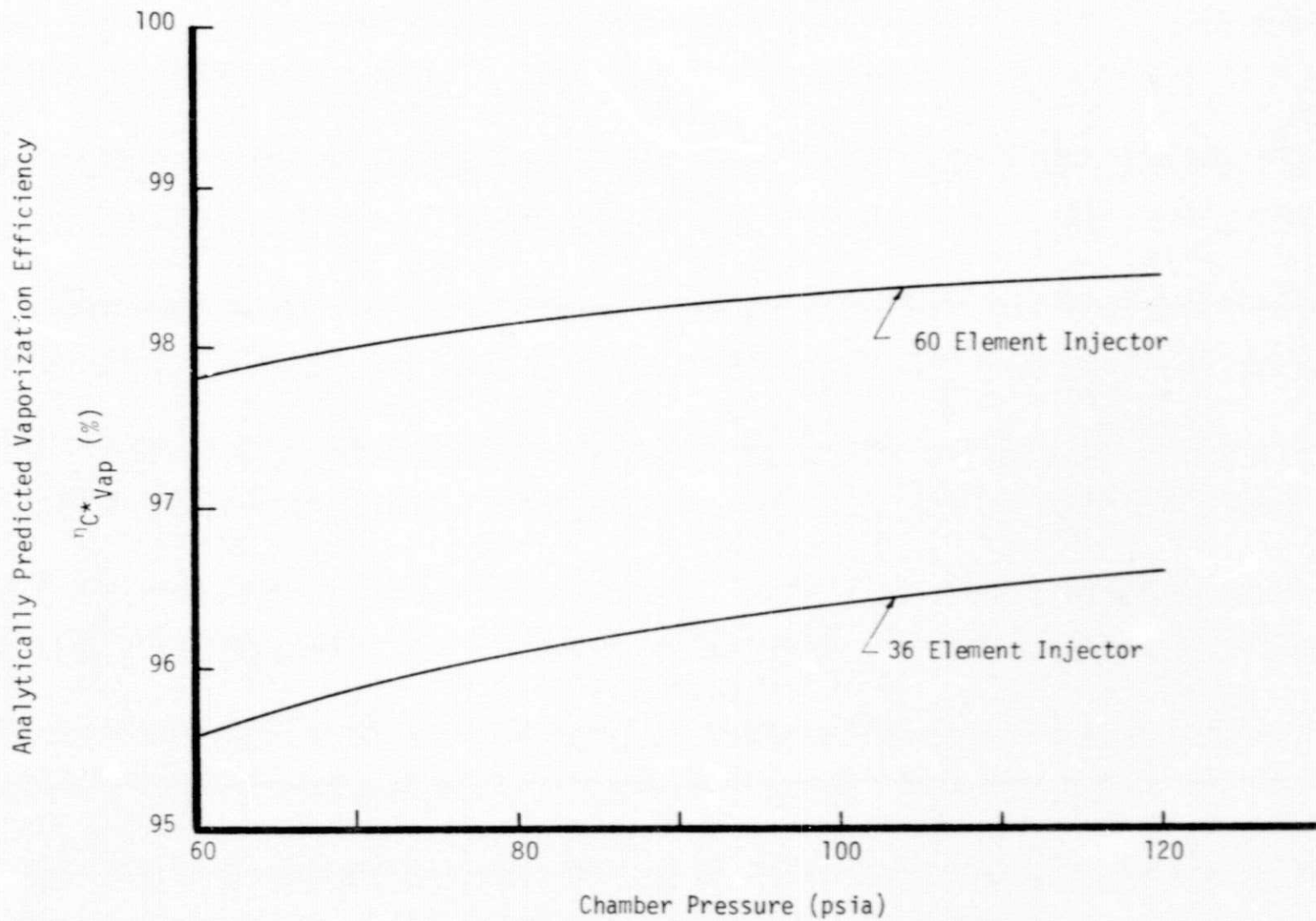


FIGURE 6. ANALYTICALLY PREDICTED VAPORIZATION EFFICIENCY FOR ITIP INJECTORS

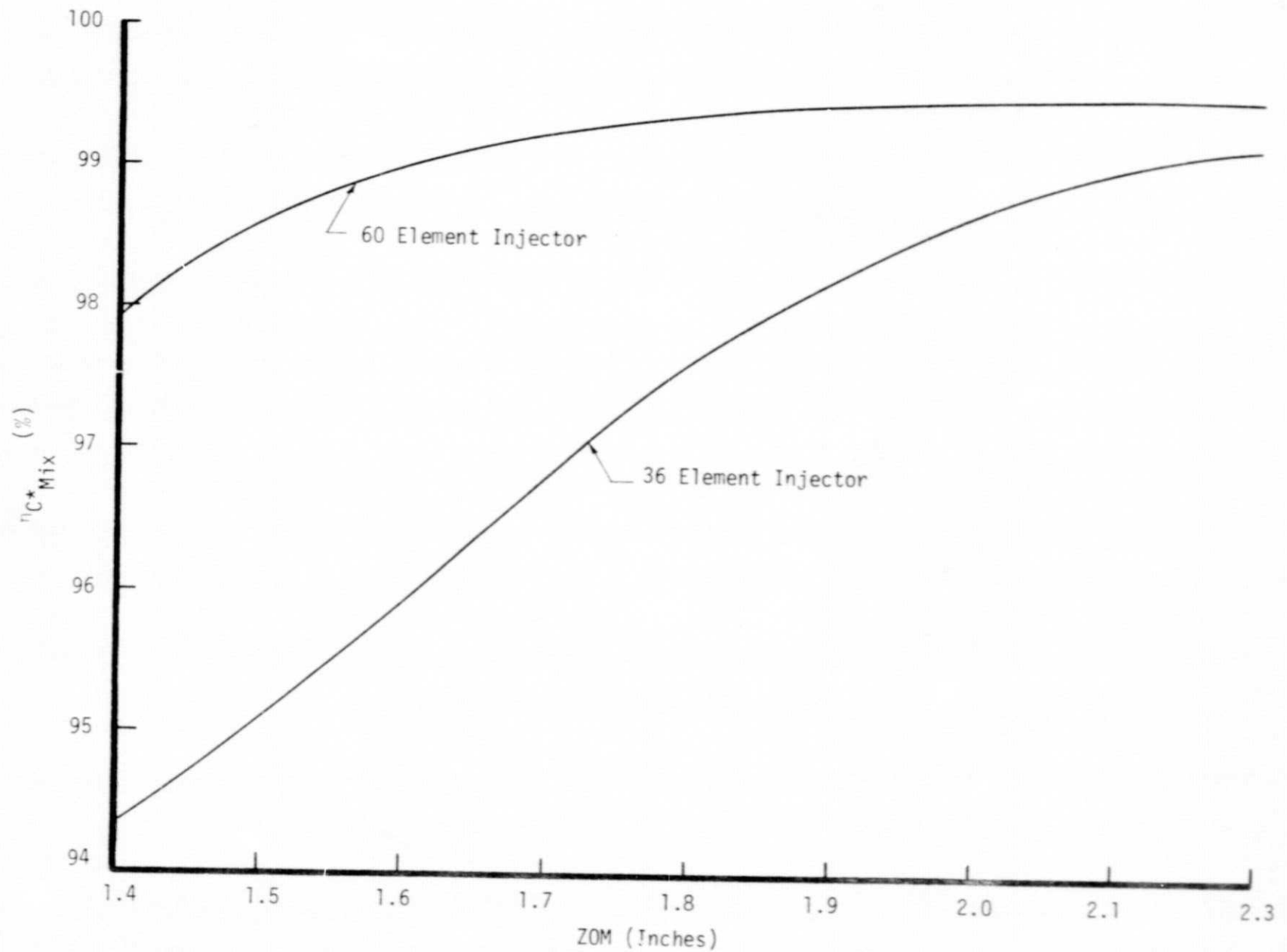


FIGURE 7. LISP CALCULATED MIXING EFFICIENCY

III ZOM Plane Identification (cont.)

The ZOM model predictions are compared to the test ZOM values in Figure 8. As for the OMS data, the incorrect ZOM slope is predicted because of the influence of injection velocity on the model calculation. Also, for the OMS data (8 inch chamber length) the ZOM prediction was at least of the right absolute value. The ITIP test correlated ZOM values are seen to be significantly higher than those predicted by the model. This is attributable to the effect of the long ITIP chamber length (19 inches) on mixing efficiency. An obvious shortcoming of the ZOM model is an inability to predict the influence of chamber length on performance improvement due to turbulent mixing. Work accomplished to characterize the influence of turbulent mixing for OMS and ITIP type like doublet pair injectors is described following the next subsection on an assessment of available RSS models.

C. Reactive Stream Separation Model Review

The ZOM gas acceleration effects model data evaluation effort has identified the need for a RSS combustion effects model in any physically mechanistic mixing model. Results of recent studies (Refs. 2 and 4) indicate the severity of RSS increases with increasing chamber pressure, fuel velocity, and fuel temperature. Models developed during these studies indicate conditions required for the presence of RSS, but no physical characterizations are presented which could be utilized to evaluate chamber performance. It is indicated in Refs. 2 and 4 that the severity of RSS increases as fuel stream Weber number increases. This characteristic is supported with the ITIP and OMS subscale injector correlated mixing efficiency data shown in Figure 9. This figure illustrates decreased mixing performance (increased RSS severity) with increasing Weber number. This correlation portends an ability to model the influence of RSS as a function of injector design and operating point. At this time, however, such work, which was beyond the scope of this current effort, has not been accomplished. Most injector designs will operate with at least some degree of RSS, and as a result a quantitative method for evaluation of RSS is required for development of a general liquid propellant mixing model.

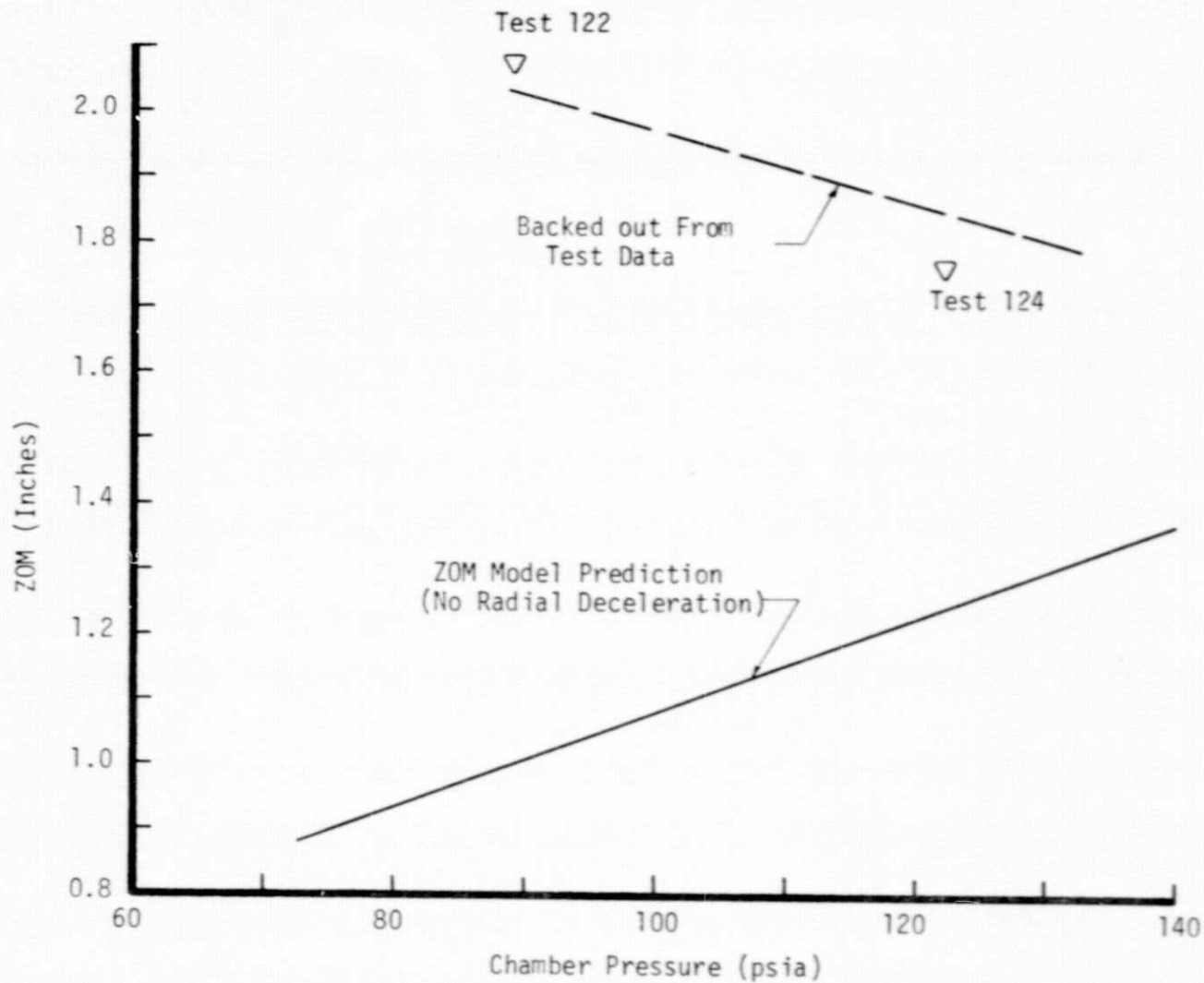


FIGURE 8. ITIP 36 ELEMENT INJECTOR ZOM PREDICTION RESULT

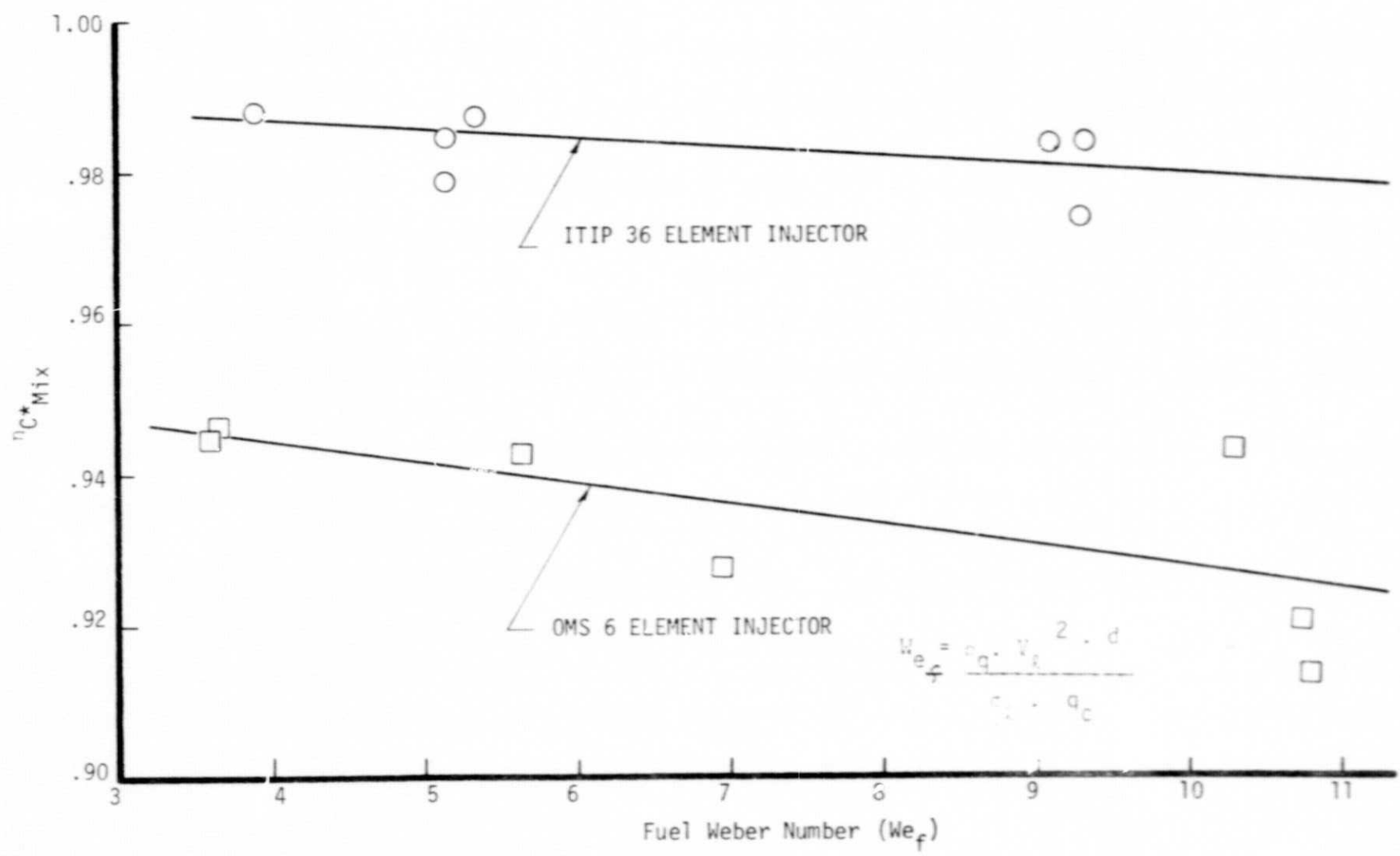


FIGURE 9. MIXING EFFICIENCY CORRELATION WITH FUEL WEBER NUMBER

III ZOM Plane Identification (cont.)

D. Turbulent Mixing Characterization

As described in Section III.B., the ZOM model correlation of the ITIP subscale injector data substantiated previous conclusions regarding the need for characterization of RSS combustion effects in any mass distribution model designed for incorporation into DER. It also identified the need for modeling of the influence of chamber length on performance improvement due to turbulent mixing.

Effort was made to derive a reasonable chamber length influence parameter by correlating test mixing efficiency for the ITIP 19 inch chamber data and the OMS 8 inch chamber data analyzed during the Task II of the first program phase (Ref. 1). The LISP program was used to calculate mixing efficiency for both the ITIP 36 element and OMS 6 element injectors as a function of ZOM. This data is illustrated in Figure 10. Included in Figure 10 are the test correlated ZOM values obtained from the equation:

$$\eta_{C^* \text{ Mix}} = \frac{\eta_{C^* \text{ Test}}}{\eta_{C^* \text{ Vap}}}$$

where:

$$\eta_{C^* \text{ Test}} = \text{Test data average } C^* \text{ efficiency at } P_c = 100 \text{ psia, } T_f = T_o = 80^\circ\text{F}$$

$$\eta_{C^* \text{ Vap}} = \text{Analytically determined } C^* \text{ vaporization efficiency (See figure 6)}$$

The results show that the OMS 6 element pattern has roughly a 2.5 percent higher mixing efficiency than the 36 element ITIP pattern at the same ZOM collection plane distance (i.e., in equal chamber lengths the OMS injector would have a mixing efficiency about 2.5 percent higher than the ITIP injector). This result occurs because of an improved spray overlap characteristic due to the relative fineness of the 6 element pattern.

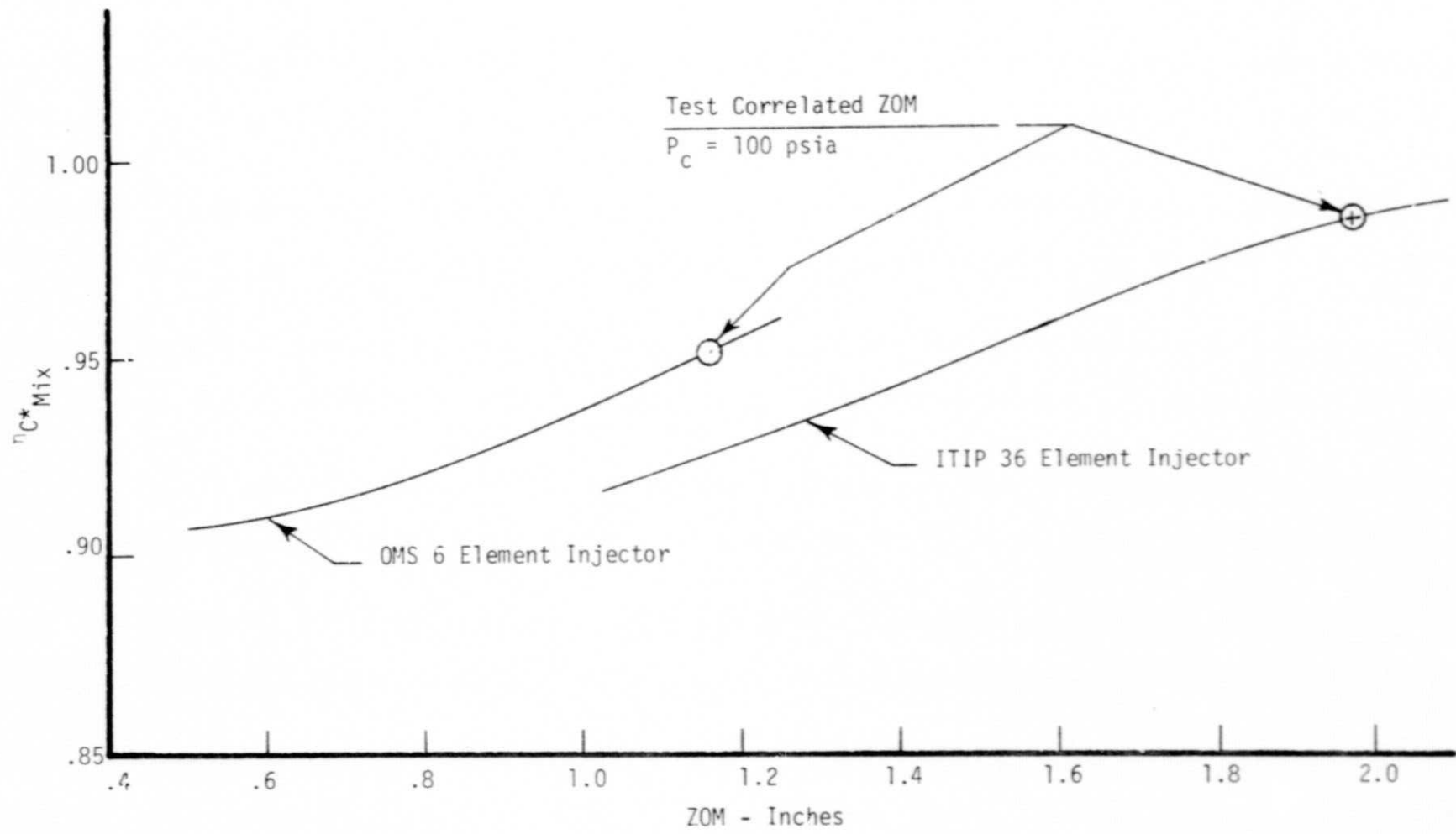


FIGURE 10. LISP MIXING EFFICIENCY FOR OMS AND ITIP INJECTORS

III ZOM Plane Identification (cont.)

The derived influence of chamber length on mixing efficiency is shown in Figure 11. Average C* mixing efficiency for the OMS 6 element and ITIP 36 element injectors are shown at their respective chamber lengths of 8 and 19 inches. To establish a chamber length influence on mixing efficiency, the OMS pattern $\eta_{mix}^{C^*}$ is adjusted downward 2.5 percent to account for the influence of pattern design. After this adjustment a chamber length reduction from 19 to 8 inches results in a 6 percent reduction in mixing efficiency for these like doublet pair injectors.

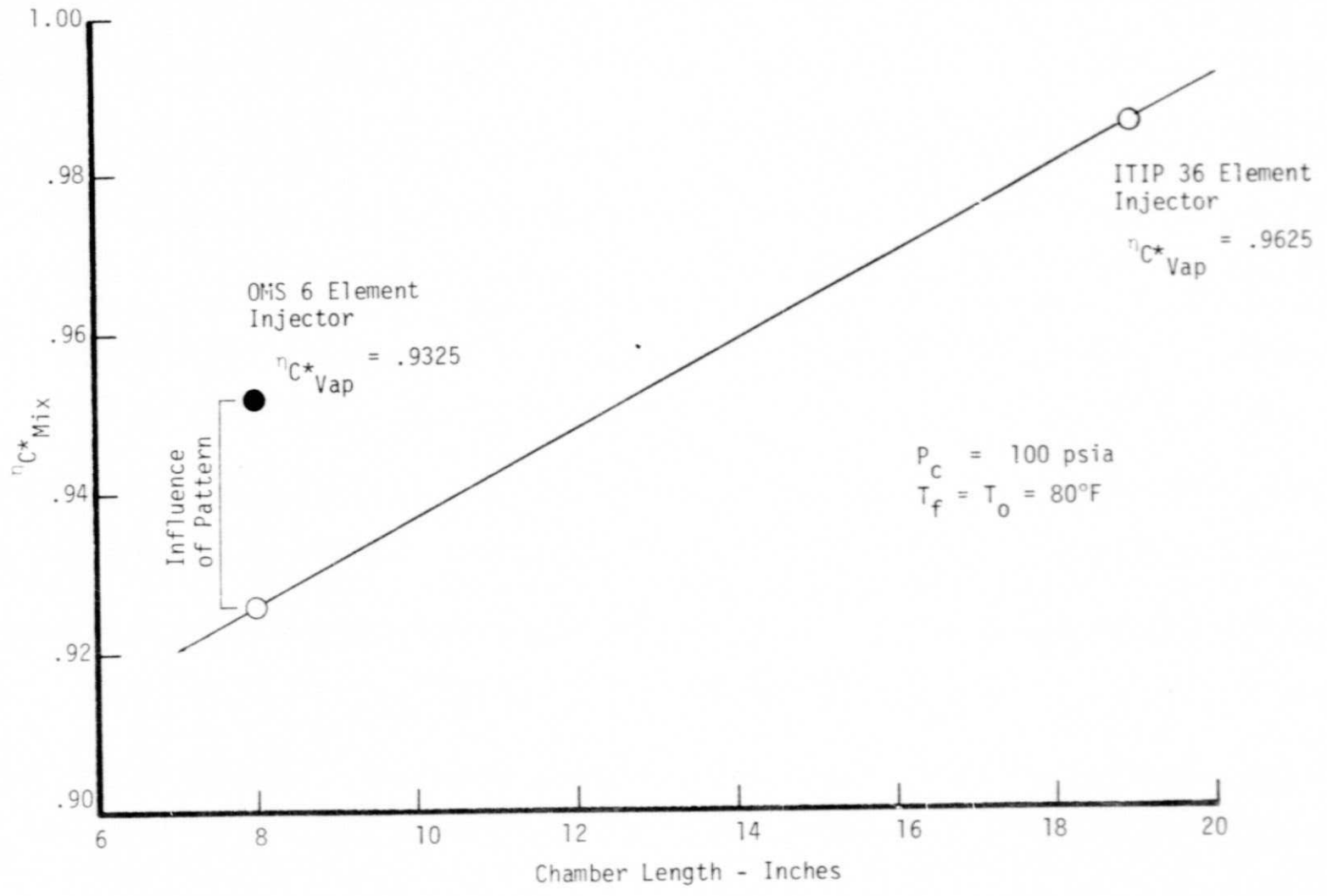


FIGURE 11. CHAMBER LENGTH INFLUENCE ON MIXING EFFICIENCY

IV CICM INTRA-ELEMENT MIXING MODEL

The objective of this program task was to develop a concise plan for incorporation of a gas/liquid coaxial intra-element mixing model into CICM. This goal evolved from a major conclusion of the CICM review conducted during Phase I of the Injection Processes Program (Ref. 1); viz., that the CICM technique for accounting for intra-element mass distribution should be improved and that, preferably, an intra-element mixing model should be developed. A literature review was conducted and judgement made with regard to applicability of available research and models.

A conclusion of the review was that relevant gas/liquid mixing work was limited to the interrelated studies described in Refs. 5 through 7. This experimental program, which is reviewed in Section IV.B.2 below, was conducted to characterize circular coaxial mixing for the FLOX(l)/methane (g) propellant combination. Available gas/gas coaxial mixing models were also reviewed during the literature search. It was concluded that the program documented in Ref. 8 resulted in an analytical model far superior to other models, with respect to applicability to analytical modeling of rocket injector coaxial elements. The gas/gas model critique, presented in Section IV.B.3 below, was limited to the Ref. 8 study for the reason cited above.

The mixing model review results guided the development of two proposed modeling approaches. (1) Adaptation of the Ref. 8 analytically formulated, empirically correlated gas/gas mixing model to the current CICM calculation scheme, and (2) a comprehensive test, data analysis, and modeling program that would apply directly to the gaseous annulus, liquid core coaxial mixing problem.

A. Recommendation

It is recommended that at least one of the following two identified gas/liquid coaxial intra-element mixing model development approaches be pursued. First, the most expedient and inexpensive plan would be to adapt an identified and available analytical gas/gas mixing model, as described below in Section IV.C.1, to the current CICM calculation scheme. CICM now calculates the dis-

IV C1CM Intra-Element Mixing Model (cont.)

integration rate of the circular oxidizer core jet, the resulting atomized drop sizes, and subsequent oxidizer droplet vaporization. The model would be expanded to account for intra-element shear mixing of the surrounding annulus fuel gas and vaporized oxidizer gas through use of an axial distance dependent streamtube mass exchange calculation based on the previously developed and verified gas/gas mixing model. The major limitations of this method would appear to be the uncertainty associated with the influence of liquid jet surface and spray combustion on the radial distribution of the vaporizing oxidizer droplets.

The second suggested model development approach consists of a comprehensive test, data analysis, and model development program that would be based on direct measurement of gas/liquid coaxial element mass distribution as a function of injector design and operating point. Albeit a more expensive and prolonged development effort would be involved, however, resulting model accuracy and generality would no doubt be improved. This model approach is described in more detail in Section IV.C.2. If this development course is selected it is still recommended, for two reasons, that the simplified model described above be formulated. First, it would serve as an interim procedure during development of the advanced model. Secondly, it could later be used in a comparative analysis to identify limitations of either model.

B. Literature Review and Critique

1. C1CM Mixing Model Assessment

C1CM allows for the effect of intra-element mass and mixture ratio distribution through user input specification. For each zone (i.e., single element) analyzed by C1CM, the user is instructed to input radial zonal oxidizer and fuel mass fractions based on single element cold flow data. There are several problems associated with accounting for intra-element mass non-uniformities in this manner.

(1) There is no available standard technique for measuring single element cold flow gas/liquid coaxial mass distribution.

IV CICM Intra-Element Mixing Model (cont.)

(2) The JANNAF methodology does not specify the axial plane (i.e., collection plane) at which the intra-element mass distribution should be specified. Face plane measurements are most easily accomplished but the results are incorrect because of the high ΔV shear mixing, inherent to coaxial element designs, that occurs between the face and chamber throat plane locations.

(3) The test cases used to back out the recommended atomization and drop size input constants to CICM assumed that the thrust chamber in question had uniform throat plane mixture ratio distributions. For most real coaxial injectors there will be a finite mixing loss because the coaxial element is a relatively slow mixing element. It is apparent that correct values for the C_A and B_A coefficients will be directly dependent on the assumed single element mixture ratio distribution. Unless a standard method for measuring or calculating single element mixture ratio distributions is developed it is extremely doubtful that universal values for the C_A and B_A constants can be verified.

(4) CICM does not allow for the influence of combustion on the single element mass and mixture ratio distribution, a limitation shared with the DER program for liquid/liquid injectors.

Currently, it appears that, without a standard coaxial element mixing model or approach, standardization of the parameters that influence the propellant vaporization rate will be difficult. That is, two processes affect coaxial injector performance (mixing and vaporization) and each process must be physically modeled to a comparable degree to result in a model that can calculate an accurate superimposed solution. At this stage CICM has been verified for engines that apparently have only one effective performance loss mechanism, i.e., incomplete propellant mass vaporization.

2. Gas/Liquid Intra-Element Mixing Models

The review of the literature on coaxial jet mixing revealed little work related to development of analytically based gas/liquid mixing

IV CICM Intra-Element Mixing Model (cont.)

models that had been verified or calibrated with experimental data. The experimental program described in Refs. 5 through 7 was the only study conducted for direct application to the rocket injector design problem. Therefore, the gas/liquid mixing review was limited to this work. This experimental program was conducted to characterize the circular coaxial injector concept for application to the Space Storable FLOX (82.6% F₂) (l)/methane (g) propellant combination. A series of single element cold flow and hot fire experiments were employed to establish design criteria for a 3000 lbf engine operating at 500 psia chamber pressure.

Parametric cold flow mixing experiments were conducted (using water and air as the oxidizer and fuel simulants, respectively) with various candidate injector core elements. The influences of gas velocity, liquid velocity, gas density, element mixture ratio, oxidizer post recess, and oxidizer jet swirl on the mixing characteristics of coaxial elements were investigated.

The experiments were designed so that the effects of gas and liquid velocity could be assessed independently of the other test variables. As an example, to determine the effects of liquid injection velocity, the diameter of the oxidizer jet was varied along with the diameter of the gas orifice to maintain a constant gas velocity.

A two-phase deceleration probe was used for the determination of local values of gas and liquid mass flux. It's basic principle of operation provides for separation of the propellant liquid phase into a stagnation chamber, where its flow rate can be measured, while simultaneously measuring the gas phase stagnation pressure. Detailed calibration and operation procedures for the two phase deceleration probe are described in Ref. 7.

Initial experimental results obtained indicated that propellant mixing proceeded rapidly within the first 2 inches of mixing length and appeared to be nearly complete at a collection distance of 5 inches. It

IV CICM Intra-Element Mixing Model (cont.)

should be remembered that this characteristic was most probably established by the particular design and operating points evaluated. It was also determined that a spray field diameter of .75 inches and 2.0 inches occurred, respectively, at the above collection distances. The larger spray field permitted the mixing characteristics to be studied in greater detail and, therefore, a common measurement plane of 5 inches was selected for subsequent tests.

Mixing experiments conducted with the coaxial element configuration showed that the mixing level, expressed as the Rupe mixing factor, E_M , was a function of the parameter shown below.

$$E_M = f \left[\frac{(\rho_g V_g)^2}{(O/F) (V_L)} \right]$$

where:

- ρ_g = the gas phase density
- V_g = the fuel velocity in the element annuli
- O/F = the injected mixture ratio
- V_L = the liquid injection velocity

The obvious shortcomings of this mixing data is that it is narrow in scope; in that it is limited to the FLOX/Methane propellant combination with gas injection velocities on the order of 300 to 500 ft/sec. Coaxial elements employing LO_2/GH_2 propellants often result in gas velocities on the order of 1000 ft/sec or greater. Also, element physical dimensions, which directly affect the shear mixing rate, vary significantly as a function of propellant combination and injector operating point. This influence is not modeled in the empirical mixing correlation described above. Therefore, it is doubtful that these empirical results could be used to develop an adequate gas/liquid coaxial intra-element mixing model.

IV CIGM Intra-Element Mixing Model (cont.)

3. Gas/Gas Intra-Element Mixing Models

Ref. 8 documents a very comprehensive program conducted to investigate injection, mixing, and combustion processes using gaseous propellants, covering a range of operating conditions originally specified for the Space Shuttle Auxiliary Propulsion System. The gas/gas mixing model literature review was limited to this work because of its generality and the fact that it has been applied to and verified by the performance of real gas/gas coaxial injectors. The end objective of the Ref. 8 program was to relate injector and chamber design parameters to combustion performance, heat flux, and combustion stability in the form of a step-by-step design handbook applicable to any selected operating condition or gaseous propellant combination. The principle efforts in this program were devoted to evaluating various injector element configurations on the basis of single element cold flow and hot fire testing. Full scale injectors were designed to verify the design criteria.

Element concepts selected in the study were:

(1) the shear coaxial element, (2) the premix element, (3) the external impingement element, and (4) elements for micro-orifice injectors. Each element concept included design variations so that a total of 74 unique element designs were evaluated.

The cold flow testing (GH_2/GN_2) of these elements consisted of sampling the flow field in the chamber with a multi-element probe which was sequenced to measure both local total pressure (which was correlated to mass flux) and composition by passing part of the probe sample into a mass spectrometer. From these measurements a mixing efficiency could be determined at any axial, radial, and circumferential position within the chamber. One of the results of this study indicated that compared to other elements, the shear coaxial element has a relatively low mixing characteristic.

In addition to the cold flow evaluations, limited combustion testing (at near ambient pressures) was conducted with a similar probe sampling technique. These experiments were conducted with the swirl coaxial

IV CICM Intra-Element Mixing Model (cont.)

element and conclusively demonstrated that combustion retarded the mixing rate. They also resulted in the development of an analytical combustion influence parameter to allow for adjustment of measured cold flow distributions to more accurately model the hot fire combustion case.

Two gaseous injector combustion models were constructed from evaluation of the test data. The first model used the test data and correlated it directly with injector/chamber design parameters which are recognized from both the theoretical and empirical standpoints as the controlling variables. This empirical model has the advantages of (1) inherently being the most accurate procedure for gaseous injectors which are to be designed within the operating envelopes and propellant combination (GO_2/GH_2) used in the test program, and (2) with the design handbook provided offers a simplified calculation procedure. As recognized, however, the empirical model lacks generality in application to larger operating envelopes and other propellant combinations since it does not concentrate on quantifying the mechanistic causal relationships of the mixing/combustion process itself.

The second, analytical, modeling approach had the objective of understanding the mixing/combustion process to the maximum extent possible, using both available theoretical knowledge and new techniques suggested and developed from correlation of the test data. It is somewhat more complex than the empirical model, but has quantitatively characterized the mixing combustion process for gaseous propellants, so that it is general in nature and can handle all gaseous propellants and operating conditions. Both of these models have been summarized into step-by-step design procedures for gaseous injectors, with the required information displayed in charts, graphs, and tables for clarity of presentation (Ref. 8). It is this analytical model, because of its generality, that seems applicable to the CICM model. Apparent limitations associated with application of this gas/gas mixing model to the gas/liquid case considered by CICM are discussed in Section IV.C.1.

IV CICM Intra-Element Mixing Model (cont.)

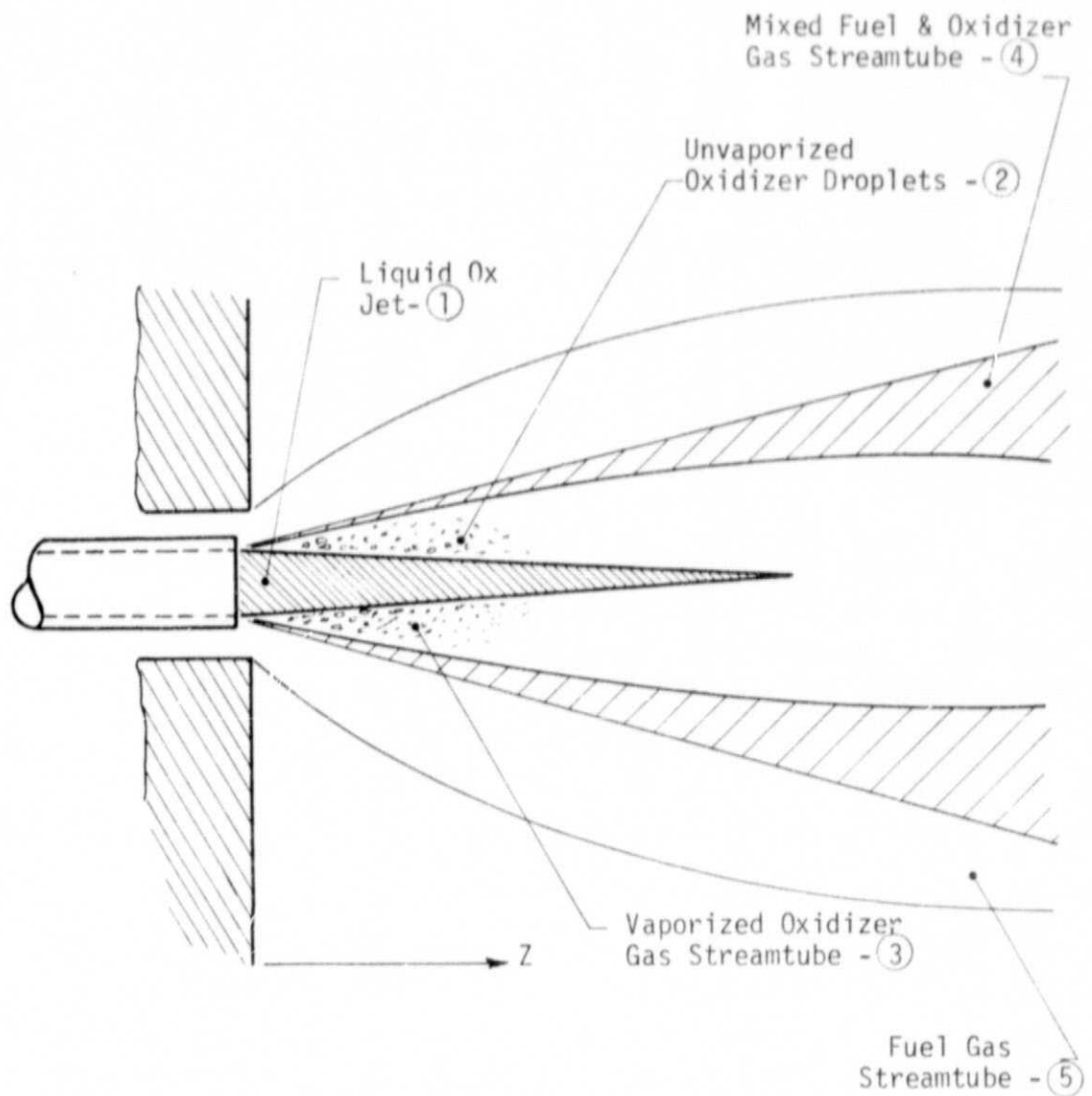
C. Model Development Approaches

1. Gas/Gas Model Adaptation to CICM

The analytical gas/gas mixing model described above (and detailed in Ref. 8) is attractive because of its generality and because it has been correlated with and verified by actual hot fire coaxial injector performance data. This model is applicable to two streamtube axisymmetric, coaxial mixing of a central circular gaseous core and a surrounding gaseous annulus.

A methodology for adapting this gas/gas model to CICM has been conceived, that is based on the assumption that the oxidizer droplets that have been stripped from the liquid jet subsequently vaporize and form an axisymmetric streamtube surrounding the liquid core. This process, and the resulting gas streamtubes and mass groups to be carried by the CICM calculation to preserve mass continuity, is sketched in Figure 12. In the current CICM calculation scheme, the jet stripping rate process is calculated until the liquid jet has completely disintegrated. Resulting droplets are grouped and their vaporization rates calculated. Vaporized oxidizer is assumed to react immediately with available gaseous fuel consistent with the intra-element mixture ratio distribution prescribed by the user through input.

The new calculation scheme, directly accounting for the gas/gas mixing rate limitation on performance, would proceed in the following manner. The oxidizer stripping, drop size atomization, and droplet vaporization processes would be calculated consistent with the current model analytical formulations. An axisymmetric oxidizer vapor streamtube would be formed consistent with the calculated vapor mass fraction and the known local circular diameter of the oxidizer liquid jet. The gas/gas analytical mixing model formulations would then be utilized to calculate shear mixing between the adjacent oxidizer gas and fuel gas streamtubes; resulting in a third streamtube of mixed combustion products.



MASS GROUPS FOR CONTINUITY SOLUTION

- (1) Liquid Oxidizer Jet
- (2) Unvaporized Oxidizer Droplets
- (3) Vaporized Oxidizer Gas Stream
- (4) Mixed Fuel & Oxidizer Gas Streamtube
- (5) Fuel Gas Streamtube

FIGURE 12. ADAPTATION OF GAS/GAS MIXING MODEL TO CICM

IV CICM Intra-Element Mixing Model (cont.)

As previously described in Section IV.B.3, a valuable salient feature of this analytical gas/gas mixing model is a combustion influence parameter that accounts for gas density differences, and their inherent influence on diffusion mixing, between the cold unmixed gases and the hot reacted combustion gases that separate them. Development of a similar parameter to account for liquid phase mixing forces in the injector near zone could improve the applicability of the gas/gas model to the gas/liquid case.

It is realized that phase and property differences and mechanical mixing characteristics of a liquid versus gaseous core could limit the applicability of the gas/gas model to the development of a physically mechanistic gas/liquid mixing model. Of particular significance is the fact that in a gas/gas system mixing is primarily dependent on shear turbulent boundary layer growth effects, whereas the gas/liquid system mixing is initially dependent on atomization of the liquid core followed by, possibly, mechanical penetration and vaporization within the gaseous fuel annulus. These questions are only answerable through the type of empirical/model development program described below. However, a simplified model approach would be a valuable forerunner and provide opportunity for gaining insight into the gas/liquid coaxial mixing problem.

2. Gas/Liquid Coaxial Mixing Program

The gas/liquid coaxial mixing work described in Section IV.B.2 is limited to a particular propellant combination and a relatively narrow injector operating range. Therefore, it is questionable that it could be applied to the development of a general gas/liquid coaxial intra-element mixing model.

The gas/gas mixing program (Ref. 8) previously described was planned so as to result in the development of a general modeling approach that could be applied to design points significantly departed from the actual designs used to inspire and calibrate the resulting analytical formulations. Based on application to this date, the program appears to have fulfilled its objective.

IV CICM Intra-Element Mixing Model (cont.)

Preliminary program plan logic, for a similar approach to creating a general gas/liquid coaxial mixing model, is shown in Figure 13. Task I would entail planning and design in regards to injector elements, operating points, and data measurement and sampling techniques. This task is based on the assumption that an accurate and efficient method for sampling gas/liquid spray field mass and mixture ratios can be devised and instituted. Sampling work accomplished in the gas/liquid mixing program (Ref. 7) previously described indicates that a reliable sampling technique can be devised. Task II would be composed of cold flow tests over a wide range of coaxial injector geometric variables and operating points. Task III would entail similar tests utilizing low pressure hot fire tests to characterize the influence of combustion on the mixing process. Task IV is considered to be optional. Single and/or multiple element injector(s) would be designed, tested, and correlated to verify the design analysis capability resulting from the previous tasks. Task V would consist of comprehensive analysis of all the test data and subsequent development of an analytically formulated, empirically correlated intra-element mixing model for gas/liquid coaxial injectors.

In summary, it appears that two paths exist for the intra-element mixing model sorely needed in CICM. The first approach would consist of adapting an existing gas/gas mixing model to CICM. The second approach would entail development of a physically mechanistic gas/liquid mixing model through conductance of a thorough test, data analysis, and model development program. The latter approach assumed to be inherently more reliable and naturally more costly.

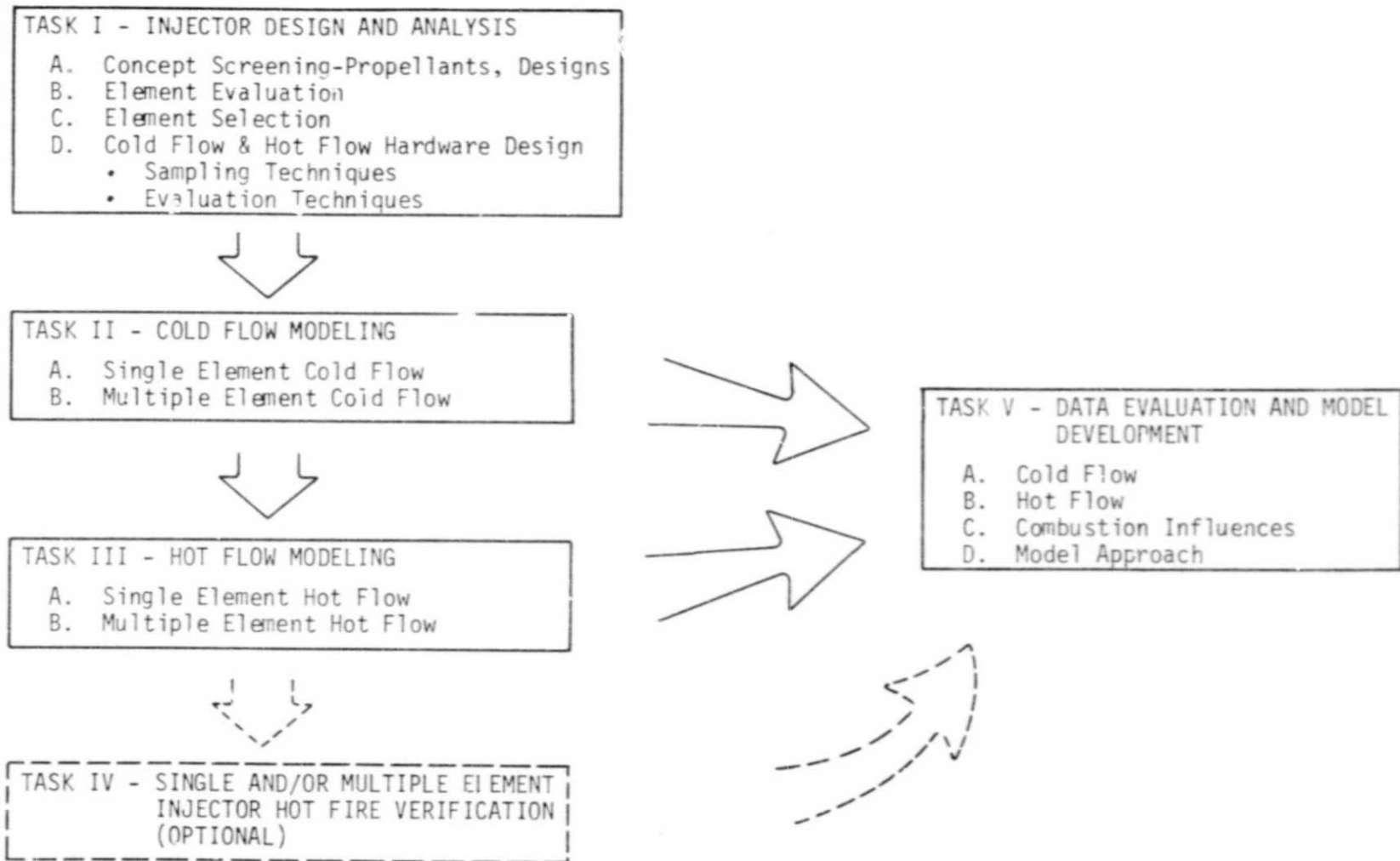


FIGURE 13. PROGRAM PLAN LOGIC FOR GAS/LIQUID COAXIAL MIXING MODEL

REFERENCES

1. Salmon, J. W., Analysis of Rocket Engine Injection Combustion Processes, Final Report Contract NAS 8-31531, Report 31531F-1, November 1976
2. Lawver, B. R., High Performance N₂O₄/Amine Elements - "Blowapart", Contract NAS 9-14186 Final Report, ALRC, to be published.
3. Priem, R. J. and Heidmann, M. F., "Propellant Vaporization as a Design Criterion for Rocket Engine Combustion Chambers", NASA TR-R-67, 1960
4. Falk, A. Y., High Performance N₂O₄/Amine Elements, Final Report, Contract NAS 9-14126, Rocketdyne, March 1976
5. Burick, R. J., "Space Storable Propellant Performance, Coaxial Injector Characterization", Final Report, R-8973-2 (NASA CR-120936) Rocketdyne, A Division of Rockwell International, Canoga Park, California, October 1972
6. Burick, R. J., Falk, A. Y., "Injector Design Guidelines for Gas/Liquid Propellant System", Final Report, R-8973-3 (NASA CR-120968), Rocketdyne, A Division of Rockwell International, Canoga Park, California, May 1973
7. Falk, A. Y., "Space Storable Propellant Performance Gas/Liquid Like Doublet Injector Characterization", Final Report, NASA CR-120935, Rocketdyne, October 1972
8. Calhoun, D. F., Ito, J. I., and Kors, D. L., "Investigation of Gaseous Propellant Combustion and Associated Injector/Chamber Design Guidelines", Final Report NASA CR-121234, Aerojet Liquid Rocket Company, Sacramento, California", July 1973