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DESIGN AND EVALUATION OF HIGH PERFORMANCE ROCKET ENGINE INJECTORS FOR USE WITH HYDROCARBON FUELS

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16. Abstract

An experimental program to determine the feasibility of using a heavy hydrocarbon fuel as a rocket propellant is reported herein. A method of predicting performance of a heavy hydrocarbon in terms of vaporization effectiveness is described and compared to other fuels and to experimental test results. The work was done at a chamber pressure of 4137 KN/M^2 (600 psia) with RP-1, JP-10, and liquefied natural gas as fuels, and liquid oxygen as the oxidizer. Combustion length effects were explored over a range of 21.6 cm (8 1/2 in) to 55.9 cm (22 in). Four injector types were tested, each over a range of mixture ratios. Further configuration modifications were obtained by "reaming" each injector several times to provide test data over a range of injector pressure drop.

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ABSTRACT

An experimental program to determine the feasibility of using a heavy hydrocarbon fuel as a rocket propellant is reported herein. A method of predicting performance of a heavy hydrocarbon in terms of vaporization effectiveness is described and compared to other fuels and to experimental test results. The work was done at a chamber pressure of 4137 KN/M^2 (600 psia) with RP-1, JP-10, and liquefied natural gas as fuels, and liquid oxygen as the oxidizer. Combustion length effects were explored over a range of 21.6 cm. (8 1/2 in) to 55.9 cm. (22 in.). Four injector types were tested, each over a range of mixture ratios. Further configuration modifications were obtained by "reaming" each injector several times to provide test data over a range of injector pressure drop.

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INTRODUCTION

In support of current interest in advanced propulsion systems for earth-to-orbit vehicles, a program was conducted to develop technology for efficient and stable combustion of high density hydrocarbon fuels with liquid oxygen in a rocket combustor. An advantage can be shown for higher density hydrocarbons in terms of improved vehicle mass fraction (see Reference 1). However high-density, high-viscosity fuels have never been evaluated as rocket propellants. Three primary objectives were pursued.

The first was to determine whether high performance could be achieved with stable combustion of heavy hydrocarbon fuels.

The second was to assess the adequacy of the Priem-Heidmann vaporization model in predicting performance of higher density, higher viscosity fuels.

The third was to investigate the effect of combustor design variables on the performance of heavy hydrocarbon fuels.

The pursuit of these objectives allowed comparisons of experimental performance data with theoretical performance data as predicted by the Priem-Heidmann vaporization model of Reference 2. Although the model is used widely to predict the quantity of propellant that is vaporized in particular configurations with conventional propellants, no one had yet tried to use it to predict the vaporization of the heavy hydrocarbons of Reference 1.

The scope of this program was limited to three commercially available fuels with liquid oxygen as the oxidizer. The fuels were:

(1) Exo-tetrahydrodicyclopentadiene, JP-10, a typical heavy hydrocarbon, recommended by Reference 1,

(2) RP-1, a conventional hydrocarbon,

(3) Liquefied natural gas (LNG, 92% methane by volume) a highly volatile hydrocarbon.

The fuels mentioned above were fired through a variety of injectors into a combustor with a 6.60 cm. (2.60 in.) diameter throat, and several combustor lengths over a range of mixture ratios, at a chamber pressure of 4137 KN/M^2 (600 psia). The work reported herein was performed at the Rocket Engine Test Facility (RETF) of the Lewis Research Center.

APPARATUS AND PROCEDURE

INJECTORS

The primary consideration in designing injectors for heavy-hydrocarbons is vaporization. The lower inherent volatility of the fuel must be compensated by better vaporization performance of the injector. The injector design process used in this work sought first to produce a good vaporizing design, and then to produce three variations of the first design for comparison purposes.

Using the Priem-Heidmann vaporization model of Ref. 2 an analysis of injector configuration options led to the selection of a triplet configuration as is shown in Figure 1. A triplet was selected because it does not need a large number of very small holes to satisfy the vaporization requirements for good performance.

The triplet elements were located on a square grid with the elements oriented mutually perpendicular to enhance inter-element mixing. In this configuration the element was composed of two jets of oxidizer impinging on a single jet of fuel (O-F-O).

In some injector design applications, such as a zoned combustor, the designer may want to consider using a F-O-F triplet instead of an O-F-O triplet element. The second injector configuration used in this program was a design that investigated this possibility. A face plate view of the second injector is shown in Figure 2. To avoid a large disparity in size between the two fuel holes impinging on a large oxidizer hole, the central oxidizer hole was changed to two smaller holes flowing parallel; referred to hereafter as the "split-triplet" configuration. (F-O-O-F). The elements for this configuration were located on a square grid, with the elements oriented mutually perpendicular.

The third configuration was designed to be identical to the second except that it had more elements of a smaller size, to allow evaluation of injector fineness. The injector had 97 elements instead of the 37 elements of the previous two configurations, and is shown in figure 3. In order to achieve the closer spacing of elements, the impingement angle was reduced on this configuration from the 60° of previous configurations to 30°.

The fourth injector configuration was a like-on-like doublet of conventional design to provide a direct comparison of performance to the triplet design. The configuration is shown in Figure 4. The elements were arranged in a circular pattern with the spray fans circumferential. The number of holes in this design was the same as in the 37 element split triplet design.

THRUST CHAMBERS

The above 4 designs were built for use with a 13.69 cm. (5.39 in.) diameter combustion chamber as is shown in figure 5. The combustor was built of several interchangeable spool-pieces which allowed the test configurations to be built to a range of lengths of from 21.6 cm. (8 1/2 in.) to 55.9 cm. (22 in.) from injector to throat. All configurations had flush-mounted high-frequency piezo-electric pressure transducers located on the combustor chamber walls in order to detect combustion chamber pressure oscillations should they occur. The combustion chamber was built up with a ring of 16 radial acoustic cavities on some configurations in order to suppress a combustion instability of approximately 5000 Hz. On other configurations, the acoustic cavity ring was not needed. These rectangular cavities were 5.51 cm. (2.169 in.) deep in a radial direction, 1.91 cm. (0.750 in.) wide in a circumferential direction, and 0.95 cm. (0.375 in.) tall in an axial direction. The combustor parts were all of heat sink design except for the throat which was water cooled. Figure 6 is a schematic diagram showing the propellant feed arrangement and the attendant instrumentation used to measure the performance of the injectors.

PROCEDURE

Figure 7 shows the firing of a typical configuration in the test stand. In the course of testing, the injectors were "reamed" several times to provide several different Δ P values for each of the four injectors. Table I is a list of the injectors used in the testing program. Shown here are the hole sizes of the injectors and the nominal flow Δ P values. The above injectors were attached to various length combustion chambers and fired with each of the three fuels (RP-1, JP-10 and LNG) as is illustrated in the configuration matrix of Table II. Shown here are the various combinations of injector, chamber length, and fuel that were tested and provided stable combustion (Pc oscillation less than $\pm$ 5%). The body of this report will consider only the data where there was stable combustion. For a discussion of the unstable firings, see the Appendix.

A thrust trace for a typical firing is shown in Figure 8. The combustor was ignited through a side port with a torch igniter and ramped to 1724 KN/M^2 (250 psia) chamber pressure. After satisfying the safety permissives the combustor was ramped to full chamber pressure of 4137 KN/M^2 (600 psia) and held for approximately 0.8 seconds until shutdown. Data was recorded every .02 seconds, averaged over five recordings and the average reported every 1/10th second. The last three such averages of every firing were used in the data reported herein as shown in Figure 8. As a check on experimental technique, characteristic exhaust velocity efficiency was calculated by two means;

1) Using measured combustor chamber pressure, propellant weight flow, and measured throat diameter, and correcting for momentum pressure loss.

2) Measuring thrust and propellant weight flow, and calculating the theoretically predicted thrust coefficient efficiency (Ref. 3).

RESULTS AND DISCUSSION

The test results will be discussed in terms of characteristic exhaust velocity efficiency as a function of mixture ratio, injection pressure drop, and combustor length for each of the configurations indicated in Table II.

MIXTURE RATIO EFFECTS

Each configuration was test fired at several different mixture ratios and the C* efficiency plotted versus mixture ratio for each configuration. Figure 9 shows such a plot for a typical configuration. In this case five firings were made, each at a different mixture ratio. Three C* efficiency values were reported for the last three 1/10th second periods of each firing. The close agreement of these three values in each case indicated steady-state conditions were achieved in the short duration of the firing.

Good agreement was also obtained between the two methods of calculating C* efficiency. In general the data scatter was less for the C* efficiency by chamber pressure and so the results reported here are from chamber pressure data, with the thrust data being used as a check. The data scatter observed was always within $\pm$ 1/2% C* efficiency. In some instances C* efficiencies in excess of 100% were calculated and the source of this bias error could not be found. It is believed that the bias error is approximately + 1/2%. Plots of C* efficiency vs. mixture ratio were prepared for each configuration. Further comparisons were made between configurations at the same mixture ratio by reading values from the faired curves of the C* efficiency vs. mixture ratio plots. Based on the location of peak theoretical vacuum specific impulse, the mixture ratios selected for crossplots were O/F = 2.7 for RP-1 and JP-10 fuels, and O/F = 3.5 for LNG.

INJECTOR ΔP EFFECTS

The next comparison between configurations was on the effect of fuel injection pressure drop on C* efficiency. The fuel injector pressure drop was systematically varied by reaming the injector orifices as described in the procedure section and Table I. The injector pressure drop effect on C* efficiency is shown in Figure 10. The experimentally measured performance of each configuration is represented by a symboled data point. Each group of experimental data points has a corresponding line of predicted performance from the Priem-Heidmann vaporization model (Ref. 2).

According to the vaporization model, no appreciable change in performance was expected with low injector pressure drop resulting from reaming any of the injectors. Apparently the increased droplet size is compensated by the lower injection velocity. The experimental data for the triplet and split injectors appears to agree with the prediction within the experimental accuracy of this program. No significant trends in performance appear between the triplets and split triplets for any of the fuels.

The experimental data for the doublet injectors does not agree with the performance prediction based on vaporization theory alone. The performance seems to be affected by something other than vaporization. The nature of the discrepancy between the experimental results and the vaporization model for the doublet is three fold:

First, there is little difference in the experimental results between RP-1 and JP-10 in spite of what the vaporization model predicts. Note on Figure 10 that the theoretical curve for RP-1 is about 2% higher than that for JP-10, whereas the experimental data is only 1/2% higher.

Second, the experimental performance varied as a function of injector ΔP, contrary to the vaporization prediction, which shows no effect of ΔP on C* efficiency.

Third, the experimental performance is significantly lower in magnitude than predicted by the vaporization model.

The performance of the doublet injector seems to be dominated by mixing losses. This is not surprising since the doublet injector design has significantly poorer mixing than the triplet design. The triplet design has two mechanisms of mixing that the doublet does not. First, the triplet has mixing occurring at the impingement point, since it is an unlike impinging element, whereas the doublet is a like impinging element. Second, the triplet design has inter-element mixing of dissimilar droplets (Ox rich vs. Ox lean) by virtue of its mutually perpendicular element orientation. The doublet design has parallel spray orientation and tends to minimize interelement mixing. The only mechanism for mixing that is available to the doublet design is diffusion of the dissimilar concentric zones of vaporized propellant. For these reasons it appears that the doublet injector's performance is dominated by mixing losses, and as such cannot be expected to be modeled by a vaporization prediction. The doublet's poor performance is apparently caused by the element orientation, and should not necessarily be generalized to include all like impinging doublets. The triplet injectors however exhibited performance that was primarily vaporization limited and therefore the vaporization model predicted their performance accuractely.

COMBUSTION LENGTH EFFECTS

All of the experimental test data, at the mixture ratio of interest (O/F = 2.7 for RP-1 and JP-10, and O/F = 3.5 for LNG) were cross plotted on a C* efficiency vs combustor length coordinate system. The triplet and split triplet data all agreed with the vaporization prediction. For clarity, only the triplet data is shown in Figure 11.

Again the experimentally measured performance is shown by symboled data points. Each group of experimental data points has a corresponding line of predicted performance from the vaporization model of Ref. 2.

According to the vaporization model an increase in C* efficiency is to be expected for all of the injectors when the combustor length is increased. The experimentally measured values of performance agreed well with the vaporization model for the injectors that were vaporization limited in their performance (triplets and split triplets).

The vaporization model alone is not adequate for a mixing limited injector design like the doublet. Increasing fuel volatility seemed to have no effect on the performance of the doublet injectors. Experimental performance increased monatonically with chamber length regardless of the fuel volatility. An anomaly occurs that has the experimental data for the JP-10 fuel falling close to the vaporization model prediction. Taken by itself this similarity might look like some agreement of experiment with prediction, but when compared to the RP-1 and LNG data and prediction it is obvious that it is only a coincidence. This coincidence will appear again in subsequent comparisons, and should be ignored.

GENERAL COMPARISONS

In order to compare the performance of the various injector configurations on a common basis, the data was further cross plotted to isolate the combustion chamber length effects. A plot of C* efficiency vs. combustion length similar to Figure 11 was made with all of the experimental data. The data was then read at two combustor lengths of interest, L = 35.6 cm. (14 in.) and 22.9 cm. (9 in.). In some cases some minor extrapolations were necessary. This data was then displayed in Figures 12, 13, and 14 as bar charts for comparisons. In each pair of bars, the upper bar is the experimentally attained C* efficiency, and the lower bar is the vaporization model prediction of C* efficiency.

Performance for three injectors (triplet, split triplet, and doublet) and their reamed modifications are shown in Figure 12 for the 35.6 cm. (14 inch) long combustor and RP-1 fuel. Several facts are obvious from this figure: One is the very high performance attained by the triplet and split triplet injectors which was in excess of 99% C* efficiency. A second fact is the good agreement of the experimental measurements with the vaporization model's prediction for injectors of good mixing effectiveness (triplet and split triplet injectors). Injectors such as the doublet that have their performance limited by mixing losses cannot have their performance predicted effectively with only a vaporization model, as previously discussed.

Figure 13 shows the performance for the same three injectors with JP-10 and LNG fuels again at a chamber length of 35.6 cm (14 in.). With a heavy hydrocarbon fuel (JP-10) of increased viscosity and decreased vaporization, high performance of in excess of 99% was again attained with the triplet and split triplet injectors. This high performance was accurately predicted by the vaporization model. The doublet injector had low performance even with the highly volatile LNG. It also had anomalous agreement with the vaporization model for the JP-10 fuel which was explained as coincidental in the discussion of Figure 11. Since mixing losses predominate, the vaporization model alone is not sufficient for evaluation of the doublet injector.

Figure 14 shows all the data that was available at a chamber length of 22.9 cm (9 in.). Several points are worth noting. First, the high performance attained in spite of the short combustor length with the first two injectors (triplet No. 250 and split triplet No. 252). Because these injectors were vaporization limited in their performance, the performance prediction and experimentally measured performance were in good agreement. Second, the lower performance of the 97 element split triplet is shown. Although it had the mutually perpendicular element orientation similar to the triplet (No. 250) and the 37 element split-triplet (No. 252) injectors for good mixing, it performed 2 to 2 1/2% below the vaporization model's prediction. The only difference (other than the number and size of the injection orifices) between the 97 element split triplet (No. 208) and the 37 element split triplet (No. 252) was the impingement angle. Because of the closer spacing of elements on the 97 element injector the impingement angle was reduced to 30° instead of the 60° used on the 37 element injectors. It is possible that the lower performance was caused by the lower impingement angle. Finally, the low performance and poor prediction correlation of the doublet injector (No. 251) that were caused by the mixing losses inherent in the design are again apparent.

CONCLUSIONS

The high performance with stable combustion of the injectors tested in this program has demonstrated the capability of the present state-of-the-art of injector design as suitable to design injectors for use with higher-viscosity, higher-density fuels. The best performing injectors were the 37 element triplet and the 37 element split triplet which achieved 98 1/2% and 99% C* efficiency respectively in combustor lengths of 25.4 cm. (10 in.) with JP-10 fuel.

The predictions of the Priem-Heidmann vaporization model are adequate in evaluating the effects of higher density and viscosity on performance. More volatile fuels showed improvements in performance of the magnitude predicted by the vaporization model except for injectors that were mixing limited.

The effect of combustor design variables such as combustor length and injector pressure drop were well characterized by the vaporization model for the higher density fuel.

The conventional concerns of designing injectors with good mixing, good vaporization, and good mass flux distribution, produces injectors that provide good combustion efficiency with the heavier fuels. Where these concerns were not vigorously pursued, as in the case of the doublet design, something less than high combustion efficiency was achieved. The worst performing of the injectors tested was the like-on-like impinging doublet for the probable reason of poor mixing. Using more volatile fuels in this injector caused no discernable improvement in performance. This injector required 48.3 cm. (19 in.) of combustor length to achieve 94% C* efficiency with JP-10 fuel.

APPENDIX

All of the data reported in the body of this report were for stable combustion conditions, i.e., Pc oscillation less than ±5% of Pc. During the course of testing however, some instances of combustion instability did occur. Although the investigation of combustion instability was out of the scope of this work, a complete listing of the configurations that were fired with predicted and attained C* efficiencies, along with a tabulation of the nature of the combustion instability when it occurred is provided in this Appendix on Table III.

This table is arranged in order of the injectors, and is not in the chronological order that the configurations were test fired. The chamber length listed is the actual length of the configuration from injector face to nozzle throat. The characteristic exhaust velocity efficiencies (experimentally measured and vaporization model's prediction) are for the nominal mixture ratio case; O/F = 2.7 for RP-1 and JP-10 and O/F = 3.5 for LNG. Also shown in this table is a listing of which configurations had the acoustic cavities. The reader is cautioned to not infer that there was a need for acoustic cavities on all the configurations that had them. Often the cavities were left on from a previous configuration as "insurance" without any demonstrated need.

The final three columns describe the nature of any combustion instability that was observed. A blank in these columns indicates stable combustion. The last column labeled "Spike" refers to the nature of the start of screech. Basically two modes of initiation were recognized. The first was a spontaneous appearance of the reported frequency and amplitude during the firing. The second mode of initiation was the immediate appearance of the reported frequency and amplitude after a significant pressure spike and was accompanied by some hardware damage noted by inspection after shutdown. In these cases it was not obvious whether the injector damage caused the combustion instability, or vice-versa.

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TABLE I. - LIST OF INJECTORS

INJECTOR NAME	INJECTOR NUMBER	NO. OF HOLES OX.	NO. OF HOLES FUEL	HOLE DIAMETER OX MM	HOLE DIAMETER OX IN.	HOLE DIAMETER FUEL MM	HOLE DIAMETER FUEL IN.	NOMINAL INJECTOR ΔP OX KN/M^2	NOMINAL INJECTOR ΔP OX PSI	NOMINAL INJECTOR ΔP FUEL KN/M^2	NOMINAL INJECTOR ΔP FUEL PSI
37 ELEMENT	250 - - 2	74	37	1.55	.061	1.40	.055	1338	194	1165	169
TRIPLET	250 - A-2	74	37	1.70	.067	1.57	.062	869	126	745	108
0 - F - 0	250 - B-2	74	37	1.85	.073	1.70	.067	627	91	565	82
37 ELEMENT	251 - - 1	72	75	1.57	.062	1.02	.040	1834	266	1462	212
DOUBLET	251 - A-1	72	75	1.73	.068	1.12	.044	1345	195	1186	172
0-0 F-F	251 - B-1	72	75	1.85	.073	1.19	.047	1096	159	814	118
	251 - C-2	72	75	1.98	.078	1.19	.047	1110	161	821	119
37 ELEMENT	252 - - 2	74	74	1.52	.060	1.02	.040	1345	195	1255	182
SPLIT-TRIPLET	252 - A-2	74	74	1.70	.067	1.09	.043	827	120	945	137
F - 0-0 - F	252 - B-2	74	74	1.85	.073	1.19	.047	621	90	690	100
97 ELEMENT	208 - - 1	194	194	0.94	.037	0.61	.024	-	-	-	-
SPLIT-TRIPLET	208 - - 2	194	194	0.94	.037	0.61	.024	-	-	-	-
F - 0-0 - F	208 - B-2	194	194	1.19	.047	0.71	.028	593	86	855	124

TABLE II. - CONFIGURATION MATRIX

INJECTOR NAME	INJECTOR NUMBER	CHAMBER LENGTH, CM. (IN.) 21½ (8½)			24 (9½)			32 (12½)			33 (13)			35½ (14)			40½ (16)			43 (17)			56 (22)		
FUEL →		RP-1	JP-10	LNG	RP-1	JP-10	LNG	RP-1	JP-10	LNG	RP-1	JP-10	LNG	RP-1	JP-10	LNG	RP-1	JP-10	LNG	RP-1	JP-10	LNG	RP-1	JP-10	LNG
37 ELEMENT TRIPLET OFO	250 - - 2			●										●			●	●		●				●	
	250 - A - 2						●							●											
	250 - B - 2			●	●	●		●	●					●	●										
37 ELEMENT DOUBLET OO FF	251 - - 1																●	●					●	●	
	251 - A - 1																						●	●	
	251 - B - 1													●	●										
	251 - C - 2			●									●												
37 ELEMENT SPLIT TRIPLET F OO F	252 - - 2													●	●										
	252 - A - 2							●	●					●	●										
	252 - B - 2					●								●	●										
97 ELEMENT SPLIT TRIPLET F OO F	208 - B - 2				●	●																			

TABLE III. - DATA SUMMARY

REPORTED AT NOMINAL MIXTURE RATIO

O/F = 2.7 for RP-1 & JP-10, O/F = 3.5 for LNG

INJECTOR NAME	INJECTOR NUMBER	CHAMBER LENGTH INJECTOR TO THROAT CM	IN	FUEL	C* EFFICIENCY PERCENT EXPERIMENTAL	PREDICTED	ACOUSTIC CAVITIES	COMBUSTION INSTABILITIES FREQUENCY Hz	AMPLITUDE KN/M²	PSI	INITIATED BY SPIKE
	250 - - 2	21.77	8.57	LNG	99.9	98.94	YES	-	-	-	-
		36.37	14.32	RP-1	-	99.42	NO	-	-	-	-
		40.82	16.07	RP-1	99.9	99.55	YES	1440	± 172	± 25	NO
		40.82	16.07	JP-10	99.4	99.08	YES	1400	± 138	± 20	NO
		43.36	17.07	RP-1	99.4	99.66	YES	1440	± 172	± 25	NO
37		56.59	22.28	JP-10	-	99.62	YES	1140	±1379	± 200	NO
ELEMENT TRIPLET	250-A-2	24.31	9.57	LNG	-	99.06	NO	5000	±2206	± 320	NO
O-F-O		24.31	9.57	LNG	-	99.06	YES	-	-	-	-
		36.37	14.32	RP-1	100.0	99.51	NO	-	-	-	-
		36.37	14.32	RP-1	100.1	99.51	NO	-	-	-	-
	250-B-2	21.77	8.57	LNG	99.1	99.00	YES	-	-	-	-
		24.94	9.82	RP-1	99.1	98.90	NO	-	-	-	-
		24.94	9.82	JP-10	98.6	97.93	NO	-	-	-	-
		31.93	12.57	RP-1	100.4	99.37	NO	-	-	-	-
		31.93	12.57	JP-10	99.9	98.73	NO	-	-	-	-
		36.37	14.32	RP-1	100.3	99.60	NO	-	-	-	-
		36.37	14.32	JP-10	99.1	99.12	NO	-	-	-	-
	251 - - 1	40.82	16.07	RP-1	93.4	95.84	YES	-	-	-	-
		40.82	16.07	JP-10	93.2	93.75	YES	-	-	-	-
		56.59	22.28	RP-1	94.3	97.65	YES	-	-	-	-
		56.59	22.28	RP-1	94.4	97.65	YES	-	-	-	-
		56.59	22.28	JP-10	94.5	96.07	YES	-	-	-	-
37	251-A-1	56.59	22.28	RP-1	95.7	97.69	YES	-	-	-	-
ELEMENT DOUBLET		56.59	22.28	JP-10	95.9	96.13	YES	-	-	-	-
O-O F-F	251-B-1	36.37	14.32	RP-1	93.9	95.46	NO	1440	± 172	± 25	NO
		36.37	14.32	JP-10	92.9	92.95	NO	1440	± 172	± 25	NO
		36.37	14.32	JP-10	-	92.95	NO	4480	± 138	± 20	NO
	251-C-2	21.54	8.48	LNG	89.4	96.56	YES	-	-	-	-
		33.60	13.23	LNG	91.0	97.96	YES	-	-	-	-
	252- - 2	36.37	14.32	RP-1	99.9	99.89	NO	-	-	-	-
		36.37	14.32	JP-10	99.4	99.53	NO	-	-	-	-
	252-A-2	31.93	12.57	RP-1	100.6	99.75	NO	-	-	-	-
		31.93	12.57	JP-10	99.7	99.42	NO	-	-	-	-
37		31.93	12.57	JP-10	99.6	99.42	NO	-	-	-	-
ELEMENT		36.37	14.32	RP-1	100.4	99.91	NO	-	-	-	-
SPLIT		36.37	14.32	RP-1	-	99.91	NO	5120	±2068	± 300	YES
TRIPLET		36.37	14.32	JP-10	99.4	99.58	NO	-	-	-	-
F-OO-F	252-B-2	24.94	9.82	RP-1	-	-	NO	4640	±3792	± 550	YES
		24.94	9.82	JP-10	98.9	99.04	NO	-	-	-	-
		36.37	14.32	RP-1	99.5	99.96	NO	-	-	-	-
		36.37	14.32	JP-10	99.7	99.66	NO	-	-	-	-
97	208 - - 1	36.37	14.32	RP-1	-	-	NO	5440	± 1931	± 280	YES
ELEMENT	208 - - 2	36.37	14.32	RP-1	-	-	NO	5360	± 1379	± 200	YES
SPLIT TRIPLET	208-B-2	24.31	9.57	RP-1	97.6	99.99	YES	-	-	-	-
F-OO-F		24.31	9.57	JP-10	97.6	99.75	YES	-	-	-	-

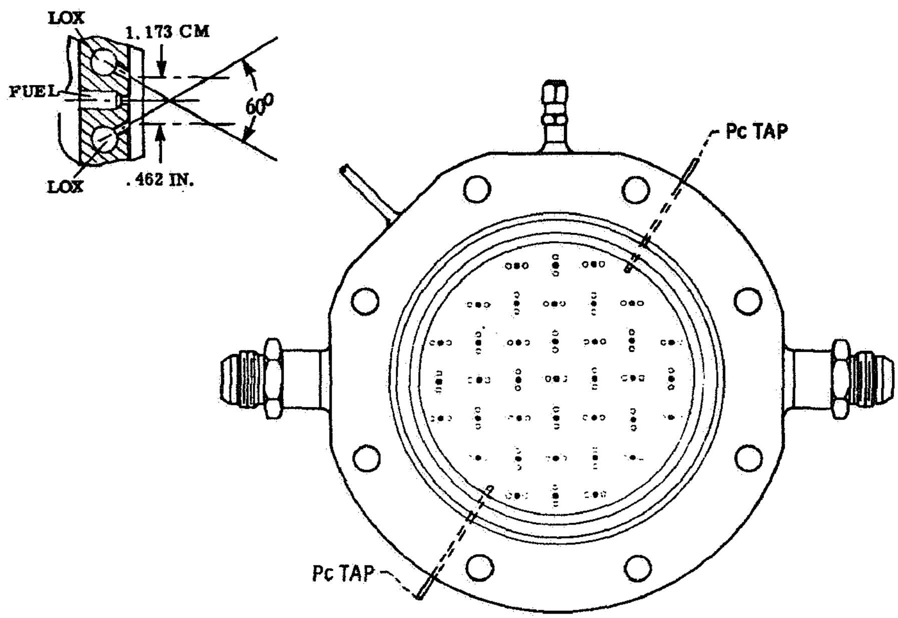

FIGURE 1. 37 ELEMENT TRIPLET (INJECTOR No. 250)

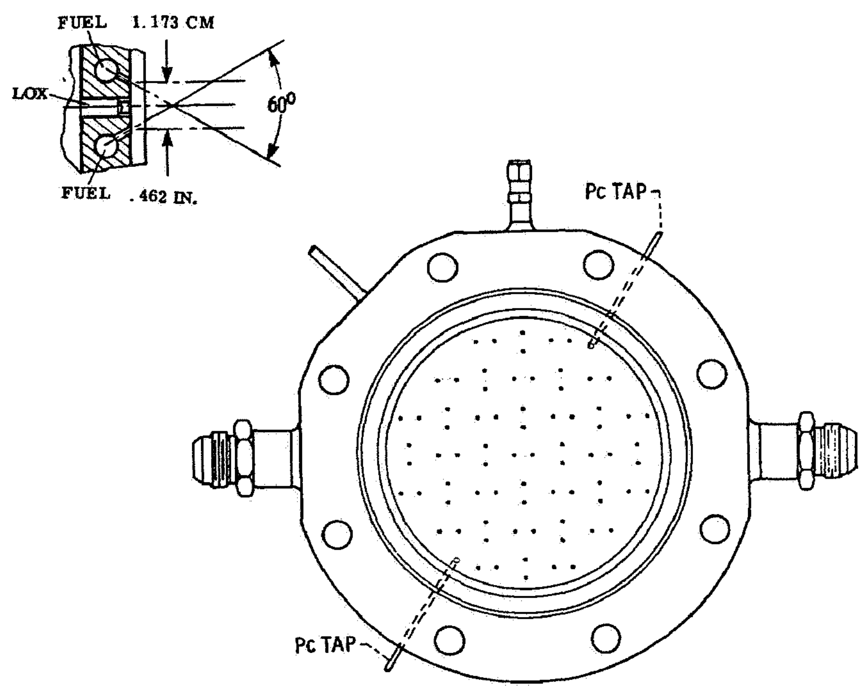

FIGURE 2. 37 ELEMENT SPLIT-TRIPLET (INJECTOR No. 252)

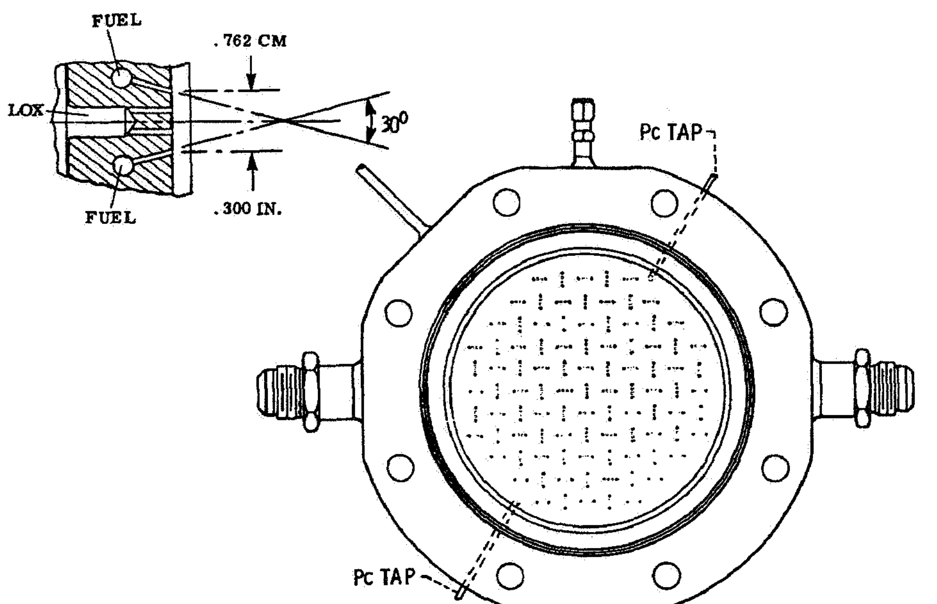

FIGURE 3. 97 ELEMENT SPLIT-TRIPLET (INJECTOR No. 208)

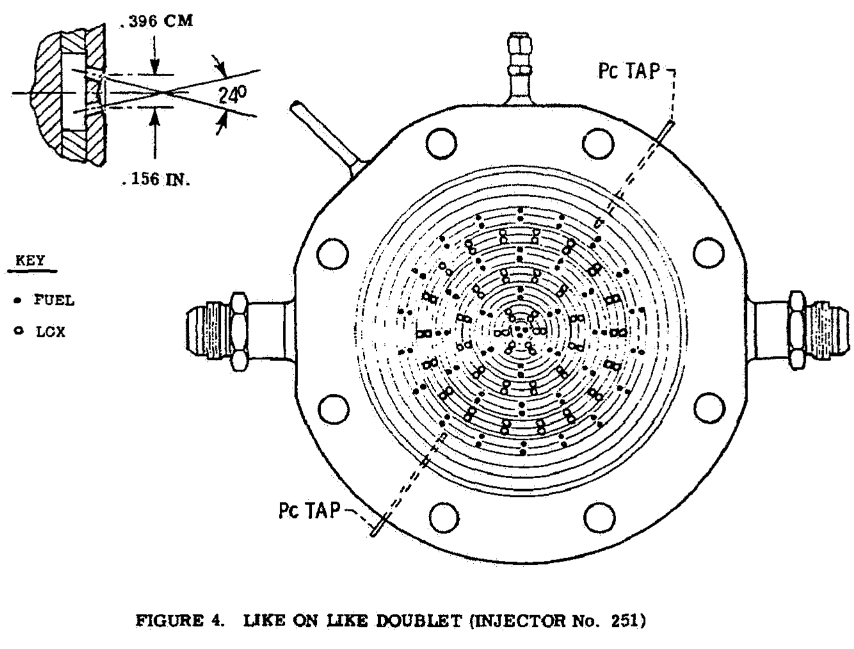

FIGURE 4. LIKE ON LIKE DOUBLET (INJECTOR No. 251)

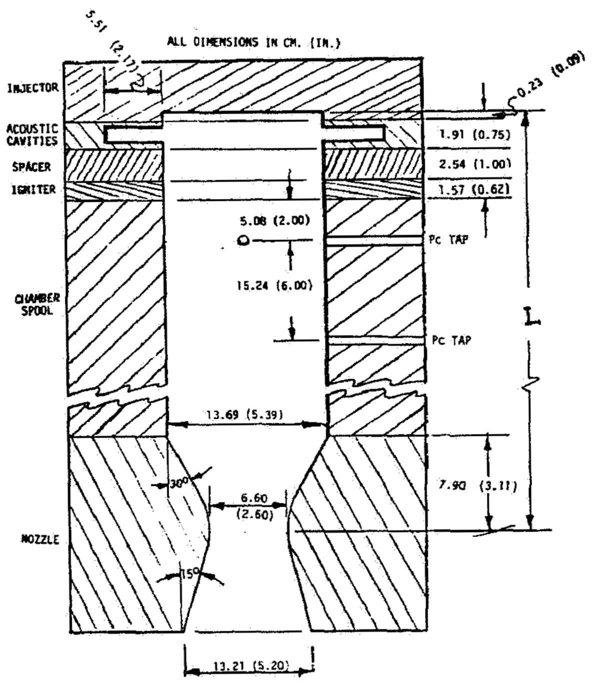

FIGURE 5. COMBUSTION CHAMBER

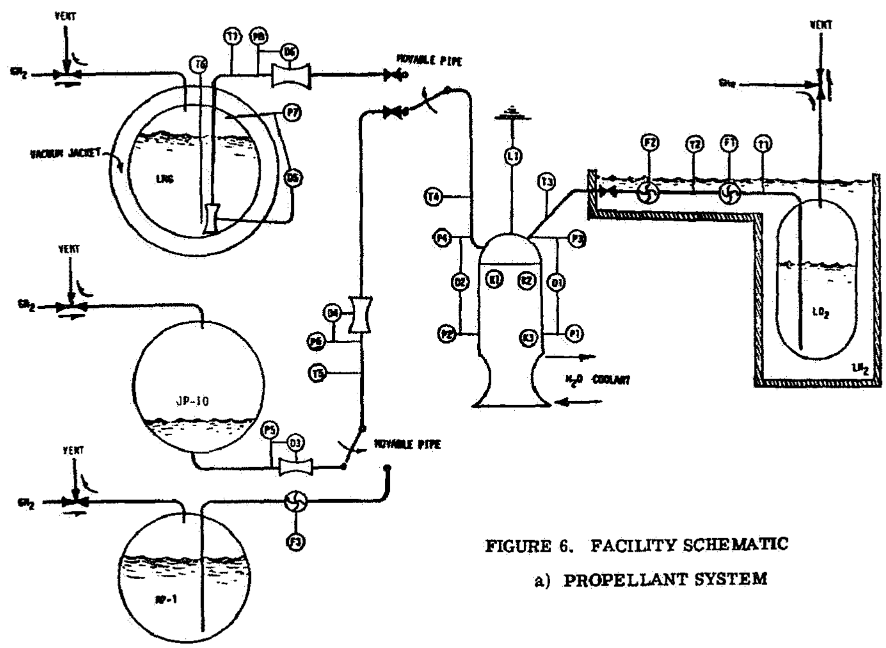

FIGURE 6. FACILITY SCHEMATIC

a) PROPELLANT SYSTEM

FIGURE 6. FACILITY SCHEMATIC (CONT.)

b) INSTRUMENTATION

NO.	NAME	TYPE
L1	Thrust	Strain Gage Bridge Load Cell
F1	Oxidizer Flow	Turbine Type Flow Meter
F2	Oxidizer Flow	Turbine Type Flow Meter
F3	Fuel Flow	Turbine Type Flow Meter
P1	Combustion Chamber Pressure	Strain Gage Bridge Pressure Transducer
P2	Combustion Chamber Pressure	Strain Gage Bridge Pressure Transducer
P3	Oxidizer Injection Pressure	Strain Gage Bridge Pressure Transducer
P4	Fuel Injection Pressure	Strain Gage Bridge Pressure Transducer
P5	Fuel Venturi Static Pressure	Strain Gage Bridge Pressure Transducer
P6	Fuel Venturi Static Pressure	Strain Gage Bridge Pressure Transducer
P7	Fuel Venturi Static Pressure	Strain Gage Bridge Pressure Transducer
P8	Fuel Venturi Static Pressure	Strain Gage Bridge Pressure Transducer
D1	Oxidizer Injection Delta Pressure	Strain Gage Bridge Pressure Transducer
D2	Fuel Injection Delta Pressure	Strain Gage Bridge Pressure Transducer
D3	Fuel Venturi Delta Pressure	Strain Gage Bridge Pressure Transducer
D4	Fuel Venturi Delta Pressure	Strain Gage Bridge Pressure Transducer
D5	Fuel Venturi Delta Pressure	Strain Gage Bridge Pressure Transducer
D6	Fuel Venturi Delta Pressure	Strain Gage Bridge Pressure Transducer
T1	Oxidizer Flow Meter Temperature	Platinum Resistance Bridge Transducer
T2	Oxidizer Flow Meter Temperature	Platinum Resistance Bridge Transducer
T3	Oxidizer Injection Temperature	Platinum Resistance Bridge Transducer
T4	Fuel Injection Temperature	Platinum Resistance Bridge Transducer Thermocouple
T5	Fuel Venturi Temperature	Thermocouple
T6	Fuel Tank Temperature	Platinum Resistance Bridge Transducer
T7	Fuel Venturi Temperature	Platinum Resistance Bridge Transducer
K1	Chamber Pressure Oscillation	Flush Mounted High Frequency Peizo-Electric Pressure Transducer
K2	Chamber Pressure Oscillation	" " " "
K3	Chamber Pressure Oscillation	" " " "

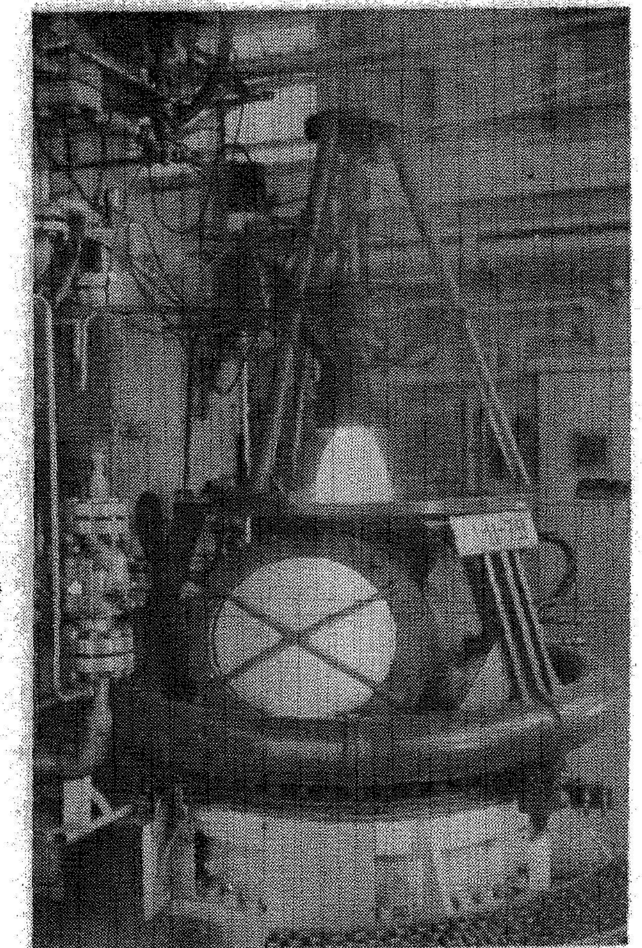

Figure 7. - Thrust stand.

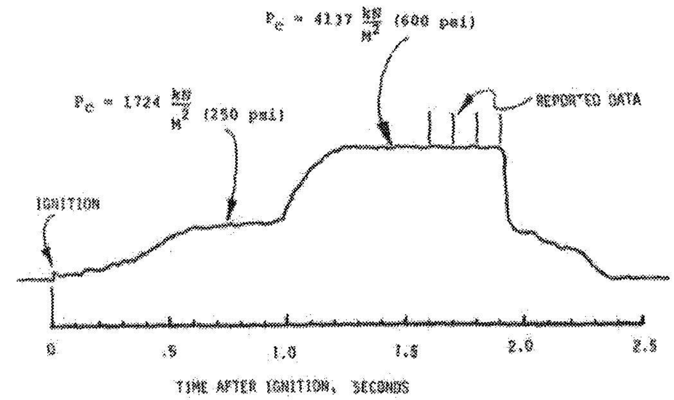

FIGURE 8. THRUST TRACE OF TYPICAL FIRING

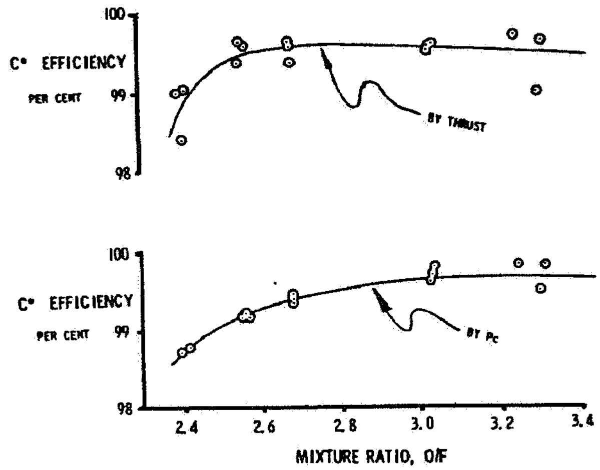

FIGURE 9. TYPICAL FIRING DATA

INJECTOR: 252- -2
FUEL: JP-10
COMBUSTOR LENGTH = 36.4 CM (14.32 IN.)

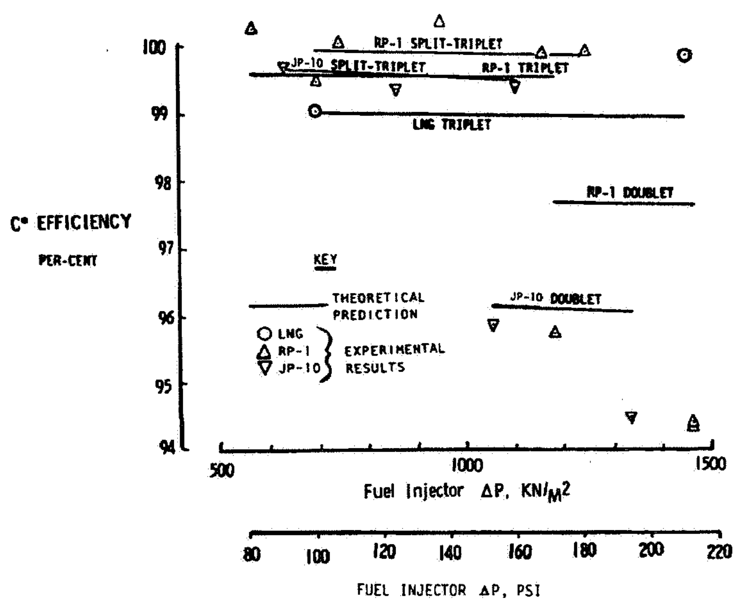

FIGURE 10. INJECTOR PRESSURE DROP EFFECT

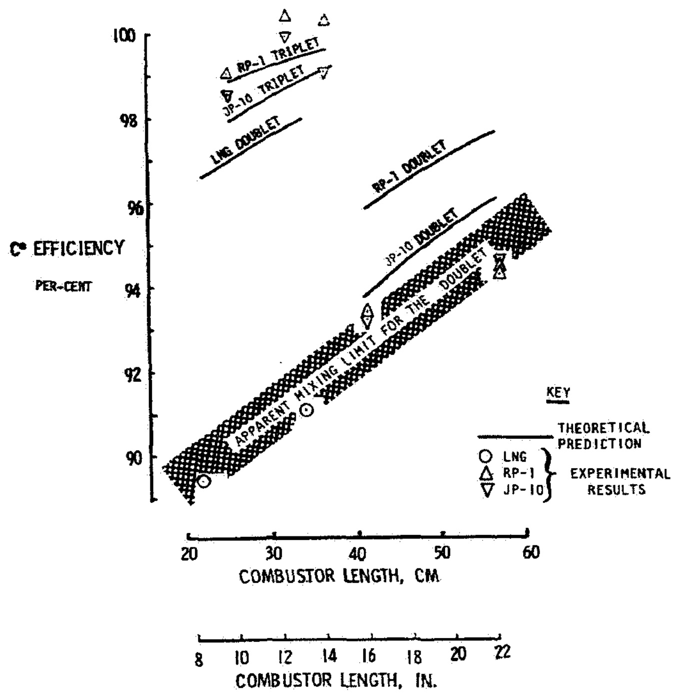

FIGURE 11. COMBUSTOR LENGTH EFFECT

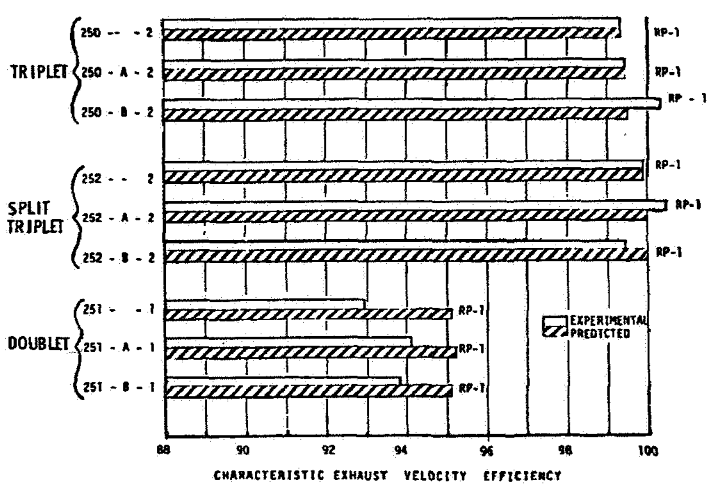

FIGURE 12. INJECTOR PERFORMANCE

L = 35.6 CM. INJECTOR TO THROAT

L = 14"

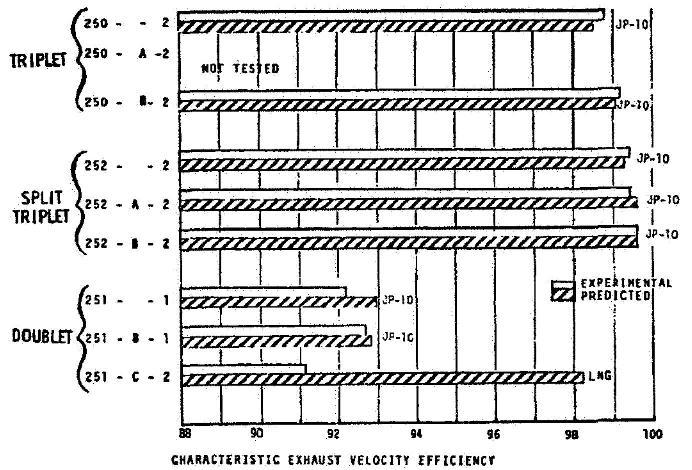

FIGURE 13. INJECTOR PERFORMANCE

L = 35.6 CM. INJECTOR TO THROAT

L = 14"

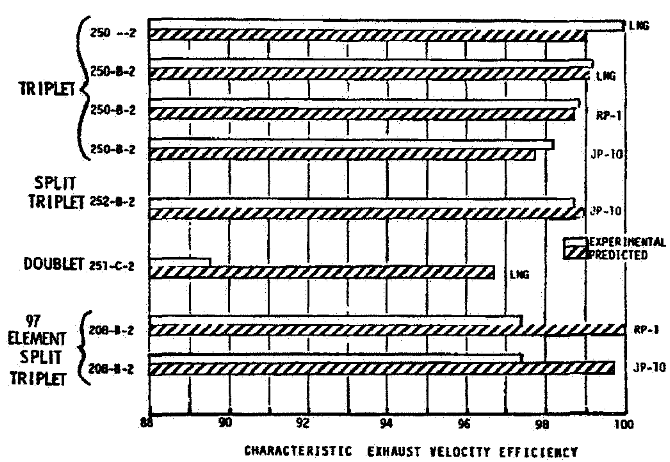

FIGURE 14. INJECTOR PERFORMANCE

L = 22.9 CM. INJECTOR TO THROAT

L = 9"