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EXPERIMENTAL EVALUATION OF THE PERFORMANCE OF A HIGH ENERGY FUEL WITH CHLORINE TRIFLUORIDE

PATRICK H. MCNAMARA, 1ST LT, USAF

TECHNICAL REPORT NO. AFRPL-TR-65-168

SEPTEMBER 1965

AIR FORCE ROCKET PROPULSION LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
EDWARDS, CALIFORNIA

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Project 3148 Task No. 314803

AIR FORCE ROCKET PROPULSION LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
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EDWARDS, CALIFORNIA

FOREWORD

The work described in this report was performed by personnel of the Exploratory Evaluation Branch, Propellant Division, Air Force Rocket Propulsion Laboratory, as part of Project 3148, Task 314803. First Lieutenant Patrick H. McNamara was the Project Engineer. The evaluation was conducted during the period November 1964 to March 1965.

This report has been reviewed and approved.

DM Ross
for ELWOOD M. DOUTHETT
Colonel, USAF
Director, Air Force Rocket Propulsion Laboratory

ABSTRACT

(C) A fuel, consisting of 19 to 21 weight percent of sodium borohydride dissolved in hydrazine, was fired with chlorine trifluoride in an uncooled engine with a nominal thrust of 150 lb_f and a nominal chamber pressure of 300 psia. The normal ambient pressure was 13.2 psia. Three injectors, a like-on-like, a splash plate and a triplet, were used. Hydrazine and chlorine trifluoride were fired in the same engine configurations to provide baseline data. There were no significant changes in the sodium borohydride-hydrazine fuel chemical composition during a 2-year storage period. The ignition and combustion of the 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 combination were hypergolic, smooth, reliable and stable. The peak delivered uncorrected specific impulse of the 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 combination ranged from 217 to 239 lb_f-sec/lb_m. This range is from 84% to 93% of the peak theoretical specific impulse as determined by the Air Force Rocket Propulsion Laboratory. The peak specific impulse was the least in the like-on-like injector and the most in the triplet injector. The peak delivered specific impulse of the N_2H_4/ClF_3 was about 5 lb_f-sec/lb_m greater than the peak delivered specific impulse of 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3. Air Force Rocket Propulsion Laboratory theoretical data were verified. General Electric theoretical data, which predicted a 17 lb_f-sec/lb_m advantage for the 19 wt.% $NaBH_4$-N_2H_4/ClF_3 combination over the N_2H_4/ClF_3 combination, were not verified. Multiple measurements of thrust, chamber pressure, flowrates and temperatures and statistical evaluation were used to determine the reliability of the test apparatus.

TABLE OF CONTENTS

Section Page

LIST OF FIGURES

List of Figures (Cont'd)

List of Figures (Cont'd)

LIST OF TABLES

SECTION I

INTRODUCTION

(C) The performance of a new fuel, 19 to 21 weight percent of sodium borohydride dissolved in anhydrous hydrazine, with chlorine trifluoride as oxidizer, was experimentally evaluated.

(C) This evaluation was undertaken to verify the theoretical performance of the 19 to 21 wt. % $NaBH_4$-N_2H_4/ClF_3 combination. The 19.11 wt. % combination, according to the manufacturer, would theoretically deliver 309.5 seconds peak shifting specific impulse at a chamber pressure of 1000 psia with expansion to 14.7 psia. This level of performance is 16.5 $lbs_f/lb_m/sec$ higher than the peak theoretical performance of N_2H_4/ClF_3 under the same conditions. The evaluation also, of necessity, involved the gathering of data on the ignition and combustion of the propellants, the compatibility of the propellants with materials of construction and the effect of the reaction products on the test engine hardware.

(C) The evaluation was made by firing the 19 to 21 wt. % $NaBH_4$-N_2H_4/ClF_3 combination in a small test rocket engine. The engine was operated at a thrust level of 150 lb_f, at a chamber pressure of 300 psia and at an ambient pressure of 13.2 psia. Three injectors employing different injection patterns were used. N_2H_4/ClF_3 was fired in the same engine under the same conditions to provide a basis for comparison of the performance of the $NaBH_4$-N_2H_4/ClF_3 combination. The firings were conducted by the Air Force Rocket Propulsion Laboratory from September 1964 through January 1965.

(U) The fuel was developed and manufactured by the Flight Propulsion Laboratory Department of the General Electric Company, Cincinnati, Ohio.

This work was performed under contracts AF 04(616)-6632 and AF 04(611)-7556, during the period of July 1959 through July 1962. The applicable reports of this work are identified in References 1, 2 and 3.

(U) The theoretical background, equipment, methods and results of the evaluation are presented in detail in the following pages.

SECTION II

DISCUSSION

A. THEORETICAL BACKGROUND.

(C) The sodium borohydride-hydrazine fuel is one of a group of fuels developed by General Electric. The development of these fuels was based on the premise "... that it is possible to combine a metal borohydride or other salt with a hydrazine fuel, and as a result, obtain performance from the resulting solution which is higher than either of the two fuels could deliver alone" (2).

(C) "Because of the relatively high combining weight of sodium as compared with that of lithium, beryllium, aluminum, and magnesium, and consequently lower heat of combustion per unit weight, sodium borohydride was considered at the start of this (General Electric) work as an alternate rather than as an equal candidate for fuel performance enhancement" (1).

(C) "However, during attempts to prepare ultra pure $Mg\ (BH_4)_2$ solutions, it was necessary to recrystallize $NaBH_4$ from hydrazine, and the remarkable stability of the resulting solution at ambient and elevated temperatures was immediately noticed. The preparation and examination of these solutions followed as a matter of course after theoretical performance calculations showed a performance of 310 sec with ClF_3, and a value of 335 sec with N_2F_4" (1).

(C) The theoretical performance of the 19.11 wt.% $NaBH_4$-N_2H_4/ClF_3 system, based on General Electric data, is plotted in Figure 1 and identified as Curve 1. The theoretical performance of the N_2H_4/ClF_3 system, based on Air Force Rocket Propulsion Laboratory data, is plotted in Figure 1 and identified as Curve 4. Based on this data, a peak-to-peak specific impulse increase of 16.5 seconds is predicted if N_2H_4 is replaced by 19.11 wt.% $NaBH_4$-N_2H_4.

(C) However, the theoretical performance of the 19.11 wt. % $NaBH_4$-N_2H_4/ClF_3 system, based on Air Force Rocket Propulsion Laboratory data, which is plotted in Figure 1 and identified as Curve 3, does not agree with the General Electric theoretical performance. An attempt to reconcile this difference was made by comparing the input data and the computer programs of General Electric and the Air Force Rocket Propulsion Laboratory. The input data are summarized in Table 1.

(U) The differences in the input data are not believed to be sufficient to cause the observed differences in the theoretical performances. Hence, a copy of the General Electric theoretical performance program (4) was obtained. This program was examined and compared with the Air Force Rocket Propulsion Laboratory program by 1st Lt J. M. Hobbs and Mr. C. Selph, who have both had extensive experience with computer programs and the equations used to calculate theoretical performance. They could not find any significant differences between the programs. Therefore, any differences in the propellant input data, shown in Table 1, and the computer programs evidently are not sufficient to cause the observed differences between Curves 1 and 3 in Figure 1. This conclusion is strengthened by the fact that the performance shown by Curve 4 for N_2H_4/ClF_3 which is based on the AFRPL data and program, has a peak specific impulse which is only one second greater than the N_2H_4/ClF_3 performance indicated by the General Electric data.

(C) Since the weight percentage of $NaBH_4$ in the fuel which was to be fired varied from 19.6 to 21.9, depending on the batch, the theoretical performance of 21 wt. % $NaBH_4$-N_2H_4/ClF_3 was determined. This theoretical was determined for an ambient pressure of 13.2 psia, which was the expected experimental exhaust pressure. The data for this condition are plotted in Figure 1 and identified as Curve 2. The input data are shown in Table 1. This change in conditions raised the performance level only 1.5 lb_f-sec/lb_m.

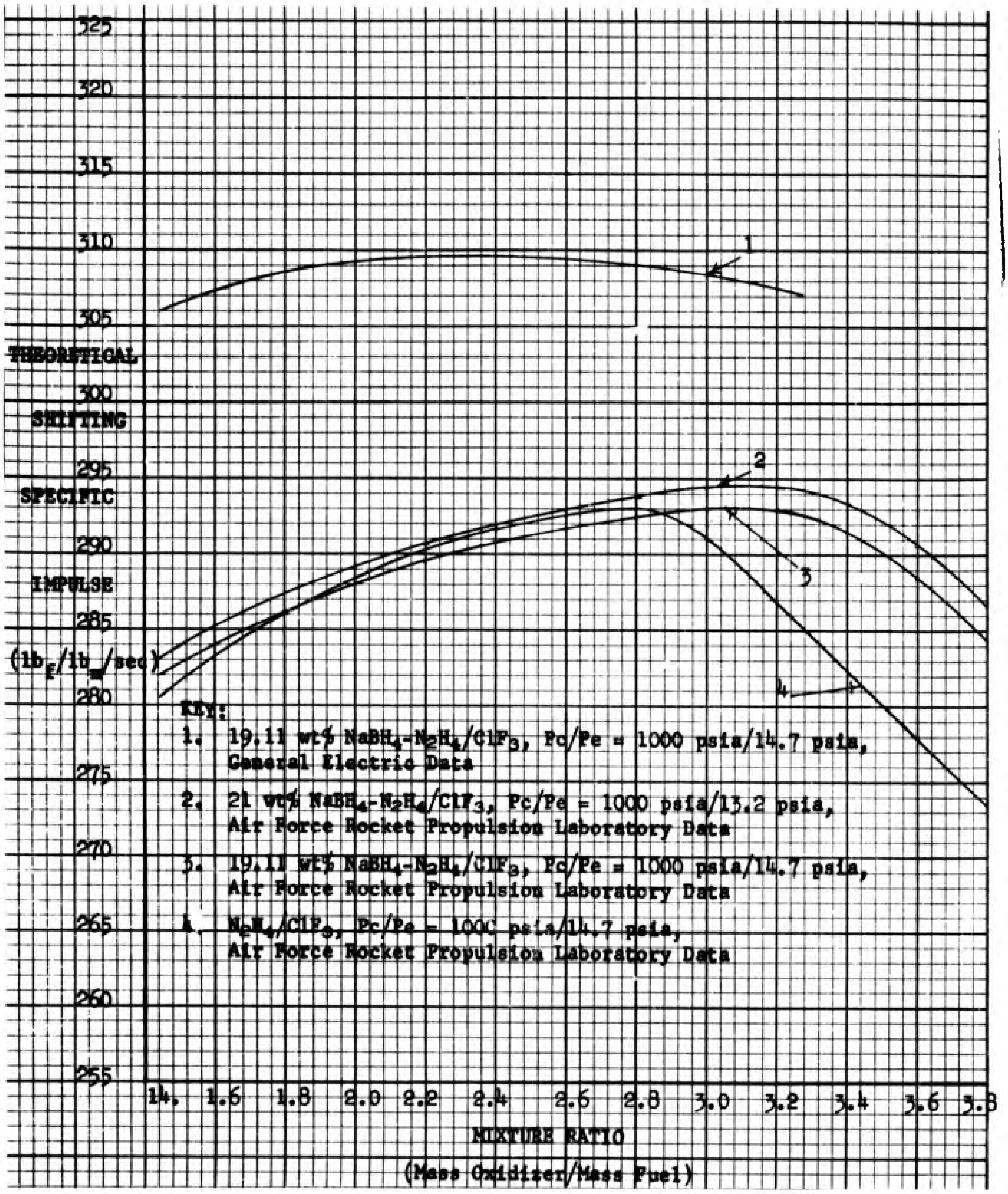
(C) TABLE 1

PROPELLANT INPUT DATA

	Heat of Formation at 298.15°K Kcal/mole			
Propellant	Curve 1 (GE)	Curve 2 (AFRPL)	Curve 3 (AFRPL)	Curve 4 (AFRPL)
$NaBH_4$ (s)	-43.43	-46.15	-43.43	------
$NaBH_4$ $4.44N_2H_4$ (ℓ) (21 wt. %)	------	3.35*	------	------
$NaBH_4$ $5.00N_2H_4$ (ℓ) (19.11 wt. %)	unknown	------	12.61**	------
N_2H_4 (1)	12.05	12.05	12.05	12.05
ClF_3 (1)	-42.74	-44.00	-42.74	-44.40

* Includes -4.00 Kcal/mole due to solution of $NaBH_4$ in N_2H_4 per Reference 3.

** Includes -4.20 Kcal/mole due to solution of $NaBH_4$ in N_2H_4 as estimated from Reference 3.



(C) Figure 1. Theoretical Specific Impulse of 19 to 21 wt. % $NaBH_4$-N_2H_4/ClF_3 and N_2H_4/ClF_3.

(U) The cause of the differences between the theoretical performance calculated by General Electric and AFRPL has not been determined.

B. APPARATUS.

(U) A flow diagram of the system used in this evaluation is shown in Figure 2. The equipment represented in this diagram is discussed in detail in the following paragraphs.

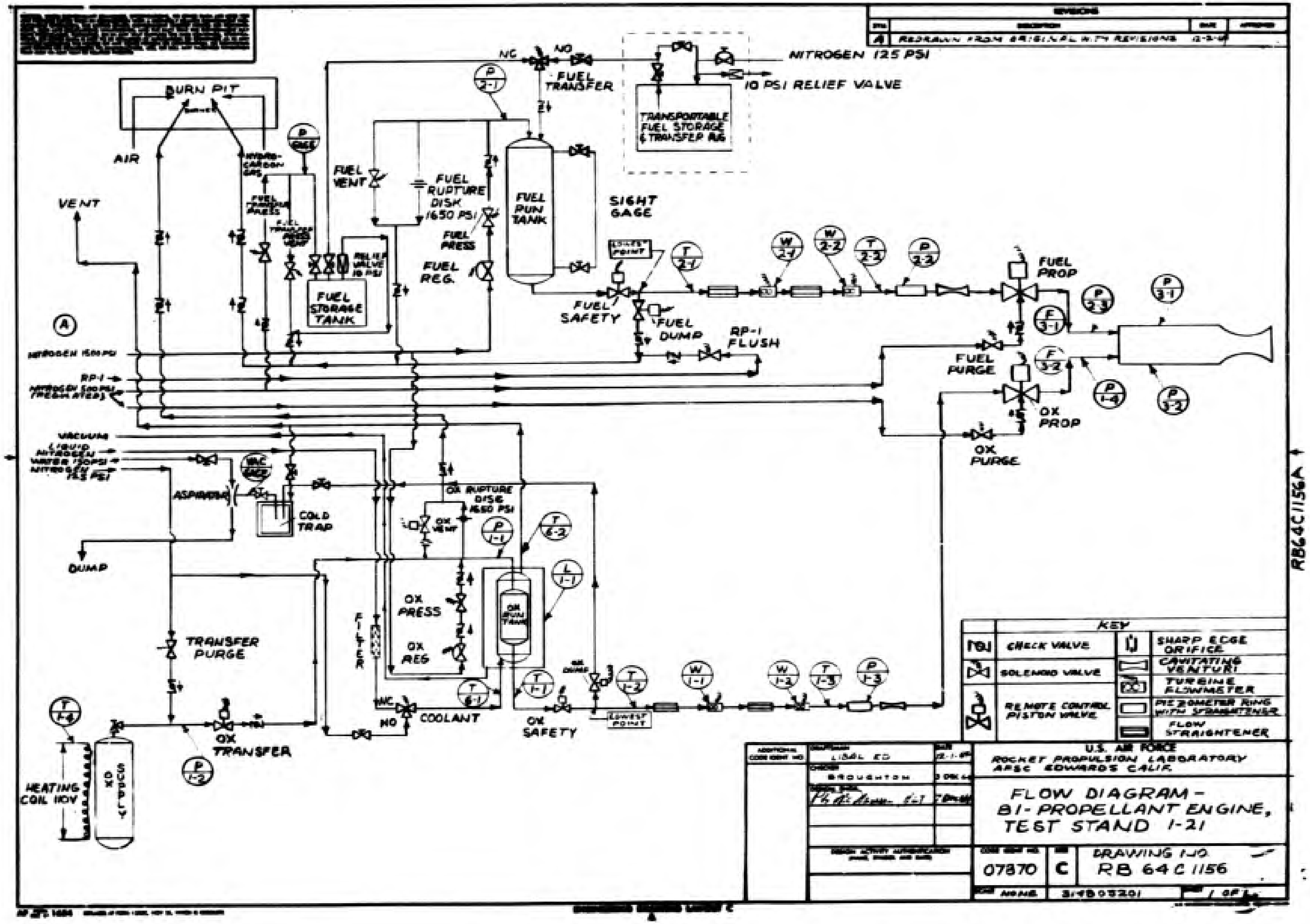
1. Engine Hardware.

(U) The engine, which is uncooled, is shown in Figure 3. The characteristic length of the engine was 287 inches.

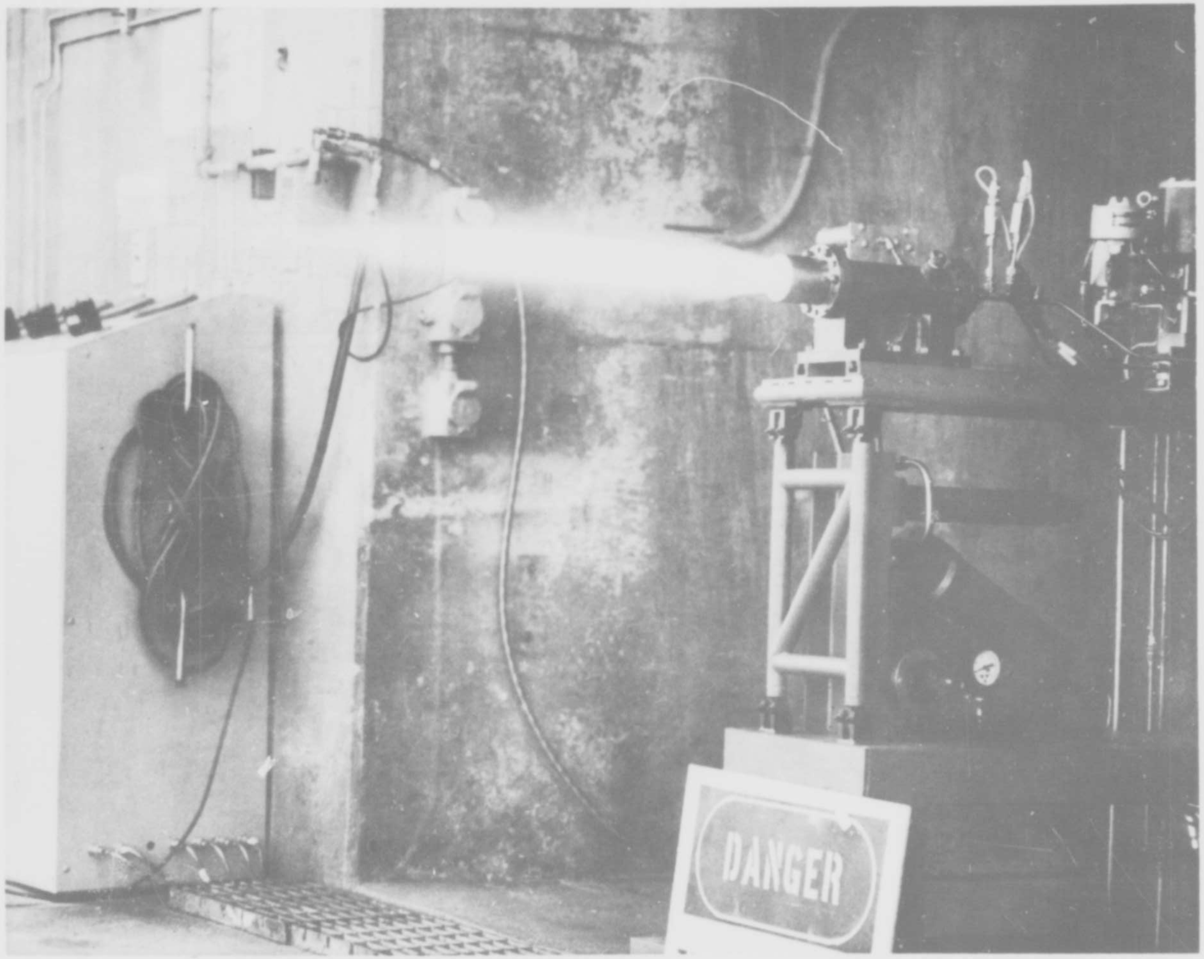
(U) Three injectors, a like-on-like doublet, a splash plate, and a triplet were used. Photos of the injector faces, which were taken after the firings were completed, and drawings showing the construction and idealized impingement patterns of the injectors, are shown in Figures 4, 5, and 6. The injectors were made of 304 stainless steel except the oxidizer splash plate which was made of copper. The design injection velocity of each stream was 100 ft/sec at an oxidizer/fuel weight ratio of three. When the splash plate injector was fired, a spacer was used between the chamber and the injector. This spacer compensated for the protrusion of the splash plate into the chamber.

(U) The chambers were made of mild steel and coated on the inside with consecutive layers of 0.005-inch molybdenum, 0.005-inch tungsten and 0.015-inch zirconium. The coatings were applied by flame spray techniques. The chambers were 10 inches long and had a 2.5-inch internal diameter.

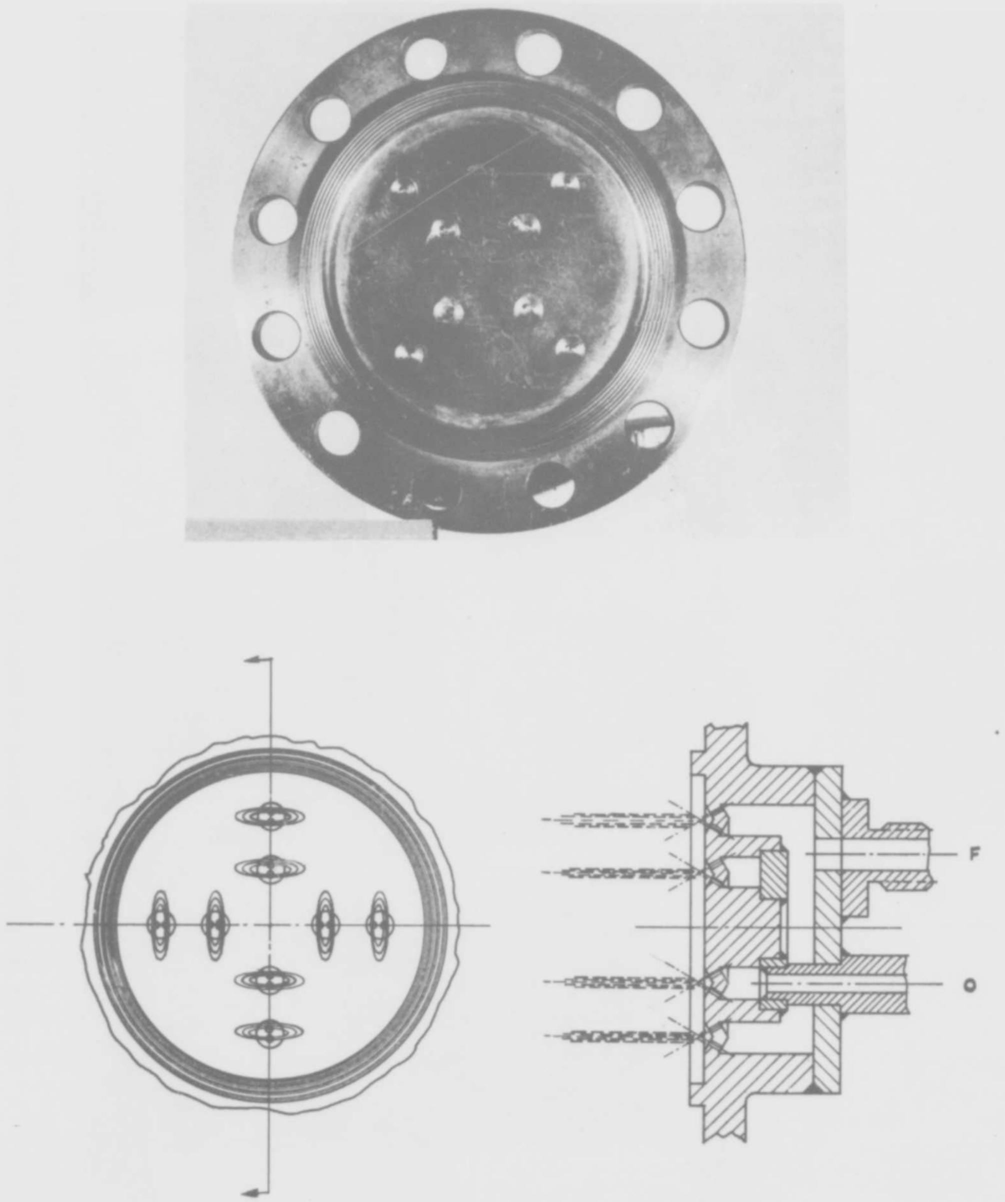
(U) The nozzles were made of "HLM-85" graphite in the form of an insert which was held in a stainless-steel shell. The insert can be seen in place in Figure 7. The insert was tapered, as shown in Figure 8, to permit easy installation and removal of the insert from the shell and to



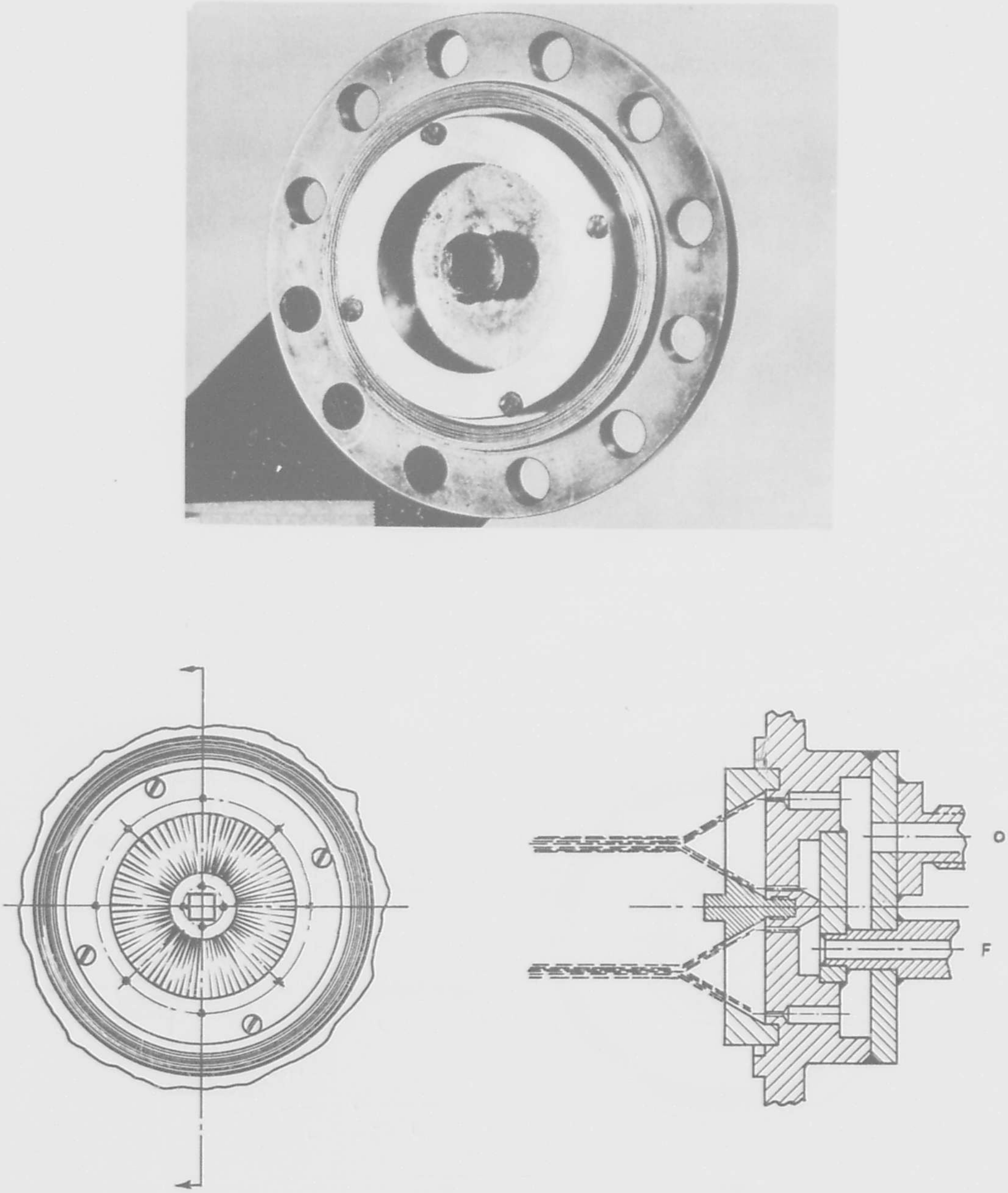
(U) Figure 2. Test System Flow Diagram



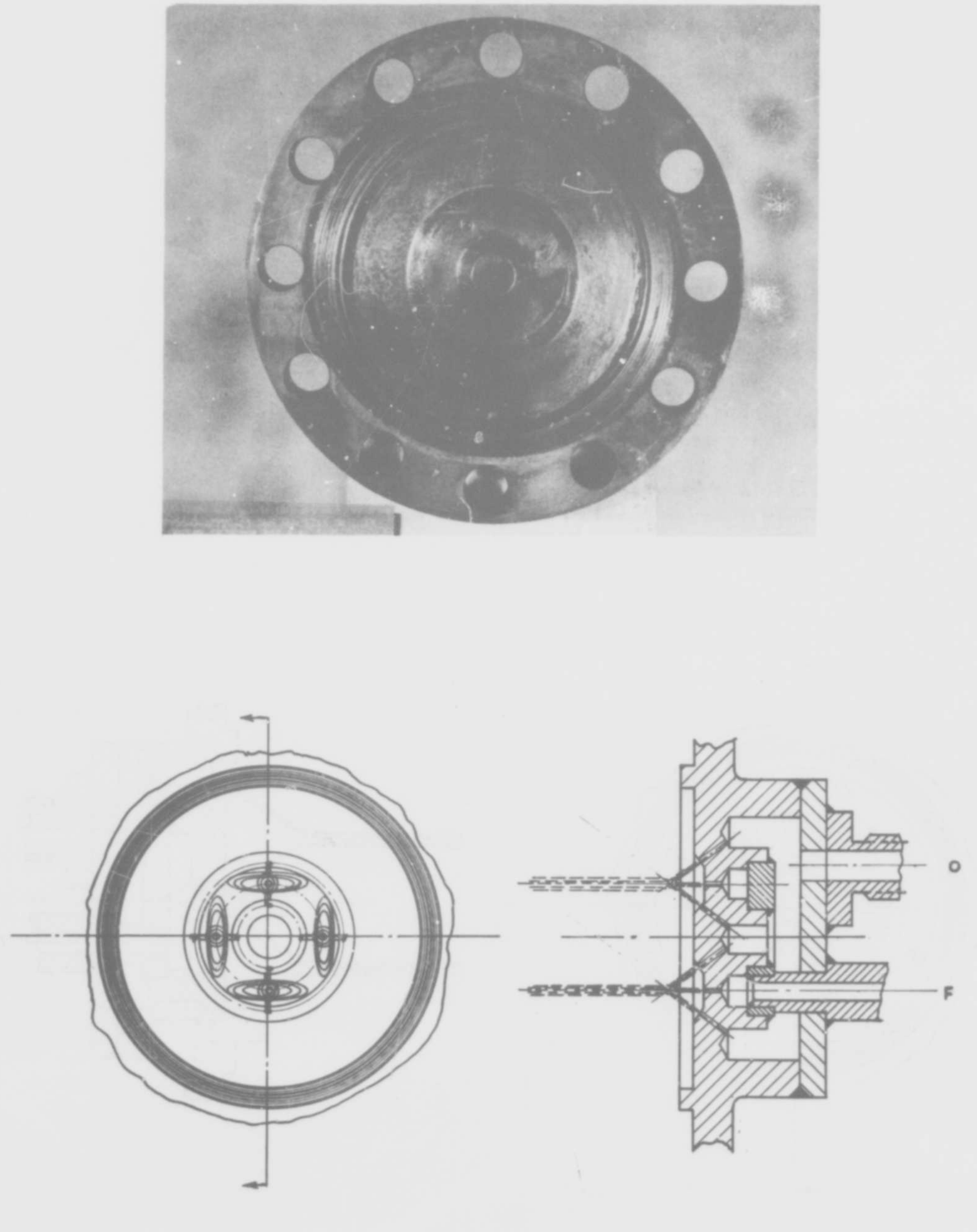
(U) Figure 3. Firing of High Energy Fuel/Chlorine Trifluoride



(U) Figure 4. Like-on-Like Injector



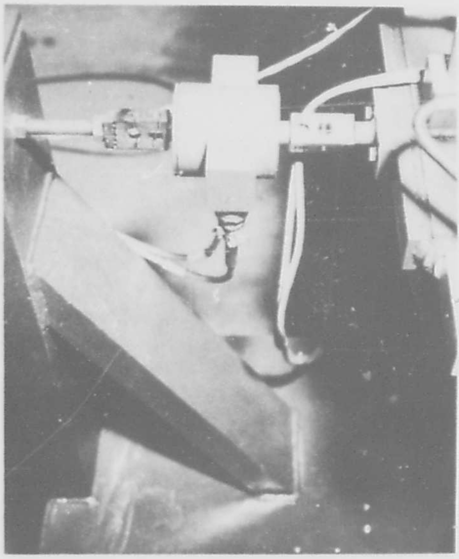
(U) Figure 5. Splash Plate Injector



(U) Figure 6. Triplet Injector

(U) Figure 7. Side View of Thrust Stand and Engine

(U) Figure 8. Graphite Nozzle Insert



(U) Figure 9. Working Load Cell and Mounting provide a large sealing surface. The nominal throat diameter was 0.7 inch. The half angle of the convergent section was 24°. The half angle of the divergent section was 14°. The expansion area ratio was 3.7.

2. Instrumentation.

(U) The chamber pressure and thrust were recorded on an oscillograph and on strip charts. Flow rates and miscellaneous parameters were recorded on an oscillograph. Other parameters, which pertained to the control of the engine, were recorded on strip charts. The rated response of the oscillograph was 500 cps and of the strip charts was 1 cps.

(U) Strain-gage-type pressure transducers were used to measure pressures. The transducers were a maximum of 6 inches from the point at which the pressure was to be measured. One type of transducer had a natural frequency response of 6,100 to 8,600 cps, the other type of transducer used had a natural frequency response of 20,000 to 28,000 cps. Pressure transducers can be seen in Figures 3 and 7 near the injector and chamber. Locations of pressure transducers in the system are shown in Figure 2 and circled P's.

(U) The thrust was measured by a strain-gage-type load cell in conjunction with the thrust stand shown in Figures 3 and 7. The load cell had dual bridges and was hard-mounted between flexures at the rear of the thrust table as shown in Figure 9. Each flexure had a spring rate less than 3.5 in-lb/degree. The thrust stand was the inverted pendulum parallelogram type. Each end of the supporting members contained a cross-spring flexural pivot which allowed movement of the stand in line with the load cell. Each of these flexures had a spring rate of 3.2 in-lb/degree. The propellant lines were hard- mounted, as shown at the rear of the stand in Figure 7, so as to make their restoring force repeatable and therefore compensable. A load cell, whose calibration is traceable to the National Bureau of Standards, was flexured similar to the cell shown in Figure 9, and inserted between the ram and support shown under the table in Figure 7. The natural frequency response of the load cells was 1000 cps ±10%. The overall thrust measuring system was experimentally determined to introduce an error of less than 0.7% of full scale at a three sigma confidence level. This work is reported in Reference 5.

(U) Flowrates were measured by turbine meters and cavitating venturis. Each propellant line contained two turbine meters and a cavitating venturi. The turbine meters had ball bearings and were preceded by flow straighteners. The venturis were preceded by a piezometer ring which had a smooth flow section with an L/D of 13. The meters and the venturis were equally spaced in a straight section of tubing 5 feet long. The relative locations of the meters in the system are shown in Figure 2 by circled W's.

(U) Enclosed blunt-tip iron-constantan thermocouples measured the temperatures of the propellants. The location of the thermocouples in the system are shown in Figure 2 by circled T's.

3. Auxiliary Systems.

(U) The propellant transfer and pressurization systems are shown in Figure 2. Most valves were remote-controlled to provide safety for operating personnel and to allow proper operation of the engine. Two electro-pneumatic valves are shown mounted o... the thrust table in Figure 7. A solenoid valve is visible in the background. The valve bodies were 304 and 347 stainless steel. The valve seats exposed to fuel were either virgin "Teflon" or aluminum. The valve seats exposed to the liquid oxidizer were either copper or aluminum. Virgin "Teflon" O-rings and seats were used as static seals and in the valves in the inert gas lines. The lines were made of 304 or 347 stainless steel.

C. EXPERIMENTAL TECHNIQUES.

1. Operation.

(U) After assembly of the system, the lines and valves were cleaned and passivated in accordance with the procedures given in References 6 and 7.

However, the oxidizer system was not treated with nitric acid because of the rapid attack of the copper valve seats which would have occurred.

(U) Pressure transducers were calibrated by applying nitrogen gas to the transducers at known pressures measured by a precision Bourdon-tube gage. The transducers were electrically checked before and after each firing. The chamber pressure and venturi pressure transducers were recalibrated with the gas system every one or two weeks. Other transducers, which were not as critical, were calibrated every month.

(U) The turbine flowmeters were calibrated using water in the AFRPL calibration facility. This facility employs the weight capture-time integration method. The meters were changed every month or sooner if data indicated erroneous readings. The cavitating venturis were calibrated by the manufacturer using water and the weight capture-time integration method. The same venturis were used throughout the program.

(U) The thrust stand was calibrated before each day's firings. The propellant lines were not pressurized during the calibration. Thrust was applied to the stand through the calibration cell by the hydraulic ram. The thrust applied was determined by nulling, in a direct read-out instrument made specifically for the purpose, the output of the calibration cell.

(U) Before opening lines containing propellant, the lines were purged with nitrogen at 25 psi. Most of the propellant could be removed from the system and forced out the dump lines to the burn pit. In the oxidizer system, a vacuum was pulled for one or two hours, after purging the system, to remove residual quantities of oxidizer. While opening the lines, the mechanics were clothed in either a hood, chemically resistant gloves and their normal clothing or in an aluminized "Teflon" suit, chemically resistant gloves and boots with an external air supply. The choice of clothing was dictated by the hazard anticipated in opening the system at a particular point. In general, the handling procedures were in accordance with the recommendations made in References 3, 6, and 7.

(U) The engine was controlled from inside a concrete block house and viewed on a closed-circuit television. Color motion pictures, at a speed of 1000 frames per second, were taken of selected firings. The firings were normally five seconds in duration. This duration was sufficient to provide 2 or 3 seconds of steady-state operation.

(U) The engine was operated over a range of mixture ratios at nearly constant chamber pressure. The mixture ratio and total flow rate were controlled by setting the tank pressures and thereby setting the inlet pressures to the venturis. Use of the cavitating venturis made operation of the engine relatively simple because pressure variations downstream of the venturis do not affect the flow rate when the downstream is less than 85% of the upstream venturi pressure. In order to check the data, three or four repeat firings were made at mixture ratios corresponding with the experimental peak specific impulse. This procedure would help identify time-dependent or equipment-dependent determinate errors.

(U) The mean throat diameter was determined before and after each run by measuring the vertical and horizontal throat diameters with a telescoping gage and a micrometer.

2. Data Analysis.

(U) Normally, three time slices were taken in the steady state portion of each test. Each time slice covered a duration of 0.2 seconds and was approximately 0.2 seconds from any other time slice. Thus, the time slices covered, at a minimum, one second of firing. The mean values of the traces during the time slices were determined manually with the aid of an optical reader which at the push of a button punched out on a data card the digital value of the trace being read. The raw data were then fed into a computer and converted to the desired output. Key data, such as specific impulse, were also calculated manually and separately from the machine-oriented system to check the machine reduction process.

(U) Specific impulse, characteristic exhaust velocity, thrust coefficient and mixture ratio were calculated for each time slice from the measured parameters using the following equations:

$$Isp = F/(\dot{W}_o + \dot{W}_f)$$

$$C = P_c A_t g/_c(\dot{W}_o + \dot{W}_f)$$

$$C_F = F/P_c A_t$$

$$O/F = \dot{W}_o/\dot{W}_f$$

Where A_t = area of throat, in^2

C_F = thrust coefficient, non-dimensional

C = characteristic exhaust velocity, ft/sec

F = thrust, lb_f

g_c = gravitational constant, 32.174 $lb_m ft/lb_f sec^2$

Isp = specific impulse, $lb_f sec/lb_m$

O/F = weight mixture ratio, non-dimensional

P_c = chamber pressure, psia

$\dot{W}_f$ = fuel weight flow rate lb_m/sec

$\dot{W}_o$ = oxidizer weight flow rate, lb_m/sec

(U) Thirty values of specific impulse and fifteen values of mixture ratio were computed for each run unless some data were known to be erroneous. These specific impulses and mixture ratios were computed as follows. Eight specific impulses and four mixture ratios per time slice were computed from the turbine meter data and the two thrust measurements. Two specific impulses and one mixture ratio per time slice were computed from the venturi data and the two thrust measurements. In the absence of determinate errors, any one of these calculations of specific impulse or mixture ratio cannot be judged a priori to be a better estimate of the true value than any other. The best, or least biased, estimate of the true value would be a mean value. Hence, two mean specific impulses and mixture ratios for each run were computed. One set of means was computed using the data gathered from the turbine meters and the other set using data gathered from the venturis. This method gives an estimate of the precision of the measurements. The method also gives a comparison of two ways of measuring flow rates; thus a rough idea of accuracy can be obtained. The IBM FORTRAN IV source program used to perform these calculations is contained in Appendix II.

(U) The data were also reduced in the more conventional method, without statistical analysis, and included in this report for comparison with the statistically analyzed data and for the benefit of persons who prefer the conventional method.

(U) The data were not corrected for losses, such as momentum, heat, and expansion losses, or variations from the reference chamber pressure. These corrections would be desirable, particularly if a method which was accepted throughout the industry existed. However, no such method exists, and there was not sufficient time to apply one of the methods to the data from the present evaluation. The correction methods of Mr. Robert C. Armstrong, III were used in a previous evaluation and the results reported in Reference 8. The use of Mr. Armstrong's methods, however, is not to be construed as an indorsement by the Air Force of those methods. Much more data must be analyzed and other methods tried and examined before a given method can be recommended as the proper one to use.

SECTION III

RESULTS AND INTERPRETATIONS

A. PROPELLANT COMPOSITION AND STORABILITY.

(C) The compositions of the propellants used in this evaluation are shown in Table 2.

(C) TABLE II

PROPELLANT COMPOSITION

Propellant	Batch	Date Analyzed	Weight Percentage				
			$NaBH_4$	N_2H_4	H_2O	ClF_3	Other
$NaBH_4$-N_2H_4	1-3	July 1962*	21.0	80.1	---	---	---
		Jan 1964	20.0	79.0	---	---	---
		Oct 1964	19.7	79.2	0.5	---	---
	II-2	July 1962*	20.8	79.3	---	---	---
		Oct 1964	20.3	79.3	0.7	---	---
	1-5	July 1962*	20.4	80.3	---	---	---
		Dec 1964	19.2	79.8	0.7	---	---
		Jan 1965	19.5	79.8	0.3	---	---
N_2H_4	1880-63	Jan 1965	---	99.3	0.1	---	0.6
ClF_3	---	Mar 1965	---	---	---	99.3	---

* General Electric analyses; others are AFRPL analyses.

(C) The totals of the percentage compositions of the $NaBH_4$-N_2H_4 analyses range from 99.0 to 101.1. Hence, the experimental absolute error in these analyses is at least ±1%. Therefore, variations of 1% between analyses of the same batch cannot be regarded as significant. Thus, the data indicate that the $NaBH_4$-N_2H_4 fuel did not undergo significant change in composition over a period of 2 years.

(C) No record was kept at the Air Force Rocket Propulsion Laboratory of the pressure in the $NaBH_4$-N_2H_4 storage tanks. These tanks had a 20% ullage and were equipped with a self-sealing poppet valve which had an opening pressure of 10 psig. Thus, the propellant would have been under a pressure of about 23 psia during storage. The fuel was stored in an earth-covered propellant bunker; the storage temperature was approximately 65°F with seasonal variations of ±10°F.

B. IGNITION AND COMBUSTION.

(C) Ignition of 19 to 21 wt.% $NaBH_4$-N_2H_4 with ClF_3 was hypergolic, smooth and reliable. The oxidizer lead was about 100 milliseconds. No ignition difficulties were encountered.

(C) The combustion of 19 to 21 wt.% $NaBH_4$-N_2H_4 with ClF_3 never went unstable. Larger oscillations of thrust and chamber pressure were observed during firings with the like-on-like injector than with the splash plate or triplet injectors. This difference is illustrated by the traces in Figure 10. This figure shows portions of runs made with each injector in the region of maximum delivered performance. Similar differences were observed in N_2H_4/ClF_3 firings as shown in Figure 11.

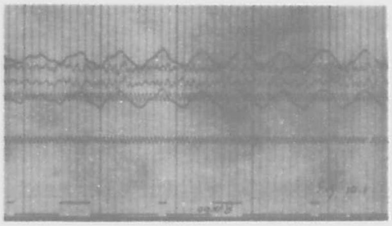
C. PERFORMANCE.

(U) The following four paragraphs describe the data included in this report and how the data should be used. The remaining paragraphs discuss in detail the performance in each injector.

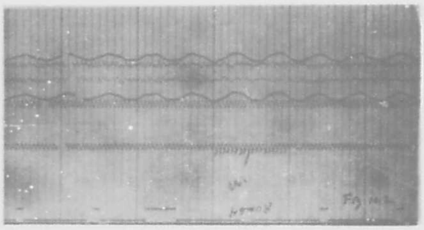
(C) Figures 12 through 17 show the specific impulse delivered by 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 and N_2H_4/ClF_3 in the like-on-like, splash plate and triplet injectors. These specific impulses are mean values which are computed as explained in the section on data analysis. The specific impulses based on both the turbine meter flowrates and the cavitating venturi flowrates are shown.

(U) Included in Appendix I are plots of individual values of specific impulse, characteristic exhaust velocity and thrust coefficient versus mixture ratio. These values were selected according to arbitary criteria established without knowledge of what the plots would look like. The values were computed from the first thrust, chamber pressure, oxidizer turbine meter flowrate and fuel turbine meter flowrate in the second time slice in each run. Sometimes this data was missing because of transducer malfunctions; thus in some cases, there are no points which correspond with the mean values which are computed from other data. These individual measurements represent the opposite extreme from the mean measurements which are plotted in Figures 12 through 17. The plots of these individual points have been included for the convenience of persons who may wish to place less than full confidence in the method of computing mean values.

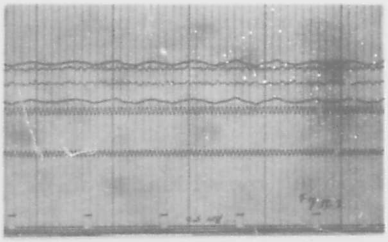
(U) Also included in Appendix I are plots of all the individual specific impulses versus mixture ratios on which are based the mean values plotted in Figures 12 through 17. These plots of all the individual points show the range of values which were calculated from the measured data. These plots show that the range of the specific impulse values is about 10 seconds when based on the turbine meter flowrates and about 5 seconds when based on the venturi flowrates. These plots are a visual indication of the precision of the measurement system. The average standard deviation of the specific impulse values based on the turbine meter flowrates is 2.0 lb_f-sec/lb_m. The standard deviations ranged from 0.74 to 6.74 lb_f-sec/lb_m.



10.1 Like-on-Like Injector O/F = 2.84



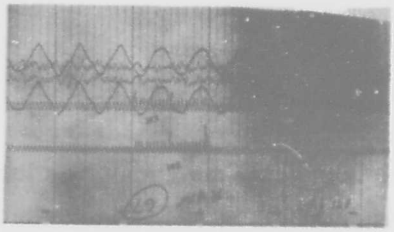
10.2 Splash Plate Injector O/F = 2.17



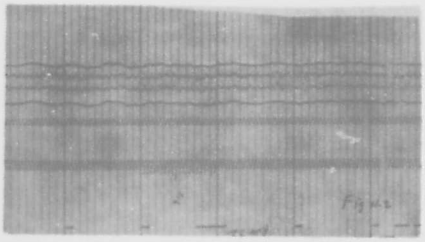
10.3 Triplet Injector O/F = 2.17

Note: Traces 1 and 4 are thrust traces; one inch deflection in vertical direction = 75 lb_f
Traces 2 and 3 are chamber pressure traces; one inch deflection in vertical direction = 125 psi/differential
One division in the horizontal direction equals 10 milliseconds

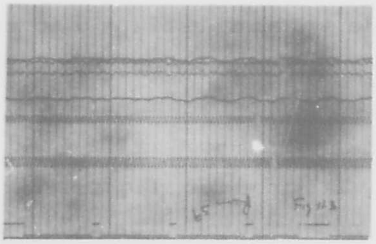
(C) Figure 10. Typical 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 Firing Traces



11.1 Like-on-Like Injector O/F = 2.48



11.2 Splash Plate Injector O/F = 2.20



11.3 Triplet Injector O/F = 2.40

Note: Traces 1 and 4 are thrust traces; one inch deflection in vertical direction = 75 lb_f differential
Traces 2 and 3 are chamber pressure traces; one inch deflection in vertical direction = 125 psi differential
One division in the horizontal direction equals 10 milliseconds

(U) Figure 11. Typical N_2H_4/ClF_3 Firing Traces

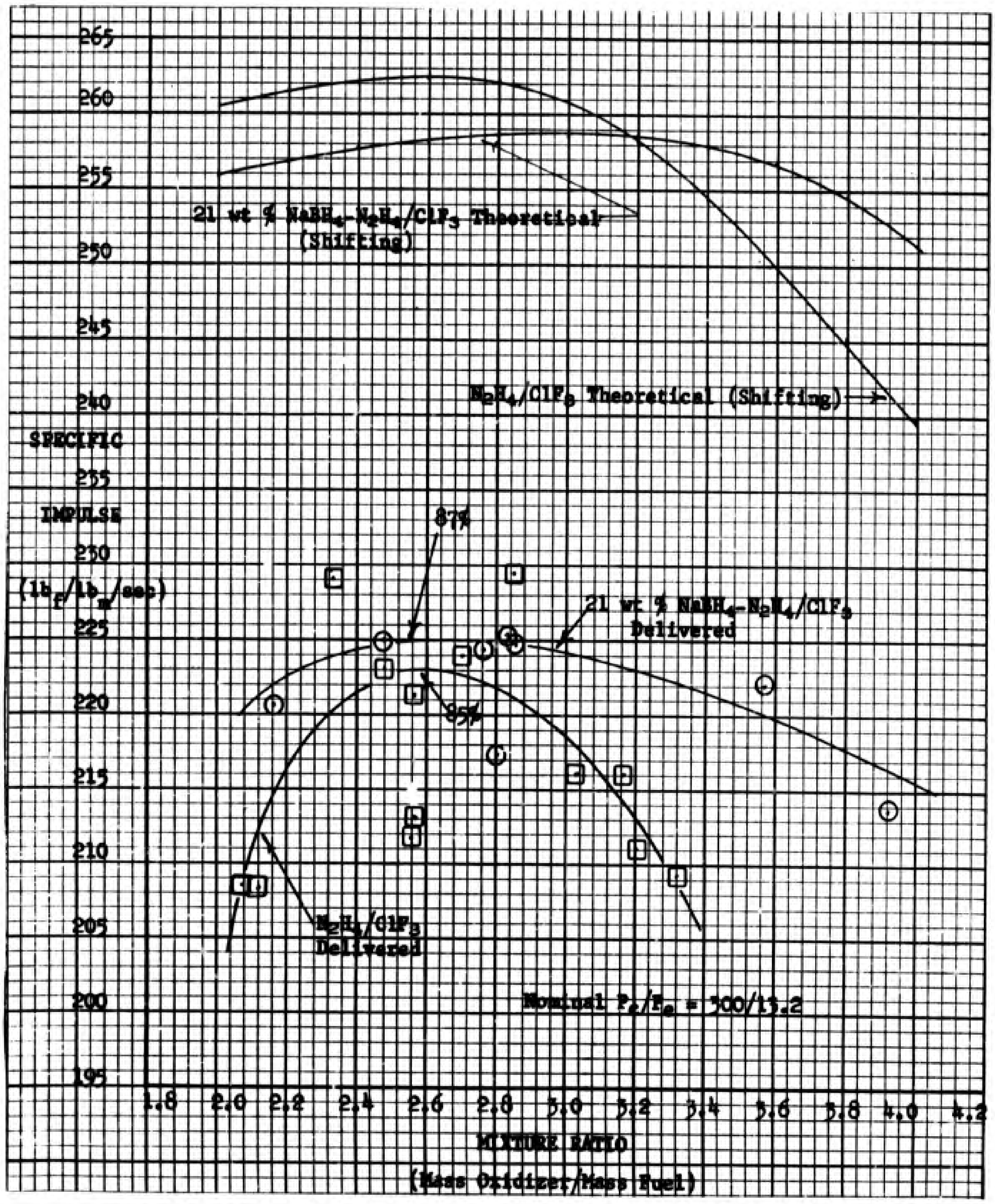
(U) The chamber pressure in this evaluation ranged from 263 to 366 psia. However, the normal chamber pressure was 300 psia. The data presented in this report have not been corrected for chamber pressure variations, heat losses, momentum losses or non-optimum expansion losses. The percentages given on these plots are the percentages of the peak theoretical performance, without regard to the mixture ratio, for a given combination which was delivered at the point indicated.

1. Performance in Like-on-Like Injector.

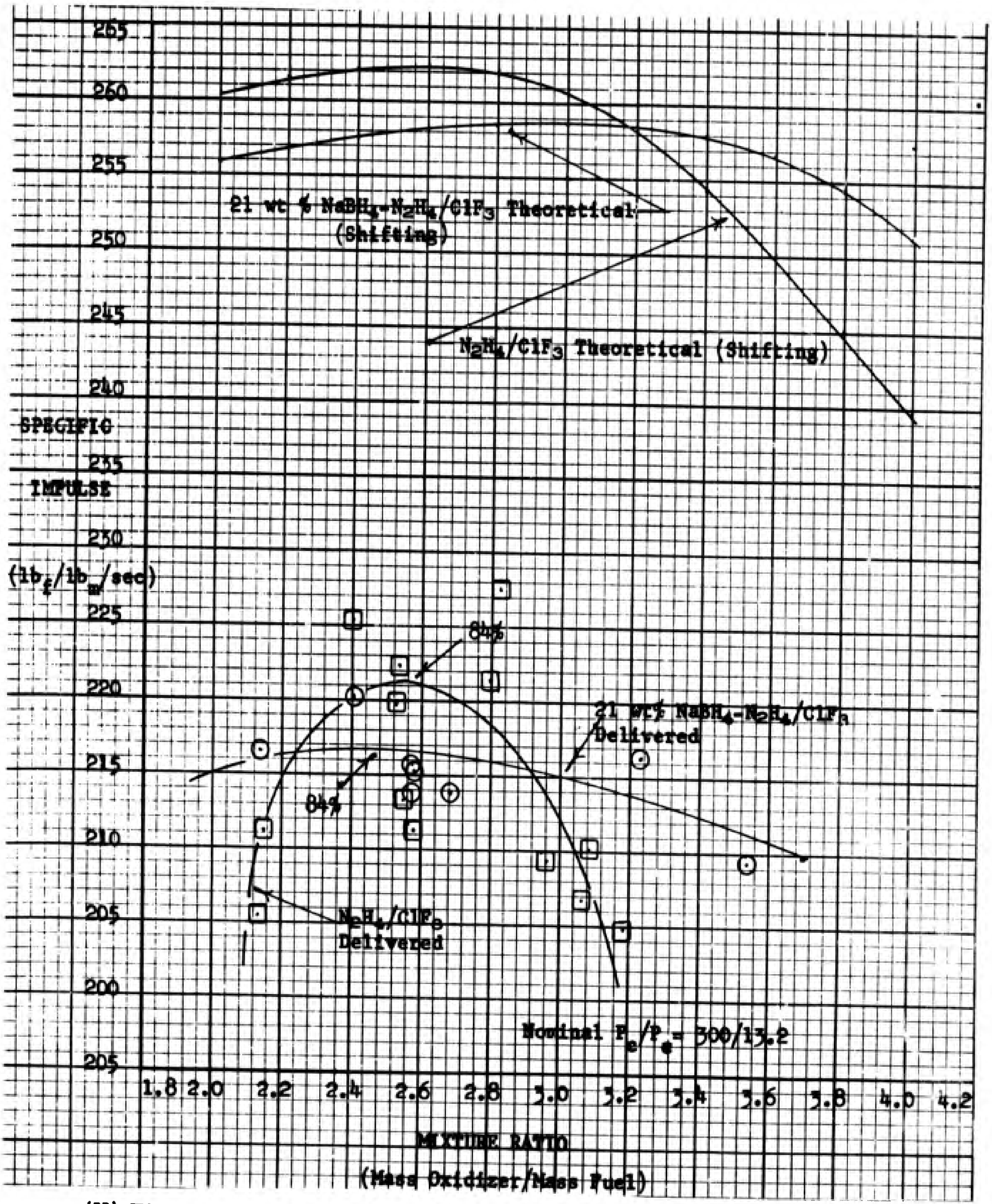
(C) The mean specific impulses delivered in the like-on-like injectors are shown in Figures 12 and 13. The first thing which the reader will probably notice about these two plots is that the $NaBH_4$-N_2H_4/ClF_3 combination is shown as performing better than the N_2H_4/ClF_3 combination in Figure 12 but not in Figure 13. This difference results mainly from the different location of the three points, which are denoted by circles, near a mixture ratio of 2.8 in Figure 12 and 2.6 in Figure 13. These three points represent three consecutive firings. A possible explanation of the discrepancy is that the turbine meters were partially bound up, thus resulting in a lower indicated flowrate and therefore a higher calculated specific impulse. Various degrees of binding were observed in the meters used in the ClF_3 system during passivation. When such binding was detected, the meters were removed. The binding resulted from the non-uniform formation of a passivation coating on the ball bearings and races. An alternate explanation is that a cavitating venturi could have been partially clogged by foreign material. Since the venturi controls the flow, clogging of the venturi would result in a lower flow than was planned. The indicated flow, in such a case, would be greater than the actual flow. Based on the higher indicated flowrate, the calculated specific impulse would be low. Unfortunately neither of these, nor other explanations, could be proven.

(U) This observed discrepancy illustrates the importance of multiple measurements made by different methods. When the results of the two methods are compared as above, a determinate error is apparent. The error is small and undoubtedly would not have been detected if either of the methods were used alone. Of course, a definite proof of which, if either, is correct in this case would be very nice. Even though such a proof was not possible in this case, the very important knowledge that the data in this case are less reliable than usual is obtained. The degree of confidence which can be placed in given data is a very important factor in making decisions which affect future programs.

(U) The second thing which the reader will probably note is that four of the square points representing N_2H_4/ClF_3 firings deviate greatly from the line drawn showing the N_2H_4/ClF_3 delivered specific impulse. These points are located at mixture ratios of about 2.4, 2.6 and 2.8 in Figures 12 and 13. Unlike the three points discussed in the previous paragraphs, the relative locations of these four points are the same in both Figures 12 and 13; the data based on the turbine meter flowrates and the data based on the venturi flowrates are consistent. Thus, the conclusion is drawn that the discrepancy in this case was not caused by errors in the flowrate measurements. Two possible explanations of this discrepancy were explored, but neither was satisfactory. The first was that a determinate error in the thrust calibration had been made. No information to support this hypothesis was found. The second was that the degree of combustion instability resulted in variances in the calculated specific impulse. The greater oscillation of thrust and chamber pressure traces observed in firings of the like-on-like injector has already been pointed out in the section on ignition and combustion. To check the hypothesis that variations in instability were affecting the computed specific impulses, the oscillograph traces of all the N_2H_4/ClF_3 firings were examined. No correlation between the amplitude of the traces and the values of the specific impulse was found. Thus, the cause of the deviation of these four points remains undetermined. However, the correlation of the remaining nine N_2H_4/ClF_3 firings is very good. Also, the N_2H_4/ClF_3 curve, as drawn, falls in approximately the middle of these four points. Hence, the N_2H_4/ClF_3 curve for this injector is reasonably well established.



(U) Figure 12. Mean Specific Impulses, Based on Turbine Flowrates, in Like-on-Like Injector



(U) Figure 13. Mean Specific Impulses, Based on Venturi Flowrates, in Like-on-Like Injector.

(U) The arbitrarily selected individual points, which are plotted in Figures 19 and 20 in Appendix I, turned out to be good approximations of the mean values. Figure 19 has essentially the same shape as Figure 12. Also encouraging is the fact that the trends indicated by the characteristic exhaust velocity and thrust coefficient plots in Figure 20 are the same as the trends indicated in Figure 19.

(U) However, the agreement of Figure 19 with Figure 12 is the result of chance. The range of values which could just as well have been plotted are shown in Figures 21 and 23. Unless determinate errors were present and undetected, any point of a given symbol on a given one of these plots is equally as valid as any other point of the same symbol on the same plot. The author is of the opinion that the least biased of the estimates of performance under these conditions is the mean of the individual points. As was mentioned earlier, the plots of the individual points have been included for the benefit of those who may be of a different opinion than the author. But, these plots are also useful because they indicate the precision of the test system. The spread of the data indicated by Figures 21, 22, 23 and 24 is much greater than that observed during the splash plate and triplet injector firings.

(U) The average standard deviation of the specific impulse values, based on turbine meter flowrates of firings in the like-on-like injector, is 2.45 lb_f-sec/lb_m. The standard deviation ranged from 0.75 to 5.28 lb_f-sec/lb_m.

(C) Finally, the reader should note that the percentage of the peak theoretical specific impulse delivered in the like-on-like injector is 84 to 87%.

(C) Neither Figure 12 nor Figure 13 suggests any verification of the increase in specific impulse which according to the General Electric theoretical data in Figure 1 would result from the substitution of 19 to 21 wt.% $NaBH_4$-N_2H_4 for N_2H_4 with ClF_3 as oxidizer. The delivered performance data in Figure 13 indicate that the trends predicted by the AFRPL theoretical data, which are shown in the same figure, are correct. However, because of the discrepancies discussed above, the like-on-like injector data are not, alone, sufficient evidence to conclude that no advantage exists when 19 to 21 wt.% $NaBH_4$-N_2H_4 is substituted for N_2H_4 in the system under study.

2. Performance in Splash Plate Injector.

(C) The mean specific impulses delivered in the splash plate injector are shown in Figures 14 and 15. In this case, the data based on the turbine flowmeters and the data based on the cavitating venturis indicate the same trends, i.e., the N_2H_4/ClF_3 combination delivered more specific impulse than did the 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 combination. This trend is in accord with the AFRPL theoretical, and the experimental difference between the performances is of the same magnitude as the AFRPL theoretical difference.

(U) The arbitrarily selected individual points also indicate the same trends. These points are plotted in Figures 25 and 26 in Appendix I.

(U) The plots of the individual specific impulse values, in Figures 27, 28, 29 and 30 in Appendix I, indicate less scatter in the data from the splash plate injector firings than was present in the data from the like-on-like injector firings. This better precision is also indicated by the mean standard deviation of the specific impulses based on the turbine meter measurements. The mean standard deviation in the splash plate firings was 2.16 lb_f-sec/lb_m. The standard deviation ranged from 0.89 to 6.74 lb_f-sec/lb_m in the splash plate firings.

(C) In the splash plate injector, the peak delivered specific impulse of both the N_2H_4/ClF_3 and the 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 combinations is shifted considerably to the left of the theoretical peak. Also, the peaking of the 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 delivered specific impulse curve is much sharper than predicted by the theoretical data. This effect could result from either the injector design or from a determinate error which is dependent on the mixture ratio.

(U) The author believes that the former reason is more likely than the latter. The evaluation was constantly monitored to detect errors. The fact that the various performance variables, as discussed above, are consistent is evidence that a determinate error did not exist. On the other hand, no data on the effect of injector design parameters was obtained except the limited effort to study the effect on performance of the three types of injection patterns. Earlier in the report, the design criterion for the injectors was stated to be to obtain stream injection velocities of 100 ft/sec at a mixture ratio of three. The criterion of 100 ft/sec injection velocities is partly arbitrary, partly traditional and partly based on observation of the fact that such a velocity results in visually good atomization of impinging streams. The mixture ratio of three was chosen because such a mixture ratio is between the theoretical peak performance of the two propellant combinations being tested. Having established these two factors, the hole size and number of elements was fixed by the hardware size, desired thrust level and chamber pressure, and the practical limit on the size of hole which could be drilled. Under these limiting conditions, the momentum level, momentum ratio, stream size, number of elements and various other factors were fixed or very limited, throughout the program, at values which are not necessarily optimum. The study of the effect of these factors is not part of the mission assigned at the level of the evaluation being reported here. However, these factors have been demonstrated by others, e.g., References 9 and 10, to affect performance. Hence, the hypothesis that some of these factors are responsible for the observed shift in peak performance is certainly a prime candidate.

(C) The data obtained definitely indicate that in the splash plate injector used, the N_2H_4/ClF_3 combination performs better than the 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 combination. The delivered performance is in accordance with the AFRPL theoretical, except for deviations in the specific shape. The delivered specific impulse is greater when the propellants are fired in the splash plate injector than when fired in the like-on-like injector.

3. Performance in Triplet Injector.

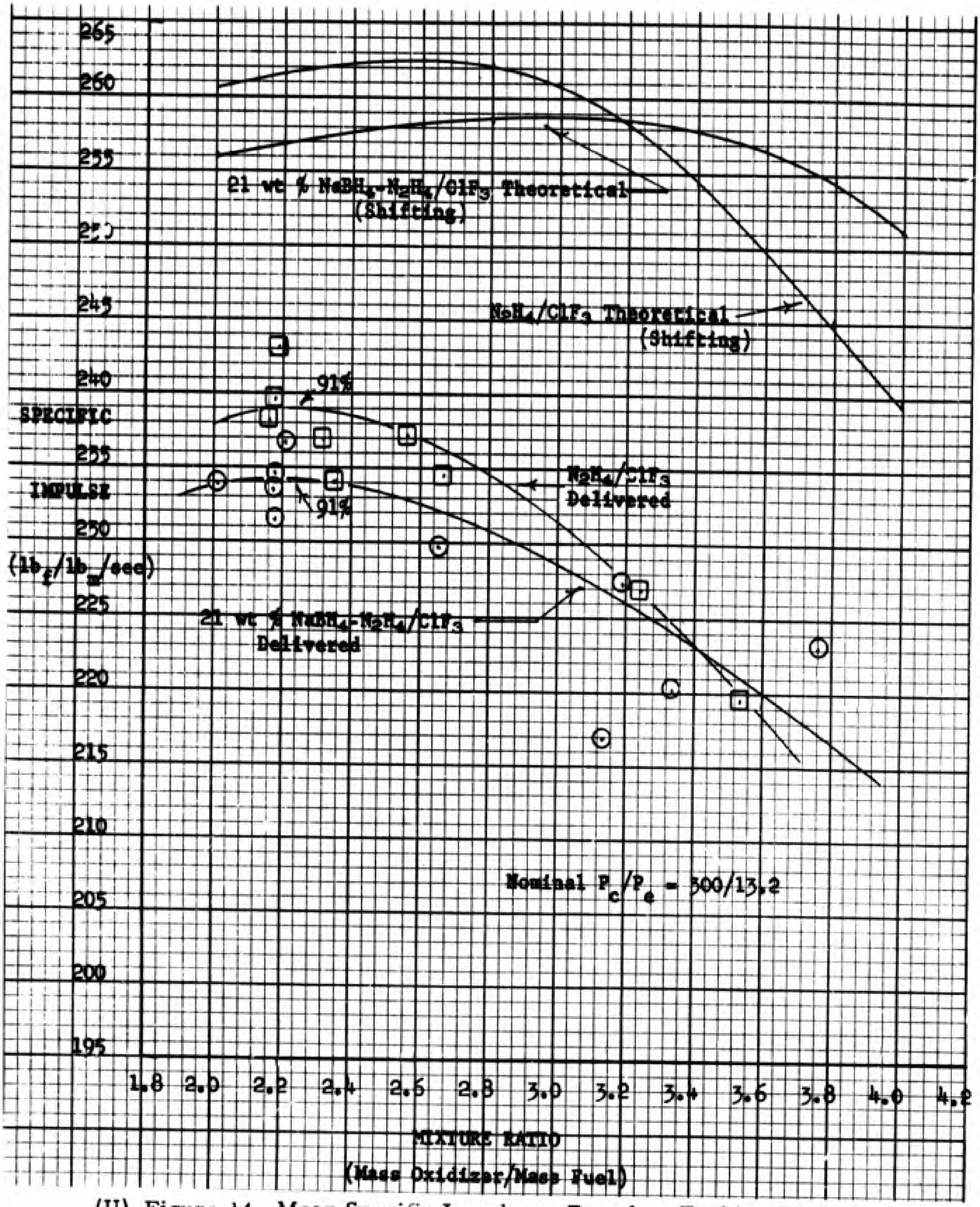
(C) The mean specific impulses delivered in the triplet injector are shown in Figures 16 and 17. The curves are of the same shape as those drawn for the splash plate injector. However, the level of performance is higher than in the splash plate or like-on-like injectors. The curves based on the turbine meter flowrates and the venturi flowrates again are consistent in showing the same trend, i.e., the N_2H_4/ClF_3 combination performs better than the 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 combination.

(U) The plots in Figures 31 and 32 in Appendix I, of the arbitrarily selected values, also show the same trends as the plots of the mean values.

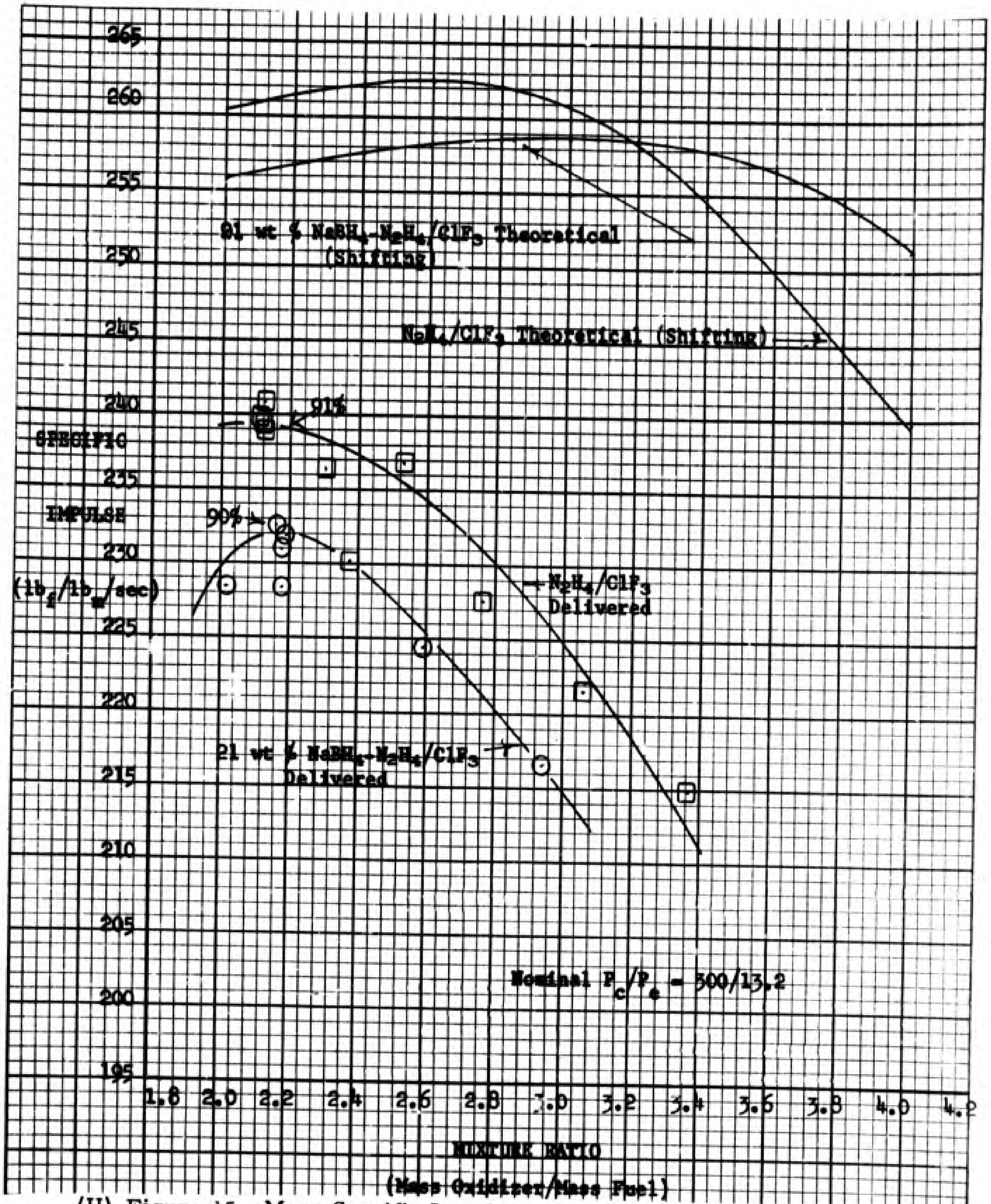
(U) Also, the data scatter for the triplet injector firings, (as shown in Figures 33, 34, 35, and 36 in Appendix I), is less than for either of the other injector firings. The average standard deviation of the specific impulses based on the turbine meter flowrates obtained in the triplet injector is 1.40 lb_f-sec/lb_m. The range of standard deviations in the triplet injector firings is from 0.74 to 3.04 lb_f-sec/lb_m.

(U) The comments made about the peak shift and shape of the experimental curves in the discussion of the splash plate performance also apply to the triplet injector curves.

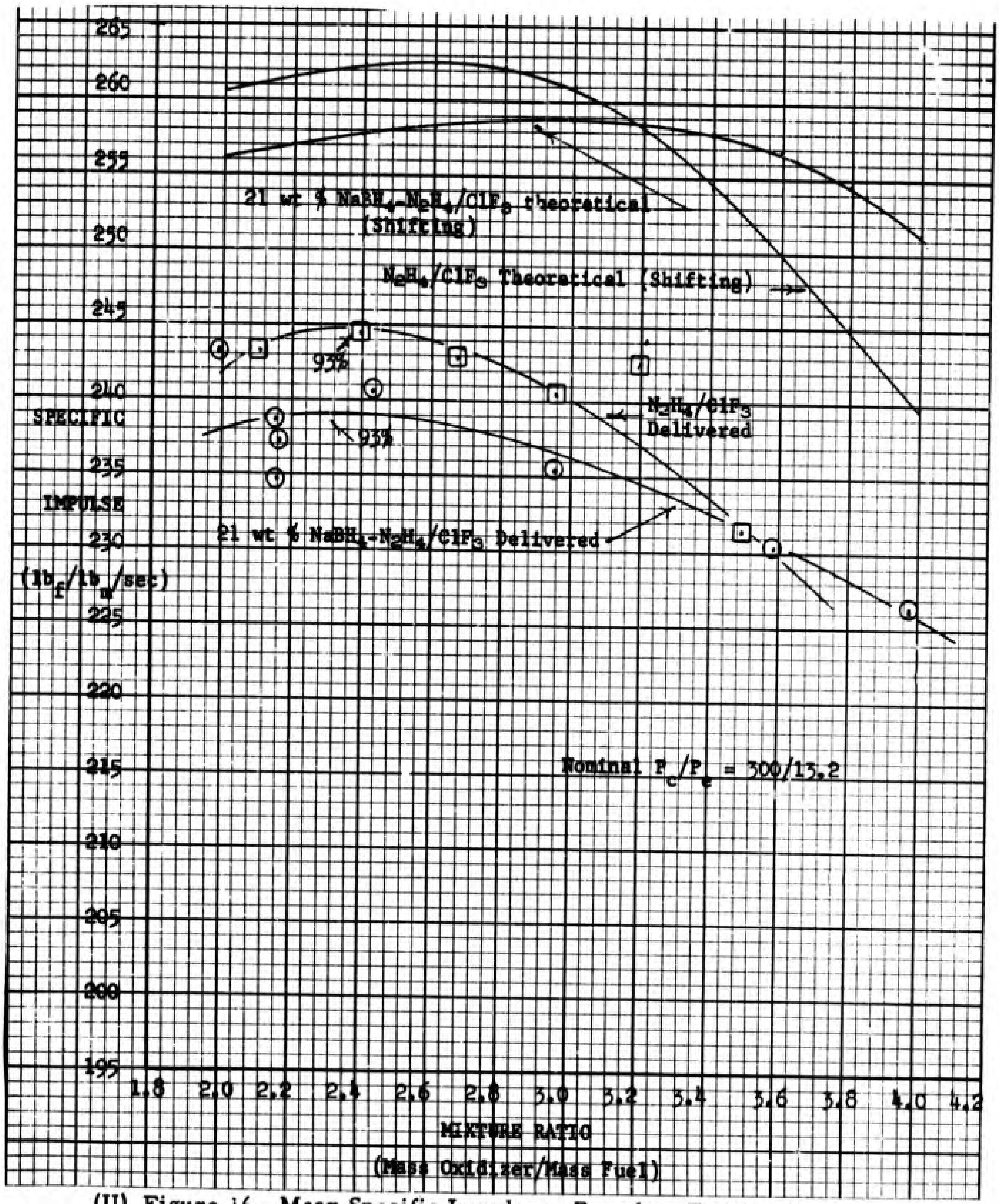
(C) Hence, the data from the triplet injector firings also definitely indicate that the AFRPL theoretical data is correct.



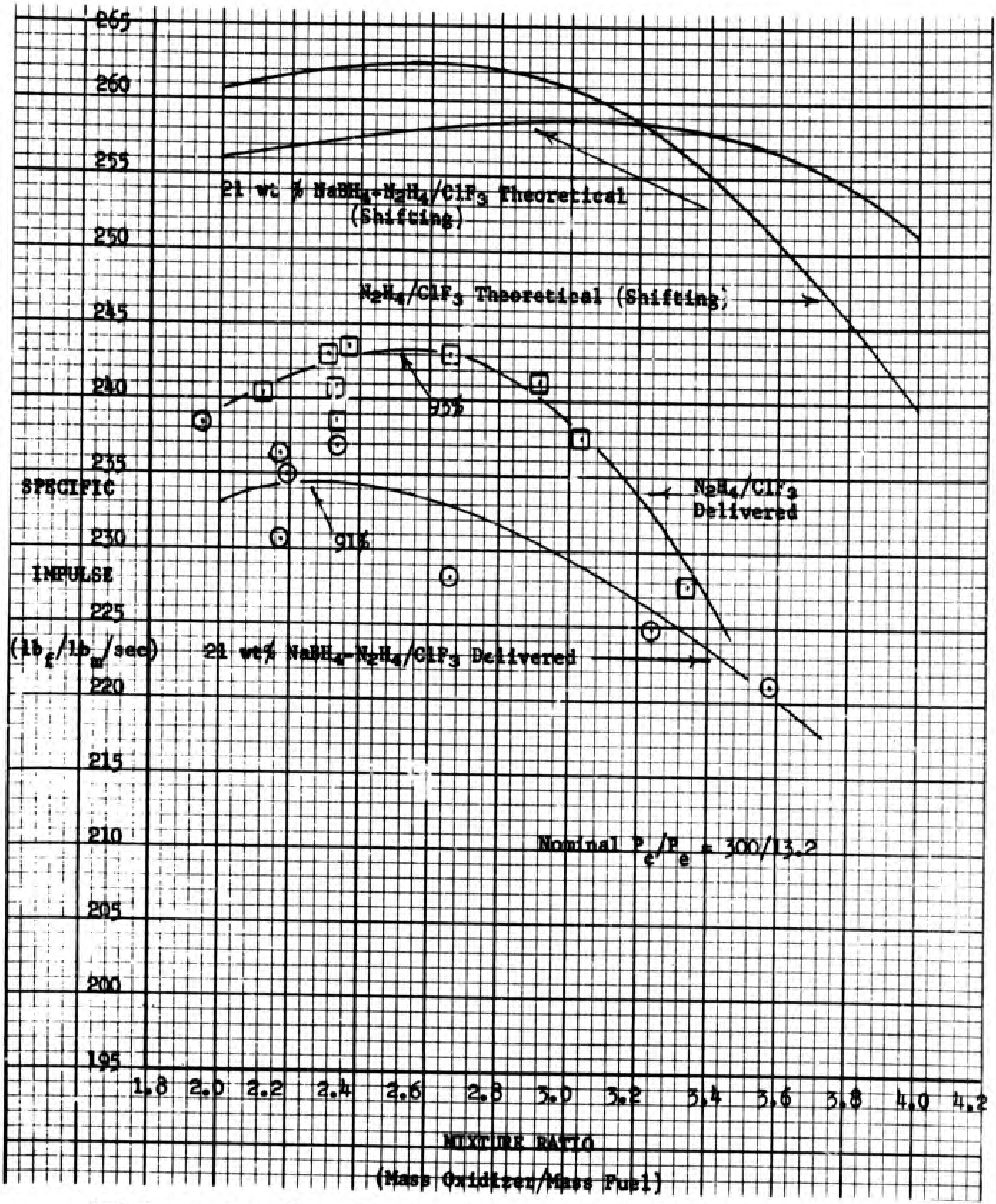
(U) Figure 14. Mean Specific Impulses, Based on Turbine Flowrates, in Splash Plate Injector



(U) Figure 15. Mean Specific Impulses, based on Venturi Flowrates, in Splash Plate Injector



(U) Figure 16. Mean Specific Impulses, Based on Turbine Flowrates, in Triplet Injector



(U) Figure 17. Mean Specific Impulses, Based on Venturi Flowrates, in Triplet Injector

D. ERRORS AND LIMITATIONS.

(U) The man making a decision should know how reliable the information is on which he is basing his decision and the degree of risk which is inherent in the decision. The discussion in the following paragraphs is an attempt to point out the risks which are involved in basing decisions on the results of this evaluation.

(U) One of the common causes of unreliable data is erroneous measurement of variables. Erroneous measurements may be imprecise, inaccurate or both because of random errors, determinate errors or both. In this evaluation, far more effort than normal was made to determine the precision and accuracy of the measurements. Multiple measurements, statistical analyses, careful attention to all aspects of instrumentation and constant surveillance were used to measure and eliminate errors.

(U) The results of these efforts have been partially discussed in the performance section. The author believes that the precision of the data is unusually well established. In addition to the standard deviations, which were quoted in the performance discussion, the average 95% confidence interval, based on turbine meter data was determined to be 1.8 lb_f-sec/lb_m wide. The maximum 95% confidence interval, based on turbine meter data, was determined to be 5.90 lb_f-sec/lb_m wide.

(U) The accuracy of the data is less well established than is the precision but is better established than normal. Two methods were used to obtain an indication of the system accuracy. First, the firings were so conducted as to outline the shape of the performance curves. After a lapse of a few weeks, three or four additional firings were made at the mixture ratio of indicated peak experimental performance on each curve. This method provided a check for the repeatability of the system over a period of time. This method serves to check the accuracy, because in the period between the initial firings and the repeat firings, transducers, propellants, and personnel were varied and changed. Thus, determinate errors which were equipment- or personnel-dependent would tend to show up. Also, this method would provide an opportunity for time-dependent determinate errors, such as those resulting from aging of the equipment, to show up. The second method used to check the accuracy was the use of cavitating venturis and turbine meters to measure the propellant flowrates. Previous experience has indicated that the flowmeters have been the source of greatest error in determination of delivered specific impulse. Thus, the accuracy of the flowrates was believed to be most critical in determining the overall accuracy of the system. Since the cavitating venturi and the turbine meters operate on different principles, the degree to which the flowrates measured by them agree is an indication of the accuracy of the flowrate measurements. The agreement between the specific impulses based on the turbine meters and based on the venturi was reasonably good, as was pointed out in the performance discussion. Therefore, the flowrates based on the two types of meters are reasonably accurate. Also, the repeat firings in the regions of peak performance were reasonably consistent. These factors indicate that the measurement system was reasonably accurate.

(U) Hence, considerable confidence may be placed in the precision and accuracy of the measurements. Certainly, far more confidence may be placed in these data than in the data resulting from the normal evaluation program in which a very limited number of tests are made using single measurements, instead of multiple measurements, or variables.

(U) Another important cause of unsuspected errors (and possibly of full-scale failures of programs based on experimental data) is the inherent limitation on the extrapolation of data to a slightly different and usually larger system. There are at least three possible limitations or factors which should be kept in mind when inferring something about the operation of a system different from the one used in this evaluation. These factors are: scale-up effects, injector optimization and correction.

(U) Most engineers are probably familiar with examples of unexpected situations which can result when large-scale equipment is designed on the basis of data obtained in small-scale equipment. Unfortunately, these size-dependent factors often are not detected until the full-scale equipment is built. Fortunately, past experience within a given field can provide general guide lines. In the present case, in which the final objective is to make inferences about the operation of large-scale rocket motors, informal feedback on the results of tests made in larger scale equipment indicate that the small-scale engines do indicate what can be expected in larger engines.

(U) The second factor, injector optimization, mentioned above also must be considered when the data obtained in this evaluation are to be applied to different equipment. The injectors used in this evaluation were designed on the basis of factors which have generally produced good performance. However, optimization of the injectors was not within the defined scope of the evaluation. Optimization of the injectors could be expected to slightly increase the level of performance and to shift the location of the peak delivered performance. However, because of the similarity of the physical and chemical properties of the propellants being compared in this evaluation, the relative performance of the two combinations would not be expected to change significantly.

(U) The third factor, correction, mentioned above should be kept in mind when applying the data to other systems. In general, correction of specific impulse data involves four main factors: heat losses, non-optimum expansion, nozzle momentum losses and chamber pressure variations. Unfortunately, no commonly accepted method exists for making these corrections. As in the case of optimizing the injectors, however, these corrections would probably be of the same magnitude for both propellant combinations. Therefore, the level of performance would be changed but the relative performance of the two combinations probably would not be changed.

(U) A final consideration which should be kept in mind is the relative intrinsic reliability of experimental values of specific impulse, characteristic exhaust velocity and thrust coefficient as indicators of performance. Representatives of one major aerospace company have stated that ". . . specific impulse is the only performance parameter which can be evaluated with any degree of accuracy."(11) The author of this present report has also decided that specific impulse is the best experimental measure of performance in the systems used in this evaluation. This latter conclusion is based on the uncertainty of the chamber pressure and throat area determinations. The chamber pressure transducers are subject to heat effects and plugging of ports. Also, the advanced propellants being tested in these evaluations often either coat or erode the nozzle, thus making determination of the throat diameter at a given time during the firing very difficult and subject to very significant errors. Hence, most of the data reported herein are specific impulse data. In this evaluation, the nozzles did not become coated by reaction products nor was erosion extreme. Therefore, the characteristic exhaust velocity and thrust coefficient values which are presented are undoubtedly more reliable than usual. However, they are still of secondary importance when compared to the specific impulse data.

(U) In summary, this evaluation can be relied on, and after careful thought is given by the user to the limitations discussed above, can be well used to make decisions about the use of the test propellants in other systems.

E. MATERIALS COMPATIBILITY.

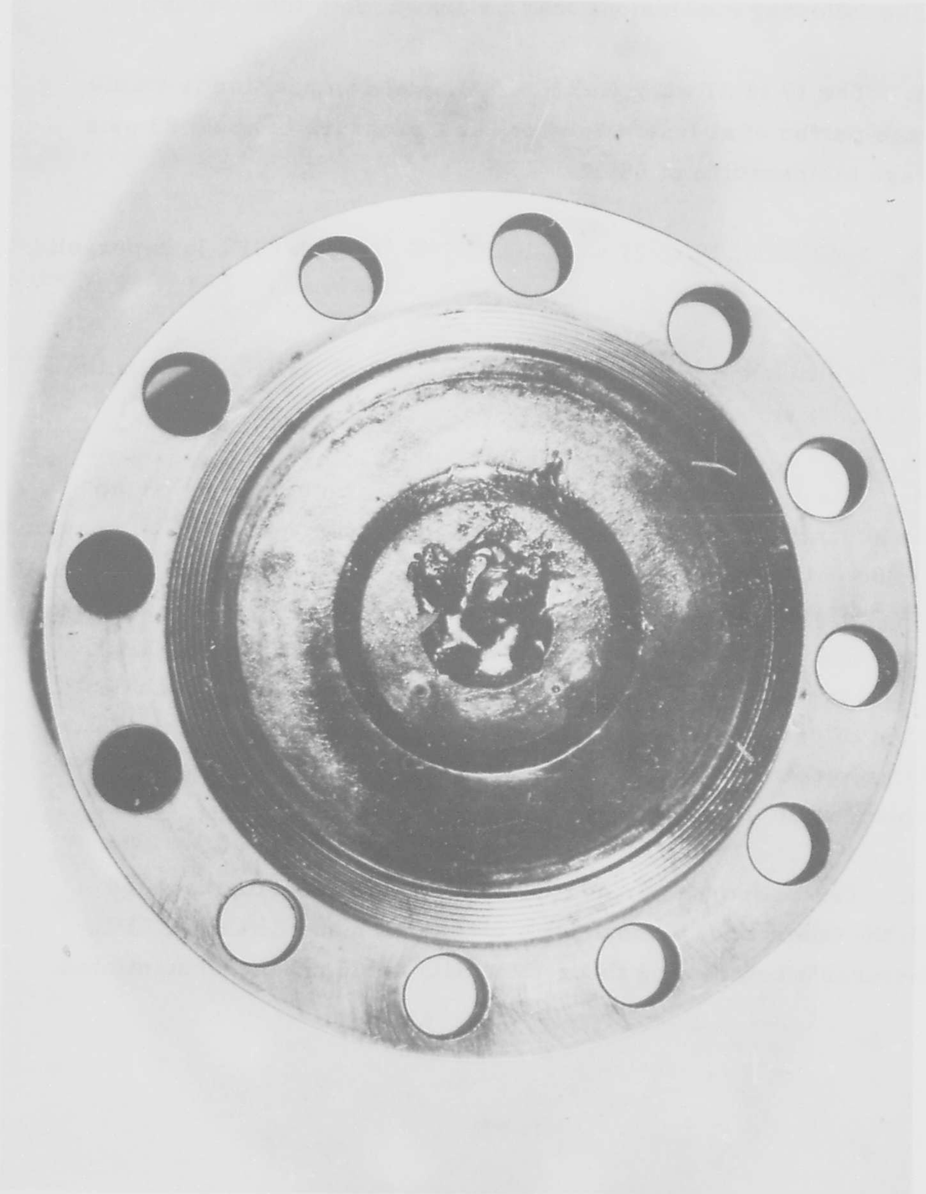
(U) Two materials problems were encountered during the evaluation. The first problem was corrosion of a solenoid valve in the nitrogen purge line. The second was the destruction of an injector during one of the firings.

(U) The solenoid valve which corroded controlled the gaseous nitrogen purge to the bottom of OX prop valve. These valves are shown in Figure 2. Also shown in Figure 2 is the check valve between the OX prop valve and the

OX purge valve. The purpose of the purge system was to remove any residual ClF_3 or other material from the bottom of the prop valves, the lines, and the engine prior to and after each firing. During the firing, the OX purge valve was closed. The check valve was installed to prevent flow of propellant to the purge valve. After two or three weeks operation, the OX purge valve would stick because of the formation of green deposits, which were undoubtedly metal halides, on the stem. This deposit always formed in the normally open port (which was capped off) of the three-port solenoid valve. A very probable explanation of this situation is as follows: The seat of the check valve was "Teflon". During the firings, the ClF_3 was normally under about 500 psia upstream of the check valve. Some very small quantity probably diffused through the "Teflon" or otherwise leaked past the seal and collected, in very low gaseous concentration, in the normally open port of the OX purge valve. After the firing, any ClF_3 in the area of the normally closed port and in the line would be removed but the ClF_3 in the normally open port would not. Repeated exposures would then lead to the accumulation of metal halides which were packed together by each operation of the valve until sufficient friction existed to bind the valve. The substitution of a powerful metal seat valve for the solenoid valve would have undoubtedly eliminated the problem. However, the change was not justified because of the expense and effort which would have been involved.

(U) The injector was destroyed during a firing when the fuel safety valve closed because of a dirty sequence-timer contact. The damaged injector is shown in Figure 18. In this firing, combustion was established in the engine when suddenly the fuel was cut off by the malfunction of the safety valve. The ClF_3 however, continued to flow into the engine. In the absence of the fuel and with the injector heated by the previous combustion, the ClF_3 undoubtedly reacted with the injector face, thus resulting in the burning shown in Figure 18.

(U) Except for these two minor problems, the system operated very well.



(U) Figure 18. Burned Triplet Injector

F. CONCLUSIONS.

(C) The following conclusions may be drawn from this evaluation.

(C) 1. The 19 to 21 wt. % $NaBH_4$-N_2H_4 fuel composition is stable over a storage period of at least two years at a pressure of about 23 psia and an average temperature of 65°F.

(C) 2. Ignition of 19 to 21 wt. % $NaBH_4$-N_2H_4 with ClF_3 is hypergolic and reliable.

(C) 3. Ignition and combustion of 19 to 21 wt. % $NaBH_4$-N_2H_4 with ClF_3 are relatively smooth and stable.

(C) 4. The 19 to 21 wt. % $NaBH_4$-N_2H_4/ClF_3 combination has no performance advantage over the N_2H_4/ClF_3 combination at a nominal chamber pressure of 300 psia with expansion to 13.2 psia.

(C) 5. The level of performance of both the 19 to 21 wt. % $NaBH_4$-N_2H_4/ClF_3 and the N_2H_4/ClF_3 combinations depends on the type of injection for a given set of design criteria. Of the three injection methods tried, the like-on-like gave the worst performance, the splash plate gave the second best performance and the triplet gave the best performance.

(C) 6. The delivered performance of the test propellant agreed closely with the theoretical performance estimates made by the AFRPL. The manufacturer's contrasting theoretical data could not be substantiated.

SECTION IV

FUTURE PLANS

(C) Further work on the 19 to 21 wt.% $NaBH_4$-N_2H_4/ClF_3 system is not recommended. The author does not know of any plans for any future work on this combination.

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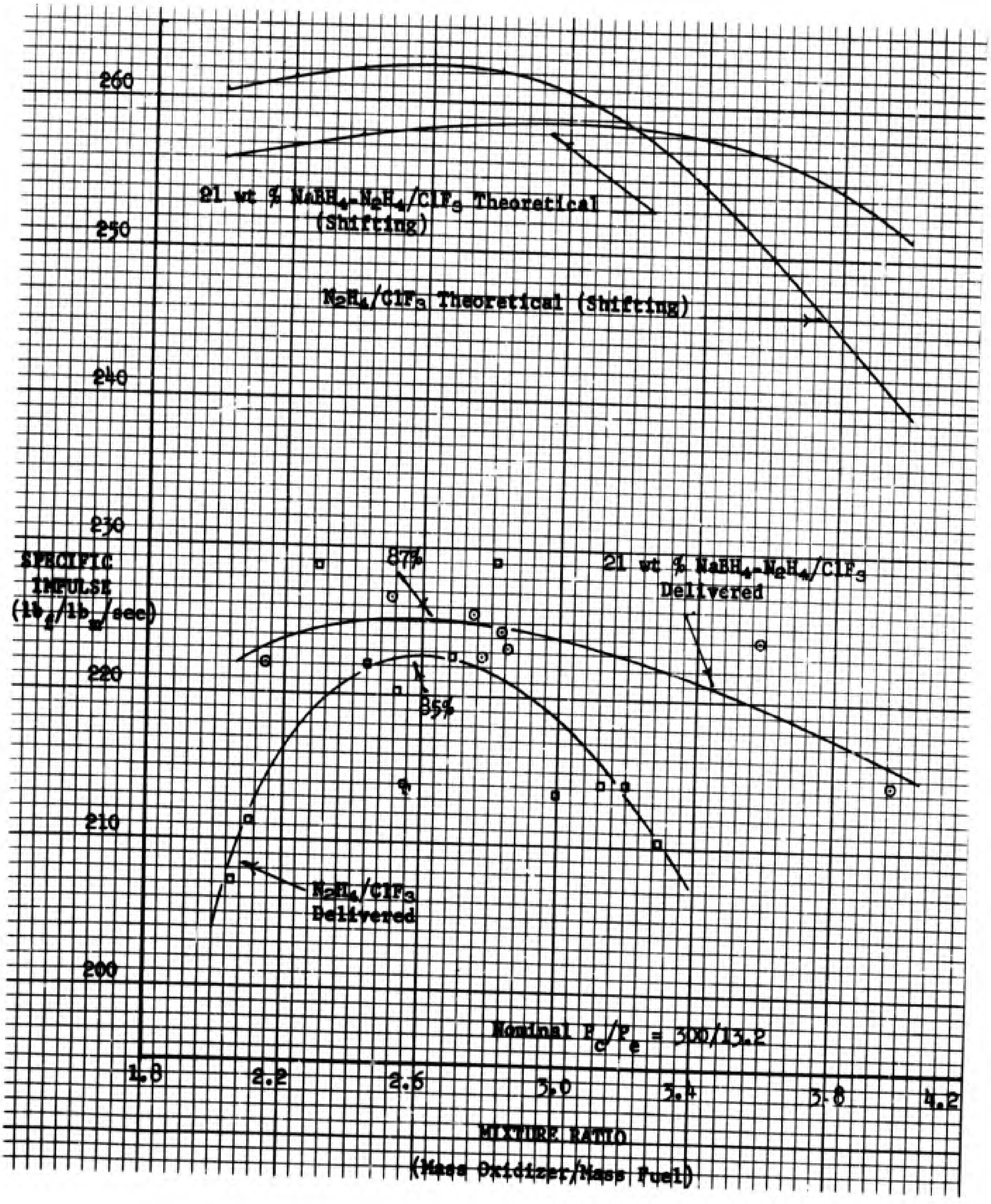
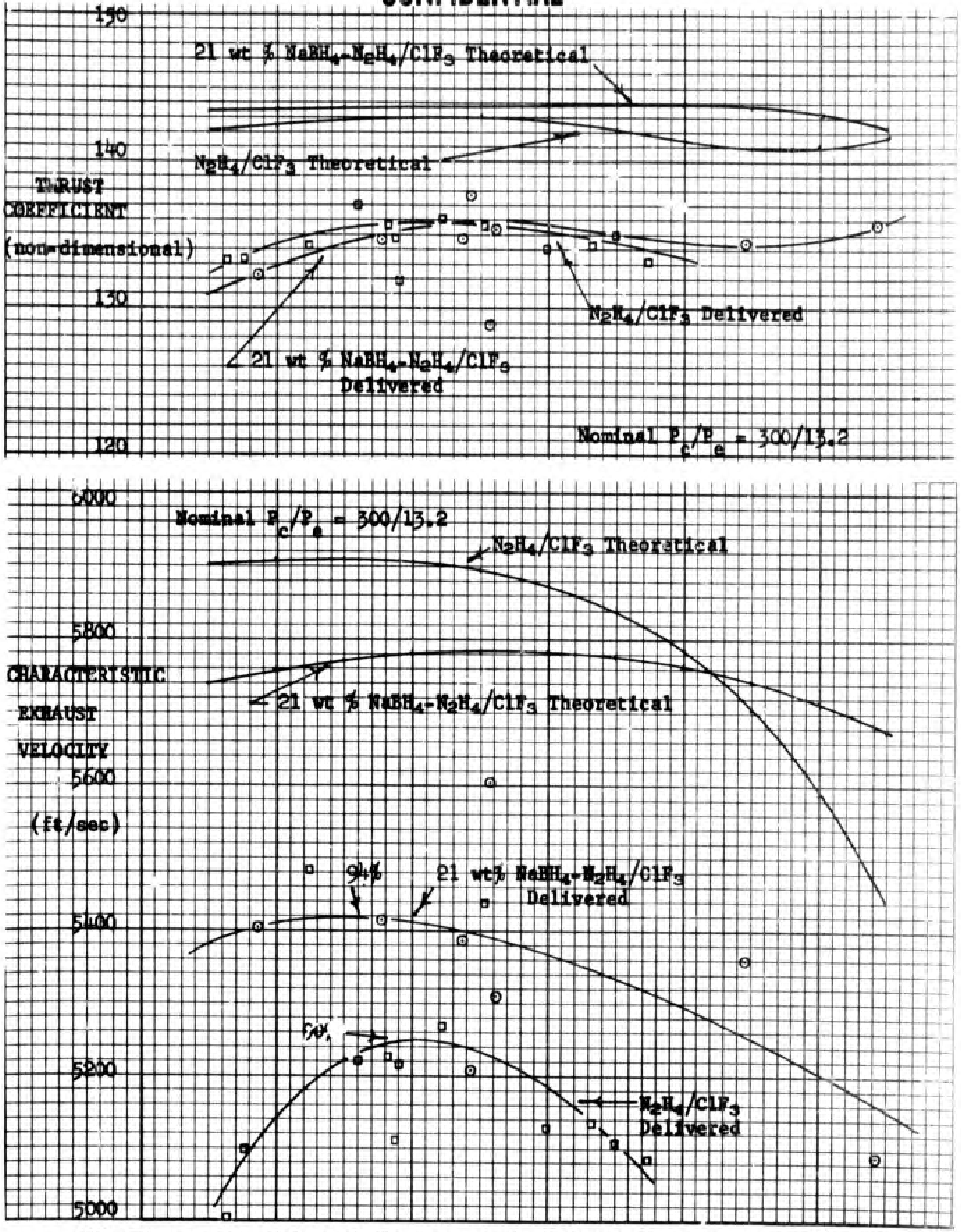
(This page is Unclassified)

APPENDIX I

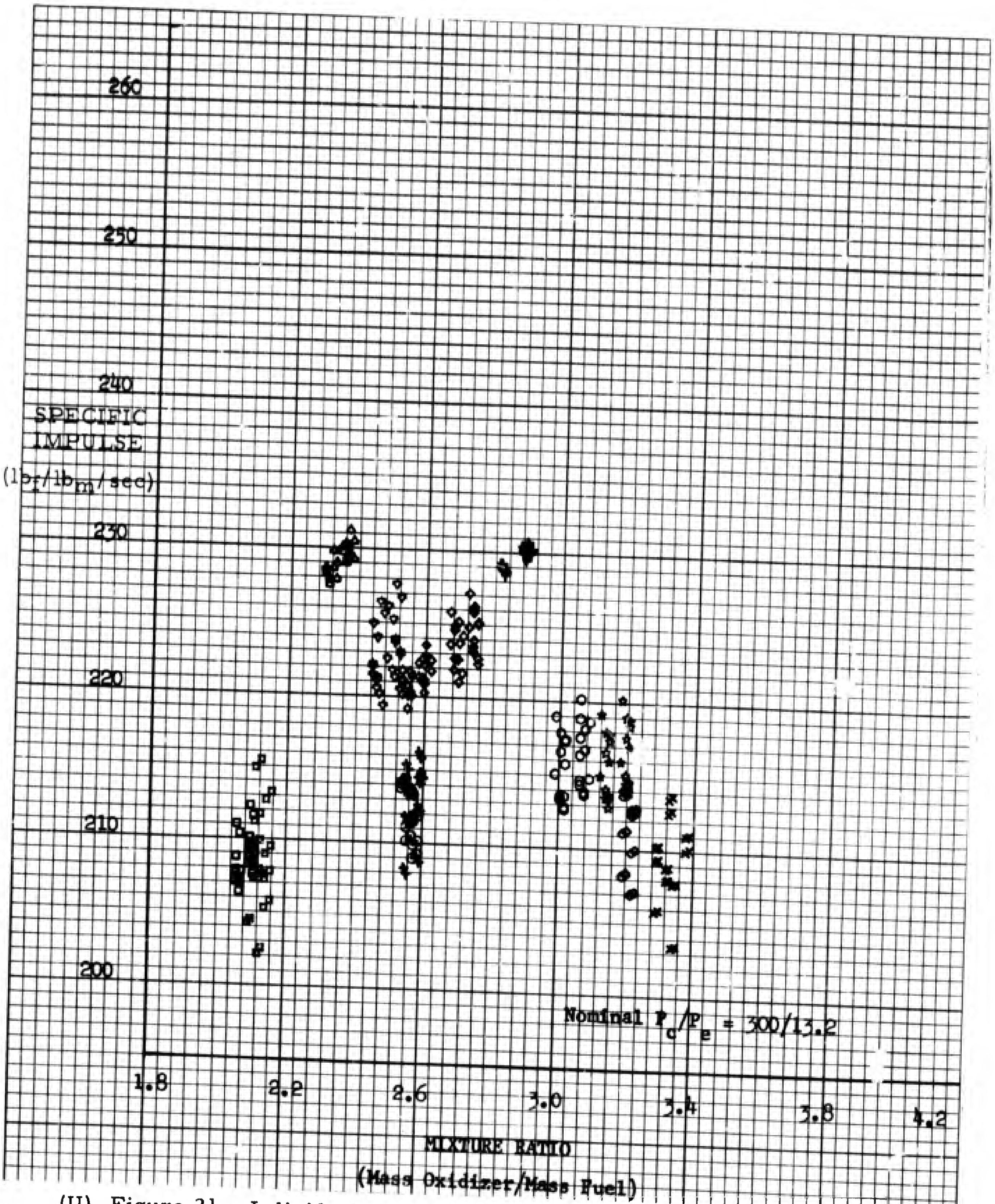
INDIVIDUAL VALUES OF SPECIFIC IMPULSE, CHARACTERISTIC EXHAUST VELOCITIES AND THRUST COEFFICIENTS



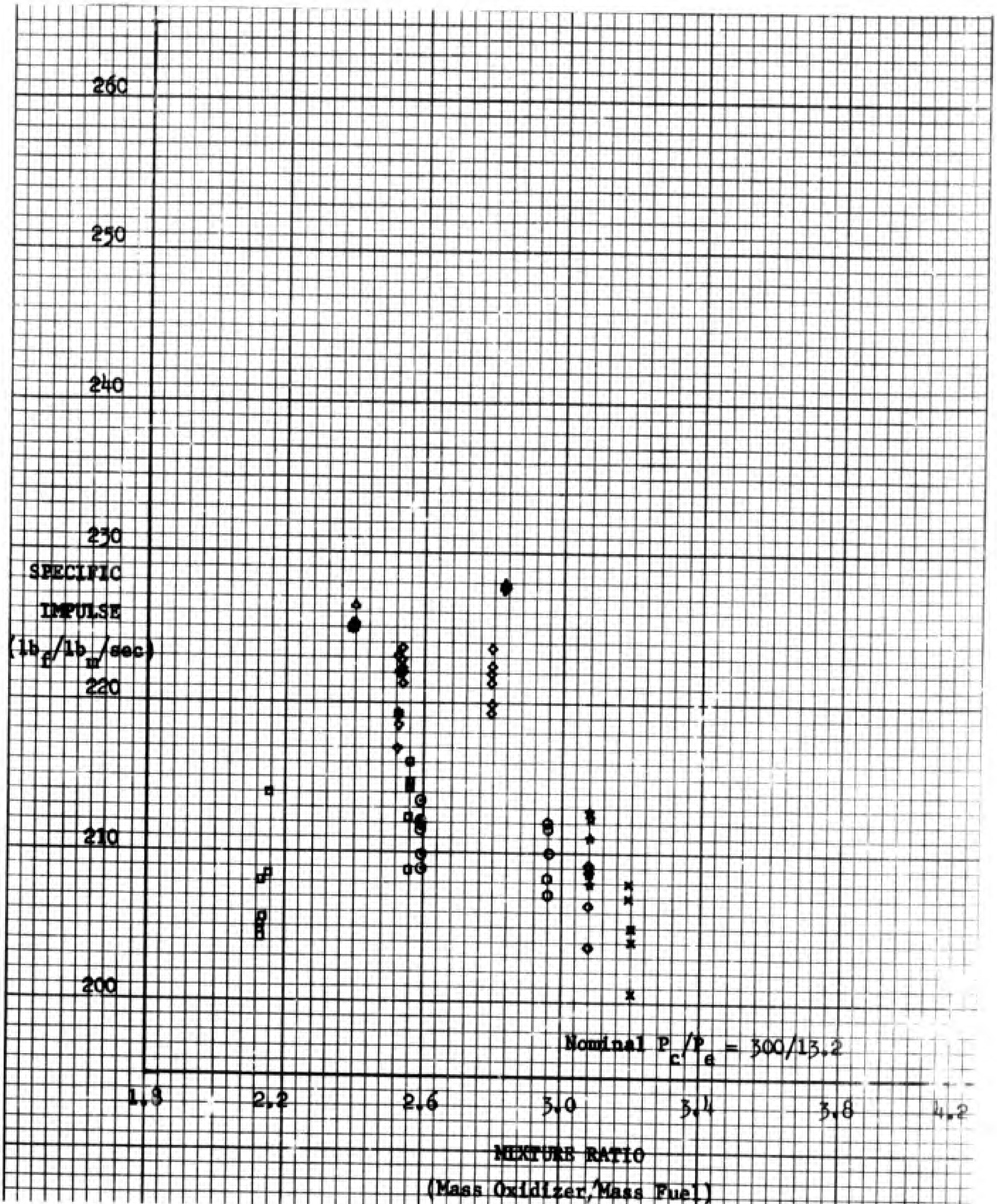
(U) Figure 19. Selected Specific Impulses in Like-on-Like Injector



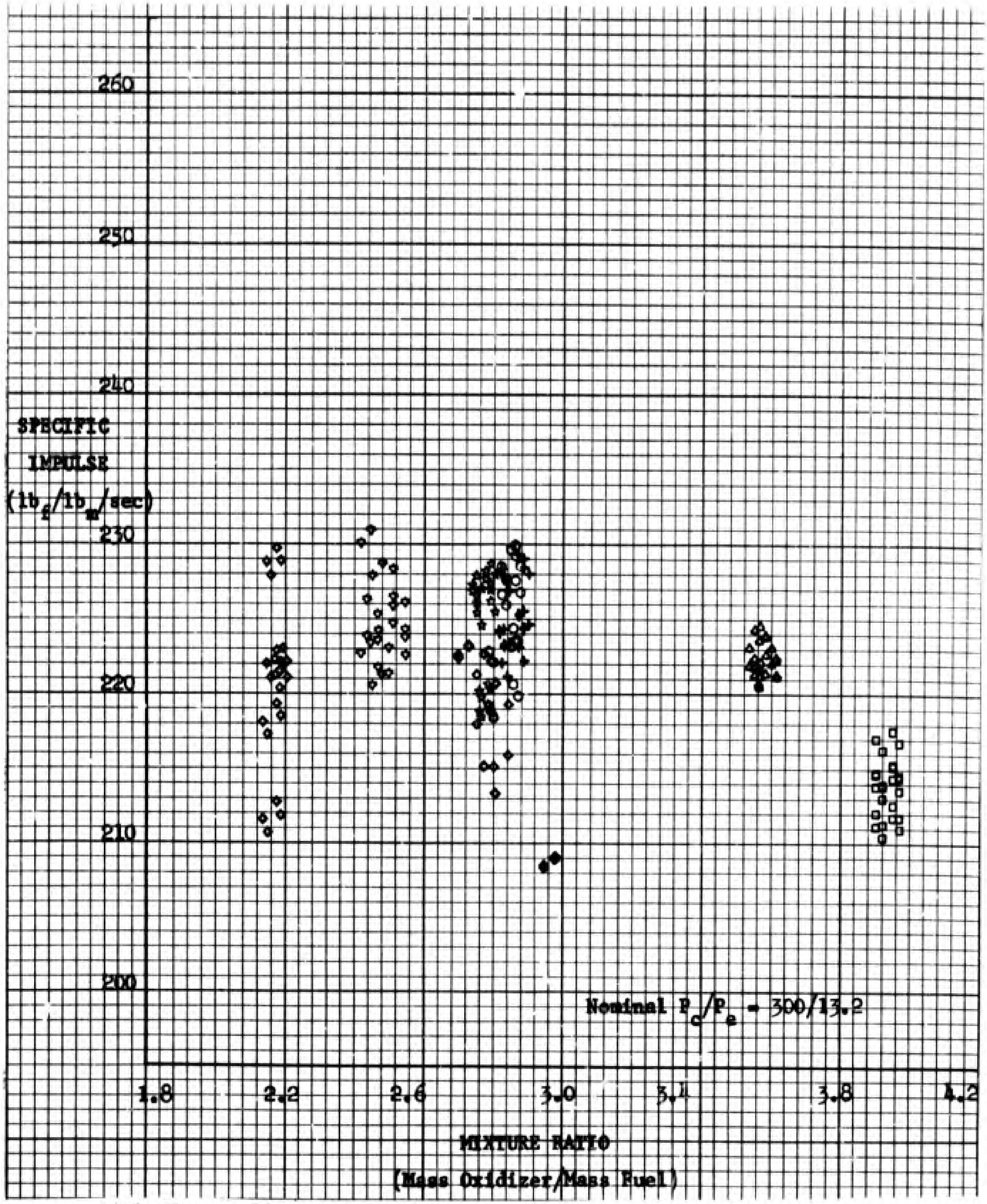
(U) Figure 20. Selected Characteristic Exhaust Velocities and Thrust Coefficients in Like-on-Like Injector



(U) Figure 21. Individual Specific Impulses, Based on Turbine Meters, of N_2H_4/ClF_3 in Like-on-Like Injector

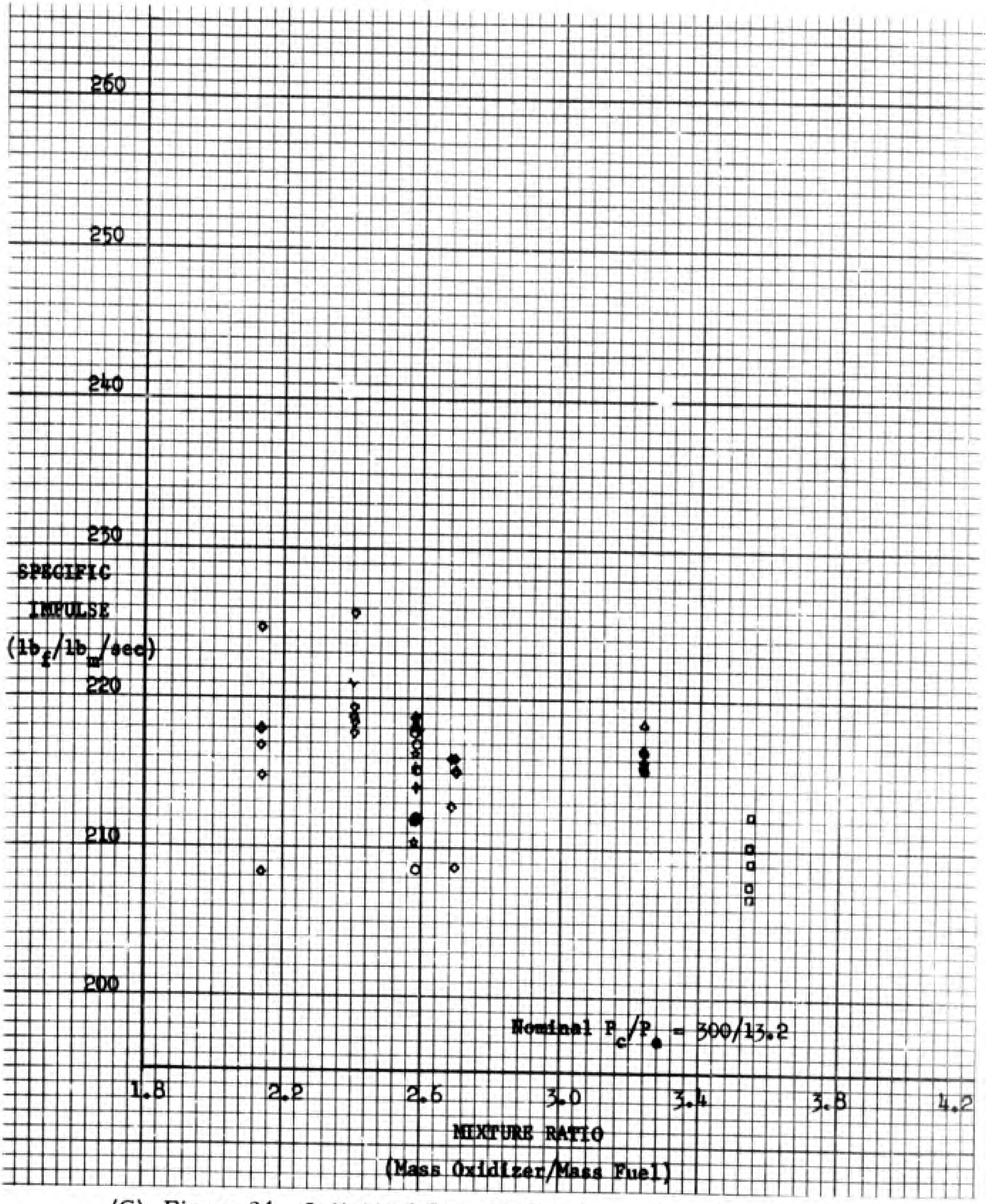


(U) Figure 22. Individual Specific Impulses, Based on Venturi Flowrates, of N_2H_4/ClF_3 in Like-on-Like Injector



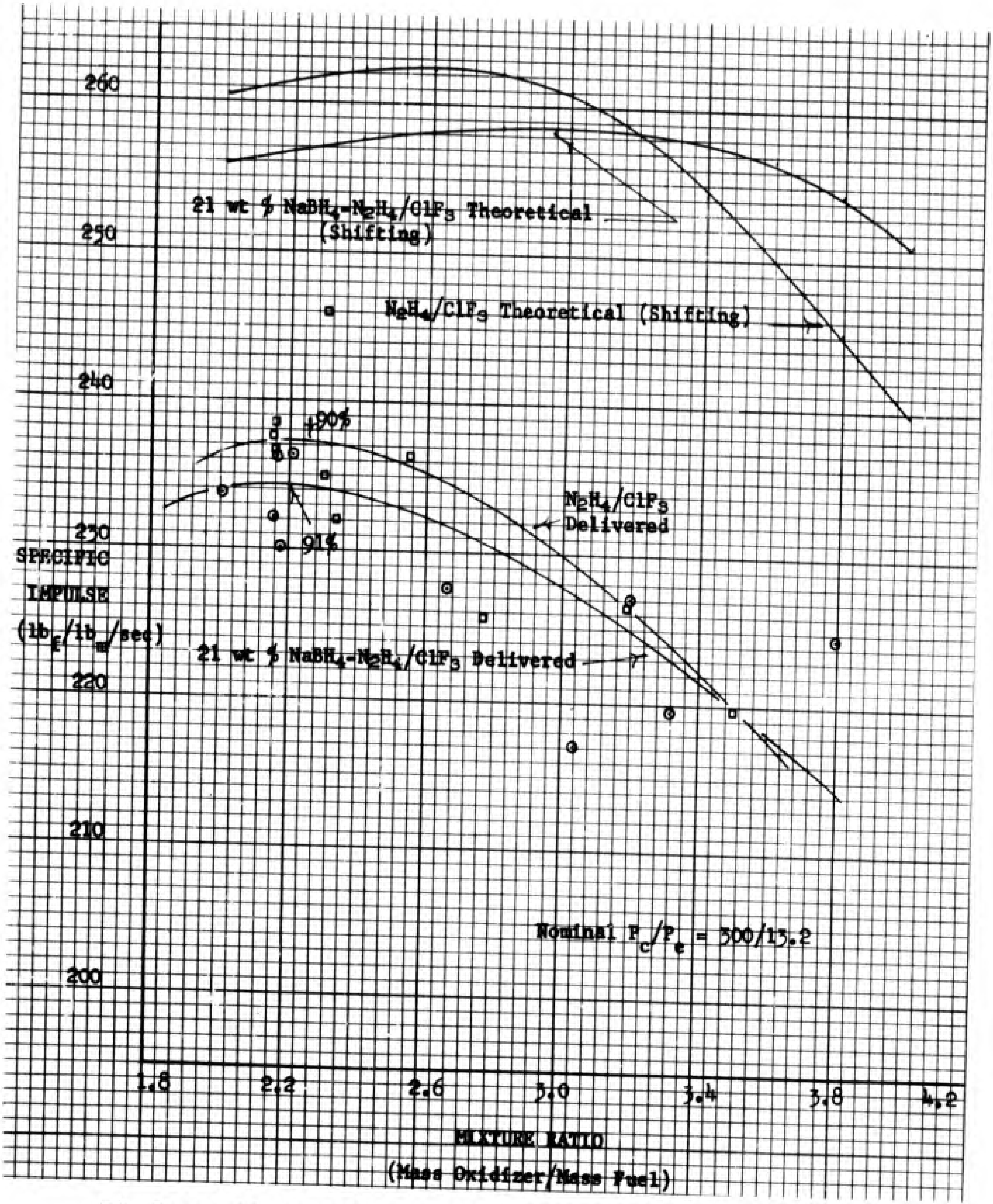
(C) Figure 23. Individual Specific Impulses, Based on Turbine Flowrates, of 19 to 21 Wt. % $NaBH_4$-N_2H_4/ClF_3 in Like-on-Like Injector

CONFIDENTIAL

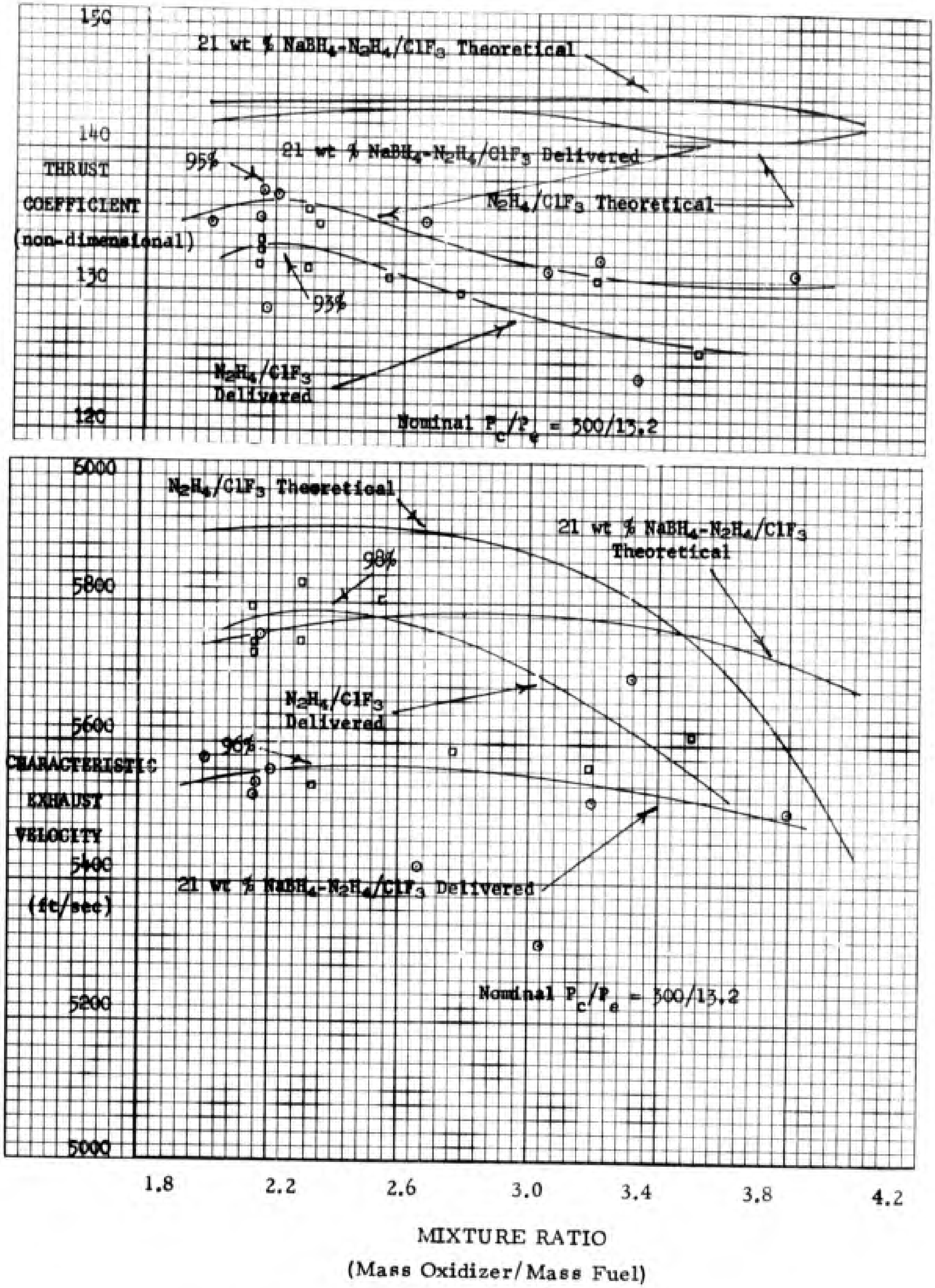


(C) Figure 24. Individual Specific Impulses, Based on Venturi Flowrates, of 19 to 21 Wt. % $NaBH_4$-N_2H_4/ClF_3 in Like-on-Like Injector

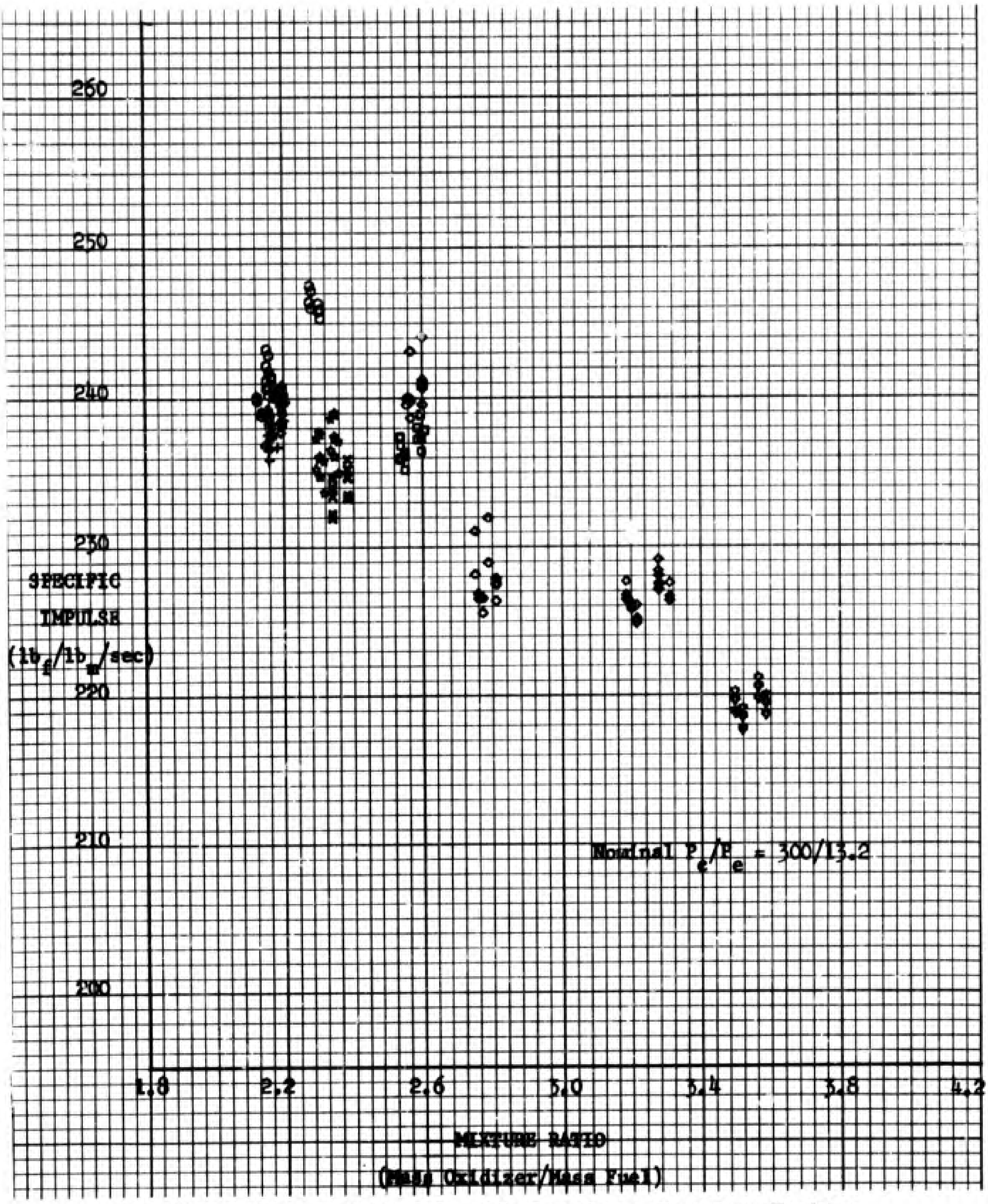
CONFIDENTIAL



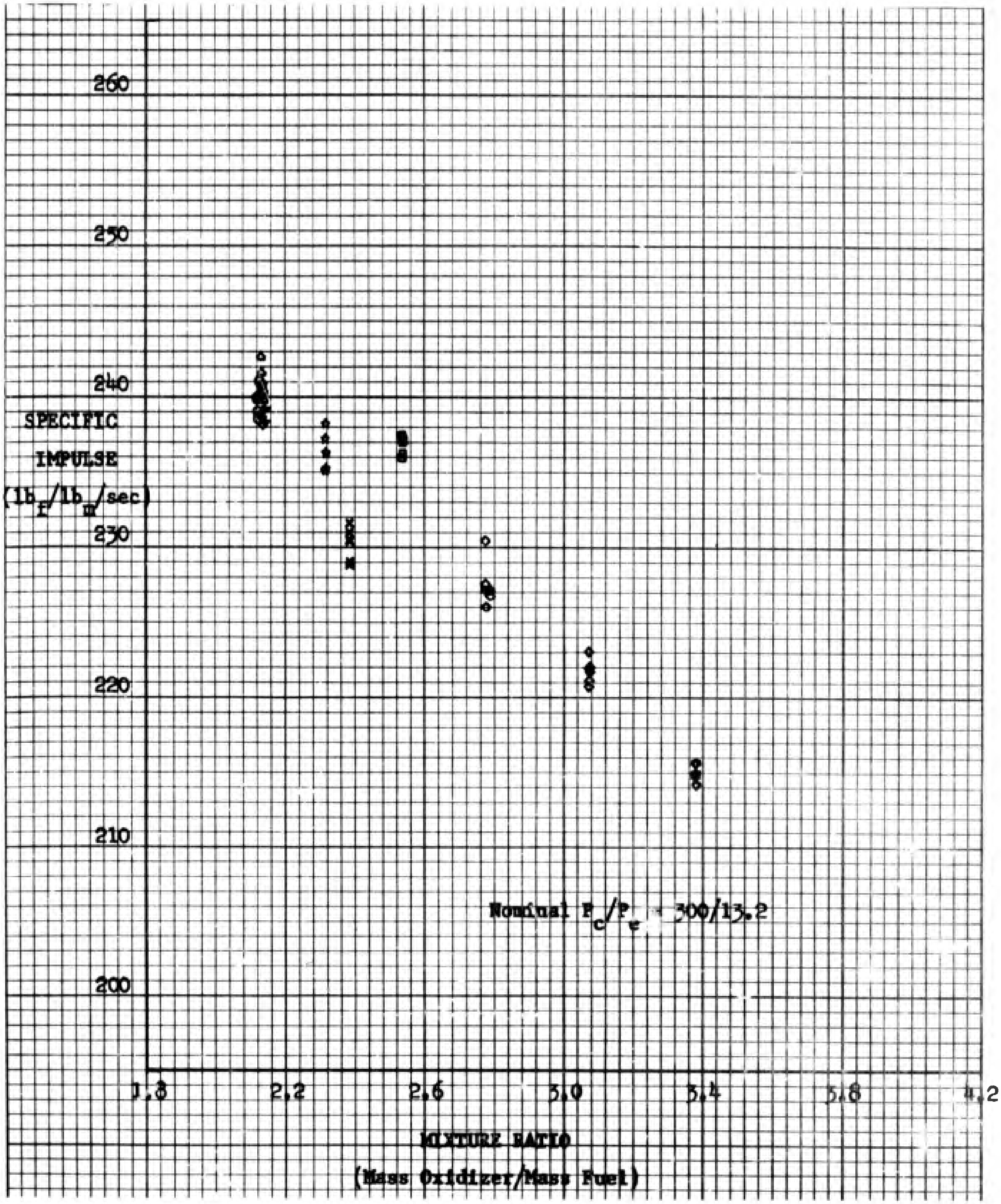
(U) Figure 25. Selected Specific Impulses in Splash Plate Injector



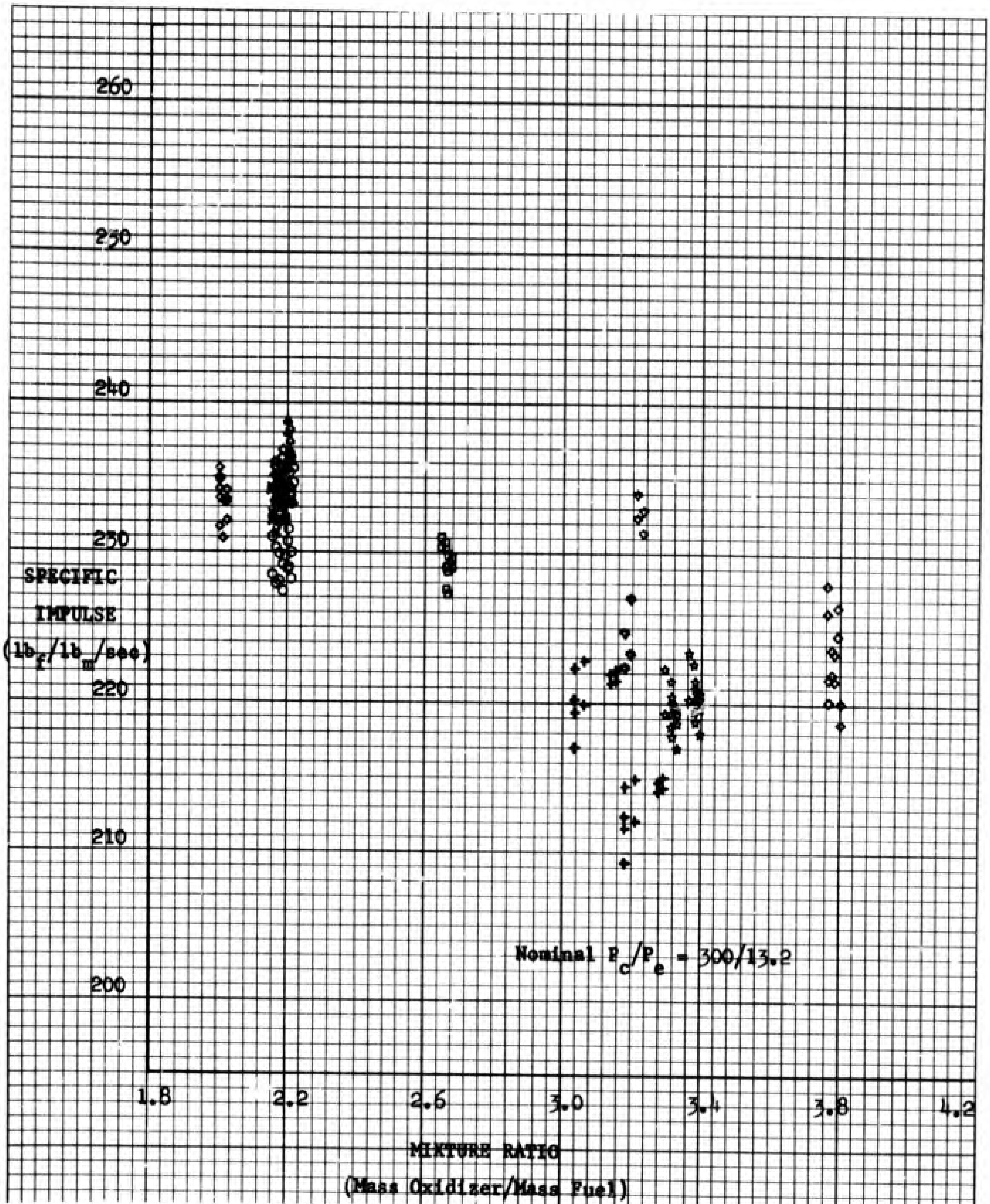
(U) Figure 26. Selected Characteristics Exhaust Velocities and Thrust Coefficients in Splash Plate Injector



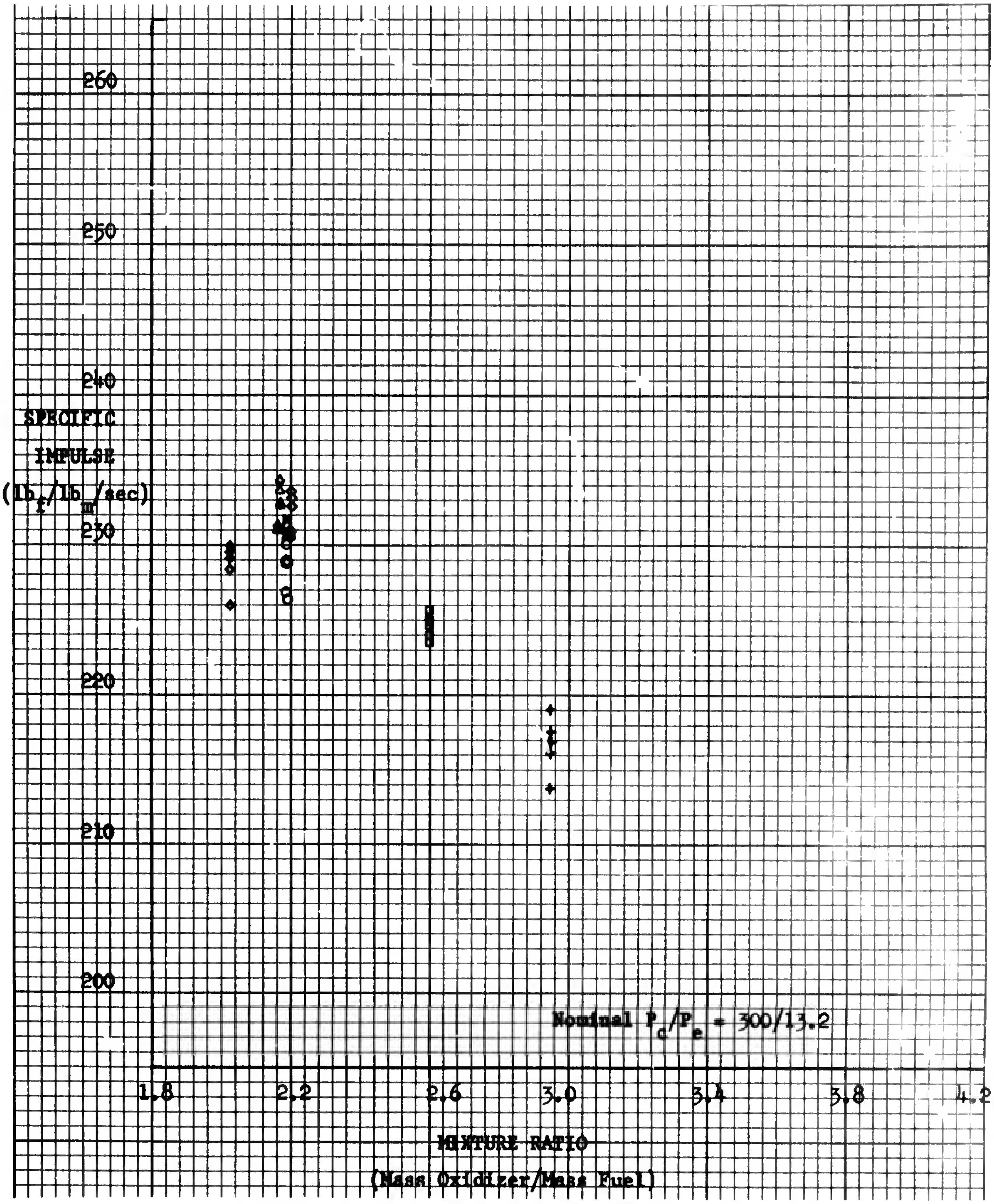
(U) Figure 27. Individual Specific Impulses, Based on Turbine Flowrates, for N_2H_4/ClF_3 in Splash Plate Injector



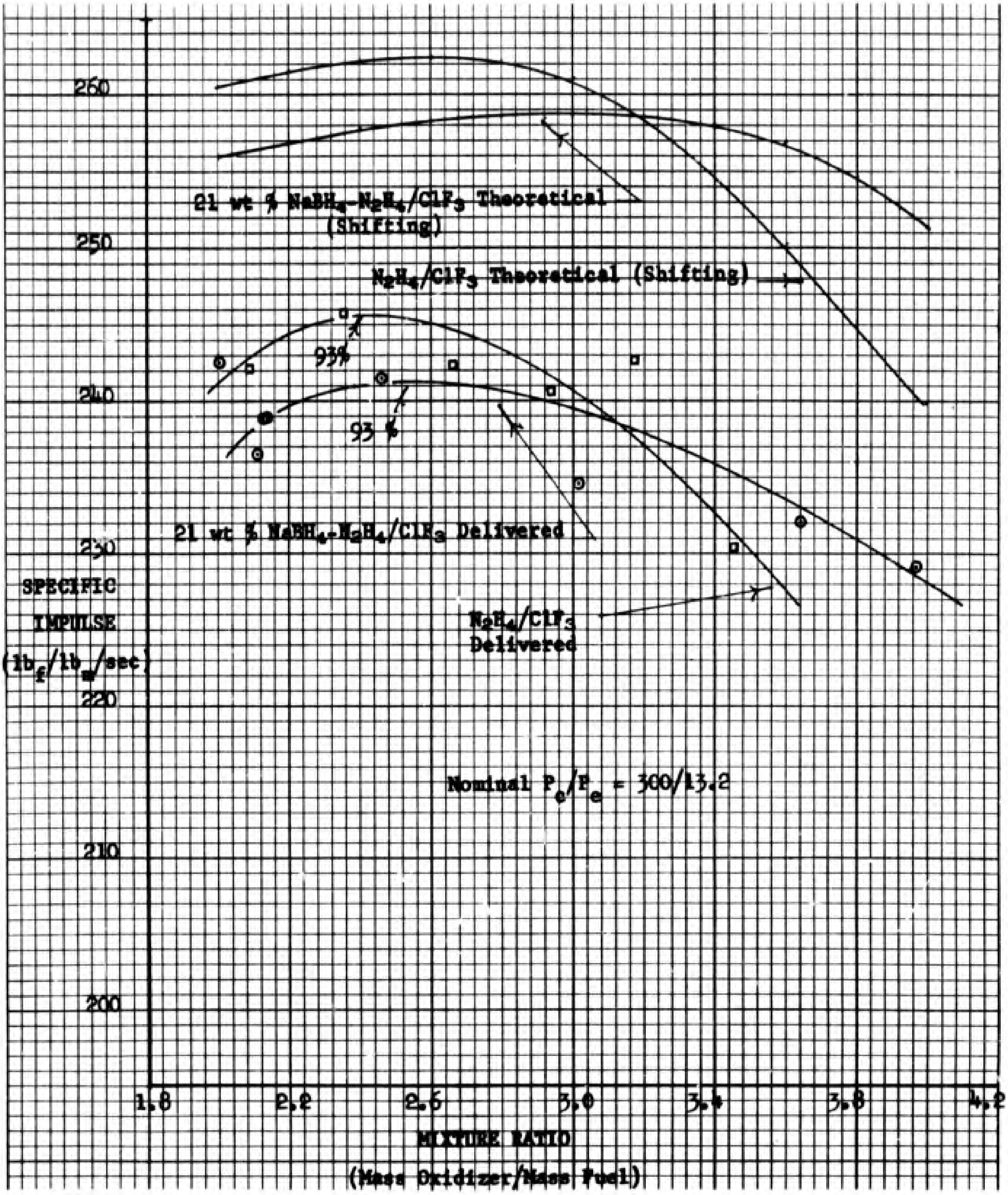
(U) Figure 28. Individual Specific Impulses, Based on Venturi Flowrates, for N_2H_4/ClF_3 in Splash Plate Injector



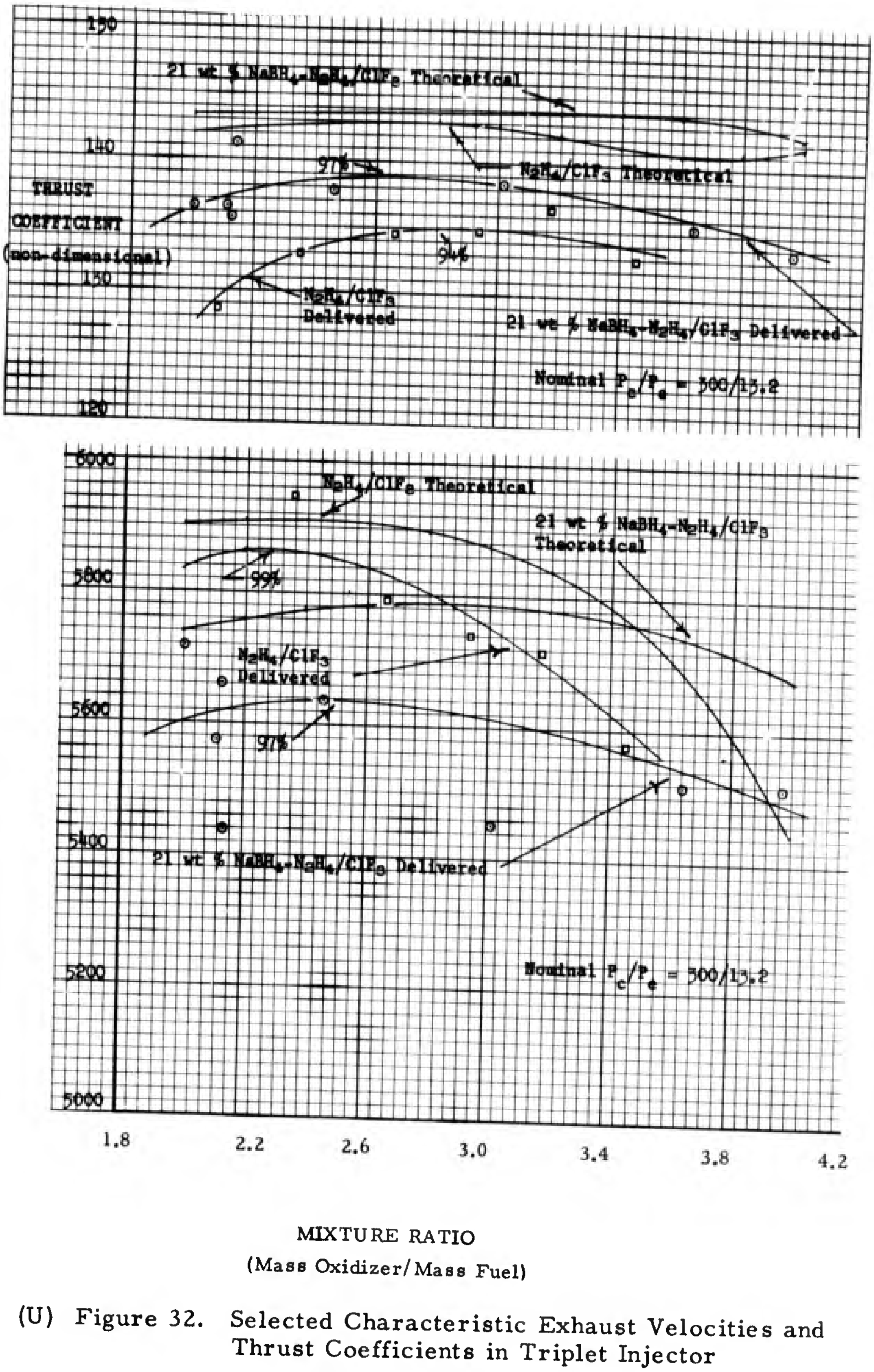
(C) Figure 29. Individual Specific Impulses, Based on Turbine Flowrates, for 19 to 21 Wt. % $NaBH_4$-N_2H_4/ClF_3 in Splash Plate Injector



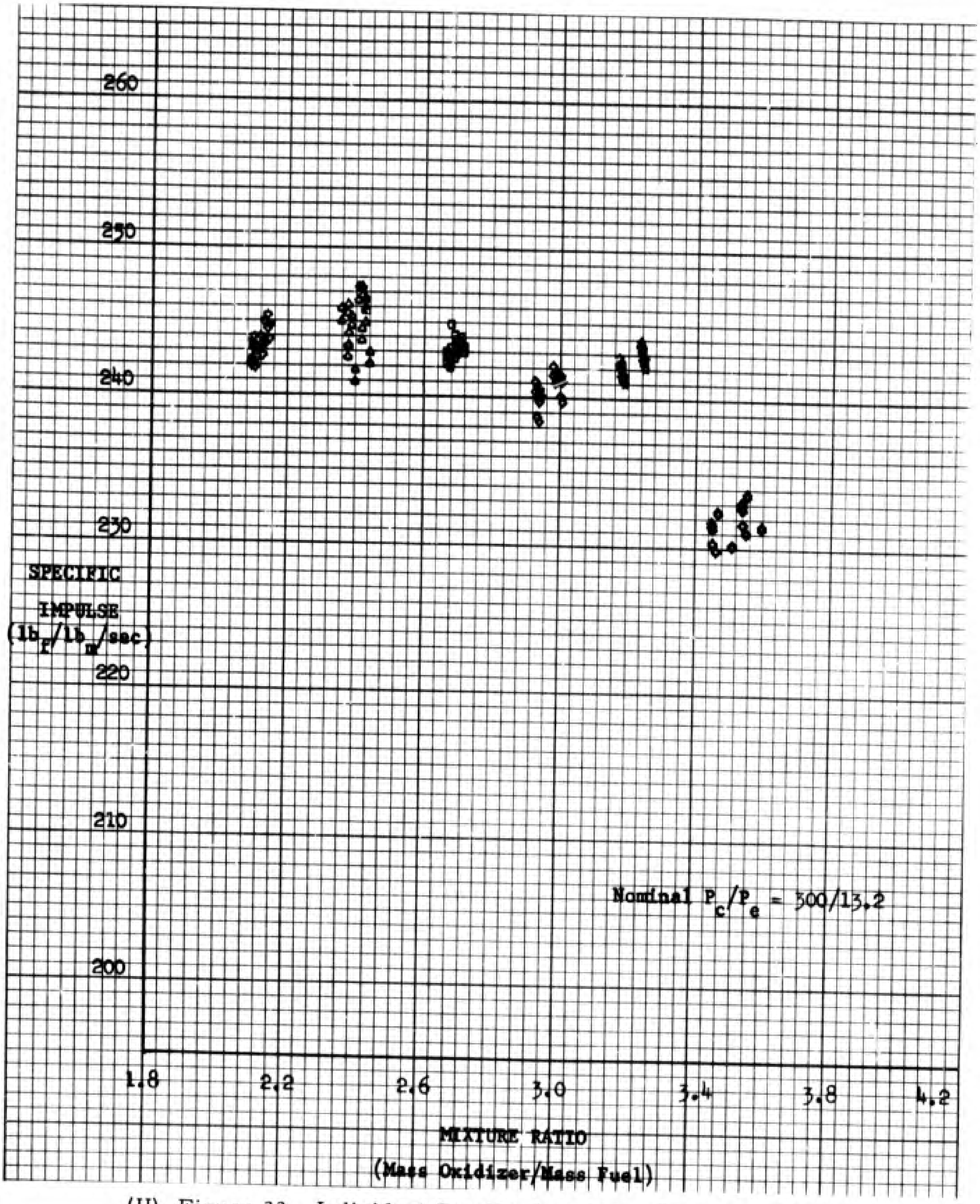
(C) Figure 30. Individual Specific Impulses, Based on Venturi Flowrates, for 19 to 21 Wt. % $NaBH_4$-N_2H_4/ClF_3 in Splash Plate Injector



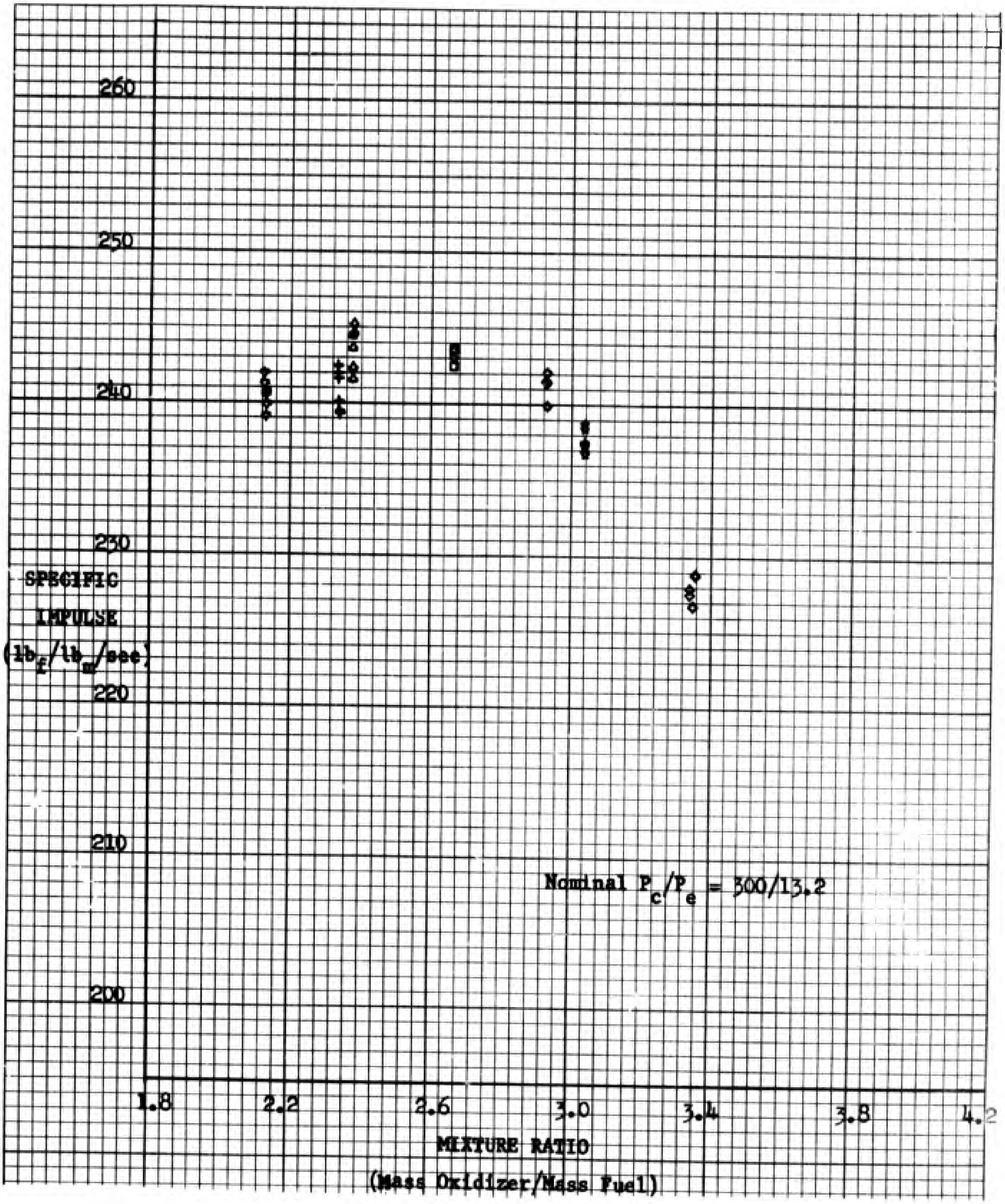
(U) Figure 31. Selected Specific Impulses in Triplet Injector



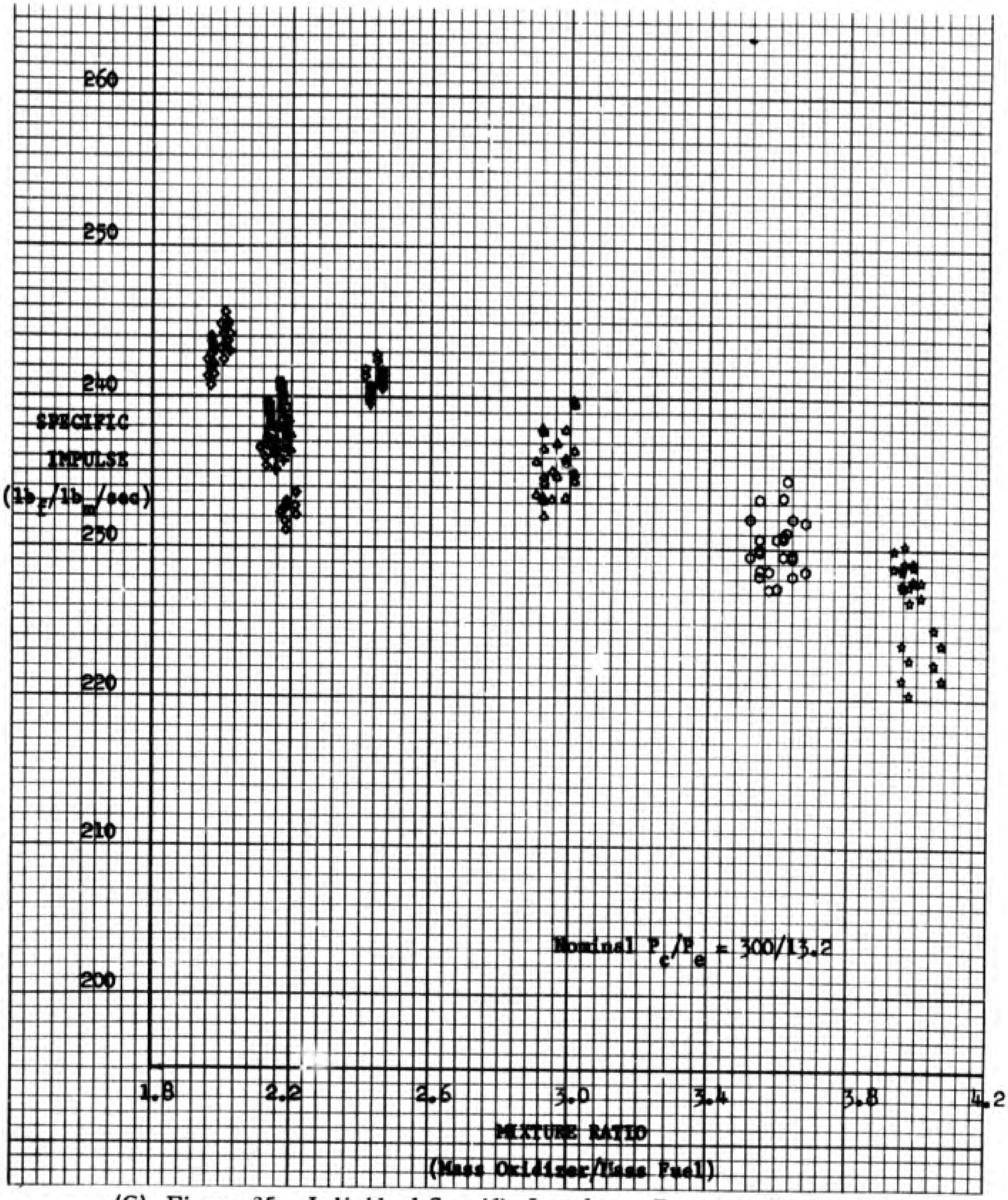
(U) Figure 32. Selected Characteristic Exhaust Velocities and Thrust Coefficients in Triplet Injector



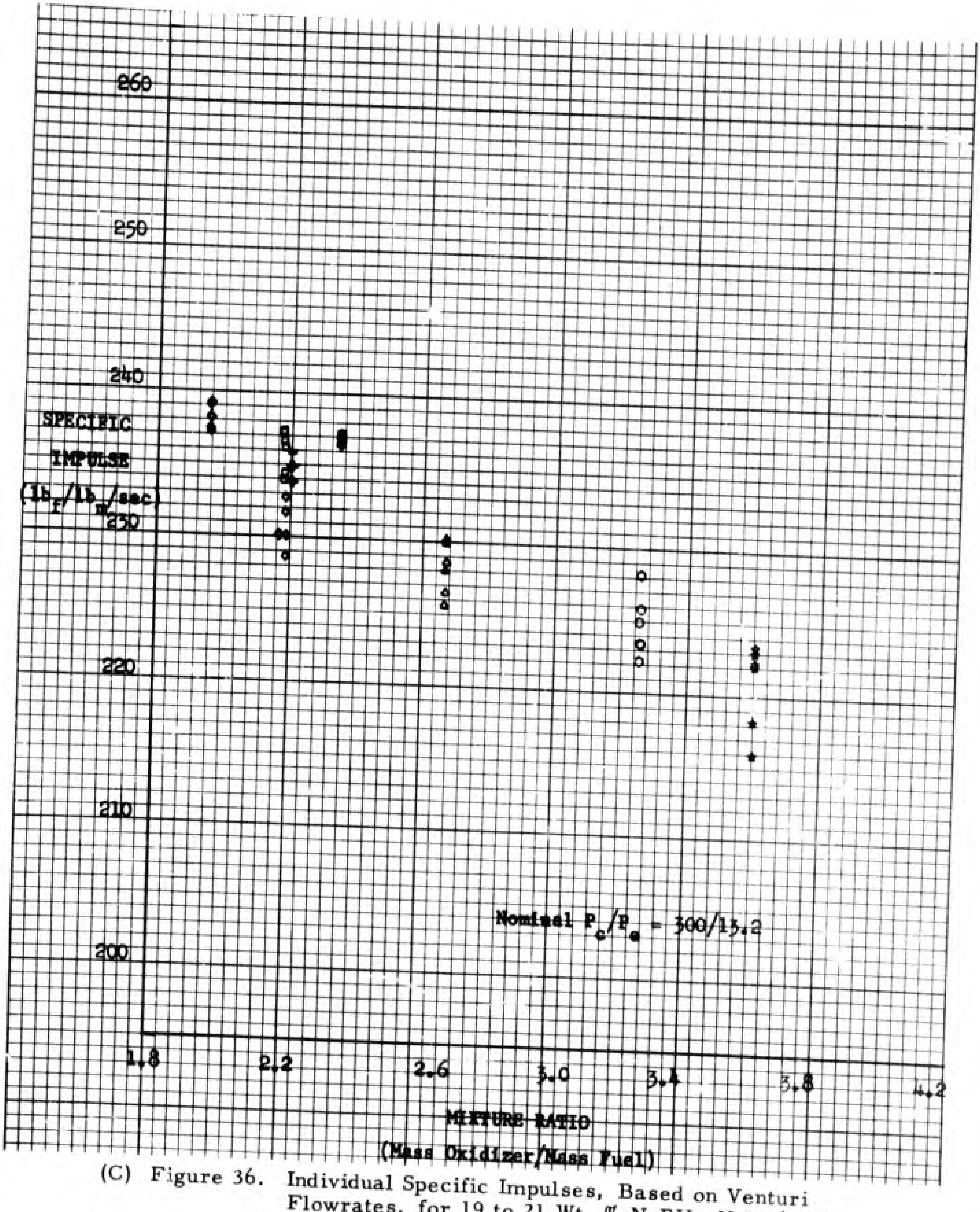
(U) Figure 33. Individual Specific Impulses, Based on Turbine Flowrates, for N_2H_4/ClF_3 in Triplet Injector



(U) Figure 34. Individual Specific Impulses, Based on Venturi Flowrates, for N_2H_4/ClF_3 in Triplet Injector



(C) Figure 35. Individual Specific Impulses, Based on Turbine Flowrates, for 19 to 21 Wt. % $NaBH_4$-N_2H_4/ClF_3 in Triplet Injector



(C) Figure 36. Individual Specific Impulses, Based on Venturi Flowrates, for 19 to 21 Wt. % $NaBH_4$-N_2H_4/ClF_3 in Triplet Injector

APPENDIX II

DATA REDUCTION

```
$IBFTC 100 LB  REF,LIST
C     100 LB BI-PROPELLANT ISP CORRECTION
      DIMENSION  MONTH(12),HDR(39,3)                          ,THEO(3,250),A(39,5
     1),FMT(12),C(5),WT(5),DUM(10),TOX(2,5),RHOX(2,5),B(17,5),FDR(17,10)
     2,THEO1(3,250),THEO2(3,250),THEO3(3,250),DMT(12),RUM(10),PVX(4),PVF
     3(4),KFCTX(4),KFCTF(4),DLTPX(5),DLTPF(5),KFACTX(5),KFACTF(5)
C
      COMMON HR1(20), GSHRCH(20), GSHREX(20), GMWCH(20), GMWEX(20),
     1       GMWTH(20), PEREF, PC(250), PAMB, AE, AT, CORISP(20),
     2       CFREF(20), CFTEST(20), XISP(20), EXISP(20), PE(20), N,
     3       K, L, BAD, AMR(250),ANG,PLOW,PHI,RLOW,RHI
      COMMON/SAM/A,SERIES,IRUN
      REAL KFCTX,KFCTF,KFACTX,KFACTF
C     INPUT-OUTPUT ASSIGNMENT
      N5=5
      N6=6
C     READ IN MONTH NAMES AND CLASSIFICATION
      READ(N5,1)(MONTH(I),I=1,12),CLASS1,CLASS2
    1 FORMAT(12A4,2A6)
C     READ IN LINE HEADERS
      READ(N5,2)((HDR(I,J),J=1,3),I=1,39)
    2 FORMAT(3A6)
C     READ IN VARIABLE FORMAT
      READ(N5,3) FMT(1),(DUM(I),I=1,10),FMT(12),BLANK
    3 FORMAT(13A6)
C     READ IN LINE HEADERS FOR PAGE 2
      READ(5,2000) ((FDR(J,LL),LL=1,10),J=1,17)
 2000 FORMAT(10A4)
C     READ IN VARIABLE PRINT FOR PAGE 2
      READ(5,3000) DMT(1),(RUM(I),I=1,10),DMT(12),BLANK
 3000 FORMAT(13A6)
C     READ FILE HEADER CARD
   10 READ(N5,11) FILE
   11 FORMAT(9XA6)
      READ(N5,4) N,ISELO,ISELF,SERIES,KODE
    4 FORMAT(3I2,A6,I4)
C     CLEAR DATA ARRAY
      BAD=1000000.
      DO 20 I=1,5
      DO 20 J=1,39
   20 A(J,I)=BAD
C     READ IN CONVERTED DATA
      DO 25 I=1,N
   25 READ(N5,26) ITEM,IRUN,C(I),IDAY,IMO,IYR
      GO TO 45
   26 FORMAT(I3,6XI3,10XF12.4,17X2I2,I1)
   30 DO 40 I=1,N
      READ(N5,31) ITEM,C(I)
   31 FORMAT(I3,19XF12.4)
      IF(ITEM.GE.999) GO TO 60
   40 CONTINUE
   45 DO 50 I=1,N
   50 A(ITEM,I)=C(I)
      GO TO 30
C     COMPUTE DELTA PRESSURES
```

```
   60 DO 70 I=1,N
      IF(A(1,I).LT.BAD) GO TO 65
      PC(I)=A(2,I)
      GO TO 67
   65 PC(I)=A(1,I)
   67 IF(PC(I).GE.BAD) GO TO 70
      IF(A(3,I).LT.BAD) A(5,I)=A(3,I)-PC(I)
      IF(A(4,I).LT.BAD) A(6,I)=A(4,I)-PC(I)
   70 CONTINUE
C     READ IN RUN CONSTANTS
      READ(5,71)PA,DT,((TOX(M,I),I=1,5),M=1,2),TOV,TFV,TF,DE,O1,O2,O3,O4
     1,F1,F2,F3,F4,ANOX,DOX,ANF,DF
   71 FORMAT(2E17.8)
      PA=PA*0.49116
      AT=DT*DT*0.7853982
      READ(5,6000) KODE1,KODE2,KODE3,PCREF,ANG,PEREF
 6000 FORMAT(3I3,F6.2,F7.4,F6.2)
      READ(5,72)(PVX(I),I=1,4),(PVF(I),I=1,4),(KFCTX(I),I=1,4),(KFCTF(I)
     1,I=1,4)
   72 FORMAT(2E17.8)
      DO 79 I=1,N
      IF(TOX(1,I).LT.BAD)RHOX(1,I)=O1+TOX(1,I)*(O2+TOX(1,I)*(O3+TOX(1,I)
     1*O4))
      IF(TOX(2,I).LT.BAD)RHOX(2,I)=O1+TOX(2,I)*(O2+TOX(2,I)*(O3+TOX(2,I)
     1*O4))
   79 CONTINUE
      RHF=F1+TF*(F2+TF*(F3+TF*F4))
      OXINJ=ANOX*DOX*DOX*0.7853982/144.
      FUINJ=ANF*DF*DF*0.7853982/144.
      DO 80 I=1,N
   80 PC(I)=PC(I)+PA
C     COMPUTE FLOW RATES,VELOCITIES,AND MIXTURE RATIO
   89 DO 90 I=1,N
      IF(A(9,I).LT.BAD)A(9,I)=0.001*A(9,I)*RHOX(1,I)
      IF(A(10,I).LT.BAD)A(10,I)=0.001*A(10,I)*RHF
      IF(A(11,I).LT.BAD)A(11,I)=0.001*A(11,I)*RHOX(2,I)
      IF(A(12,I).LT.BAD)A(12,I)=0.001*A(12,I)*RHF
C
C     VENTURI FLOW COMPUTATIONS
C
      IF(A(13,I).EQ.BAD.OR.A(14,I).EQ.BAD) GO TO 892
      RHOXV=O1+TOV*(O2+TOV*(O3+TOV*O4))
      RHOFV=F1+TFV*(F2+TFV*(F3+TFV*F4))
      VPOX=PVX(1)+TOV*(PVX(2)+TOV*(PVX(3)+TOV*PVX(4)))
      VPF=PVF(1)+TFV*(PVF(2)+TFV*(PVF(3)+TFV*PVF(4)))
      DLTPX(I)=SQRT(((A(13,I)+PA)-VPOX)*RHOXV)
      DLTPF(I)=SQRT(((A(14,I)+PA)-VPF)*RHOFV)
      KFACTX(I)=KFCTX(1)+DLTPX(I)*(KFCTX(2)+DLTPX(I)*(KFCTX(3)+DLTPX(I)*
     1KFCTX(4)))
      KFACTF(I)=KFCTF(1)+DLTPF(I)*(KFCTF(2)+DLTPF(I)*(KFCTF(3)+DLTPF(I)*
     1KFCTF(4)))
      A(13,I)=KFACTX(I)*DLTPX(I)*12.
      A(14,I)=KFACTF(I)*DLTPF(I)*12.
  892 IF(A(2*ISELO+7,I).LT.BAD)A(15,I)=A(2*ISELO+7,I)/(RHOX(ISELO,I)*
     1OXINJ)
```

```
      IF(A(2*ISELF+8,I).LT.BAD)A(16,I)=A(2*ISELF+8,I)/(RHF*FUINJ)
      IF(A(2*ISELO+7,I).GE.BAD.OR.A(2*ISELF+8,I).GE.BAD)GO TO 90
      A(17,I)=A(2*ISELO+7,I)/A(2*ISELF+8,I)
      WT(I)=A(2*ISELO+7,I)+A(2*ISELF+8,I)
   90 CONTINUE
C     COMPUTE PERFORMANCE DATA
      DO 110I=1,N
      IF(WT(I).LE.0.)GO TO 100
      IF(A(7,I).LT.BAD) A(18,I)=A(7,I)/WT(I)
      IF(A(8,I).LT.BAD) A(19,I)=A(8,I)/WT(I)
      IF(A(1,I).LT.BAD)A(20,I)=(A(1,I)+PA)*AT*32.174/WT(I)
      IF(A(2,I).LT.BAD)A(21,I)=(A(2,I)+PA)*AT*32.174/WT(I)
  100 IF(A(7,I).LT.BAD.AND.A(1,I).LT.BAD)A(22,I)=A(7,I)/((A(1,I)+PA)*AT)
      IF(A(8,I).LT.BAD.AND.A(2,I).LT.BAD)A(23,I)=A(8,I)/((A(2,I)+PA)*AT)
  110 CONTINUE
C     PREPARE FOR THEOR SBRT
      IF(KODE.LE.0) GO TO 135
      DO 120 I=1,N
  120 AMR(I)=A(17,I)
      CALL THEOR (KODE,AMR,PC,N,THEO)
      DO 130 I=1,N
      A(24,I)=THEO(1,I)
      A(25,I)=THEO(2,I)
      A(26,I)=THEO(3,I)
      IF(A(24,I).GE.BAD) GO TO 130
      IF(A(19,I).LT.BAD) A(27,I)=100.0*A(19,I)/A(24,I)
      IF(A(18,I).LT.BAD) A(27,I)=100.0*A(18,I)/A(24,I)
      IF(A(21,I).LT.BAD) A(28,I)=100.0*A(21,I)/A(25,I)
      IF(A(20,I).LT.BAD) A(28,I)=100.0*A(20,I)/A(25,I)
      IF(A(23,I).LT.BAD) A(29,I)=100.0*A(23,I)/A(26,I)
      IF(A(22,I).LT.BAD) A(29,I)=100.0*A(22,I)/A(26,I)
  130 CONTINUE
C     SELECT LINE HDRS FOR VO,VF
  135 HDR(15,2)=HDR(2*ISELO+7,2)
      HDR(16,2)=HDR(2*ISELF+8,2)
C     COMPUTE WATER DATA
      DO 140 I=1,N
      IF(A(33,I).GE.BAD) GO TO 137
      RHOWAT=62.2605+A(33,I)*(0.954087E-02-A(33,I)*(0.143281E-03-A(33,I)
     1* 0.215133E-06))
      IF(A(30,I).LT.BAD) A(30,I)=0.001*A(30,I)*RHOWAT
      IF(A(31,I).LT.BAD) A(31,I)=0.001*A(31,I)*RHOWAT
      IF(A(32,I).LT.BAD) A(32,I)=0.001*A(32,I)*RHOWAT
      CP=1.01855-A(33,I)*(0.461127E-03-A(33,I)*(0.316745E-05-A(33,I)*0.5
     189207E-08))
      IF(A(30,I).LT.BAD.AND.A(34,I).LT.BAD)A(37,I)=CP*A(30,I)*(A(34,I)-A
     1(33,I))
      IF(A(31,I).LT.BAD.AND.A(35,I).LT.BAD)A(38,I)=CP*A(31,I)*(A(35,I)-A
     1(33,I))
      IF(A(32,I).LT.BAD.AND.A(36,I).LT.BAD)A(39,I)=CP*A(32,I)*(A(36,I)-A
     1(33,I))
      GO TO 140
  137 A(30,I)=BAD
      A(31,I)=BAD
      A(32,I)=BAD
```

```
  140 CONTINUE
      DO 141 JI=1,4
      DO 141 I=1,N
      A(JI,I)=A(JI,I)+PA
  141 CONTINUE
      PAMB=PA
C     PREPARE FOR PRINTOUT
  150 WRITE(N6,151)CLASS1,CLASS2
  151 FORMAT(15H1XXXXXXXXXXXXXX/2H X2A6,1HX10X27H100 LB BI-PROPELLANT EN
     1GINE/15H XXXXXXXXXXXXXX3X17HPROJECT 3148032018X15HTEST STAND 1-21)
      WRITE(N6,152)FILE,SERIES,IRUN,IDAY,MONTH(IMO),IYR,AT
  152 FORMAT(6H0FILE A6,6X11HSERIES NO. A6,3X7HRUN NO.I4,5XI2,A4,4H 196I
     11/12H THROAT AREAF7.3,7H SQ.IN.)
      DO 220 J=1,39
      DO 210 I=1,5
      IF(A(J,I).GE.BAD) GO TO 160
      IF(A(J,I).GE.1000.)GO TO 170
      IF(A(J,I).GE.100.)GO TO 180
      IF(A(J,I).GE.10.) GO TO 190
      K=1
      GO TO 200
  160 K=5
      A(J,I)=BLANK
      GO TO 200
  170 K=4
      GO TO 200
  180 K=3
      GO TO 200
  190 K=2
  200 FMT(2*I)=DUM(K)
      FMT(2*I+1)=DUM(K+5)
  210 CONTINUE
  220 WRITE(N6,FMT)(HDR(J,L),L=1,3),(A(J,L),L=1,5)
      WRITE(N6,221)CLASS1,CLASS2
  221 FORMAT(55X14HXXXXXXXXXXXXXX/55X1HX2A6,1HX/55X14HXXXXXXXXXXXXXX)
C     CLEAR PRINTOUT ARRAY FOR PAGE 2
      DO 888 J=1,17
      DO 888 M=1,5
      B(J,M)=BAD
  888 CONTINUE
      L=2*N
      K=N+1
      AE=DE*DE*0.7853982
      EPSILN=AE/AT
      DO 333 I=1,N
      J = I+N
      PC(J)=PC(I)
      AMR(J)=AMR(I)
  333 CONTINUE
      DO 334 I=1,N
      XISP(I)=A(18,I)
      PC(I)=PCREF
  334 CONTINUE
      READ(5,889)PLOW,PHI,RLOW,RHI
  889 FORMAT (4F8.3)
```

```
      DO 444 KI=K,L
      IF(PC(KI).LT.PLOW) PC(KI)=PLOW
      IF(PC(KI).GT.PHI) PC(KI)=PHI
  444 CONTINUE
      DO 445 KIK=1,L
      IF(AMR(KIK).LT.RLOW) AMR(KIK)=RLCW
      IF(AMR(KIK).GT.RHI) AMR(KIK)=RHI
  445 CONTINUE
C
C     CALL THEOR SUBRT TO INTERPOLATE FOR HEAT RATIO IN CHAMBER
C            AND FOR HEAT RATIO IN THROAT
      CALL THEOR(KODE1,AMR,PC,L,THEO1)
      DO 1101 I=1,L
      GSHRCH(I) = THEO1(1,I)
      HR1(I)= THEO1(2,I)
 1101 CONTINUE
C
C     CALL THEOR SBRT TO INTERPOLATE FOR HEAT RATIO IN NOZZLE EXIT
C            AND FOR GAS MOLECULAR WEIGHT IN CHAMBER
      CALL THEOR(KODE2,AMR,PC,L,THEO2)
      DO 91 I=1,L
      GSHREX(I) = THEO2(1,I)
      GMWCH(I) = THEO2(2,I)
   91 CONTINUE
C
C     CALL THEOR SBRT TO INTERPOLATE FOR GAS MOLECULAR WEIGHT IN
C             THE NOZZLE THROAT AND THE NOZZLE EXIT
      CALL THEOR(KODE3,AMR,PC,L,THEO3)
      DO 92 I=1,L
      GMWTH(I) = THEO3(1,I)
      GMWEX(I) = TH 03(2,I)
   92 CONTINUE
      ANG=COS(ANG/57.29578)
C
C     CALL THE ISP CORRECTION SUBROUTINE
      CALL ISPCOR
C
C     STORE DATA IN OUTPUT ARRAY
      DO 900 M=1,N
      B(1,M)=HR1(M)
      B(2,M)=GSHRCH(M)
      B(3,M)=GSHREX(M)
      B(4,M)=GMWTH(M)
      B(5,M)=GMWCH(M)
      B(6,M)=GMWEX(M)
      B(14,M)=CFREF(M)
  900 CONTINUE
      DO 9000 MM=K,L
      M=MM-N
      B(7,M)=HR1(MM)
      B(8,M)=GSHRCH(MM)
      B(9,M)=GSHREX(MM)
      B(10,M)=GMWTH(MM)
      B(11,M)=GMWCH(MM)
      B(12,M)=GMWEX(MM)
```

```
      B(13,M)=PE(MM)
      B(15,M)=CFTEST(MM)
      B(16,M)=CORISP(MM)
      B(17,M) = EXISP(MM)
 9000 CONTINUE
      WRITE(6,700) CLASS1,CLASS2
  700 FORMAT(15H1**************/2H *2A6,1H*,24X20H100 LB BI-PROPELLANT/1
     115H **************,24X20H...ISP CORRECTION.../1H 39X17HPROJECT 3148
     203201,18X15HTEST STAND 1-21)
      WRITE(6,710) FILE,IRUN,IDAY,MONTH(IMO),IYR,PC(1),EPSILN
  710 FORMAT(11H0 FILE NO. A6,3X4HRUN I3,3X12,A4,4H 196I1,2X13HPC REFERE
     1NCE F4.0,5H PSIA,3X8HEPSILON F6.3/19H0              SLICE NO.26X1H1,9X1
     2H2,9X1H3,9X1H4,9X1H5)
      DO 2020 J=1,17
      DO 2010 M=1,5
      IF(B(J,M).GE.BAD) GO TO 1010
      IF(B(J,M).GE.100.) GO TO 1020
      IF(B(J,M).GE.10.) GO TO 1030
      KK=1
      GO TO 1990
 1010 KK=4
      B(J,M)=BLANK
      GO TO 1990
 1020 KK=3
      GO TO 1990
 1030 KK=2
 1990 DMT(2*M)=RUM(KK)
      DMT(2*M+1)=RUM(KK+6)
 2010 CONTINUE
 2020 WRITE(6,DMT)(FDR(J,LL),LL=1,10),(B(J,M),M=1,5)
      WRITE(6,2021)CLASS1,CLASS2
 2021 FORMAT(///55X14H**************/55X1H*2A6,1H*/55X14H**************)
      CALL ISPCOM
      GO TO 10
      END
```

```
$IBFTC ISPCOR  REF,LIST
      SUBROUTINE ISPCOR
      COMMON   HR1(20), GSHRCH(20), GSHREX(20), GMWCH(20), GMWEX(20),
     1GMWTH(20), PEREF, PC(250), PAMB, AE, AT, CORISP(20), CFREF(20),
     2CFTEST(20), XISP(20), EXISP(20), PE(20), N, K, L,BAD,AMR(250),ANG
     3,PLOW,PHI,RLOW,RHI
C
C     THIS SUBROUTINE WILL CORRECT ISP FOR A STATIC LIQUID ROCKET
C     ENGINE TEST TO PREDEFINED REFERENCE CONDITIONS
C
      DIMENSION HR2(20), HR3(20), AGMWCE(20), BAL(20), DIF(20),
     1OLDC(20), OBAL(20), CNEW(20)
C
C     COMPUTE AVERAGE VALUES FOR GAS MOLECULAR WEIGHT BETWEEN THE
C     CHAMBER AND NOZZLE EXIT,AND FOR SPECIFIC HEAT RATIOS BETWEEN
C     THE CHAMBER,NOZZLE THROAT AND NOZZLE EXIT
C
      DO 230 I1=1,L
      IF(PC(I1).GE.BAD.OR.AMR(I1).GE.BAD) GO TO 230
      DO 100 I=1,L
      AGMWCE(I) = (GMWCH(I)+GMWEX(I))/2.0
      HR2(I) = (GSHRCH(I)+GSHREX(I))/2.0
      HR3(I) = (GSHRCH(I)+HR1(I))/2.0
  100 CONTINUE
C
C     COMPUTE THRUST COEFFICIENT UNDER REFERENCE CONDITIONS
C
      DO 230 I2=1,N
      IF(PC(I2).GE.BAD.OR.AMR(I2).GE.BAD) GO TO 230
      DO 110 I=1,N
      CFREF(I) =((2.0*HR2(I)*HR1(I)/(HR2(I)-1.0))*
     1            (2.0/(HR3(I)+1.0))**((HR3(I)+1.0)/
     2            (HR3(I)-1.0))*((GMWCH(I)*GMWCH(I))/
     3            (AGMWCE(I)*GMWEX(I)))*(1.0-(PEREF/
     4            PC(I))**((HR2(I)-1.0)/HR2(I)))))**.5
  110 CONTINUE
C
      RAT=AT/AE
C
C     COMPUTE EXIT PRESSURE UNDER TEST CONDITIONS
C     BY AN ITERATION SCHEME
C
      DO 230 I3=K,L
      IF(PC(I3).GE.BAD.OR.AMR(I3).GE.BAD) GO TO 230
      DO 210 I=K,L
      J=0
      PE(I)=14.0
  125 BAL(I) =    ((HR3(I)+1.0)/2.0)**(1.0/(HR3(I)-1.0))*
     1            (PE(I)/PC(I))**(1.0/HR2(I))*(((HR3(I)+
     2            1.0)/(HR3(I)-1.0))*(1.0-(PE(I)/PC(I))**
     3            ((HR2(I)-1.0)/HR2(I))))**.5* (GMWEX(I)/
     4            GMWTH(I))*((GMWTH(I)/AGMWCE(I))*(HR2(I)/
     5            HR1(I))) **.5
      DIF(I) = ABS(RAT-BAL(I))
      IF(DIF(I)-0.001) 200,150,150
```

```
  150 IF(J.GT.0) GO TO 175
      J=J+1
      OLDC(I)=PE(I)
      OBAL(I)=BAL(I)
      PE(I)=15.0
      GO TO 125
  175 CNEW(I)=PE(I)-(BAL(I)-RAT)/(BAL(I)-OBAL(I))*(PE(I)-OLDC(I))
      OLDC(I)=PE(I)
      OBAL(I)=BAL(I)
      PE(I)=CNEW(I)
      GO TO 125
C
C     COMPUTE THRUST COEFFICIENT UNDER TEST CONDITIONS
C
  200 CFTEST(I) =((2.0*HR2(I)*HR1(I)/(HR2(I)-1.0))*
     1               (2.0/(HR3(I)+1.0))**((HR3(I)+1.0)/
     2               (HR3(I)-1.0))*((GMWCH(I)*GMWCH(I))/
     3               (AGMWCE(I)*GMWEX(I)))*(1.0-(PE(I)/
     4               PC(I))**((HR2(I)-1.0)/HR2(I)))))**.5
     5               +((PE(I)-PAMB)/PC(I))*(AE/AT)
  210 CONTINUE
      DO 230 I4=1,N
      IF(PC(I4).GE.BAD.OR.AMR(I4).GE.BAD) GO TO 230
      DO 220 I=1,N
      IN=I+N
      CFREF(IN) = CFREF(I)
      XISP(IN)=XISP(I)
  220 CONTINUE
C
C     COMPUTE ISP CORRECTED TO REFERENCE CONDITIONS AND ZERO DEGREE
C                         HALF ANGLE
      DO 230 I5=K,L
      IF(XISP(I5).GE.BAD)GO TO 230
      CORISP(I5) = (CFREF(I5)/CFTEST(I5))*XISP(I5)
      EXISP(I5)=CORISP(I5)/((1.+ANG)/2.)
  230 CONTINUE
      RETURN
      END
```

```
$IBFTC THECR    REF
      SUBROUTINE THECR (KODE,AMR,PC,N,THEO)
      DIMENSION AMR(250),PC(250),THEO(3,250),B(8,100),DUM(6,100),A(50,30
     1,2)
      EQUIVALENCE (A,B)
      REWIND 1
C     CHECK TO SEE IF NECESSARY ARRAY NOW IN CORE
      IF(KODE.EQ.IKODE) GO TO 20
      READ(1) ((DUM(J,I),J=1,6),(B(J,I),J=1,8),I=1,100)
      RATL=B(1,KODE)
      RATLA=B(3,KODE)
      RATHA=B(4,KODE)
      RATDEL=B(2,KODE)
      PCL=B(5,KODE)
      PCLA=B(7,KODE)
      PCHA=B(8,KODE)
      PCDEL=B(6,KODE)
      IKODE=KODE
      DO 10 I=1,KODE
   10 READ(1) JKODE,A
      REWIND 1
   20 DO 150 I=1,N
      IF(AMR(I).GT.RATHA.OR.AMR(I).LT.RATLA) GO TO 30
      IF(PC(I).LE.PCHA.AND.PC(I).GE.PCLA) GO TO 40
   30 DO 35 J=1,3
   35 THEO(J,I)=1000000.
      GO TO 150
   40 IPC=1.5+(PC(I)-PCL)/PCDEL
      IMR=1.5+(AMR(I)-RATL)/RATDEL
C     CHECK TO SEE IF BOUNDARY LINE SELECTED
      IF(PC(I).LT.PCLA+0.5*PCDEL) IPC=IPC+1
      IF(PC(I).GE.PCHA-0.5*PCDEL) IPC=IPC-1
      IF(AMR(I).LT.RATLA+0.5*RATDEL) IMR=IMR+1
      IF(AMR(I).GE.RATHA-0.5*RATDEL) IMR=IMR-1
      DX=(AMR(I)-RATL)/RATDEL-FLOAT(IMR-1)
      DY=(PC(I)-PCL)/PCDEL-FLOAT(IPC-1)
      D1=0.5*DX*(DX-1.0)
      D2=(DX-1.0)*(DX+1.0)
      D3=0.5*DX*(DX+1.0)
      IMRP=IMR+1
      IMRM=IMR-1
      IPCP=IPC+1
      IPCM=IPC-1
      DO 100 J=1,2
      YZ1=A(IMRM,IPCM,J)*D1-A(IMR,IPCM,J)*D2+A(IMRP,IPCM,J)*D3
      YZ2=A(IMRM,IPC,J)*D1-A(IMR,IPC,J)*D2+A(IMRP,IPC,J)*D3
      YZ3=A(IMRM,IPCP,J)*D1-A(IMR,IPCP,J)*D2+A(IMRP,IPCP,J)*D3
  100 THEO(J,I)=YZ1*0.5*(DY*(DY-1.0))-YZ2*(DY-1.0)*(DY+1.0)+YZ3*0.5*DY*(
     1DY+1.0)
      THEO(3,I)=32.174*THEO(1,I)/THEO(2,I)
  150 CONTINUE
      RETURN
      END
```

```
$IBFTC ISPCOM  REF,L
      SUBROUTINE ISPCOM
C     100 LB BI-PROPELLANT ISP AND MIXTURE RATIO COMBINATIONS, AVERAGE
C     AND STANDARD DEVIATION OF ISP AND MIXTURE RATIO FOR EACH RUN -
C     LT P. H. MC NAMARA
      DIMENSION A(39,5),T(25)
      COMMON/SAM/A,SERIES,IRUN
      NSER = SERIES
C     PARAMETERS REPRESENTED BY A(J,I),  IN ORDER FROM A(1,I) THRU A
C     (23,I), ARE F1, F2, WO1, WO 2, WO3, WF1, WF2, WF3, (ISP,O/F)1
C     THRU (ISP,O/F)10 FOR EACH TIME SLICE
C     ESTABLISH T(L) = STUDENT'S T DISTRIBUTION FOR TWO SIDED TEST WITH
C     ALPHA = 0.05, L= DEGREES OF FREEDOM + 1 = NUMBER OF SAMPLES
      T(1)=1000000.
      T(2)=12.706
      T(3)=4.303
      T(4)=3.182
      T(5)=2.776
      T(6)=2.571
      T(7)=2.447
      T(8)=2.365
      T(9)=2.306
      T(10)=2.262
      T(11)=2.228
      T(12)=2.201
      T(13)=2.179
      T(14)=2.160
      T(15)=2.145
      T(16)=2.131
      T(17)=2.120
      T(18)=2.110
      T(19)=2.101
      T(20)=2.093
      T(21)=2.086
      T(22)=2.080
      T(23)=2.074
      T(24)=2.069
      DO 10 I=1,3
      A(1,I)=A(7,I)
      A(2,I)=A(8,I)
      A(3,I)=A(9,I)
      A(4,I)=A(11,I)
      A(5,I)=A(13,I)
      A(6,I)=A(10,I)
      A(7,I)=A(12,I)
   10 A(8,I)=A(14,I)
C     CLEAR DATA ARRAY
   20 BAD=1000000.
      DO 25 I=1,3
      DO 25 J=9,28
   25 A(J,I)=BAD
C     COMPUTE ISP, AND O/F
      DO 70 I=1,3
      DO 27 J=1,8
      IF(A(J,I))26,26,27
```

```
   26 A(J,I) = BAD
   27 CONTINUE
      IF(A(1,I).GE.BAD)GO TO 45
      IF(A(3,I).GE.BAD)GO TO 35
      IF(A(6,I).GE.BAD)GO TO 30
      A(9,I)=A(1,I)/(A(3,I)+A(6,I))
      A(10,I)=A(3,I)/A(6,I)
   30 IF(A(7,I).GE.BAD)GO TO 35
      A(11,I)=A(1,I)/(A(3,I)+A(7,I))
      A(12,I)=A(3,I)/A(7,I)
   35 IF (A(4,I).GE.BAD)GO TO 45
      IF(A(6,I).GE.BAD)GO TO 40
      A(13,I)=A(1,I)/(A(4,I)+A(6,I))
      A(14,I)=A(4,I)/A(6,I)
   40 IF(A(7,I).GE.BAD)GO TO 45
      A(15,I)=A(1,I)/(A(4,I)+A(7,I))
      A(16,I)=A(4,I)/A(7,I)
   45 IF(A(2,I).GE.BAD)GO TO 65
      IF(A(3,I).GE.BAD)GO TO 55
      IF(A(6,I).GE.BAD)GO TO 50
      A(17,I)=A(2,I)/(A(3,I)+A(6,I))
      A(18,I)=A(3,I)/A(6,I)
   50 IF(A(7,I).GE.BAD)GO TO 55
      A(19,I)=A(2,I)/(A(3,I)+A(7,I))
      A(20,I)=A(3,I)/A(7,I)
   55 IF(A(4,I).GE.BAD)GO TO 65
      IF(A(6,I).GE.BAD)GO TO 60
      A(21,I)=A(2,I)/(A(4,I)+A(6,I))
      A(22,I)=A(4,I)/A(6,I)
   60 IF(A(7,I).GE.BAD)GO TO 65
      A(23,I)=A(2,I)/(A(4,I)+A(7,I))
      A(24,I)=A(4,I)/A(7,I)
   65 IF(A(5,I).GE.BAD.OR.A(8,I).GE.BAD)GO TO 70
      IF(A(1,I).LT.BAD)A(25,I)=A(1,I)/(A(5,I)+A(8,I))
      A(26,I)=A(5,I)/A(8,I)
      IF(A(2,I).LT.BAD)A(27,I)=A(2,I)/(A(5,I)+A(8,I))
      A(28,I)=A(26,I)
   70 CONTINUE
C     COMPUTATION OF MAXIMUM AND MINIMUM ISP AND MIXTURE RATIO
      BMINI= A(9,1)
      BMAXI = 0.
      DO 71 I=1,3
      DO 71 J=9,23,2
      IF(A(J,I).GE.BAD)GO TO 71
      IF(A(J,I).GT.BMAXI)BMAXI=A(J,I)
   71 IF(A(J,I).LT.BMINI)BMINI=A(J,I)
      IF(BMINI.GE.BAD)BMINI = 0.
      BMINM = A(10,1)
      BMAXM = 0.
      DO 72 I=1,3
      DO 72 J=10,24,2
      IF(A(J,I).GE.BAD)GO TO 72
      IF(A(J,I).GT.BMAXM)BMAXM = A(J,I)
   72 IF(A(J,I).LT.BMINM)BMINM = A(J,I)
      IF(BMINM.GE.BAD)BMINM = 0.
```

```
C     COMPUTATION OF MEAN ISP AND PRECISION PARAMETERS
      REAL LCLISP,LCLMR
C     CLEAR DATA POSITIONS
      BARISP =0.
      SDISP=BAD
      ERRISP=BAD
      UCLISP=0.
      LCLISP=0.
      BARMR=0.
      SDMR=BAD
      ERRMR=BAD
      UCLMR=0.
      LCLMR=0.
      BARIV=0.
      SDIV=BAD
      BARMV=0.
      SDMV=BAD
      M1=9
      M2=23
   75 SUMX = 0.
      SUMXSQ = 0.
      L = 0
      DO 85 I=1,3
      DO 85 J=M1,M2,2
      IF (A(J,I)-BAD)80,85,85
   80 SUMX = SUMX + A(J,I)
      SUMXSQ = SUMXSQ + A(J,I)*A(J,I)
      L= L+1
   85 CONTINUE
      DS = FLOAT(L)*SUMXSQ-SUMX*SUMX
      IF(DS.LT.0.) DS=0.
      IF(L-1)86,86,88
   86 IF(M1-10)91,96,87
   87 IF(M1-26)106,117,117
   88 IF (M1-10)90,95,100
   90 BARISP =SUMX/FLOAT(L)
      SDISP=SQRT(DS/(FLOAT(L*(L-1))))
      ERRISP=T(L)*SDISP/SQRT(FLOAT(L))
      UCLISP = BARISP + ERRISP
      LCLISP = BARISP - ERRISP
C     COMPUTATION OF MEAN MIXTURE RATIO AND PRECISION PARAMETERS
   91 M1 =10
      M2 =16
      GO TO 75
   95 BARMR=SUMX/FLOAT(L)
      SDMR =SQRT(DS/(FLOAT(L*(L-1))))
      ERRMR=T(L)*SDMR/SQRT(FLOAT(L))
      UCLMR = BARMR + ERRMR
      LCLMR = BARMR - ERRMR
C     COMPUTATION OF MEAN ISP AND MIXTURE RATIO AND STANDARD DEVIATION
C     BASED ON VENTURI FLOW RATES
   96 M1 = 25
      M2 = 27
      GO TO 75
  100 IF(M1-26)105,110,117
```

```
 105 BARIV=SUMX/FLOAT(L)
     SDIV =SQRT(DS/(FLOAT(L*(L-1))))
 106 M1 = 26
     M2 = 26
     GO TO 75
 110 BARMV=SUMX/FLOAT(L)
     SDMV =SQRT(DS/(FLOAT(L*(L-1))))
C    PRINT OUT
     IR = 0
     IK = 1
 117 WRITE(6,116)NSER,IRUN
 116 FORMAT(15H1XXXXXXXXXXXXXX41X24HISP AND O/F COMBINATIONS/15H XCONFI
    1DENTIALX/15H XXXXXXXXXXXXXX/1H 20X7HSERIES I3,9X4HRUN I5,9X17HPROJ
    2ECT 31480320110X20HBI-PROPELLANT ENGINE/1H010X2HF16X2HF26X3HW015X
    33HW025X3HW035X3HWF15X3HWF25X3HWF35X2HI16X2HM16X2HI26X2HM26X2HI36X
    42HM36X2HI4/1H010X2HM46X2HI56X2HM56X2HI66X2HM66X2HI76X2HM76X2HI86X
    52HM86X2HI96X2HM96X3HI105X3HM10)
     DO 125 I=1,3
     DO 120 J=1,28
 120 IF (A(J,I).GE.BAD)A(J,I)=0.
 125 WRITE(6,121) (A(J,I),J=1,28)
 121 FORMAT(1H-6X,2F8.2,6F8.4,3(F8.2,F8.4),F8.2/1H06X,F8.4,6(F8.2,F8.4)
    1)
     WRITE(6,130) BMAXI,BMINI,BARISP,SDISP,UCLISP,LCLISP,ERRISP
 130 FORMAT(1H-6X78H(THE FOLLOWING PARAMETERS DO NOT INCLUDE I9, I10, M
    19, M10 FOR EACH TIME SLICE)/1H06X11HMAXIMUM ISPF8.2, 5X11HMINIMUM
    2ISPF8.2, 6X8HMEAN ISPF8.2, 5X9HSIGMA ISPE15.5/1H06X37H95 PERCENT U
    3PPER CONFIDENCE LIMIT ISPF8.2, 9X37H95 PERCENT LOWER CONFIDENCE LI
    4MIT ISPF8.2/1H06X32H95 PERCENT ERROR OF THE ESTIMATEE15.5)
     WRITE(6,135)BMAXM, BMINM, BARMR, SDMR, UCLMR, LCLMR, ERRMR
 135 FORMAT(1H-6X11HMAXIMUM O/FF8.4, 5X11HMINIMUM O/FF8.4, 6X8HMEAN O/F
    1F8.4, 5X9HSIGMA O/FE15.5/1H06X37H95 PERCENT UPPER CONFIDENCE LIMIT
    2 O/FF8.4, 9X37H95 PERCENT LOWER CONFIDENCE LIMIT O/FF8.4/1H06X32H9
    35 PERCENT ERROR OF THE ESTIMATEE15.5)
     WRITE(6,140) BARIV, SDIV, BARMV, SDMV
 140 FORMAT(1H-6X76H(THE FOLLOWING PARAMETERS INCLUDE ONLY I9, I10, M9,
    1 M10 FOR EACH TIME SLICE)// 7X,8HMEAN ISPF8.2, 8X9HSIGMA ISPE15.5/
    21H06X8HMEAN O/FF8.4, 8X9HSIGMA O/FE15.5//1H050X14HXXXXXXXXXXXXXX/
    31H 50X14HXCONFIDENTIALX/1H 50X14HXXXXXXXXXXXXXX)
C    PUNCH CARDS FOR USE ON X-Y PLOTTER
     IF(BARISP.LE.0.)GO TO 146
 145 WRITE(7,155) BARISP,BARMR,IRUN,IR,IK,SERIES
 146 IF(BARIV.LE.0.)GO TO 147
     WRITE(7,155) BARIV,BARMV,IRUN,IR,IK,SERIES
 147 DO 150 I=1,3
     DO 150 J=9,28,2
     IF(A(J,I).LE.0.)GO TO 150
     M=J+1
     WRITE(7,155) A(J,I), A(M,I),IRUN,J,I,SERIES
 150 CONTINUE
 155 FORMAT(F8.1,F8.3,I4,I3,I2,I4)
     RETURN
     END
```

DATA INPUT TO 100-LB BIPROPELLANT

Program 769

1. File Header Card
2. Run Information Card:
    - A. Column 2 - Number of time slices
    - B. Column 4 - Oxidizer flow selection: 1, 2, 3
    - C. Column 6 - Fuel flow selection: 1, 2, 3
    - D. Columns 7-12 - Series number
    - E. Columns 14-16 - Code number of Theoretical file
3. Converted data as received from General Data Program (including ending 999 card)
4. The following cards in 2E 17.8 Format:
    - A. Ambient pressure ("HG); throat diameter
    - B. First and second coefficient of oxidizer density equation
    - C. Third and fourth coefficient of oxidizer density equation
    - D. First and second coefficient of fuel density equation
    - E. Third and fourth coefficient of fuel density equation
    - F. Oxidizer temperatures (per five slices for each FLOWMETER)
    - G. Temperature of oxidizer venturi; temperature of fuel venturi
    - H. Number of oxidizer injector holes; diameter of holes
    - I. Number of fuel injector holes; diameter of holes
    - J. Fuel temperature; diameter of exit (in.)
    - K. KODE 1, KODE 2, KODE 3, P. C. REF., ANGLE, P. E. REF.
      (I3) (I3) (I3) (F6.2) (F7.4) (F6.2)
    - L. Oxidizer vapor pressure coefficient 1, 2
    - M. Oxidizer vapor pressure coefficient 3, 4
    - N. Fuel vapor pressure coefficient 1, 2
    - O. Fuel vapor pressure coefficient 3, 4
    - P. K-Factor oxidizer coefficient 1, 2
    - Q. K-Factor oxidizer coefficient 3, 4
    - R. K-Factor fuel coefficient 1, 2
    - S. K-Factor fuel coefficient 3, 4
    - T. P. C LOW, P. C HIGH, M. R LOW, M. R HIGH
      (F8.3) (F8.3) (F8.3) (F8.3)

DEFINITION OF SYMBOLS USED IN ISP CORRECTION PROGRAM

A = Array of Answer

AE = Nozzle Exit Area

AGMWCE = Avg. Gas Molecular Weight Between Chamber And Nozzle Exit

AMR = Mixture Ratio

AT = Nozzle Throat Area

BAD = 1,000,000

BAL = Computed Ratio Valve Of Throat Area To Exit Area

BLANK = Input - Output Printout Variable

CFREF = Thrust Coefficient For Reference Conditions

CFTEST = Thrust Coefficient For Test Conditions

CLASS = Input - Output Printout Variable For Classification

CORISP = ISP Corrected To Ref. Conditions

CNEW = New Exit Pressure

DE = Exit Diameter

DIF = Difference Between Computed Valve And Actual Valve

DUM = Input - Output Printout Variable

EPSILN = Expansion Ratio (Epsilon)

EXISP = ISP Corrected To Zero Divergence

FILE = File Header Card

FMT = Input - Output Printout Variable

GMWCH = Gas Molecular Weight in Chamber

GMWEX = Gas Molecular Weight At Nozzle Exit Plane

GMWTH = Gas Molecular Weight At Throat

GSHRCH = Gas Specific Heat Ratio In Chamber

GSHREX = Gas Specific Heat Ratio In Nozzle Exit

HDR = Array of Output Names

HR 1 = Gas Specific Heat Ratio At Nozzle Throat

HR 2 = Avg. Gas Specific Heat Ratio Between Chamber And Nozzle Exit

HR 3 = Avg. Gas Specific Heat Ratio Between Chamber And Throat

IRUN = Run Number

KODE 1 = Fuel Code 1 (On Tape)

KODE 2 = Fuel Code 2 (On Tape)

KODE 3 = Fuel Code 3 (On Tape)

OBAL = Last Computed Area Ratio Valve

OLDC = Last Trial Exit Pressure

PAMB = Ambient Pressure

PC = Combustion Chamber Pressure

PE = Nozzle Exit Pressure

PEREF = Reference Nozzle Exit Pressure

RAT = Ratio Of Throat Area To Exit Area To Be Used When Computing Exit Pressure

THEO 1 =

THEO 2 = Answers From Theor (Interpolation) Subroutine

THEO 3 =

XISP = Calculated ISP From Run Data

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13. ABSTRACT

(C) A fuel, consisting of 19 to 21 weight percent of sodium borohydride dissolved in hydrazine, was fired with chlorine trifluoride in an uncooled engine with a nominal thrust of 150 lb_f and a nominal chamber pressure of 300 psia. The normal ambient pressure was 13.2 psia. Three injectors, a like-on-like, a splash plate and a triplet, were used. Hydrazine and chlorine trifluoride were fired in the same engine configurations to provide baseline data. There were no significant changes in the sodium borohydride-hydrazine fuel chemical composition during a 2-year storage period. The ignition and combustion of the 19 to 21 wt. % $NaBH_4$-N_2H_4/ClF_3 combination were hypergolic, smooth, reliable and stable. The peak delivered uncorrected specific impulse of the 19 to 21 wt. % $NaBH_4$-N_2H_4/ClF_3 combination ranged from 217 to 239 lb_f-sec/lb_m. This range is from 84% to 93% of the peak theoretical specific impulse as determined by the Air Force Rocket Propulsion Laboratory. The peak specific impulse was the least in the like-on-like injector and the most in the triplet injector. The peak delivered specific impulse of the N_2H_4/ClF_3 was about 5 lb_f-sec/lb_m greater than the peak delivered specific impulse of 19 to 21 wt. % $NaBH_4$-N_2H_4/ClF_3. Air Force Rocket Propulsion Laboratory theoretical data were verified. General Electric theoretical data, which predicted a 17 lb_f-sec/lb_m advantage for the 19 wt. % $NaBH_4$-N_2H_4/ClF_3 combination over the N_2H_4/ClF_3 combination, were not verified. Multiple measurements of thrust, chamber pressure, flowrates and temperatures and statistical evaluation were used to determine the reliability of the test apparatus.

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	ROLE	WT	ROLE	WT	ROLE	WT
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Chlorine Trifluoride						
Evaluation						
High Energy Fuel						
Propellants						

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