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AN ANALYSIS OF THE ACCURACY OF LIQUID-PROPELLANT ROCKET ENGINE PERFORMANCE MEASUREMENTS IN THE PROPULSION ENGINE TEST CELL (J-2A)

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ARO, Inc.

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ROCKET TEST FACILITY

ARNOLD ENGINEERING DEVELOPMENT CENTER

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NOTICES

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FOREWORD

The work and results presented herein were obtained by ARO, Inc. (a subsidiary of Sverdrup and Parcel, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Contract AF 40(600)-1000, Program Area 921E/9071. The test was conducted from May 28 to September 4, 1964, under ARO Project No. RL1422, and the report was submitted by the author on February 12, 1965.

This technical report has been reviewed and is approved.

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ABSTRACT

Measurements obtained during recent testing in the Propulsion Engine Test Cell (J-2A) are analyzed to determine the accuracy of measuring liquid-propellant rocket engine performance. The equipment and calibration techniques used to obtain the data and the statistical methods employed for error analysis are discussed. The results demonstrated that the one standard deviation errors in thrust, chamber pressure, cell pressure, oxidizer flow rate, and fuel flow rate measurements are less than ±0.110, ±0.198, ±0.769, ±0.181, and ±0.150 percent, respectively. The accuracy of the primary calculated performance parameters, thrust coefficient, specific impulse, and characteristic velocity, are ±0.226, ±0.166, and ±0.234 percent (one standard deviation), respectively.

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NOMENCLATURE

A_{nc}	Nozzle exit area, in.^{2}
A_t	Throat area, in.^{2}
C_F	Thrust coefficient
c^*	Characteristic velocity, ft/sec
D	Weighting factor (for addition error propagation)
d	Mean difference between duplicate data for a sample, percent
F	Thrust, lb_f
g	Dimensional constant, 32.174 lb_f-ft/lb_m-sec^2
h	A measure of precision
I_{sp}	Specific impulse, lb_f-sec/lb_m
K_w	Propellant flowmeter constant, lb_m/cycle
N	Number of redundant channels
n	Number of observations
P_a	Cell pressure, psia
P_c	Chamber pressure, psia
SG	Specific gravity

S(X)	One standard deviation of the variable (X) when calculated from a sample
	$S(X) = \sqrt{\frac{\Sigma(X - \bar{X})^2}{n-1}}$ or $\sqrt{\frac{\Sigma(\Delta - \bar{\Delta})^2}{n-1}}$ or $\sqrt{\frac{\Sigma \Delta^2 - n(\bar{\Delta})^2}{n-1}}$
T	Propellant temperature, °F
w	Propellant flow rate, lb_m/sec
X	An independent variable, the abscissa of a graph
$\bar{X}$	The mean of the independent variables
Y	A measure of the relative frequency of occurrence, the ordinate of a graph
Δ	The difference between the average of duplicate observations and the observation, percent
$\bar{\Delta}$	The average Δ
δ	The deviation from the mean $(\bar{\Delta} - \Delta)$, percent
ϵ	The error of a measurement
$\Sigma\epsilon$	The sum of the errors
$\bar{\epsilon}$	The average error of a measurement
σ	One standard deviation

SUBSCRIPTS

cc	Calibrator constant
dwc	Deadweight calibrator
F	Force
f	Fuel
ip	In-place
m	Measured, or minimum, or mass
o	Oxidizer
r	Random
SG	Specific gravity
s	Systematic
t	Total

SECTION I
INTRODUCTION

The primary product obtained from tests conducted in the Propulsion Engine Test Cell (J-2A) is the published technical information and data. These data are of limited value unless some statement is made concerning the accuracy and precision of the measurements used to obtain the data.

The purpose of this report is to characterize the quality of performance data by stating the possible errors in measurement of engine test data and to combine these by standard statistical methods to show the quality of measured and calculated performance parameters. The primary rocket performance parameters, thrust coefficient, characteristic velocity, and vacuum specific impulse, are calculated from the measured data by the following equation:

$$C_F = F / P_c A_t$$

$$c^* = P_c A_t g / \dot{w}_t$$

$$I_{sp} = F / \dot{w}_t$$

where

$$F = F_m + P_a A_{ne}$$

This report presents the accuracy of steady-state measurements of F_m, P_c, $\dot{w}_o$, $\dot{w}_f$, P_a, A_{ne}, and A_t by demonstrating the precision of the data (random error) and by estimating the magnitude of systematic errors. These errors are then combined by "propagation of error" mathematics to compute the standard deviation of the parameters, C_F, c^*, and I_{sp}.

The data used for these analyses were obtained during three phases of testing (I, II, and III) of the LEM Ascent engine[1]. For Phases I and III, the prototype LEM Ascent engine was a 3500-lb nominal thrust, ablatively cooled engine. For Phase II, a water-cooled, hard-contour engine was used. Firings were performed at pressure altitudes ranging from 77,000 to 108,000 ft and at temperatures from 70 to 80°F. Phases I, II, and III consisted of twelve, twenty-eight, and nine firings, respectively.

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[1]The results of these tests are published in four AEDC technical reports. One of these is a summary report covering all three phases. The other three reports cover the phases separately.

The data analyzed were obtained from the steady-state portion of rocket firings using high resolution recording systems for all measurements except propellant flow rates. Analog transducer signals of axial thrust, chamber pressure, and cell pressure were converted to frequency form (20,000 to 80,000 cps) for recording on magnetic tape.

Propellant flow data were derived from flowmeter pulses generated by turbine-type flowmeters (proportional to volumetric flow rate) and were recorded on magnetic tape. Analog tape data were reduced to engineering units by a digital computer and were averaged and printed at 0.2-sec intervals.

SECTION II
APPARATUS

2.1 TEST CELL

The Propulsion Engine Test Cell (J-2A) (Fig. 1 and Ref. 1) is an ultrahigh altitude simulation, rocket engine test chamber which can provide pressure altitudes in excess of 400,000 ft. A complete description of the test cell can be found in Ref. 2.

The test cell was operated in a conventional manner for the tests discussed; that is, no ultrahigh altitude pumping or cryogenic systems were used. The pressure altitude was obtained by facility exhausters, mechanical pumps, and a rocket exhaust-driven ejector-diffuser.

2.2 ENGINE THRUST MEASURING SYSTEM

The rocket engine was rigidly mounted in a thrust cradle which was supported by five universal flexures as shown in Fig. 1. Two of these flexures were mounted in a vertical plane on the centerline of the engine to provide vertical support to the cradle and to prevent pitch and vertical movement. Three flexures were mounted in horizontal planes. Two of these flexures were located in a horizontal plane on the centerline of the engine to restrict horizontal movement and yaw. The other flexure was displaced from the centerline to prevent roll of the cradle about the centerline or engine axis. The system of flexures allowed the cradle freedom of movement axially with a minimum of interacting forces. The axial force of the engine was restrained by the thrust butt through a load-cell train consisting of two flexures and two load cells mounted in tandem on the centerline of the engine. The flexures were attached to the cradle and to the thrust butt.

The propellant supply lines, cooling water lines, and instrumentation connections to the engine and cradle were installed in a manner which would minimize tare loads.

2.3 INSTRUMENTATION

The primary measured parameters required for this analysis were rocket engine thrust, chamber pressure, propellant flow rate, and cell pressure.

2.3.1 Engine Thrust

Two 0 to 5000-lb, dual-bridge, strain-gage-type load cells were mounted in series (Fig. 1) and provided four thrust data channels. The tnrust measuring system (Fig. 2) was calibrated by using an in-place deadweight calibrator. The calibrator is remotely controlled and applies known incremental forces on the cradle assembly in the same direction as engine thrust. This calibrator allows in-place deadweight calibrations at altitude conditions and has a mechanical advantage of 10.22. The calibrator weights were corrected for a local gravity constant of 32.141 $ft\text{-}lb_f/sec^2\text{-}lb_m$.

2.3.2 Propellant Flow Rate

The propellant flow measuring system consisted of two 1-in. volumetric, turbine-type flowmeters and two resistance temperature transducers in each propellant supply line as shown in Fig. 3.

Before the first test, the flowmeters and sections of the propellant supply lines (immediately upstream and downstream of the flowmeters) were removed and bench calibrated as an assembly using propellants as the flowing fluid. Before the first firing and during the test series, the flowmeter sections were bench calibrated using water as the flowing fluid (Fig. 4). Corrections for the difference between the propellant and water calibrations (viscosity effects) were applied to all subsequent water calibrations of the flowmeters.

Since the flowmeter calibrations based on the propellants as the working fluids were not accomplished at AEDC, no attempt was made to statistically determine the accuracy of those calibrations (the viscosity corrections).

Because the flowmeter measured volumetric flow rate, it was necessary to know the specific gravity of the propellant in order to convert the volumetric flow rate to a weight flow rate. The specific gravity was determined by measuring the temperature of the propellant immediately downstream of the downstream flowmeter. The corresponding specific gravity was determined from a graph of temperature as a function of the specific gravity. Specific gravity data for this graph were measured in the laboratory from propellant samples obtained from each propellant tank prior to each test period.

Propellant temperatures (used for specific gravity determination during testing) were measured with resistance temperature transducers (Fig. 5). This instrument contains a platinum resistor in an a-c bridge circuit. As temperature changes, the bridge is unbalanced, and a voltage proportional to temperature results.

2.3.3 Chamber Pressure

Chamber pressure measurements were made with strain-gage-type transducers. The transducer outputs were analog voltages proportional to pressure (Fig. 6).

Calibrations of the pressure transducers were performed in two different ways. For Phases I and II, the pressure transducers were bench calibrated in the laboratory using a system of air deadweight gages as the standard. For Phase III testing, in-place calibrations were performed. The secondary standard used for the in-place calibrations was a variable-reluctance-type pressure head.

2.3.4 Cell Pressure

The device used to measure test cell pressure was a variable-capacitance sensor (Fig. 7). This instrument contains a taut metal diaphragm which forms the center plate of a three-plate capacitor. One side of the diaphragm is open to cell pressure, while the other side is exposed to a known reference pressure. The capacitance sensor forms an a-c bridge circuit with an excitation transformer. As pressure deflects the diaphragm, the bridge is unbalanced, and a voltage proportional to the pressure is developed and is transmitted to the recording system.

The capacitance sensors were calibrated prior to installation in the test cell by using a precision micromanometer as a pressure standard. The capacitance sensors were calibrated in the cell by placing a known voltage change in the a-c bridge circuit and correlating the analog output with the laboratory calibration.

Heaters in the cell pressure sensors maintain the head temperature within specified limits. The heaters are also used for vacuum bakeout of the sensors up to 300°F. This allows vacuum outgassing of any residue accumulated on the sensing components.

2.3.5 Recording Systems

The recording systems used for thrust, chamber pressure, cell pressure, and propellant temperatures each consisted of a voltage-controlled oscillator, recording amplifier, and one or more channels of a magnetic tape recorder. The voltage-controlled oscillator provided a linear frequency deviation proportional to the analog voltage input signal from the transducer. The oscillator operating frequency range was approximately 20,000 to 80,000 cps. This 60,000-cps range corresponded to the range of the measurement. The measurements were recorded in frequency form on the magnetic tape and were averaged and printed at 0.2-sec intervals by a digital computer.

The recording systems were electrical resistance calibrated immediately before each rocket firing while the transducers were at altitude conditions.

The propellant flow rate recording systems did not utilize the voltage controlled oscillator. The flowmeters generate pulses (proportional to volumetric flow) which are amplified and recorded directly on magnetic tape. A digital computer determined the number of pulses per unit time from the magnetic tape and printed a corresponding flow rate at 0.2-sec intervals.

SECTION III
ANALYSIS

3.1 STANDARD DEVIATION

The standard deviation is the most accepted measure of variability of randomly distributed data. A discussion of the standard deviation and its derivation may be found in numerous text books dealing with statistical analysis. It must be emphasized that the standard deviation, in practice, is a statement of probability based on the assumption that the data are randomly distributed about a mean. The standard deviation is the square root of the mean-squared deviation of the individual measurements from the mean of the population and is designated sigma (σ),

$$\sigma = \sqrt{\frac{\Sigma (X - \bar{X})^2}{n}}$$

This equation is valid only when n represents the total number of possible observations (the entire population). In practice, the standard deviation $S(X)$ is estimated from a sample of the total possible observations and is defined as

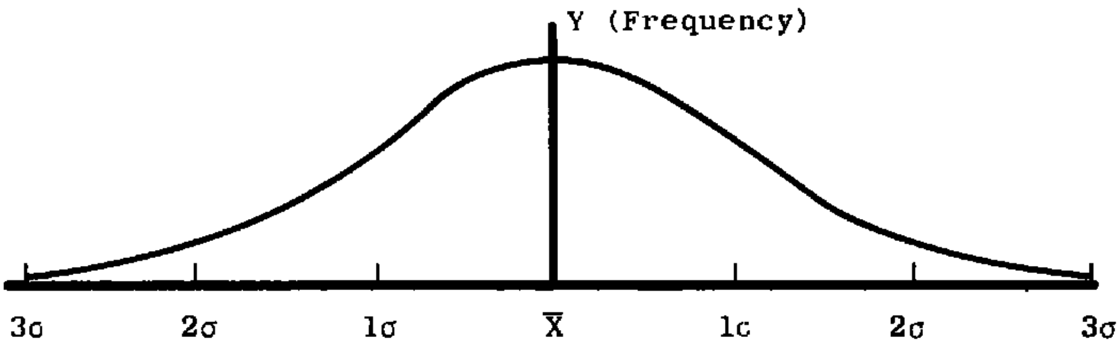
$$S(X) = \sqrt{\frac{\Sigma (X - \bar{X})^2}{n - 1}}$$

In this equation, the denominator under the radical is reduced by one from n to $n-1$, causing $S(X)$ to be conservatively large. $S(X)$ is, therefore, an estimate of σ based on a sample of less than the total number of possible observations. As the ratio of $\frac{n}{n-1}$ approaches one, $S(X)$ approaches σ.

The equation of the normal distribution curve in terms of the relative frequency of occurrence (as a function of the variable X), the mean $\bar{X}$, and the standard deviation σ ($S(X)$ is often used interchangeably) is

$$Y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{X-\bar{X}}{\sigma}\right)^2}$$

The distribution of all the data obeying the normal curve can be established by two numbers: the mean ($\bar{X}$) and the standard deviation (σ). Sketch 1 shows the frequency distribution of observations following the normal law. The abscissa is scaled to the magnitude of errors, whereas the ordinate measures the number of observations.



SKETCH 1

The percentage of the total population that lies within the various ranges about the mean are shown in the following table:

Percent of Total Data	Error
50.0	$\bar{X} \pm 0.674\,\sigma$
68.26	$\bar{X} \pm 1.000\,\sigma$
90.00	$\bar{X} \pm 1.645\,\sigma$
95.00	$\bar{X} \pm 1.960\,\sigma$
95.45	$\bar{X} \pm 2.000\,\sigma$
99.73	$\bar{X} \pm 3.000\,\sigma$

3.2 COMPARISON OF OBSERVED SAMPLES AND THE NORMAL DISTRIBUTION

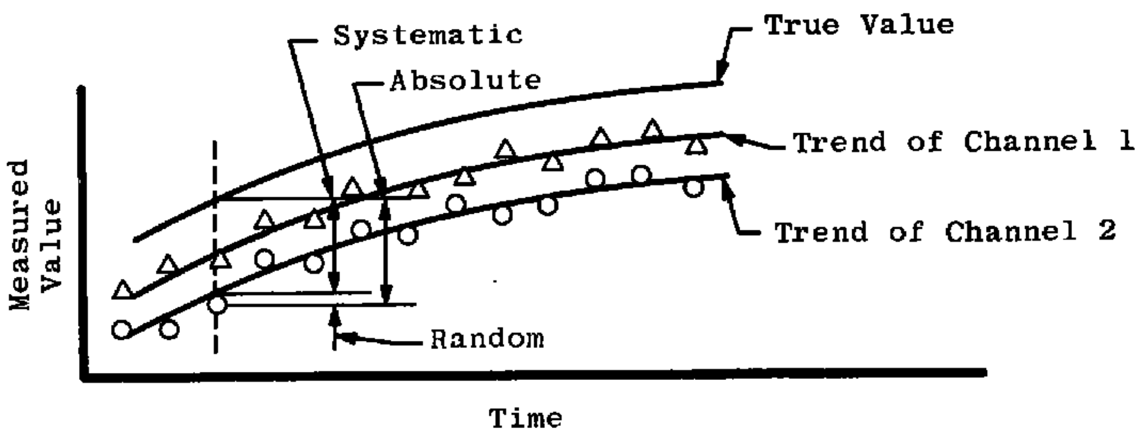
An analysis was made to determine if the observed data were randomly distributed (followed the normal law) so that standard statistical methods could be employed. The method used was the comparison of histograms of the observed data with the normal curve calculated from the observed mean deviation of the data from the average values of redundant measurements and the estimated standard deviation, S(X). The comparisons of histograms and calculated normal curves (Fig. 8) show the character of the randomness of the data. The data presented in these figures have been reduced to the difference between measurements of redundant channels and the mean ($\bar{X}$). The mean is the arithmetic average difference between individual channels and the average of the redundant channels (corresponds to $\bar{X}$ in the previous equations). S(X) (the best estimate of σ) was calculated from the equation

$$S(X) = \sqrt{\frac{\Sigma \Delta^2 - n(\bar{\Delta})^2}{n-1}}$$

The abscissa of the histogram was divided into finite increments, and the number of observations in each increment was counted. An inspection of the histograms shows that the observed data are normally distributed to a degree sufficient for employment of the best estimate of the standard deviation, S(X), for the statistical analysis.

3.3 ERROR NOTATION

During a test firing, primary data (F_m, P_c, $\dot{w}$, and P_a) were measured by multiple instrumentation, and steady-state values (observations) were determined from averages of each channel measurement over a predetermined time interval (0.2 sec). A typical plot of these observations and the error notations are shown in Sketch 2.



SKETCH 2

Error definitions are as follows:

3.3.1 Absolute Error

The absolute error of a single observation represents the difference between the observed value and the true value.

3.3.2 Random Error

The random error of a single observation represents the difference between the observed value and a value associated with the trend of the data. Random errors are those which cannot be directly established because of random variations in the system. (Random variations must follow the normal distribution. Otherwise, these variations are biased and, therefore, are not completely random.) Measurement electronics are so improved that random errors of instrumentation systems make up a very minor part of the total error. For instance, consider the errors in chamber pressure measurements of the Phase II series of testing. The total estimated error of P_c is ±0.201 percent, whereas the random error is ±0.007 percent.

3.3.3 Systematic Error

The systematic error represents the difference between the best estimate of the true value and the value associated with the trend of the data. By assuming that the systematic errors are randomly distributed, these errors may be shown to be related to the average difference between duplicate data. The following analysis shows that the mean difference gives an estimate of the lower limit (one σ) of the systematic error.

In Section 3.1, the probability density curve was given by

$$Y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{X-\bar{X}}{\sigma}\right)^2}$$

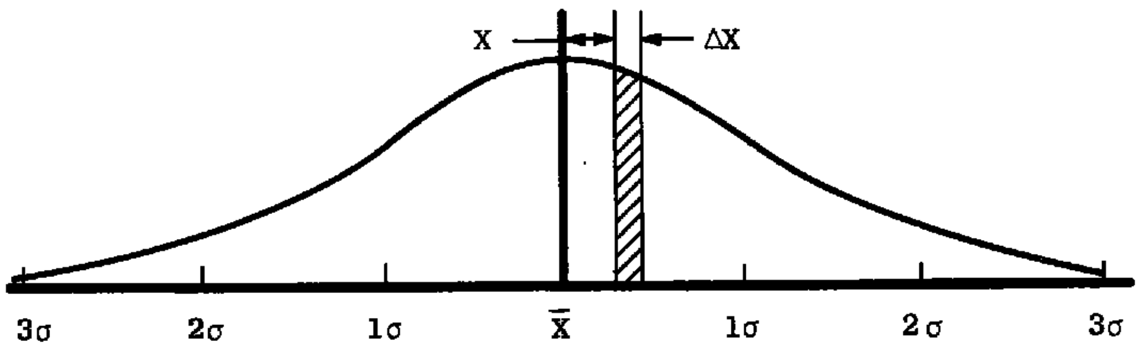
where $\bar{X}$ is the mean of the differences between the average of the redundant measurements and the measurement. For ease of calculation, let $\bar{X} = 0$ so that

$$Y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{X}{\sigma}\right)^2}$$

If $h = \frac{1}{\sigma\sqrt{2}}$, then $Y = \frac{h}{\sqrt{\pi}} e^{-h^2X^2}$. The term, h, is now a measurement of precision; with a large value of h, the probability density curve has a sharp high peak with narrow limits, and with a small value of h, the density curve is shallow with a large spread.

From the equation $Y = \frac{h}{\sqrt{\pi}} e^{-h^2 X^2}$, the probability of an error between X and $X + \Delta X$ is the area under the curve between X and $X + \Delta X$ or $Y \cdot \Delta X$ (see Sketch 3).

$$Y \cdot \Delta X = \left(\frac{h}{\sqrt{\pi}} e^{-h^2 X^2} \right) \Delta X$$



SKETCH 3

The probable number of errors of size X to $X + \Delta X$ in n measurements is n times this probability or $\left(\frac{nh}{\sqrt{\pi}} e^{-h^2 X^2} \right) \Delta X$, and the sum of the errors of this magnitude is the product of the magnitude of a single error, X, times the number of errors, or $\left(\frac{Xnh}{\sqrt{\pi}} e^{-h^2 X^2} \right) \Delta X$.

The sum of all errors of all sizes is

$$\Sigma \epsilon = \int_{-\infty}^{+\infty} \frac{Xnh}{\sqrt{\pi}} e^{-h^2 X^2} dX$$

$$= \frac{2nh}{\sqrt{\pi}} \int_{0}^{+\infty} e^{-h^2 X^2} X dX$$

$$= \frac{2nh}{(-2h^2)\sqrt{\pi}} \int_{0}^{+\infty} e^{-h^2 X^2} (-2h^2) X dX$$

$$= \frac{n}{h\sqrt{\pi}} \left[e^{-h^2 X^2} \right]_0^{\infty}$$

Therefore

$$\Sigma \epsilon = \frac{n}{h\sqrt{\pi}}$$

The arithmetic average error of a set of single channel measurements is equal to the sum of all errors divided by the number of observations.

$$\bar{\epsilon} = \frac{\Sigma \epsilon}{n} = \frac{n}{n h \sqrt{\pi}} = \frac{1}{h \sqrt{\pi}}$$

and $$\sigma = \frac{1}{h \sqrt{2}} \quad \therefore \quad \bar{\epsilon} = \frac{\sigma \sqrt{2}}{\sqrt{\pi}}$$

or $$\sigma = \frac{\bar{\epsilon} \sqrt{\pi}}{\sqrt{2}}$$

For multiple channel measurements, the variance of the average is merely the variance of the individual channel divided by the number of channels. The standard deviation is proportional to the square root of the variance so that for multiple channels

$$\sigma = \frac{\bar{\epsilon} \sqrt{\pi}}{\sqrt{2} \sqrt{N}}$$

where N is the number of channels and $\bar{\epsilon} = \bar{\Delta}$.

The estimate of the lower limit of the systematic errors is tabulated in Tables I through IV.

3.4 VARIANCE

The variance is the mean squared deviation from the mean which is simply σ^2 [or $S(X)^2$ when the standard deviation is estimated from a sample] and is a basic measure of the distribution.

The pooled estimate of the standard deviation of a population which has known sample variance is

$$S(X) = \sqrt{\frac{(n_1 - 1) S(X)^2 + (n_2 - 1) S(X_2)^2 + \cdots}{(n_1 - 1) + (n_2 - 1) + \cdots}}$$

This equation is good for a unique population only; that is, all S(X)'s must be sample deviations of the same error. The S(X) values for the systematic and random errors were determined by this equation.

3.5 CALIBRATION STANDARD

In order to calibrate any measuring device, a basis of comparison or true value must be found with which to compare the outputs of the instruments. Absolute accuracy is unobtainable, even in the laboratory.

The following table lists the calibrating equipment, the one sigma errors, and the parameters concerned. Errors of calibrating equipment are traceable to the National Bureau of Standards. Transfer errors are included where applicable.

Parameter	Description of Equipment	1σ
Thrust	In-place deadweight calibrator	0.100 percent
Chamber Pressure	Laboratory air deadweight calibrator	0.12 percent
	In-place reluctance-type standard	0.069 percent
Cell Pressure	Micromanometer pressure standard	0.104 percent
Propellant Flow Rate	Flow bench calibrator	0.100 percent
	Hydrometer	0.0005 lb/lb
	Mercury thermometer (for SG versus temperature curve)	0.2°F

3.6 PROPELLANT FLOW MEASUREMENT ERROR

In addition to random error and systematic error, flow data are subject to the additional errors in the flowmeter calibration constants (see Section 2.3.2) and specific gravity (SG) determination.

The specific gravity of the propellant is a function of temperature and may be determined from the following typical equations:

$$SG_o = 1.534 \quad (\text{at } 0°F) + (-0.001185/°F)\ (T°F)$$

$$SG_f = 0.9359 \quad (\text{at } 0°F) + (-0.000509/°F)\ (T°F)$$

The error in the determination of the propellant specific gravity is then a function of the errors in the hydrometer readings of a propellant sample, in temperature measurements of the laboratory samples, and in the propellant temperature measurements in the supply lines during testing. The 1σ errors in specific gravity readings of the propellant sample were 0.0534 and 0.0328 percent for fuel and oxidizer, respectively. The errors in specific gravity resulting from temperature measurement of the sample were 0.0109 and 0.0154 percent for fuel and oxidizer, respectively. The 1σ errors in specific gravity readings, which can be attributed to the errors in temperature measurement of the propellants in the supply lines, were 0.0152 and 0.0164 percent for the fuel and oxidizer, respectively. The deviations in the propellant flows caused by these deviations in specific gravity determination were:

$$S(\dot{w}_o)SG = 0.0386 \text{ percent}$$

$$S(\dot{w}_f)SG = 0.0328 \text{ percent}$$

3.7 AREA MEASUREMENTS

The diameter of the nozzle throat and exit were measured with inside micrometers. An average diameter reading was used in the area calculation. Two micrometer measurements each were taken at a minimum of four different locations in 45-deg increments. The rocket nozzle throats measured for this series of tests were constructed of aluminum or ablative material. The pre-fire throat measurements were accurate to 0.0022 percent (one sigma). Post-fire measurements of ablative material throats are less accurate than pre-fire measurements because of erosion and the soft texture of the charred surface material. Post-fire ablative throat measurements were accurate to 0.1306 percent (one sigma). The one sigma value for pre-fire nozzle exit diameter measurements was 0.00416 percent. The one sigma value for post-fire ablative nozzle exit diameter measurements was 0.0150 percent.

These measurements and results are presented in Table V. Since the area is proportional to the square of the diameter and since the one sigma error of the diameter measurements is much less than 1.00, the error in the area is twice that of the diameter measurement[1]. The 1σ errors for pre-fire ablative and hard contour engines were:

$$S(A_t) = 0.00440 \text{ percent}$$

$$S(A_{ne}) = 0.00834 \text{ percent}$$

Post-fire ablative measurements were:

$$S(A_t) = 0.278 \text{ percent}$$

$$S(A_{ne}) = 0.0302 \text{ percent}$$

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[1] $(1+\epsilon)^2 - 1$ when ϵ is small equals 2ϵ

SECTION IV
RESULTS

4.1 ENGINE THRUST MEASUREMENT

The number of observations, system errors, and random errors of the individual firings are tabulated in Table I. The values of 1σ systematic error and random errors determined from these data are:

$$S(F)_s = 0.010 \text{ percent}$$

$$S(F)_r = 0.005 \text{ percent}$$

In addition,

$$S(F)_{dwc} = 0.10 \text{ percent (deadweight calibrator)}$$

The standard deviation of the thrust measurements is the square root of the sum of the squares:

$$S(F) = \sqrt{S(F)_s^2 + S(F)_r^2 + S(F)^2{}_{dwc}}$$

$$= 0.101 \text{ percent}$$

4.2 CHAMBER PRESSURE MEASUREMENT

The number of observations and the calculated values for $S(P_c)_s$ and $S(P_c)_r$ for individual firings are tabulated in Table II. The error values for those firings using laboratory calibrated transducers are:

$$S(P_c)_s = 0.159 \text{ percent}$$

$$S(P_c)_r = 0.008 \text{ percent}$$

$$S(P_c)_{cc} = 0.120 \text{ percent console calibrated}$$

$$S(P_c) = \sqrt{S(P_c)_s^2 + S(P_c)_r^2 + S(P_c)^2{}_{cc}}$$

$$= 0.198 \text{ percent}$$

The errors for those firings using in-place calibrations are:

$$S(P_c)_s = 0.170 \text{ percent}$$

$$S(P_c)_r = 0.019 \text{ percent}$$

$$S(P_c)_{ip} = 0.0693 \text{ (in-place calibration)}$$

$$S(P_c) = \sqrt{S(P_c)_s^2 + S(P_c)_r^2 + S(P_c)_{ip}^2}$$

$$= 0.183 \text{ percent}$$

4.3 PROPELLANT FLOW RATE MEASUREMENT

4.3.1 Oxidizer Flow Rate Measurement

The number of observations and the calculated values of $S(\dot{w}_o)_s$ and $S(\dot{w}_o)_r$ for individual firings are tabulated in Table IIIa. The 1σ errors are:

$$S(\dot{w}_o)_s = 0.141 \text{ percent}$$

$$S(\dot{w}_o)_r = 0.040 \text{ percent}$$

$$S(\dot{w}_o)_{cc} = 0.100 \text{ percent}$$

$$S(\dot{w}_o)_{SG} = 0.0386 \text{ percent}$$

$$S(\dot{w}_o) = \sqrt{S(\dot{w}_o)_s^2 + S(\dot{w}_o)_r^2 + S(\dot{w}_o)_{cc}^2 + S(\dot{w}_o)_{SG}^2}$$

$$= 0.180 \text{ percent}$$

4.3.2 Fuel Flow Rate Measurement

The number of observations and the calculated values of $S(\dot{w}_f)_s$ and $S(\dot{w}_f)_r$ for individual firings are tabulated in Table IIIb. The 1σ errors are:

$$S(\dot{w}_f)_s = 0.073 \text{ percent}$$

$$S(\dot{w}_f)_r = 0.079 \text{ percent}$$

$$S(\dot{w}_f)_{cc} = 0.100 \text{ percent}$$

$$S(\dot{w}_f)_{SG} = 0.0328 \text{ percent}$$

$$S(\dot{w}_f) = \sqrt{S(\dot{w}_f)_s^2 + S(\dot{w}_f)_r^2 + S(\dot{w}_f)_{cc}^2 + S(\dot{w}_f)_{SG}^2}$$

$$= 0.150 \text{ percent}$$

4.3.3 Total Propellant Flow Rate

The total propellant flow rate deviations are estimated from the standard propagation of errors for addition to be 0.125 percent (one sigma).

4.4 CELL PRESSURE MEASUREMENT

Cell pressure was the only measured condition which did not attain steady-state during any of the firings. During the 30-sec firing, the systematic errors were unusally high. The systematic errors recorded during two long duration firings were much less, indicating the effect of transient data on cell pressure accuracy. The results obtained during the long duration firing are presented below for comparison.

The number of observations and the calculated values of $S(P_a)_s$ and $S(P_a)_r$ for individual firings are tabulated in Table IV. The error values are:

$$S(P_a)_s = 0.673 \text{ percent}$$

$$S(P_a)_r = 0.339 \text{ percent}$$

$$S(P_a)_c = 0.104 \text{ percent (calibration)}$$

$$S(P_a) = \sqrt{S(P_a)_s^2 + S(P_a)_r^2 + S(P_a)_c^2}$$

$$= 0.751 \text{ percent}$$

The errors for the long duration firings are:

$$S(P_a)_s = 0.147 \text{ percent}$$

$$S(P_a)_r = 0.403 \text{ percent}$$

$$S(P_a)_c = 0.104 \text{ percent (calibration)}$$

$$S(P_a) = 0.441 \text{ percent}$$

4.5 ACCURACY OF THE PERFORMANCE PARAMETERS

It can be shown (Ref. 3) that the error of any function (Q) of independent quantities (q_1, q_2, q_3, j ·· q_n) whose errors (R_1, R_2, R_3, ··· R_n) are known, and if Q is a product function of independent quantities, the errors can be expressed by $R = \sqrt{R_1^2 + R_2^2 + R_3^2 + \cdots R_n^2}$ when the errors are expressed in percentages. When Q is a sum or difference function of the independent quantities (q_n), then the q's must be weighted before they are expressed as R_s. By using these relationships, the errors of the performance parameters were established.

The equation for vacuum thrust is

$$F = F_m + P_a A_{ne}$$

The deviation of vacuum corrected thrust is

$$S(F) = \sqrt{D_1\ S(F)_m^2 + D_2\ S(P_a)\ S(A_{ne})^2}$$

$$= 0.110 \text{ percent}$$

D_1 and D_2 = weighting factors for addition propagation of errors

where

$$D_1 = \frac{F_m}{F}$$

$$D_2 = \frac{P_a A_{ne}}{F}$$

The equation for thrust coefficient is

$$C_F = \frac{F}{P_c A_t}$$

The deviation of thrust coefficient for tests using laboratory calibrated chamber pressure transducers was

$$S(C_F) = \sqrt{S(F)^2 + S(P_c)^2 + S(A_t)^2}$$

$$= 0.226 \text{ percent}$$

The deviation of thrust coefficient for tests using in-place calibrated chamber pressure transducers was

$$S(C_F) = 0.214 \text{ percent}$$

The percentage error in I_{sp} from the equation $I_{sp} = \frac{F}{\dot{w}_t}$ was

$$S(I_{sp}) = \sqrt{S(F)^2 + S(\dot{w}_t)^2}$$

$$= 0.166 \text{ percent}$$

The percentage error in c^*, from the equation $c^* = P_c A_t \, g/\dot{w}_t$ was

$$S(c^*) = \sqrt{S(P_c)^2 + S(A_t)^2 + S(\dot{w}_t)^2}$$

The deviation in c^* for those tests using laboratory calibrated chamber pressure transducers was

$$S(c^*) = 0.234 \text{ percent}$$

The deviation in c^* for those tests using in-place calibrated chamber pressure transducers was

$$S(c^*) = 0.222 \text{ percent}$$

SECTION V
SUMMARY OF RESULTS

The accuracy of measured steady-state engine data obtained during recent testing in the Propulsion Engine Test Cell (J-2A) has been determined and is stated in terms of one standard deviation, $S(X)$, as a percentage of the steady-state point:

Thrust, P	$S(F) = 0.101$ percent
Chamber pressure, P_c (laboratory calibrations)	$S(P_c) = 0.198$ percent
Chamber pressure, P_c (in-place calibrations)	$S(P_c) = 0.183$ percent
Propellant weight flow, $\dot{w}_t$	$S(\dot{w}_t) = 0.125$ percent
Throat area, A_t	$S(A_t) = 0.0044$ percent
Nozzle exit area, A_{ne}	$S(A_{ne}) = 0.0083$ percent

The 1σ errors of the calculated engine performance parameters, F, C_F, I_{sp}, and c^*, from the measured data were:

	In-place P_c Calibrations	Laboratory with Resistance Substitution P_c Calibrations
Vacuum thrust, $S(F)$	0.110 percent	0.110 percent
Vacuum thrust coefficient, $S(C_F)$	0.214 percent	0.226 percent
Specific impulse, $S(I_{sp})$	0.166 percent	0.166 percent
Characteristic velocity, $S(c^*)$	0.222 percent	0.234 percent

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1. Test Facilities Handbook, (5th Edition). "Rocket Test Facility, Vol. 2." Arnold Engineering Development Center, July 1963.

2. Reeves, J. R., Jr. "General Description and Performance of the Propulsion Engine Test Cell (J-2A)." AEDC-TDR-64-138 (AD444326), August 1964.

3. Scarborough, J. B. Numerical Mathematical Analysis. John Hopkins Press, Baltimore, 1958. (Fourth Edition).

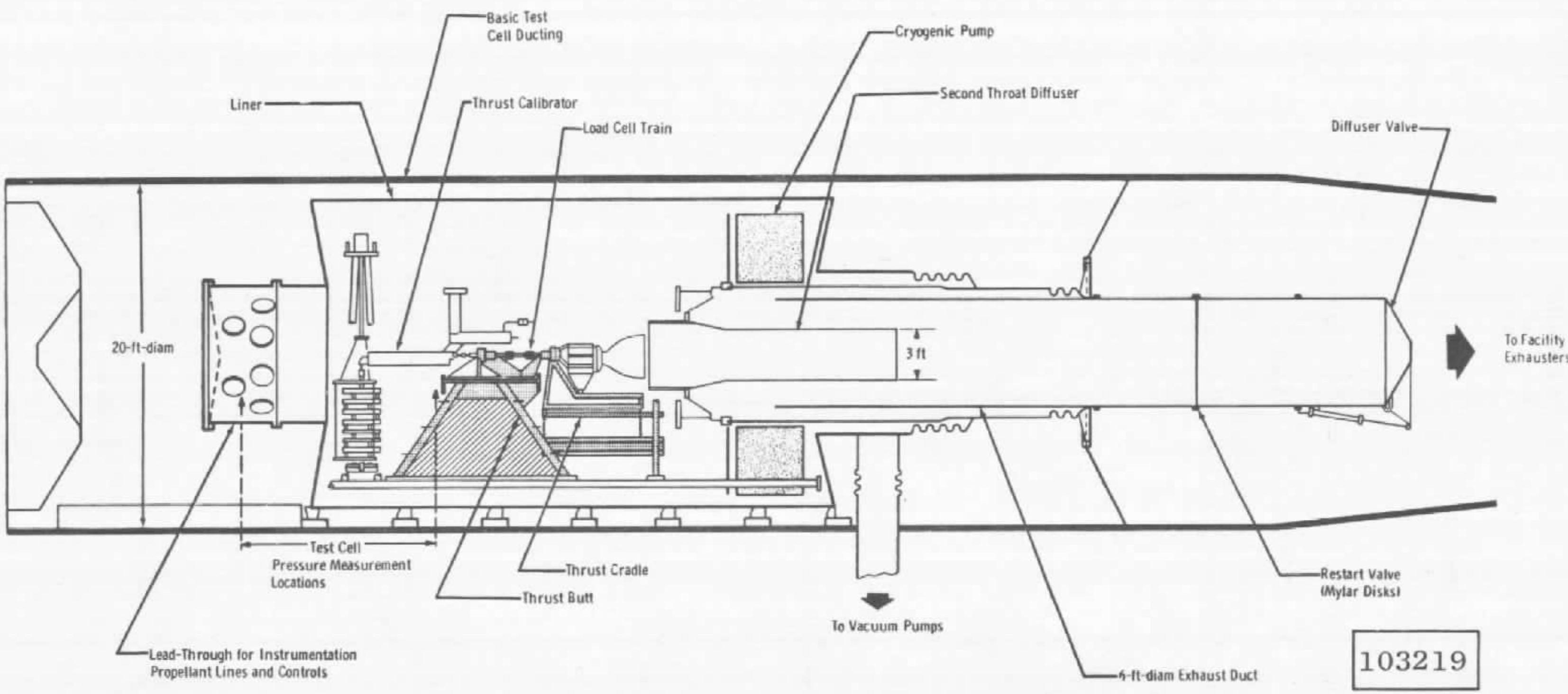


Fig. 1 Propulsion Engine Test Cell (J-2A)

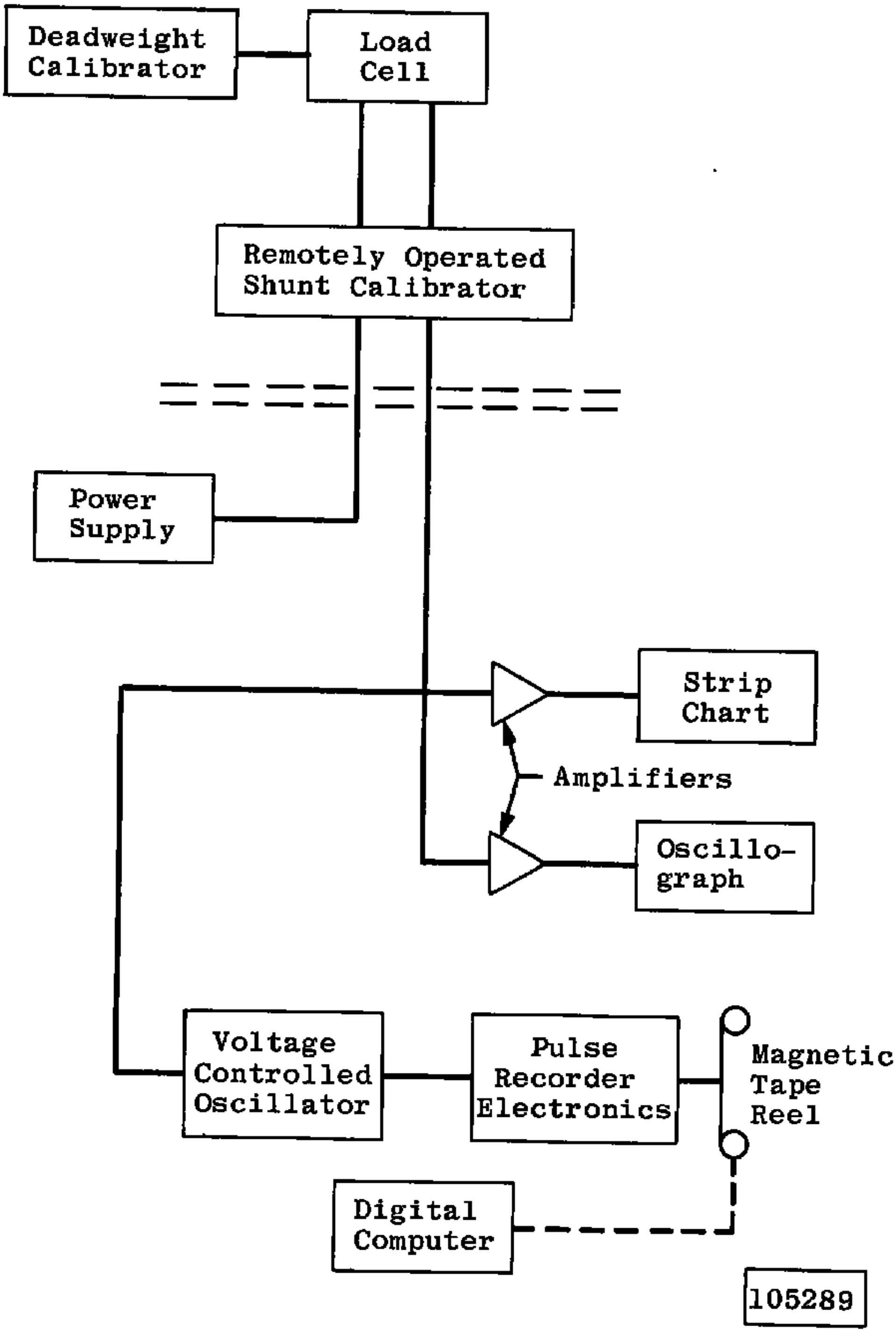


Fig. 2 Thrust Measuring System

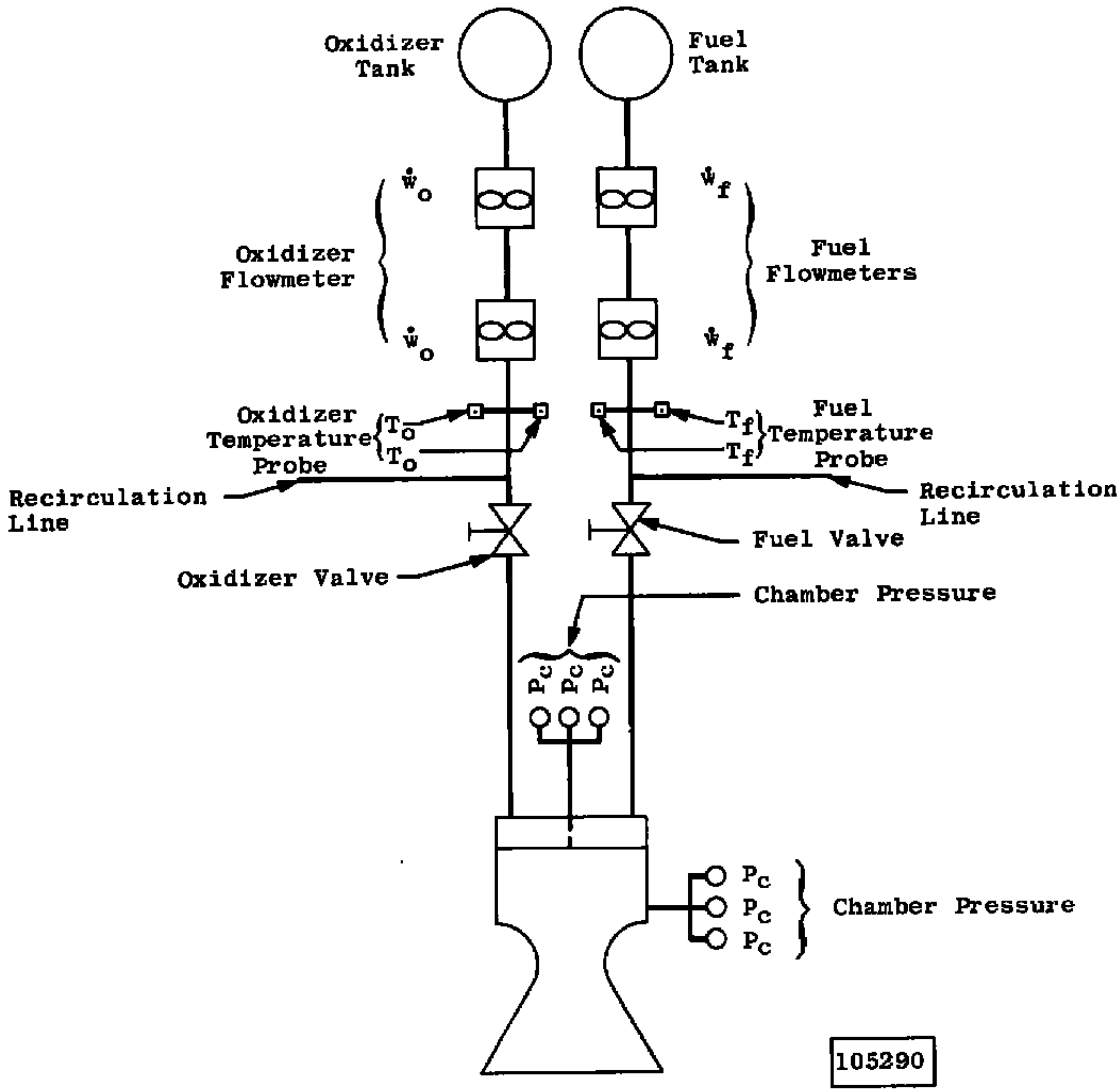


Fig. 3 Propellant System Schematic

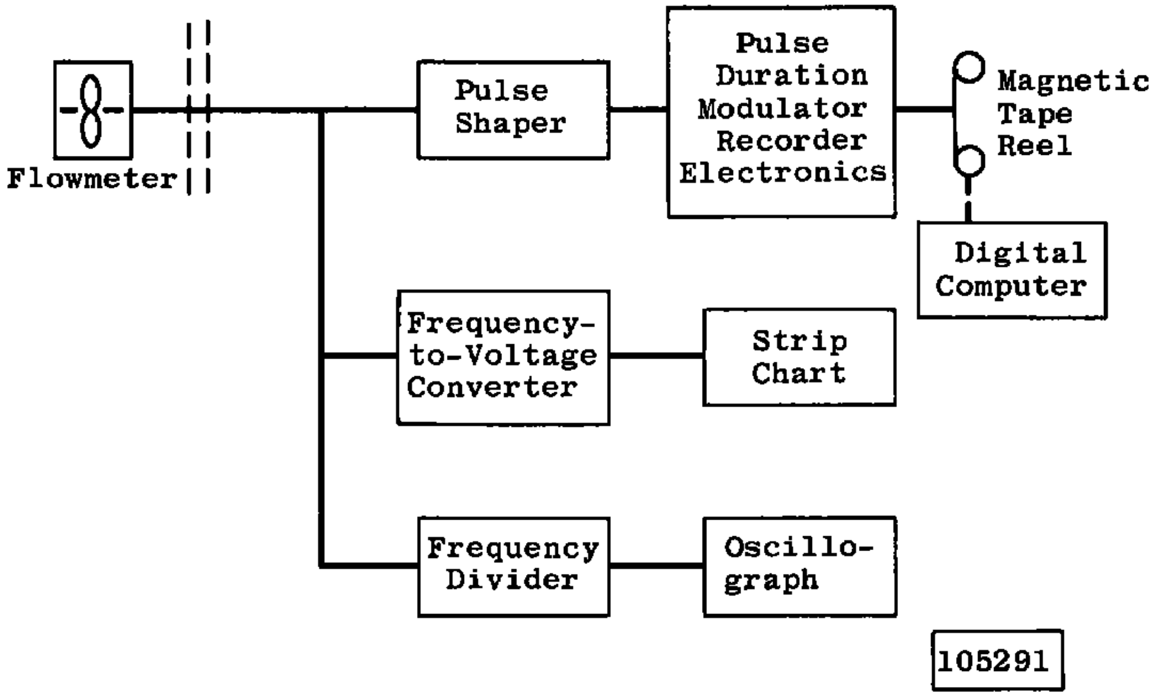


Fig. 4 Propellant Flow Measuring System

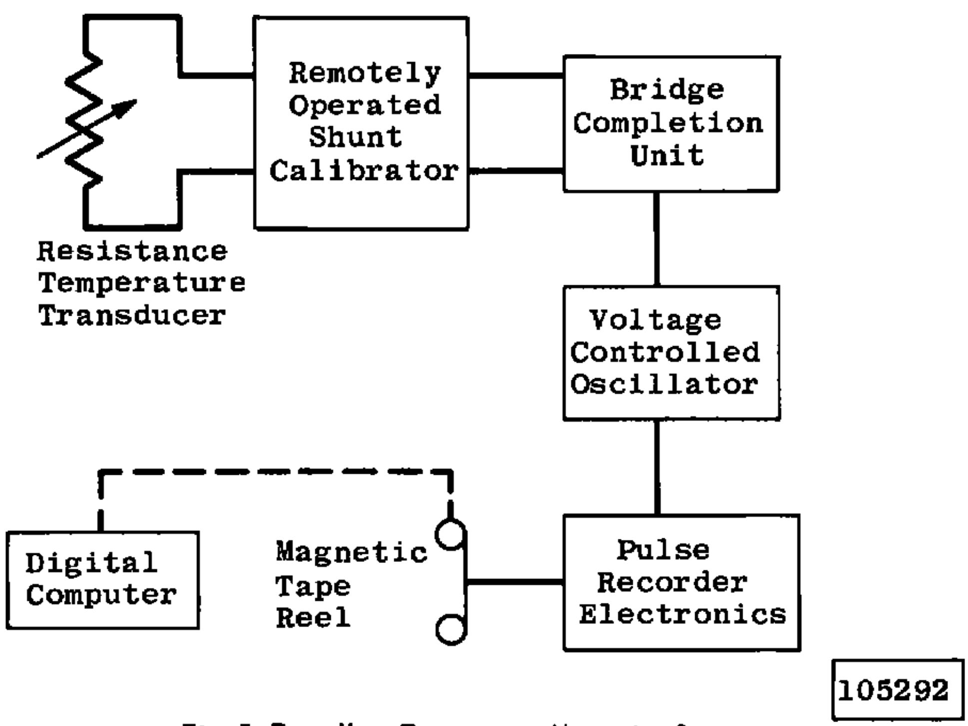


Fig. 5 Propellant Temperature Measuring System

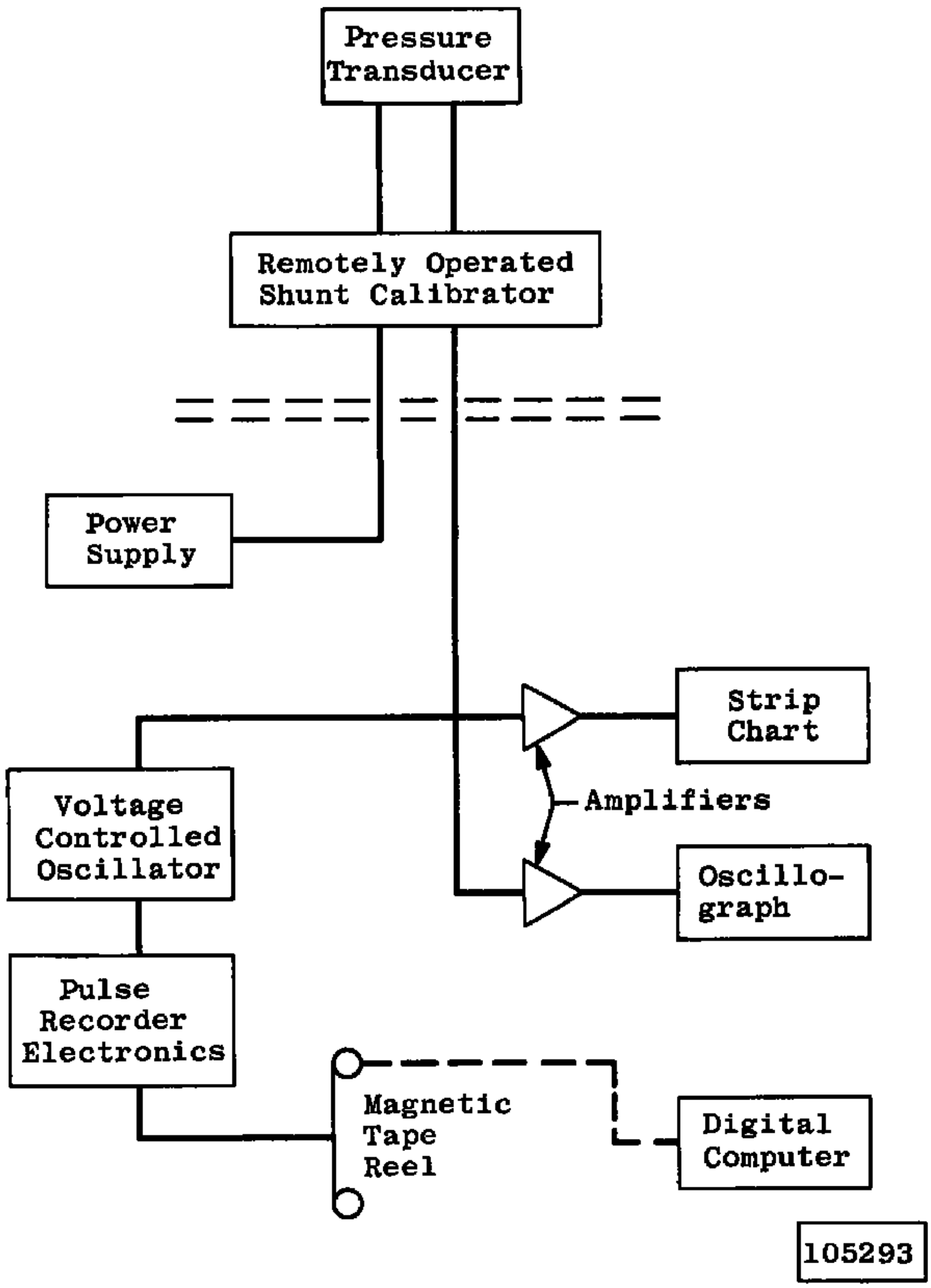


Fig. 6 Chamber Pressure Measuring System

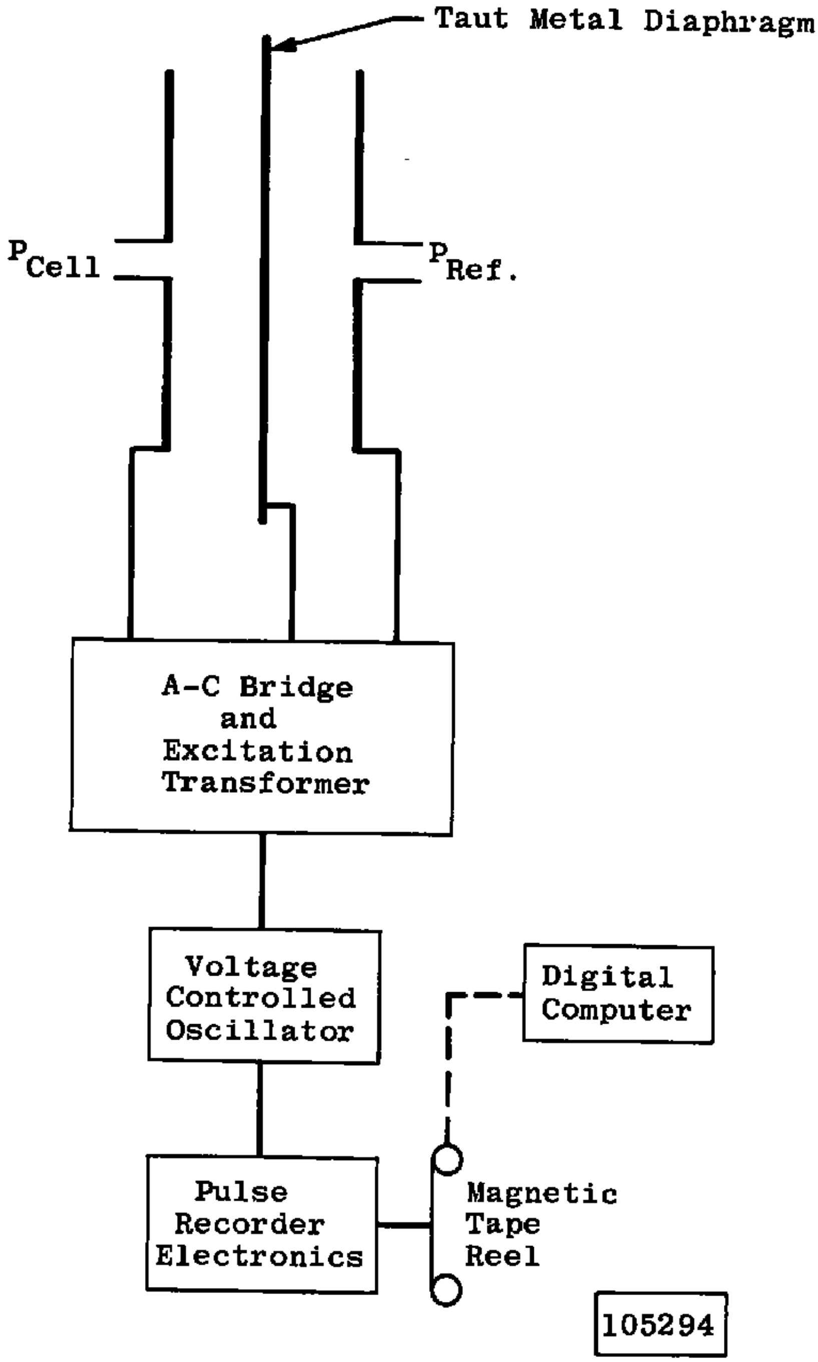
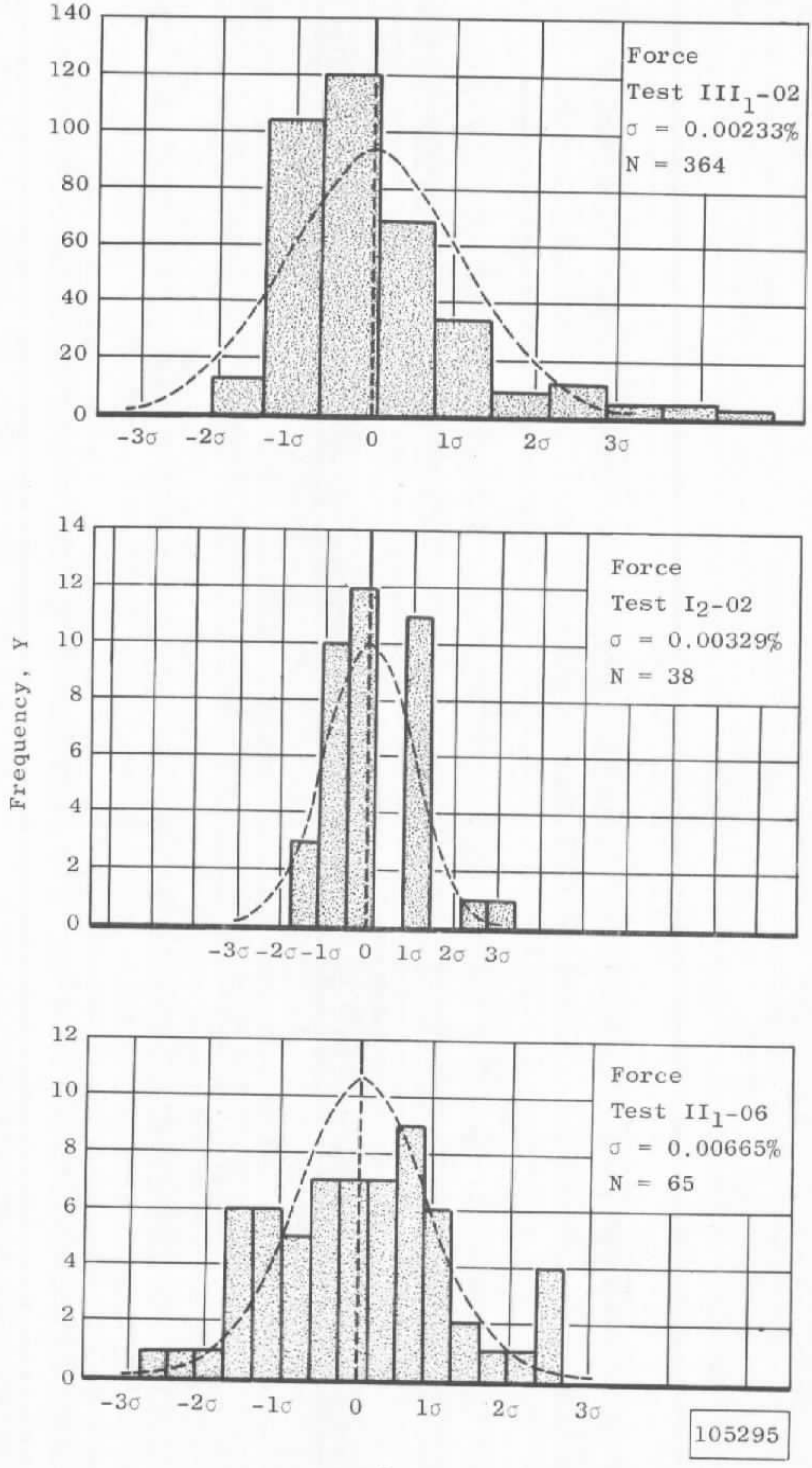
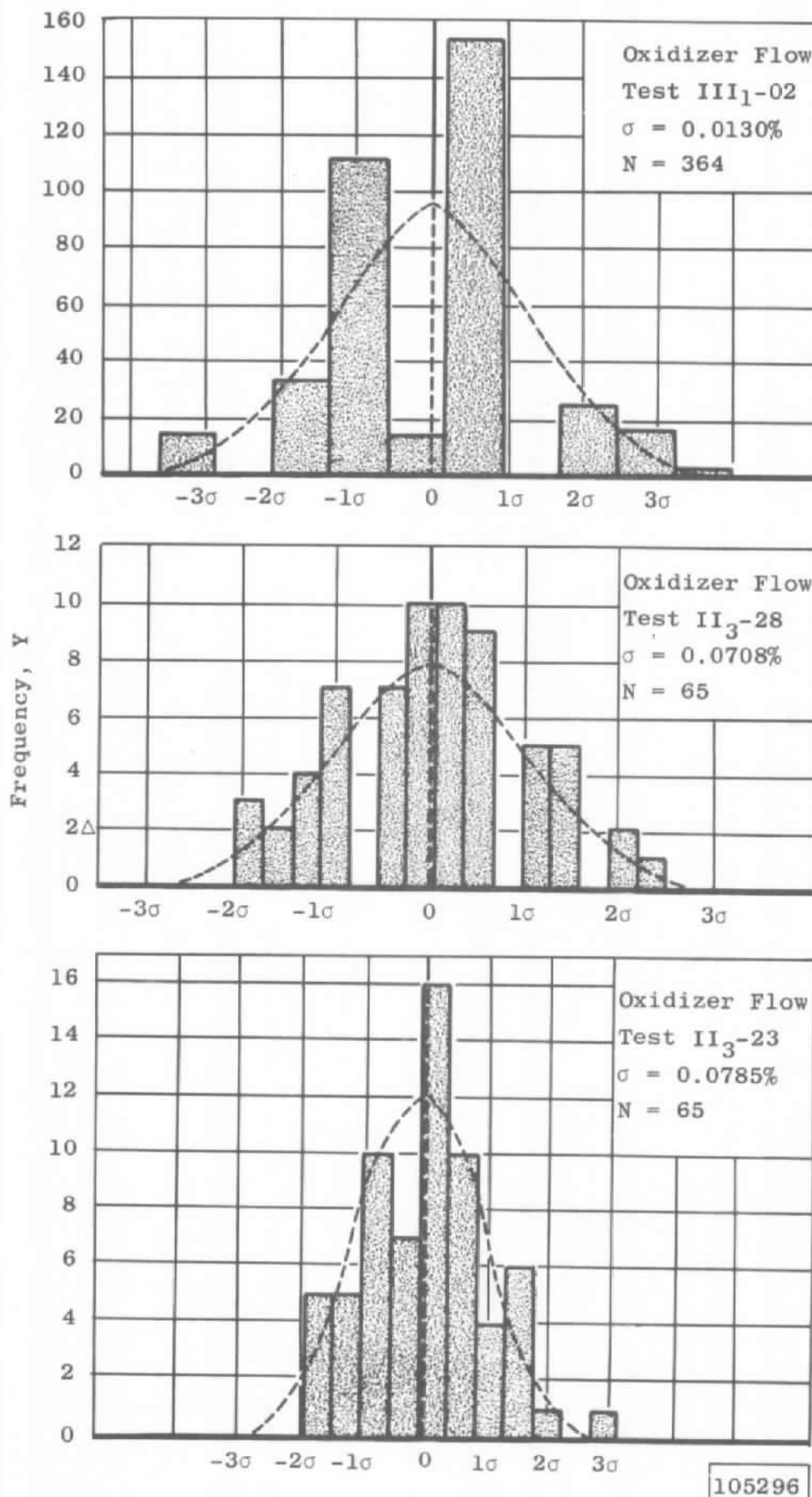


Fig. 7 Cell Pressure Measuring System

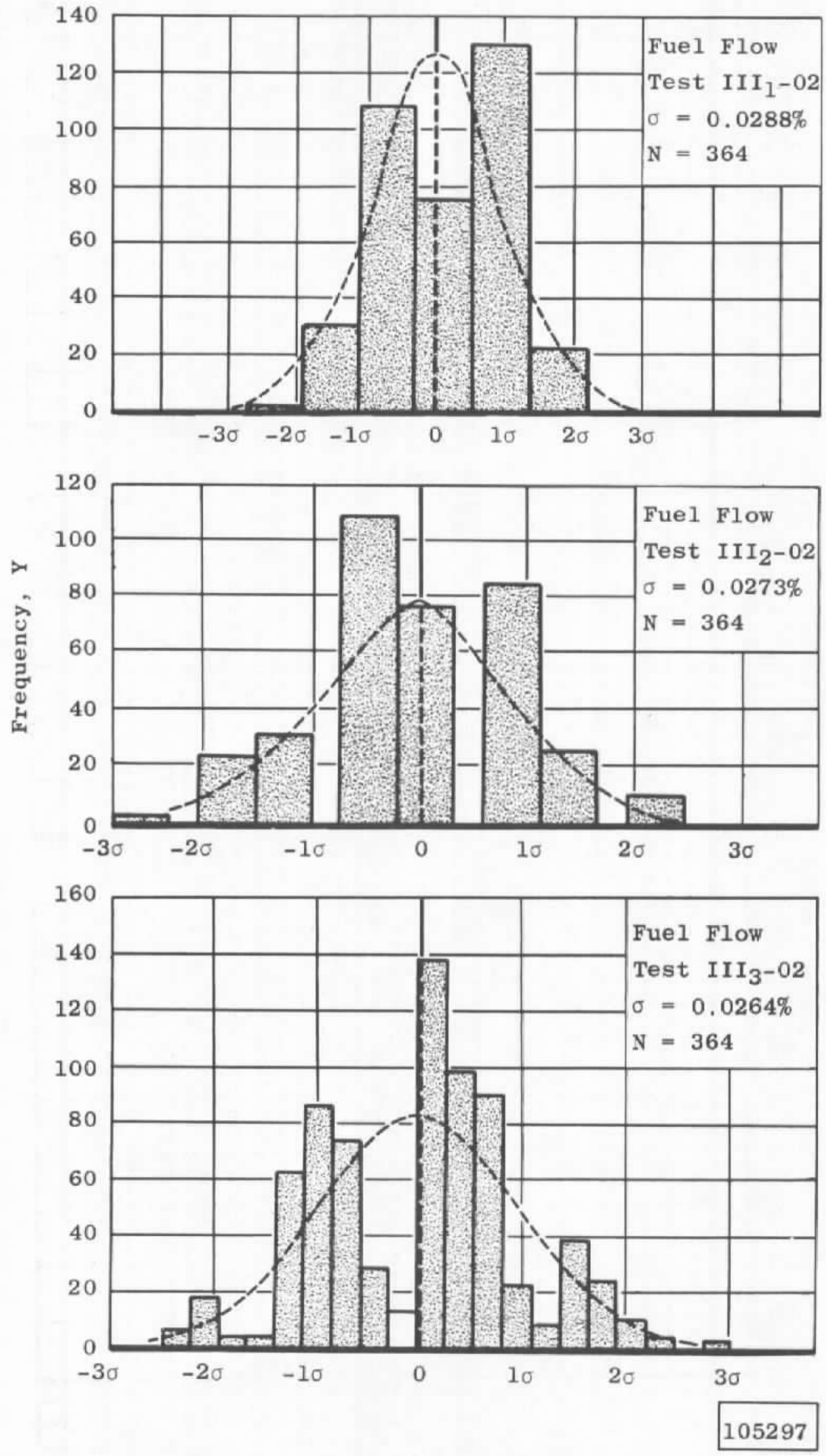


a. Thrust

Fig. 8 Histograms Showing Relationship of Sample Distribution and Normal Distribution

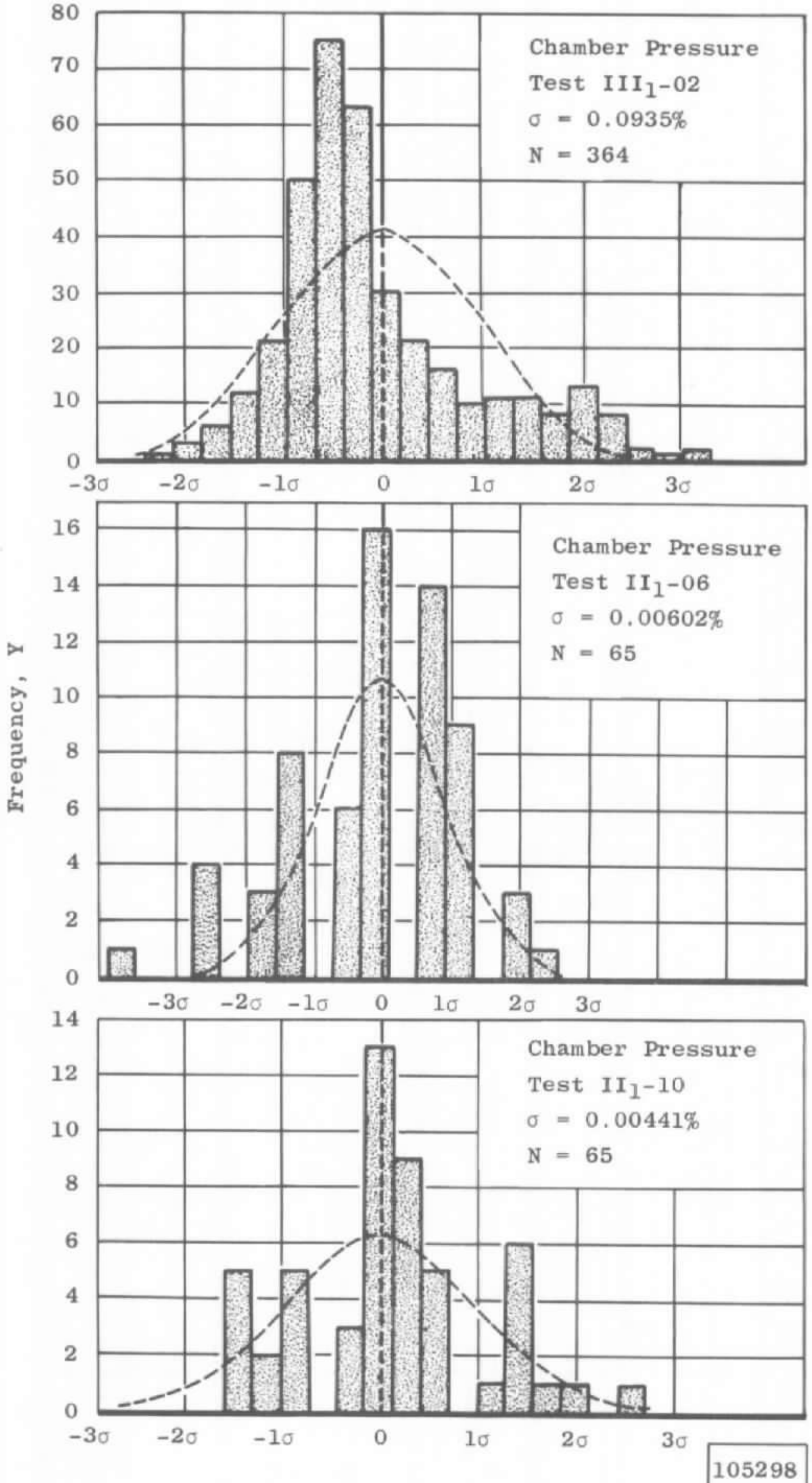


b. Oxidizer Flow Rate
Fig. 8 Continued



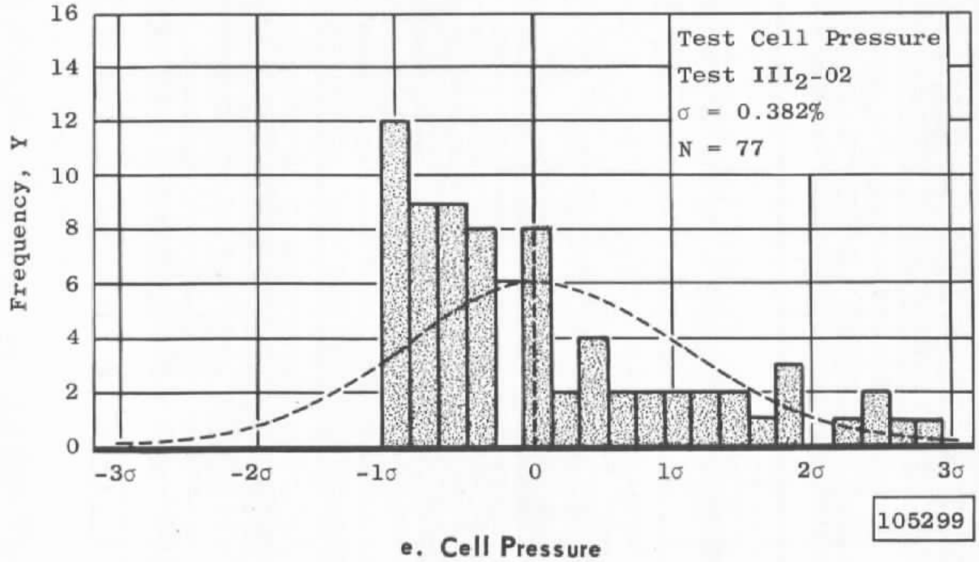
c. Fuel Flow Rate

Fig. 8 Continued



d. Chamber Pressure

Fig. 8 Continued



e. Cell Pressure

Fig. 8 Concluded

TABLE I
THRUST MEASUREMENT SYSTEMATIC AND RANDOM DEVIATIONS

Firing Number	n	$S(F)_s$, percent	$S(F)_r$, percent
I_1-03	37	0.00168	0.00441
2-02	38	0.00500	0.00329
3-02	38	0.00390	0.00493
4-02	38	0.00461	0.00373
II_1-02	65	0.00258	0.00655
-04	65	0.00361	0.00726
-05	65	0.00455	0.00664
-06	65	0.00578	0.00664
-07	65	0.00611	0.00808
-08	65	0.02138	0.00563
-10	65	0.00374	0.00557
II_2-13	65	0.00407	0.00635
-14	65	0.00334	0.00734
-15	65	0.00518	0.00680
-16	65	0.00396	0.00626
-17	65	0.00420	0.00688
-18	65	0.00660	0.00582
-19	65	0.00490	0.00706
-20	65	0.00743	0.00646
-21	65	0.00510	0.00715
II_3-22	65	0.00324	0.00519
-23	65	0.00462	0.00462
-24	65	0.00558	0.00537
-25	65	0.01195	0.00501
-26	65	0.00390	0.00568
-27	65	0.00950	0.00509
-28	65	0.01037	0.00587
-29	65	0.01564	0.00552
III_1-01	44	0.01229	0.00108
-02	364	0.01077	0.00233
III_2-01	44	0.01209	0.00159
-02	364	0.00892	0.00553
III_3-01	44	0.01741	0.00129
-02	364	0.01850	0.00162

$\overline{S(F)_s} = 0.010$ percent

$\overline{S(F)_r} = 0.005$ percent

TABLE II
CHAMBER PRESSURE MEASUREMENT SYSTEMATIC AND RANDOM DEVIATIONS

a. Using Laboratory Calibrations

Firing Number	n	$S(P_c)_s$, percent	$S(P_c)_r$, percent
I1-03	37	0.0034	0.01701
I3-02	38	0.0545	0.00801
I4-02	38	0.0245	0.00909
II1-02	65	0.0104	0.00540
-04	65	0.1650	0.00720
-05	65	0.1400	0.00581
-06	65	0.1440	0.00602
-07	65	0.1570	0.00562
-08	65	0.1330	0.00502
-10	65	0.1690	0.00441
II2-13	65	0.1730	0.00553
-14	65	0.1330	0.00625
-15	65	0.1430	0.00564
-16	65	0.1660	0.00636
-17	65	0.1460	0.00439
-18	65	0.3250	0.00475
-19	65	0.1470	0.02393
-20	65	0.1400	0.00635
-21	65	0.1510	0.00581
II3-22	65	0.1620	0.00452
-23	65	0.1660	0.00537
-24	65	0.1460	0.00437
-25	65	0.1643	0.00487
-26	65	0.1701	0.00644
-27	65	0.1522	0.00699
-28	65	0.1660	0.00497
-29	65	0.1609	0.00505

$S(P_c)_s$ = 0.159 percent

$S(P_c)_r$ = 0.008 percent

b. Using In-Place Calibrations

Firing Number	n	$S(P_c)_s$, percent	$S(P_c)_r$, percent
III1-01	44	0.1648	0.02050
-02	364	0.0866	0.09350
III2-01	44	0.1434	0.01389
-02	364	0.2382	0.00258
III3-01	44	0.1552	0.00252
-02	364	0.1488	0.00530

$S(P_c)_s$ = 0.170 percent

$S(P_c)_r$ = 0.019 percent

TABLE III
PROPELLANT FLOW RATE MEASUREMENT SYSTEMATIC AND RANDOM DEVIATIONS

a. Oxidizer

Firing Number	n	$S(\dot{w}_o)_s$, percent	$S(\dot{w}_o)_r$, percent
I1-03	37	0.0173	0.0596
I2-02	38	0.1177	0.0549
I3-02	38	0.3634	0.0433
I4-02	38	0.1422	0.0521
II3-23	65	0.1440	0.0785
-24	65	0.1472	0.0510
-25	65	0.1642	0.0657
-26	65	0.1477	0.0644
-27	65	0.1417	0.0701
-28	65	0.1498	0.0708
-29	65	0.1504	0.0575
III1-01	44	0.1122	0.0204
-02	364	0.1202	0.0165
III2-01	44	0.1286	0.0130
-02	364	0.1314	0.0176
III3-01	44	0.1117	0.0218
-02	364	0.1222	0.0182

$S(\dot{w}_o)_s$ = 0.141 percent

$S(\dot{w}_o)_r$ = 0.040 percent

TABLE III (Concluded)

b. Fuel

Firing Number	n	$S(\dot{w}_f)_s$, percent	$S(\dot{w}_f)_r$, percent
II1-02	65	0.1390	0.1157
-04	65	0.1349	0.0961
-05	65	0.0792	0.0863
-06	65	0.1249	0.1110
-07	65	0.1268	0.1101
-08	65	0.1128	0.1347
-10	65	0.0911	0.0836
II3-22	65	0.0631	0.1364
-23	65	0.0222	0.1098
-24	65	0.0432	0.1068
-25	65	0.0481	0.1061
-26	65	0.0426	0.1181
-27	65	0.0200	0.1062
-28	65	0.0320	0.1202
-29	65	0.0404	0.1297
III1-01	44	0.0516	0.0755
-02	364	0.0535	0.0288
III2-01	44	0.0531	0.0275
-02	364	0.0571	0.0273
III3-01	44	0.0597	0.0240
-02	364	0.0669	0.0264

$S(\dot{w}_f)_s$ = 0.073 percent

$S(\dot{w}_f)_r$ = 0.079 percent

TABLE IV
CELL PRESSURE MEASUREMENT SYSTEMATIC AND RANDOM DEVIATIONS

Firing Number	n	$S(P_a)_s$, percent	$S(P_a)_r$, percent
II_2-13	65	0.6035	0.2420
-14	65	0.6741	0.0838
-15	65	0.6211	0.1077
-16	65	0.7147	0.2440
-17	65	1.1300	0.2357
-18	65	1.0820	0.2203
-19	65	1.2474	0.2429
-20	65	1.3442	0.2439
-21	65	1.3461	0.2525
III_1-01	44	0.4318	0.3560
III_2-01	44	0.3933	0.3574
-02*	364	0.0592	0.4236
III_3-01	44	0.1990	0.3453
-02*	364	0.1965	0.3816

$S(P_a)_s$ = 0.673 percent

$S(P_a)_r$ = 0.339 percent

* Long Duration Firings

$S(P_a)_s$ = 0.147 percent

$S(P_a)_r$ = 0.403 percent

TABLE V
CALCULATED PRE- AND POST-FIRE DIAMETER MEASUREMENT DEVIATIONS

a. Pre-Fire Nozzle Throat

Firing Series	Reading No. 1	Reading No. 2	Δ	δ	$\delta^2 \times 10^{-6}$
I1	4.930	4.930	0	0	0
	4.929	4.930	0.001	0.005	0.25
	4.930	4.930	0	0	0
	4.930	4.930	0	0	0
I2	4.947	4.947	0	0	0
	4.946	4.947	0.001	0.0005	0.25
	4.947	4.948	0.001	0.0005	0.25
	4.948	4.948	0	0	0
I3	4.947	4.950	0.003	0.0015	2.25
	4.944	4.951	0.007	0.0035	12.35
	4.943	4.943	0	0	0
	4.944	4.943	0.001	0.0005	0.25
I4	4.935	4.935	0	0	0
	4.936	4.936	0	0	0
	4.936	4.934	0.002	0.0010	1.0
	4.933	4.934	0.001	0.0005	0.25

$\Sigma\ \delta^2 = 16.85 \times 10^{-6}$

$n = 16$

Diam = 4.940

S(X) = 0.00215 percent

TABLE V (Continued)

b. Pre-Fire Nozzle Exit

Firing Series	Reading No. 1	Reading No. 2	Δ	δ	$\delta^2 \times 10^{-6}$
I_1	31.321	31.320	0.001	0.0005	0.25
	31.334	31.324	0.010	0.0050	25.00
	31.306	31.318	0.012	0.0060	36.00
	31.321	31.320	0.001	0.0005	0.25
I_2	31.230	31.231	0.001	0.0005	0.25
	31.211	31.210	0.001	0.0005	0.25
	31.215	31.215	0	0	0
	31.282	31.282	0	0	0
I_3	31.319	31.319	0	0	0
	31.272	31.272	0	0	0
	31.207	31.207	0	0	0
	31.284	31.284	0	0	0
I_4	31.267	31.272	0.005	0.0025	6.25
	31.221	31.213	0.008	0.0040	16.00
	31.220	31.217	0.003	0.0015	2.25
	31.258	31.259	0.001	0.0005	0.25
III_1	30.847	30.862	0.015	0.0075	56.25
	30.839	30.841	0.002	0.0010	1.00
	30.844	30.847	0.003	0.0015	2.25
	30.838	30.861	0.023	0.0165	272.25
III_2	30.892	30.893	0.001	0.0005	0.25
	30.880	30.879	0.001	0.0005	0.25
	30.872	30.873	0.001	0.0005	0.25
	30.868	30.871	0.003	0.0015	2.25

S(X) = 0.00416 percent

TABLE V (Continued)

c. Post-Fire Ablative Throat

Firing Series	Reading No. 1	Reading No. 2	Δ	δ	$\delta^2 \times 10^{-6}$
I1	5.117	5.120	0.003	0.0015	2.25
	4.873	4.865	0.008	0.0040	16.00
	4.907	4.900	0.007	0.0035	12.25
	4.911	4.920	0.009	0.0045	20.25
I2	4.998	4.998	0	0	0
	4.975	4.971	0.004	0.0020	4.00
	4.965	4.998	0.033	0.0165	272.25
	4.965	5.011	0.046	0.0230	529.00
I3	4.884	4.882	0.002	0.0010	1.00
	4.888	4.886	0.002	0.0010	1.00
	4.869	4.868	0.001	0.0005	0.25
	4.885	4.887	0.002	0.0010	1.00
	4.928	4.930	0.002	0.0010	1.00
I4	4.839	4.841	0.002	0.0010	1.00
	4.881	4.882	0.001	0.0005	0.25
	4.887	4.892	0.005	0.0025	6.25
	4.852	4.847	0.005	0.0025	6.25
III1	4.574	4.572	0.002	0.0010	1.00
	4.546	4.540	0.006	0.0030	9.00
	4.544	4.546	0.002	0.0010	1.00
	4.555	4.548	0.008	0.0040	16.00
III2	4.556	4.558	0.002	0.0010	1.00
	4.612	4.613	0.001	0.0005	0.25
	4.586	4.590	0.004	0.0020	4.00
	4.543	4.545	0.002	0.0010	1.00
III3	4.495	4.518	0.023	0.0115	132.25
	4.555	4.565	0.010	0.0050	25.00
	4.595	4.596	0.001	0.0005	0.25
	4.512	4.539	0.027	0.0140	196.00

S(X) = 0.1306 percent

TABLE V (Concluded)

d. Post-Fire Ablative Nozzle Exit

Firing Series	Reading No. 1	Reading No. 2	Δ	δ	$\delta^2 \times 10^{-6}$
I_1	31.256	31.256	0	0	0
	31.321	31.317	0.004	0.0020	4.00
	31.304	31.309	0.005	0.0025	6.25
	31.306	31.312	0.006	0.0030	9.00
I_2	31.202	31.205	0.003	0.0015	2.25
	31.200	31.206	0.006	0.0030	9.00
	31.155	31.162	0.007	0.0035	12.25
	31.125	31.162	0.037	0.0185	342.25
I_3	30.957	30.951	0.006	0.0030	9.00
	30.900	30.907	0.007	0.0035	12.25
	31.011	31.012	0.001	0.0005	0.25
	31.015	31.021	0.006	0.0030	9.00
	31.015	31.021	0.006	0.0030	9.00
I_4	30.520	30.521	0.001	0.0005	0.25
	31.422	31.420	0.002	0.0010	1.00
	31.130	31.122	0.008	0.0040	16.00
	30.760	30.685	0.015	0.0075	56.25
III_1	30.616	30.610	0.006	0.0030	9.00
	30.952	30.956	0.002	0.0010	1.00
	30.905	30.911	0.006	0.0030	9.00
	30.498	30.496	0.002	0.0010	1.00
III_2	30.858	30.859	0.001	0.0005	0.25
	30.825	30.826	0.001	0.0005	0.25
	30.652	30.654	0.002	0.0010	1.00
	30.613	30.613	0	0	0
III_3	30.753	30.745	0.008	0.0040	16.00
	30.744	30.727	0.017	0.0085	72.25
	30.595	30.592	0.003	0.0015	2.25
	30.875	30.876	0.001	0.0005	0.25

S(X) = 0.015 percent

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Security Classification

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13 ABSTRACT

Measurements obtained during recent testing in the Propulsion Engine Test Cell (J-2A) are analyzed to determine the accuracy of measuring liquid-propellant rocket engine performance. The equipment and calibration techniques used to obtain the data and the statistical methods employed for error analysis are discussed. The results demonstrated that the one standard deviation errors in thrust, chamber pressure, cell pressure, oxidizer flow rate, and fuel flow rate measurements are less than ±0.110, ±0.198, ±0.769, ±0.181, and ±0.150 percent, respectively. The accuracy of the primary calculated performance parameters, thrust coefficient, specific impulse, and characteristic velocity, are ±0.226, ±0.166, and ±0.234 percent (one standard deviation), respectively.

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