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STATISTICAL DERIVATION OF DESIGN CRITERIA FOR LIQUID ROCKET COMBUSTION INSTABILTY

by

E. K. BASTRESS, G. H. HARRIS, AND I. MILLER

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FINAL REPORT

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E. K. Bastress, G. H. Harris, and I. Miller

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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NASA Lewis Research Center
Cleveland, Ohio
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Cambridge, Massachusetts

STATISTICAL DERIVATION OF DESIGN CRITERIA FOR LIQUID ROCKET COMBUSTION INSTABILITY

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ABSTRACT

The objective of this program was the establishment of criteria for the design of stably operating liquid propellant rocket engines by means of a systematic analysis of existing test data. In this analysis, relationships were sought between engine design variables, operating variables, and stability characteristics. The results of theoretical and experimental studies of combustion instability were used as guides in seeking these relationships.

The program consisted of the following series of tasks:

1. Development of a system for collecting rocket engine stability test data and utilization of this system to collect such data from a wide variety of engines.
2. Definition and evaluation of functions of engine variables (parameters) which may be related to stability characteristics.
3. Establishment of relationships between engine design and stability parameters by analysis of the collected experimental data.
4. Formulation of an approach for utilizing these design - stability relationships in the development of new engines.

The results of this program provide a comprehensive description of past experience with combustion instability in various engine types. The suggested design approach offers a means for utilizing this experience to avoid development of new engines which are prone to instability.

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This program was sponsored by the National Aeronautics and Space Administration, Office of Advanced Research and Technology, Division of Liquid Rocket Research and Technology. The program was initiated in June 1965 with Mr. Henry Burlage, Jr., as Project Manager. Mr. Jack A. Suddreth and Dr. Robert S. Levine served as Project Managers later in the program. Dr. Richard J. Priem of the Lewis Research Center was the program Technical Manager.

A Steering Group was formed to provide technical guidance to the program, and the following persons served on this group:

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The following persons contributed to the program as consultants in specific technical areas:

Name and Organization	Activity
Dr. Vito D. Agosta Polytechnic Institute of Brooklyn	Parameter Definition
Dr. George E. P. Box University of Wisconsin	Data Analysis
Dr. Luigi Crocco Princeton University	Parameter Definition
Dr. William A. Sirignano Princeton University	Parameter Definition

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SUMMARY

This program consisted of a study of existing data on combustion stability in liquid propellant rocket engines. The purpose of the study was to derive empirical relationships between engine design and stability characteristics. The objective of the program was the establishment of criteria, based on these relationships, for the design of stably operating engines. The program was directed by Arthur D. Little, Inc., with technical guidance from a Steering Group consisting of representatives of organizations active in engine research and development.

The first task in the program was the collection of experimental data from records of engine stability tests. To facilitate the collection process, a data collection format was prepared in the form of a series of computer coding sheets. Data items were tabulated on the sheets by several organizations supplying data to the project. The data were submitted to Arthur D. Little, Inc., where they were checked and filed on magnetic tape by means of a computer filing program. Of 3878 test records that were submitted, 3749 were filed.

The second project task was the definition and evaluation of functions of engine variables which may be related to stability. These functions, referred to as parameters in this project, were required as a means of deriving non-linear relationships between engine design and stability characteristics. A list of parameters was formulated by reviewing past work in combustion instability and listing functions of variables which have been shown theoretically or experimentally to be related to stability. In addition to these independent design parameters, a number of dependent parameters, or stability indices, were defined to serve as measures of stability for each engine test. Each parameter was evaluated for each test record in the data file.

The third program task was the analysis of the collected data to determine correlations between stability indices and design parameters. To facilitate this analysis, the data were divided into groups based upon major engine design features. The data also were divided into pulsed and

non-pulsed tests. A correlation, or stability equation, was developed for each data group, and combined equations also were developed for all pulsed tests and for all non-pulsed tests. In addition to stability-prediction equation development, relations were determined between static and dynamic stability, and between stability and engine performance.

The final task was the formulation of an approach for utilizing the stability equations in the development of a new engine. In the recommended approach, reference is made to the distribution of stability index values in the appropriate data group. From this distribution, a cutoff index value is determined which corresponds to a specified frequency of occurrence of instability in that data group. By using the stability equation for that group, the index can be evaluated for a new engine design. By comparing this index value with the cutoff value, the designer can determine whether or not the probability of his new engine being stable is within acceptable limits.

The results of this program provide a comprehensive description of past experience with combustion instability in various engine types. The suggested design approach offers criteria which utilize this experience to avoid development of new engines which are prone to instability. However, the results of this program do not provide specific guidelines for the design of stable engines.

CONCLUSIONS

The following salient conclusions can be drawn from the results of this study:

1. It is possible to predict the stability of liquid propellant rocket engines on the basis of design information with sufficient accuracy so that significant cost savings can result from the future application of the prediction equations.
2. The predictive power of the equations for static stability is considerably better than that of the equations representing dynamic stability.
3. For certain categories of engine design, it is possible to find special equations having better predictive power than that of the applicable general equation.
4. There appears to be little or no relationship between stability and c-star efficiency. Thus, the designer can be assured that, in the process of selecting design parameter values to maximize stability, he is not per se reducing c-star efficiency.
5. Dynamic stability is not readily predictable on the basis of observations on static stability. The occurrence of dynamic instability depends strongly upon the values of many engine design parameters that are not strongly related to the occurrence of static instability.

With further effort the resulting design criteria could be improved. The methodology used to develop the mathematical equations and the suggested approach for applying these equations are sound. We would expect that, with further effort, the "predictive ability" of the equations could be improved and they could be made applicable to a wider range of engine types.

We recommend that any follow-on effort to this program include:

1. Collection and filing of additional data with emphasis on

designs and operating conditions not included in the present file.

2. Definition of additional design parameters and stability indices.
3. Application of regression analysis to the increased data file utilizing an expanded list of parameters.

The results of this initial program have demonstrated the usefulness of this approach to this particular problem.

INTRODUCTION

Objectives

A universal problem associated with the development of liquid propellant rocket engines is the occurrence of combustion instability in its various forms in newly-designed engines. In spite of the fact that many stably operating engines have been developed successfully, the designer has been unable to utilize this experience to assure stable operation in new engines. Instability arises unpredictably and is remedied most often by design changes or by the addition of auxiliary attenuation devices. This approach is costly because the remedial process must be conducted with full-scale engines in an advanced state of development.

In recent years, a vast quantity of experimental data has been generated on engine performance during combustion chamber research and development programs. Engines of widely varied designs have been operated and have demonstrated varying degrees of combustion stability. The purpose of this program is to derive, from this backlog of data, empirical relationships between engine design and stability characteristics.

The objective of the program has been to establish criteria for the design of stably operating liquid propellant rocket engines by means of a systematic analysis of existing test data. In this analysis, relationships were sought between engine design variables, operating variables, and stability characteristics. The results of theoretical and experimental studies of combustion instability were used as guides in seeking these relationships.

Approach

The program consisted of a series of tasks leading to the intended objective. The specific objectives of the individual tasks were to:

1. Develop a system for collecting rocket engine stability

test data and utilize this system to collect such data from a wide variety of engines.

2. Define and evaluate functions of engine variables (parameters) which may be related to stability characteristics.
3. Establish relationships between engine design and stability parameters by analysis of the collected experimental data.
4. Formulate an approach for utilizing these design-stability relationships in the development of new engines.

These tasks were accomplished by Arthur D. Little, Inc., in association with qualified subcontractors and consultants. A Steering Group was formed consisting of representatives of organizations active in the areas of engine development and combustion instability research. This group provided technical guidance for the program, and met regularly to review progress. Organizations included on the Steering Group and individual participants are listed in the acknowledgements.

EXPERIMENTAL DATA

Variable Selection

The initial step in the first task of the program was to formulate a list of variables which would serve to describe the design, operational, stability, and performance characteristics of a liquid propellant rocket engine. In formulating the list, two opposing considerations were dominant. Firstly, it was necessary to incorporate in the list all aspects of engine design which are considered to be related to stability. These design aspects must be described in sufficient detail so that relevant differences in engine characteristics can be distinguished. Secondly, the list, when completed, formed the basis for data collection. Therefore, the information contained had to be limited so that data on a specific test could be collected in a reasonable length of time.

At the time this program was initiated, the ICRPG Working Group on Liquid Propellant Combustion had formed a subcommittee to prepare a data collection format. This committee had prepared a preliminary list of pertinent variables, and this was used as a basis for preparation of a variable list for this project.

The list of engine variables prepared for use in the program is included in this report as Appendix C. The list is divided into four categories: design, operational, stability, and performance variables.

The design variables include characteristics of the combustion chamber, feed system, injector, baffle, and acoustic absorption liner. For purposes of this project, each category is sufficiently comprehensive, except the list of injector variables. All pertinent design features of an injector could not conveniently be included in a list of variables. Instead, a sketch of the injector face was called for during data collection.

Performance variables were included in the list so that if parameters were found which affect stability, their effects on performance also could be investigated. A correlation between engine design and performance characteristics was not an objective of this program.

Data Collection

To facilitate the collection of experimental data from engine stability tests, a set of fifteen data collection sheets was prepared and an instruction manual written. The data collection forms were designed to ease, as far as possible, the actual process of selecting and recording useful data items and to minimize the quantity of repetitious information that collectors need report. The data sheets and the collection procedure were described in our Interim Report (Ref. 1), and the instruction manual, including copies of the data sheets, has been published as an official CPIA publication (Ref. 2).

Experimental data were collected from records of engine stability tests at nine different organizations. Each organization was supplied with data collection sheets and instruction manuals, and the collection process was supervised by a member of the organizaton staff. When the data had been entered on the collection sheets, they were shipped to Arthur D. Little, Inc., for filing.

A total of 3878 test records were received, including 3328 individual test descriptions and 550 replicates. Upon receipt, the data were checked, and 3749 records were filed on magnetic tape. The remaining records were incomplete and could not be filed. After filing, values of individual variables were tabulated. These procedures are described in Appendix A, and tables describing the data collection are contained in Appendix B.

At the conclusion of this program, a copy of the data file tape was delivered to the NASA Lewis Research Center together with the original data collection sheets, tables of values of variables and parameters, and copies of the output from the data analysis program. These materials can be made available for review of this program, or for further analysis of the data.

PARAMETERS

Independent Parameters

The statistical techniques which have been used in this program to correlate experimental data are based on an assumed linear relationship between the dependent and independent variables. However, it is highly unlikely that a simple linear relationship exists between engine stability (our dependent variable) and engine design variables. If such a relationship exists, it probably is complex and highly non-linear.

To introduce non-linearity into such an analysis, it is necessary to define functions of variables, and then to seek linear relationships between these functions. In this study, the term "parameter" has been used to indicate a function of variables. A parameter can be dependent or independent, depending on whether or not it contains dependent or independent variables.

Since the number of variables used to describe an engine is large, the potential number of non-linear functions of these variables is virtually endless. Consequently, a highly selective process had to be utilized in defining parameters to be included in the analysis in order to limit the number to a manageable level. The approach taken in this study was to define parameters based on the results of theoretical and experimental studies of combustion instability. One of the tasks undertaken was a review of pertinent literature to glean from it relationships among variables which might be related to stability. In addition to parameters taken from the literature, a number of parameters were defined specifically for use in this program.

A list of parameters included in the analysis is contained in this report as Appendix D, and is divided into design parameters, frequency-independent and frequency-dependent operational parameters, and qualitative design and operational parameters. Design parameters are functions only of physical characteristics of the engine hardware. Operational parameters are functions of propellant properties and engine operating conditions, and their values may vary with time during a given test. These parameters can be evaluated for a specific time during a test, or for a real or specified steady state condition. Qualitative parameters are utilized to distinguish gross design features such as the presence of a baffle or acoustic absorption liner, or operational factors such as the use of pulsing. Each of the parameters listed in Appendix D was evaluated for each test in the data collection and the value filed in the test record. The methods used for parameter evaluation and filing are described in Appendix A.

In the evaluation of frequency-dependent parameters, frequency was set equal to unity. As these parameters were used in the analysis, they were multiplied or divided, as appropriate, by the frequency of the first tangential mode. This frequency was calculated as follows (3):

$$f_{1t} = 0.586\ a/D_1$$

where a = acoustic velocity of combustion product

D_1 = chamber diameter at injector end

Attempts were made to correlate frequency dependent parameters, evaluated in this manner, with the occurrence of the first tangential mode of instability. However, no significant correlations were found, and the use of these parameters was discontinued.

Stability Parameters

In order to relate engine design and operational variables to stability characteristics, it is necessary to define a function which serves as a measure of stability when evaluated for a specific test. Several such functions were defined for use in this program. These are referred to as "stability parameters" and are listed in Appendix E. The stability parameters were utilized as dependent variables in data analysis.

Both qualitative and quantitative stability parameters were utilized. Qualitative parameters are two-valued functions which distinguish between stable and unstable tests, but do not indicate a "degree" of stability. These include SP1, SP1A, and SP7 which pertain to static stability, and SP6, SP8, SP10 and SP12 which pertain to dynamic stability. Each is assigned a value of zero for a stable test and unity for an unstable test. Quantitative parameters are continuous functions which indicate a level of stability for each test. These include SP1B, SP3 and SP5 which pertain to static stability, and SP2, SP2A, SP2B, SP2C, SP2D and SP9 which pertain to dynamic stability. For each test in the data collection, all applicable stability parameters were evaluated and the values filed with the test record.

During the analysis, the qualitative stability parameters were used most extensively. SP1A and SP10 were adopted as the most suitable indicators of static and dynamic stability respectively. The quantitative parameters were found to assume their extreme values for most tests, so that, in effect, their significance was only qualitative. As a result, the use of quantitative stability indices was discontinued after preliminary attempts at data analysis.

Performance Parameter

The scope of this program did not include a correlation of engine performance with design characteristics. However, a correlation between engine performance and stability characteristics was established. The purpose of this correlation was to determine the effects on performance of using the criteria developed in this program for improvement of stability.

Selection of a performance parameter was necessary for correlating performance with stability. (C-star characteristic exhaust velocity) efficiency, that is, the ratio of delivered c-star to theoretical c-star, was utilized for this purpose. C-star efficiency (CSE) was calculated for each test as follows:

$$CSE = g\gamma G\ A_t\ P_c/a(\dot{m}_f + \dot{m}_o)$$

where

g = proportionality constant, Newton's law

γ = specific heat ratio of combustion products

$G = [2/(\gamma + 1)]^{(\gamma + 1)/2(\gamma - 1)}$

A_t = nozzle throat area

a = acoustic velocity of combustion products

$\dot{m}_f$ = fuel flow rate

$\dot{m}_o$ = oxidizer flow rate

P_c = effective chamber stagnation pressure, evaluated approximately as follows:

$$P_c = (p_{ci}/2)\ [1 + (1/(1 + \gamma M^2))]$$

$$M = (1/2BG)\ [R_c - (R_c^{\ 2} - 4BG^2)^{1/2}]$$

$$B = (\gamma + 1)/4$$

P_{ci} = chamber pressure, injector end

R_c = nozzle contraction ratio

CSE was evaluated for each test in the data collection using values of operational variables reported for the intended steady-state condition (condition code 0). Values of CSE were filed with the test records. Results of the correlation of CSE with stability are discussed later in this report.

STABILITY PREDICTION EQUATIONS

Introduction

A prediction equation establishes a mathematical relationship between a stability characteristic and both operating variables and design characteristics. This relationship enables the prediction of the value of the stability characteristic based on given values of the operating and design variables. The stability characteristic is measured by the appropriate stability parameter, defined in Appendix E, and throughout the remainder of this report we shall mean the value of the appropriate stability parameter when we refer to measures of stability or instability.

In the development of a prediction equation, the problem is one of describing a complex multivariate relationship. The resulting relationship, expressed in the form of a "regression equation", is determined from the observations by the method of least squares, which minimizes the sum of the squared deviations between the observed values of the stability characteristic (y) and the predicted values(y_p).

A prediction equation of the type developed in this study is of the form

$$y_p = b_0+b_1x_1+b_2x_2+\ldots+b_mx_m$$

In this equation, y_p is called the <u>dependent variable</u> (read "y-predicted"), and it is a measure of predicted stability (a value of a stability parameter); the variables $x_1,x_2,\ldots,x_m$ are called the <u>independent variables</u>, and they are measures of operating conditions and design parameters. This equation is linear in the coefficients $b_0,b_1,b_2,\ldots,b_m$ but it may be non-linear in one or more of the x-variables. Non-linearities can be introduced by means of such terms as log x, x^2, etc.

The coefficients $b_0,b_1,\ldots,b_m$ are constants, estimated from the data, which purport to give the effects of the corresponding x-values on y as approximated by y_p. For example, b_1 purports to measure the effect on stability of a unit change in the operating or design variable x_1. If b_1 has a value not statistically significantly different from zero, then we say that x_1 "has no influence" on stability.

Unfortunately, the interpretation of b_1 as the "effect of x_1" is seriously clouded if x_1 is highly correlated with, say x_2. The effects of two or more highly correlated independent variables are divided in some difficult-to-determine way among the values of their coefficients. Thus, in a non-orthogonal relationship (one with correlated independent variables) such as one ordinarily encounters when working with historical data rather than with the results of a statistically designed experiment, it can be grossly misleading to isolate a given coefficient and argue that its value expresses the effect of varying the associated independent variable. This statement does not imply, however, that use of the <u>entire equation</u> for the purpose of predicting values of the dependent variable is invalid.

Associated with a prediction equation are a number of statistical measures which describe its efficacy. Let us denote the original variability of the values of y (the observed stability measure) over all the data points entering the analysis by S_y^2, and the remaining (residual) variability after fitting the regression equation by S_e^2. If the regression equation is to be useful for prediction, we would expect S_e^2 to be much smaller than S_y^2; the quantity $S_y^2-S_e^2$ measures the <u>reduction</u> in variability achieved by the equation. The <u>relative</u> reduction in variability,

$$R^2 = \frac{S_y^2-S_e^2}{S_y^2}$$

is called the <u>coefficient of determination</u> and its square root, R, is the <u>multiple correlation coefficient</u> associated with the regression equation.

In the process of developing prediction equations for stability, we have been guided by the principle that each equation should contain the least number of meaningful terms consistent with as high a value of R^2 as possible while containing correlations among the independent variables (internal correlations) that are as small as possible. The criterion of "least number of meaningful terms" is a simple application of the philosophical principle of "Occam's Razor" which states in essence that of two competing descriptions of nature which are equally verifiable, the simpler one is preferable. The criterion of high R^2 was adopted to assure the maximum predictive power, and the criterion of low internal correlations was adopted to avoid the inclusion of grossly misleading coefficients in the equations.

These general criteria are in constant competition with one another. One can usually increase R^2 by the simple expedient of including more independent variables (though the increase may be illusory); even when the increase in R^2 is significant (though perhaps slight from a practical point of view), the inclusion of extra terms may "confound" the relationship by introducing high internal correlations. Thus, in the development of prediction equations for rocket-engine stability, it was found necessary to pass through many iterations, and to apply both engineering and statistical judgment at each step. If, at any step, the criteria or judgments applied in the selection of which independent variables to include had been materially altered, the final prediction equations as presented in this report may well have been different. We can claim only that the resulting equations "make sense" and that they statistically demonstrate evidence of reasonable predictive power.

A General Equation for Non-Pulsed Tests

The response of an engine to pulsing is essentially different from a "spontaneous" instability, and it became necessary to describe these two basic kinds of instability by means of different dependent variables. For this reason, it is necessary to construct separate prediction equations for pulsed and for non-pulsed tests.

The prediction equation derived for the non-pulsed tests is given in Table I. The variables and parameters included in this model are defined in Appendices C and D. This table also shows the physical units,

TABLE I

General Equation for Non-Pulsed Tests

Variable*	Units	Mean	Std. Dev.	1%	99%
BF		0.3683	0.4826	0	1
EPA	in^{-2}	3.766	18.51	0.06	10
F03		0.2851	0.4517	0	1
IDE_f		1.922	2.187	0	7.2
$\log(ID_f)$		-0.01452	0.04544	-0.20	0.1
L_1	in	16.24	6.143	4.0	34
LD		2.138	2.445	0.42	11.6
LR		0.2507	0.4336	0	1
MPE	lbm/sec	1.932	3.586	0	17
P_{ci}	psia	330.0	282.9	80	1300
PE1		0.1656	0.3719	0	1
$\log(R_c)$		0.3343	0.2430	0.0	1.4

$$
\begin{aligned}
(SP1A)_p = [\ & 0.49583 - 0.0014639(LR - 0.25068)(P_{ci} - 329.95023) \\
& + 0.024960(L_1 - 16.24385) - 0.45096(\log R_c - 0.33429) \\
& - 7.15205(BF - 0.36833)(\log ID_f + 0.01452) \\
& + 0.11250\ (LR - 0.25068)(LD - 2.13785) \\
& - 0.05177(F03 - 0.28507)(IDE_f - 1.92209) \\
& - 0.27789(F03 - 0.28507) \\
& - 0.0006173(IDE_f - 1.92209)(EPA - 3.76607) \\
& + 1.43317(LR - 0.25068)(MPE - 1.93154) \\
& + 2.09309(LR - 0.25068) - 0.30534(BF - 0.36833) \\
& - 0.80153(PE1 - 0.16561) + 0.001229(L_1 - 16.24385)^2 \\
& + 0.002199(MPE - 1.93154)^2 - 0.26849(\log R_c - 0.33429)^2 \\
& + 0.00035321(P_{ci} - 329.95023)(LD - 2.13785)
\end{aligned}
$$

(CONTINUED)

TABLE I (Cont'd)

$- 0.087008(L_1 - 16.24385)(\log R_c - 0.33429)$

$- 0.17222(L_1 - 16.24385)(\log ID_f + 0.01452)$

$- 0.000131(L_1 - 16.24385)(MPE - 1.93154)$

$- 0.81565(\log ID_f + 0.01452)(IDE_f - 1.92209)$

$- 0.030990(LD - 2.13785)(MPE - 1.93154)$

$- 0.033444(IDE_f - 1.92209)(MPE - 1.93154)$

$+ 0.25448(PE1 - 0.16561)(LD - 2.13785)$

$- 0.90924(PE1 - 0.16561)(MPE - 1.93154)$

$+ 0.17428(PE1 - 0.16561)(IDE_f - 1.92209)$

$+ 0.0957(PE1 - 0.16561)(\log R_c - 0.33429)$

$- 0.0003465(F03 - 0.28507)(P_{ci} - 329.95023)$

$+ 0.03243(F03 - 0.28507)(L_1 - 16.24385)$

$+ 0.00098624(BF - 0.36833)(P_{ci} - 329.95023)$

$- 1.20213(LR - 0.25068)(\log R_c - 0.33429)]$

*See Appendix F for full names of variables.

Note: All logarithms are taken to base 10.

mean value, standard deviation, and first and ninety-ninth percentiles of each variable. The purpose of these measures is to display the range of data over which the equations were constructed. The mean value of each variable is the "center of mass" of the data points; the standard deviation measures their "spread" about the mean.

Since many of the variables or parameters had distributions that were highly skewed (asymmetric), the common interpretation that most of the data are contained within two or three standard deviations of the mean is to be avoided. (In some cases, the standard deviation is nearly equal to, or even greater than the mean, indicating a high degree of positive skewness.) The percentiles are included for this reason. The first percentile is the value of the corresponding variable or parameter such that one percent of the observations were smaller than this value; the ninety-ninth percentile is such that one percent of the observations exceeded it in value.

The user of this equation is cautioned not to make predictions of stability in cases for which the value of one or more of the independent variables is outside the two percentiles given. The statistical methods used are such that the error in prediction increases very rapidly as one extrapolates beyond the range of the data.

The given prediction equation includes a number of non-linear terms; the parameters themselves are generally non-linear in the variables, and in some cases logarithms were taken. In addition, the equation explicitly contains squared terms and cross-product or "interaction" terms. Care must be taken in the determination of the coefficient of a given variable to include all terms containing that variable. For example, the fuel-oxidizer parameter F03 appears in four terms of the model; thus, its coefficient is <u>not</u> -0.27789, the coefficient of F03 alone. The effect of F03 is measured by the coefficient:

$$(-0.59082 - 0.05177\ IDE_f - 0.0035\ P_{ci} + 0.03243\ L_1)$$

which is obtained by combining all the terms containing F03.

Thus, we see that the effect on stability of changing the value of F03 depends upon the values of the parameters IDE_f, P_{ci}, L_1. For example, if

$$IDE_f = 1.5,\ P_{ci} = 750,\ \text{and}\ L_1 = 10.4$$

the coefficient of F03 is -0.594, which implies that the effect of a unit increase in F03 would be a sizeable <u>decrease</u> in instability. However, if

$$IDE_f = 3.0,\ P_{ci} = 250,\ \text{and}\ L_1 = 31.0$$

this coefficient becomes 0.172, which implies that, for such an engine design, the effect of a unit increase in F03 is a somewhat smaller <u>increase</u> in instability.

The predictive power of this equation will be discussed in greater detail in the following chapter; however, the values of the associated statistics give preliminary indications of its usefulness. The model is based on 1105 observations of non-pulsed tests, and the coefficient of determination is

$$R^2 = 0.592$$

The standard error of estimate is

$$S_e = 0.278$$

Thus, approximately 59 percent of the original variability in the values of the stability parameters was "explained" by the regression equation. The standard error of estimate, $S_e = 0.278$, gives the amount of variability (as measured by the standard deviation) remaining in the value of the stability parameter after the regression equation has been applied.

As a numerical illustration of the application of this equation, suppose that an engine is designed so that the independent variables assume the following values. (For simplicity in calculation, many variables have been set equal to their mean values.)

Variable	Value	Variable	Value
LR	0	LD	2.1379
P_{ci}	329.95 $\mathrm{lbf/in^2}$ abs	F03	1
L_1	16.2439 in	IDE_f	1.9221
$\log R_c$	0.33429	EPA	3.7661 $\mathrm{in^{-2}}$
BF	0	MPE	1.9315 lbm/sec
$\log ID_f$	-0.01452	PE1	1

Substitution of these values into the formula given in Table I gives

$$(SP1A)_{\bar{p}} = -0.7839$$

A General Equation For Pulsed Tests

The prediction equation derived for pulsed tests is given in Table II. This table also shows the ranges of the independent variables used in the regression analysis. The equation includes a number of non-linear terms, and the same general interpretation of the interaction terms as given in the previous section applies.

This equation is based on 1284 observations of pulsed tests, and the coefficient of determination is

$$R^2 = 0.259$$

The standard error of estimate is

$$S_e = 0.434$$

Note that the predictive power of the non-pulsed equation ($R^2 = 0.592$) is considerably better than that obtained for the pulsed equation. The reasons for this difficulty in describing the results of pulsed tests are not clearly understood. However, lack of knowledge of the exact positioning of the pulse, difficulties in measuring the severity of the pulse and the resulting behavior of the engine probably have contributed to the poorer predictive power of the pulsed equation.

TABLE II

General Equation for Pulsed Tests

Variable*	Units	Mean	Std. Dev.	1%	99%
BF		0.1168	0.3213	0	1
$\log(D_{of})$	log (in x 1000)	1.696	0.2336	0.9	2.4
F02		0.1246	0.3304	0	1
LD_f		8.210	17.51	0.13	100
LR		0.08022	0.2717	0	1
LD		1.459	1.974	0.43	13
PE1		0.1433	0.3505	0	1
PE2		0.4299	0.4953	0	1
TPVM	lbf/in^3	4.404	4.207	0.1	26
V_o	in/sec	1066	556.7	77	3300

$$
\begin{aligned}
(SP10)_p = [& - 5.56684 - 0.16675(LD - 1.45926) - 0.26577(LD_f - 8.20992) \\
& + 0.03456\ (TPVM - 4.40439) + 0.00009267(V_o - 1065.97697) \\
& - 13.67581(\log D_{of} - 1.69583) + 0.15923(F02 - 0.12461) \\
& - 74.95672(LR - 0.08022) - 0.36162(BF - 0.11682) \\
& + 12.57151(LR - 0.08022)(PE1 - 0.14330) \\
& + 0.27624(BF - 0.11682)(PE2 - 0.42991) \\
& - 0.003242(TPVM - 4.40439)^2 - 0.42891(\log D_{of} - 1.69583)^2 \\
& - 0.044068(LD - 1.45926)(TPVM - 4.40439) \\
& + 0.0003075(V_o - 1065.97697)(\log D_{of} - 1.69583) \\
& - 3.09641(LR - 0.08022)(LD_f - 8.20992) \\
& + 0.0003577(LR - 0.08022)(V_o - 1065.97697) \\
& - 163.91664(LR - 0.08022)(\log D_{of} - 1.69583)
\end{aligned}
$$

(CONTINUED)

TABLE II (Cont'd)

$$- 0.12184(\mathrm{PE1} - 0.14330)(\mathrm{LD}_f - 8.20992)$$

$$- 0.15581(\mathrm{PE2} - 0.42991)(\mathrm{LD} - 1.45926)$$

$$- 0.00002194(\mathrm{PE2} - 0.42991)(V_o - 1065.97697)$$

$$+ 0.03835(\mathrm{PE2} - 0.42991)(\mathrm{TPVM} - 4.40439)$$

$$- 0.40008(\mathrm{PE2} - 0.42991)(\log D_{of} - 1.69583) \;]$$

[*] See Appendix F for full names of variables.

Note: All logarithms are taken to base 10.

Special Equations For Certain Engine Types

For certain engine types it was possible to find special equations having better predictive power than the applicable general equation. Data groups were defined by considering all 32 combinations of the five variables (Baffle, Liner, Pulsing, Impinging Jets, Annular Jets) shown in Table III. Based on the availability of data, the fourteen principal groups presented were selected for individual study (Table IV). A separate prediction equation was developed for each of these groups and compared with the applicable general equation.

The basis of this comparison is better understood after reading the following chapter on "Use of Stability Equations in Decision Making". However, a brief argument is as follows. For a given data group, the value of the dependent variable predicted by its special model, y_p [i.e., $(SP1A)_p$ or $(SP10)_p$] is computed. Then, the mean value and the standard deviation of the predicted values y_p are computed separately for the stable and for the unstable tests. Denoting the difference between the two means by Δy_p and the "pooled" (weighted root mean square) standard deviation by S_e, we define the "generalized distance" between the stable and unstable groups to be

$$D = \frac{\Delta y_p}{S_e}$$

The statistic D describes the degree of discrimination between stable and unstable tests achieved by the equation. It can be interpreted as the number of standard deviations separating the distributions of the stable and the unstable tests.

This calculation can be repeated when the predicted instability value is calculated by means of the applicable general equation. The values of Δy_p, S_e, and D so calculated are shown in Table V. In deciding whether it would be better to use a special equation for a given data group, rather than the applicable general equation, we adopted the following criterion: recommend use of the applicable general equation unless the value of D for the special equation is clearly larger. It

TABLE III

Principal Data Groups

Principal Group No.	Baffle	Liner	Pulsing	Impinging Jets	Annular Jets	No. of Tests	Percentage Frequency
1	No	No	No	No	Yes	443	11.8
2	No	No	No	Yes	No	381	10.2
3	No	No	Yes	No	Yes	201	5.4
4	No	No	Yes	Yes	No	932	24.9
5	No	Yes	No	Yes	No	178	4.7
6	Yes	No	No	Yes	No	667	17.8
7	Yes	No	Yes	Yes	No	225	6.0
8	No	No	No	No	No	60	1.6
9	No	No	Yes	No	No	109	2.9
10	No	Yes	No	No	Yes	108	2.9
11	No	Yes	Yes	No	Yes	38	1.0
12	No	Yes	Yes	Yes	No	68	1.8
13	Yes	No	No	No	Yes	99	2.6
14	Yes	No	Yes	No	No	62	1.7
15	Other combinations*					178	4.7
Total						3749	100.0

---

* Includes 166 tests for which no principal element type could be defined. A principal element type is defined when the elements carrying over 50 percent of the fuel and the elements carrying over 50 percent of the oxidizer are of the same class (showerhead, coaxial, or impinging).

TABLE IV

Regression Analyses of Principal Data Groups

Principal Group No.	Total No. Tests in Group	No. Tests Used in Regression Analysis[1]	Percent of Tests Used in Regression Analysis	Stability Index	Percentage of Unstable Tests	R^2 for Prediction Model
1	443	182	41.1	SP1B	116[2]	0.525
2	381	362	95.0	SP1A	27.3	0.567
3	201	148	73.6	SP10	59.5	0.327
4	932	834	89.5	SP10	56.7	0.198
5	178	169	93.9	SP1A	33.7	0.686
6	667	621	93.1	SP1A	1.77	0.269
7	225	167	74.2	SP10	17.4	0.292
8[3]	60	-	0.0	SP1A	0.0	-
9	109	107	98.2	SP10	14.0	0.636
10	108	108	100.0	SP1A	63.9	0.183
11	38	35	92.1	SP10	40.0	0.800
12	68	68	100.0	SP1A	42.6	0.227
13	99	75	75.8	SP1A	42.7	0.361
14	62	52	83.9	SP10	15.4	0.217
Non-Pulsed[4]	1493	1105	74.0	SP1A	24.3	0.592
Pulsed	1635	1284	78.5	SP10	51.9	0.259

---

[1] In each group not every test could be used to construct the regression model because of occasional missing values of one or more variables or parameters.

[2] This is the average value of SP1B over the 182 tests used in the regression analysis of Group 1.

[3] No regression analysis of Group 8 could be made because all tests were stable.

[4] Group 1 was excluded from this category.

TABLE V

Comparison of General and Special Equations

	General Equation			Special Equation			Recommended Equation	Table
Data Group	Δy_p	S_e	D	Δy_p	S_e	D		
1	--	--	--	--	--	--	Special	VI
2	0.58	0.21	2.76	0.57	0.22	2.59	General	I
3	0.16	0.31	0.52	0.32	0.23	1.39	Special	VII
4	0.18	0.19	0.95	0.44	0.33	1.33	Special	VIII
5	0.67	0.22	3.05	0.65	0.21	3.10	General	I
6	0.13	0.06	2.17	0.27	0.06	4.50	Special	IX
7	0.35	0.16	2.19	0.29	0.18	1.61	General	II
8	--	--	--	--	--	--	General	I
9	0.10	0.04	2.50	0.64	0.17	3.76	Special	X
10	0.20	0.20	1.00	0.18	0.19	0.95	General	I
11	0.78	0.21	3.71	0.79	0.20	3.95	General	II
12	0.10	0.11	0.91	0.22	0.22	1.00	General	II
13	0.34	0.23	1.48	0.34	0.22	1.55	General	I
14	0.04	0.12	1.83	0.22	0.15	1.47	General	II

can be seen from an examination of Table V that data groups 3, 4, 6, and 9 warrant the use of special equations.

Before specifying the special equations to be recommended for these groups, we pause to note the reasons for the absence of comparative information for Data Groups 1 and 8 in Table V. Group 1 consists of test records from hydrogen-oxygen engines where the fuel temperature was varied (ramped) downward during each test. The fuel temperature at the onset of instability (SP1B) was used as the dependent variable, and, thus, the data cannot be divided into stable and unstable tests. With respect to Group 8, it was found that the tests to be included in the regression analysis all were stable. The data of this group were included in the construction of the general non-pulsed equation. Since that equation contains one independent variable LR, the effect of introducing liners can be determined.

The special equations recommended for use are presented in Tables VI - X. Values of the associated statistics R^2 and S_e are given in Tables IV and V.

Examples of Predicted Stability Values

The general non-pulsed and pulsed equations, given in Tables I and II, were used to calculate y_p - values for all tests for which all necessary data items were available. Sample values are listed in Table XI for pulsed tests of three Rocketdyne engines accepted for use in the Apollo program. The predicted stability parameter values are very low (actually negative) for all tests, except for four J-2 tests run at off-design conditions. Two of these tests were unstable; that is, the oscillations resulting from the pulse did not damp.

These sample values are not a clear verification of the general pulsed equations since these tests were included in the data used to develop the relationship. Nevertheless, the ability of the equation to identify a potentially unstable operating condition is demonstrated by these results.

TABLE VI

Special Equation for Group 1

Variable*	Units	Mean	Std. Dev.	1%	99%
P_{ci}	psia	303.1	55.72	105	570
MPE	lbm/sec	0.1873	0.1645	0.06	0.70
$\log(R_c)$		0.3088	0.1038	0.0	0.67

$$
\begin{aligned}
(\mathrm{SP1B})_p = [\ & 96.63515 - 0.63218(P_{ci} - 303.10439) \\
& + 110.21252(\log R_c - 0.30878) \\
& - 3.75040(P_{ci} - 303.10439)(\mathrm{MPE} - 0.18727) \\
& + 0.0078209(P_{ci} - 303.10439)^2 \\
& - 2.27870(P_{ci} - 303.10439)(\log R_c - 0.30878) \\
& + 625.86734(\log R_c - 0.30878)^2\ ]
\end{aligned}
$$

*See Appendix F for full names of variables.

Note: All logarithms are taken to base 10.

TABLE VII

Special Equation for Group 3

Variable*	Units	Mean	Std. Dev.	1%	99%
EPA	in^{-2}	3.562	1.084	0.09	5.2
LD_f		0.9382	0.9116	0.13	4.0
LD		1.118	0.6178	0.43	2.8
ER		0.5084	0.2567	0.16	1.2
TPVM	lbf/in^3	7.534	5.987	0.13	30

$$
\begin{aligned}
(SP10)_p = [\ & 0.46287 - 0.50940(LD - 1.11761) - 0.05661(LD_f - 0.93824) \\
& + 0.23615(EPA - 3.56220) \\
& + 0.36327(EPA - 3.56220)(ER - 0.50838) \\
& - 0.17352(EPA - 3.56220)(LD - 1.11761) \\
& + 0.28446(LD - 1.11761)^2 \\
& - 0.007232(LD - 1.11761)(TPVM - 7.53387) \\
& - 0.087395(TPVM - 7.53387)(ER - 0.50838)\ ]
\end{aligned}
$$

*See Appendix F for full names of variables.

Note: All logarithms are taken to base 10.

TABLE VIII

Special Equation for Group 4

Variable*	Units	Mean	Std. Dev.	1%	99%
$\log(D_{of})$	log (in x 1000)	1.770	0.1185	1.5	2.2
F02		0.1271	0.3333	0	1
LD_f		9.608	19.05	1.0	100
LD		1.666	2.394	0.44	14
ER		0.8037	0.2036	0.38	1.3
TPVM	lbf/in^3	3.677	2.921	0.12	9.8
V_o	in/sec	1184	547.7	300	3000
x_{if}	in	0.2641	0.2938	0	1.0

$$\begin{aligned}
(SP10)_p = [\ & 0.54318 - 0.110461(LD - 1.66635)(TPVM - 3.67749) \\
& - 0.0008714(LD_f - 9.60760) + 0.0001488(V_o - 1183.73428) \\
& - 0.46751(\log D_{of} - 1.76964) \\
& - 0.08384(F02 - 0.12710)(TPVM - 3.67749) \\
& + 0.08926(ER - 0.80367)(TPVM - 3.67749) \\
& + 0.28447(ER - 0.80367) + 0.85622(LD - 1.66635)(x_{if} - 0.26406) \\
& - 0.000000497(V_o - 1183.73428)(LD_f - 9.60760) \\
& + 0.0004150(V_o - 1183.73428)(\log D_{of} - 1.76964) \\
& - 0.00001110(V_o - 1183.73428)(TPVM - 3.67749)\ ]
\end{aligned}$$

*See Appendix F for full names of variables.

Note: All logarithms are taken to base 10.

TABLE IX

Special Equation for Group 6

Variable*	Units	Mean	Std. Dev.	1%	99%
EPA	in^{-2}	2.239	10.01	0.06	10
F03		0.5008	0.5004	0	1
h_b	in	2.912	0.5519	1.0	4.0
IDE_f		1.740	1.610	0.8	6.3
$\log(ID_f)$		-0.02333	0.01598	-0.048	0.007

$$
\begin{aligned}
(SP1A)_p = [\ & 0.01594 + 0.07347(h_b - 2.91245)(F03 - 0.50081) \\
& - 0.07539(h_b - 2.91245)(IDE_f - 1.74030) \\
& - 3.96507(h_b - 2.91245)(\log ID_f + 0.02333) \\
& - 3.33025(F03 - 0.50081)(\log ID_f + 0.02333) \\
& - 0.005565(EPA - 2.23850)(IDE_f - 1.74030)\ ]
\end{aligned}
$$

*See Appendix F for full names of variables.

Note: All logarithms are taken to base 10.

TABLE X

Special Equation for Group 9

Variable*	Units	Mean	Std. Dev.	1%	99%
$\log(D_{of})$	log (in x 1000)	1.647	0.06760	1.6	1.8
FO2		0.8972	0.3051	0	1
LD		7.054	3.901	0.6	12.7
ER		0.7400	0.1085	0.5	1.0
TPVM	lbf/in^3	5.143	2.380	2.7	9.0

$$
\begin{aligned}
(SP10)_p = [\ & 0.12453 - 0.03216(LD - 7.05435) \\
& - 1.89801(LD - 7.05435)(\log D_{of} - 1.64708) \\
& + 0.50326(FO2 - 0.89720) - 0.17377(TPVM - 5.14302) \\
& + 0.58099(ER - 0.74000) - 0.020723(LD - 7.05435)^2 \\
& - 0.032354(LD - 7.05435)(TPVM - 5.14302) \\
& + 0.024874(TPVM - 5.14302)^2 \\
& - 1.55340(TPVM - 5.14302)(\log D_{of} - 1.64708) \\
& - 3.13452(ER - 0.74000)^2\ ]
\end{aligned}
$$

*See Appendix F for full names of variables.

Note: All logarithms are taken to base 10.

TABLE XI

Predicted Stability Values Obtained for Selected Engines Using the General Pulsed Equation

Engine	Test No.	SP10	$(SP10)_p$
F-1, FRT	421077	0	-.00675
	421108	0	-.00078
	423003	0	-.00525
	423065	0	-.02401
	424006	0	-.03186
	424067	0	-.00288
F-1, Qual	423087	0	-.03193
	424098	0	-.03080
	424102	0	-.03325
	424104	0	-.03748
	435039	0	-.04390
	435059	0	-.02492
J-2	84132*	1	.73268
	84133*	0	.73962
	84134*	1	.73962
	84135	0	-.05616
	84136*	0	.69931

*Test run at low oxidizer flow rate.

Test data provided by Rocketdyne. All tests pulsed.

Limitations on Applicability of Prediction Equations

Earlier in this chapter, a numerical illustration was given of the application of the general non-pulsed equation. In this example, all values of variables and parameters in the equation were selected to be within the respective first and ninety-ninth percentiles; in fact, all except the 0-1 variables (BF, LR, F03, PE1) were set equal to their mean values. Furthermore, the reader was cautioned not to employ this equation, or any other equation, outside the range for which it is applicable. Unfortunately, it is not possible to precisely define the region in variable-parameter space over which each equation is valid. The equations presented in this report are limited in accuracy and generality by the data used to construct them. Since the data were obtained a posteriori rather than from statistically designed experiments, all possible combinations of design variables and parameters are not represented. There are, in fact, large gaps in variable-parameter space for which there are no data. Consequently, the equations presented in this report cannot be expected to apply in regions for which there is no experience.

A prime example is furnished by the paucity of pulsed tests on engines with liners (106 tests out of 3749 total, Principal Groups 11 and 12). Clearly, the region of space over which the general pulsed equation is valid for engines with liners is extremely limited and difficult to define. The following two examples illustrate these points.

Suppose one wishes to evaluate the stability index for an engine with the following characteristics:

No baffle present
Liner present
Annular, non-impinging jets

and the engine was pulsed. Consulting Table III, one sees that this engine falls into Principal Group No. 11. Table V in turn shows that the appropriate equation to use for an engine in Group 11 is the general equation for pulsed tests given in Table II. Table IV shows that only 35 tests from Group 11 were used in the regression analysis. It is quite possible, therefore, that the engine under consideration may not bear a close physical resemblance to any of the 35 tests, even though all variables and parameters are within the stipulated percentile limits.

Example 1

The variables and parameters for the test under consideration have the values given below:

BF = 0	$\log D_{of} = 1.696$	log (in x 1000)
LR = 1	$LD_f = 8.210$	
F02 = 1	$LD = 1.459$	
PE1 = 1	$TPVM = 4.404$	lbf/in^3
PE2 = 0	$V_o = 1066$	in/sec

When these values are inserted into the equation in Table II, the result is

$$(SP10)_p = -64.41$$

Example 2

In this example we merely change the value of $\log D_{of}$ to 1.0 and maintain the same values of other variables and parameters used in Example 1. In this case the result is

$$(SP10)_p = 49.52$$

In these two examples we see that although all variables and parameters have acceptable values, the stability indexes are extremely large in absolute terms. We have found that the predicted stability indexes $(SP1A)_p$ and $(SP10)_p$ calculated from our test file data normally lie in the range -2 to +2 (See Figures 2 - 7). Consequently, any value outside this range should be viewed as suspect. The index values in the two examples are outside all recorded experience in this study; they relate to engines which have no counterparts in our test file and must, therefore, be rejected. By varying the value of $\log D_{of}$ from 1.696 to 1.0, one can obtain any stability index in the range -64.41 to

49.52. Had the value of log D_{of} been such that the calculated stability index was between -2 and +2, there would have been no reason to doubt the validity of the index.

The above examples have been especially selected to illustrate the difficulties that may arise from the application of stability equations to engines that appear to satisfy variable-parameter range criteria, yet nevertheless, are outside common experience. We expect these are extreme examples and that similar results would be far less likely to occur with more commonplace engine designs.

USE OF STABILITY EQUATIONS IN DECISION MAKING

Introduction

Previously we stated that: "...it can be grossly misleading to isolate a given coefficient and argue that its value expresses the effect of varying the associated independent variable". In addition, although the prediction equations given in the previous chapter are based on a wide range of engines, they are not applicable to engines with design innovations not represented in the data. The example given at the end of the previous chapter illustrates this limitation of applicability. Under these circumstances, how does an engine designer make use of the appropriate stability equation in designing engines?

There are three legitimate uses of the prediction equations which do not violate the caveat implied by the above statements, and nonetheless should be helpful in saving both time and funds. The designer can use the equations as a checking device, to verify whether the application of his ideas is likely to produce a stable engine; he can use them as a standard against which proposed design changes can be evaluated; and the program manager can use the equations to assist in making the final decision on whether or not the engine should be built and tested. In no case should it be inferred that a prediction equation can substitute for the application of engineering and physical principles to rocket engine design, and we would be the last to suggest that decisions involving construction and testing should be based solely on the predicted stability value obtained from an instability regression equation.

In using the prediction equation as a checking device, the designer develops his ideas to the point where he can supply a value for each of the independent parameters or variables called for by the stability equation. Substitution of these values into the equation yields a predicted stability value, y_p [i.e., $(SP1A)_p$ or $(SP10)_p$], which we shall call the index of stability. If the analogy is not carried too far (values of y_p occasionally will be less than zero or greater than 1), it is possible to regard the index of stability as an estimate of the probability that the engine, if built and tested as represented by the values chosen for the independent variables, will be unstable.* This index provides the designer with an early check on whether the direction of his thinking is inherently sound from a stability point of view. It should cause him to reevaluate his concepts if he gets an "early warning" of the liklihood of instability in the form of an unacceptably large value of y_p.

In using the prediction equation as a standard for evaluation of proposed design changes, the designer recalculates y_p to conform to each change in design and reacts to the trend in the resulting values. A progression of design changes leading to reduced values of y_p (all other things -- such as cost, efficiency, etc. -- being equal) is the direction in which he should wish to proceed. Note that we are not recommending the use of the equation for direct mathematical "optimization" of stability. It usually is not possible to change the value of one design parameter without also being required to alter other parameters in compensation. Some of these other parameters may not even appear in the equation. Thus, it is necessary for the designer continually to "use his best judgment", checking stability retrospectively by means of the equation each step of the way.

One of the frustrating consequences of the use of equations such as the stability prediction equations given in this report involves the interpretation of the resulting number, y_p. According to our heuristic interpretation, large values of y_p are less desirable than small values because they reflect a higher probability that the resulting engine will be unstable. But what interpretation should be placed on a result such as $y_p = 0.35$? Is it "good" or is it "bad"? The answer to this question comes best from experience with its application; after repeated application for a given class of engines, the line between "acceptable" and

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*This interpretation applies to all equations except the special equation for data group 1. With this group, the equation predicts the fuel temperature below which the engine will be unstable.

"unacceptable" values of y_p will begin to emerge.

A discussion of how the past experience represented by this study can be brought to bear in determining the line between acceptable and unacceptable values of y_p is given in the following section. It should not be inferred from the ensuing discussion, however, that there really exists a sharp dividing line. To ask what values of y_p represent unstable engines is somewhat like asking for a height beyond which a person can be described as being "tall". (Anyone who thinks that this height is six feet has never watched a professional basketball game or observed a 6'1" quarterback trying to throw a forward pass over the heads of onrushing linemen.)

Distribution of the Stability Index

Ideally, a perfect stability-prediction equation should produce the predicted value $y_p = 0$ for each stable test and the value $y_p = 1$ for each unstable test. In this context we can say that the equation produces "complete separation" of the stable and unstable tests. More realistically, a prediction equation will produce values of y_p that are somewhat scattered; hopefully, however, the y_p -values for stable tests will cluster about some small value, the y_p -values for unstable tests will cluster about some large value, and the distance between these two "cluster points" will be large relative to the scatter.

To put these ideas into more precise form, we can consider the distributions of the values y_p for the stable and the unstable tests separately, as indicated in Figure 1. The mean of the distribution of stable tests will be denoted by $\bar{y}_s$, and the mean of the distribution of unstable tests will be denoted by $\bar{y}_u$. The symbol S_e denotes the standard error of estimate associated with the prediction equation. As defined in the previous chapter, the generalized distance between these two distributions is given by

$$D = \frac{\bar{y}_u - \bar{y}_s}{S_e} = \frac{\Delta\bar{y}_p}{S_e}$$

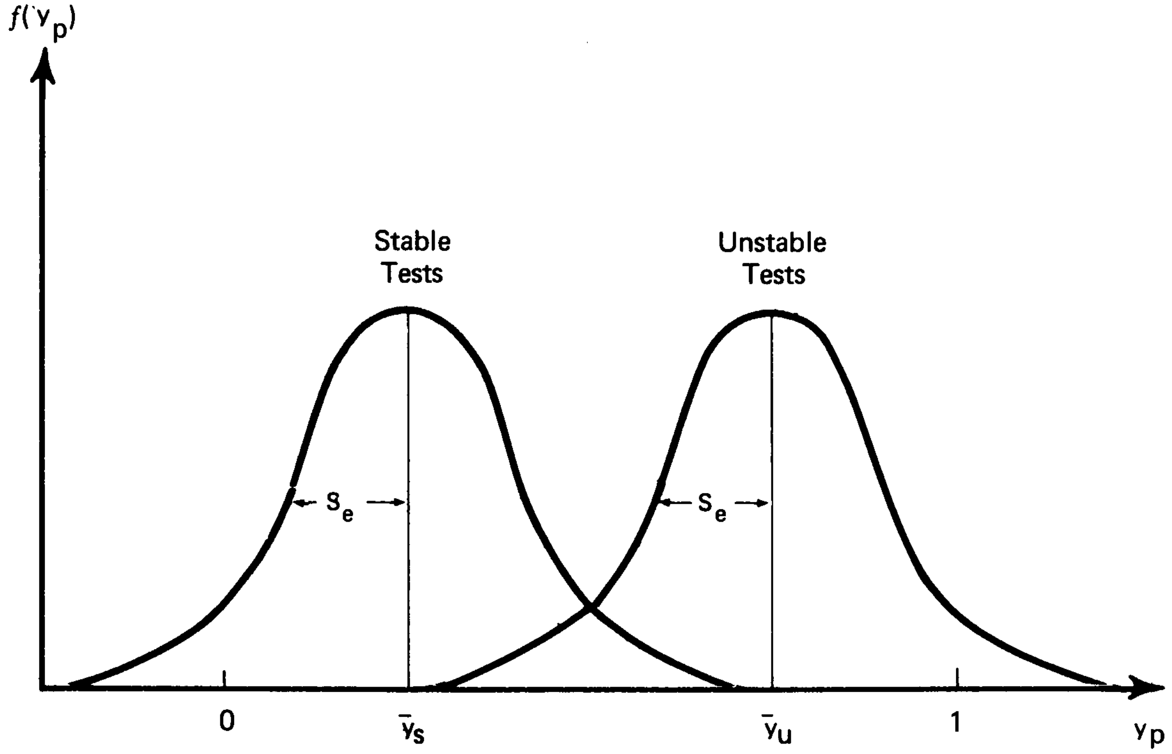

FIGURE 1 DISTRIBUTIONS OF PREDICTED STABILITY INDEX

and it provides a figure-of-merit for evaluating the goodness of the prediction equation. Values of these figures of merit were given in Table V.

To examine these distributions in greater detail, we can graph them on a probability scale. On this scale, the cumulative distribution plots as a straight line for normally-distributed data, and the slope of the line provides a measure of the standard deviation. Such graphs are shown in Figures 2 - 7 for the general non-pulsed equation, the general pulsed equation, and for the special models for data groups 3, 4, 6, and 9. Notice that the data points do not always lie in a straight line, indicating occasional departures from the normal distribution. However in most cases, the trends are nearly parallel, indicating approximately equal standard deviations. (The major exceptions involve data groups 6 and 9, where the numbers of unstable observations are quite small.) The parallel line shown on the graphs represent the best-fitting normal distributions with equal standard deviations. The lines pass through the points ($\bar{y}$, 50%) and ($\bar{y} + S_e$, 84%) where S_e is the appropriate pooled standard deviation given in Table V.

Use of the Equations in Decision Making

In Figure 8 we have reproduced the two parallel lines of Figure 2. Assuming that the underlying distributions of y_p are as represented by these lines, we can state, for example, that the probability is approximately 0.10 that an unstable test would have yielded a stability index value (y_p) <u>less than</u> 0.36. Similarly, the probability that a stable test would have yielded a predicted value greater than 0.36 is approximately 0.12. In other words, if we had decided to reject as potentially unstable all designs having $y_p > 0.36$ (and accept as potentially stable all designs having $y_p < 0.36$) we would never have built 90% of the engines that actually went unstable! The cost of this decision is characterized by the statement that we would also never have built 12% of the engines that proved to be stable.

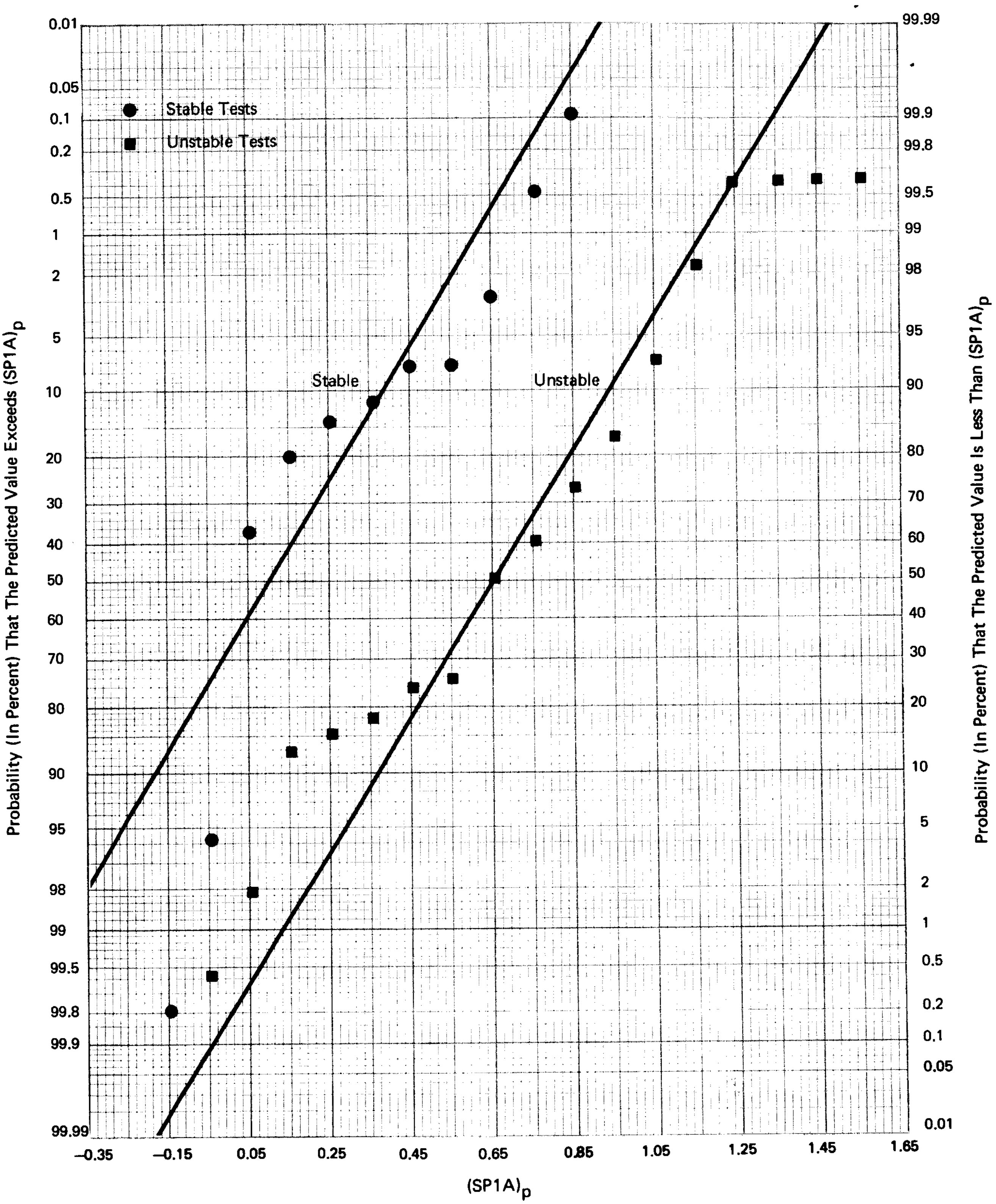

FIGURE 2 CUMULATIVE DISTRIBUTIONS OF PREDICTED STABILITY INDEX $(SP1A)_p$ FOR STABLE AND UNSTABLE TESTS – GENERAL NON-PULSED GROUP

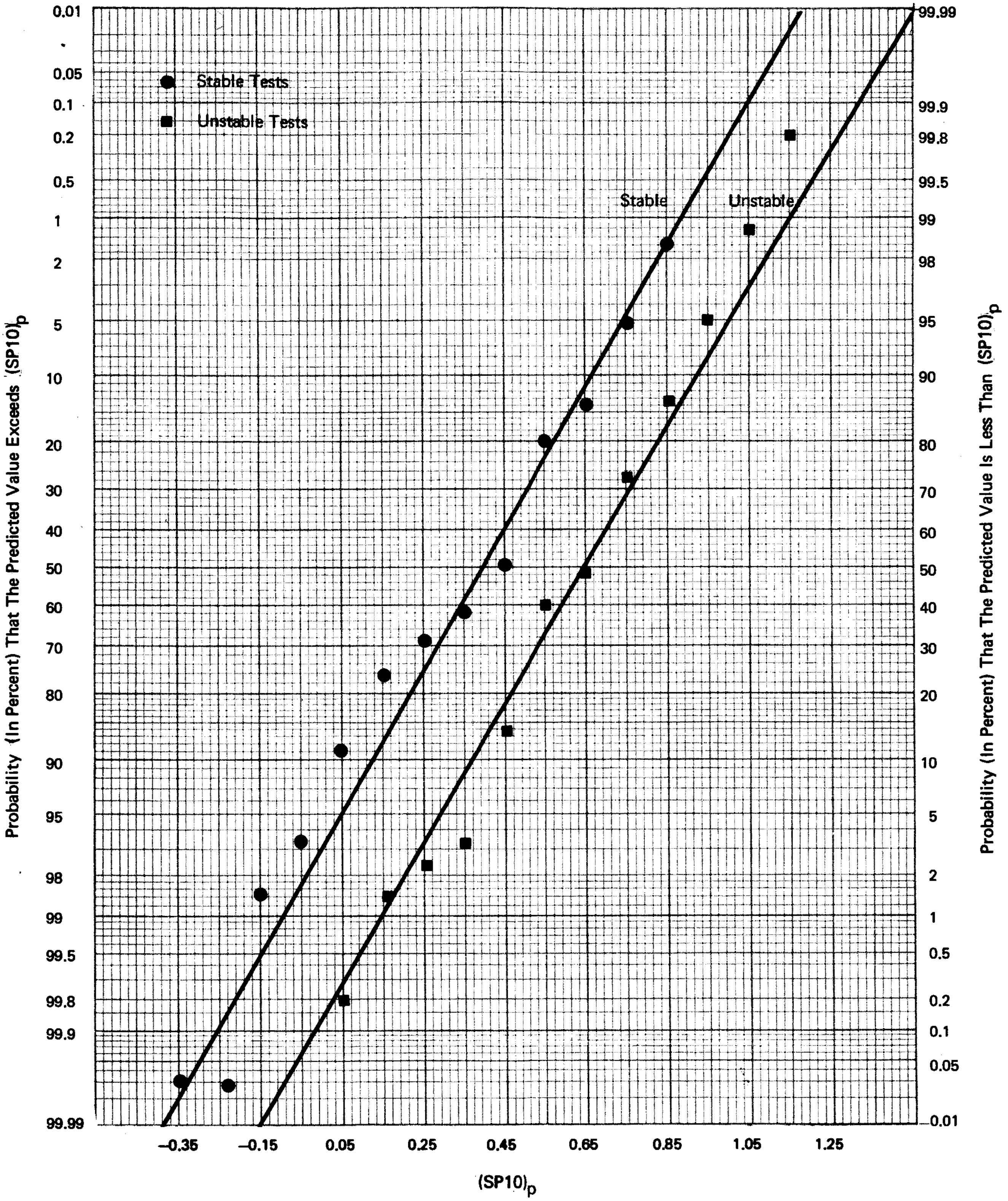

FIGURE 3 CUMULATIVE DISTRIBUTIONS OF PREDICTED STABILITY INDEX $(SP10)_p$ FOR STABLE AND UNSTABLE TESTS – GENERAL PULSED GROUP

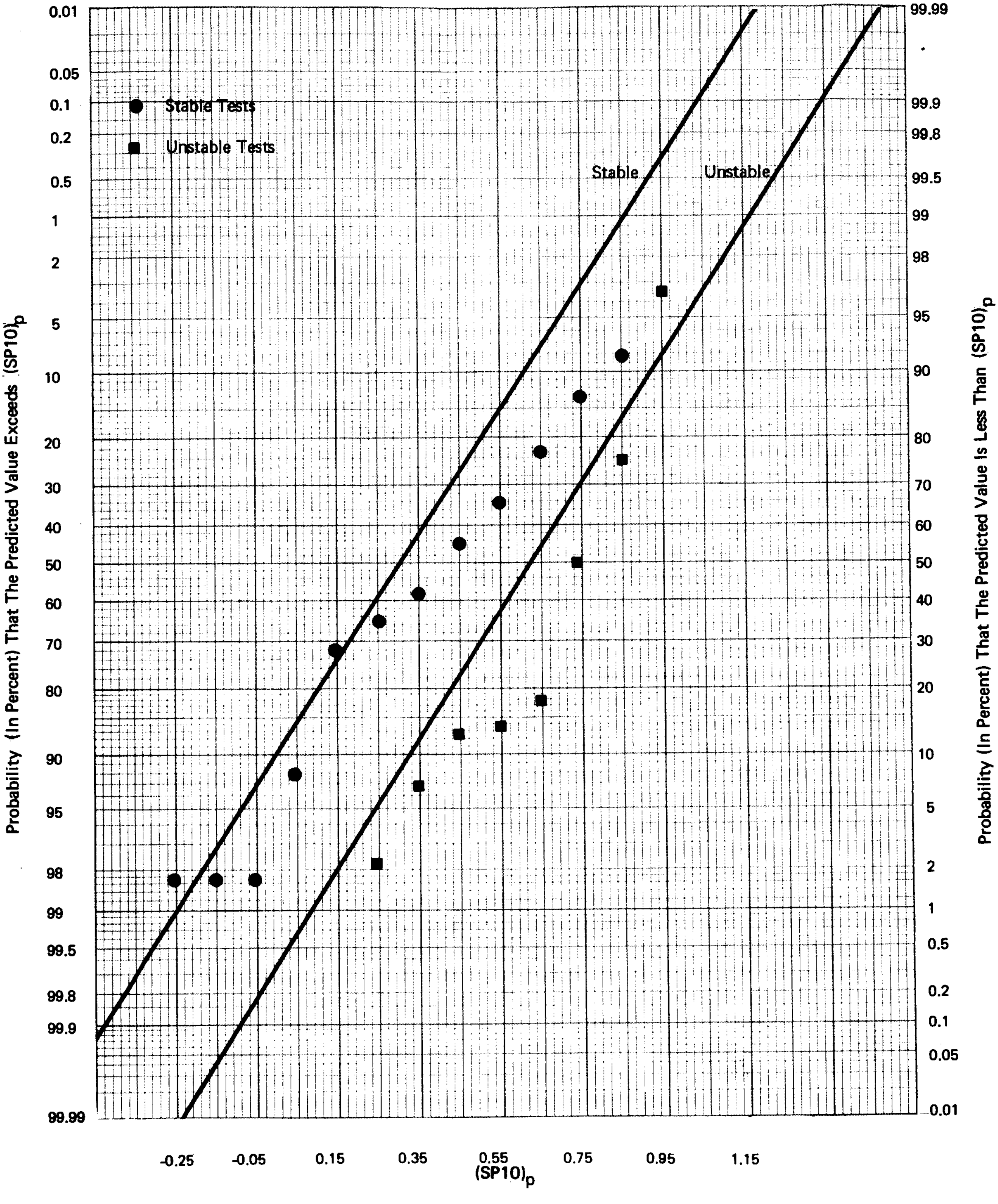

FIGURE 4 CUMULATIVE DISTRIBUTIONS OF PREDICTED STABILITY INDEX $(SP10)_p$ FOR STABLE AND UNSTABLE TESTS – GROUP 3

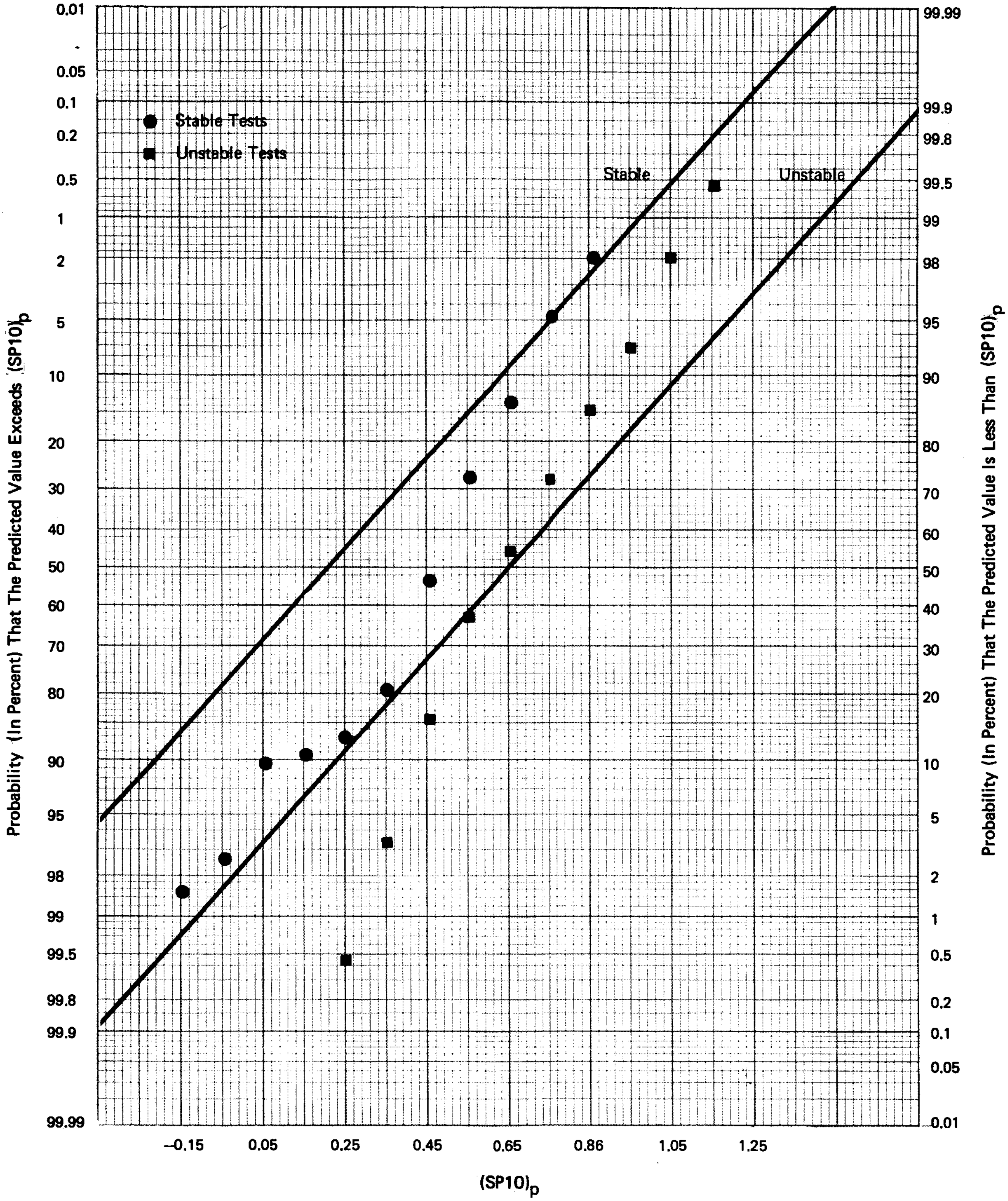

FIGURE 5 CUMULATIVE DISTRIBUTIONS OF PREDICTED STABILITY INDEX $(SP10)_p$ FOR STABLE AND UNSTABLE TESTS – GROUP 4

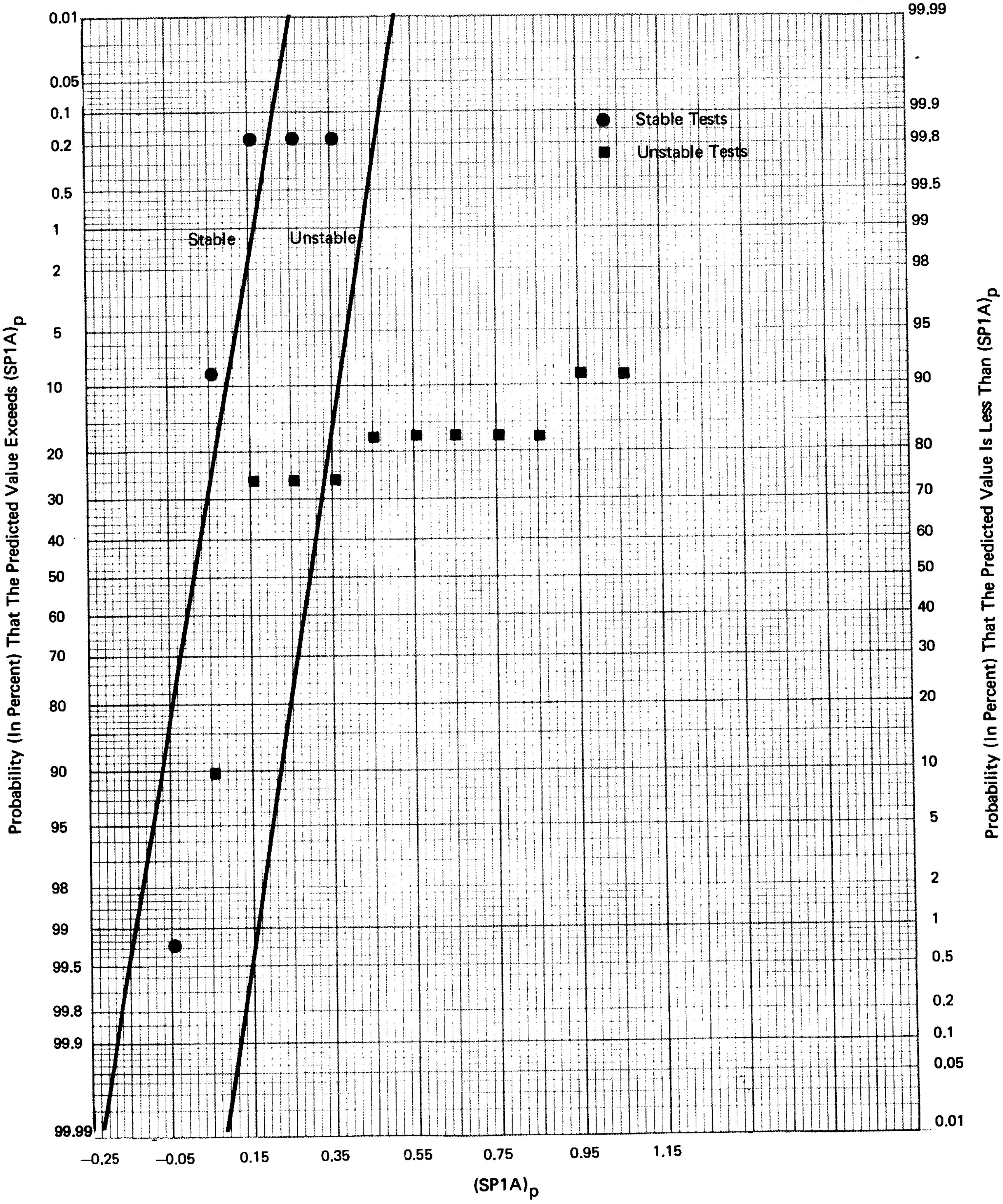

FIGURE 6 CUMULATIVE DISTRIBUTIONS OF PREDICTED STABILITY INDEX $(SP1A)_p$ FOR STABLE AND UNSTABLE TESTS — GROUP 6

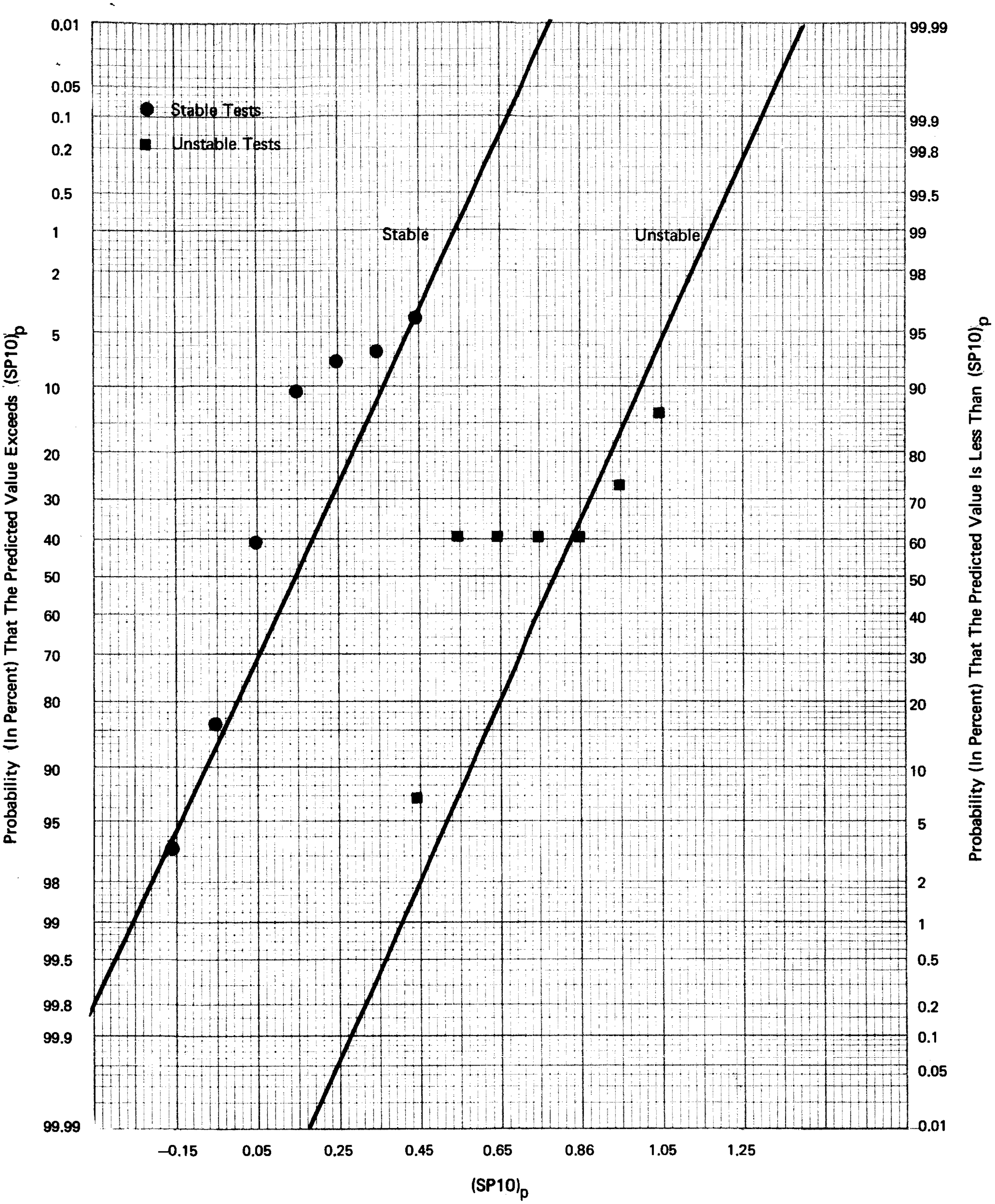

FIGURE 7 CUMULATIVE DISTRIBUTIONS OF PREDICTED STABILITY INDEX $(SP10)_p$ FOR STABLE AND UNSTABLE TESTS – GROUP 9

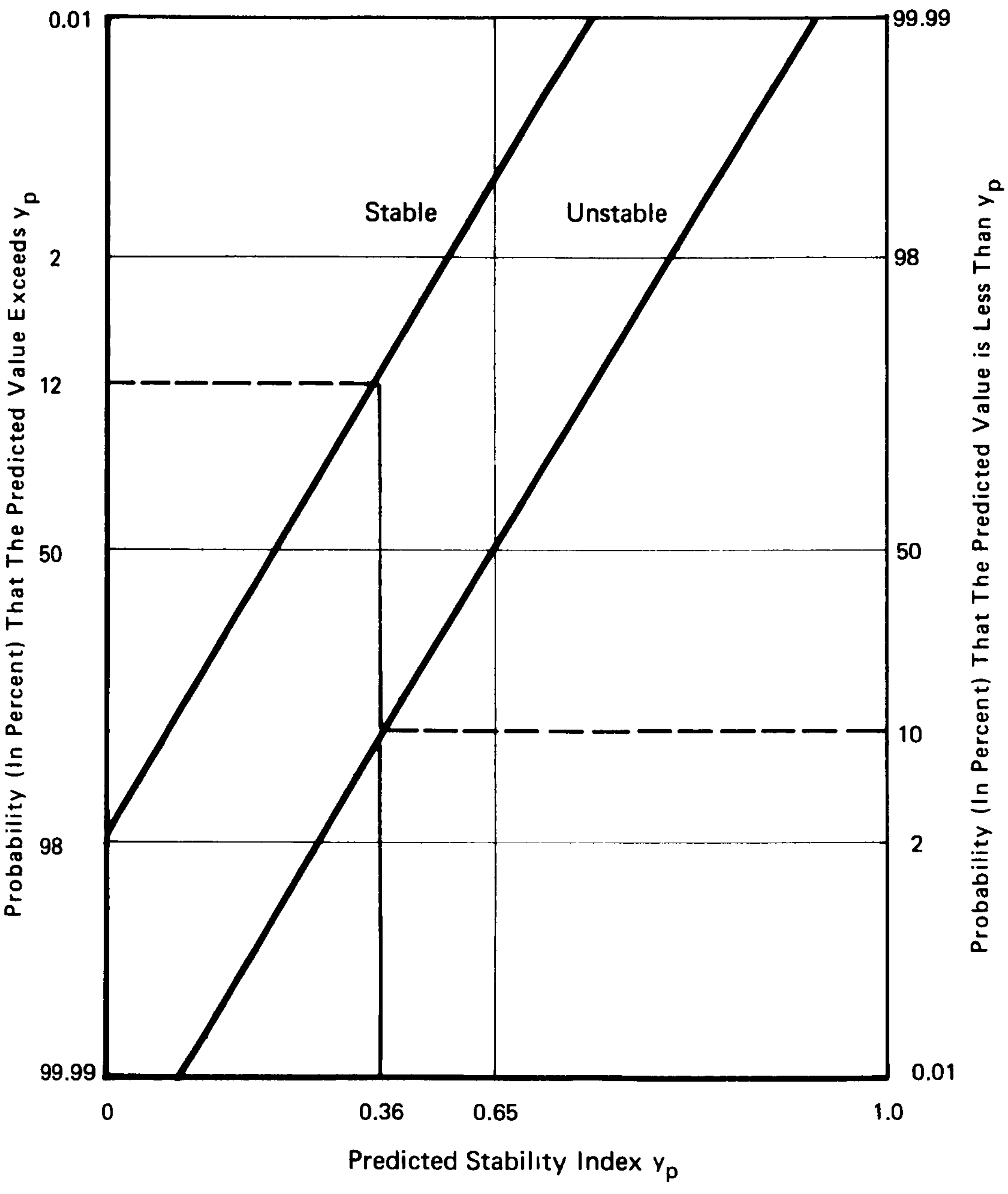

FIGURE 8 INTERPRETATION OF CUMULATIVE DISTRIBUTIONS OF PREDICTED STABILITY INDEX

More generally, we can view the errors associated with any such decision process with the aid of the following table:

		Result if Built and Tested	
		Stable	Unstable
Prediction Based on Design	Stable	No Error	Type I Error (α)
	Unstable	Type II Error (β)	No Error

If we let

α = Probability of a Type I error

and

β = Probability of a Type II error

it is possible to select a "cutoff value" of y_p such that either α or β is determined in advance. The remaining probability is then determined from a graph (such as Figure 7) and its value depends upon the predictive power of the model.

As an illustration, suppose we arbitrarily decide to choose $\alpha = 0.10$; in other words, we wish to regard as "unacceptable" any stability-index value greater than y_p^*, where y_p^* is chosen so that the probability that an unstable test would have yielded a lower value of y_p is 0.10. Table XII shows the resulting value of y_p^* for six of the prediction equations given in the previous chapter, and the corresponding value of β.

From this table we estimate, for example, that a decison criterion that would have eliminated all but 10 percent of the unstable tests, would also have eliminated 12% of the stable tests in the general non-pulsed group, 54% of the stable tests in the general pulsed group, and 46%, 47%, 0.05% and 0.05%, respectively, of the stable tests in groups 3, 4, 6, and 9. To obtain these values of β, we simply draw a vertical line that intersects the line marked "unstable" at the value 10% on the

TABLE XII

Cutoff Values of y_p For $\alpha = 0.10$

Data Group	Cutoff Value y_p^*	β
General Non-pulsed	0.36	0.12
General Pulsed	0.37	0.54
3	0.43	0.46
4	0.24	0.47
6	0.23	0.0005
9	0.22	0.0005

right-hand scale, and note the value on the left-hand scale at the intersection of this vertical line with the line marked "stable". For example, referring to Figure 3 (general pulsed data group) we observe that a vertical line intersecting the "unstable" line at 10% (right-hand scale) intersects the "stable" line at 54% (left-hand scale).

The cutoff values shown in Table XII are by no means recommended values. They have been chosen for illustrative purposes only. The selection of these values could be based upon the relative costs of building engines that would later prove to be unstable and deciding not to build engines that would have been stable. The value of this kind of analysis lies not in that it provides a hard-and-fast rule for making the decision to build and test an engine (it should not), but that it gives otherwise unavailable insights into the consequences of any proposed decision criterion.

Any method of stability assessment that leads to a substantial reduction in the number of unsatisfactory and costly engines constructed and tested, without at the same time causing an unacceptable number of potentially useful engines not to be constructed, has inherent cost-saving potential. In this section we have attempted to demonstrate that such potential exists (with greater or lesser success, depending upon the data group associated with a given design) in connection with the stability prediction equations resulting from this research.

STABILITY AND EFFICIENCY

Introduction

The designer of a rocket engine is concerned with the "yield" of the engine, as well as with its stability. We have used c-star efficiency as a measure of yield in this study, and in this section, we study the trade-off between stability and c-star efficiency.

The selection of design parameters that optimize stability, as determined by the appropriate stability equation, also may optimize c-star efficiency, it may seriously degrade c-star efficiency or it may not be related to c-star efficiency. In the first case, a joint optimum is achieved at once; in the second case, a compromise must be sought, sacrificing some efficiency to achieve less instability, and in the third case each of these two desiderata can be optimized independently of the other. Our findings indicate that the third case applies; that is, there appears to be little or no relationship between stability measures and c-star efficiency. Thus, the designer can be assured that, in the process of selecting design parameter values to minimize instability, he is not per se paying a serious price in terms of reduced c-star efficiency.

Our research in this area consisted of three studies. First, we developed regression equations which allow the prediction of c-star efficiency by means of essentially the same variables and parameters contained in the corresponding stability equation. We found that the predictive power of these equations is about as good as that of the equations representing stability. Second, we directly observed the strength of the relationship between c-star efficiency and the observed value of the stability parameter. We found that the distribution of c-star efficiency when the value of the stability parameter equals zero (stable) is not markedly different from that distribution when the value of the stability parameter equals 1(unstable). Third, we examined the extent to which c-star efficiency could be predicted from a knowledge of the predicted value of the stability parameter. We found a statistically significant linear relationship, but one that showed only a slight decrease in c-star efficiency as the predicted stability is improved.

Prediction of C-Star Efficiency

The prediction equations for c-star efficiency use essentially the same terms as those in the corresponding prediction equations for stability. The coefficients are different, however, having been determined by the method of least squares to optimize prediction of c-star efficiency, rather than stability. The statistics associated with the six equations for c-star efficiency, corresponding to the six equations for stability are summarized in Table XIII.

TABLE XIII

Summary of Equations for C-Star Efficiency

Data Group	R^2	S_e	No. of Tests Used In Regression Analysis	Table in Which Equation Can Be Found
All Non-pulsed Tests	0.588	0.052	1090	XIV
All Pulsed Tests	0.255	0.065	1240	XV
3	0.291	0.075	153	XVI
4	0.292	0.062	832	XVII
6	0.844	0.026	633	XVIII
9	0.823	0.062	88	XIX

After the designer has chosen the appropriate one of the six equations to predict stability, he can utilize the corresponding c-star efficiency equation to predict the associated efficiency. In this way, the designer can take steps to ensure that the particular design chosen for its acceptable predicted stability value is not expected to produce an unacceptable c-star efficiency.

The same interpretations and cautions apply in the use of these equations as applied for the stability prediction equations. The ranges of values of the independent variables and parameters are the same as those given in Tables I, II, and VII - X. The mean standard deviation, and first and ninety-ninth percentiles of the corresponding c-star efficiency data are given in Tables XIV - XIX.

Relationship Between C-Star Efficiency and Observed Stability

For a given engine test, the observed stability takes on one of two values: stable ($y = 0$) or unstable ($y = 1$). The distributions of the c-star efficiency values were examined separately for the non-pulsed and for the pulsed tests.

For the non-pulsed tests 1010 data points were available for this analysis, of which 699 represented stable tests and 311 represented unstable tests. The percentage distributions of these two sets of data are shown in Table XX.

For the pulsed tests 1402 data points were available, of which 690 represented stable tests and 712 represented unstable tests. The percentage distributions of these two sets of data are shown in Table XXI. Histograms depicting these distributions are shown in Figure 10. Note again that the means ($\bar{X}$) of the two distributions are fairly close, although the standard deviation (S) of the c-star efficiency values seems to be somewhat higher for the stable pulsed tests than for the unstable pulsed tests.

It can be concluded from these results that the distribution of values of c-star efficiency is essentially the same for both stable and unstable tests.

Relationship Between C-Star Efficiency and Predicted Stability

Since observed values of stability are restricted (by definition) to 0 or 1, it would be meaningless to attempt to quantify the relationship

TABLE XIV

General C-Star Efficiency Equation

For Non-Pulsed Tests

Variable*	Units	Mean	Std. Dev.	1%	99%
BF		0.3683	0.4826	0	1
EPA	in^{-2}	3.766	18.5100	0.06	10
F03		0.2851	0.4517	0	1
IDE_f		1.922	2.187	0	7.2
$\log(ID_f)$		-0.01452	0.04544	-0.20	0.1
L_1	in	16.24	6.143	4.00	34
LD		2.138	2.445	0.42	11.6
LR		0.2507	0.4336	0	1
MPE	lbm/sec	1.932	3.586	0	17
P_{ci}	psia	330.0	282.900	80	1300
PE1		0.1656	0.3719	0	1
$\log(R_c)$		0.3343	0.2430	0.0	1.4

$$
\begin{aligned}
(CSE)_p = {} & 0.74560 + 0.00038\ (LR)\ (P_{ci}) \\
& + 0.00557\ (L_1) + 1.36984\ (BF)\ (\log ID_f) \\
& - 0.06361\ (LR)(LD) - 0.00920\ (F03)\ (IDE_f) \\
& + 0.10167\ (F03) - 0.00262\ (IDE_f)\ (EPA) \\
& - 0.40286\ (LR)\ (MPE) + 0.07322\ (LR) \\
& + 0.09789\ (BF) + 0.19814\ (PE1) \\
& - 0.00014\ (L_1)^2 - 0.00145\ (MPE)^2 \\
& + 0.05893\ (\log R_c)^2 + 0.00002\ (P_{ci})\ (LD) \\
& + 0.00083\ (L_1)\ (\log R_c) + 0.00178\ (L_1)\ (MPE) \\
& - 0.01720\ (L_1)\ (MPE) + 0.00285\ (IDE_f)\ (MPE) \\
& + 0.02600\ (PE1)\ (IDE_f) - 0.50797\ (PE1)\ (\log R_c) \\
& + 0.00019\ (F03)\ (P_{ci}) - 0.00008(BF)\ (P_{ci})
\end{aligned}
$$

*See Appendix F for full names of variables.

Note: All logarithms are taken to base 10.

TABLE XV

General C-Star Efficiency Equation

For Pulsed Tests

Variable*	Units	Mean	Std. Dev.	1%	99%
BF		0.1168	0.3213	0	1
$\log(D_{of})$	log (in x 1000)	1.696	0.2336	0.9	2.4
F02		0.1246	0.3304	0	1
LD_f		8.210	17.51	0.13	100
LR		0.08022	0.2717	0	1
LD		1.459	1.974	0.43	13
PE1		0.1433	0.3505	0	1
PE2		0.4299	0.4953	0	1
TPVM	lbf/in^3	4.404	4.207	0.1	26
V_o	in/sec	1066	556.7	77	3300

$$\begin{aligned}(CSE)_p = {} & 0.83005 + 0.01269\ (LD) \\ & - 0.00058\ (LD_f) + 0.02450\ (TPVM) \\ & + 0.00014\ (V_o) + 0.01440\ (F02) \\ & + 0.02264\ (BF) - 0.00060\ (TPVM)^2 \\ & - 0.01047\ (LD\ )\ (TPVM) - 0.00006\ (V_o)\ (\log D_{of}) \\ & - 0.00002\ (LR)\ (V_o) - 0.01166\ (PE1)\ (LD_f) \\ & + 0.03564\ (PE2)\ (LD) - 0.00006\ (PE2)\ (V_o) \\ & + 0.01168\ (PE2)\ (TPVM)\end{aligned}$$

*See Appendix F for full names of variables.

Note: All logarithms are taken to base 10.

TABLE XVI

Special C-Star Efficiency Equation
For Group 3

Variable*	Units	Mean	Std. Dev.	1%	99%
EPA	in^{-2}	3.562	1.084	0.09	5.2
LD		1.118	0.6178	0.43	2.8
TPVM	lbf/in^3	7.534	5.987	0.13	30

$$\begin{aligned}(CSE)_p = {} & 1.15271 - 0.33009\ (LD) \\ & - 0.04925\ (EPA) + 0.05334\ (EPA)\ (LD) \\ & + 0.05865\ (LD)^2 + 0.00354\ (LD)\ (TPVM)\end{aligned}$$

*See Appendix F for full names of variables.

TABLE XVII

Special C-Star Efficiency Equation
For Group 4

Variable*					
F02		0.1271	0.3333	0	1
LD_f		9.608	19.05	1.0	100
ER		0.8037	0.2036	0.38	1.3
TPVM	lbf/in^3	3.677	2.921	0.12	9.8

$$\begin{aligned}(CSE)_p = {} & 0.88416 - 0.00054\ (LD_f) \\ & + 0.01219\ (F02)\ (TPVM) + 0.01660\ (ER)\ (TPVM)\end{aligned}$$

*See Appendix F for full names of variables.

TABLE XVIII

Special C-Star Efficiency Equation

For Group 6

Variable*	Units	Mean	Std. Dev.	1%	99%
EPA	in^{-2}	2.239	10.01	0.06	10
F03		0.5008	0.5004	0	1
h_b	in	2.912	0.5519	1.0	4.0
IDE_f		1.740	1.610	0.8	6.3
$\log(ID_f)$		-0.02333	0.01598	-0.048	0.007

$$(CSE)_p = 0.89505 + 0.03275\ (h_b)\ (F03) + 0.34172\ (h_b)\ (IDE_f) - 1.46550\ (F03)\ (\log ID_f) + 0.00090\ (EPA)\ (IDE_f)$$

*See Appendix F for full names of variables.

TABLE XIX

Special C-Star Efficiency Equation

For Group 9

Variable*	Units	Mean	Std. Dev.	1%	99%
$\log(D_{of})$	log(in x 1000)	1.647	0.06760	1.6	1.8
F02		0.8972	0.3051	0	1
LD		7.054	3.901	0.6	12.7
ER		0.7400	0.1085	0.5	1.0
TPVM	lbf/in^3	5.143	2.380	2.7	9.0

$$(CSE)_p = 0.95756 - 0.09256\ (LD)\ (\log D_{of}) - 0.06250\ (F02) + 0.00873\ (LD)^2 + 0.00619\ (LD)\ (TPVM) + 0{,}10316\ (ER)^2$$

*See Appendix F for full names of variables.

TABLE XX

Percentage Distributions of C-Star Efficiency
For Non-Pulsed Tests

C-Star Efficiency	Percent of Observations	
	Stable Tests	Unstable Tests
50 - 54.9	0.3	0.6
55 - 59.9	0.7	0.0
60 - 64.9	1.0	0.4
65 - 69.9	0.9	0.0
70 - 74.9	1.5	0.6
75 - 79.9	3.6	4.2
80 - 84.9	11.2	11.6
85 - 89.9	22.7	19.3
90 - 94.9	34.6	31.5
95 - 99.9	15.9	27.0
100 - 104.9	7.2	3.5
105 - 109.9	0.3	0.7
110 - 114.9	0.1	0.6
	100.0	100.0

Histograms depicting these distributions are shown in Figure 9. Note the close agreement between the means ($\bar{X}$) and standard deviations (S) of these two distributions as shown in the figure.

TABLE XXI

PERCENTAGE DISTRIBUTIONS
OF C-STAR EFFICIENCY FOR PULSED TESTS

C-Star Efficiency	Percent of Observations	
	Stable Tests	Unstable Tests
50 - 54.9	1.2	0.1
55 - 59.9	0.8	0.2
60 - 64.9	1.3	0.0
65 - 69.9	1.9	0.0
70 - 74.9	3.5	0.1
75 - 79.9	2.9	2.1
80 - 84.9	8.4	4.5
85 - 89.9	12.6	11.7
90 - 94.9	24.5	29.9
95 - 99.9	29.7	38.6
100 - 104.9	10.3	11.4
105 - 109.9	1.9	1.2
110 - 114.9	0.7	0.0
115 - 119.9	0.0	0.0
120 - 124.9	0.3	0.0
125 - 129.9	0.0	0.2
	100.0	100.0

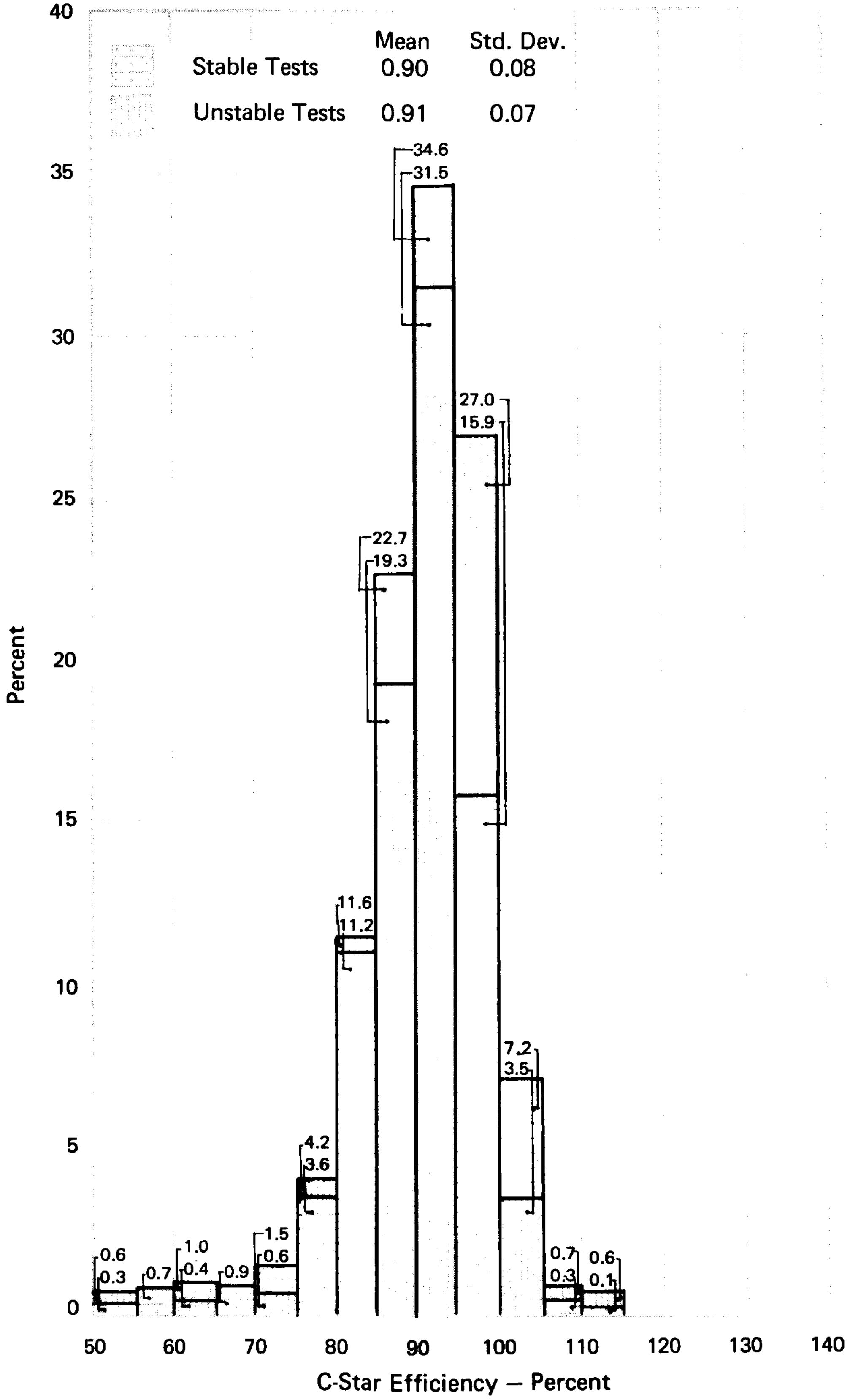

FIGURE 9 DISTRIBUTIONS OF C–STAR EFFICIENCY FOR NON–PULSED TESTS

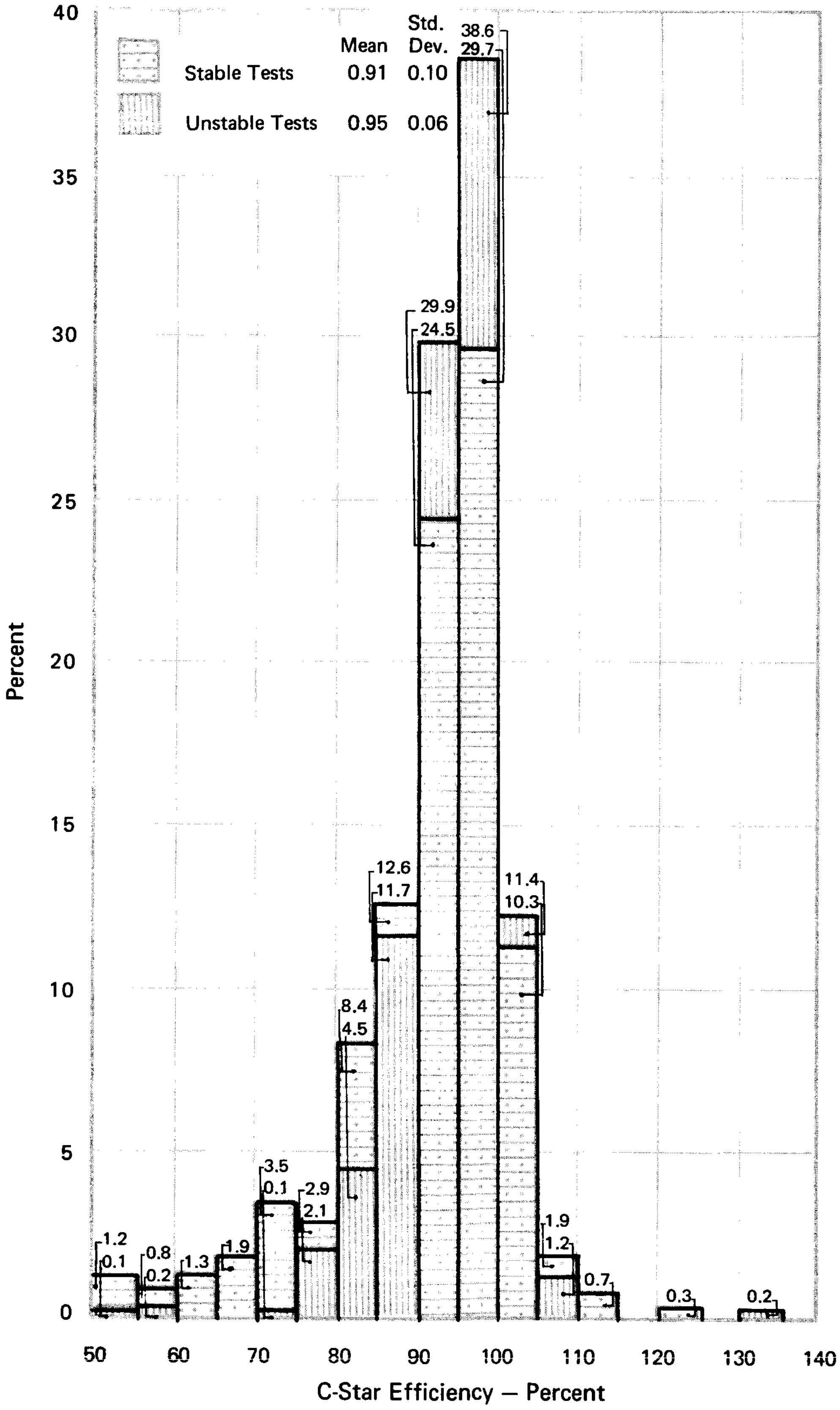

FIGURE 10 DISTRIBUTIONS OF C–STAR EFFICIENCY FOR PULSED TESTS

(or lack of relationship) between c-star efficiency and observed stability other than by a comparison of distributions as we have done in the previous section. However, we can compute the predicted stability value by means of the appropriate prediction equation, and since this number can assume values on a continuum, it is meaningful to quantify its relationship to c-star efficiency. Such quantitative relationships have been developed separately for the non-pulsed and for the pulsed data groups.

For the non-pulsed tests 1092 data points were available for this analysis. A linear regression equation of c-star efficiency $(\mathrm{CSE})_p$ versus predicted stability $(\mathrm{SP1A})_p$, where $(\mathrm{SP1A})_p$ is obtained from the equation given in Table I, is as follows:

$$(\mathrm{CSE})_p = 0.879 + 0.050\ (\mathrm{SP1A})_p$$

The relationship is a very weak one, the coefficient of multiple correlation being only $R^2 = 0.043$. However, a test of the null hypothesis that the true coefficient of $(\mathrm{SP1A})_p$ equals zero shows that it cannot be rejected at the 0.001 level of significance. In other words, the relationship, however weak, nonetheless is statistically significant. Furthermore, an examination of the residuals indicates that the relationship is well approximated by a straight line; use of higher-order polynomials, e.g., an equation of the form

$$(\mathrm{CSE})_p = \alpha + \beta\ (\mathrm{SP1A})_p + \gamma\ (\mathrm{SP1A})_p^{\,2}$$

would contribute little if anything to the predictive power.

The coefficient of $(\mathrm{SP1A})_p$ in this equation (0.050) indicates that, for every decrease of 0.10 unit in the predicted stability index, c-star efficiency decreases by 0.005. In other words, an engine design change that decreases the expectation of instability by ten percent is expected (on average) to decrease c-star efficiency by 0.5 percent. However, because the relationship is as weak as it is, we cannot even be sure that any decrease in c-star efficiency actually would result.

For the pulsed tests 1240 data points were available for analysis, and the linear regression equation is

$$(CSE)_p = 0.903 + 0.057\ (SP10)_p$$

Here, $(SP10)_p$ is obtained from the model given in Table II.

Again, the relationship is a very weak one; $R^2 = 0.035$. It is encouraging to note that the coefficient of $(SP10)_p$ has changed only slightly from the corresponding value of $(SP1A)_p$ for the non-pulsed tests. Thus, the statements that were made concerning the relationship between c-star efficiency and stability for non-pulsed tests are, broadly speaking, applicable also to pulsed tests.

THE ROLE OF PULSING IN STABILITY DETERMINATION

Introduction

The stability parameters adopted to provide the dependent variables were, of necessity, different for the non-pulsed and the pulsed tests. For this reason it is not possible to provide a single general equation applicable to all the data.

Two distinct efforts were made, however, to reveal what possibly could be learned about the relative nature of the pulsed and the non-pulsed tests. First, in order to determine whether instability under pulsing is related to spontaneous (non-pulsed) instability, we predicted the value of SP1A (the non-pulsed stability parameter) for the pulsed tests. Second, in an effort to understand the nature of pulsed instability <u>vis-a-vis</u> spontaneous instability, we pooled all the data into a single model, letting the dependent variable assume the value of SP1A for tests in the non-pulsed data group and the value of SP10 for the pulsed data group. Broadly speaking, it can be concluded from these studies that the effect of pulsing is not readily predictable on the basis of non-pulsed instability, and that its magnitude depends strongly upon the values of many engine design parameters that are not strongly related to spontaneous instability.

Prediction of Spontaneous Instability for Pulsed Tests

Using the general stability equation for <u>non-pulsed</u> tests (Table I), we obtained a value of $(\text{SP1A})_p$ for each of 1234 <u>pulsed</u> tests. This value is the stability index for <u>spontaneous</u> instability, because it was obtained from the non-pulsed equation. It is possible to evaluate SP1A for pulsed tests since spontaneous oscillations are reported for these tests when they occur.

In order to determine the relationship between the predicted <u>spontaneous</u> instability and the observed <u>pulsed</u> instability, we can examine the distribution of the values of $(SP1A)_p$ thus obtained separately for the stable and unstable (pulsed) tests. These distributons are shown in Figure 11. Their means are

$$\bar{y}_s = 0.50,\ \bar{y}_u = 0.62 \text{ where } y = (SP1A)_p$$

and their standard deviations are 0.71 and 0.39, respectively.

Using the weighted average standard deviation $S_e = 0.55$ to represent the standard error of estimate, we can compute the generalized distance between these two distributions as follows:

$$D = \frac{\bar{y}_u - \bar{y}_s}{S_e} = \frac{0.12}{0.55} = 0.218$$

Comparing this value with those in Table V, we observe that there is a very poor separation of the stable and unstable tests. It can be concluded from this discussion that knowledge of the likelihood of spontaneous instability contributes little if any information about whether or not the test will react stably to a pulse.

The Effect of Pulsing

In a further effort to determine how the stability response of a test to a pressure pulse is related to its spontaneous stability characteristics, we computed a regression equation for all available complete data points (2133 data points). The dependent variable assumed the value of SP1A for tests in the non-pulsed data group and it assumed the value of SP10 for tests in the pulsed data group. The independent variables were chosen from the general non-pulsed and pulsed data groups; those that appeared significant in <u>either</u> group were included in this model (See Table XXII). In addition, an independent variable, z, was included to denote whether or not the test belonged to the pulsed group. If a test was pulsed, Z = 1, and Z = 0 otherwise.

The resulting model, including squares and cross products of the variables, contained 79 terms. The value of R^2 after the first 32 terms were included in the model was $R^2 = 0.37$, and the standard error of

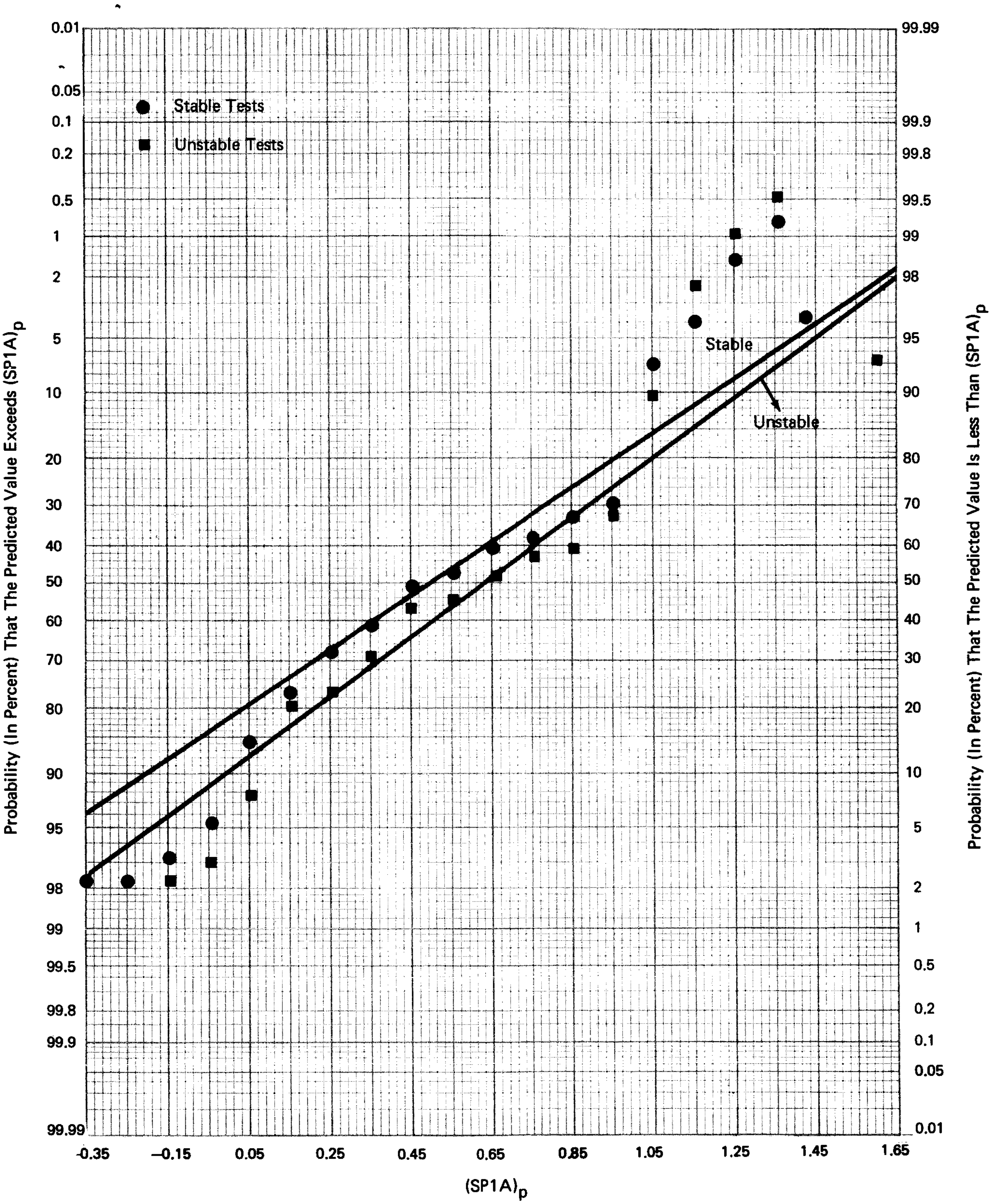

FIGURE 11 CUMULATIVE DISTRIBUTIONS OF PREDICTED SPONTANEOUS STABILITY INDEX $(SP1A)_p$ FOR STABLE AND UNSTABLE TESTS – GENERAL PULSED GROUP

TABLE XXII

Independent Variables Included in the "Effects of Pulsing" Model

1. (P_{ci}) (LD)
2. L_1
3. z
4. $\log R_c$
5. F03
6. LR
7. BF
8. PE1
9. LD
10. LD_f
11. TPVM
12. V_o
13. $\log D_{of}$
14. F02
15. (PE2) (LD)
16. (MPE) (L_1)
17. $(\log ID_f)$ (L_1)
18. (IDE_f) (MPE)
19. (EPA) (IDE_f)
20. (LR) (P_{ci})
21. (BF) $(\log ID_f)$
22. (LR) (LD)
23. (F03) (IDE_f)
24. (LR) (MPE)
25. L_1^2
26. $(MPE)^2$
27. $(\log R_c)^2$
28. (L_1) $(\log R_c)$
29. (IDE_f) $(\log ID_f)$
30. (LD) (MPE)
31. (PE1) (LD)
32. (PE1) (MPE)
33. (PE1) (IDE_f)
34. (PE1) $(\log R_c)$
35. (F03) (P_{ci})
36. (F03) (L_1)
37. (BF) (P_{ci})
38. (LR) $(\log R_c)$
39. (LR) (PE1)
40. (LR) (PE2)
41. $(TPVM)^2$
42. $(\log D_{of})^2$
43. (LD) (TPVM)
44. (V_o) $(\log D_{of})$
45. (LR) (LD_f)
46. (LR) $(\log D_{of})$
47. (LR) (V_o)
48. (PE1) (LD_f)
49. (PE2) (V_o)
50. (PE2) (TPVM)
51. (PE2) $(\log D_{of})$
52. (z) (L_1)
53. (z) $(\log R_c)$
54. (z) (F03)
55. (z) (LR)
56. (z) (BF)
57. (z) (PE1)
58. (z) (LD)
59. (z) (LD_f)
60. (z) (TPVM)
61. (z) (V_o)
62. (z) $(\log D_{of})$
63. (z) (F02)
64. (z) (L_1^2)
65. (z) $(MPE)^2$
66. (z) $(\log R_c)^2$
67. (z) $(TPVM)^2$
68. (z) $(\log D_{of})^2$
69. (z) (P_{ci}) $(\log ID_f)$
70. (z) (L_1) (V_o)
71. (z) (L_1) $(\log D_{of})$
72. (z) (L_1) (LD_f)
73. (z) (L_1) (TPVM)
74. (z) (P_{ci}) (LD_f)
75. (z) (P_{ci}) (TPVM)
76. (z) (P_{ci}) (V_o)
77. (z) $(\log R_c)$ (TPVM)
78. (z) $(\log R_c)$ (V_o)
79. (z) $(\log R_c)$ (LD_f)

estimate was $S_e = 0.39$. The actual model equation is not given here; its use for prediction is not recommended because of the inhomogeneous nature of the dependent variable.

Of interest, however, is the coefficient of z, the pulsing variable. This variable occurs not only as an individual term in the equation, but also in combination with other parameters. The terms containing z are

$$z[1.232-0.078L_1-0.740 \log R_c-0.001\ \mathrm{F03}-0.463\ \mathrm{PE1} \\ +0.159(\mathrm{LD})+0.029\ \mathrm{TPVM}+0.039(\mathrm{MPE})^2-0.180(\log R_c)^2 \\ -0.076(\log D_{of})^2-0.003(P_{ci})(\log D_{of})+0.00001(L_1)(V_o)$$

Thus, it is evident that the effect of pulsing (roughly approximated here by the coefficient of z) depends in a highly complex way on the particular engine design.

References

1. E. K. Bastress, G. H. Harris, and I. Miller, "Stable Liquid Propellant Rocket Engine Design Criteria Project", Interim Report, Contract NASW-1236, Arthur D. Little, Inc., December 1966.

2. "Format for the Collection of Liquid Propellant Rocket Combustion Instability Test Data", CPIA Publication No. 149, The Johns Hopkins University, Applied Physics Laboratory, September 1967.

2. R. P. Smith and D. F. Sprenger, "Combustion Instability in Solid-Propellant Rockets", Fourth Symposium (International) on Combusiton, page 893, Williams and Wilkins, Baltimore, 1953.

APPENDIX A

DATA HANDLING METHODOLOGY

1. Data Sheets

To facilitate the collection of experimental data from engine stability tests, standard forms were prepared on which to record this information. Standarization of data collection methods was essential to ensure the unambiguous and accurate recording of variables. The data collection forms were to satisfy the following criteria:

(1) Be relatively easy to use by contributors.
(2) Clearly specify the requisite data types.
(3) Minimize the likelihood of incurring errors.
(4) Limit use of qualitative data to an enumerated list of characteristics.
(5) Present the data in a form suitable for keypunching onto punched cards.
(6) Provide a means for qualifying or supplementing any of the recorded data by comments.
(7) Provide a means to indicate reasons for the absence of certain data.

A set of fifteen data sheets was prepared according to the above specifications and an instruction manual written. The data collection forms were designed to ease, as far as possible, the actual process of selecting and recording useful data items and to minimize quantity of repetitious information that collectors need report. The data sheets were patterned after the familiar 80-column punched card. Their detailed use is described in CPIA Publication No. 149, and only the basic structure of these sheets is discussed here.

The description of an engine stability test consists of two distinct types of information: (1) that pertaining to engine hardware, and (2) that pertaining to test conditons and results arising from the use of the described engine. A test "datum point" is viewed as the collection of all variables, i.e., both hardware and test data, associated with a given engine test firing. Since certain hardware components of an engine, or the engine itself, may be employed in several test firings, it would be extremely inefficient to require a complete engine description for every test. In fact, entire tests may be identical in all requested variables to within a specified degree, so that it should not be necessary to repeat any portion of certain test descriptions. The data sheets as designed reflect these considerations.

The fifteen data sheets consist of the following types:

	(1)	Comment
ENGINE HARDWARE	(2)	Engine Components
	(3)	Combustion Chamber
	(4)	Acoustic Absorption Liner
	(5)	Feed System
	(6)	Injector - Master
	(7)	Injector Element Group Master
	(8)	Injector Element - Fuel Orifices
	(9)	Injector Element - Oxidizer Orifices
	(10)	Baffle
TEST CONDITIONS AND RESULTS	(11)	Test Summary
	(12)	Disturbance
	(13)	Instability Mode
	(14)	Operating Conditions - Part I
	(15)	Operating Conditions - Part II

As can be seen, the types of data sheets divide into two general classifications, those pertaining to engine hardware (Nos. 2-10) and those pertaining to test conditions (Nos. 11-15). The Comment Sheet may be used to qualify or supplement any of the information presented on other data forms; however, comments cannot be processed as quantitative data in an analysis.

A collector defines an engine by means of the Engine Components Data Sheet and assigns it an Engine Assembly Number. This number, as well as all engine component and test numbers, must be unique within a given organization but need not have any special significance. This data sheet specifies the identification numbers of the components which comprise the engine and describes the propellants. The following engine components, if present, must in turn be described on their respective data sheets, each bearing its proper identification number:

(1) Combustion Chamber
(2) Acoustic Absorption Liner
(3) Feed System
(4) Injector (4 types of data sheets)
(5) Baffle

Thus, it is possible via the Engine Components Data Sheet to define new engines merely by referencing different combinations of previously described hardware components; each component need be described but once.

The conditions and results of engine test firings are entered on the five types of data sheets below:

(1) Test Summary
(2) Disturbance
(3) Instability Mode
(4) Operating Conditions - Part I
(5) Operating Conditions - Part II

Data items on these sheets are linked together by a common Test Number assigned by the collector. If several tests have identical data, it is only necessary to enter the total number of runs bearing the same test number on the Test Summary Data Sheet; one does not need to fill out duplicate test data sheets in such a case. However, if any single item (corresponding to the same test number) on any of these five types of data sheets changes, the complete set of new test conditions and results must be recorded bearing a new test number.

Finally, the test conditions and results are linked to the engine hardware used through the Engine Assembly Number appearing on the Test Summary Sheet. Provided an engine has been previously defined and assigned an identification number, this engine may be referenced on any number of Test Summary Sheets. The computer filing system will automatically construct the engine from its component identification numbers and then relate the engine to the proper test data. It should be pointed out that all data supplied by a particular contributing organization bears a common organization code, thereby permitting independence of hardware and test identification numbers among contributors.

2. Collection Procedure

Experimental data were collected from records of engine stability tests at nine different organizations listed in Appendix B. Each organization was supplied with data collection sheets and instruction manuals, and the collection process was supervised by a member of the organization staff.

Administrative arrangements for funding the data collection effort were different for each type of organization. At the commercial organizations, subcontracts were issued and collection was carried out by technical staff members. At NASA-Lewis, NASA-Marshall, and JPL, subcontracts were issued to outside organizations who provided data tabulating service. At Polytechnic Institute of Brooklyn and Princeton University, data collection was accomplished by staff members who were funded by project consultants.

When the data had been entered on the collection sheets, they were shipped to Arthur D. Little, Inc., for filing. Each organization was instructed to retain a copy of each data sheet to facilitate future correspondence referring to the data supplied.

3. Filing

The objective of the data filing system was to organize the test data into a form suitable for subsequent high-speed computer processing. This latter processing was to tabulate, transform, statistically analyze, and test portions of the data bank. Before actually filing the data, however, it seemed appropriate to perform certain routine checks on the data for internal consistency and compliance with prescribed data collection standards. This was important in order to ensure that only meaningful data would be accepted for future analysis; as it turned out, about 50 percent of the test descriptions contained at least one error.

Each test was to be recorded as a "datum point" on magnetic tape such that all data pertaining to the test, both hardware and test conditions, would occupy the same physical (logical) tape record. This was desirable in order to shorten future tape-oriented operations, such as tabulation.

After the completed data sheets were received at Arthur D. Little, Inc., they were first scanned to locate any obvious deficiencies, and, if none were found, the sheets were sent to be keypunched. Punched cards formed the primary input to the computer filing system. If the data cards corresponding to a test contained no detected errors, that test was written on the Test/Engine Master (TEM) tape. If, however, certain cards contained errors, these discrepancies were identified by the computer program and the corresponding test was not written on the TEM. The erroneous cards were then corrected by hand, frequently after consultation with the data collectors, and resubmitted for filing. This process, in many cases, was repeated several times until a consistent set of test data was achieved.

Approximately 3900 test records were received from contributing organizations, of which 3749 were successfully processed and filed on tape; thus, 97% of all submitted data were subsequently used in analyses.

The computer system employed to create the test data file from punched cards consisted of a set of seven programs plus four sorts, written for an IBM 1401 machine in Autocoder language.

Each test record after being filed on tape was edited and printed with all data items identified by name. The collection of these printed test records serves as a complete, uniform description of the entire data file and eliminates the need to reference the original data collection sheets. The edit and print program was written in Autocoder language for an IBM 1401 computer.

With all test data ultimately filed on magnetic tape, there was no longer any need to use the punched cards, although they were retained. The data sheets were retained as an original reference source for the test file on tape. The original data sheets, magnetic tape data file, and collection of printed test records have been sent to NASA Lewis

Research Center for retention.

4. Tabulation

Tabulations of test data, some of which are shown in Appendix B, were found useful for several reasons:

(1) They conveniently summarize the data.

(2) They serve to identify various combinations of variables or characteristics that are present.

(3) They can describe the distribution of data (histograms) as a prerequisite to statistical analysis. In particular, this last point was most important in ensuring the success of the regression analysis.

With the test data on magnetic tape such that an individual test corresponds to a physical record, tabulation becomes quite simple. Tabulations may be performed counting each occurrence of a variable once or by weighting the count according to a number of replicate tests indicated on the Test Summary Data Sheet.

A computer program has been developed by Arthur D. Little, Inc. to anlayze business, survey, and scientific data and produce tables which summarize the file of information which has been processed. The program is designed to operate with an IBM 7090/94 or equivalent computer. The basic functions performed are essentially those which are currently handled by mechanical punched card sorting and tabulating equipment. However, the processing and output features of the program provide much more flexibility then can conveniently be obtained with conventional equipment. In addition, the computer program offers considerable advantage in speed of operation, cost, accuracy of results, and ability to work conveniently with long records and large quantities of data.

The program processes an input data file and produces cross-tabulations of the data. The processing and output options available make it possible to produce tables which contain in each cell either counts or weighted counts of the number of times the individual records can be classified by the characteristics which define the cell. Grand total, and row and column sub-totals are provided, and tables showing percentages based on the grand total or any of the sub-totals can be presented. On option, the average weights within each cell of a table can also be computed. Tabulations involving three and four fields, i.e., three- and four-dimensional tables, and tabulations restricted to a number of selected portions of a file can be performed in a single run.

The output is in the form of printed tables containing run, table, and field identifications. It is easily read and suitable for immediate presentation.

The number of tabulations and cross-tabulations of data that can be produced from the master test file is practically infinite. Besides the extensive number of possible variable combinations appearing in tables, there is an almost unlimited number of ways to define tabulating ranges for even one variable. Appendix B contains six tables indicating the distribution of values of certain descriptive variables in the data file. The file contained 3749 tests, including replicates, corresponding to 3199 individual test descriptions. This set of tables is not intended to provide a comprehensive summary of the entire test file but merely to indicate the distribution of certain representative variables. Note that tabulating ranges have an arithmetic distribution (e.g., combustion chamber diameter), a logarithmic or geometric distribution (e.g. thrust), or a discrete nature (e.g. propellant combinations). Other range distributions are, of course, possible.

Finally, it should be mentioned that parameters, i.e. functions of variables, may also be tabulated by the foregoing methods; however, no parameter tables are presented here because they do not add significantly to the data file description.

5. Parameter Evaluation

To evaluate design and stability parameters, a means was required whereby multivariable functions of existing test data could be automatically evaluated and recorded on magnetic tape. These functions, or parameters, were formulated from numerous combinations of test variables and previously defined parameters. Functions were either continuous or discrete, and pertained to either design parameters or stability parameters. In addition, there was no practical limitation to the number and complexity of parameters to be developed. Regardless of their precise nature, the inclusion of new parameters in the overall computer program was to be relatively straightforward procedure. To retain the concept of a test "datum point", the parameters for a given test were to be located in the same file record as the variables for that test.

Two computer programs were designed to meet the above specifications. Furthermore, these programs were written to accommodate an expanding TEM; parameters were defined, coded, and evaluated during and after the period in which tests were being added to the master data file. Both programs were written for an IBM 7090/7094 series computer.

The first program, written in COBOL language, operates on the TEM to produce a new tape with greatly expanded record sizes. Each test record is enlarged from 2388 characters to 5988 characters in order to reserve space for as many as 300 future 12-character parameter fields. At the same time, all alphabetic characters (A, N, U) are replaced by the symbol "-9". This numeric tape becomes an input to the second program and is created each time the TEM is updated. Once all test data had been filed, this operation was no longer required.

The second program, entitled PARAMETERS, was also written in IBM 7090/7094 COBOL but uses eight FORTRAN IV subroutines. This program operates under the IBSYS Operating System. Since new parameters were continually being developed throughout the course of the project, it was desirable to minimize the effort and repetition involved in coding, evaluating, and adding new parameters to the master data file. Parameters were grouped into individual FORTRAN subroutines to take advantage of their similarities, and thereby reduce total programming and computation time. The definition and evaluation of a new parameter affected only the subroutine in which it appeared, with minor control changes to the main program. Therefore, the addition of a new parameter necessitated redundant calculation of only those parameters in the altered subroutine. New subroutines were readily incorporated into the COBOL main program.

The main program reads and writes both variables and parameters onto the master data file and converts all numbers to floating-point notation. The FORTRAN subroutines operate on these floating point numbers to produce new parameters, which are then returned to the main program to be written on tape. Before calculating new parameters, however, the subroutines examine all input variables for the absence of valid data, these data having been previously flagged by "-9" to indicate the symbols A, N, or U. If certain input variables do not have valid data, the normal parameter calculations are bypassed and the parameter in question flagged to indicate its unavailability. The program PARAMETERS, then, updates a previously evaluated variable-parameter file, thereby producing a new file containing additional parameters.

The PARAMETERS program, in addition to updating the master data file, provides the following printed information:

(1) For each parameter, a count of the number of records in which that parameter could not be calculated due to missing input data.

(2) The minimum and maximum value calculated for each parameter.

(3) For each parameter, an identification of the first two tests in which that parameter could not be calculated (useful for manual verification).

(4) The identification of any data point in which a parameter calculation resulted in a negative value (other than the "-9" flag). This is an error check since no defined parameter could assume a negative value.

(5) On request, the values of all parameters and variables associated with any desired test.

All parameters and properties of propellants and combustion products defined in Appendices C and D have been programmed and evaluated. Propellant densities and surface tensions have been approximated as linear functions of the respective fuel or oxidizer temperature at the orifice inlet (T_{fo} or T_{oo}). The four combustion product properties, adiabatic chamber temperature, mean product molecular weight, mean product specific heat ratio, and theoretical frozen c-star, have been calculated for propellant combinations included in the test data file by means of a program* developed by the NASA Lewis Research Center. The calculated combustion product property values were then approximated by polynomial expansions in the pressure and mixture ratio. Frequency dependent operational parameters, such as the fuel penetration distance parameter, have been coded with frequency assigned a nominal value of unity. By multiplying or dividing these parameters by the true frequency, they may be evaluated for a specific test condition or at an arbitrary frequency.

Thus far, only "permanent" parameters have been discussed; these are parameters deemed of sufficient import to be recorded on the master data file. Other parameters were defined during the course of analysis which consisted of simple functions (products, ratios, etc.) of these permanent parameters and variables. Values of these additional, or "temporary", parameters were not filed unless they acquired a higher status of permanence.

Before the variable-parameter master file could be subjected to statistical analysis, two additional operations were performed. First, those variables and parameters to be statistically analyzed were extracted from the data file records and copied onto a new file, thereby forming smaller "data points". Each datum point corresponds to a vector of variables, both dependent and independent, from one test. If any variable in a datum point was absent (A, N, U), that test had to be discarded prior to statistical analysis since it was not possible to operate on a vector, one of whose elements was undefined. A general IBM 1401 Autocoder program was written to facilitate the extraction of records from a tape file and to put all or part of the records onto a second

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*NASA TN D-1454 and TN D-1737, "A General IBM 704 or 7090 Computer Program for Computation of Chemical Equilibrium Compositions, Rocket Performance, and Chapman-Jouguet Detonations," Zeleznik, F. J. and Gordon, S., October 1962 and October 1963, Lewis Research Center, Cleveland, Ohio.

tape, printer, or punched cards, or a combination of these. The program can handle unblocked records of variable length and can make decisions based on the contents of these records concerning what information, if any, should go into the output records. Finally, each resulting datum point was reproduced as many times as there were replicate tests that it represented.

6. Statistical Analysis

The primary statistical tool employed in the development of prediction equations was regression analysis. In particular, we made extensive use of the BMD02R Stepwise Regression program, one of the extremely effective and flexible routines in the BMD BIOMEDICAL Computer Programs* series. These "package" programs use a common input/output data format and are written for an IBM 7090/7094 computer using the IBM FORTRAN II Monitor System.

"BMD02R computes a sequence of multiple linear regression equations in a stepwise manner. At each step, one variable (or "parameter" in the terminology of this study) is added to the regression equation. The variable added is the one which makes the greatest reduction in the error sum of squares. Equivalently it is the variable which has highest partial correlation with the dependent variable partialed on the variables which have already been added; and equivalently it is the variable which, if it were added, would have the highest F value. Variables are automatically removed when their F values become too low. Output from this program includes:

1. At each step:
    - (a) Multiple correlation coefficient R
    - (b) Standard error of estimate
    - (c) Analysis-of-variance table
    - (d) For variables in the equation:
        - (1) Regression coefficient

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*BMD Biomedical Computer Programs; W. J. Dixon, Editor; Health Sciences Computing Facility, Department of Preventive Medicine and Public Health, School of Medicine, University of California, Los Angeles, revised September 1965.

        (2) Standard error
        (3) F to remove
    (e) For variables not in the equation:
        (1) Tolerance
        (2) Partial correlation coefficient
        (3) F to enter

2. Optional output prior to performing regression:
    (f) Means and standard deviation
    (g) Covariance matrix
    (h) Correlation matrix
3. Optional output after performing regression:
    (i) List of residuals
    (j) Plots of residuals vs. input variables
    (k) Summary table

It should be pointed out that the form of the regression equations is necessarily linear in the coefficients, but may be nonlinear in one or more of the independent variables. The only practical limitations are:

1. No more than 80 variables can be used, i.e., at most 79 independent variables.
2. A maximum of 9999 data points. This was not a restriction in this study as there were less than 4000 total data points.

APPENDIX B - DESCRIPTION OF DATA

LIST OF TABLES

TABLE B-1

TESTS SUBMITTED BY ORGANIZATION

Organization	Individual Tests*	Total Tests* (including replicates)
Aerojet	175 (5.5)	418 (11.1)
JPL	319 (10.0)	468 (12.5)
NASA Lewis	1359 (42.4)	1361 (36.3)
NASA Marshall	10 (0.3)	10 (0.3)
Rocketdyne	394 (12.3)	394 (10.5)
Princeton	549 (17.2)	549 (14.6)
United Aircraft	194 (6.1)	194 (5.2)
PIB	116 (3.6)	272 (7.3)
AFRPL	83 (2.6)	83 (2.2)
Total	3199 (100.0)	3749 (100.0)

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* Numbers enclosed in parentheses are percentages of the appropriate totals.

TABLE B-2

PROPELLANT COMBINATIONS

Fuel	Oxidizer	Frequency	Percentage Frequency
RP-1	Oxygen	438	11.7
RP-1	70% Oxygen/30% Fluorine	5	0.1
RP-1/Hybaline A-14	Oxygen	12	0.3
Hydrogen	Oxygen	877	23.4
Hydrogen	70% Oxygen/30% Fluorine	14	0.4
Hydrazine	Nitrogen Tetroxide	93	2.5
Hydrazine	Pentaborane	6	0.2
Hydrazine	SFNA	7	0.2
Hydrazine/Monomethyl Hydrazine	Nitrogen Tetroxide	9	0.2
UDMH	Oxygen	3	0.1
UDMH	Nitrogen Tetroxide	92	2.5
UDMH	SFNA	12	0.3
50% Hydrazine/50% UDMH	Nitrogen Tetroxide	1270	33.9
Monomethyl Hydrazine	Nitrogen Tetroxide	35	0.9
Ethanol	Oxygen	384	10.2
Corporal	SFNA	186	5.0
DETA	SFNA	11	0.3
JP-5A	Oxygen	272	7.2
JPX	SFNA	9	0.2
JPX	Nitrogen Tetroxide	4	0.1
Other	Other	10	0.3
Total		3749	100.0

TABLE B-3

COMBUSTION CHAMBER DIAMETER AT INJECTOR

Diameter, In.	Frequency	Percentage Frequency
0.0 - 2.2	269	7.2
2.2 - 3.0	83	2.2
3.0 - 4.2	13	0.3
4.2 - 5.8	144	3.9
5.8 - 8.0	71	1.9
8.0 -11.0	2217	59.1
11.0 -15.0	251	6.7
15.0 -21.0	540	14.4
21.0 -29.0	42	1.1
29.0 -40.0	119	3.2
40.0 -55.0	0	0
Total	3749	100.0

TABLE B-4

CHAMBER PRESSURE, INJECTOR END

Chamber Pressure*, psia	Frequency	Percentage Frequency
0 - 72	41	1.1
72 - 98	246	6.6
98 - 131	845	22.5
131 - 178	452	12.1
178 - 240	138	3.7
240 - 324	1323	35.3
324 - 437	178	4.7
437 - 589	92	2.5
589 - 794	49	1.3
794 - 1072	144	3.8
1072 - 1445	148	3.9
1445 - 9999	3	0.1
Unknown or not available	90	2.4
Total	3749	100.0

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*This is the chamber pressure, injector end for actual or intended steady-state conditions.

TABLE B-5

THRUST

Thrust*, lbf	Frequency	Percentage Frequency
0 - 2000	70	1.9
2000 - 4160	36	1.0
4160 - 8640	459	12.2
8640 - 17940	810	21.6
17940 - 37280	864	23.0
37280 - 77460	76	2.0
77460 - 160950	59	1.6
160950 - 334440	45	1.2
334440 - 694880	0	0
694880 - 1443800	55	1.5
1443800 - 3000000	62	1.7
Unknown or not available	1213	32.4
Total	3749	100.0

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*This is the thrust for actual or intended steady-state conditions

TABLE B-6

STABILITY CATEGORY

Stability	Frequency	Percentage Frequency
High Frequency Oscillations		
Spontaneous, Sustained	763	20.4
Spontaneous, Resurgent or Damped	50	1.3
Pulsed, Sustained	675	18.0
Pulsed, Resurgent or Damped	570	15.2
Low or Intermediate Frequency and Aperiodic Oscillations	271	7.2
No Oscillations, No Pulsing	1267	33.8
No Oscillations with Pulsing	115	3.1
Undetermined	38	1.0
Total	3749	100.0

APPENDIX C - LIST OF VARIABLES

I: DESIGN VARIABLES[†]

A. Combustion Chamber

1. Quantitative Variables

Symbol	Location*	Name
** D_1	04Z03	Chamber diameter at injector
D_2	05Z03	Chamber diameter at nozzle
D_3	06Z03	Nozzle throat diameter
** L_1	07Z03	Length of chamber
** L_2	08Z03	Length of chamber plus nozzle entrance
R_1	09Z03	Radius of curvature, nozzle entrance
R_2	10Z03	Radius of curvature, nozzle throat
β	11Z03	Half-angle, nozzle convergence
A_t	12Z03	Area of nozzle throat
ε	17Z03	Nozzle area expansion ratio
D_c	13b03	Characteristic dimension, non-circular chambers

2. Qualitative (Coded) Variables

13a03	Geometry description
14Z03	Wall material
15Z03	Wall construction
16Z03	Cooling method

[†] For a more complete definition of all variables, together with examples of typical values, please see Reference 2, "Format for the Collection of Liquid Propellant Rocket Combustion Instability Test Data", CPIA Publication No. 149, The Johns Hopkins University, Applied Physics Laboratory, September, 1967.

*Refers to location of each variable in data collection sheets. First two characters of location code indicate field number, third character indicates sub-field number (Z if none), fourth and fifth characters indicate Data Sheet number.

**These variables were used as independent variables in data analysis. Other variables were incorporated in parameters. (See Appendix D.)

B. Acoustic Absorption Liner

1. Quantitative Variables

Symbol	Location	Name
** L_ℓ	07Z04	Length of liner
** X_ℓ	08Z04	Axial position of liner
D_ℓ	09Z04	Diameter of liner, injector end
** T_ℓ	10Z04	Thickness of liner
** C_ℓ	11Z04	Cavity spacing of liner, injector end
β_ℓ	12Z04	Half-angle of liner convergence
** $D_{\ell h1}$	14a04	Diameter of liner holes, group one
$D_{\ell h2}$	14c04	Diameter of liner holes, group two
** $P_{\ell h1}$	14b04	Percent of liner area, hole group one
$P_{\ell h2}$	14d04	Percent of liner area, hole group two
** $T_{\ell g}$	15Z04	Temperature of gas in liner
$P_{\ell s}$	16Z04	Liner design sound pressure
** $f_{\ell r}$	17Z04	Liner design resonant frequency
** $C_{\ell a}$	18Z04	Liner acoustic absorption coefficient

2. Qualitative (Coded) Variables

04Z04	Liner material
05Z04	Liner construction
06Z04	Cooling method
13Z04	Hole array

C. Feed System

1. Quantitative Variables

Symbol	Location	Name
L_{ofs}	05a05	Effective length, oxidizer feed system
D_{ofs}	05b05	Effective diameter, oxidizer feed system
L_{ffs}	06a05	Effective length, fuel feed system
D_{ffs}	06b05	Effective diameter, fuel feed system

2. Qualitative (Coded) Variables

04Z05	Feed type

D. Baffle

1. Quantitative Variables

Symbol	Location	Name
** N_{po}	08Z10	Number of baffle pockets
h_{b1}	09a10	Maximum baffle blade height
** h_{b2}	09b10	Minimum baffle blade height
h_b	09c10	Average baffle blade height

2. Qualitative Variables

04Z10	Material
05Z10	Cooling method
06Z10	Geometry
07Z10	Symmetry

E. Injector

1. Quantitative Variables

Symbol	Location	Name
L_i	06Z06	Depth of injector face
$R_{if}(n_a)$	07-06	Fuel injection distribution as ratio of local fuel injection density (flow rate per unit area) to overall fuel injection in density, for area n_a
$R_{io}(n_a)$	07-06	Oxidizer injection distribution as ratio of local oxidizer injection density (flow rate per unit area) to overall oxidizer injection density, for area n_a
n_a		Injector area number
N_a		Total number of injector areas
p_{fc}	08Z06	Percent of fuel for film or transpiration cooling
p_{oc}	09Z06	Percent of oxidizer for film or transpiration cooling
N_g	10Z06	Number of element groups
n_g	04Z07	Element group number
$p_{fg}(n_g)$	05Z07	Percent of fuel flow through group n_g
$p_{og}(n_g)$	06Z07	Percent of oxidizer flow through group n_g
$N_{eg}(n_g)$	09Z07	Number of elements in group n_g
$N_{ofe}(n_g)$	10a07	Number of fuel orifices per element, group n_g
$N_{ooe}(n_g)$	10b07	Number of oxidizer orifices per element, group n_g
$D_{ofg}(n_g)_1$	07a08	Maximum fuel orifice diameter, group n_g
$D_{ofg}(n_g)_2$	07b08	Minimum fuel orifice diameter, group n_g
$D_{ofg}(n_g)$	07c08	Average fuel orifice diameter, group n_g
$D_{oog}(n_g)_1$	07a09	Maximum oxidizer orifice diameter, group n_g
$D_{oog}(n_g)_2$	07b09	Minimum oxidizer orifice diameter, group n_g
$D_{oog}(n_g)$	07c09	Average oxidizer orifice diameter, group n_g
$D_{ifg}(n_g)$	08Z08	Inner diameter, annular fuel orifice, group n_g

E. Injector

1. Quantitative Variables (continued)

Symbol	Location	Name
$D_{iog}(n_g)$	08Z09	Inner diameter, annular oxidizer orifice, group n_g
$A_{ofg}(n_g)$	09Z08	Area of fuel orifices, group n_g
$A_{oog}(n_g)$	09Z09	Area of oxidizer orifices, group n_g
$LD_{fg}(n_g)_1$	10a08	Maximum fuel orifice L/D, group n_g
$LD_{fg}(n_g)_2$	10b08	Minimum fuel orifice L/D, group n_g
$LD_{fg}(n_g)$	10c08	Average fuel orifice L/D, group n_g
$LD_{og}(n_g)_1$	10a09	Maximum oxidizer orifice L/D, group n_g
$LD_{og}(n_g)_2$	10b09	Minimum oxidizer orifice L/D, group n_g
$LD_{og}(n_g)$	10c09	Average oxidizer orifice L/D, group n_g
$\alpha_{fg}(n_g)_1$	11a08	Maximum fuel orifice stream angle, group n_g
$\alpha_{fg}(n_g)_2$	11b08	Minimum fuel orifice stream angle, group n_g
$\alpha_{fg}(n_g)$	11c08	Average fuel orifice stream angle, group n_g
$\alpha_{og}(n_g)1$	11a09	Maximum oxidizer orifice stream angle, group n_g
$\alpha_{og}(n_g)_2$	11b09	Minimum oxidizer orifice stream angle, group n_g
$\alpha_{og}(n_g)$	11c09	Average oxidizer orifice stream angle, group n_g
$x_{ifg}(n_g)_1$	12a08	Maximum fuel impingement distance, group n_g
$x_{ifg}(n_g)_2$	12b08	Minimum fuel impingement distance, group n_g
$x_{ifg}(n_g)$	12c08	Average fuel impingement distance, group n_g
$x_{iog}(n_g)_1$	12a09	Maximum oxidizer impingement distance, group n_g
$x_{iog}(n_g)_2$	12b09	Minimum oxidizer impingement distance, group n_g
$x_{iog}(n_g)$	12c09	Average oxidizer impingement distance, group n_g

E. Injector (continued)

2. Qualitative (Coded) Variables

Location	Name
04Z06	Material
05Z06	Shape
07Z07	Element function
08Z07	Element type
05Z08	Fuel stream type
06Z08	Fuel orifice entrance shape
05Z09	Oxidizer stream type
06Z09	Oxidizer orifice entrance shape

II. OPERATIONAL VARIABLES

A. Quantitative Variables

Symbol	Location	Name
c_t	(Col 5, Sh.14)	Test condition
** $P_{ci}(c_t)$	04a14	Chamber pressure, injector end, condition c_t
$P_{cn}(c_t)$	04b14	Chamber pressure, nozzle end, condition c_t
$OF(c_t)$	05Z14	Ox-fuel ratio, condition c_t
$\dot{m}_f(c_t)$	06Z14	Fuel flow rate, condition c_t
$\dot{m}_o(c_t)$	07Z14	Ox flow rate, condition c_t
$P_{fi}(c_t)$	08a14	Fuel pressure injector inlet, condition c_t
$P_{fo}(c_t)$	08b14	Fuel pressure, orifice inlet, condition c_t
$P_{oi}(c_t)$	09a14	Ox pressure, injector inlet, condition c_t
$P_{oo}(c_t)$	09b14	Ox pressure, orifice inlet, condition c_t
$T_{fi}(c_t)$	10a14	Fuel temperature, injector inlet, condition c_t
$T_{fo}(c_t)$	10b14	Fuel temperature, orifice inlet, condition c_t
$T_{oi}(c_t)$	11a14	Ox temperature, injector inlet, condition c_t
$T_{oo}(c_t)$	11b14	Ox temperature, orifice inlet, condition c_t
$P_{ffs}(c_t)$	12a14	Fuel pressure, feed system inlet, condition c_t
$P_{ofs}(c_t)$	12b14	Ox pressure, feed system inlet, condition c_t
t_t	16Z11	Test duration
n_d	(Col. 4, Sh. 12)	Disturbance number
$x_d(n_d)$	05a12	Disturbance location, axial, disturbance n_d
$y_d(n_d)$	05b12	Disturbance location, radial, disturbance n_d

II. OPERATIONAL VARIABLES (CONTINUED)

A. Quantitative Variables (continued)

Symbol	Location	Name
$t_d(n_d)$	07Z12	Disturbance time, disturbance n_d
$\dot{m}_{dg}(n_d)$	08Z12	Disturbance, gas flow rate, disturbance n_d
$m_{de}(n_d)$	09Z12	Disturbance, explosive weight, disturbance n_d
$P_{db}(n_d)$	10Z12	Disturbance, disc strength, disturbance n_d
$\Delta P_d(n_d)$	11Z12	Disturbance pressure, disturbance n_d
N_d	15Z11	Number of disturbances

B. Qualitative (Coded) Variables

09a02	Fuel identification
09e02	Oxidizer identification
04Z12	Disturbance type
06Z12	Disturbance direction

III. STABILITY VARIABLES

A. Quantitiative Variables

Symbol	Location	Name
N_m	09Z11	Number of modes
n_m	(Col 5, Sh.13)	Mode number
ΔP_{n1}	10a11	Background noise (PTP)
ΔP_{n2}	10b11	Background noise (RMS)
N_p	11Z11	Number of pressure taps
f_t	13Z11	Transducer frequency response
$f(n_m)$	05Z13	Frequency, mode n_m
$\Delta P_1(n_m)$	06a13	Maximum amplitude (PTP), mode n_m
$\Delta P_2(n_m)$	06b13	Maximum amplitude (RMS), mode n_m
$t(n_m)$	07Z13	Time of occurrence, mode n_m
$\Delta t_1(n_m)$	08Z13	Rise time, mode n_m
$\Delta t_2(n_m)$	10Z13	Duration at maximum amplitude, mode n_m
$\Delta t_3(n_m)$	12Z13	Damp time, mode n_m

B. Qualitative (Coded) Variables

08Z11	Stability
12Z11	Pressure Tap distribution
14Z11	Instability analysis method
04Z13	Mode description
09Z13	Maximum amplitude duration
11Z13	Damping at end of test

IV. PERFORMANCE VARIABLES

A. Quantitative Variables

Symbol	Location	Name
$c*(c_t)$	04Z15	Characteristic exhaust velocity, condition c_t
$F(c_t)$	06Z15	Thrust, condition c_t
$I_{spd}(c_t)$	07Z15	Specific impulse, delivered, condition c_t
$P_{amb}(c_t)$	09Z15	Ambient pressure, condition c_t
$E_s\ (c_t)$	10Z15	I_{sp} efficiency, one-dimensional, frozen flow, condition c_t

V. PROPERTIES OF PROPELLANTS AND COMBUSTION PRODUCTS*

Symbol	Name
** $\rho_f(T_{fo})$	Fuel density
** $\rho_o(T_{oo})$	Oxidizer density
** $\sigma_f(T_{fo})$	Fuel surface tension
$\sigma_o(T_{fo})$	Oxidizer surface tension
T_{Bf}	Fuel boiling temperature
T_{Bo}	Oxidizer boiling temperature
T_{cf}	Fuel critical temperature
T_{co}	Oxidizer critical temperature
K	Droplet vaporization constant**
** $T(P_{ci},OF)$	Adiabatic chamber temperature
** $\overline{M}(P_{ci},OF)$	Mean product molecular weight
** $\overline{\gamma}(P_{ci},OF)$	Mean product specific heat ratio
$c_f^{*o}(P_{ci},OF)$	Theoretical, frozen c*
a	Chamber gas acoustic velocity
** OF_s	Stoichiometric oxidizer-fuel ratio

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*These quantities are not entered in the data collection sheets, but are calculated for each test as it is filed. Property data for each propellant combination were calculated by means of a program provided by the NASA Lewis Research Center, and are stored in the filing program as functions of propellant temperature, chamber pressure, and mixture ratio.

**R. J. Priem and G. Morrell, Progress in Astronautics and Rocketry, Vol.6, Academic Press, New York, 1962, page 305.

APPENDIX D - LIST OF DESIGN AND OPERATIONAL PARAMETERS

I. DESIGN PARAMETERS

Symbol	Formula	Description
N_e	$\sum_{n_g=1}^{N_g} N_{eg}(n_g)$	Number of elements
N_{of}	$\sum_{n_g=1}^{N_g} N_{ofe}(n_g) N_{eg}(n_g)$	Number of fuel orifices
N_{oo}	$\sum_{n_g=1}^{N_g} N_{ooe}(n_g) N_{eg}(n_g)$	Number of oxidizer orifices
D_{of}	$\frac{1}{N_{of}} \sum_{n_g=1}^{N_g} N_{ofe}(n_g) N_{eg}(n_g) \frac{D_{ofg}(n_g)-m}{n}$	Average fuel orifice diameter
	For circular orifice $m = o$ $\quad n = 1$	
	For annular orifice $m = D_{ifg}(n_g)$ $\quad n = 2$	
D_{oo}	$\frac{1}{N_{oo}} \sum_{n_g=1}^{N_g} N_{ooe}(n_g) N_{eg}(n_g) \frac{D_{oog}(n_g)-p}{q}$	Average oxidizer orifice diameter
	For circular orifice $p = o$ $\quad q = 1$	
	For annular orifice $p = D_{iog}(n_g)$ $\quad q = 2$	
LD_f	$\frac{1}{N_{of}} \sum_{n_g=1}^{N_g} N_{ofe}(n_g) N_{eg}(n_g) LD_{fg}(n_g)$	Average fuel orifice L/D
LD_o	$\frac{1}{N_{oo}} \sum_{n_g=1}^{N_g} N_{ooe}(n_g) N_{eg}(n_g) LD_{og}(n_g)$	Average oxidizer orifice L/D
x_{if}	$\frac{1}{N_{of}} \sum_{n_g=1}^{N_g} N_{ofe}(n_g) N_{eg}(n_g) x_{ifg}(n_g)$	Average fuel impingement distance

I. DESIGN PARAMETERS (CONTINUED)

Symbol	Formula	Description
x_{io}	$\frac{1}{N_{oo}} \sum_{n_g=1}^{N_g} N_{ooe}(n_g) N_{eg}(n_g) x_{iog}(n_g)$	Average oxidizer impingement distance
LD	$\frac{L_1}{D_1}$	Chamber length-diameter ratio
LL	$\frac{L_\ell}{L_1}$	Liner length-chamber length ratio
R_c	$(D_2/D_3)^2$	Nozzle contraction ratio
ID_f	$p\left[\sum_{n_a=1}^{N_a} n_a^{q} R_{if}(n_a)\right]$	Fuel injection distribution
ID_o	$p\left[\sum_{n_a=1}^{N_a} n_a^{q} R_{io}(n_a)\right]$	Oxidizer injection distribution

Chamber shape	p	q
Circular, conical, square or rectangular	$\frac{6}{N_a(N_a+1)(2N_a+1)}$	2
Slab	$\frac{2}{N_a(N_a+1)}$	1

Symbol	Formula	Description
IDE_f	$\sum_{n_a=1}^{N_a} \left\| R_{if}(n_a) - 1 \right\|$	Fuel injection dist. eccentricity
IDE_o	$\sum_{n_a=1}^{N_a} \left\| R_{io}(n_a) - 1 \right\|$	Oxidizer injection dist. eccentricity

II. OPERATIONAL PARAMETERS, FREQUENCY INDEPENDENT

Symbol	Formula	Description
$V_f\ (c_t)$	$\dfrac{\dot{m}_f(c_t)}{\rho_f \sum\limits_{n_g=1}^{N_g} A_{ofg}(n_g)}$	Average fuel jet velocity
$V_o\ (c_t)$	$\dfrac{\dot{m}_o(c_t)}{\rho_o \sum\limits_{n_g=1}^{N_g} A_{oog}(n_g)}$	Average oxidizer jet velocity
$VRP(c_t)$	$\dfrac{V_o(c_t)}{V_f(c_t)}$	Propellant velocity ratio
$MRP(c_t)$	$\dfrac{\dfrac{[\dot{m}_o(c_t)]^2}{\rho_o} \sum\limits_{n_g=1}^{N_g} \dfrac{[P_{og}(n_g)]^2 \cos\alpha_{og}(n_g)}{A_{oog}(n_g)}}{\dfrac{[\dot{m}_f(c_t)]^2}{\rho_f} \sum\limits_{n_g=1}^{N_g} \dfrac{[P_{fg}(n_g)]^2 \cos\alpha_{fg}(n_g)}{A_{ofg}(n_g)}}$	Propellant momentum ratio
$ER(c_t)$	$\dfrac{OF(c_t)}{OF_s}$	Propellant equivalence ratio
$XL(n_d)$	$\dfrac{x_d(n_d)}{L_1}$	Axial disturbance location-chamber length ratio
$YD(n_d)$	$\dfrac{y_d(n_d)}{D_1}$	Radial disturbance location chamber diameter ratio

II. OPERATIONAL PARAMETERS, FREQUENCY INDEPENDENT (CONTINUED)

Symbol	Formula	Description
$MPE(c_t)$	$\frac{\dot{m}_f(c_t) + \dot{m}_o(c_t)}{N_e}$	Mass flow rate per element
$MPO(c_t)$	$\frac{\dot{m}_f(c_t) + \dot{m}_o(c_t)}{N_{of} + N_{oo}}$	Mass flow rate per orifice
$TPE(c_t)$	$\frac{F(c_t)}{N_e}$	Thrust per element
$TPEM(c_t)$	$\frac{P_{ci}(c_t) A_t}{N_e}$	Modified thrust per element
$MPV(c_t)$	$\frac{\dot{m}_f(c_t) + \dot{m}_o(c_t)}{v_c}$	Mass flow rate per unit volume

Chamber shape	v_c
Cylindrical or conical	$\frac{\pi}{12}\left[L_1(D_1^2 + D_2^2 + D_1 D_2) + (L_2 - L_1)(D_2^2 + D_3^2 + D_2 D_3)\right]$
Slab	$\frac{D_c}{2}\left[L_1(D_1 + D_2) + (L_2 - L_1)(D_2 + D_3)\right]$
Square or rectangular	$\frac{D_1^2 L_1}{D_c}$

II. OPERATIONAL PARAMETERS, FREQUENCY INDEPENDENT (CONTINUED)

$TPV(c_t)$ $$\frac{F(c_t)}{v_c}$$ Thrust per unit volume

v_c evaluated as in MPV.

$TPVM(c_t)$ $$\frac{P_{ci}(c_t)A_t}{v_c}$$ Modified thrust per unit volume

v_c evaluated as in MPV.

$MPA(c_t)$ $$\frac{\dot{m}_f(c_t) + \dot{m}_o(c_t)}{A_i}$$ Mass flow per unit area.

Chamber shape	A_i
Cylindrical or conical	$\frac{\pi D_1^2}{4}$
Slab	$D_1 D_c$
Square or rectangular	$\frac{D_1^2}{D_c}$

EPA $$\frac{N_e}{A_i}$$ Elements per unit area

A_i evaluated as in MPA.

$SAF(c_t)$ $$\left[VRP(c_t)\right]^{0.25}\left[\tan^{0.38}\alpha_o + 0.07\right]$$ Stream Angle Function

$$\alpha_o = \frac{1}{N_{oo}} \sum_{n_g=1}^{N_g} N_{ooe}(n_g)\, N_{eg}(n_g)\, \alpha_{og}(n_g)$$

$VDP(c_t)$ $$\frac{c^*(c_t)\,[T\,\overline{M}]^{0.5}}{D_1\, P_{ci}(c_t)}$$ Viscous dissipation parameter

BRPV (c_t)	$\frac{2\ A_t\ r_{pv}}{\pi\ D_2}$	Burning rate parameter; Vaporization rate controlling

If $r_{pvf} > r_{pvo}$, $r_{pv} = r_{pvo}$

If $r_{pvf} < r_{pvo}$, $r_{pv} = r_{pvf}$

$$r_{pvf} = r_{fv}\ \frac{1 + OF_s}{1 + OF}$$

$$r_{pvo} = r_{ov}\ \frac{OF\ (c_t)}{OF_s}\ \frac{1 + OF_s}{1 + OF}$$

$$r_{fv} = \frac{K_f\ (P_{ci}/300)^{0.5}}{R_c\left[1 - \frac{T_{fo}}{T_{cf}}\right]^{0.2} \left[\frac{V_f}{1200}\right]^{0.8} \left[\frac{x\ D_{of}^{\ y}}{.003}\right]^{1.5}}$$

$$r_{ov} = \frac{K_o\ (P_{ci}/300)^{0.5}}{R_c\left[1 - \frac{T_{oo}}{T_{co}}\right]^{0.2} \left[\frac{V_o}{1200}\right]^{0.8} \left[\frac{x\ D_{oo}^{\ y}}{.003}\right]^{1.5}}$$

Principal Element Type	x	y
Showerhead or coaxial	.032	.625
Unlike Impinging	.0058	.625
Like Impinging	.046	1.0

BRPD (c_t)	$\frac{2\ A_t\ r_{pd}}{\pi\ D_2}$	Burning rate parameter; Drop Atomization Rate Controlling

If $r_{pdf} > r_{pdo}$, $r_{pd} = r_{pdo}$

If $r_{pdf} < r_{pdo}$, $r_{pd} = r_{pdf}$

II. OPERATIONAL PARAMETERS, FREQUENCY INDEPENDENT (CONTINUED)

$$r_{pdf} = r_{fd} \, \frac{1 + OF_s}{1 + OF}$$

$$r_{pdo} = r_{od} \, \frac{OF}{OF_s} \, \frac{1 + OF_s}{1 + OF}$$

$$r_{fd} = \frac{1}{2 \pi V_f} \left[\frac{8 \sigma_s}{\rho_f \times D_{of}^{3y}} \right]^{0.5}$$

$$r_{od} = \frac{1}{2 \pi V_o} \left[\frac{8 \sigma_f}{\rho_o \times D_{oo}^{3y}} \right]^{0.5}$$

x and y defined as in BRPV

BRPJ (c_t) $\quad \dfrac{2 A_t r_{pj}}{\pi D_2}$ Burning rate parameter, Jet Atomization Rate Controlling

If $r_{pjf} > r_{pjo}$, $r_{pj} = r_{pjo}$

If $r_{pjf} < r_{pjo}$, $r_{pj} = r_{pjf}$

$$r_{pjf} = r_{fj} \, \frac{1 + OF_s}{1 + OF}$$

$$r_{pjo} = r_{oj} \, \frac{OF}{OF_s} \, \frac{1 + OF_s}{1 + OF}$$

$$r_{fj} = \frac{1}{2 \pi V_f} \left[\frac{48 \sigma_f}{\rho_f D_{of}^{3}} \right]^{0.5}$$

$$r_{oj} = \frac{1}{2 \pi V_o} \left[\frac{48 \sigma_o}{\rho_o D_{oo}^{3}} \right]^{0.5}$$

III. OPERATIONAL PARAMETERS, FREQUENCY DEPENDENT

Symbol	Formula	Description
$CP_1(c_t)$	$\frac{f\ L_1\ V_\ell\ (c_t)}{a^3\ M}$ $V_\ell(c_t) = V_o(c_t)$ if fuel is hydrogen $V_\ell(c_t) = V_f(c_t)$ for other fuels $M = \frac{1}{2BG}\left[R_c - (R_c^2 - 4\ BG^2)\right]^{1/2}$ $B = \frac{\gamma+1}{4} \quad G = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$ (Approximate formula for Mach number at nozzle entrance.)	Correlation parameter
$CP_2(c_t)$	$\frac{F\ \gamma\ v_c\ P_{ci}\ V_\ell\ (c_t)^2}{a^4\ (\ \dot{m}_f\ (c_t) + \dot{m}_o\ (c_t)\ )}$ v_c evaluated as in MPV $V_\ell\ (c_t)$ evaluated as in CP_1	Correlation parameter
$CP_3(c_t)$	$\frac{f\ P_{ci}(c_t)}{\dot{m}_f(c_t)+\dot{m}_o(c_t)} \left[\frac{F(c_t)}{N_e}\right]^{0.5}$	Correlation parameter*
$CP_4(c_t)$	$\frac{f\ P_{ci}(c_t)^{1.5}}{\dot{m}_f(c_t) + \dot{m}_o(c_t)} \left[\frac{A_t}{N_e}\right]^{0.5}$	Correlation parameter

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*O. W. Dykema, Proceedings of the 2nd ICRPG Combustion Conference, CPIA Publication No. 105, May 1966, pp. 205-223.

III. OPERATIONAL PARAMETERS, FREQUENCY DEPENDENT (CONTINUED)

STLVF (c_t)	$\frac{2 \pi f r_{fv}}{V_f}$	Sensitive time lag parameter, fuel vaporization rate controlling
	r_{fv} defined as in BRPV	
STLVO (c_t)	$\frac{2 \pi f r_{ov}}{V_o}$	Sensitive time lag parameter, oxidizer vaporization rate controlling
	r_{ov} defined as in BRPV	
STLDF (c_t)	$\frac{\pi f}{r_{fd} V_f}$	Sensitive time lag parameter, fuel drop atomization rate controlling
	r_{fd} defined as in BRPD	
STLDO (c_t)	$\frac{\pi f}{r_{od} V_o}$	Sensitive time lag parameter, oxidizer drop atomization rate controlling
	r_{od} defined as in BRPD	
STLJF (c_t)	$\frac{\pi f}{r_{fj} V_f}$	Sensitive time lag parameter, oxidizer jet atomization rate controlling
	r_{fj} defined as in BRPJ	
STLJO (c_t)	$\frac{\pi f}{r_{oj} V_o}$	Sensitive time lag parameter, oxidizer jet atomization rate controlling
	r_{oj} defined as in BRPJ	

III. OPERATIONAL PARAMETERS, FREQUENCY DEPENDENT (CONTINUED)

$FDTP(c_t)$	$\frac{f\ P_{ci}(c_t)\ D_{of}^{2}\ \bar{M}^{0.5}}{T^{1.5}}$	Fuel diffusion time parameter
$ODTP(c_t)$	$\frac{f\ P_{ci}(c_t)\ D_{oo}^{2}\ \bar{M}^{0.5}}{T^{1.5}}$	Oxidizer diffusion time parameter
$FPDP(c_t)$	$\frac{V_f(c_t)}{f\ x_{if}}$	Fuel penetration distance parameter
$OPDP(c_t)$	$\frac{V_o(c_t)}{f\ x_{io}}$	Oxidizer penetration distance parameter

IV. QUALITATIVE DESIGN AND OPERATIONAL PARAMETERS

Propellant Combination Parameters

Propellants	Parameter Values F01	F02	F03	F04
H_2/LOX	1	0	0	0
RP-1 or JP-5A/LOX	0	1	0	0
N_2H_4-UDMH/N_2O_4	0	0	1	0
Ethanol/LOX	0	0	0	1
Other	0	0	0	0

Principal Element Type Parameters

Principal Element Type*	Parameter Values PE1	PE2	PE3
Coaxial	1	0	0
Unlike impinging	0	1	0
Like impinging	0	0	1
Showerhead	0	0	0

* The principal element type for an injector is that element type which carries over 50 percent of the fuel and over 50 percent of the oxidizer. A principal element type cannot be designated for all injectors.

Liner Parameter

LR = 1 if liner present; 0 if no liner.

Baffle Parameter

BF = 1 if baffle present; 0 if no baffle.

Pulse Parameter

Z = 1 if test was pulsed; 0 if not pulsed.

APPENDIX E

STABILITY PARAMETERS

SPO indicates the general character of each test with respect to combustion stability. SPO is not used directly in data analysis, but is used as a means of categorizing tests and for evaluating other stability parameters. SPO is the stability code entered in the Test Summary Data Sheet and is interpreted as follows:

Stability Description	SPO
High Frequency Oscillations	
Spontaneous, Sustained	01
Spontaneous, Resurgent	02
Spontaneous, Damped	03
Pulsed, Sustained	04
Pulsed, Resurgent	05
Pulsed, Damped	06
Intermediate Frequency Oscillations	07
Low Frequency Oscillations (Chugging)	08
Aperiodic Oscillations (Popping)	09
No Oscillations, No Pulsing	10
No Oscillations with Pulsing	11
Stability Undetermined	50

For a test where two or more values are applicable, the lowest applicable value of SPO is entered.

SP1 indicates the occurrence of a spontaneous, high frequency oscillation. SP1 is 0 for a stable test, 1 for an unstable test, and is evaluated according to the entry in the stability code on the Test Summary Data Sheet (SPO) as follows:

a. If SPO = 1, 2 or 3, SP1 = 1

b. If SPO = 7, 8, 9, 10, or 11, SP1 = 0

In all other cases, SP1 is not applicable.

SP1A indicates the occurrence of a spontaneous, high or intermediate frequency oscillation, and is applicable to all tests. SP1A is 1 for a test where spontaneous, high frequency oscillation is reported, and 0 for all other tests. SP1A is evaluated according to entries on the Instability Mode Data Sheet as follows:

a. If a mode is reported where the disturbance number is 0, and the mode type is 1-8, 14, 24, then SP1A = 1.

b. In all other cases, SP1 = 0.

SP1B is a measure of static stability of hydrogen-fueled engines, and is applicable only to a test wherein the fuel temperature has been decreased steadily (ramped) during the test. SP1B is equal to the fuel temperature at the time of occurrence of the first high or intermediate frequency oscillation. It is evaluated from entries on the Instability Mode and Test Conditions Data Sheets as follows:

$$SP1B = T_{fi}\ (n)$$

where n is mode number of first reported mode for which disturbance number is 0 and mode type is 1-8, 14, or 24.

If no such mode is reported, SP1B is not applicable

SP2 is a measure of the damping rate of an induced, high frequency oscillation and is applicable to all pulsed tests wherein no spontaneous, high frequency oscillations are reported. SP2 can vary from 0 (no damping) to 1000, and is assigned a value of 1000 for pulsed tests for which no high frequency oscillations are reported. SP2 is evaluated according to the stability code (SP0) and entries in the Instability Mode Data Sheet, for the first mode reported, as follows:

SP0	Disturbance No.	Decay Code	SP2
4 or 5			0
6		1	$1/\Delta t_3$
6		2 or 3	0
7,8 or 9	>0		1000
11			1000

In all other cases, SP2 is not applicable.

SP2A is a measure of the damping rate of an induced, high or intermediate frequency oscillation, and is applicable to all pulsed tests. SP2A can very from 0 (no damping) to 1000, and is assigned a value 1000 for pulsed tests where no high or intermediate frequency oscillations are reported. If two or more instability modes are reported, SP2A is evaluated for each mode and assigned the lowest applicable value. It is evaluated according to entries on the Instability Mode Data Sheet as follows:

a. For each mode where disturbance number >0, mode type is 1-8, 14 or 24, and decay code is 1, SP2A = $1/\Delta t_3$.

b. For each mode where disturbance number >0, mode type is 1-8, 14 or 24, and decay code is 2 or 3, SP2A = 0.

c. For each mode where disturbance number >0 and mode type 9 or 10, SP2A = 1000.

d. For pulsed tests ($N_d > 0$) with no modes reported ($N_m = 0$), SP2A = 1000.

SP2B, SP2C and SP2D are measures of the damping rate of an induced, high or intermediate frequency oscillation, and are applicable only to tests where such oscillations are reported. They can very from 0 (no damping) to 1000. If two or more induced modes are reported, SP2B, SP2C and SP2D are evaluated for each mode and assigned the lowest applicable values. They are evaluated according to entries on the Instability Mode Data Sheet as follows:

a. For each mode where disturbance number >0, mode type is 1-8, 14 or 24, and decay code is 1:

$$SP2B = 1/(\Delta t_1 + \Delta t_2 + \Delta t_3)$$
$$SP2C = 1/(\Delta t_2 + \Delta t_3)$$
$$SP2D = 1/\Delta t_3$$

b. For each mode where disturbance number >0, mode type is 1-8, 14 or 24, and decay code is 2 or 3:

SP2B = 0

SP2C = 0

SP2D = 0

SP3 is a measure of the damping rate of a spontaneous high frequency oscillation. SP3 can vary from 0 (no damping) to 1000, and is assigned a value of 1000 for non-pulsed tests for which no high frequency oscillations are reported. SP3 is evaluated according to the stability code (SP0) and entries on the Instability Mode Data Sheet for the first mode reported as follows:

SP0	Disturbance No.	Decay Code	SP3
1 or 2			0
3		1	$1/\Delta t_3$
3		2 or 3	0
7,8 or 9	0		1000
10			1000

In all other cases, SP3 is not applicable.

SP5 is a measure of the fraction of the total test duration completed prior to the occurrence of a spontaneous high or intermediate frequency oscillation. SP5 can vary from 0 (no spontaneous modes) to 1 (spontaneous mode occurring at start of test). It is evaluated from entries on the Instability Mode Data Sheet as follows:

$$SP5 = 1 - t(n_m)/t_t$$

where $t(n_m)$ is time of occurrence of first spontaneous high or intermediate frequency mode (disturbance number = 0, mode type = 1-8, 14 or 24), and t_t is test duration . If no spontaneous modes occurred, SP5 = 0.

SP6 indicates the occurrence of an induced, high or intermediate frequency oscillation, and is applicable to all pulsed tests. SP6 is 1 for a test where a high or intermediate frequency oscillation is reported as a result of a disturbance, and 0 for other pulsed tests. It is evaluated from entries on the Instability Mode Data Sheet as follows:

a. If a mode is reported where disturbance number >0, and mode type is 1-8, 14 or 24, SP6 = 1.

b. For other pulsed tests (N_d>0), SP6 = 0.

SP7 indicates the occurrence of a spontaneous, first tangential mode, and is applicable to all tests. SP1A is 1 for a test where a spontaneous, first tangential mode is reported, and 0 for all other tests. It is evaluated according to entries on the Instability Mode Data Sheet as follows:

a. If a mode is reported for which disturbance number is 0, harmonic code is 1, mode type code is 3-6, 14 or 24, and mode is a pure mode, SP7 = 1.

b. In all other cases, SP7 = 0.

SP8 indicates the occurrence of an induced, first tangential mode, and is applicable to all pulsed tests. SP8 is 1 for a test where a first tangential mode is reported as a result of a disturbance, and 0 for other pulsed tests. It is evaluated from entries on the Instability Mode Data Sheet as follows:

a. If a mode is reported where disturbance number >0, harmonic code is 1, mode type is 3-6, 14 or 24, and mode is a pure mode, SP8 = 1.

b. For other pulsed tests (N_d>0), SP8 = 0.

SP9 is a measure of the damping rate of an induced, first-tangential oscillation, and is applicable only to tests where such oscillations are reported. SP9 can vary from 0 (no damping) to 1000. If two or more induced, first-tangential modes are reported, SP9 is evaluated for each and assigned the lowest applicable value. It is evaluated from entries on the Instability Mode Data Sheet as follows:

a. For each mode where disturbance number >0, harmonic code is 1, mode type is 3-6, 14, or 24, and the mode is a pure mode:

(1) If decay code is 1, SP9 = $1/\Delta t_3$.

(2) If decay code is 2 or 3, SP9 = 0.

SP10 inidcates the occurrence of an induced, undamped, high or intermediate frequency oscillation, and is applicable to all pulsed tests. SP10 is 1 for a test where an undamped, high or intermediate frequency oscillation is reported as a result of a disturbance, and is 0 for other pulsed tests. It is evaluated from entries on the Instability Mode Data Sheet as follows:

a. If a mode is reported where disturbance number >0, mode type is 1-8, 14, 24, and decay code is 2 or 3, SP10 = 1.

b. For other pulsed tests (N_d>0), SP10 = 0.

SP12 indicates the occurrence of an induced, undamped first-tangential oscillation, and is applicable to all pulsed tests. SP12 is 1 for a test where an undamped, first-tangential oscillation is reported as a result of a disturbance, and is 0 for other pulsed tests. It is evaluated from entries on the Instability Mode Data Sheet as follows:

a. If a mode is reported where disturbance number >0, harmonic code is 1, mode type is 3-6, 14 or 24, mode is a pure mode, and decay code is 2 or 3, SP12 = 1.

b. For other pulsed tests (N_d>0), SP12 = 0.

SP13 indicates the static stability of non-pulsed tests and the dynamic stability of pulsed tests. It has been used only as a means for determining relationships between static and dynamic stability. It is evaluated from other stability parameters as follows:

a. For non-pulsed tests (N_d = 0), SP13 = SP1A

b. For pulsed tests (N_d>0), SP13 = SP10.

APPENDIX F - VARIABLES AND PARAMETERS USED IN REGRESSION EQUATIONS[†]

Symbol	Function of		Defined on Page	Name, Units
BF			115	Baffle parameter
CSE			11	C-star efficiency
D_{of}			105	Average fuel orifice diameter, 1000ths of in.
	N_g		96	Number of element groups
	n_g		96	Element group number
	N_{of}		105	Number of fuel orifices
	$N_{ofe}(n_g)$		96	Number of fuel orifices per element, group n_g
	$N_{eg}(n_g)$		96	Number of elements in group n_g
	$D_{ofg}(n_g)$		96	Average fuel orifice diameter, group n_g, 1000ths of in.
EPA			109	Elements per unit area, in^{-2}
	N_e		105	Number of elements
		N_g	96	Number of element groups
		n_g	96	Element group number
		$N_{eg}(n_g)$	96	Number of elements in group n_g
	A_i		109	Cross-sectional area of chamber, in^2
ER			107	Propellant equivalence ratio
	$OF(c_t)$		99	Ox-fuel ratio, condition c_t
	OF_s		103	Stoichiometric oxidizer-fuel ratio
	c_t		99	Test condition (=0)

[†] For a more complete definition of all variables, together with examples of typical values, please see Reference 2, "Format for the Collection of Liquid Propellant Rocket Combustion Instability Test Data", CPIA Publication No. 149, The Johns Hopkins University, Applied Physics Laboratory, September, 1967.

Symbol	Function of	Defined on Page	Name, Units
F02		115	Propellant combination parameter 2
F03		115	Propellant combination parameter 3
h_b		95	Average baffle blade height, in
IDE_f		106	Fuel injection dist. eccentricity
	$R_{if}(n_a)$	96	Fuel injection distribution as ratio of local fuel injection density (flow rate per unit area) to overall fuel injection density, for area n_a
	n_a	96	Injector area number
	N_a	96	Total number of injector areas
ID_f		106	Fuel injection distribution
	n_a	96	Injector area number
	N_a	96	Total number of injector areas
	$R_{if}(n_a)$	96	Fuel injection distribution as ratio of local fuel injection density (flow rate per unit area) to overall fuel injection density, for area n_a
L_1		93	Length of chamber, in
LD		106	Chamber length-diameter ratio
	L_1	93	Length of chamber, in
	D_1	93	Chamber diameter at injector, in
LD_f		105	Average fuel orifice L/D
	N_g	96	Number of element groups
	n_g	96	Element group number
	N_{of}	105	Number of fuel orifices
	$N_{ofe}(n_g)$	96	Number of fuel orifies per element, group n_g
	$N_{eg}(n_g)$	96	Number of elements in group n_g
	$LD_{fg}(n_g)$	97	Average fuel orifice L/D, group n_g

Symbol	Function of	Defined on Page	Name, Units
LR		115	Liner parameter
MPE		108	Mass flow rate per element at test condition c_t
	$\dot{m}_f(c_t)$	99	Fuel flow rate, condition c_t, lbm/sec
	$\dot{m}_o(c_t)$	99	Ox flow rate, condition c_t, lbm/sec
	N_e	105	Number of elements
	N_g	96	Number of element groups
	n_g	96	Element group number
	$N_{eg}(n_g)$	96	Number of elements in group n_g
	c_t	99	Test condition (=0)
P_{ci}		99	Chamber pressure, injector end, condition c_t, psia
	c_t	99	Test condition (=0)
PE1		115	Principal element type 1
PE2		115	Principal element type 2
R_c		106	Nozzle contraction ratio
	D_2	93	Chamber diameter at nozzle, in
	D_3	93	Nozzle throat diameter, in
SP1A		118	Stability parameter 1A
SP1B		118	Stability parameter 1B
SP10		121	Stability parameter 10
TPVM		109	Modified thrust per unit area, lbf/in^3
	P_{ci} (c_t)	99	Chamber pressure, injector end, condition c_t, psia
	A_t	93	Area of nozzle throat, in^2
	v_c	108	Chamber volume, in^3

Symbol	Function of	Defined on Page	Name, Units
	L_1	93	Length of chamber, in
	L_2	93	Length of chamber plus nozzle entrance, in
	D_1	93	Chamber diameter at injector, in
	D_2	93	Chamber diameter at nozzle, in
	D_3	93	Nozzle throat diameter, in
	D_c	93	Characteristic dimension, non-circular chambers
	c_t	99	Test condition (=0)
V_o		107	Average oxidizer jet velocity, in/sec
	$\dot{m}_o(c_t)$	99	Ox flow rate, condition c_t, lbm/sec
	ρ_o	103	Oxidizer density, lbm/in^3
	$T_{oo}(c_t)$	99	Ox temperature, orifice inlet, condition c_t, °R
	N_g	96	Number of element groups
	n_g	96	Element group number
	$A_{oog}(n_g)$	97	Area of oxidizer orifices, group n_g, in^2
	c_t	99	Test condition (=0)
x_{if}		105	Average fuel impingement distance, in
	N_g	96	Number of element groups
	n_g	96	Element group number
	N_{of}	105	Number of fuel orifices
	$N_{ofe}(n_g)$	96	Number of fuel orifices per element, group n_g
	$N_{eg}\ (n_g)$	96	Number of elements in group n_g
	$x_{ifg}(n_g)$	97	Average fuel impingement distance, group n_g, in

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