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Reliab ity Assessment of Liquid Rocket gines

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INTRODUCTION

The extremely high reliability requirements of NASA space flight vehicles present a challange to those of us interested in reliability assessment. Reliability demonstration via flight tests are out of the question. Ground tests, on the other hand, are not representative of flight condition.

The challange then is one of using ground test to establish a confidence related to flight reliability. A further restriction is that of the contract requirements we of NASA impose for a determination of reliability through assessment.

Although demonstration of propulsion system reliability is less of a problem than that of the vehicle as an entity, the mechanism for assessment is far from simple. Our technique is one of evaluating static firing test data. This paper will deal with various techniques of treatment of such data and associated graphic displays.

CONTRACT REQUIREMENTS

In order to meet the vehicle reliability goals, the engine system reliability is apportioned and contractually stated. For example, a sample required reliability is .99 at a 50% confidence level at the end of qualification testing. At an earlier milestone, Pre-Flight Rating Tests (PFRT), the required reliability is .95 at the 50% level. The contract further specifies a demonstration plan based on the Lloyd & Lipow method[1] to be used to demonstrate achievement of these reliability goals. In addition, a monthly report is required to show achievement and progress. Both the reliability goals and the demonstration plan are negotiated between NASA and the contractor.

PURPOSE OF ASSESSMENT

Monthly assessment and reporting of reliability levels to the negotiated demonstration procedure is necessary for the contractor to fulfill his contract obligations. In addition, the contractor's reliability staff is expected to provide to their design department a multitude of related data from the assessment such as:

a. identity of components of high failure rates

b. performance tolerances & repeatability

c. contributions of facilities and human factors to test failures.

Although the contractual assessment program is useful, it does not of itself fulfill all of the needs of NASA for program assessment of reliability. In particular, no real time data for program management is provided by this reporting system. Under the circumstances, we began to examine the assessment method to determine if other methods of scorekeeping might provide a more fruitful and useful (to management) tool for identifying current reliability.

Furthermore, we experimented with data display charts to try to find graphic means of giving our top management quick looks at program status.

THE CURRENT DEMONSTRATION PROCEDURE

The techniques used by most aerospace propulsion industries are modifications of the Lloyd and Lipow method. This consists of taking all static firing test data whether from development tests or production engines and using attribute grading on a selected sample. The selection excludes engines having experimental subsystems, of an untrimmed condition, or those where the test objectives are beyond an ambient environment.

To obtain an unbiased estimate of reliability, a weighting factor is applied based on run duration. This also increases sample size by allowing the statistic to include tests simulating only a part of the performance requirement.

There is considerable merit in this approach to assessment. It makes use of data from a normal development and qualification test program without requiring additional expense for special reliability demonstration tests. It also provides a measure of expected inflight reliability without flight tests.

There are several shortcomings to the current procedure. These are based principally on the problem of quantity of tests and how to best utilize the test results without biasing the estimated reliability. For the larger engine, the total number of tests to be conducted prior to qualification for flight missions is less than 1,000. Even demonstrating the reliability goals at the 50% confidence limit is a difficult task because of the low yield of tests useful in the evaluation. For example the following are samples of yields in current NASA programs:

Engine	a. a block of static firing tests	b. tests applicable for reliability assessment from block	b/a
RL10	1071	453	42.3%
F-1	293	240	82%
H-1	565	356	63%

Variations in yield are primarily due to differences in the performance tolerance limits.

Two additional shortcomings of the present system occur: first at the inception of the test program and again after the PFRT milestone. In the former case, almost all tests are exclusions; in the latter case there is so little change in the reliability trend line that the scorekeeping fails to provide a measure of change.

Other problems in assessment are those related to determination of reliability for a mission requiring engine restarting or throttling. In any event the reliability of production engines, development engines, and combinations of both provide different numbers.

NEW TECHNIQUES

One resolution to the job of assessment is that of grading (by attributes) of all tests against the achieved test objectives. In so doing, a growth curve then becomes evident. A second resolution for the problem of the stable, high reliability, portion of the demonstration program is that of grading by variables to show probability of meeting design criteria as a deviation from the mean values. This technique is more difficult to develop since the forms of the performance level distributions are unknown. Using the three main parameters of specific impulse, thrust, and mixture ratio, the distribution appears to be normal. Reliability of conformance to specification limits may then be estimated from the noncentral-t distribution.[2,3]

A third, less explored method is that related to overstress testing and use of such test data to establish safety margins. Reliability can then be estimated from safety margins as per the technique developed by the Army Missile Command and NASA.[4,5,6]

RESULTS OF ANALYSIS

Case I: A general look at all tests.

The first step in developing better techniques was to examine the over-all test program. For a particular engine program, all tests of development and production engines are plotted sequentially with time. The ordinate represents the run duration. Engines are color coded by engine number. Reliability trend lines can then be overlaid on the base chart on a probability scale by any of the scorekeeping techniques. This form of presentation identifies the engine, the run duration, the test period, and the test frequencies.

Case II: Attribute grading of test objectives.

For a new development program where virtually no tests were declarable for the Lloyd-Lipow technique in the grading, the test objectives were segregated into the following:

Objective	Weight
Gas Tubine Operation	.20
Turbopump Operation	.20
Spark and Ignition	.20
Transition	.20
Main Stage	.20

A growth curve was then plotted which is related to reliability though not correlated to a probability figure.

Case III: Variables

In the case where reliability is close enough to 1.0 to be virtually unchanged by the Lloyd-Lipow method, a measure of the successful program can be the run-to-run variation of certain performance parameters. These may include thrust level attained, mixture ratio, and specific impulse. This is, in essence a performance repeatability assessment. The reliability, then, may be defined as the probability of performing within specification limits. The form of the distribution for a particular engine must be determined from early test results.[3]

Case IV:

As an example of the Limit Testing assessment, it is possible to collect the tests excluded by the Lloyd-Lipow method due to overstress, overage components, or extra-environmental stresses. These can be analyzed with the intent of drawing valid conclusions as to criticality of the failure mode, safety margins in the design, and performance degradation.

RELATED STUDIES

Reliability demonstration is an important facit of a reliability program. However, a go/no-go answer regarding whether reliability goals have been met would of itself be of small value in project management. Of more use to management and engineering are the related studies of the test program. Some of these are as follows:

1. The rate of testing. An analysis to determine test facility needs.

2. Malfunction frequency of occurrence and cumulative malfunction cost.

3. Unit cost per static firing test.

SUMMARY

Reliability assessment of NASA development programs is essential in order to provide information for management decisions. Although a great effort has been expended over the years to standardize in scorekeeping techniques, satisfactory methods are not yet available. For rocket engines, the technique developed by Lloyd and Lipow for evaluating static firing tests has been widely implemented. However, shortcomings of their system makes it mandatory for NASA to investigate better techniques. The most promising approaches are by using test objectives as a criteria, by comparing performance variables data on a probability of conformance to specification limits, or by special treatment of overstress test results.

REFERENCES

1. "Reliability: Management, Methods, and Mathematics;" Lloyd & Lipow, Prentice Hall, Chapter 16.
2. "Reliability of Compliance with One-sided Specification Limits When Data is Normally Distributed," ARGMA report TR 2BIR, September 1961.
3. Special study in progress by Pratt & Whitney Aircraft at Florida Research and Development Center by Mr. Dennis Nickle.
4. "Reliability Through Safety Margins," U. S. Army Ordnance Missile Command, October 1958.
5. "Estimating Reliability as a Function of Stress/Strength Data," ARGMA, November 1961.
6. Special study in progress by Marshall Space Flight Center on reliability and confidence levels associated with safety margins by Messrs. Ray Heathcock and E. L. Bombara.

APPENDIX

NOTE: Reliability growth curves are omitted for security reasons.

FIGURE 1

The data plot shows a segment of 300 RL10 static firings during the mid period of development. Each firing is represented by one vertical bar of height equal to run duration against a non-linear scaled ordinate. The non-linear scale was used so that the high failure region of ignition and thrust buildup would be more prominent. Production engines and Development engines are color coded. The abcissa is time based showing tests sequentially by month. Zero time is noted above the base line to indicate tests of ignition only without thrust buildup.

FIGURE 2

The same portion of the RL10 test program presented in Figure 1 is shown with only tests declared for reliability. Exclusions are those by Lloyd and Lipow rules as being engines of experimental components, overage components, limits tests, or failures due to facility or human error.

FIGURE 3

The same portion of the RL10 test program presented in Figure 1 is shown with only overstress and limits tests plotted. Each stress condition (time, vibration, temperature conditioning) can be related to the ambient strain to be imposed during flight. A safety margin or safety factor can then be determined and a reliability estimate made of survival probability to each condition.

FIGURE 4

All static firing tests of the J-2 engine are plotted with each of the eight development engines color coded. Run duration is plotted against the time base as in Figure 1.

FIGURE 5

Figure 4 is shown with the trend line of growth against meeting test objectives as per Case II previously discussed. The growth curve is a 20 round moving average of opportunities x success of each of 5 test objectives on the zero to 1 probability scale.

FIGURE 6

Figure 4 is shown with each test run extended to indicate declared run duration. Intended duration vs. actual duration is an additional test objective success criteria.

FIGURE 7

The rate of testing (tests per month) of each of four NASA rocket engine development programs are shown. Test rate is higher for the smaller engines. The data plotted shows that the test rate did not increase appreciably during the report period for any of these programs. Neither facility nor hardware limitations affected the test rate.

FIGURE 8

Performance repeatability is not a test objective at program inception nor are the engines usually trimmed (mixture ratio adjusted). However, run-to-run thrust variability, as plotted of each engine, is a measurable quantity that merits our interest.

FIGURE 9

Mathematic modeling of systems are a requirement in most NASA development contracts. The prediction model is based on generic failure rate data, a priori, of similar components. For liquid rocket engines, failure rates are rarely identical for the same component in different engines. More useful in assessment are failure rates determined from malfunctions in a particular engine configuration. Figure 9 is a plot of failure recurrences and provides an indication or critical areas.

RL 10 A-3 STATIC TESTS

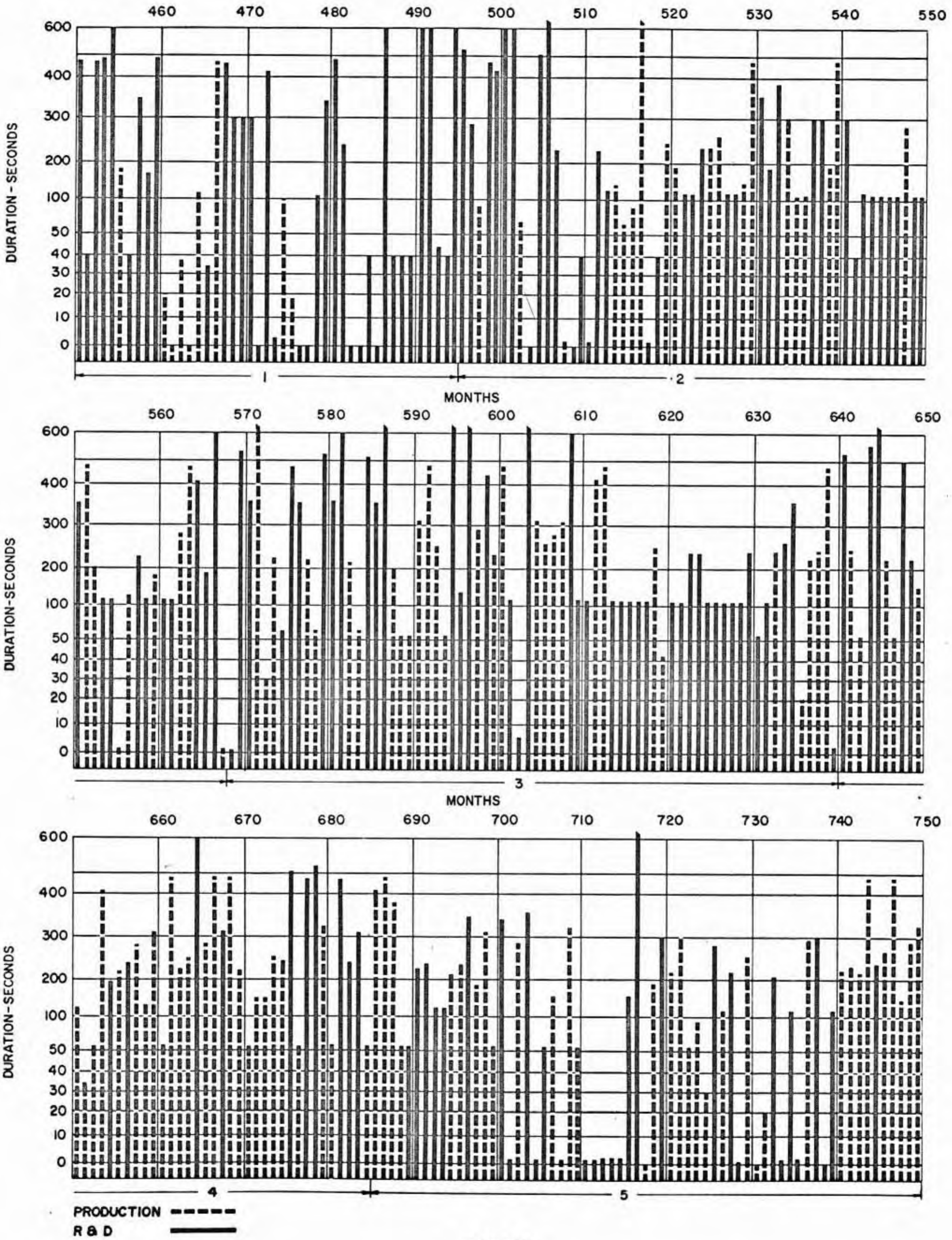


FIGURE I

RELIABILITY ASSESSMENT
RL 10 A-3 STATIC TESTS

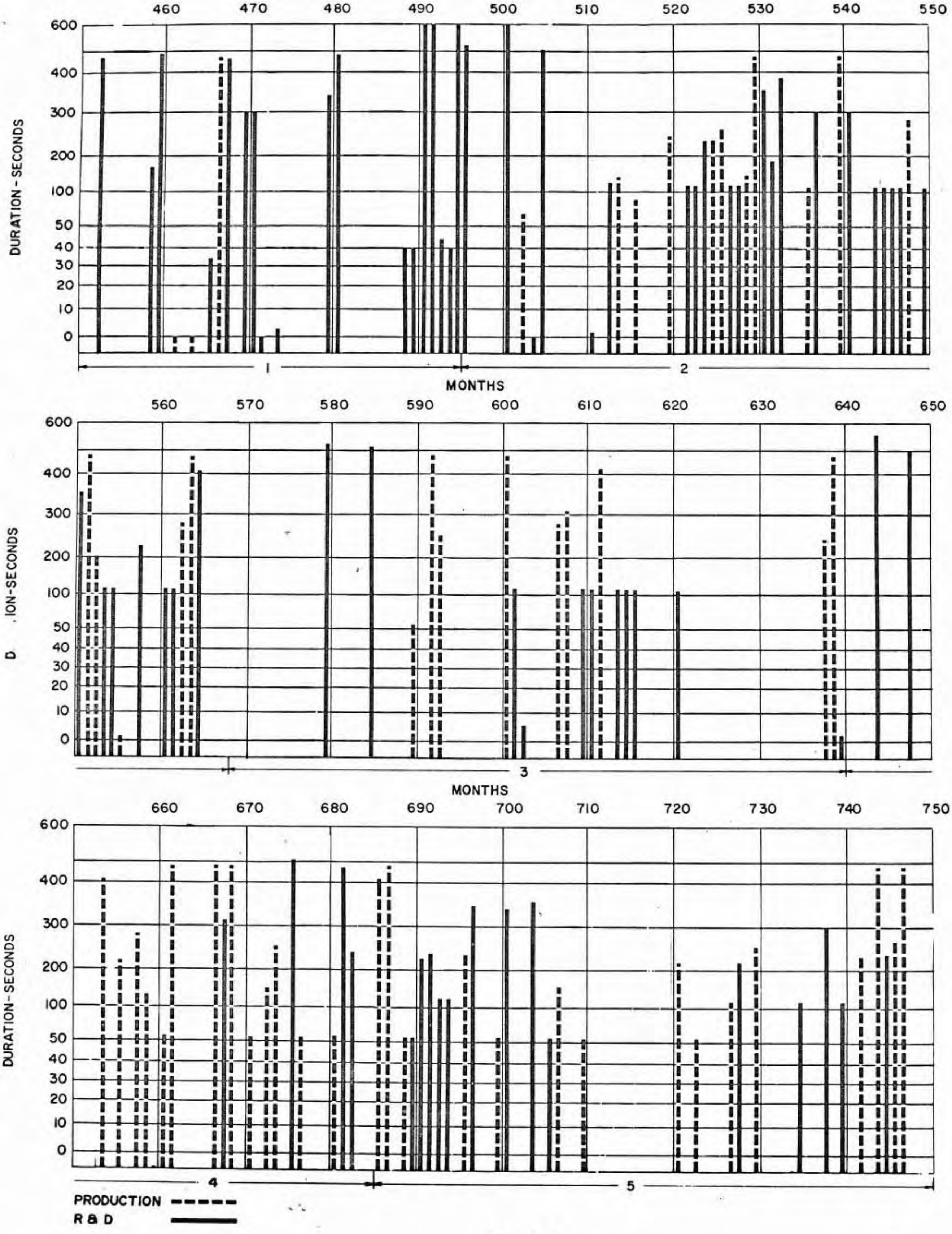


FIGURE 2

OVERSTRESSED
RL 10 A-3 STATIC TESTS

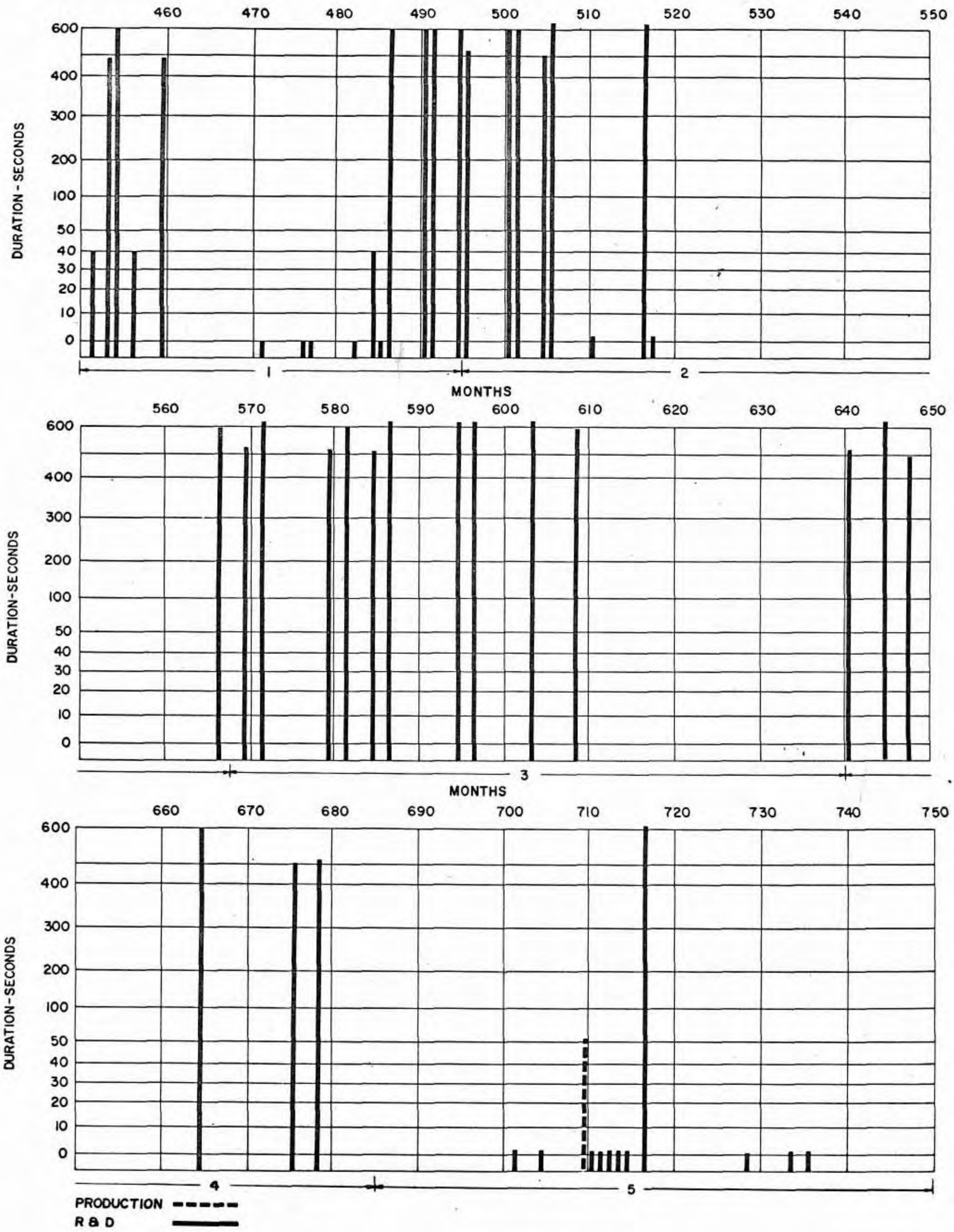


FIGURE 3

J-2 STATIC TESTS

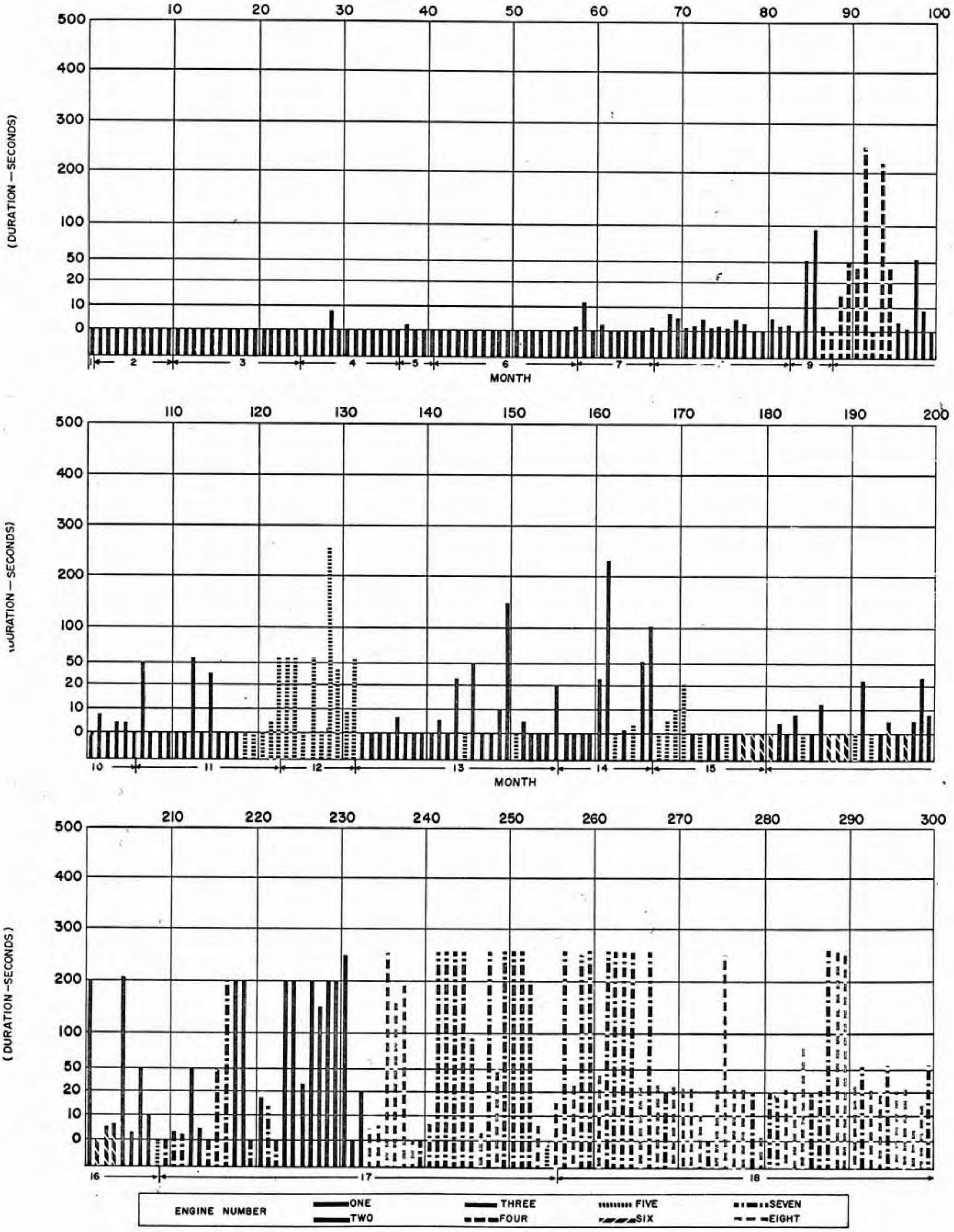


FIGURE 4

J-2 STATIC TESTS

TEST OBJECTIVES

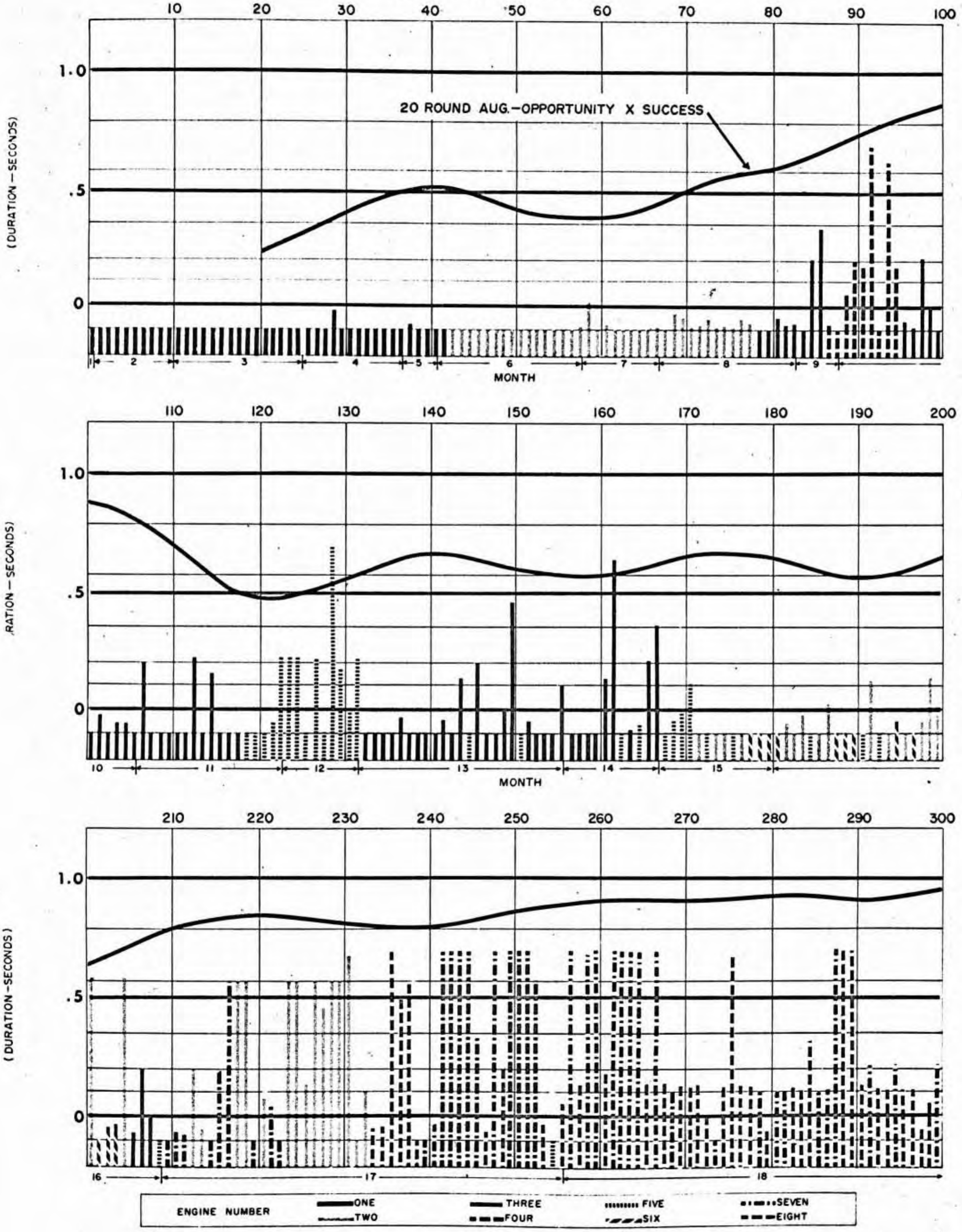
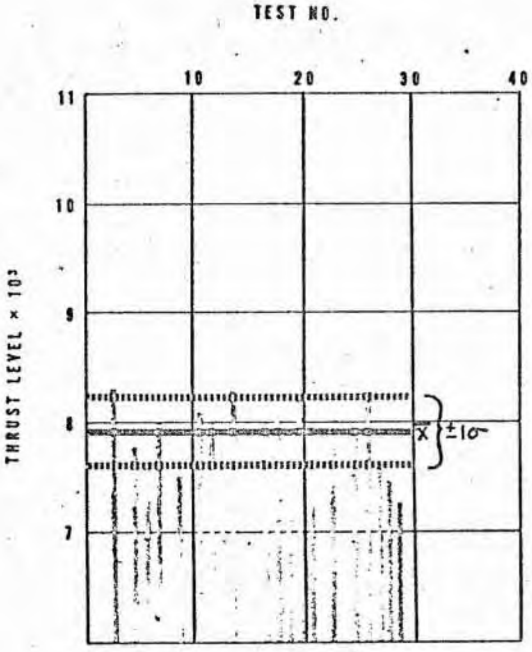


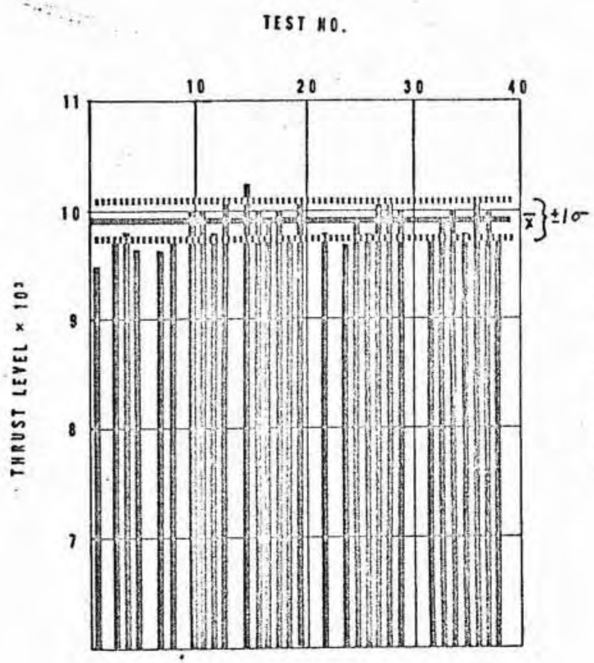
FIGURE 5

HYPOTHETICAL R & D 10K ENGINE

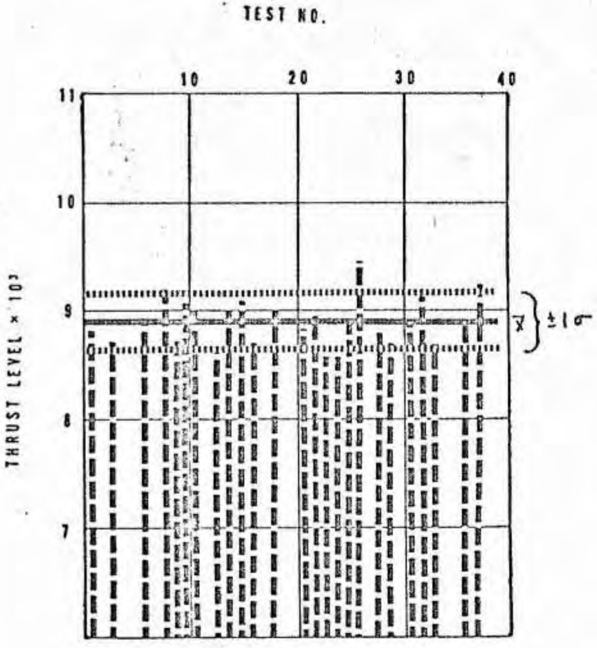
THRUST VARIABILITY



ENGINE # 1



ENGINE # 2



ENGINE # 3

STATIC FIRING

ALL ENGINES

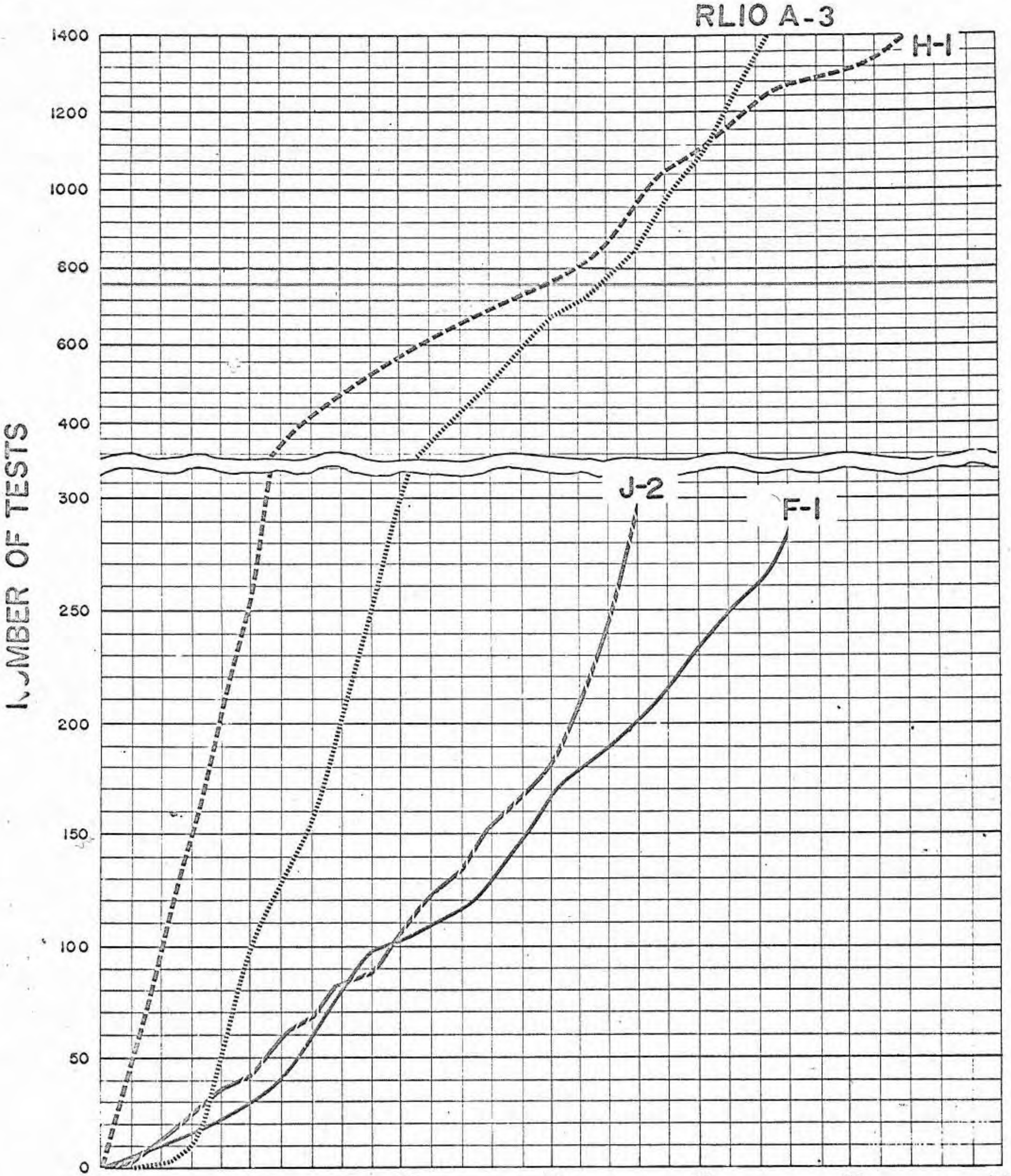


FIGURE 7