MSC-00154

MSC-00154

144

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA PROGRAM APOLLO WORKING PAPER

A STATISTICAL LOADS STUDY OF S-IC CONTROL ENGINE-OUT CONDITIONS ON THE APOLLO SATURN V VEHICLE

MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
September 25, 1969

MSC-00154

NASA PROGRAM APOLLO WORKING PAPER

A STATISTICAL LOADS STUDY OF S-IC CONTROL ENGINE-OUT CONDITIONS ON THE APOLLO SATURN V VEHICLE

PREPARED BY

May T. Meadows

May T. Meadows
AST, Flight Loads Section

AUTHORIZED FOR DISTRIBUTION

Warren Gillespie, Jr.

for Maxime A. Faget
Director of Engineering and Development

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
September 25, 1969

CONTENTS

FIGURES

A STATISTICAL LOADS STUDY OF S-IC CONTROL ENGINE-OUT CONDITIONS ON THE APOLLO SATURN V VEHICLE

By May T. Meadows

SUMMARY

A statistical loads study that was used to evaluate the adequacy of the spacecraft structure for one Saturn IC control engine-out conditions on the Apollo-Saturn V vehicle is presented. The spacecraft was not designed for these conditions. The Monte Carlo approach is used to obtain the probability distribution for the maximum bending moment at the command module/service module interface, which is the most critical structural location. The results of the study show that the command module/service module interface has a factor of safety of 1.2 for a 4.2-sigma loading condition. Because this is considered an adequate factor of safety for such a low-probability loading condition, the existing Apollo spacecraft structure is judged acceptable for Saturn IC control engine-out conditions.

INTRODUCTION

Engine-out failure conditions were not considered in the original design of the Apollo spacecraft. Later calculations showed that "worse-on-worse" engine-out loads significantly exceeded the capability of the Apollo command module/service module (CM/SM) interface structure. Extensive modifications would have been required to allow the structure to withstand these worst-case loads. However, because the occurrence of such worst-case load conditions appeared to be considerably remote, it was first considered desirable to evaluate the probability of their occurrence. The results could then be used to establish the extent of any structural redesign. Therefore, it is the intent of this paper to determine a rational set of loads for the Saturn IC (S-IC) control engine-out conditions and, thereby, assess the adequacy of the existing Apollo spacecraft structure.

DISCUSSION

An S-IC engine shutdown can be caused by a slow mechanical failure, an electrical failure, or an explosive failure. In the case of a slow mechanical failure, a safe shutdown occurs when the Thrust OK Pressure Switch (TOPS) senses a pressure loss in the chamber. The TOPS cuts off the engine only after it drops to a preset pressure level, which is about 80 percent of a full thrusting engine. The probability of such an event is 0.00044 (ref. 1). Although a TOPS-type shutdown is considered a safe type of failure, it could produce large loads.

An electrical failure in any of the engine components results in an engine decaying from its full thrust value and, therefore, has a greater decay rate than the TOPS shutdown. However, this type of failure has a probability of only 0.000005 (ref. 1).

Catastrophic failure of propulsion system components can occur, with resulting loads grossly exceeding spacecraft capability. This type of failure has a probability of 0.000061 (ref. 1), which is approximately seven times less likely than the TOPS shutdown.

Since the TOPS-type shutdown is by far the most probable way an engine will shutdown and because the other failure modes are very unlikely to occur, only the TOPS-type shutdowns are considered in this study.

The determination of vehicle loads due to an engine-out on a launch vehicle during boost is complicated by the numerous time-varying parameters involved. For example, the time history of thrust for the failed engine depends on a number of factors such as rate of thrust decay, type of shutdown, and time of failure. Also, because wind profiles have a large daily variance, any parametric study combining wind response and loss of thrust of one outboard engine would entail extensive calculations.

The manner in which these parameters are combined is important. Discrete cases could be calculated based on judgement from the entire range of possible input parameters. However, there would be no probability level associated with the loads, and experience may well be insufficient in selecting these discrete cases.

A Monte Carlo statistical analysis provides a method of obtaining the loads associated with a given probability level. This is a method of calculating loads based on values chosen randomly from the various parameters represented by some type of probability distribution so that completely random cases are generated for calculating the loads. These loads are analyzed satistically to obtain a probability of occurrence corresponding to each load.

ANALYSIS

The initial S-IC engine-out calculations were based on the engine decaying from its full thrust level with a maximum thrust-decay rate. At the same time, the peak wind magnitudes (both shear and direction) were imposed on the vehicle. This worse-on-worse failure condition resulted in excessively high loads. The probability of all these extreme conditions occurring simultaneously is extremely low, but no logical method of combining these parameters could be performed until sufficient information on the performance of the thrust decay was available. Results of recent static engine tests conducted by Marshall Space Flight Center (ref. 2) now provide statistical data on the shutdown of an S-IC engine.

Because the loads resulting from an engine shutdown vary considerably according to the combinations of thrust level cut-off, thrust decay rate, flight time, and wind magnitude and direction, some method of combining these parameters is needed for a conclusive study. The Monte Carlo approach, in which the input data are selected at random either from direct measurements or from statistical distribution, was used in this study. A random number generator digital program was used to make the selection from the specified distributions. All parameters were assumed to be statistically independent. The parameters with their associated distribution are as follows:

1. Thrust OK pressure cut-off level. (Static tests show this to have a normal (Gaussian) distribution.)

2. Thrust decay rate of cut-off engine. (Static tests show this to have a normal distribution.)

3. Time of engine loss. (A uniform distribution was used since the engine failure could occur at any time from lift-off until separation.)

4. Position of failed engine. (A uniform distribution was used since any of the four control engines is equally likely to fail.)

5. Wind profile. (A uniform distribution was used for the quarter of the year with the highest winds.)

The wind profiles were selected from daily samples measured at Cape Kennedy during the first 3 months of 1966 and 1967, which provided sufficient data for performing a Monte Carlo type of analysis. The most severe winds occur during the first quarter of the year. The daily wind profiles were considered to constitute a uniform distribution and, thus, were considered equally likely to occur. The complete wind profile for each sample was used in a loads digital computer program, FALL, which computes the lateral loads during flight. The program has time-varying coefficients for the complete boost trajectory and includes the structural dynamic characteristics, linear and nonlinear aerodynamics, and the launch vehicle control system. Trajectory data for the Apollo 9 mission were used in this study and were obtained from reference 3. Output consisted of the vehicle responses and loads as a function of time for all vehicle stations, including the most critical structural location, the CM/SM interface.

Winds at Cape Kennedy are predominately from the west during the high-wind months and could increase or decrease the loads depending on which one of the four control engines fails. Figure 1 shows the location of the four control engines in the standard Apollo coordinate system. With the number 4 engine out, a west wind could increase the loads, but the same wind would tend to decrease the loads with the number 2 engine out.

CALCULATIONS

Random values of the input parameters, which were considered mutually independent, were generated by the computer program Random Input Generator (RIG) for 300 cases. For a 3-sigma confidence limit, these 300 cases are sufficient to predict a load which will not be exceeded 97 percent of the time. These results are presented in figure 2 and show that the maximum bending moment will not exceed 4.24×10^6 in.-lb 97 percent of the time (for the most critical location, the CM/SM interface). In a static structural test, this interface was tested to 5.0×10^6 in.-lb before failure.

The probability of losing one S-IC control engine that would be sensed by the TOPS is 0.00044. Thus, the probability of having a load greater than 4.24×10^6 in.-lb due to a TOPS engine failure for a launch during the first 3 months is $0.00044 \times 0.03 = 0.000013$. The CM/SM interface bending moment versus probability is presented on figure 3.

CONCLUDING REMARKS

The Apollo spacecraft was not designed for Saturn-IC engine-out conditions. This study assesses the adequacy of the existing structure for these conditions. The most probable way a Saturn-IC engine will lose thrust is by a slow failure that would be sensed by the Thrust OK Pressure Switch. A Monte Carlo analysis of Thrust OK Pressure Switch shutdowns shows that the probability of having a bending moment greater than 4.24×10^6 in.-lb at the command module/service module interface is 0.000013 or 4.2 sigma. This interface was tested to 5.0×10^6 in.-lb before it failed. Thus, the existing Apollo spacecraft structure has approximately a 1.2 factor of safety for a 4.2-sigma loading condition, which is considered an adequate factor of safety for such a low-probability loading condition. Therefore, the existing Apollo spacecraft structure is judged adequate for the one Saturn-IC control engine-out conditions.

REFERENCES

1. Anon.: Probability of an S-IC503 Stage Outboard Engine Premature Shutdown. Memorandum R-P and VE-DIR-68-741, MSFC, Nov. 15, 1968.

2. Anon.: Launch Vehicle to Spacecraft Functional Requirements. Interface Control Document No. 13M07083, MSFC, July 8, 1968.

3. Anon.: Saturn V AS-504 Launch Vehicle Reference Trajectory. Boeing Document No. 05-15481-1, May 15, 1967.

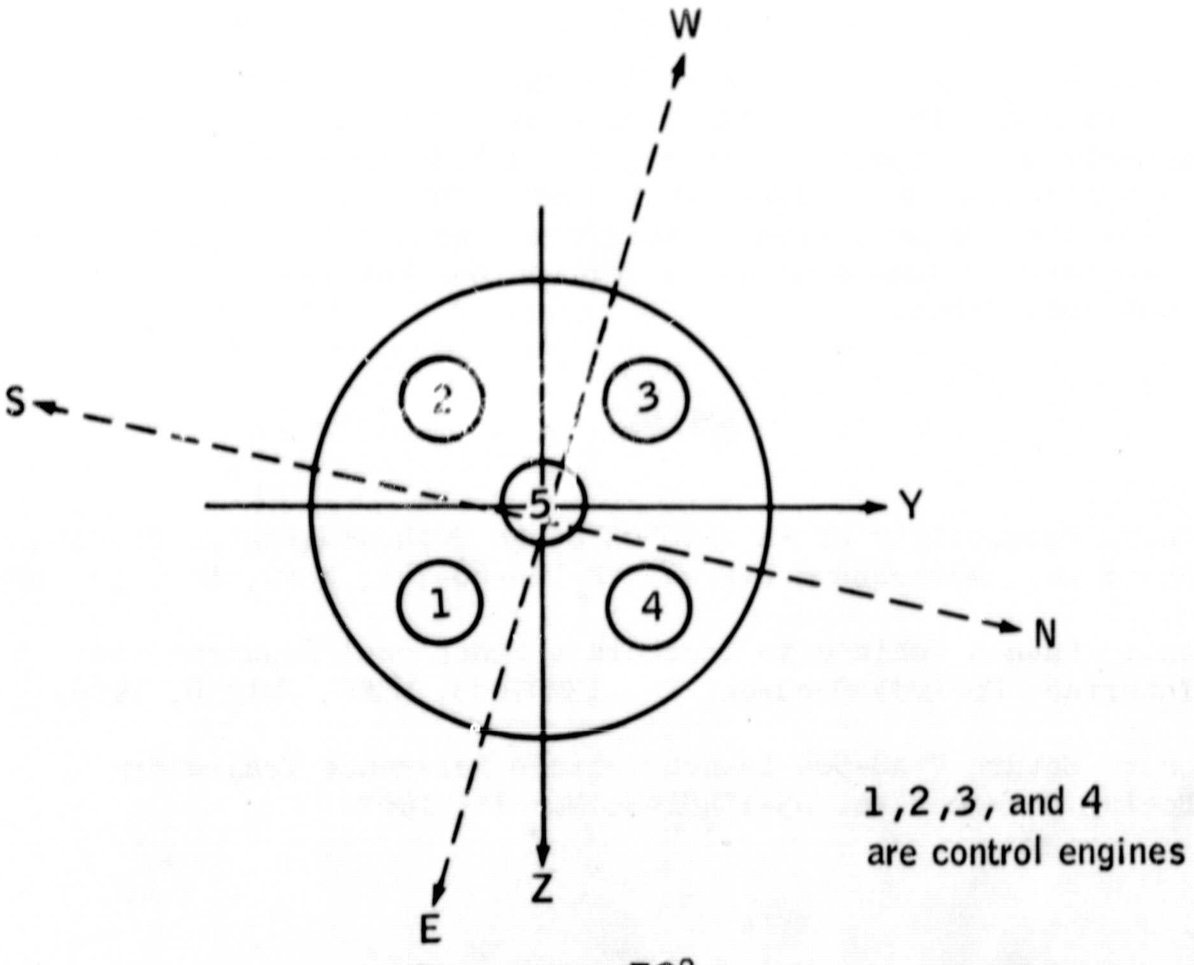

Figure 1.- Saturn IC engine layout showing relation of control engines to wind direction.

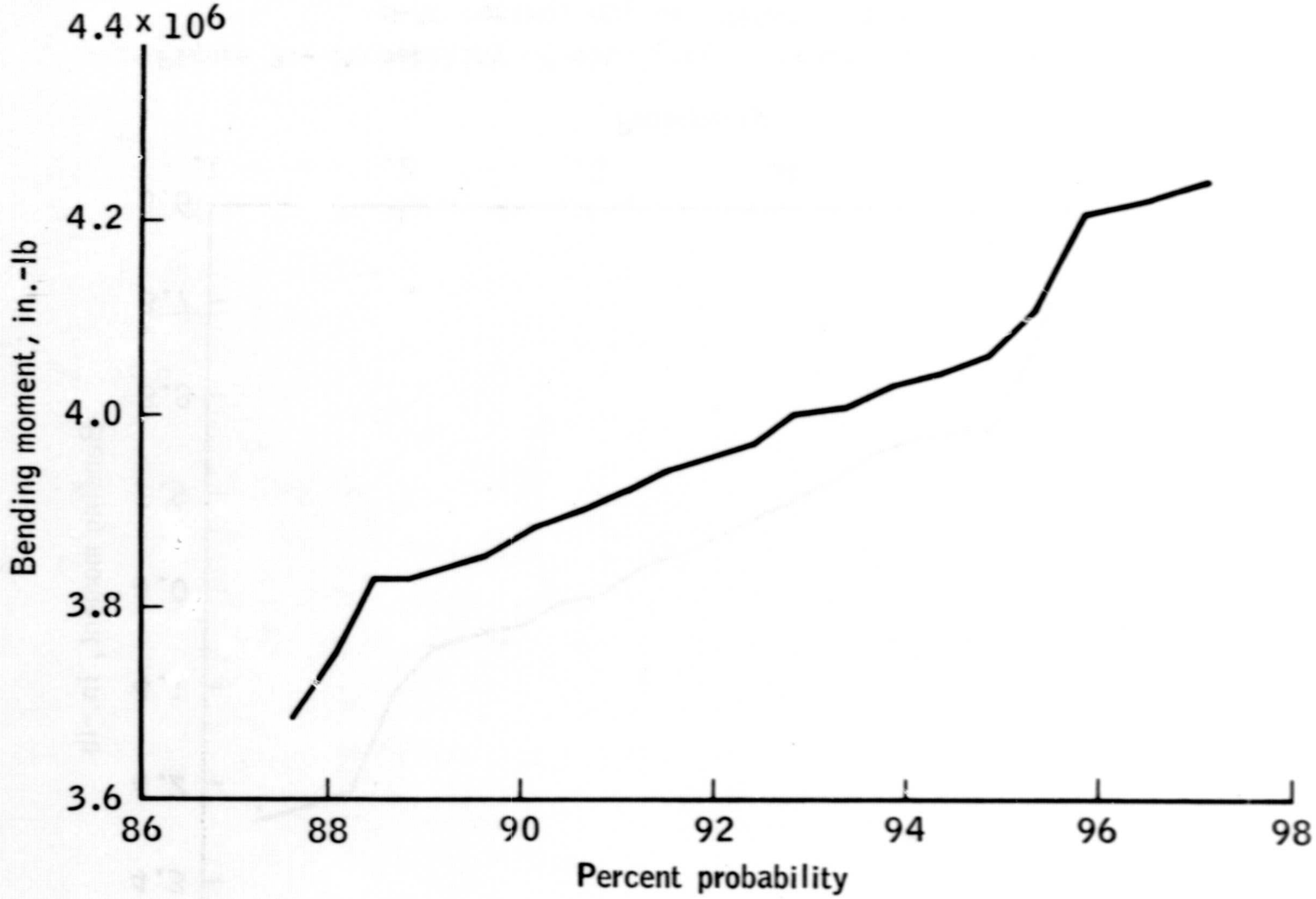

Figure 2.- Percent probability that a bending moment will not be exceeded if an S-IC control engine has failed (CM/SM interface).

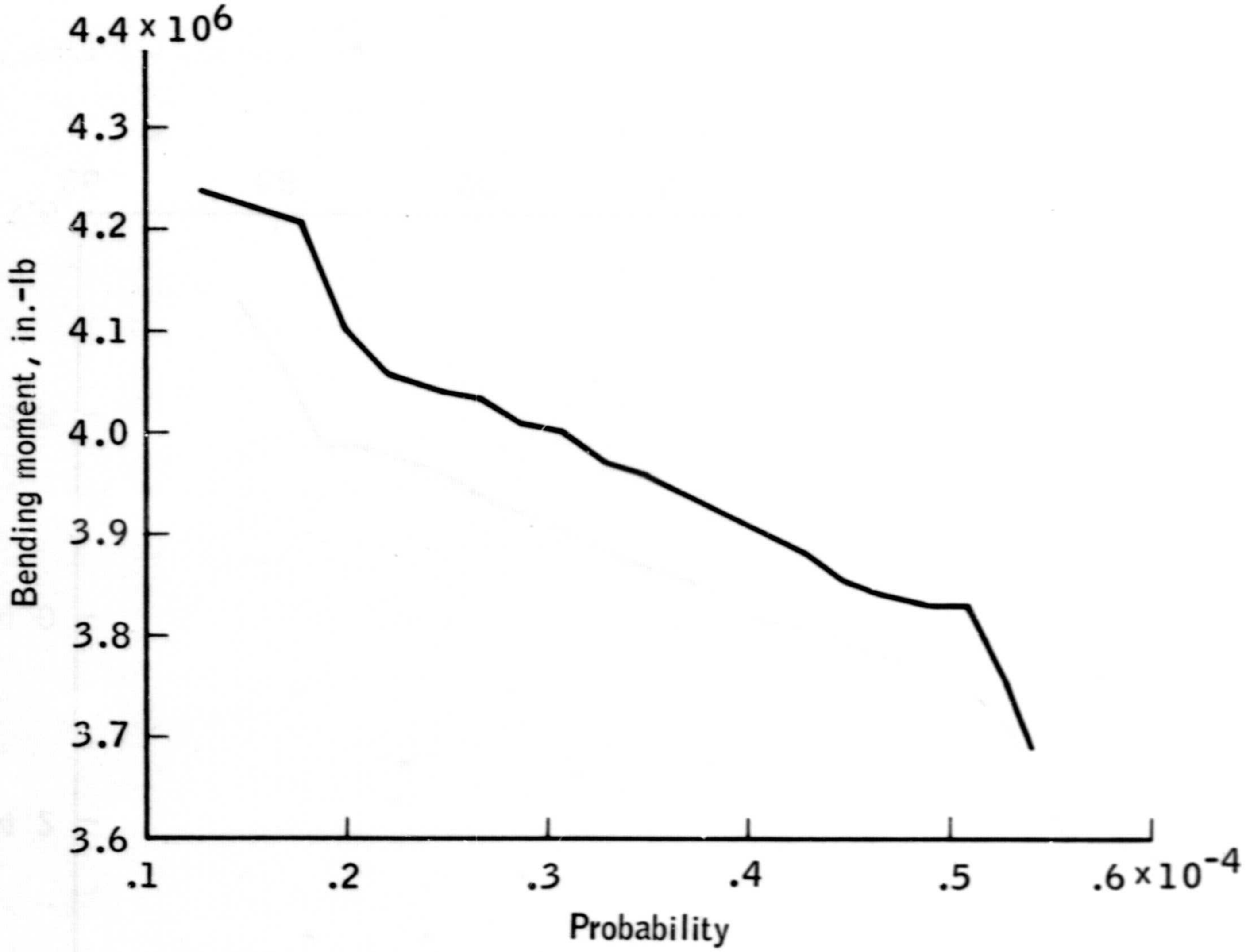

Figure 3.- Probability of obtaining a bending moment due to loss of an S-IC control engine (CM/SM interface).