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SPECIAL TECHNICAL REPORT NO. 13

THE RELIABILITY OF THE ALL-UP CONCEPT

15 June 1964

Prepared for
GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama
Under Contract NAS8-11087

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by
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TABLE OF CONTENTS

Page

1. INTRODUCTION 1

2. CONCLUSIONS AND RECOMMENDATIONS 2

2.1 Conclusions 2
2.2 Recommendations 3

3. DISCUSSION 4

3.1 The All-Up Concept 4
3.2 Reliability Prediction 5
3.3 Design Maturity 5
3.4 Adjusted Prediction 9
3.5 Engine-Out Capability 9
3.6 Past History 13

4. IMPLEMENTATION OF THE ALL-UP CONCEPT 15

4.1 General 15
4.2 Test Information 15
4.3 System Availability 15
4.4 Prelaunch Test and Checkout 17
4.5 Overall Approach 18

APPENDIX A: APPLICATION OF DESIGN MATURITY VALUES 19

1. INTRODUCTION

The Saturn/Apollo Systems Office at the George C. Marshall Space Flight Center (MSFC) requested ARINC Research Corporation to make a brief study of the reliability aspects of the All-Up concept. Under the requirements of Task 294-02 of Contract NAS8-11087, the study included a comparison between the reliability of the first Saturn V vehicle if All-Up, and its reliability with dummy upper stages.

The All-Up concept may be described as the concept of conducting the Saturn V R&D launch-vehicle program without the use of dummy stages. In addition to having a live S-IC stage, all Saturn V launches starting with SA-501 would also have a live S-II second stage, a live S-IVB third stage, live interstages, a complete Instrument Unit, and a live (but unmanned) Apollo capsule.

This study was undertaken as an investigation of the effect of the All-Up concept on the success probability of the initial Saturn V flights. It consisted primarily of completing a preliminary reliability prediction of the Saturn V stages and reviewing data from previous launches. This report presents the results of the reliability prediction and unclassified results from the study of previous launches.* Related classified results from the study of previous launches will be given in oral presentations.

In the course of the study, several approaches to implementation of the All-Up concept were considered. This report discusses these approaches, and presents two recommendations for implementation.

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* With the exception of the additional reliability prediction for the Saturn V stages, this report is identical to a previously submitted letter report (dated 25 March 1964).

2. CONCLUSIONS AND RECOMMENDATIONS

2.1 Conclusions

During the course of this reliability study, three interdependent conclusions were reached:

(1) The predicted reliability for an All-Up SA-501 Saturn V vehicle was 0.497 with no engine-out capability*, and 0.682 with one-engine-out capability. The predictions for the SA-501 vehicle with only a live S-IC stage and a live Instrument Unit were 0.921 with no engine-out capability, and 0.932 with one-engine-out capability.

(2) One-engine-out capability would effect a significant increase in the reliability of all possible configurations of the SA-501 vehicle.

(3) Benefits may be derived from the All-Up concept when it is implemented to any one of various degrees. However, conclusions 1 and 2 do not constitute a basis for deciding the optimum degree of implementation for initial flights. Rather, this decision must be based on a study of the probable amount of test information to be obtained, the probable launch date, and the probable status of the individual systems.

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* See pages 9-12 for a description of this capability.

2.2 Recommendations

On the basis of the above conclusions, two recommendations are made for implementation of the All-Up concept:

(1) Incorporate one-engine-out capability on the S-IC and S-II stages for initial Saturn V flights, and plan the flights to be compatible with thrust produced from only four engines in each stage.

(2) Develop a continuing surveillance program to determine, periodically, the optimum configuration for each Saturn V flight. This determination should be based on: the probable amount of test information expected from each system, the probable launch date (considering prelaunch- and checkout-time requirements), and the availability and probable status of the individual systems.

3. DISCUSSION

3.1 The All-Up Concept

The All-Up concept may be simply described as the concept of conducting the Saturn V R&D launch-vehicle program without the use of dummy stages. In addition to having a live S-IC stage, all Saturn V launches starting with SA-501 would also have a live S-II second stage, a live S-IVB third stage, live interstages, a complete Instrument Unit, and a live (but unmanned) Apollo capsule.

This concept has considerable merit because it provides for the earliest possible flight-testing of all the systems of the Apollo mission in their flight configuration and environment. Early flight-testing has two advantages:

(1) Successful checkout of hardware would bring the achievement of a successful Apollo mission much nearer in time.

(2) The discovery of major flaws in the design would allow the longest possible time for correction.

However, these two advantages are accompanied by two possible disadvantages:

(1) The difficulties involved in concurrently preparing several new systems for launch may significantly delay the SA-501 schedule, thus causing delay even for those systems actually test-ready on schedule.

(2) A malfunction in one of the systems may abort a portion or all of the flight, thereby defeating the objectives of the All-Up concept.

Thus, because of this balance of advantages and disadvantages, the procedure used to decide whether or not to implement the All-Up concept is a classical example of trade-offs.

The major effort in this study was directed at evaluating the probability of occurrence of the second disadvantage, i.e., occurrence of a malfunction that could cause catastrophic loss of an entire mission. ARINC Research utilized two approaches in applying data from previous experience. The first approach was to compare the reliability prediction for an All-Up configuration with the predictions for each of several partially up configurations (S-IC and dummies). The second approach was to study the flight records for previous launches to determine any significant trends in reliability growth (design maturity) and differences between the reliabilities of single and multi-stage launches. The following sections will discuss the two approaches and the results they produced.

3.2 Reliability Prediction

A preliminary prediction of the Saturn V vehicle has just been completed by ARINC Research under a separate task and is being prepared as Special Technical Report No. 16. Table 1 presents a summary of the predictions for the Saturn V stages. These values are based on the assumption of a mature design.

3.3 Design Maturity

The degree of initial design maturity is a function of several design factors. Among the more important ones are: (1) the flight experience of the design and of similar designs, (2) the prior experience of the design group, (3) the quality of the reliability program, and (4) the advances in the state of the art required by the design specifications.

TABLE 1

PRELIMINARY RELIABILITY PREDICTIONS FOR SATURN V STAGES AND VARIOUS LIVE-STAGE SA-501 CONFIGURATIONS

Stage or Configuration	Predicted Reliability	
	No Engine-Out Capability	One-Engine-Out Capability* (S-IC, S-II)
Stage		
S-IC	0.977	0.985
S-II	0.800	0.907
S-IVB	0.899	0.899
Instrument Unit (IU)	0.957	0.957
Configuration		
S-IC, IU	0.935	0.943
S-IC, S-II, IU	0.748	0.855
S-IC, S-II, S-IVB, IU	0.672	0.769
S-IC, S-IVB, IU	0.841	0.847

* Values based on assumed mature design.

The S-I stage is an example of early design maturity. Much of the detailed design is derived from earlier rockets, particularly Redstone and Jupiter. The design group is well experienced, and the reliability program, although informal, is comprehensive. The most significant advance in the state of the art is represented by the cluster technique.

The S-IV stage is considered to be lower in design maturity than the S-I stage. Some of the reasons for this are: the unusual nature of the dual cryogenic propulsion system (in spite of the advanced state of development of the RL-10 engines); the rudimentary nature of the S-IV reliability program; and the various problems encountered to date in the S-IV development program. Although the first S-IV stage flight was a success, it was immediately preceded by a catastrophic explosion of the All Systems Test Vehicle, which was caused by a valve malfunction. Other major failures may well occur before the development or "debugging" process is completed.

The predicted reliabilities in Table 1 were calculated by using historical data from designs that had reached maturity. Early design problems were corrected, and the systems were thoroughly "debugged" before the data were compiled. However, for the initial flights of the Saturn V, the stages cannot be expected to have reached a high level of design maturity. Failures can be expected to result from design flaws that remain undetected because of: inability to duplicate the environments, test procedures that do not include all contingencies, or unanticipated interactions between components and systems. In an attempt to compensate for the design immaturity of the Saturn V stages for the initial launches, ARINC Research assigned a design maturity value for each stage. These values are based on the characteristics listed in Table 2, and are used for the purpose of modifying the prediction values to make them more nearly representative of the initial launches.

TABLE 2

DESIGN-MATURITY CHARACTERISTICS OF SATURN V STAGES

Stage	Design	Manufacturer	Engines	Assigned Value of Design Maturity
S-IC	Designed by MSFC; based on S-I.	First S-IC to be built by Boeing.	Order of magnitude larger than previous engines. Minimum engine-development test time.	0.7
S-II	Designed by NAA*; no previous design of cryogenic stage.	First S-II to be built by NAA.	Five-engine cluster. Engine proven on Saturn IB.	0.5
S-IVB	Designed by DAC*; close extension of S-IV.	Built by DAC. Follows a number of S-IV and S-IVB stages for IB.	One engine. Engine proven on Saturn IB.	1.0
IU	Designed by MSFC; close extension of Saturn I and IB.	Follows a number of I and IB Instrument Units.		0.9

* NAA - North American Aviation (Space and Systems Information Division)

DAC - Douglas Aircraft Corporation

3.4 Adjusted Prediction

Using the design maturity values from Table 2, the reliabilities from Table 1 were recalculated for each stage and for each possible vehicle configuration.* The adjusted reliabilities shown in Table 3 represent the probability of success for initial flights. For successive flights, the probability of success can be expected to increase as a result of an increase in design maturity, brought about by failure analyses and corrective actions on failures experienced on early flights.

Inspection of Table 3 shows that the reliability of a configuration consisting of the S-IC and Instrument Unit is 0.932 with one-engine-out capability, and 0.682 for a complete live SA-501 with one-engine-out capability. A useful way of comparing the reliabilities in Table 3 is to normalize the reliability for each configuration by using an arbitrary standard. Figure 1 shows the reliability for each configuration as compared to the reliability of the complete SA-501 vehicle with one-engine-out capability.

3.5 Engine-Out Capability

Figure 1 shows that the reliability for each configuration is higher when one-engine-out capability is incorporated. This difference is most significant in configurations that use the S-II stage.

One-engine-out capability must include:

(1) Capability to sense that an engine has malfunctioned.

(2) Capability to cut off a malfunctioning engine before it damages other engines or critical portions of the stage.

---

* Appendix A explains the method of applying design maturity values.

TABLE 3

RELIABILITY PREDICTIONS FOR INITIAL FLIGHTS OF SATURN V STAGES AND VARIOUS LIVE-STAGE SA-501 CONFIGURATIONS CORRECTED BY ASSIGNED VALUES OF DESIGN MATURITY

Stage or Configuration	Predicted Reliability	
	No Engine-Out Capability	One-Engine-Out Capability (S-IC, S-II)
Stage		
S-IC	0.967	0.979
S-II	0.600	0.814
S-IVB	0.899	0.899
IU	0.952	0.952
Configuration		
S-IC, IU	0.921	0.932
S-IC, S-II, IU	0.552	0.759
S-IC, S-II, S-IVB, IU	0.497	0.682*
S-IC, S-IVB, IU	0.828	0.838

* Value used for normalizing the probabilities shown in Figure 1.

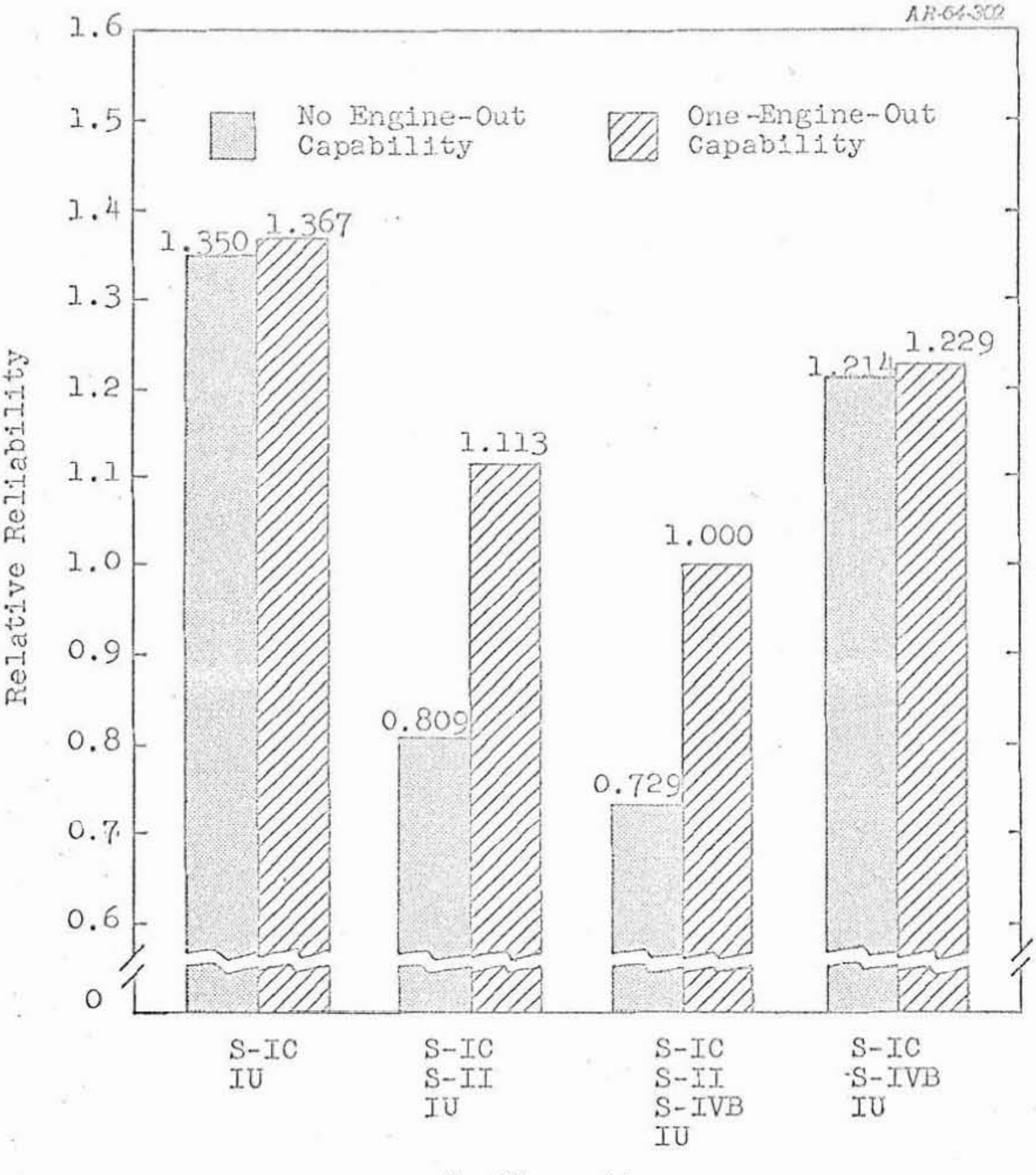

FIGURE 1

COMPARISON BETWEEN PREDICTED RELIABILITY FOR SA-501 SATURN V CONFIGURATIONS WITH AND WITHOUT ENGINE-OUT CAPABILITY

(3) Capability to attain an acceptable flight profile with the thrust from n-1 engines (n = number of engines on stage).

At the time of the first Saturn V flight, the F-1 and J-2 engines will have completed less testing than was accomplished on the H-1 or RL-10 engines before their initial flights. The principal reason for the lower level of testing is the costs of the voluminous propellant requirements for each test with the larger engines. Additional development testing would be valuable for the purpose of achieving higher engine reliability if these costs were not prohibitive.

Engine-out capability provides a means of obtaining a considerable increase in propulsion system reliability for early R&D flights. Since the purpose of the early Saturn V flights is to obtain flight test information rather than to place a specific payload in orbit, it is recommended that one-engine-out capability be included in the S-IC and S-II stages. To be effective, this recommendation would also require that the flight plan for the SA-501 shots and other early Saturn V shots be designed for a safe and useful flight in the event of partial loss of thrust in either stage.

For early flights, it may be advantageous to increase the number of malfunction sensors over the number presently planned for the emergency detection system. These extra sensors would provide an early warning system to detect malfunctions before they cumulatively result in catastrophic failure conditions.

3.6 Past History

A survey was conducted of success-failure data from previous launches. The first objective of this investigation was to determine if past experience would indicate a significant difference between the launch-flight reliability of a single stage and that of multiple stages. The second objective was to determine any existing reliability growth trends.

Some data were available from the Vitro study described in MSFC document MTP-MS-IS-61-4, Missile and Space Project Information Manual, which is classified SECRET. This document presents launch data for all firings through December 1961. Data were also obtained from the Report to Congress from the President of the United States on U. S. Aeronautics and Space Activities in 1963 (unclassified). The material presented here was drawn from the unclassified document. Conclusions based on the classified report will be given in oral presentations.

The data from the Report to Congress are plotted in Figure 2. The bars show the percentage of yearly launches classified as successful* from 1957 through 1963. The success percentage rose steadily each year and has remained nearly constant (between 80% and 85%) for 1962 and 1963. This increase in reliability may be attributed to an increase in design maturity, improvement in the state of the art (such as simplification of the Jupiter engine into the H-1), and refined prelaunch test-and-checkout procedures.

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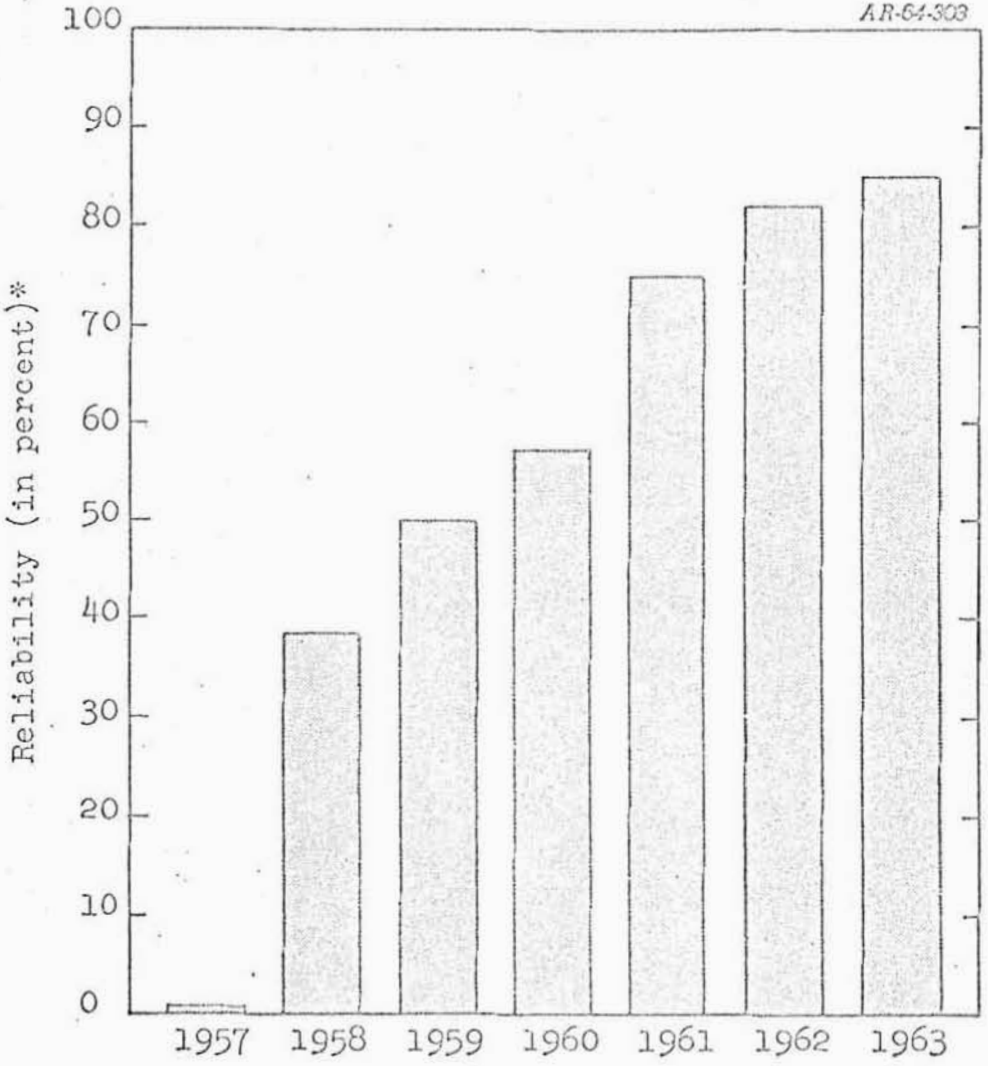
* A launch was classified as a success provided earth orbit, as a minimum, was attained. The percentage shown is equal to number of successes divided by number of attempts x 100.



$$* \quad \text{Reliability \%} = \frac{\text{Number of Successful Launches}}{\text{Number of Attempts}} \times 100.$$

FIGURE 2

YEARLY GROWTH IN RELIABILITY OF U. S. ROCKET LAUNCHES, 1957-1963

(Based on Report to Congress from the President of the United States on U.S. Aeronautics and Space Activities 1963.)

4. IMPLEMENTATION OF THE ALL-UP CONCEPT

4.1 General

Although a decision must be made in the near future concerning implementation of the All-Up concept, the decision as to the degree of implementation should be postponed. There are advantages to be gained by implementing the All-Up concept in any of several degrees, and a complete range of systems that can be included or omitted from the SA-501 launch-flight test shot. The actual decision to include a particular system should be made as late as possible and should be based on:

(1) Amount of test information expected from the system.
(2) Estimated availability date of the system.
(3) Estimates of time required for prelaunch test-and-checkout activities.

4.2 Test Information

Each of the various possible configurations of the SA-501 will produce a specific, individual set of test information. The probability of obtaining some or all of each set of test information is, of course, a function of the probability of success of one or more of the live systems in the particular configuration. This latter probability is predictable, and the accuracy of such a prediction increases as the launch date approaches.

4.3 System Availability

The most important areas of consideration in determining the configuration for the initial SA-501 flight are the estimates of stage and subsystem availability and the predicted probability of mission success. Preparation of these estimates will be facilitated by monitoring the progress of each stage assembly very closely and by keeping a running assessment of the test program. From such efforts, good estimates may be compiled of stage availability dates and the probability of satisfactory performance.

PERT charts for each stage will be useful for monitoring the progress in assembling stages. For each programmed launch date, the charts should include as a milestone the latest possible time for ordering an alternate or dummy system. This time is based on time required for collecting information and making appropriate decisions. As with all monitoring programs that use PERT, the precision of the time estimates will increase with proximity to the milestones.

It is expected that the S-II stage will be the major pacing item in implementing the All-Up concept for the Saturn V vehicle. The S-IC stage will be used whether or not the vehicle is all live. The S-IVB will have already flown several flights in the Saturn IB vehicle, and the Instrument Unit is expected to be available since it is very similar to the one in the Saturn IB.

These considerations are further emphasized by the factors listed in Table 2 regarding design maturity. Because the S-II stage is a completely new design and the first of its kind to be built by the supplier, the development progress will require close monitoring for schedule compliance and to ensure attainment of reliability goals.

It must be pointed out that the design maturity factors and schedule considerations do not present the complete picture. The S-II contractor has demonstrated considerable management capability in the development of complex systems in the past. Application of these same capabilities to the S-II stage could result in circumstances more auspicious than presently anticipated.

4.4 Prelaunch Test and Checkout

The probability of launch occurrence at a given point in time for the various possible SA-501 configurations can be predicted. The occurrence and duration of delays in the prelaunch activities are functions of the occurrence and detection of malfunctions that require corrective action and of the time required to accomplish such action. An analysis of past experience relating such delays to system complexity, design maturity, and competence of personnel can be expected to yield estimates of delays that are sufficiently accurate for use in choosing the optimum configuration. As the launch date approaches, more applicable experience will accumulate, and, correspondingly, the accuracy of the delay estimates will improve.

The complexity of the configuration and the number of live systems on a launch vehicle directly affect the time required to complete prelaunch test-and-checkout activities. Since an All-Up SA-501 would be the largest vehicle ever launched, extensive time delays in completing the prelaunch test and checkout can be expected. However, as discussed previously, these delays can be anticipated and estimated. The level of competent effort required for checkout activity on SA-501 should be a natural extension of the capability already demonstrated at Kennedy Space Center. Launch of the Saturn IB vehicle with manned Gemini flights is expected to aid in extending the prelaunch-and-checkout capability at Kennedy Space Center to the necessary level.

4.5 Overall Approach

An extensive analysis of past experience and of information on the current development status seems to be the best method for choosing an optimum SA-501 configuration, system by system, at the earliest possible time. Furthermore, such an analysis should provide the greatest amount of available information at the earliest practicable time. The advantage of an analysis of this kind is that it provides management with valid deductions based on past experience and current status. These deductions are in the form in which management most needs them for making decisions when they must be made.

It appears that the proper course to follow in implementation of the All-Up concept is to "hope for the best and prepare for the worst". In other words, the activities necessary for implementation should be carried out. However, the predictions and estimates discussed in this report should be continually updated and closely monitored by management. Through such action, appropriate preparations can be made for substituting any dummy stages required by the final optimum configuration.

APPENDIX A

APPLICATION OF DESIGN MATURITY VALUES

This appendix briefly describes the application of design maturity values. These values are used to adjust predicted reliabilities based on mature design so that the predictions will reflect the probability of success for initial flights. The use of design maturity values is required because the predictions are based on data from previous systems that have been completely debugged insofar as both the hardware and the operational procedures are concerned.

The design maturity value may be applied to predicted reliability in the following manner:

Stage Unreliability (Q) = 1 - Stage Reliability (R),

or

$$Q = 1 - R. \qquad (1)$$

$$Q_p = (D.M.)(Q_A), \qquad (2)$$

where

Q_p = Predicted unreliability,
$(D.M.)$ = Assigned value of design maturity, $(D.M. < 1.0)$, and
Q_A = Actual unreliability.

Equation (2) may be rewritten as:

$$(1 - R_p) = (D.M.)(1 - R_A) \qquad (3)$$

where

R_p = Predicted reliability, and
R_A = Actual reliability.

Design maturity operates on system unreliability. The operation takes into account the best estimate of the number of undetected potential failures in the vehicle at the time of launch. Since the design maturity is always equal to or less than unity, the predicted unreliability will be less than the actual unreliability; in other words, the predicted reliability is optimistic. It can be expected that design maturity (D.M.) will increase rapidly with successive launches. Inherent in this statement, however, is the assumption that an effective program of failure reporting, failure analysis, and corrective action will be implemented.