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COMPONENT FAILURE EFFECT ON SYSTEMS
AN ANALYTIC MODEL

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PREPARED BY:
R.L. PARKHILL
SECTION CHIEF
SATURN S-IVB
RELIABILITY ANALYSIS
AND
J. PAUPERAS JR.
ASST. SECTION CHIEF
SATURN S-IV
RELIABILITY ANALYSIS

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SUMMARY

In today's complex systems, such as Saturn, many traditional reliability analysis concepts are not acceptable. Because of time and budget restrictions, and the requirement to provide a "man rated" space vehicle, the Douglas Saturn Engineering Reliability Section has developed a new analytical approach; it is call "criticality ranking." It is a "totem pole" of components whose single failure may lead to system loss. "Criticality ranking" is one of the results of an analytical model which encompasses failure effect and reliability prediction.

This paper describes this analytical model, discusses some of the techniques and ground rules, and presents examples. A discussion of the application of the results is also included.

INTRODUCTION

The old proverb, "a chain is no stronger than its weakest link," has been the basic philosphy of reliability since its conception. The initial design approach generated by this philosophy was to attempt to make each "link" in the reliability "chain" as strong as the next "link". This approach originally produced markedly increased reliability for nominal dollar investment but as the components have become more reliable, the cost has increased exponentially. This cost aspect of increased reliability has spawned many new approaches towards reliability and reliability testing. Douglas Aircraft Co., in its Saturn Reliability Philosophy, believes that it has found an approach that will allow the next major increase in reliability to be accomplished at relatively low cost. The method considers the use of the reliability "chain" but takes advantage of the fact that the "links" are neither equally stressed nor are the "links" equally important to the success of a mission. Therefore, they do not have to be equally strong. This approach leads to "criticality ranking" of the "links" that are essential to the success of a mission and necessitates the shift of design and test attention from the simple reliability of a part to its criticality.

The purpose of this paper is to present how this "criticality ranking" is determined and how it may be applied to optimizing the reliability of a system. This will be accomplished in three steps. First, a Reliability Mathematical Model - Failure Effect Analysis technique will be presented. This will determine those "links" in the chain that are essential to the success of a mission. Next, an analytical technique, which includes reliability prediction, will be discussed. This technique will determine the stress on these "links." Finally, a brief discussion of the combined analytical model results will be presented. It will stress the application and use of the results.

I. RELIABILITY MATHEMATICAL MODEL

The purpose of the Reliability Mathematical Model is to provide early prediction analysis to determine whether initial allocations can be met, and to point out weak "links" in the system. It consists of basically four major elements of effort:

1. Preparation of reliability block diagrams for functional systems.
2. Preparation of a single-failure effect analysis at the component/part level.
3. Reliability allocation.
4. Reliability prediction.

Even though Item 4 is part of the Reliability Mathematical Model, it will be discussed in the second portion of this paper since it deals with the stress on the "link."

The Functional System used as an example in our discussion of the Reliability Mathematical Model will the the "Ullage Positioning" subsystem of the Saturn S-IV Stage (Figure 1). During Saturn S-I to S-IV Stage separation four ullage rocket motors on the S-IV Stage are fired to avoid any unseating of the S-IV propellant tank contents. This occurs between the decay of S-IV thrust and build-up of thrust from S-IV engines, when zero "g" is experienced. Figure 2 is an artist's conception of the S-I/S-IV Stage separation after the ullage rocket motors have ceased thrusting and the stages are still relatively close together.

A. RELIABILITY BLOCK DIAGRAMS

To prepare a functional reliability block diagram for this particular subsystem, the total S-IV Stage must first be separated into its major functional subsystems. This breakdown is shown in Figure 3. Since the "Ullage Positioning" subsystem is considered as part of the separation function, it is contained within a breakdown of the Separation Subsystem, coded as V-IV-60 in Figure 3. Figure 4 provides this subfunctional breakdown of the Separation Subsystem. Finally, Figure 5 shows the reliability block diagram of the components that provide the "Ullage Positioning" function. It should be noted, that the subsystem depends on functional inputs from other subsystems which are shown by the two arrows with a coded reference. This subsystem is highly redundant; that is, proper ullage positioning may be accomplished with any three rocket motors firing which in turn are initiated by redundant Exploding Bridgewire (EBW) Firing Units and EBW Motor Initiators. A better picture of the physical arrangment of the actual hardware is provided by Figure 6 which shows the relative location of the components in the S-IV Stage.

Charging of the EBW firing units is accomplished in flight, approximately seven seconds prior to triggering. The power for charging these units comes from the "Electrical Power" subsystem, which is coded as V-IV-51 (Figure 7) and is a subfunction of the "Auxiliary Power" subsystem. The "Ullage Rocket Ignition Charging 28VDC Power" subfunction is shown as "Function K" in Figure 8. Figure 9 provides the block diagram of the hardware which provides this function. It should be noted here, that this diagram is arranged for failure effect analysis rather than as strictly a reliability type block diagram. The "Ullage Rocket Ignition Charging Relay," coded as V-IV-51-22, provides for connection of battery power to charging the EBW firing units upon receipt of a command from the **Instrument** Unit (I.U.) which is located above the S-IV Stage. The I.U. command and the power output are shown by the coded arrows in the block diagram of Figure 9. The output is coded V-IV-60-09, which references back as an input (charging) in Figure 5.

The triggering function of EBW firing units is accomplished upon receipt of an electrical signal from the S-IV Sequencer. This item is a component of the "S-IV Sequencing" subsystem, which is shown as a subfunction of the "Electrical" subsystem, coded as V-IV-72 in Figure 10. The S-IV sequencer subfunctions are shown in Figure 11. Since firing of the ullage rockets occurs prior to S-IV Stage powered flight, this function appears under "Sequencing Pre S-IV Flight Functions" and is noted as "Function C" in Figure 12. Upon receipt of a command from the I.U. either relay can provide 28VDC electric power to trigger four EBW firing units, one per rocket, and thus fire all four ullage rockets.

B. FAILURE EFFECT ANALYSIS

The Failure Effect Analysis is a study of the system or subsystem from the standpoint that any single component/part may fail inopportunely. The failure effect analysis considers what happens after such an event occurs. The results of this analysis then serve to direct design attention and test efforts in the early design and development stages of a program.

The Saturn S-IV Stage Reliability philosophy is that no single independent failure in a subsystem should abort the flight. Since strict adherence to this policy is not practical within the confines of a time and budget limited program, it is important to minimize stage loss probability. This dictates an analysis which is based on component reliabilities and single failure effect. As will be noted later in this paper, the occurrence of a particular type or mode of failure does not always result in a loss of the system and consequently, not all of the component unreliability contributes to stage loss probability. Accordingly, these significant portions of the unreliabilities must be determined. To accomplish this, the components essential to mission success must first be identified. This calls for a failure effect analysis and ground rules which produce analytical results consistent with probability theory. The concept shown in Figure 13, developed and used by the Douglas Saturn Reliability Analysis Sections, has been used as the basic ground rule. It shows that all single failures of components must be analyzed to determine the effect of the failure on the S-IV Stage; i.e., whether or not the failure will lead to stage loss. For analytical purposes, the effects of a component failure on the system have been classified as follows:

Effect of Failure	Probability of Loss
(Certain) loss of (Name of System)	100%
Probable loss of ...	50%
Possible loss of ...	10%
None	0%

Since failure of a component may or may not cause loss of the subsystem performance, the probability of loss can be determined from analysis of the function of the component in the system, system test results and past experience. Effect of a component failure on the performance of a subsystem is dependent on the time and type of failure, the degree of severity of the failure, and the amount of redundancy in the subsystem. (The manner in which these conditional probability values are used for evaluating component unreliabilities is illustrated in Figures 19 and 24).

Figures 14 through 17 are actual examples of the failure effect analysis for the components which were discussed earlier in connection with the "Ullage Positioning" function. The code in the "item" column is the Reliability Mathematical Model identification number and it can be used to refer back to the particular block diagrams associated with the item in the failure effect analysis.

The analysis itself is prepared by utilizing system or subsystem functional schematics, logic diagrams, component and part drawings and specifications, failure data, test results, and other pertinent information. In determining the effect of component failure on subsystem performance or the effect on the S-IV Stage, the four following <u>failure modes</u> are considered:

1. Premature operation.
2. Failure to operate when required.
3. Failure during operation.
4. Failure to stop operation.

Since a single <u>failure type</u>, such as "open circuit on a relay" may cover the failure effect analysis of several <u>failure modes</u>, it may also be used, especially in conjunction with pneumatic or mechanical components. As indicated in Figures 14 through 17, the analysis describes the effect of component failure on subsystem performance. It also points out the effect on the S-IV Stage and the Saturn Vehicle should failure occur during the manual countdown (checkout on launch pad), the automatic countdown sequence, the boost phase of flight and the powered phase of S-IV Stage flight. Since the time from component failure to the effect of the failure on the Saturn Vehicle is an important parameter for Emergency Detection and Abort Systems, this information is also included. It is termed Failure Reaction Time (FRT) and is defined in Figure 18. Applicable FRT's are shown in the failure effect analysis (Figure 15, 16 and 17) in conjunction with "Mission Loss" or "Vehicle Loss." These latter terms are also defined in Figure 18.

It should be noted, that the physical cause of a given failure type, or mode, is not emphasized in analyzing the effect of the failure. For example, the effect of a solenoid valves's failure to operate when required (failure to open or close as required) is considered and analyzed without any attempt to pinpoint whether the failure was caused by lack of command (effect of a primary failure), defective solenoid wiring, jammed valve-stem, etc. Thus there can be multiple causes for the applicable type or mode appearing in the failure effect analysis. Many of these causes of component failure are well known to the designer and the test engineer. During the R&D program every effort is taken to eliminate the critical component failure types by "designing out" the potential causes of failure.

The results of the failure effect analysis can be summarized by listing those components that are essential to mission success. In other words, any component whose single failure in flight may lead to S-IV Stage or Saturn Vehicle loss is an essential component to mission accomplishment. It should be emphasized, that this ground rule contains the terms "single failure" and "in flight". These "essential components" in the Saturn Program are called "Flight Critical Items." By reviewing the failure effect analysis in our example (Figures 14 through 17), the following Flight Critical Items can be listed:

"Ullage Positioning" Subsystem

Ullage Rocket Motor (4)

"Electrical Power" Subsystem

Ullage Rocket Ignition Charging Relay (1)

"S-IV Sequencing" Subsystem

Firing Ullage Rocket EBW Relay (2)

In this example, it is assumed, that other components in the "Electrical Power" and "S-IV Sequencing" subsystems are reliable. In actual practice, other components may be added to this list of "Flight Critical Items" for the complete "Ullage Positioning" function; however, the items would be listed under their subsystem breakdown. This is because many electrical and sequencing components provide multiple functions and each component's unreliability must be accounted for in its respective subsystem. To determine the reliability of a complete system, such as the S-IV Stage, the subsystem reliabilities are taken into account only once. On the other hand, when we speak of the reliability of a particular function, the reliability of all components contributing to this function must be considered. In our example, two reliability figures can be established: (1) the reliability of the "Ullage Positioning" subsystem and (2) the reliability of the "Ullage Positioning" function. The use of the Reliability Mathematical Model Code and the Block Diagrams enables the user to establish both reliabilities.

C. RELIABILITY ALLOCATION

It is imperative that a well integrated reliability program be aggressively pursued in the design of a system to assure, with high confidence, that an acceptable "inherent reliability" is designed into the equipment. The mathematical model is a most useful reliability tool for this purpose, which among other uses allows the apportionment of the overall system reliability requirement (contractually applicable) down to the component or part level. This apportionement is the reliability allocation, and should not be confused with the reliability prediction.

The individual component and subsystem reliability allocation (actually the unreliability is apportioned) for determining which subsystem components are potentially the most unreliable, is based on results of a paired comparison analysis and operating time considerations. This statistical analysis is made using several engineers' rating of the severity of such qualitative variables as physical complexity, functional complexity and state-of-the-art for the component. For consistency, the following definitions of the variables were used:

Physical Complexity

This relates to the number of elements in the system, the number of dependent structural (physical) relationships between them, and the possible structural (physical) reactions to their expected environment.

Functional Complexity

This relates to the number of functions performed, the tolerances on these functions, and the inter-relationships of these various functions with each other and their exterior stimuli.

State of the Art

This relates to the amount of history available on the use of similar materials, devices, or techniques.

The Saturn S-IV stage component and subsystem reliability allocations, together with the failure effects analyses, serve to indicate potential reliability problems. This applies to components or subsystems in which the state-of-the-art is new and to components and subsystems whose known failure probabilities are higher than the allocated unreliability.

The actual **S-IV Stage** allocated component reliability is classified. Reliability allocation was discussed here only to complete the picture of the Reliability Mathematical Model.

II. CRITICALITY RANKING

"Criticality ranking" is a "totem pole" of flight critical items, with each item having an associated relative criticality. These criticality numbers are derived by assessing all applicable component/part failures for their contribution to stage loss. The item which contributes more to probability of stage loss than another item, will end up with the larger criticality number. The ranking of all items provides a convenient comparison of their contribution toward stage loss.

In judging the criticality of an item, i.e., in assessing the contribution toward stage loss, it is necessary to use a consistent set of rules. Figure 19 shows the worksheet used by DAC Reliability Analysis

Section personnel to determine the criticality of an item. It also defines the data columns. This worksheet is divided into two phases of effort. The first phase summarizes the reliability failure effect analysis and the second phase selects the critical items and determines their degree of criticality. To use this worksheet, four major factors must be considered and applicable data entered prior to further mathematical handling:

1. The possible types or modes of failure for the item.
2. The frequency with which the item fails in each of the applicable failure types or modes.
3. The probability of item failure (for all failure types/modes).
4. The stage loss frequency when the particular type or mode of failure occurs.

Specifically, the criticality number is the portion of the inherent item unreliability assignable to all of the applicable failure types or modes of an item which contribute to stage loss, multiplied by 10^6. A simpler definition of the criticality number is: "item unreliability which leads to stage loss, multiplied by 10^6 to facilitate handling of the number."

To determine the criticality of the items in our example, a more detailed description of the item function and the actual hardware is necessary. Figure 20 provides a picture of the Ullage Rocket Motor Installation which lists all components of the "Ullage Positioning" subsystem. The unlisted, but shown items belong to the "Ullage Rocket Jettison" subsystem and will not be discussed.

One EBW firing unit is provded for each point of initiation. Since there are two points of initiation for each rocket igniter, eight EBW firing units are provided, two in each of the four ullage rocket motor installations (see Figure 5). An EBW firing unit consists of the following functional elements (Refer to Figure 21):

a. A high voltage power supply which converts the 28 vdc input power to approximately 4,000 vdc.

b. A storage circuit consisting of a capacitor and an associated bleed-and-monitoring network.

c. A trigger circuit that receives a signal from the S-IV sequencer and ionizes a gap switch.

d. A gap switch wich is connected in series with the charged capacitor and the EBW load. When ionized, the switch allows energy to be transferred to the EBW load, therby, firing the motor initiator.

e. A pendant high-voltage cable that transmits the firing pulse, minimizes the generation of noise, and protects the EBW motor initiator from picking up stray fields of radio frequency energy.

The EBW firing unit is triggered by 28 vdc power coming through the S-IV sequencer. Firing unit charge time is less than 4 seconds; discharge time, upon removal of power input, is 15 seconds maximum.

A cross section of an EBW Motor Initiator is shown in Figure 22. When the EBW firing unit is triggered, the discharge literally explodes the bridgewire in the EBW Motor Initiator. This wire in turn initiates the pyrotechnic mix which reacts rapidly and ruptures the closure disk. The output of the initiator ignites the Ullage Rocket Igniter.

Figure 23 provides a view of the igniter and rocket motor assembly. The Ullage Rocket Igniter, when activated by the two initiators, starts the solid propellant rocket motor. The propellant grain burns for approximately 3.6 seconds providing forward thrust to the S-IV Stage.

The Reliability Mathematical Model Summary for the "Ullage Positioning" subsystem is shown in Figure 24. The "Ullage Rocket Ignition Charging Relay" of the "Electrical Power" subsystem is included for comparison purposes only. The first four columns in Figure 24 summarize the results of the failure effect analysis. Taking the EBW firing unit as an example, it is shown that there is no associated stage loss when either a single unit fails to fire when required or fires prematurely. Therefore, the stage loss frequency is shown as zero in both cases. The justification for this "no failure effect on S-IV Stage can be found in the failure effect analysis, Figure 14. The same applies to the EBW motor initiator and the ullage rocket igniter, except that premature failure is not applicable and therefore not included in the analysis. These units, by themselves, cannot operate prematurely.

Four failure types are listed as applicable for the ullage rocket motor. The failure effect analysis in Figure 15 provides the data for the "Stage loss frequency" column in Figure 24. As previously indicated, the ullage rocket motor is a "Flight Critical Item," since burst, burn-through and "Chuff" of the rocket can cause an S-IV Stage loss, which in all cases can be classed as a catastrophic type of loss. The "probable loss of the S-IV Stage" is weighted as 50% and the "possible loss" as 10% in the "stage loss frequency" column. This type of weighting derates the failure effect statement in the analysis since the effect of the mentioned failure types is neither totally "black" (100%) nor totally "white" (0%). (Burst or burn-through of the rocket motor can occur radially in any direction, even away from the airframe).

Since the actual reliability of these components is classified, the entries to the right of the "stage loss frequency" column in Figure 24 have been selected as "typical" for this type of hardware as used in our example. At this point, Figure 19 can be referred to for definition of the various columns of data.

Again, taking the EBW firing unit as an example, it is shown that the criticality number is a summation of the item unreliability assignable to the applicable failure types which contribute to stage loss, multiplied by 10^6. Since neither premature firing nor failure to fire of this unit leads to stage loss, the criticality number is zero and all the unreliability of this item is listed in the "Unreliability NOT contributing to stage loss" column. It should be noted, that this will be true regardless of the reliability of the item. With low item reliability, however, the probability of multiple independent failures becomes significant. In our particular example a double premature failure of two unadjacent units (see Figure 5) would negate the redundancy of the system if the failures occur right after the units have been charged. The premature discharge of these two units would fire two ullage rocket motors at least three seconds prematurely (difference between time of charging and time of triggering minus time required for charging) which would leave approximately 1/2 second of burning time for the two rockets when the function is actually required. The probability of any two units firing prematurely in our example (Figure 24) is extremely remote: 28 (.00002) x (.00002) or 1.12×10^{-8}. (Since there are 28 combinations for premature double failure of the 8 units). This prediction is very conservative, since it assumes failure of any two units (rather than unadjacent units).

The above example brings out the importance of the "Failure type-mode frequency" which is very much responsible for the remoteness of the premature double failure. This term is defined as the "fraction of item unreliability associated with the indicated failure type." The data in this column indicates, for example, that only one percent of all EBW firing unit failures will be of the "premature firing" type. When sufficient test data is not available to determine this factor, analysis of the circuit or component parts can be made to arrive at a reasonable estimate. For instance, a circuit stress and part failure rate count analysis of the EBW firing unit can be performed to determine which part failure will lead to the breakdown of the gap tube causing it to discharge without receipt of a trigger signal. Comparing the probabilities of the circuit part failures leading to "premature firing" with the probabilities of the circuit part failures leading to "failure to fire" establishes this "Failure type-mode frequency" factor. It should be noted, that this factor for the EBW firing unit is only important from the multiple failure standpoint. The criticality number for this item is zero and will remain zero as long as the single failure effect ground rules are in effect. By the same ground rules, the criticality numbers for the EBW motor initiator and the ullage rocket igniter is determined as zero.

The fourth item of this attribute (one shot) group is the ullage rocket motor. Here "failure to fire" is the only noncritical failure type; however, its adjusted failure rate or failure probability contributes to stage loss on a double failure basis because the "Failure type-mode frequency" is high for a "dud". The probability of a "double dud" is still much smaller, however, than the combined probability of any catastrophic failure, such as burst, burn-through or "chuff" of a single rocket.

Even though the criticality number for this item is based on a single-failure basis, the "No Stage Loss" prediction in the Mathematical Model (See Figure 13) considers multiple failure probabilities of redundant items. An analysis made of many ballistic missile flight tests justifies this single failure effect ground rule for the selection of "Flight Critical Items."

The criticality number for the "Ullage Rocket Ignition Charging Relay" (Figure 24) is more than two times larger than the criticality number of a single ullage rocket motor. This amazes many engineers since the relay is 20 times more reliable than the rocket motor (compare the failure probabilities in Figure 24). This great difference obviously is partially governed by the effect of failure and the failure type-mode frequency ratio. This necessitates the shift of design and test attention from simple reliability of a part to its criticality, i.e., to the degree of importance that the item be highly reliable. For example, if the relay in our example would be only as reliable as the rocket motor, the criticality number for the relay would increase to 4,950. This would mean that the relay would contribute 45 times (4950 divided by 110) more to the probability of stage loss than a single ullage rocket motor. This example brings out strongly the fact that it is extremely important to know not only the "links" in the chain that are important to mission success, but also the stress that these essential "links" must endure.

III. METHODS OF TECHNIQUE APPLICATION

There isn't one of us who has not been faced with the problem of a program with too little money and too little time to do the job. The analytical technique presented gives early, realistic discrimination criteria which provide greatest assurance the program will meet its requirements with the most effective money expenditure. Given critical items, failure modes, and the criticality index the components designer becomes concerned with their application in the following areas:

"premature firing" with the probabilities of the circuit part failures leading to "failure to fire" establishes this "Failure type-mode frequency" factor. It should be noted, that this factor for the EBW firing unit is only important from the multiple failure standpoint. The criticality number for this item is zero and will remain zero as long as the single failure effect ground rules are in effect. By the same ground rules, the criticality numbers for the EBW motor initiator and the ullage rocket igniter is determined as zero.

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The designer may use critical items to establish which supplier specifications should have more stringent than normal requirements for design, monitoring, and test imposed. Since effectively, the components will undergo very little change once the supplier has delivered an approved part to the system, it is imperative that the design reflect minimum critical failure mode probability. Criticality ranking and failure effect analysis becomes the basis upon which competing suppliers may be evaluated. An example of this would be three prospective suppliers for the ullage rocket ignition charging relay. We know that failure to operate and maintain operation is critical. The supplier's relays should then be evaluated for 1) contact bounce, 2) vibration resistance, 3) threshold pull in voltage, and 4) continuous duty electrical and thermal rating of the coil. Such non-critical failure modes as welded contacts (failure to cease operation) should not be rated as heavily as such modes as contact bounce. Additionally, the supplier test program should reflect stringent consideration of these characteristics. Such test programs should analyze the effects of combined environmental and critical operational stresses on the hardware in order that the interaction of environments on the hardware will be properly investigated.

Traceability requirements have been with us for a number of years. However, as reflected today in the various military and space program requirements, they are somewhat different than we are used to. We now basically have the choice of making everything traceable down to mill and melt, or we can take the route of putting traceability requirements on certain selected items.

Criticality ranking is an excellent discrimination criterion in that it will give the best return for traceability per dollar invested. If program money is too short to provide traceability on all critical items, the criticality ranking index should be used. For instance only those items with a criticality number greater than 100 could be made traceable. Therefore, in the system discussed both the ullage rockets and the charging relay should be made traceable. The portions of components to be made sub-traceable should be generated from the failure effects analysis. In the case of the relay, critical failure modes center primarily around the coil, e.g., threshold pull-in voltage and electrical and thermal rating of the coil. This critical relay should have the coil and even possibly the coil wire traceable. Traceability in this case should go to the extent of samples of the physical and chemical analysis of the wire used. The alternative is an expensive time consuming program that could well run into many millions of dollars and many months of schedule delay.

High reliability programs exist today. It is quite clear that they have one characteristic in common: that is components with which they deal are all more expensive than the normal Military Specification hardware. Because of this, high reliability requirements indiscriminately specified will lead to an excessive cost and schedule slippage in the program with a disproportionately poor return per dollar. Critical items and failure effect analysis give us a means for establishing which of these components should be Hi-Rel and what characteristics should be emphasized. For instance, the charging relay would very well justify high reliability specification whereas a relay of similar rating in application in general non-critical power circuitry has absolutely no justification for it. It therefore follows that the designer, where he has a critical application, should use high reliability parts when they are available. The critical failure modes from failure effect analysis provide the basic characteristics around which the Hi-Rel specification is written. Today's weapon systems such as Minuteman require high reliability specifications for components for GSE and for the flight vehicle. However, in the present space programs, the greater emphasis is placed on the launch vehicle itself. As time goes on and the requirements for meeting specific limited launch windows imposed, we will see the advent of high reliability parts being incorporated into space vehicle ground support equipment also. It is well to bear this in mind because we now have a tool in criticality ranking which tells us what should be Hi-Rel for ground support equipment.

Emergency detection systems represent a basic technical problem most particularly with regard to manned space vehicles because first the question must be asked "What should we detect?" and then "How shall we detect it?" and finally "How and where shall it be displayed?" - in the capsule, on the ground, or both? An example of the use of the technique might be as follows: Criticality numbers associated with particular failure modes give us the first point upon which we can begin to base a program and discrimination criteria. It should be pointed out here that any critical system failure must reflect itself through a critical end item failure. The item itself does not have to have failed but it must manifest a failure as though it had. For instance, our critical relay would appear the same to the system if it failed as it would if power to the relay coil failed. Because of this the problem of selection of what to monitor becomes definitely simplified. The components man now knows by using criticality numbers, failure effect analysis, and failure reaction time where and what character of monitoring he must supply. In the case of the ullage rocket motor, failure effect analysis points out that the critical failure modes are 1) burst, 2) burn through, and 3) chuff. Failure reaction time (Fig. 15) for the stated failure effects is .01, .5, and 1.0 sec. respectively. We should now instrument the motors for chamber pressure and temperature sensing (burst and chuff) and nozzle skin temperature sensing (burn through). Depending on customer evaluation, we should also provide for automatic abort for rocket burst and perhaps burn through because of the extremely short failure reaction time and catastrophic results.

Screening specifications can now be established by the designer to assure that any components entering the plant which have an inherent weakness in the critical functions will be caught and rejected. The items to be screened should be selected from the total critical items list or, if program money is limited, a more discriminating selection can be made from the criticality index. The characteristics to be inspected should be taken from the failure effect analysis. This can be done in the same manner as discussed for the charging relay under supplier requirements.

Finally, the component designer should establish that the failure reporting system which exists in his company, specifically reports failures on all critical items as such, namely, a critical failure. He should also see that the reporting system stipulates the specific mode in which the component failed. The critical items list should be used to establish which items will receive special expedited attention in the failure reporting and corrective action system. Provision should be incorporated into the reporting system for directly identifying on the report those failure modes which have been established by failure effect analysis as critical. With this type of information plus the normal reliability statistical information surrounding failures and failure analysis, we can go back to the math model and specifically report in critical areas what has in fact happened. This provides for a much more expedited and meanful analysis.

It has been the purpose of this presentation to describe an effective tool for technical management of systems and components reliability programs. There is no doubt that the type of analysis presented can be carried further. Its probable ultimate end lies in the area of the actual physical laws surrounding failure. Considerable work is being provided by Armour Research Foundation in this area under Air Force funding. However, it is not presently available today and not in the immediate future. It is for both the reliability manager and designer to take this technique which has been presented, fashion, mold, shape, and polish it to specific needs, and redirect it toward the industry. In this manner, will respect for reliability as a technology grow. The degree to which reliability grows depends a great deal on how much the designer respects and uses the reliability information and techniques provided him.

S-IV STAGE CUTAWAY

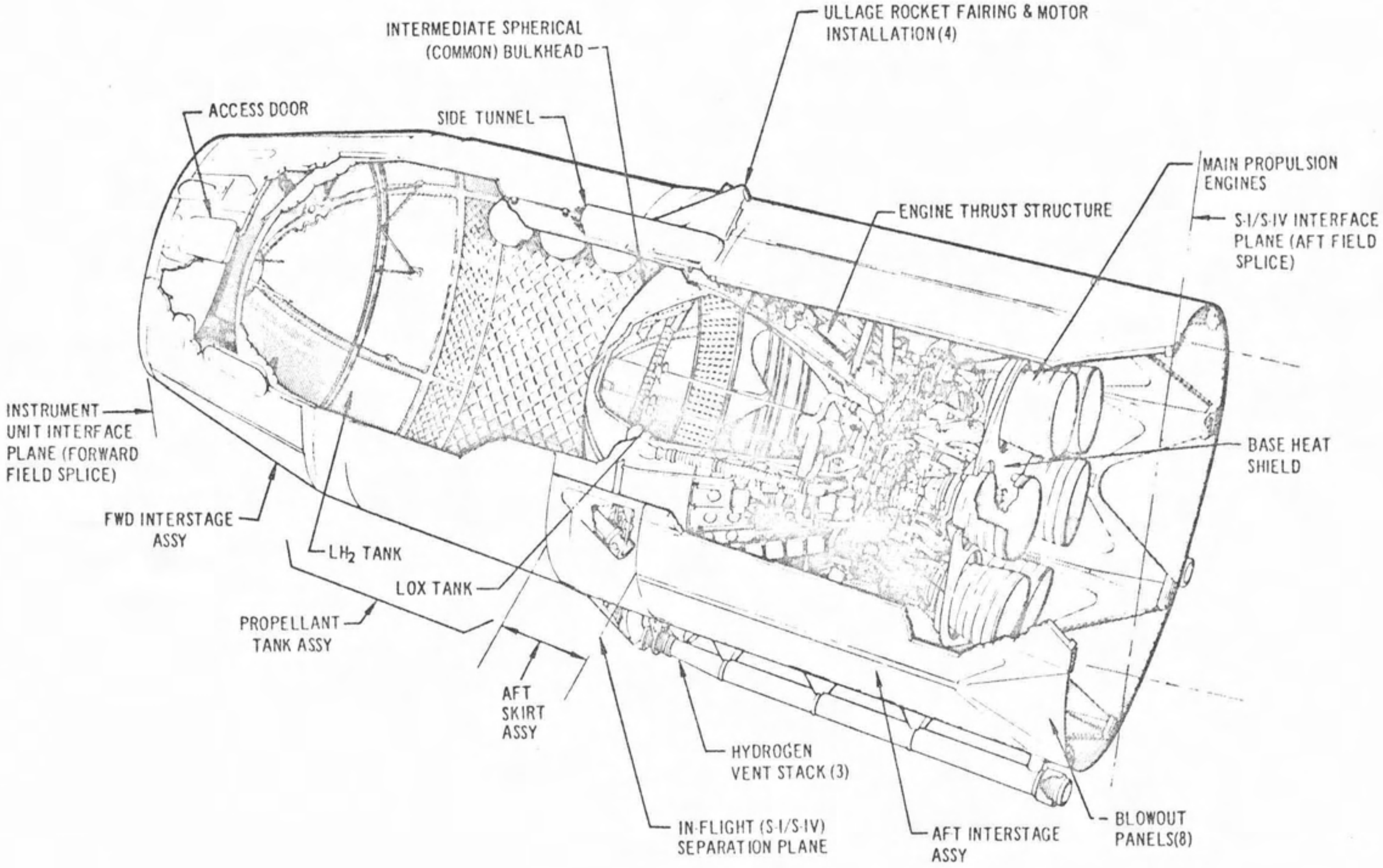


FIGURE 1

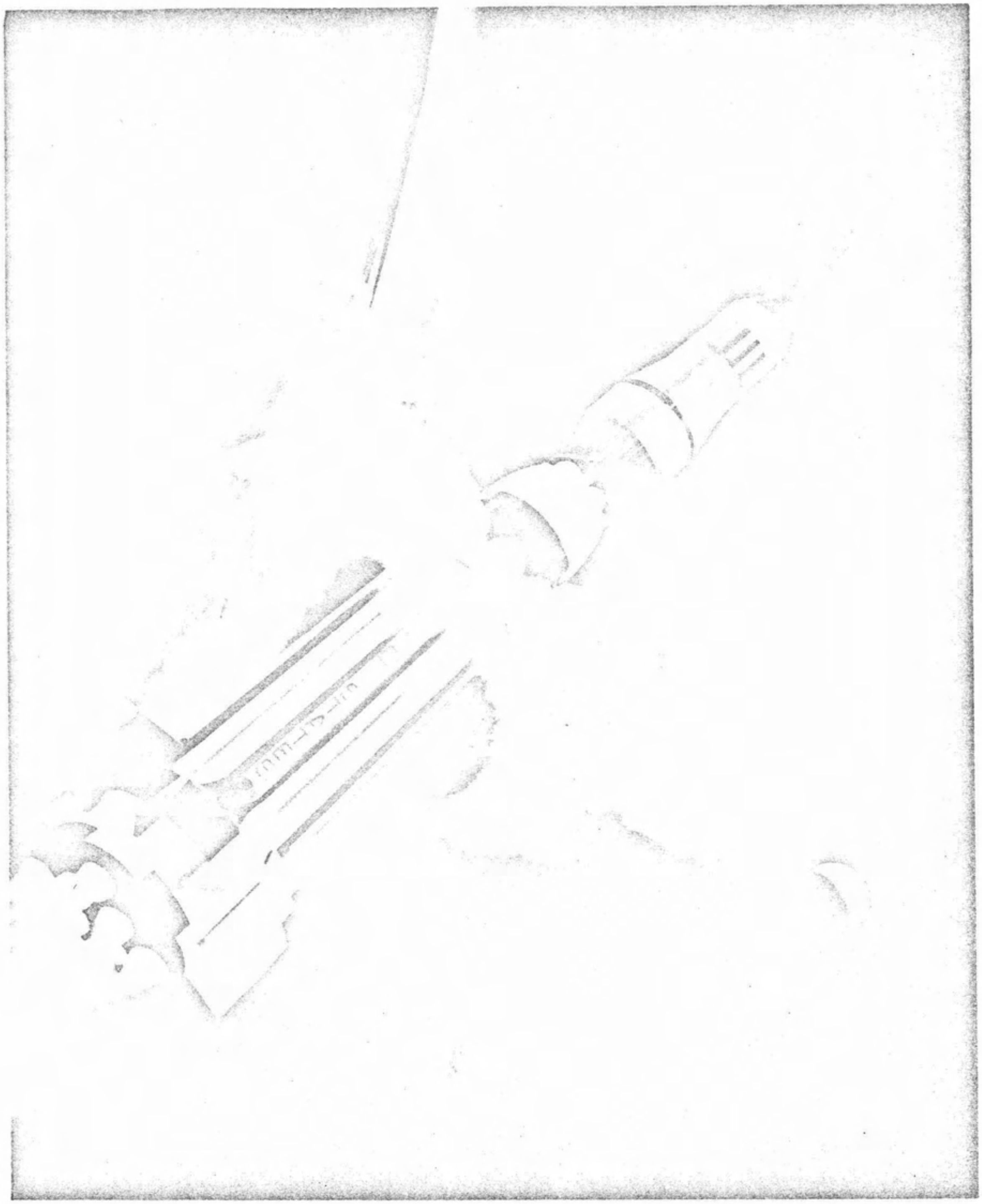


FIGURE 2

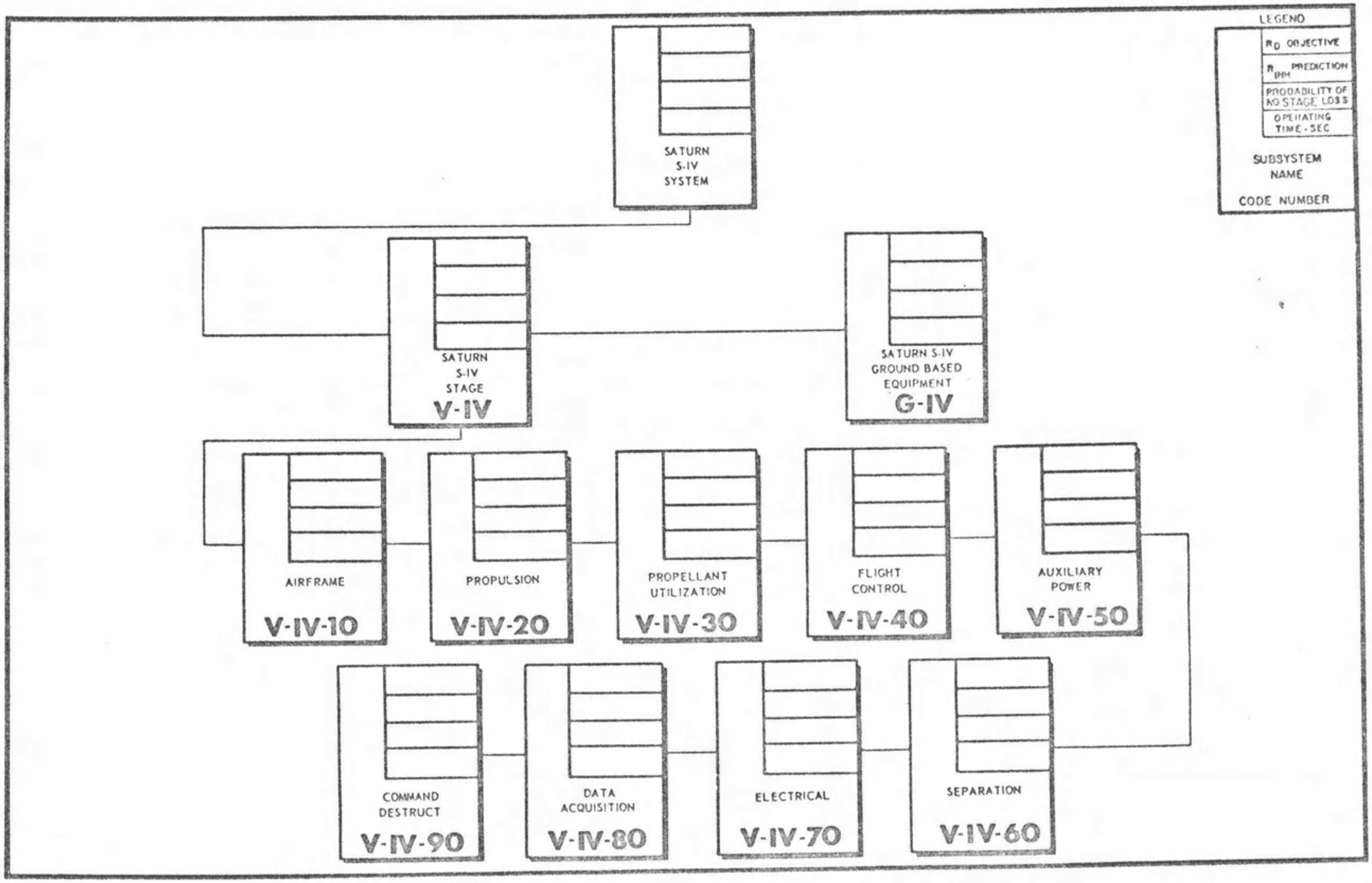

LEGEND
R_D OBJECTIVE
R_{INH} PREDICTION
PROBABILITY OF NO STAGE LOSS
OPERATING TIME - SEC
SUBSYSTEM NAME
CODE NUMBER
SATURN S-IV SYSTEM
SATURN S-IV STAGE
V-IV
SATURN S-IV GROUND BASED EQUIPMENT
G-IV
AIRFRAME
V-IV-10
PROPULSION
V-IV-20
PROPELLANT UTILIZATION
V-IV-30
FLIGHT CONTROL
V-IV-40
AUXILIARY POWER
V-IV-50
SEPARATION
V-IV-60
ELECTRICAL
V-IV-70
DATA ACQUISITION
V-IV-80
COMMAND DESTRUCT
V-IV-90

FIGURE 3

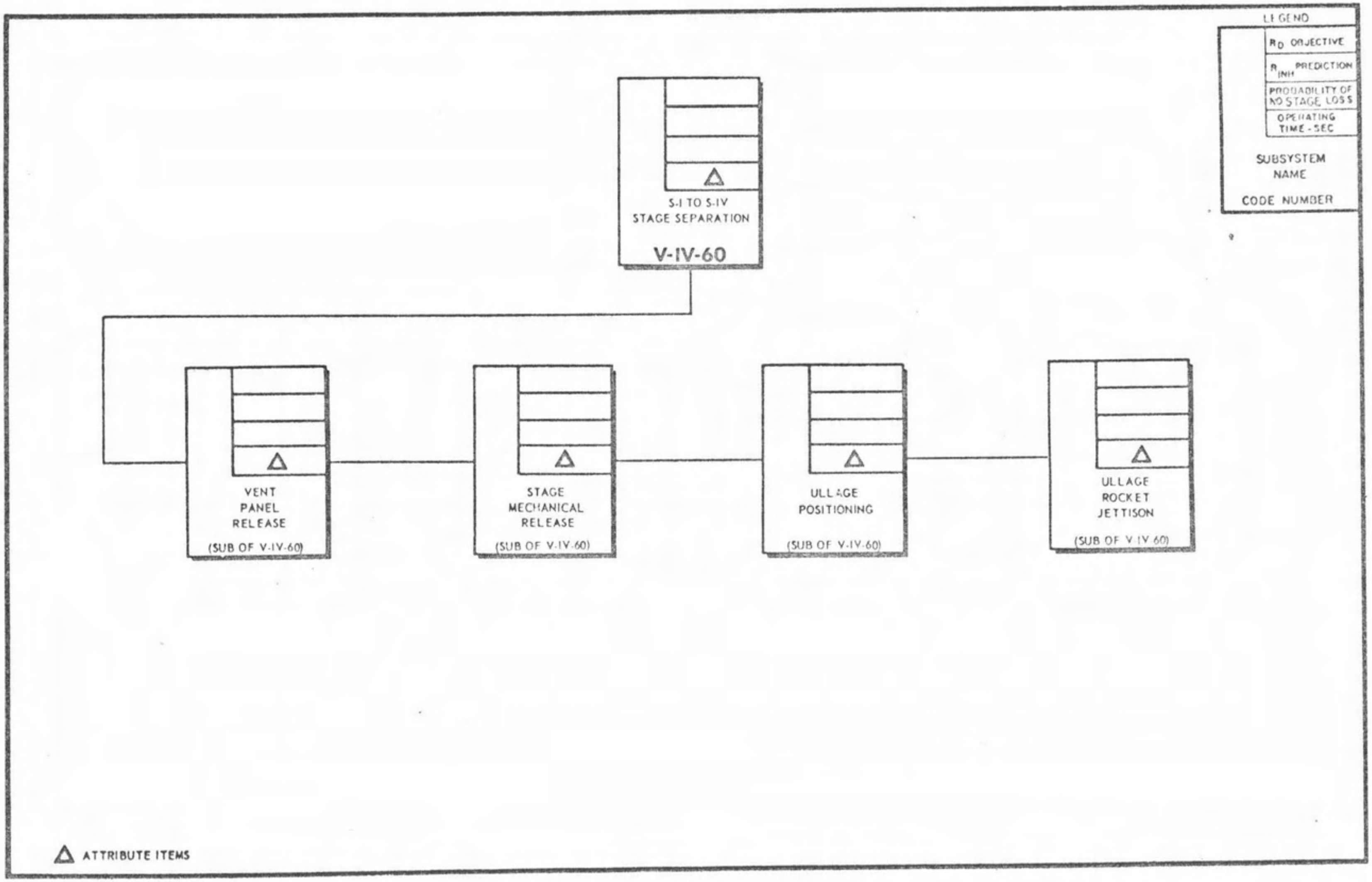
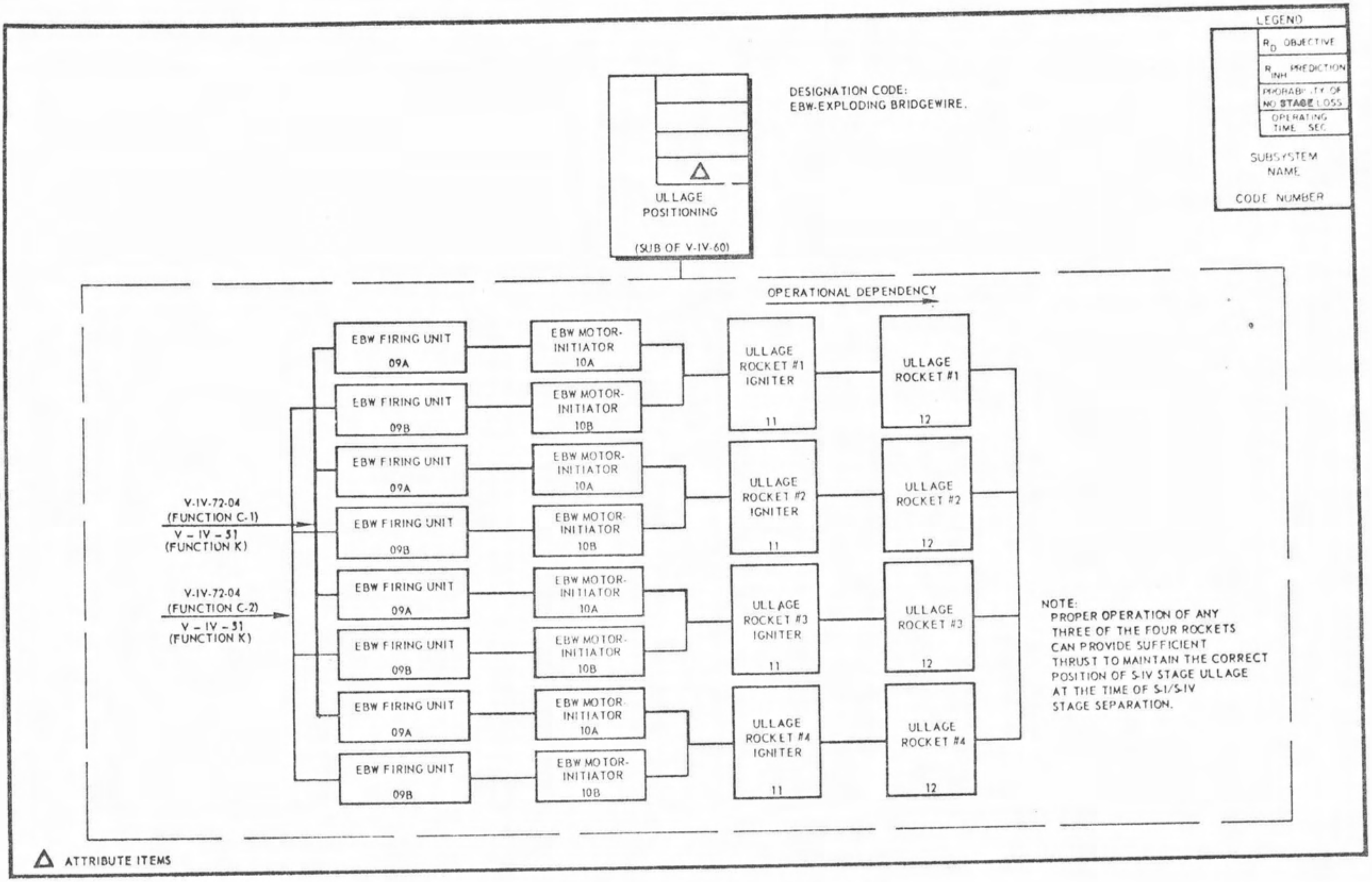
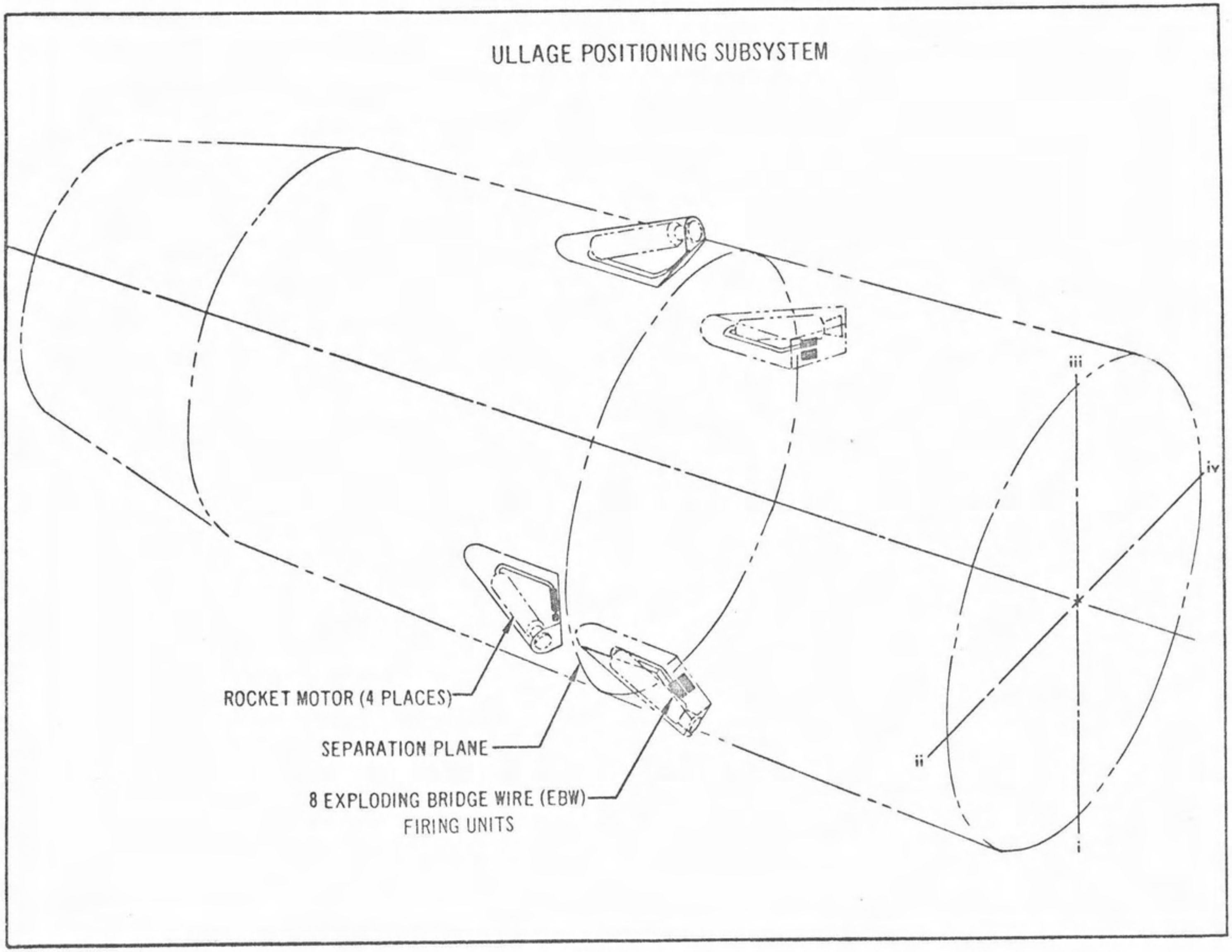

LEGEND
R_D OBJECTIVE
R_{INH} PREDICTION
PROBABILITY OF NO STAGE LOSS
OPERATING TIME - SEC
SUBSYSTEM NAME
CODE NUMBER
S-I TO S-IV STAGE SEPARATION
V-IV-60
VENT PANEL RELEASE
(SUB OF V-IV-60)
STAGE MECHANICAL RELEASE
(SUB OF V-IV-60)
ULLAGE POSITIONING
(SUB OF V-IV-60)
ULLAGE ROCKET JETTISON
(SUB OF V-IV-60)
△ ATTRIBUTE ITEMS

FIGURE 4



NOTE:
PROPER OPERATION OF ANY THREE OF THE FOUR ROCKETS CAN PROVIDE SUFFICIENT THRUST TO MAINTAIN THE CORRECT POSITION OF S-IV STAGE ULLAGE AT THE TIME OF S-I/S-IV STAGE SEPARATION.

FIGURE 5



ULLAGE POSITIONING SUBSYSTEM

FIGURE 6

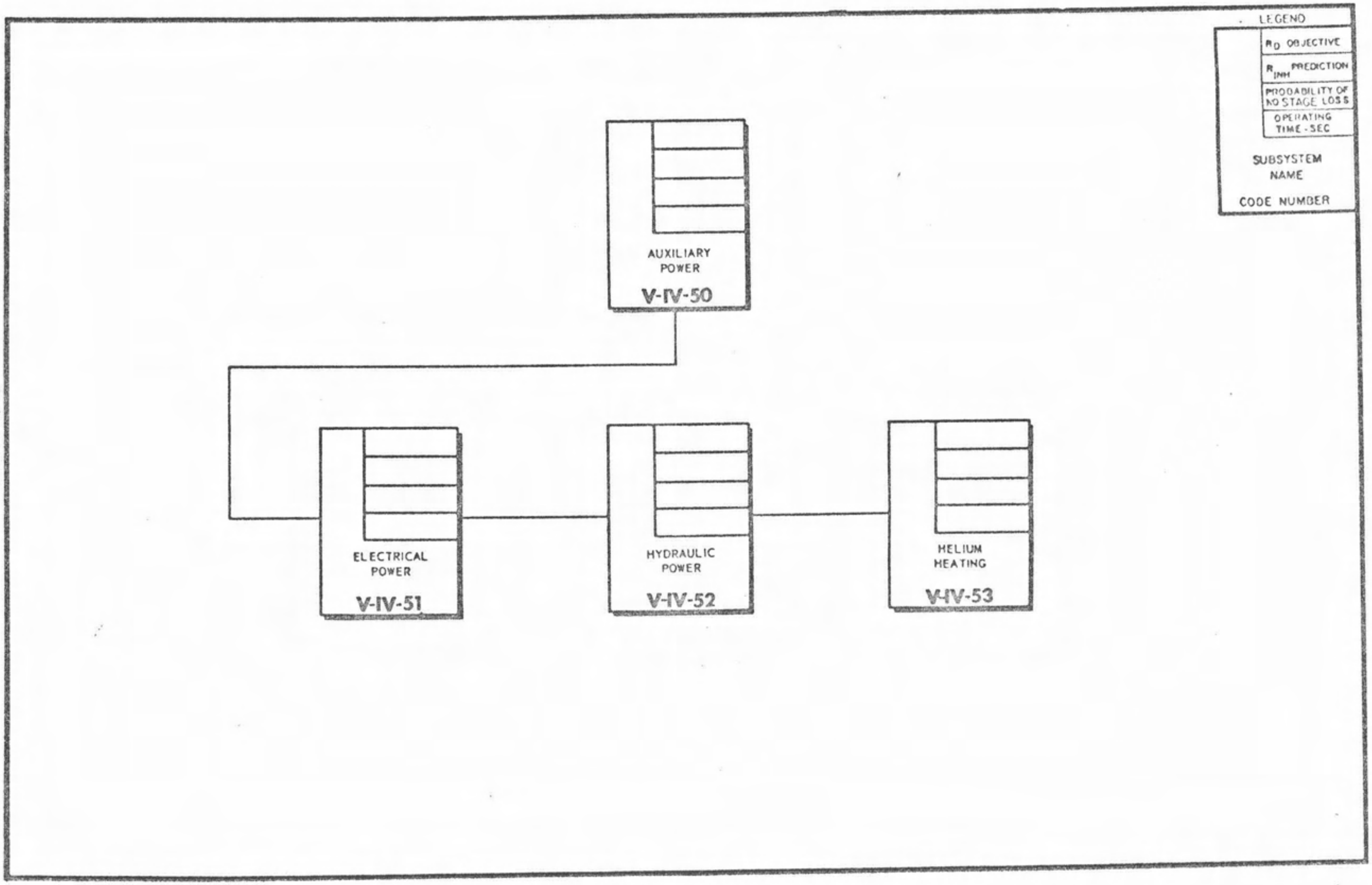
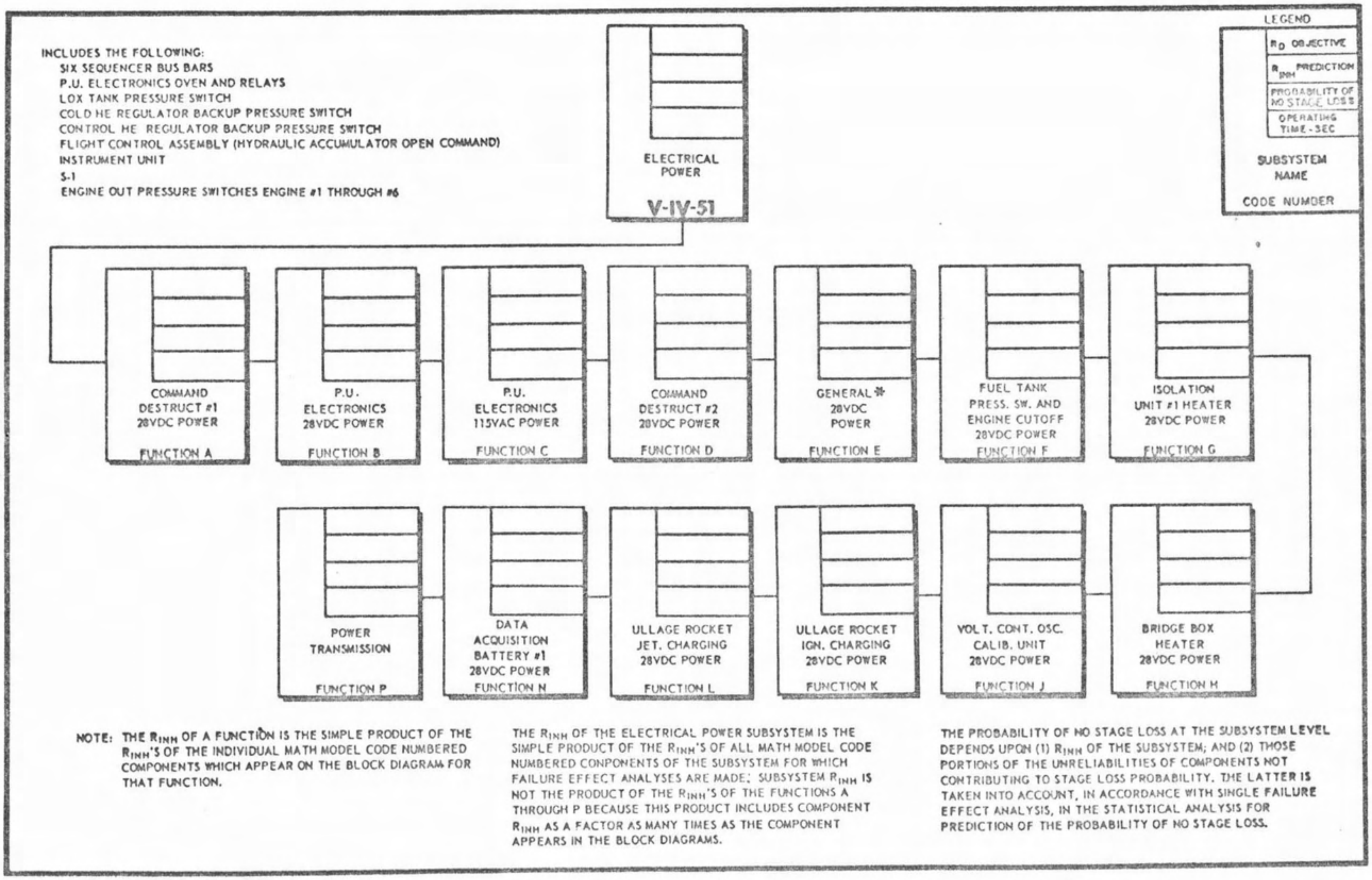

LEGEND
R_D OBJECTIVE
R_{INH} PREDICTION
PROBABILITY OF NO STAGE LOSS
OPERATING TIME - SEC
SUBSYSTEM NAME
CODE NUMBER
AUXILIARY POWER
V-IV-50
ELECTRICAL POWER
V-IV-51
HYDRAULIC POWER
V-IV-52
HELIUM HEATING
V-IV-53

FIGURE 7



* INCLUDES THE FOLLOWING:
- SIX SEQUENCER BUS BARS
- P.U. ELECTRONICS OVEN AND RELAYS
- LOX TANK PRESSURE SWITCH
- COLD HE REGULATOR BACKUP PRESSURE SWITCH
- CONTROL HE REGULATOR BACKUP PRESSURE SWITCH
- FLIGHT CONTROL ASSEMBLY (HYDRAULIC ACCUMULATOR OPEN COMMAND)
- INSTRUMENT UNIT
- S-1
- ENGINE OUT PRESSURE SWITCHES ENGINE #1 THROUGH #6

NOTE: THE R_{INH} OF A FUNCTION IS THE SIMPLE PRODUCT OF THE R_{INH}'S OF THE INDIVIDUAL MATH MODEL CODE NUMBERED COMPONENTS WHICH APPEAR ON THE BLOCK DIAGRAM FOR THAT FUNCTION.

THE R_{INH} OF THE ELECTRICAL POWER SUBSYSTEM IS THE SIMPLE PRODUCT OF THE R_{INH}'S OF ALL MATH MODEL CODE NUMBERED CONPONENTS OF THE SUBSYSTEM FOR WHICH FAILURE EFFECT ANALYSES ARE MADE; SUBSYSTEM R_{INH} IS NOT THE PRODUCT OF THE R_{INH}'S OF THE FUNCTIONS A THROUGH P BECAUSE THIS PRODUCT INCLUDES COMPONENT R_{INH} AS A FACTOR AS MANY TIMES AS THE COMPONENT APPEARS IN THE BLOCK DIAGRAMS.

THE PROBABILITY OF NO STAGE LOSS AT THE SUBSYSTEM LEVEL DEPENDS UPON (1) R_{INH} OF THE SUBSYSTEM; AND (2) THOSE PORTIONS OF THE UNRELIABILITIES OF COMPONENTS NOT CONTRIBUTING TO STAGE LOSS PROBABILITY. THE LATTER IS TAKEN INTO ACCOUNT, IN ACCORDANCE WITH SINGLE FAILURE EFFECT ANALYSIS, IN THE STATISTICAL ANALYSIS FOR PREDICTION OF THE PROBABILITY OF NO STAGE LOSS.

FIGURE 8

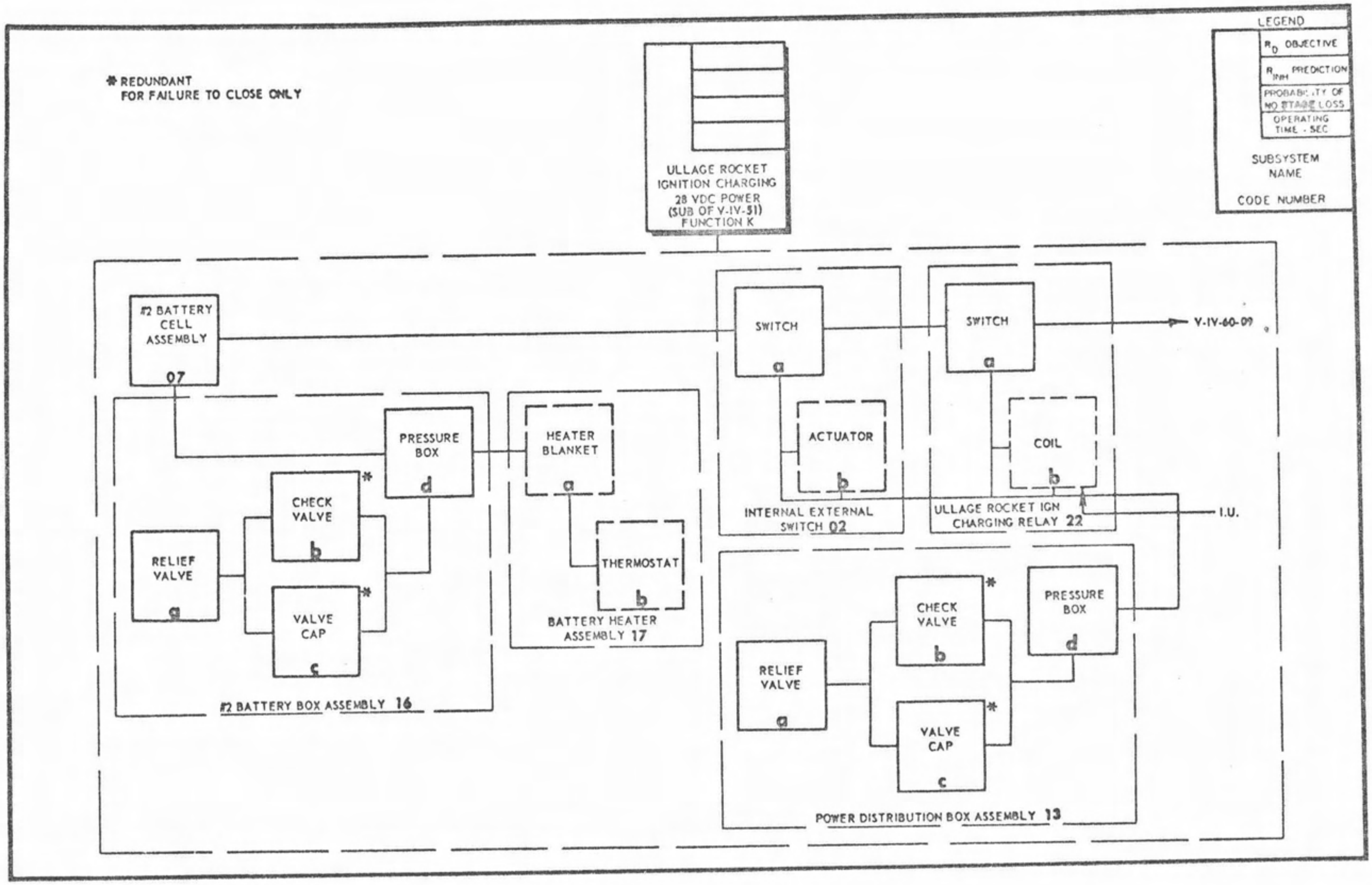

* REDUNDANT
FOR FAILURE TO CLOSE ONLY
LEGEND
R_O OBJECTIVE
R_{INH} PREDICTION
PROBABILITY OF NO STAGE LOSS
OPERATING TIME - SEC
SUBSYSTEM NAME
CODE NUMBER
ULLAGE ROCKET IGNITION CHARGING 28 VDC POWER (SUB OF V-IV-51) FUNCTION K
#2 BATTERY CELL ASSEMBLY
07
PRESSURE BOX
d
CHECK VALVE
b
RELIEF VALVE
a
VALVE CAP
c
#2 BATTERY BOX ASSEMBLY 16
HEATER BLANKET
a
THERMOSTAT
b
BATTERY HEATER ASSEMBLY 17
SWITCH
a
ACTUATOR
b
INTERNAL EXTERNAL SWITCH 02
SWITCH
a
COIL
b
ULLAGE ROCKET IGN CHARGING RELAY 22
V-IV-60-09
I.U.
CHECK VALVE
b
PRESSURE BOX
d
RELIEF VALVE
a
VALVE CAP
c
POWER DISTRIBUTION BOX ASSEMBLY 13

FIGURE 9

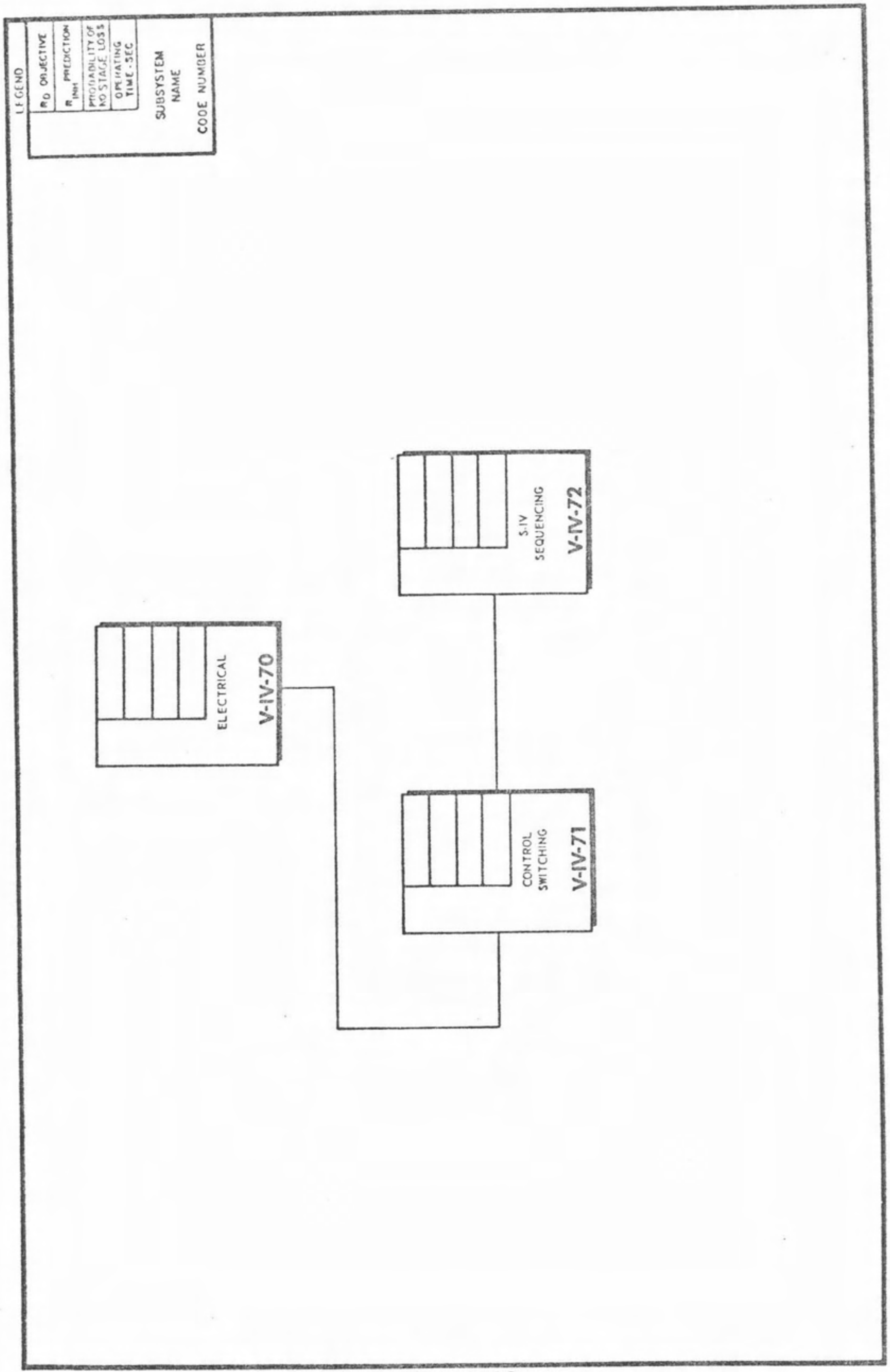

LEGEND
R_O OBJECTIVE
R_{INH} PREDICTION
PROBABILITY OF NO STAGE LOSS
OPERATING TIME - SEC
SUBSYSTEM NAME
CODE NUMBER
ELECTRICAL
V-IV-70
S-IV SEQUENCING
V-IV-72
CONTROL SWITCHING
V-IV-71

FIGURE 10

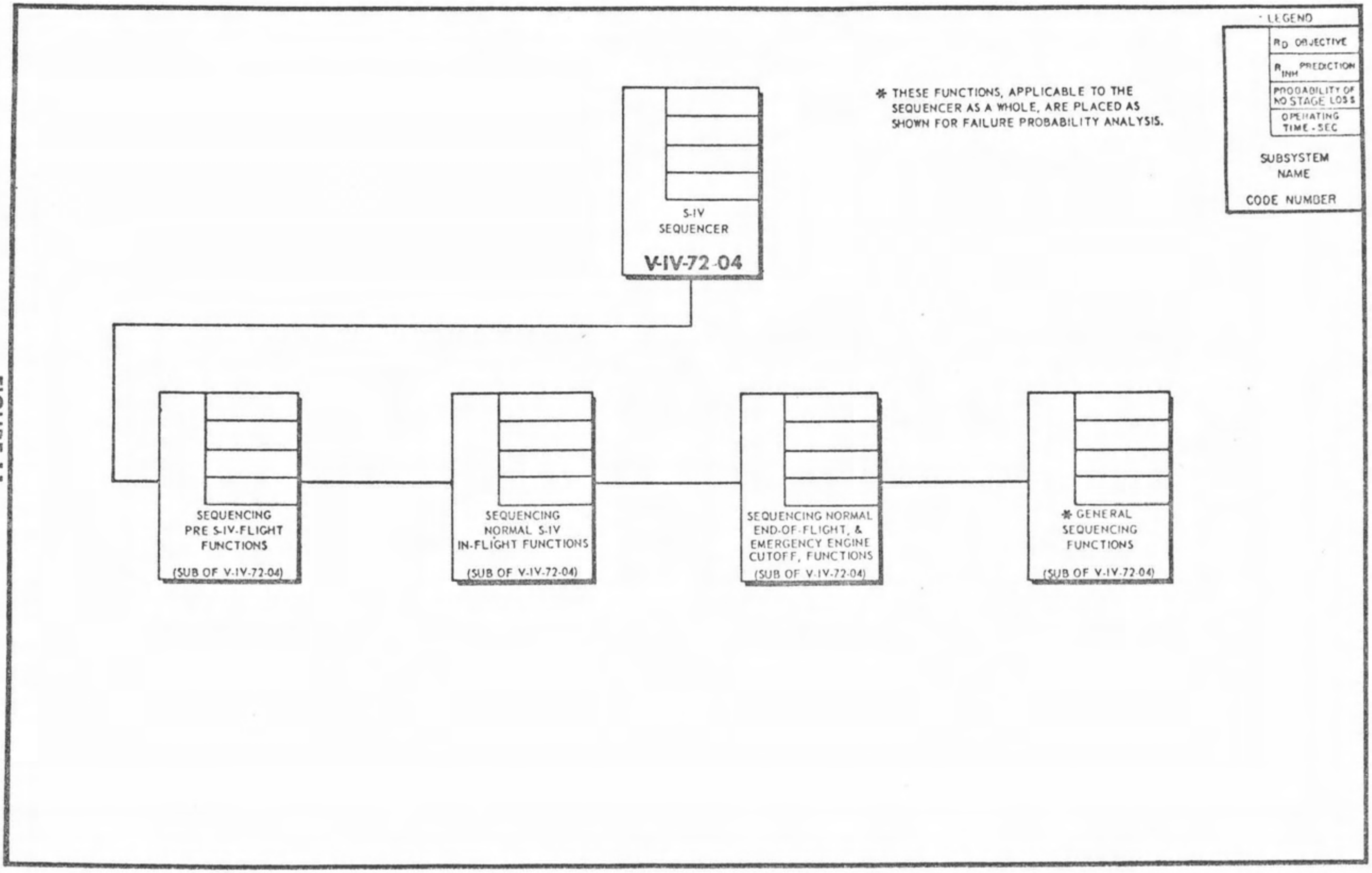
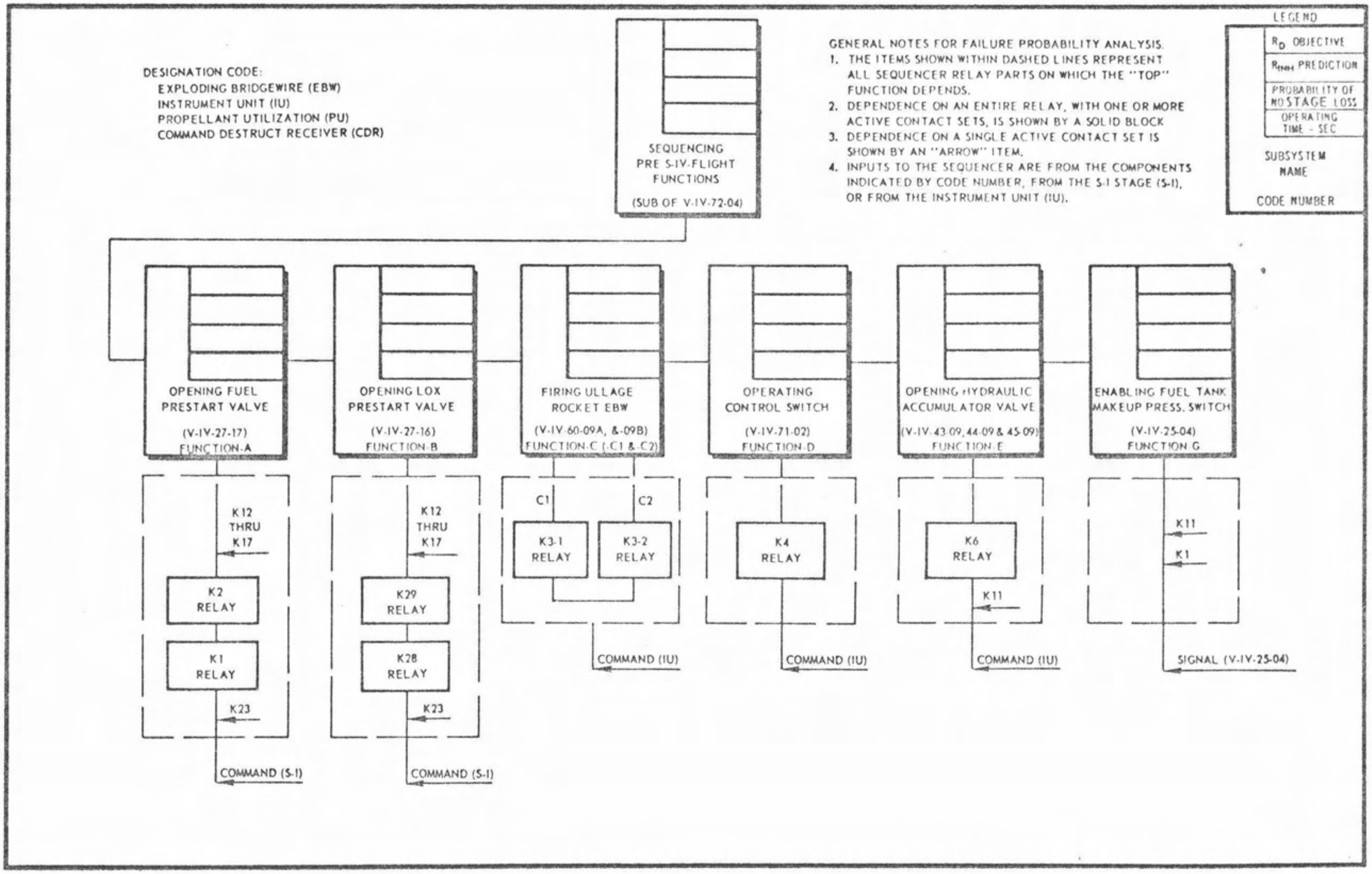

LEGEND
R_D OBJECTIVE
R_{INH} PREDICTION
PROBABILITY OF NO STAGE LOSS
OPERATING TIME - SEC
SUBSYSTEM NAME
CODE NUMBER
* THESE FUNCTIONS, APPLICABLE TO THE SEQUENCER AS A WHOLE, ARE PLACED AS SHOWN FOR FAILURE PROBABILITY ANALYSIS.
S-IV SEQUENCER
V-IV-72-04
SEQUENCING PRE S-IV-FLIGHT FUNCTIONS
(SUB OF V-IV-72-04)
SEQUENCING NORMAL S-IV IN-FLIGHT FUNCTIONS
(SUB OF V-IV-72-04)
SEQUENCING NORMAL END-OF-FLIGHT, & EMERGENCY ENGINE CUTOFF, FUNCTIONS
(SUB OF V-IV-72-04)
* GENERAL SEQUENCING FUNCTIONS
(SUB OF V-IV-72-04)

FIGURE 11

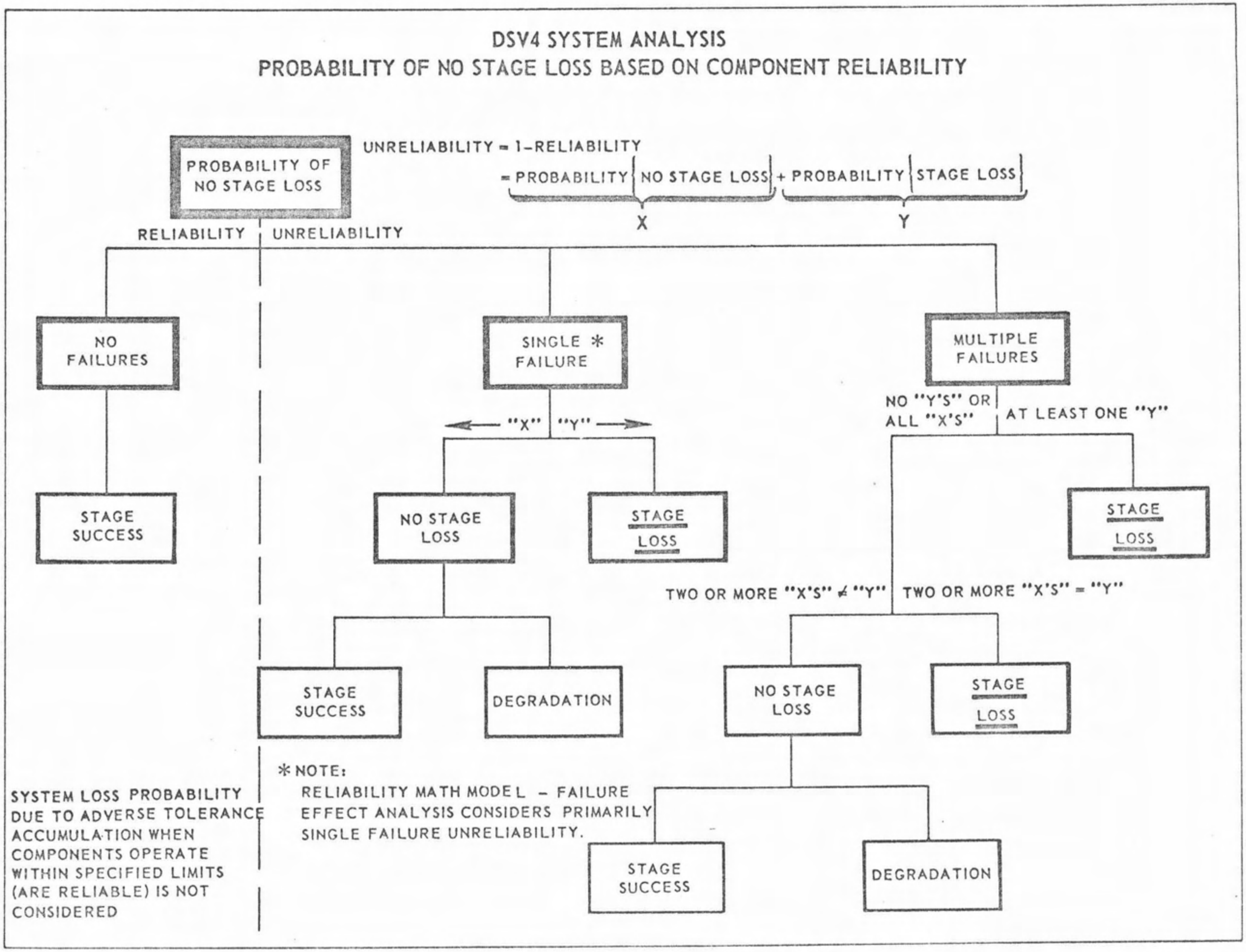


DESIGNATION CODE:
EXPLODING BRIDGEWIRE (EBW)
INSTRUMENT UNIT (IU)
PROPELLANT UTILIZATION (PU)
COMMAND DESTRUCT RECEIVER (CDR)

GENERAL NOTES FOR FAILURE PROBABILITY ANALYSIS.

1. THE ITEMS SHOWN WITHIN DASHED LINES REPRESENT ALL SEQUENCER RELAY PARTS ON WHICH THE "TOP" FUNCTION DEPENDS.
2. DEPENDENCE ON AN ENTIRE RELAY, WITH ONE OR MORE ACTIVE CONTACT SETS, IS SHOWN BY A SOLID BLOCK
3. DEPENDENCE ON A SINGLE ACTIVE CONTACT SET IS SHOWN BY AN "ARROW" ITEM.
4. INPUTS TO THE SEQUENCER ARE FROM THE COMPONENTS INDICATED BY CODE NUMBER, FROM THE S-I STAGE (S-I), OR FROM THE INSTRUMENT UNIT (IU).

FIGURE 12



DSV4 SYSTEM ANALYSIS
PROBABILITY OF NO STAGE LOSS BASED ON COMPONENT RELIABILITY

SYSTEM LOSS PROBABILITY DUE TO ADVERSE TOLERANCE ACCUMULATION WHEN COMPONENTS OPERATE WITHIN SPECIFIED LIMITS (ARE RELIABLE) IS NOT CONSIDERED

* NOTE:
RELIABILITY MATH MODEL – FAILURE EFFECT ANALYSIS CONSIDERS PRIMARILY SINGLE FAILURE UNRELIABILITY.

FIGURE 13

FIGURE 14

Δ ITEMS MARKED THUS (Δ) DO NOT OPERATE IN FLIGHT

RELIABILITY FAILURE EFFECT ANALYSIS

A) COUNTDOWN - MANUAL
B) COUNTDOWN - AUTOMATIC SEQUENCE
C) FLIGHT - BOOST PHASE
D) FLIGHT - POWERED PHASE

ULLAGE POSITIONING SUBSYSTEM (SUB OF V-IV-60)

Δ	ITEM	FUNCTION	FAILURE TYPE	FAILURE EFFECT ON SUBSYSTEM PERFORMANCE	FAILURE EFFECT ON S-IV STAGE	FAILURE EFFECT ON SATURN I VEHICLE
	Exploding Bridgewire (EBW) Firing Unit (8) For Ullage Rocket Ignition Ref. Dwg. 7865719-541 V-IV-60-09A, V-IV-60-09B	Explodes bridgewire in an associated initiator upon receipt of an electrical trigger signal. Charging of units begins approx. seven seconds prior to triggering. Time of triggering is between T-.116 sec and T-.106 sec.	1) Premature explosion of bridgewire (Subseouent ignition of associated explosive train is assumed to occur.).	None for single failure. Proper operation of three rockets out of four gives sufficient thrust to maintain correct ullage position.	A) B) None; premature mode is not applicable because EBW units are not charged until C) phase.	Same
					C) None; redundancy provided.	None; effect of unbalanced side thrust is considered negligible.
					D) Not applicable. Start of function occurs prior to D) phase.	Same
			2) Failure to explode bridgewire when required.	None; redundancy provided.	A) B) None: not applicable because function is not required until C) phase.	Same
					C) None; redundancy provided.	Same
					D) Not applicable. Function occurs prior to D) phase.	Same
	EBW Motor-Initiator (8) For Ullage Rocket Igniter (GFE) V-IV-60-10A, V-IV-60-10B	Activates ullage rocket igniter.	Failure to start igniter when required.	None; redundancy provided. Two initiators are provided for each rocket, and either one can start the rocket igniter.	A) B) None; not applicable because function is not required until C) phase.	Same
					C) None; redundancy provided.	Same
					D) Not applicable. Function occurs prior to D) phase.	Same
	Ullage Rocket Igniter (4) (GFE) P/N DR36691 Thiokol V-IV-60-11	Starts rocket motor.	Failure to start motor when required.	None; redundancy is provided to the extent that proper starting of three out of four motors gives sufficient thrust to maintain correct ullage position.	A) B) None: not applicable because function is not required until C) phase.	Same
					C) None; redundancy provided.	Same
					D) Not applicable. Function occurs prior to D) phase.	Same

(REFERENCE FIGURE 5)

Δ ITEMS MARKED THUS (Δ) DO NOT OPERATE IN FLIGHT

RELIABILITY FAILURE EFFECT ANALYSIS

A) COUNTDOWN - MANUAL
B) COUNTDOWN - AUTOMATIC SEQUENCE
C) FLIGHT - BOOST PHASE
D) FLIGHT - POWERED PHASE

ULLAGE POSITIONING SUBSYSTEM (SUB OF V-IV-60)

Δ	ITEM	FUNCTION	FAILURE TYPE	FAILURE EFFECT ON SUBSYSTEM PERFORMANCE	FAILURE EFFECT ON S-IV STAGE	FAILURE EFFECT ON SATURN I VEHICLE
	Ullage Rocket Motor (4) GFE) Thiokol Model TX280 P/N FR36192 V-IV-60-12	Gives forward thrust to S-IV stage at time of S-I/S-IV separation. Rockets are ignited approximately one-tenth second prior to the end of boost phase and burn for approximately 3.6 seconds, for the purpose of avoiding any unseating of S-IV tank contents between the decay of S-I thrust and the build-up of thrust from S-IV engines.	1) Failure to provide thrust when required.	None; redundancy is provided to the extent that firing three motors, out of four, gives sufficient thrust to maintain correct ullage position.	A) B) None; not applicable because function is not required until C) phase. C) D) None; redundancy provided.	Same Same
			2) Failure during operation, in the form of a rocket burst.	None; subsystem can still function. Proper operation of any three of the four rockets can provide sufficient thrust to maintain the correct position of S-IV stage ullage at the time of S-I/S-IV stage separation.	A) B) None; not applicable because separation occurs in C) and D) phase. C) D) <u>PROBABLE LOSS OF STAGE</u> Rocket burst could cause structural failure.	Same <u>PROBABLE LOSS OF VEHICLE</u> FRT $>$ <u>.01</u> sec.
			3) Failure during operation in the form of a rocket "burn-through".		A) B) None; not applicable because operation occurs in C) and D) phase. C) D) <u>PROBABLE LOSS OF STAGE</u> Flame from burn-through opening in rocket case could cause structural failure.	Same <u>PROBABLE LOSS OF VEHICLE</u> FRT $>$ <u>0.5</u> sec.
			4) Failure to stop operation in form of "chuff" from residual unburned fuel.		A) B) C) Not applicable. Failure to stop operation can only occur during D) phase. D) <u>POSSIBLE STAGE LOSS</u> A "chuff" after rocket has been jettisoned could cause rocket to strike and damage the stage.	Same <u>POSSIBLE LOSS OF VEHICLE</u> FRT$>$<u>1.0</u> sec.

(REFERENCE FIGURE 5)

FIGURE 15

FIGURE 16

Δ ITEMS MARKED THUS (*) DO NOT OPERATE IN FLIGHT

RELIABILITY FAILURE EFFECT ANALYSIS

ELECTRICAL POWER SUBSYSTEM

A) COUNTDOWN - MANUAL
B) COUNTDOWN - AUTOMATIC SEQUENCE
C) FLIGHT - BOOST PHASE
D) FLIGHT - POWERED PHASE
E) FLIGHT - COAST PHASE

Δ	ITEM	FUNCTION	FAILURE TYPE	FAILURE EFFECT ON SUBSYSTEM PERFORMANCE	FAILURE EFFECT ON S-IV STAGE	FAILURE EFFECT ON "C" VEHICLE
	Voltage Control Oscillator Calibration Start Switch Ref. Dwg. No. 1A77710-1 V-IV-51-21 NOTE: This item includes switch (relay) contacts and coil. (continued)		3) Failure to stop operation when required to the extent of not de-energizing calibration box when required.	None; the power subsystem performance is not affected by this failure.	A) Delay in launching or scrub.	Same
					B) This failure does not hold automatic countdown sequence.	Same
					C) D) Loss of all data acquisition from S-IV stage.	Same
	Ullage Rocket Ignition Charging Relay For Charging Exploding Bridgewire (EBW) Units Ref. Dwg. No. 5884428 V-IV-51-22 NOTE: This item includes switch (relay) contacts and coil	Provides for the connection of battery #2 power to the charging circuit of EBW firing units (V-IV-60-09A, -09B) used in starting ullage rockets (V-IV-61-12). NOTE: Nominal time for start of EBW charging is 7.106 seconds before S-I/S-IV separation time.	1) Premature operation to the extent of connecting charging power sooner than required.	None; the power subsystem performance is considered unaffected by premature charging of EBW units as a result of this failure.	A) Delay in launching.	Same
					B) This failure holds automatic countdown sequence. The signal showing uncharged condition is not ready.	Same
					C) None; the resultant EBW-charged condition is considered significant only in the event a second failure causes premature discharge of these units.	Same
					D) None; not applicable because units are charged prior to this phase.	Same
			2) Failure to operate when required, and to maintain the connection.	PARTIAL LOSS OF SUBSYSTEM Power is not supplied for charging EBW firing units.	A) B) None; not applicable because operation is not required until C) phase.	Same
					C) PROBABLE LOSS OF STAGE Due to possible thrust loss, through engine pump cavitation resulting from lack of ullage positioning.	PROBABLE LOSS OF MISSION FRT>0.1 sec.
					D) None; not applicable because operation is required in C) phase.	Same

(REFERENCE FIGURE 9)

Δ ITEMS MARKED THUS (Δ) DO NOT OPERATE IN FLIGHT

RELIABILITY FAILURE EFFECT ANALYSIS

S-IV SEQUENCING SUBSYSTEM (S-IV SEQUENCER)

A) COUNTDOWN - MANUAL
B) COUNTDOWN - AUTOMATIC SEQUENCE
C) FLIGHT - BOOST PHASE
D) FLIGHT - POWERED PHASE
E) FLIGHT - COAST PHASE

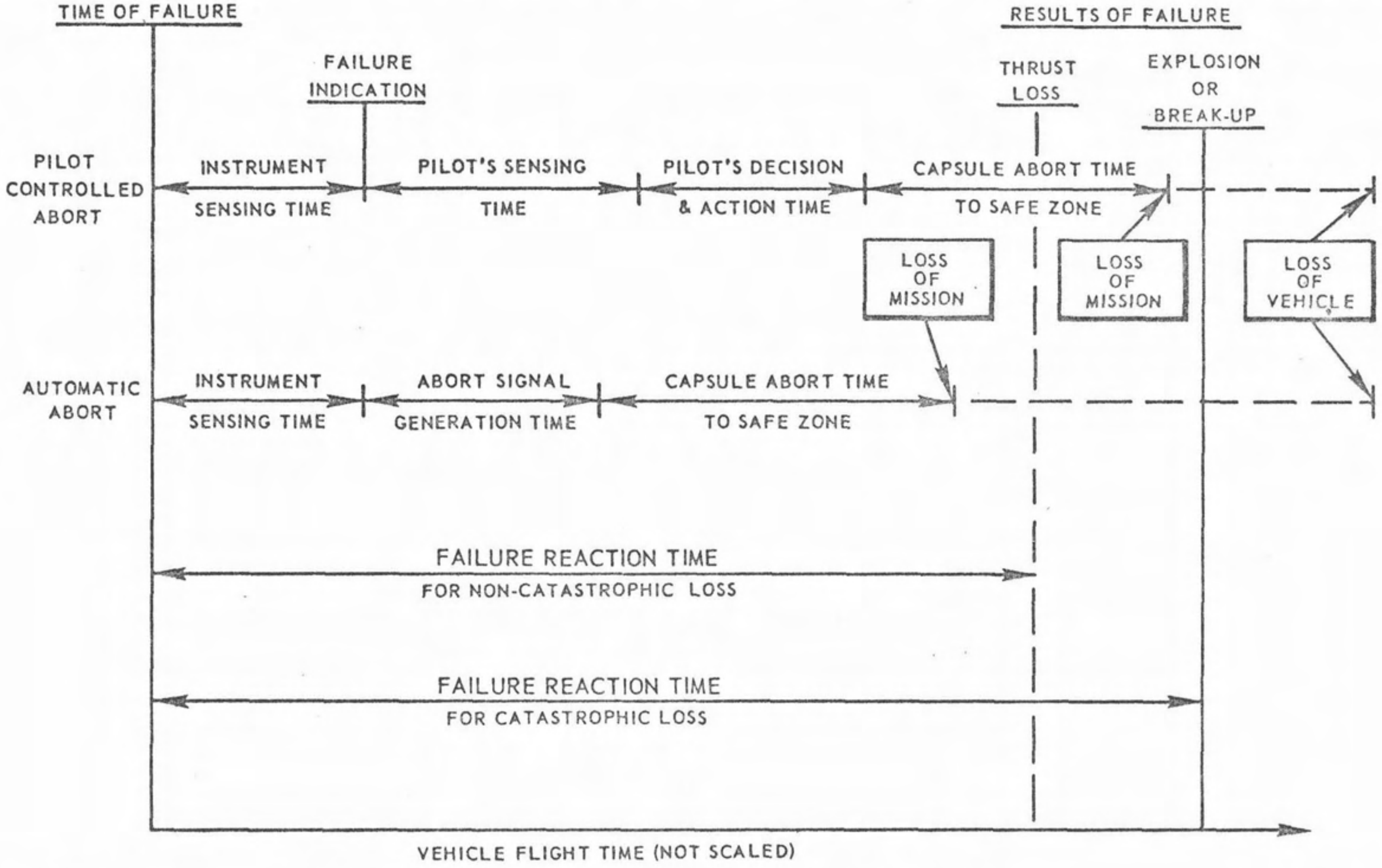
Δ	ITEM	FUNCTION	FAILURE TYPE	FAILURE EFFECT ON SUBSYSTEM PERFORMANCE	FAILURE EFFECT ON S-IV STAGE	FAILURE EFFECT ON "C" VEHICLE
	S-IV Sequencer 5873792 V-IV-72-04 (continued)	Function -C, firing ullage rocket EBW, provides 28VDC electric power to trigger eight exploding bridge-wire (EBW) units (V-IV-60-09A, and -09B). Either relay (K3-1 or K3-2) can trigger four EBW units, one per rocket, and thus fire all four ullage rockets. NOTE: Charging of these EBW units begins at nominal T-7.106 seconds, approximately seven seconds ahead of the required time of triggering at nominal T-.106 seconds near end of C) phase. An EBW unit cannot be charged while 28VDC is connected to its trigger circuit.	1) Premature operation of a single relay to connect power to four EBW trigger circuits. a) Premature triggering before EBW units are charged.	None; subsystem performance can still be accomplished.	A) Delay in launching. B) This failure does not hold automatic countdown sequence. C) D) None; redundancy provided.	Same Same Same
			b) Premature triggering after EBW units are charged.	PARTIAL LOSS OF SUBSYSTEM Function -C not in sequence.	A) B) None; not applicable because charging occurs in approximately the last seven seconds of C) phase. C) None; the resultant firing of ullage rockets is considered significant for only its effect on the vehicle in phase D). D) PROBABLE LOSS OF STAGE Due to possible "no engine start" through pump cavitation resulting from lack of ullage positioning.	Same Same PROBABLE LOSS OF MISSION FRT >3 sec.
			2) Single failure of either relay (K3-1 or K3-2) to fire the four associated EBW units when required.	None; redundancy provided.	A) B) None; not applicable, not required until C) phase. C) None; redundancy provided. D) None; the failure to fire when required mode is not applicable because the firing is required in C) phase.	Same Same Same

(REFERENCE FIGURE 12)

FIGURE 17

FIGURE 18

DEFINITION OF FAILURE REACTION TIME, LOSS OF VEHICLE AND LOSS OF MISSION



- LOSS OF VEHICLE – LOSS OF THE VEHICLE INCLUDING THE PAYLOAD OR CAPSULE
- LOSS OF MISSION – LOSS OF THE VEHICLE EXCLUDING THE PAYLOAD OR CAPSULE
- THIS DEFINITION APPLIES TO THE VEHICLE WITH A PAYLOAD ABORT CAPABILITY;

RELIABILITY MATHEMATICAL MODEL SUMMARY

SYSTEM Name of System
SUBSYSTEM Name of Subsystem
Math Model Number/Code

FOR C & D OPERATIONAL TIME PHASE(S)

OPERATIONAL TIME PHASES
A) COUNTDOWN - MANUAL
B) COUNTDOWN - AUTOMATIC SEQUENCE
C) FLIGHT - BOOST PHASE
D) FLIGHT - POWERED PHASE
E) FLIGHT - COAST PHASE

RELIABILITY FAILURE EFFECT ANALYSIS SUMMARY - PHASE 1				SELECTION OF CRITICAL ITEMS - PHASE 2									
					TIME/CYCLE SIGNIFICANT			ATTRIBUTE					
ITEM	MATH MODEL NUMBER	FAILURE TYPE	(β) STAGE LOSS FREQUENCY	(α) FAILURE TYPE-MODE FREQUENCY	(t) OPERATING TIME (CYCLES OR HOURS)	(κ) OPERATIONAL MODE FACTOR	(λ) FAILURE RATE	(q) FAILURE PROBABILITY OR $(t \cdot k \cdot \lambda)$	(r) ITEM RELIABILITY $(e^{-tk\lambda})$ OR $(1-q)$	UNRELIABILITY NOT CONTRIBUTING TO STAGE LOSS $\alpha(1-r)(1-\beta)$	UNRELIABILITY CONTRIBUTING TO STAGE LOSS $\alpha\beta(1-r)$	CRITICALITY NUMBER $(\Sigma\alpha_n\beta_n) \times (1-r)10^6$	DATA SOURCE CODE
			β is the conditional probability of stage loss associated with the indicated failure type.	α is the fraction of item unreliability associated with the indicated failure type.	t is the expected number of cycles or time of operation in hours for an item during a mission (operational time phases specified).	κ is the adjustment factor for raw failure rate of an item to reflect realistic failure rate under mission environment.	λ is the failure rate determined from historical data of the items' operation collected under room ambient, specific, simulated, or actual environments.	q is the probability that the item will not operate as required for a specified mission time and mission operating environment; the inherent item unreliability for the mission intended.	r is the probability that the item will operate as required for a specified mission time and mission operating environment; the inherent item reliability for the mission intended.	The portion of inherent item unreliability assignable to the indicated failure type which does not contribute to stage loss.	The portion of inherent item unreliability assignable to the indicated failure type which does contribute to stage loss.	The portion of inherent item unreliability assignable to all of the indicated failure types of an item which contribute to stage loss, multiplied by 10^6.	The coded data source and page number used for α, κ, and λ or q as applicable.

FIGURE 19

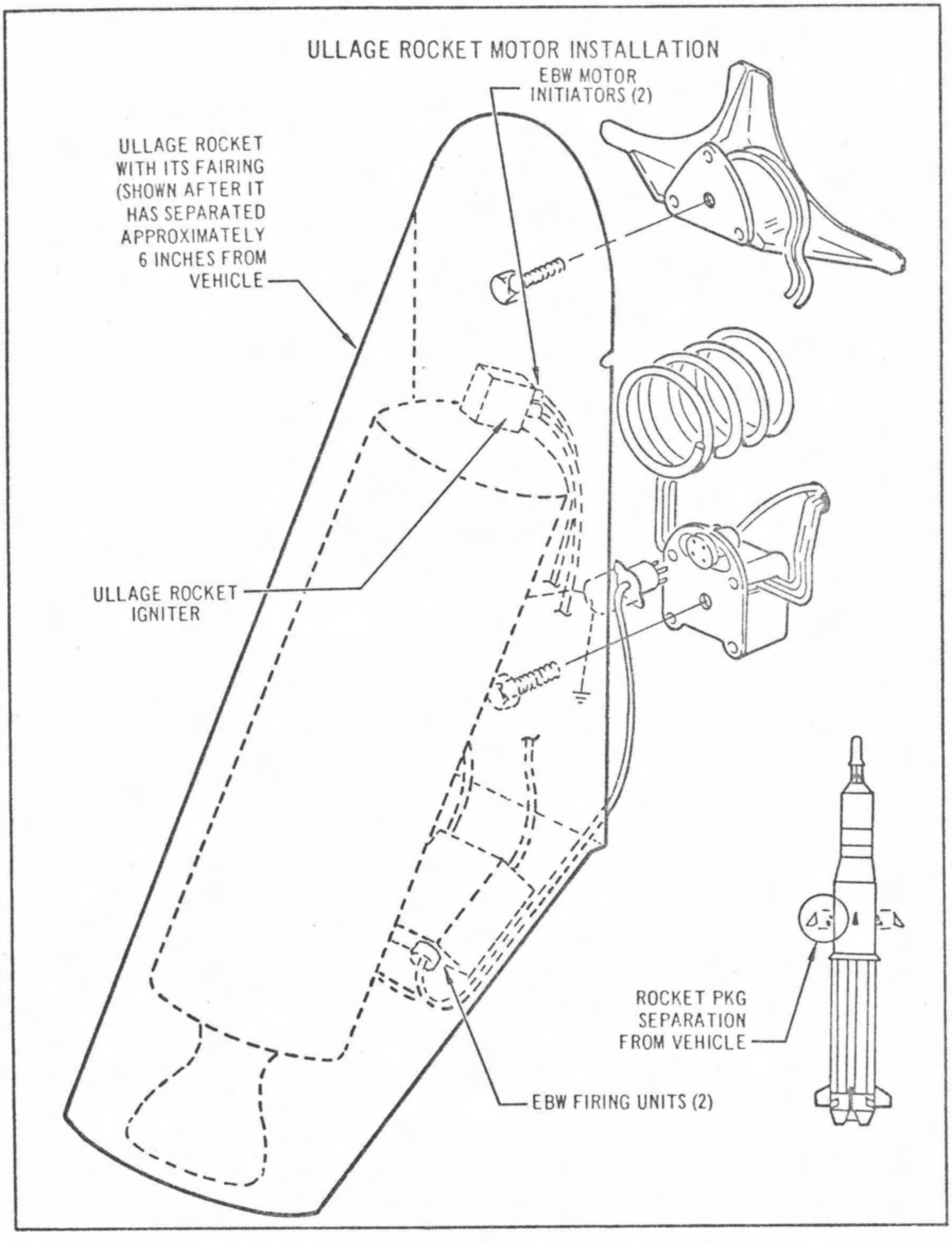

ULLAGE ROCKET MOTOR INSTALLATION
EBW MOTOR INITIATORS (2)
ULLAGE ROCKET WITH ITS FAIRING (SHOWN AFTER IT HAS SEPARATED APPROXIMATELY 6 INCHES FROM VEHICLE
ULLAGE ROCKET IGNITER
ROCKET PKG SEPARATION FROM VEHICLE
EBW FIRING UNITS (2)

FIGURE 20

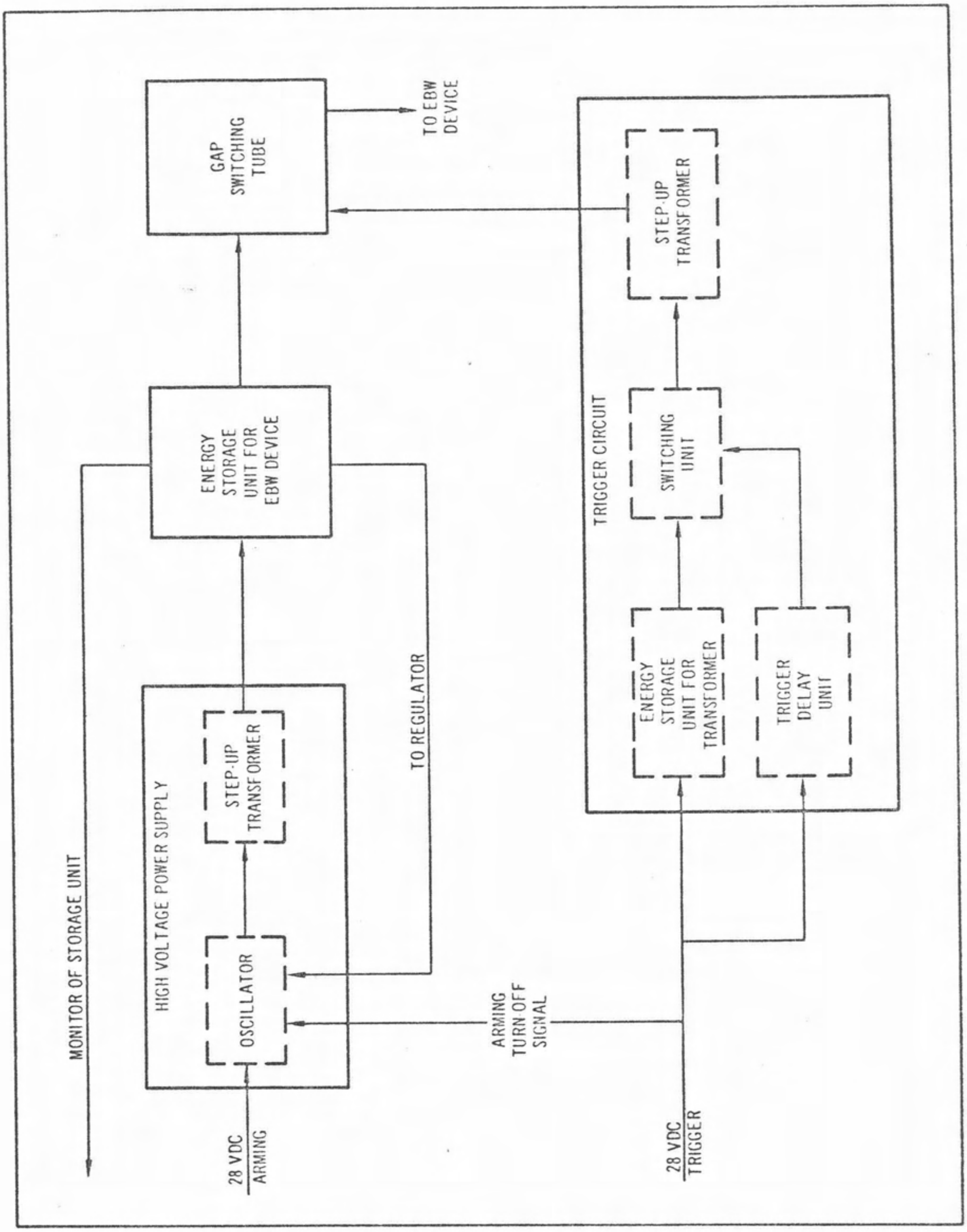
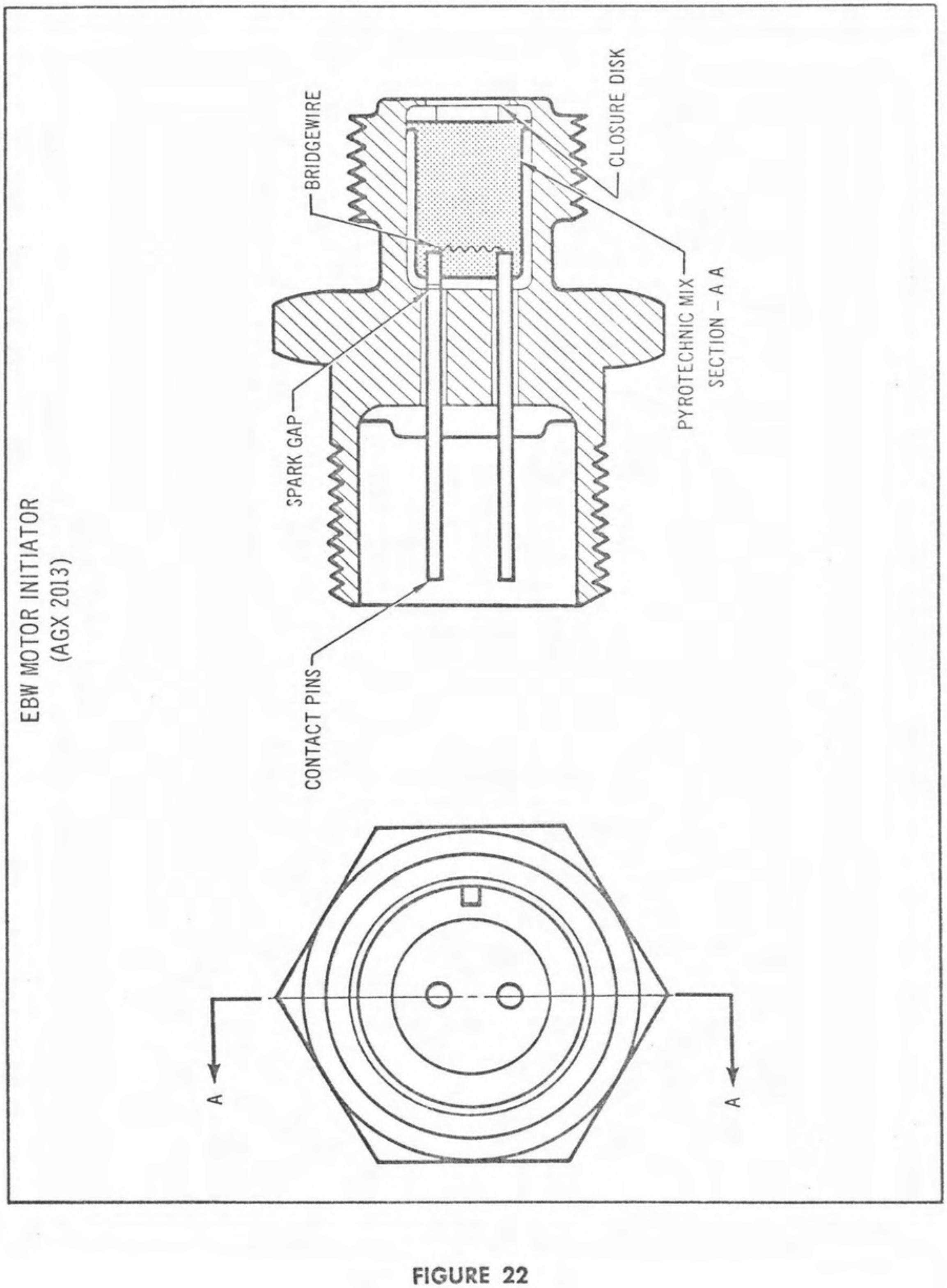
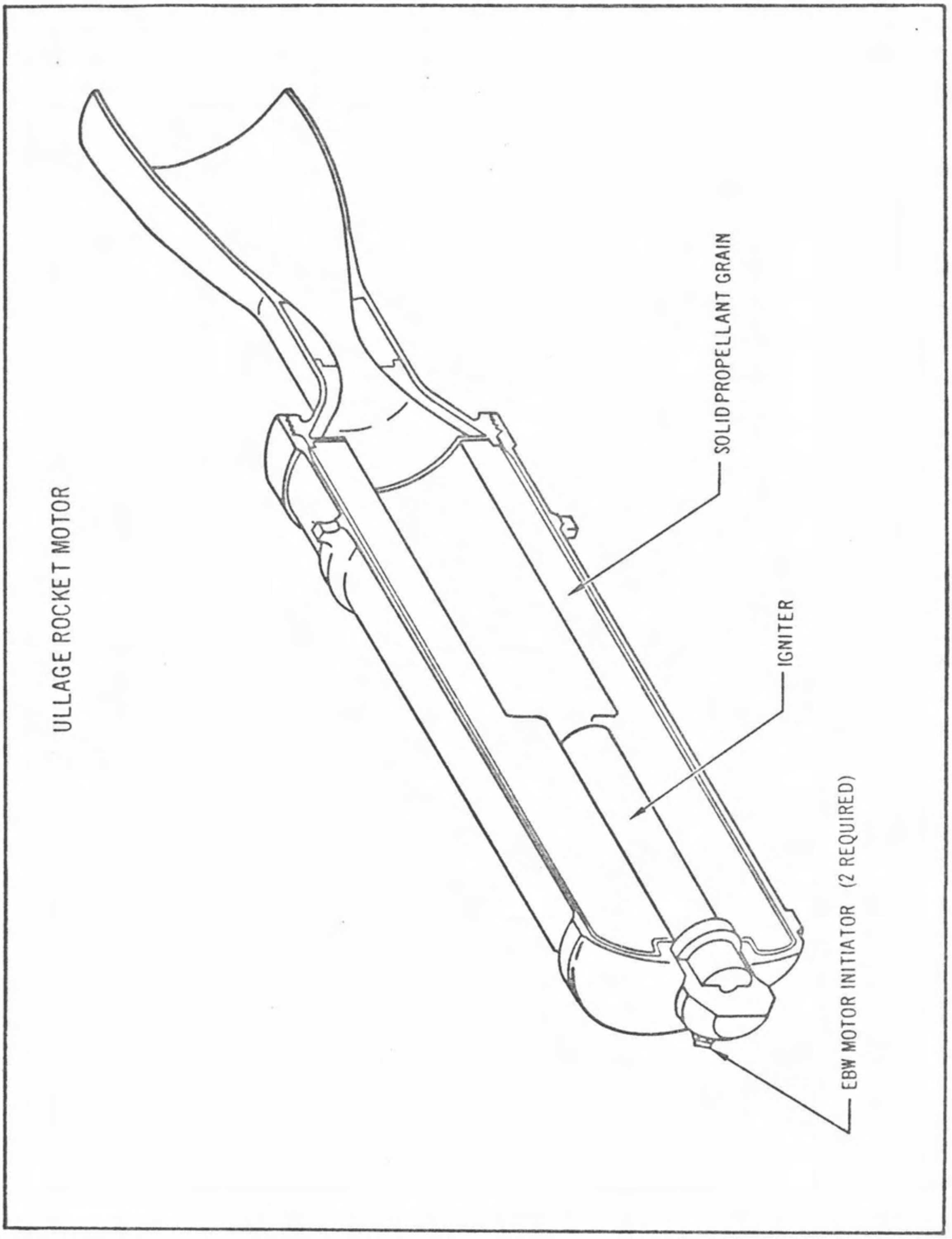

MONITOR OF STORAGE UNIT
HIGH VOLTAGE POWER SUPPLY
OSCILLATOR
STEP-UP TRANSFORMER
28 VDC
ARMING
ENERGY STORAGE UNIT FOR EBW DEVICE
TO REGULATOR
GAP SWITCHING TUBE
TO EBW DEVICE
ARMING TURN-OFF SIGNAL
28 VDC
TRIGGER
TRIGGER CIRCUIT
ENERGY STORAGE UNIT FOR TRANSFORMER
TRIGGER DELAY UNIT
SWITCHING UNIT
STEP-UP TRANSFORMER

FIGURE 21



EBW MOTOR INITIATOR
(AGX 2013)

FIGURE 22



ULLAGE ROCKET MOTOR

FIGURE 23

RELIABILITY MATHEMATICAL MODEL SUMMARY

SYSTEM SEPARATION (V IV 60)
SUBSYSTEM ULLAGE POSITIONING (SUB OF V-IV-60)

FOR C AND D OPERATIONAL TIME PHASE(S)

OPERATIONAL TIME PHASES
A) COUNTDOWN – MANUAL
B) COUNTDOWN – AUTOMATIC SEQUENCE
C) FLIGHT – BOOST PHASE
D) FLIGHT – POWERED PHASE
E) FLIGHT – COAST PHASE

RELIABILITY FAILURE EFFECT ANALYSIS SUMMARY – PHASE 1				SELECTION OF CRITICAL ITEMS – PHASE 2									
					TIME/CYCLE SIGNIFICANT			ATTRIBUTE					
ITEM	MATH MODEL NUMBER	FAILURE TYPE	(β) STAGE LOSS FREQUENCY	(α) FAILURE TYPE–MODE FREQUENCY	(t) OPERATING TIME (CYCLES OR HOURS)	(κ) OPERATIONAL MODE FACTOR	(λ) FAILURE RATE $F/10^6$	(q) FAILURE PROBABILITY OR ($t \cdot k \cdot \lambda$)	(r) ITEM RELIABILITY ($e^{-tk\lambda}$) OR ($1-q$)	UNRELIABILITY NOT CONTRIBUTING TO STAGE LOSS $\alpha(1-r)(1-\beta)$	UNRELIABILITY CONTRIBUTING TO STAGE LOSS $\alpha\beta(1-r)$	CRITICALITY NUMBER $(\Sigma\alpha_n\beta_n) \times (1-r)10^6$	DATA SOURCE CODE
EBW FIRING UNIT	60-09	PREMATURE FIRING FAILURE TO FIRE	0.0 0.0	0.01 0.99	ATTRIBUTE ATTRIBUTE	1000	2.0	.002	.998	.00002 .00198	0	0	X
EBW MOTOR INITIATOR	60-10	FAILURE TO START IGNITER	0.0	1.0	ATTRIBUTE	1000	8.0	.008	.992	.008	0	0	X
ULLAGE ROCKET IGNITER	60-11	FAILURE TO START MOTOR	0.0	1.0	ATTRIBUTE	1000	6.0	.006	.994	.006	0	0	X
ULLAGE ROCKET MOTOR	60-12	FAILURE TO FIRE ROCKET BURST ROCKET BURN-THROUGH ROCKET CHUFF	0.0 0.50 0.50 0.10	0.97 0.01 0.01 0.01	ATTRIBUTE ATTRIBUTE ATTRIBUTE ATTRIBUTE	1000	10.0	.010	.990	.00970 .00005 .00005 .00009	0 .00005 .00005 .00001	110	X
ULLAGE ROCKET IGNITION CHARGING RELAY	51-22	PREMATURE OPERATION FAILURE TO OPERATE	0.0 0.5	0.01 0.99	1 CYCLE	1000	0.5 CY.	.0005	.9995	.000005 .000247	0 .000247	247	X

FIGURE 24