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SNAP 2
RELIABILITY PROGRAM

AEC Research and Development Report

ATOMICS INTERNATIONAL

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NAA-SR-8419
SPECIAL

SNAP 2
RELIABILITY PROGRAM

By
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Facsimile Price \$ 2.60

Microfilm Price \$ 1.09

Available from the
Office of Technical Services
Department of Commerce
Washington 25, D. C.

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA

CONTRACT: AT(11-1)-GEN-8
ISSUED: AUGUST 31, 1963

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ABSTRACT

The basic concept of the SNAP 2 reliability program is discussed. The basis for the requirements of NR7550-05 "Specification for SNAP 2 Reliability Requirements" is presented, and the fundamental methods by which these requirements can be accomplished are described.

The report is divided into two sections covering the design program and the demonstration testing program. The design program section contains the reliability objectives of the system, a description of basic failure characteristics, and design considerations for reliability margins and component selection. The demonstration program section contains test plans for establishing reliability margins and for demonstrating system reliability.

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I. INTRODUCTION

Total system effectiveness has been described as the product of how well a system performs times how often the system performs. A reliability program deals primarily with maximizing the "how often" part of the equation, but such a program must also be concerned with maintaining a balance between performance and reliability in order to obtain maximum effectiveness.

Reliability is generally defined as the probability of successfully performing a specified mission under specified operating conditions; it is a quantitative value of the proportion of items that will be successful or the proportion of attempts that will be successful. The reliability of a group of items is a definite and measurable quantity. The success of a reliability program depends upon how well these measurements can be made and how well this knowledge can be applied. Included in this application is the very important area of quality control. In these respects, the technology of structural design and stress analysis is probably the best example of a very specialized field of reliability.

The major objective of the SNAP 2 reliability program is to provide guidance for balanced efforts in order to optimize reliability with economy. Guidance for balancing the expenditure of funds for development and refinement of components is initially contained in the allocation of reliability objectives. Continual guidance for development and improvement efforts is provided by monitoring the reliability status of the system and updating the reliability allocation. It is intended to provide a sensible approach to design margins in order to emphasize close control where the benefits are high and to relax costly control where wide variations can be tolerated. Reliability improvement is very often accomplished through the sacrifice of performance; the most common sacrifice is increased weight. It is intended to account for these trade-offs in order to provide guidance for maximum effectiveness.

A major cost of any development program is the cost of testing. The demonstration framework of the SNAP 2 reliability program provides guidance in this area so that balanced and complete demonstration of reliability can be accomplished in perspective with the other objectives of the project. Reasonable confidence is required that all potentially weak areas of the system are discovered and that adequate reliability is demonstrated before committing the system to the flight test phase of the program.

II. RELIABILITY DESIGN PROGRAM

It is often postulated that a given equipment has an achieved reliability resulting from the inherent design reliability which is subsequently degraded through the effects of manufacturing, handling, storage, and usage. The accuracy of this postulate is not as important as the recognition that the greatest and most economical improvements in reliability are gained through a major effort during the design of a system. Even the negating effects of manufacturing and usage errors can be controlled, to a great extent, by design.

Reliability objectives have been established so that design efforts can be guided early in the program toward attainment of the objectives. The objectives are based on a flight test program objective of 0.99 probability that at least one out of two SNAP 2 systems will be successful. The associated risk of failure has been accepted as reasonable and the resulting equipment objectives appear to be feasible based on past experience.

The reliability objectives for the SNAP 2 system are:

Probability of surviving launch and prestartup	0.990
Probability of successful startup	0.943
Probability of successful operation for 90 days	0.964
Probability of total flight test mission success including 90-day operation, excluding meteoroid hazard	0.900
Probability of total design mission success including 1-year operation, excluding meteoroid hazard	0.800
Probability of no critical meteoroid damage for 1 year	0.900

A. RELIABILITY ALLOCATION

The total system reliability objectives have been allocated to the major components listed in Table I. With the exception of meteoroid protection, each component objective has been allocated on the basis of design judgement, past experience, state-of-the-art data, and individual operating requirements. The

TABLE I
SNAP 2 RELIABILITY ALLOCATION

(MAJOR SUBSYSTEMS)						
Subsystem	Mission Phase					
	Launch		Startup		1-Year Endurance	
	%	Q	%	Q	%	Q
Reactor	26.8	0.002678	10.0	0.00601	14.5	0.02169
Radiation Shield	0.7	0.000072	0.4	0.00026	1.3	0.00189
Primary	16.1	0.001613	6.2	0.00373	4.2	0.00632
Power Conversion	29.2	0.002922	42.5	0.02554	49.2	0.07392
Structural Heat-Rejection	6.5	0.000648	5.4	0.00322	4.8	0.00717
Electrical, Startup, and Control	18.7	0.001867	34.3	0.02054	26.0	0.03901
Destruct Charge	2.0	0.00020	1.2	0.00070	-	-
TOTAL	100	0.0100	100	0.0600	100	0.1500

(REACTOR SUBSYSTEM)						
Component	Mission Phase					
	Launch		Startup		1-Year Endurance	
	%	Q	%	Q	%	Q
Reactor Structure						
Core Vessel	1.9	5.2×10^{-5}	3.3	2.0×10^{-4}	8.5	18.5×10^{-4}
Reflector Assembly						
Reflector	0.7	2.0×10^{-5}	1.3	0.8×10^{-4}	0.2	0.4×10^{-4}
Reflector Drums	5.4	14.4×10^{-5}	8.7	5.2×10^{-4}	8.9	19.3×10^{-4}
Stepper Motors	10.7	28.6×10^{-5}	18.8	11.3×10^{-4}	25.9	56.2×10^{-4}
Control Drum Mechanism	4.5	12.1×10^{-5}	13.3	8.0×10^{-4}	8.5	18.4×10^{-4}
Safety Drum Mechanism	3.4	9.1×10^{-5}	15.3	9.2×10^{-4}	8.5	18.4×10^{-4}
Bearings	2.7	7.2×10^{-5}	4.3	2.6×10^{-4}	8.8	19.0×10^{-4}
Fusible Links	43.0	115.0×10^{-5}	10.0	6.0×10^{-4}	1.4	3.0×10^{-4}
End-of-Life Actuator	7.5	20.0×10^{-5}	15.3	9.2×10^{-4}	3.4	7.5×10^{-4}
Core Fuel	20.2	54.2×10^{-5}	9.7	5.8×10^{-4}	25.9	56.2×10^{-4}
TOTAL	100	0.002678	100	0.00601	100	0.02169

(RADIATION SHIELD SUBSYSTEM)						
Shield Assembly	100	7.2×10^{-5}	100	2.6×10^{-4}	100	18.9×10^{-4}

(PRIMARY SUBSYSTEM)						
Piping Assembly	9.3	$15. \times 10^{-5}$	2.1	0.8×10^{-4}	1.1	0.7×10^{-4}
NaK Flow Meter	11.8	$19. \times 10^{-5}$	2.1	0.8×10^{-4}	0.8	0.5×10^{-4}
Parasitic Load Heaters	14.3	23.1×10^{-5}	23.1	8.6×10^{-4}	67.9	42.9×10^{-4}
Expansion Compensator	22.9	$37. \times 10^{-5}$	18.0	6.7×10^{-4}	15.8	10.0×10^{-4}
Thermoelectric Pump	15.5	$25. \times 10^{-5}$	9.7	3.6×10^{-4}	11.4	7.2×10^{-4}
Startup Pump	11.8	$19. \times 10^{-5}$	23.6	8.8×10^{-4}	-	-
Startup Heater	9.1	14.6×10^{-5}	19.0	7.1×10^{-4}	-	-
Ground Test Heater	2.5	$4. \times 10^{-5}$	0.3	0.1×10^{-4}	0.2	0.1×10^{-4}
Support Structure	2.8	4.6×10^{-5}	2.1	0.8×10^{-4}	2.8	1.8×10^{-4}
TOTAL	100	0.001613	100	0.00373	100	0.00632

(POWER CONVERSION SUBSYSTEM)						
CRU Module						
CRU	15.8	46.2×10^{-5}	22.7	58.1×10^{-4}	48.2	$356. \times 10^{-4}$
Bearing Flow Orifices	5.2	15.3×10^{-5}	4.6	11.7×10^{-4}	3.8	28.3×10^{-4}
Bearing Lube Filter	13.1	38.4×10^{-5}	2.3	6.0×10^{-4}	5.8	42.9×10^{-4}
Hg Pump Check Valve	0.8	2.4×10^{-5}	3.4	8.6×10^{-4}	1.0	7.0×10^{-4}
Bearing Drain Heat Exchanger	2.7	7.8×10^{-5}	1.1	2.9×10^{-4}	0.9	6.8×10^{-4}
CRU Piping	2.7	7.8×10^{-5}	1.1	2.9×10^{-4}	0.9	6.8×10^{-4}
Boiler	7.9	23.1×10^{-5}	5.7	14.6×10^{-4}	8.7	64.4×10^{-4}

TABLE I (Continued)

Component	Mission Phase					
	Launch		Startup		1-Year Endurance	
	%	Q	%	Q	%	Q
PCS Piping and Structure	3.5	10.3×10^{-5}	1.1	2.8×10^{-4}	2.0	14.6×10^{-4}
Hg Flow Regulator	7.9	23.1×10^{-5}	6.9	17.5×10^{-4}	11.6	85.9×10^{-4}
Hg Flow Meter	2.0	5.8×10^{-5}	1.1	2.8×10^{-4}	0.8	6.2×10^{-4}
Hg Pressure Regulator Tank	8.0	23.4×10^{-5}	9.1	23.2×10^{-4}	14.4	106.2×10^{-4}
Hg Start Components						
RC Exit Valve	1.7	5.0×10^{-5}	6.9	17.6×10^{-4}	0.7	5.3×10^{-4}
Injection Tank	6.6	19.4×10^{-5}	10.1	25.7×10^{-4}	-	-
Injection Tank Heaters	8.2	23.8×10^{-5}	-	-	-	-
Injection Valve	1.7	4.8×10^{-5}	6.8	17.4×10^{-4}	0.2	1.8×10^{-4}
Squib Seal Valve	1.6	4.6×10^{-5}	3.4	8.6×10^{-4}	1.0	7.0×10^{-4}
N ₂ Tank	0.8	2.2×10^{-5}	0.7	1.8×10^{-4}	-	-
N ₂ Pressurization Valve	6.6	19.4×10^{-5}	10.3	26.2×10^{-4}	-	-
N ₂ Pressure Regulator	3.2	9.4×10^{-5}	2.7	7.0×10^{-4}	-	-
TOTAL	100	0.002922	100	0.02554	100	0.07392

(STRUCTURAL HEAT-REJECTION SUBSYSTEM)

Radiator Condenser	59.3	38.4×10^{-5}	36.4	11.7×10^{-4}	99.2	71.1×10^{-4}
Mating Structure						
Panel Assemblies	6.2	$4. \times 10^{-5}$	0.3	0.1×10^{-4}	0.4	0.3×10^{-4}
Thermal Barrier	4.6	$3. \times 10^{-5}$	0.3	0.1×10^{-4}	0.4	0.3×10^{-4}
Nose Cone Ejection Structure	14.5	9.4×10^{-5}	32.9	10.6×10^{-4}	-	-
Destruct Charge Ejection Mechanism	15.4	$10. \times 10^{-5}$	30.1	9.7×10^{-4}	-	-
TOTAL	100	0.000648	100	0.00322	100	0.00717

(ELECTRICAL, STARTUP, AND CONTROL SUBSYSTEM)

Reactor Temperature Control Equipment						
Controller	22.9	42.8×10^{-5}	13.8	28.4×10^{-4}	38.4	$150. \times 10^{-4}$
Temperature Switches	9.2	17.2×10^{-5}	6.9	14.1×10^{-4}	19.1	74.7×10^{-4}
Parasitic Load Control	16.2	30.3×10^{-5}	14.1	29.0×10^{-4}	36.4	142.3×10^{-4}
Electrical Power Distribution Equipment						
Load-Switch Module	3.7	7.0×10^{-5}	9.7	20.0×10^{-4}	1.1	4.1×10^{-4}
Short-Circuit Capacitors	1.6	3.0×10^{-5}	1.0	2.0×10^{-4}	0.7	2.6×10^{-4}
Cable and Connectors	2.1	4.0×10^{-5}	0.9	1.8×10^{-4}	0.7	2.6×10^{-4}
Startup Circuitry						
Control Circuit and Components	17.8	33.2×10^{-5}	26.2	53.7×10^{-4}	-	-
Startup Battery	2.5	4.6×10^{-5}	1.7	3.5×10^{-4}	-	-
Drum Release Squibs	2.5	4.6×10^{-5}	1.7	3.5×10^{-4}	-	-
RC Pressure Sensor	3.7	7.0×10^{-5}	6.7	13.8×10^{-4}	0.5	1.8×10^{-4}
Nose Cone Squibs, Cables, and Connectors	2.5	4.6×10^{-5}	1.7	3.5×10^{-4}	-	-
Boiler Temperature Sensor	4.0	7.4×10^{-5}	6.7	13.8×10^{-4}	-	-
Safety Circuitry						
Low Voltage Trip	8.6	$16. \times 10^{-5}$	8.4	17.3×10^{-4}	2.3	9.0×10^{-4}
Band-Release Heater	2.7	$5. \times 10^{-5}$	0.5	1.0×10^{-4}	0.8	3.0×10^{-4}
TOTAL	100	0.001867	100	0.02054	100	0.03901

(DESTRUCT CHARGE SUBSYSTEM)

Destruct Charge	25	5.0×10^{-5}	31.4	2.2×10^{-4}	-	-
Charge Initiator	25	5.0×10^{-5}	14.3	1.0×10^{-4}	-	-
Connectors and Cable	50	10.0×10^{-5}	54.3	3.9×10^{-4}	-	-
TOTAL	100	0.00020	100	0.00070	-	-

allocated values in the tables are presented in terms of failure rate per mission phase. Considering the distribution of failures per mission phase to be a Poisson distribution, the allocated Q values are the negative logarithm of the mission-phase reliability. Reliability in this case is defined as the probability of successfully surviving or performing for the indicated mission phase. The following equations can be used to convert the allocated failure rates to other terms:

Reliability:

$$R = e^{-Q}$$

Reliability of components A, B, and C all performing successfully:

$$R_{A,B,C} = e^{-Q_A - Q_B - Q_C}$$

Reliability of performance for mission phases 1, 2, and 3:

$$R_{1,2,3} = e^{-Q_1 - Q_2 - Q_3}$$

Endurance: all allocated values for endurance are for 1 year. The failure rate for a 90-day mission phase is

$$Q_{90} = 0.2466 Q_{1 \text{ year}}$$

Mean time between failure:

$$MTBF = 8,760 / Q_{1 \text{ year}}$$

B. METEOROID PROTECTION ALLOCATION

The objective probability of no critical meteoroid damage for 1 year has been allocated to all components with exposed vulnerable area, Table II. This allocation is based on the proportion of component vulnerable area to the total system vulnerable area in accordance with Reference 1. The method of calculating the nonpuncture probability is:

$$P(0) = e^{-GAt^\beta}$$

where:

$P(0)$ = probability of 0 punctures in 1 year,

G = a function of material and thickness to be taken from Reference 1,

A = the vulnerable area in ft^2 ,

t = the material thickness in in.

β = the shape parameter of the distribution depending on material and thickness also to be taken from Reference 1.

Solving this equation for t gives the material thickness required to meet the allocated nonpuncture probability.

TABLE II
SNAP 2 METEOROID PROTECTION ALLOCATION
TO EXPOSED VULNERABLE COMPONENTS

Component	Nonpuncture Probability for 1 year
Radiation Shield	0.956
Radiator Condenser Tubes	0.962
Radiator Condenser Liquid Manifold	0.999
Exposed NaK Piping	0.988
Parasitic Load Heaters	0.999
Reactor Vessel	0.999
Stepper Motors	0.999
Equipment Mounted on Panels	0.994
TOTAL	0.90

The reliability objective allocation is a first-round estimate of critical areas of the system in which the most rewarding improvement efforts can be made. Very little total system reliability can be gained by improving components which already have a rather high reliability. Total system reliability is affected more drastically by fluctuations of less reliable components; it is in these areas that improvement expenditures pay the highest dividends.

C. COMPONENT LIFE CHARACTERISTICS

To translate reliability objectives into effective design criteria, it is first useful to consider the typical failure rate characteristics of most components.

Figure 1 shows the three regimes of failure or mortality rate which most component populations exhibit throughout their age in hours, cycles, or appropriate exposure units. The life period from T_0 to T_1 is the period of infant mortality

Figure 1. Failure Rate vs Life Characteristic

where the failure rate is decreasing. This period is usually associated with the run-in or acceptance-test period of component operation where marginal components are discovered and eliminated. The life period from T_1 to T_2 is often considered as the economical-life period in which a component population exhibits a low constant failure rate. The implication of such a constant failure rate is that the probability of failure at any instant in life is constant so long as the component life is within the limits from T_1 to T_2 . The life period beyond T_2 is the wear-out period in which a component population exhibits an increasing failure rate indicating that the useful life has been exceeded. Not all components exhibit these distinct failure-rate life characteristics; electronic equipment, such as diodes and transistors, have not shown a wear-out tendency, but rather

a slightly decreasing failure rate which continues indefinitely. Structural components, on the other hand, show mainly a wear-out or structural limit beyond which the failure rate increases sharply.

D. GENERAL DESIGN CRITERIA

To meet the high reliability objectives of each component, two general design criteria must be followed:

- 1) All components must be designed such that their operating requirements do not exceed their economical-life period.
- 2) Each component application must be controlled to minimize the constant failure rate associated with its economical life. The acceptable level of constant failure rate is established by the reliability allocation.

The application of these general criteria becomes very specialized when each component is considered.

For structural and mechanical components, the main emphasis necessarily must be on maintaining adequate strength margins. If the design strength is held at 136% of the maximum applied loading, the probability of failure due to understrength is 0.0000317. This is the probability associated with a 4-standard-deviations (4σ) margin. When the loading and strength are associated with fatigue cycles, the economical-life relationship is readily apparent. Electronic components are treated in a statistical manner where past history indicates a constant failure rate to be expected at a given operating level and environment. Many electronic components may also have an economical-life characteristic.

E. RELIABILITY STRENGTH MARGINS

Load and strength parameters in reliability analyses are not necessarily in terms of physical loads; such as lb/in.². A critical load may be temperature, voltage, radiation dose, or any other condition imposed on the component in question. The strength of a component is the level of the critical load parameter which will cause a yield, failures, or out-of-limit performance.

Assuming that the applied load and the component strength are both distributed normally about their mean values, a graphic representation of this condition

might be as shown in Figure 2. The distribution of load has a standard deviation σ_L , and the distribution of strength has a standard deviation σ_S . The primary concern is to design for a low probability that the load will equal or

Figure 2. Normal Distribution of Applied Load and Component Strength

exceed the strength. In this case, if the actual load were equal to L , and the actual strength were equal to S a strength margin of $S - L$, would exist. Because each of these values is distributed normally, the difference is also distributed normally with a standard deviation:

$$\sigma_{S-L} = \sqrt{\sigma_S^2 + \sigma_L^2}.$$

By establishing a difference between the mean strength and the mean load equal to several standard deviations of this difference, the probability of the load exceeding the strength becomes correspondingly less, i. e., the shaded area of Figure 2 becomes smaller. When this difference or margin is increased, it

generally affects a component failure-rate life characteristic by lowering the constant failure rate and increasing the economical-life period. A margin of 4 standard deviations of the margin distribution is considered adequate for optimum gain in reliability. It should be noted that a load or operating requirement which has a critical effect on the constant failure rate may not be the same requirement which is the controlling influence on economical life.

F. NOMOGRAPHS FOR DESIGN MARGINS

When the applied load is expressed as a mean value with a given tolerance (usually $3\sigma_L$) and a tolerance can also be estimated for the component strength value, the nomograph in Figure 3 can be used to determine the reliability factor ($\overline{RF}$) necessary to give a desired probability that the load will not exceed the strength. The reliability factor is a margin ratio of M_S/M_L where:

M_S = mean strength (design strength)

M_L = mean design load.

The nomograph is expressed in:

T_L = tolerance on mean load as a percentage of mean load:

100 ($3\sigma_L/M_L$); it should be noted that this tolerance includes analytical uncertainties associated with the method of calculating the applied load,

T_S = tolerance on mean strength as a percentage of mean strength:

100 ($3\sigma_S/M_S$),

$\overline{RF}$ = the reliability factor of mean strength to mean load: M_S/M_L ;

Z = the number of standard deviations associated with the reliability or probability that the load will not exceed the strength.

If any three of these values can be estimated or are known, the fourth value can be found from the nomograph. Most design considerations will involve estimating the tolerances on load and strength and then finding the reliability factor necessary to give a desired reliability. For example, suppose it is desired to establish the design power of the magnet for the electromagnetic startup pump. Assume the following design conditions to be known:

Figure 3. Reliability Nomograph

Required magnet strength for startup	2 kilogauss $\pm$ 12%
Degradation of magnet strength due to launch and startup environment	20% of original strength
Estimate of tolerance on magnetic strength after launch	$\pm$ 15% of design strength

The two tolerance values to be entered on the nomograph are:

$T_L = 12\%$ = the percentage of the mean operating requirement

T_S = the percentage of the mean magnet strength after launch and during startup thermal transient.

If $T_S = 15\%$ of the original magnet design strength, then $T_S = 0.15/1 - 0.2(100\%)$ of the nominal magnet strength after launch and thermal transient. This nominal magnet strength is the mean strength used in the nomograph, and $T_S = 18.75\%$. By drawing a line between these two tolerance values the curve labeled $Z = 4$ is intersected at a value $\overline{RF} = 1.38$. The value $Z = 4$ is the number of standard deviations (σ) associated with the probability that the actual operating requirement will not exceed the actual magnet strength. This probability for $Z = 4$ is 0.9999683. The value of $\overline{RF} = 1.38$ means that the design magnet strength after launch and during startup must be 1.38 times as great as the nominal operating strength requirement. Using the assumed nominal operating strength requirement of 2 kilogauss gives:

$$M_L = 2 \text{ kilogauss} = \text{mean load}$$

$$M_S = \overline{RF} (M_L) = 1.38)(2) = 2.76 \text{ kilogauss} = \text{mean strength after launch and thermal transient.}$$

This mean strength value represents 80% of the nominal design value when accounting for degradation; in this case, the nominal design value for the magnet should be 3.45 kilogauss.

If a lower probability of obtaining adequate magnet strength were acceptable, say 0.977 ($Z = 2$) a lower value for $\overline{RF}$ could be used. In this case, $\overline{RF} = 1.166$. For this lower probability, the nominal design value would have to be 2.915 kilogauss instead of 3.45 kilogauss. The general value to be used is four standard deviations ($Z = 4$).

G. CONSTANT FAILURE RATES

The margin of strength-to-load estimates, which have been covered so far, are intended to assure that each design will perform within an optimum range for reliability. The second point of the general criteria (see page 14) must be developed in greater detail. Estimates of constant failure rates for different classes of equipment have been made by statistical analysis of past performance. Most of these estimates are for electronic equipment; very little data are available for mechanical equipment. References 2, 3, and 4 are among the best sources for these data on equipment classes. When specific components are being considered, the manufacturer can very often supply more accurate failure-rate information. One of the main reasons that little constant failure-rate data are available for mechanical or structural components is that these classes of equipment generally exhibit extremely low or nonexistent constant failure rates. Their behavior can be described entirely by wear-out failure distributions for most practical purposes. The required constant failure rate for a given component is obtained from the allocated reliability objective. These allocated objectives are expressed as the negative natural logarithm of the reliability for the particular mission segment. For an example of how the required failure rate may be obtained from the allocation, consider the parasitic load heaters. Both heaters are allocated a 1-year endurance reliability for which the logarithm is -4.29×10^{-3} . This is the $-Q$ value given in Table I. There are two heaters, so each heater must have a reliability for which the $\log = (4.29/2) \times 10^{-3}$ or -2.145×10^{-3} . If the heater is designed for a useful load margin of 4σ , the probability of not being overloaded is 0.9999683 or $e^{-3.17 \times 10^{-5}}$.

The remaining allocated reliability attributed to constant failure rate is $e^{-2.145 \times 10^{-3} + 3.17 \times 10^{-5}}$ or $e^{-2.113 \times 10^{-3}}$.

Reliability for the constant failure-rate period is calculated by

$$R = e^{-\lambda t} ,$$

where

λ = the constant failure rate, failures/hr or cycles

t = the time or cycles for the total operation.

In this example, $t = 8,760$ hr and $\lambda t = 2.113 \times 10^{-3}$. The required constant failure rate is 2.41×10^{-7} failures/hr.

From Reference 2, failure rates for the equipment classification of heaters and electrical heaters range from 0.8×10^{-7} to 76.7×10^{-7} with the mean values ranging from 7.0×10^{-7} to 76.7×10^{-7} . These data indicate that the state-of-the-art may be near its limit for this particular application, and reliability must be emphasized, therefore, in the development of a long-endurance heater. One consideration might be derating the heater elements. Reference 3 indicates that operation of high-power resistors beyond 40% of their rated voltage capacity produces considerable increases in failure rate.

H. SPECIFIC DESIGN CRITERIA

To meet the two objectives of the general design criteria, numerous additional determinations must be made in the design of each component. The following checklist is intended to set down the most important of these considerations as a more specific set of criteria. Not all the points will apply to every component, but if such applicability can be determined, it is a major step toward recognizing where to place reliability design emphasis. Each component designer will be expected to document these considerations:

- 1) Determine the critical operating requirements, environments, and loads
- 2) Establish tolerances and margins on the critical parameters using the nomographs; margins should be 4σ where possible
- 3) Determine the constant failure-rate requirement from the allocation, remembering to account for strength-margin probability where it is a consideration
- 4) Determine state-of-the-art failure rates, where they exist, and compare with the constant failure-rate requirements
- 5) For complex equipment consisting of many components or parts in redundant and series relationship, consult a reliability engineer for a probability analysis
- 6) Design structural or mechanical equipment to a nominal strength of at least 136% of the maximum design load.

III. RELIABILITY DEMONSTRATION PROGRAM

One of the most important objectives of a reliability demonstration is to point out potential weaknesses in the design. While this may appear to be a paradox, it must be remembered that testing does not improve reliability; it isolates those areas which require corrective action to improve reliability. Corrective action often involves design and manufacturing changes, quality control measures, and procedures for usage. The requirement for corrective action can best be determined through careful analysis of failures induced by testing.

Another and more obvious purpose of a reliability demonstration is to gain confidence in system reliability prior to actual flight test. Every bit of test experience, from the first development test to the final qualification test, provides a record of reliability progress and confidence in meeting the objectives. If parts of this record are lost or omitted, the measured confidence becomes that much less, and the progress becomes more obscure.

The demonstration objectives for the program are:

- 1) Demonstration of a 4σ reliability strength margin for critical environment with 80% confidence for each critical component
- 2) Demonstration of a 4σ startup cycle reliability margin with 80% confidence for all components critical to system startup
- 3) Demonstration of the total-system flight-test-mission reliability objective (0.900) with 50% confidence
- 4) Demonstration of effective corrective action where weaknesses have been indicated by previous testing
- 5) Demonstration of adequate burn-in, for elimination of marginal components by acceptance testing.

The following test requirements are presented as a means to attain these demonstration objectives.

A. TESTING FOR RELIABILITY STRENGTH MARGIN

The primary objective of these tests is to produce failures of the test items. The tests are given for structural testing and for reliability margins. These tests are to be conducted during the prototype development phase.

1. Structural Testing

These tests shall be conducted for all components which are structurally critical to the success of the mission. Three test units are to be subjected to increased stress levels until failures occur. The following conditions are defined for the demonstration:

- a) If all three units fail at levels higher than 136% maximum design load, the demonstration is successful.
- b) If any one of the three units fails at a level below 132% of maximum design load, the strength margin is inadequate.
- c) If any one of the three units fails at a level between 132 and 136% of the maximum design load, the range in load to failure between the lowest and the highest failure level must not exceed 9.4% of the maximum design load.

2. Reliability Margin Testing

These tests shall be conducted for all components which have been designed to critical operating or environmental margins other than physical strength margins. Three test units are to be subjected to increased levels of the critical parameter until all units have failed. The mean level at which the failures occur and the range of these levels shall then be converted to percentages of the maximum design operating level. Plotting the point of these coordinates on Figure 4 will show the condition of demonstration. As an example, assume that the critical operating requirement for the parasitic load heater is power input. Also, assume that the maximum design power input to each heater is 2 kw. If three heaters are subjected to increased power loading until all three have failed, the results might be the following:

Heater	Power Level at Failure (kw)
1	3.5
2	3.2
3	3.6

The mean power level at failure is 3.43 kw, and the range of power levels to failure is 0.4 kw. Converting this to percentages of the maximum design power gives:

Figure 4. Mean vs Range of Loads to Failure for Three Tests
(80% confidence of 4σ of margin over maximum design load)

Mean = 171%

Range = 20%

Plotting these values on Figure 4 shows the point is below the line for demonstration requirements. A mean of 171% requires a tighter range of only 16.4%, or a range of 20% requires a higher mean value of 187%. Two generalized corrective actions are immediately apparent; derate the heater by designing it to a higher power capacity, and/or tighten up on manufacturing and quality control procedures to reduce the large variation in power capacity.

B. TESTING FOR STARTUP CYCLE MARGIN

These tests shall be conducted for all components which will be functionally cycled each time the compact power unit (CPU) is started. This includes acceptance and checkout startups, as well as orbital startup. It is estimated that 10 of each component will be available including system test components which can be used for startup testing after the system test objectives have been completed. The maximum number of startup cycles on a flight system is 10.

The following test program is required to give an estimate of 80% confidence that each component is capable of 10 startups with a 4σ margin. Because of the chronological order of component availability for startup testing, it will not be possible to test 10 of each component in a short time span and then make a demonstration decision. Therefore, the test plan is set up sequentially (Figure 5) so that decisions can be made after 2, 3, 4, or possibly 10 tests have been completed.

Here again all tests are exhaustive cycle-to-failure operations with one major exception; any test which goes to 260 cycles without failure can be terminated.

The following example is presented to show how Figure 5 can be used. Assume that the component to be demonstrated is one of the startup valves. The first two valves tested give the following results:

<u>Valve</u>	<u>Cycles-to-Failure</u>
1	63
2	72

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Figure 5. Mean vs Range of Startup Cycles to Failure
(80% confidence of 4 σ margin over 10 operating cycles)

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The mean cycles-to-failure is 67.5 and the range in results is $72 - 63 = 9$ cycles. Entering these values on the curve for two tests, it can be seen that the range of nine cycles is too large for a mean of 67.5 and that three tests might give adequate results. Assume valve 3 fails on the 81st startup cycle. The mean is now 72 cycles-to-failure and the range has increased to 18 cycles. Entering these values, this time on the curve for three tests, it can be seen that a range of 18 is still too large for a mean of 72 cycles, but four tests might give the desired demonstration. If valve 4 fails at 75 startup cycles, the total experience is now:

<u>Valve</u>	<u>Cycles-to-Failure</u>
1	63
2	72
3	81
4	75

Mean cycles-to-failure = 72.2

Range = 18 cycles.

These results, when plotted on Figure 5, fall to the left of the curve for four tests and show that the demonstration is adequate; further testing to failure is not required.

If the results of two or three tests had fallen near, or to the right of the curve for 10 tests, it would be apparent that the component could not meet the demonstration requirements, and corrective action would be in order.

C. FLIGHT TEST RELIABILITY DEMONSTRATION

It is not within the realm of funding or schedule to demonstrate that every component meets its allocated reliability objective. For example, it would require 2.84×10^6 component hours of testing without failure to demonstrate the endurance objective for the parasitic load heater to a 50% confidence level. It would require 1561 component startup cycles without failure to demonstrate the heater's allocated startup reliability objective to 50% confidence. This may very possibly be accomplished by the startup margin tests; 10 heaters accumulating 156 cycles each before failure could demonstrate an adequate cycle constant failure rate and the margin objectives.

The flight-test reliability demonstration is concentrated on obtaining 50% confidence of the total-system flight-test mission reliability objective. These tests, unlike the tests for margin, have the primary purpose of being completed without failures. From Figures 6 and 7, it can be seen that a program which consists of testing each of seven complete systems through an exactly simulated flight-test mission would meet the demonstration requirement. The flight-test mission in this sense is considered to include all acceptance testing, system checkout, handling, and the actual mission from launch through 90 days of operation in orbit. At present, only one complete flight system test (FS-1) will simulate the complete flight-test mission. Two nonnuclear systems (FSM-1 and FSM-2) will also simulate flight-test missions. The remainder of the demonstration requirements will be obtained through component and subsystem tests as much as possible. Obviously, the demonstration of six additional reactors is not economically feasible. Excluding the reactor, four additional units of each component must be tested through simulated missions. Bearing in mind that total mission reliability is being demonstrated, it is emphasized that each test item must be subjected to a complete mission cycle with the environments and operations being in proper sequence.

In general, the basic tests for mission simulation will be as follows:

<u>Sequence</u>	<u>Test</u>
1	Component acceptance tests
2	System acceptance environmental tests including vibration and shock
3	Nine nonnuclear system startups and operation for 48 hours at 10^{-2} mm vacuum and 100°F maximum test-chamber wall temperature
4	System qualification environmental tests including vibration, shock, acceleration, acoustic noise, and aerodynamic heating
5	Prestart, cold temperature soak, and hard vacuum simulating orbital environment
6	Orbital startup: nuclear startup, where applicable, in simulated space environment
7	Endurance operation for 90 days in simulated space environment.

(Details of these tests are contained in Reference 5.)

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Figure 6. Maximum Confidence Level vs Reliability

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Figure 7. Maximum Confidence Level of Demonstrated Reliability
 for Combination of Tests and Failures

Any failures which occur during these tests must be cause for corrective action. While it is not intended to demonstrate component reliability objectives, the occurrence of failures, on the other hand, give a high confidence-level demonstration that the failed components cannot meet their reliability objectives.

D. CORRECTIVE ACTION DEMONSTRATION

If a component design fails to pass a reliability demonstration test program, the design will be modified and resubmitted to the test program. This is a flexible requirement and will be relaxed in situations where time and expense dictate. Components which are improved early in the development of the flight system must be included in all subsequent demonstration tests where possible. Components which are determined deficient late in the demonstration program must be improved and verified prior to flight-system delivery. In no case shall a component which has not met demonstration requirements be included in a delivered flight system in its unimproved configuration. If the corrective action is a quality control requirement, the components may be updated for delivery by meeting the new quality control requirements.

E. TEST REPORTING

To verify that the reliability demonstration objectives in the preceding sections are being attained, it will be necessary to account for approximately 700 to 1000 separate tests. Accounting for each test includes monitoring continuous tests, recording failures, and verifying that each test has been completed. A systematic procedure for this accounting is required. Each recorded bit of information must be submitted on a standardized form. As 700 to 1000 tests could generate as high as 3000 reports, filing and processing can best be handled by machine if the input is formalized for electronic data processing. The Compact Systems Division "Data Report" form 730-L-81 has been developed for this accounting task. All SNAP 2 testing shall be reported on this form in accordance with the instructions of Appendix A of NR 7550-05, "Specification for SNAP 2 Reliability Requirements." The requirement for complete coverage of all tests cannot be overemphasized. It is very possible that with the updating of PSM system tests to include flight design hardware, and with development tests of components which are eventually used for flight design, many of the reliability demonstration objectives may be exceeded. This will not be known, however, if the records are not complete.

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