[redacted]

UNCLASSIFIED

NAA-SR-MEMO-6599
COPY 31 OF 75
73 PAGES
SERIES A

M93031651

FILE COPY

A RELIABILITY IMPROVEMENT PROGRAM PLANNING REPORT FOR THE SNAP 10A SPACE NUCLEAR POWER UNIT

This document is
PUBLICLY RELEASABLE
Jerry Keyes
Authorizing Official
Date: 2-12-09

[redacted]

[redacted]

[redacted]

DEPARTMENT OF ENERGY DECLASSIFICATION REVIEW	
1st REVIEW-DATE: 6-16-97	DETERMINATION [CIRCLE NUMBER(S)]
AUTHORITY: ☐ AOC ☐ ADC ☐ ADD	1. CLASSIFICATION RETAINED
NAME: Jerry E. Keyes	2. CLASSIFICATION CHANGED TO:
2ND REVIEW-DATE: 6-19-97	3. CONTAINS NO DOE CLASSIFIED INFO
AUTHORITY: ADD	4. COORDINATE WITH:
NAME: Ted Davis	5. CLASSIFICATION CANCELED
	6. CLASSIFIED INFO BRACKETED
	7. OTHER (SPECIFY):

ATOMICS INTERNATIONAL
A DIVISION OF NORTH AMERICAN AVIATION, INC.

UNCLASSIFIED

[redacted]

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

[redacted] [redacted]

NAA-SR-MEMO-6599

UNCLASSIFIED

CLASSIFICATION CHANGED TO
[redacted]
DATE 8-26-66
H. B. Carroll
Chief, Declassification Branch

A RELIABILITY IMPROVEMENT PROGRAM PLANNING REPORT FOR THE SNAP 10A SPACE NUCLEAR POWER UNIT

By

M. G. COOMBS
C. K. SMITH
L. A. WILSON

[redacted]

[redacted]

ATOMICS INTERNATIONAL

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

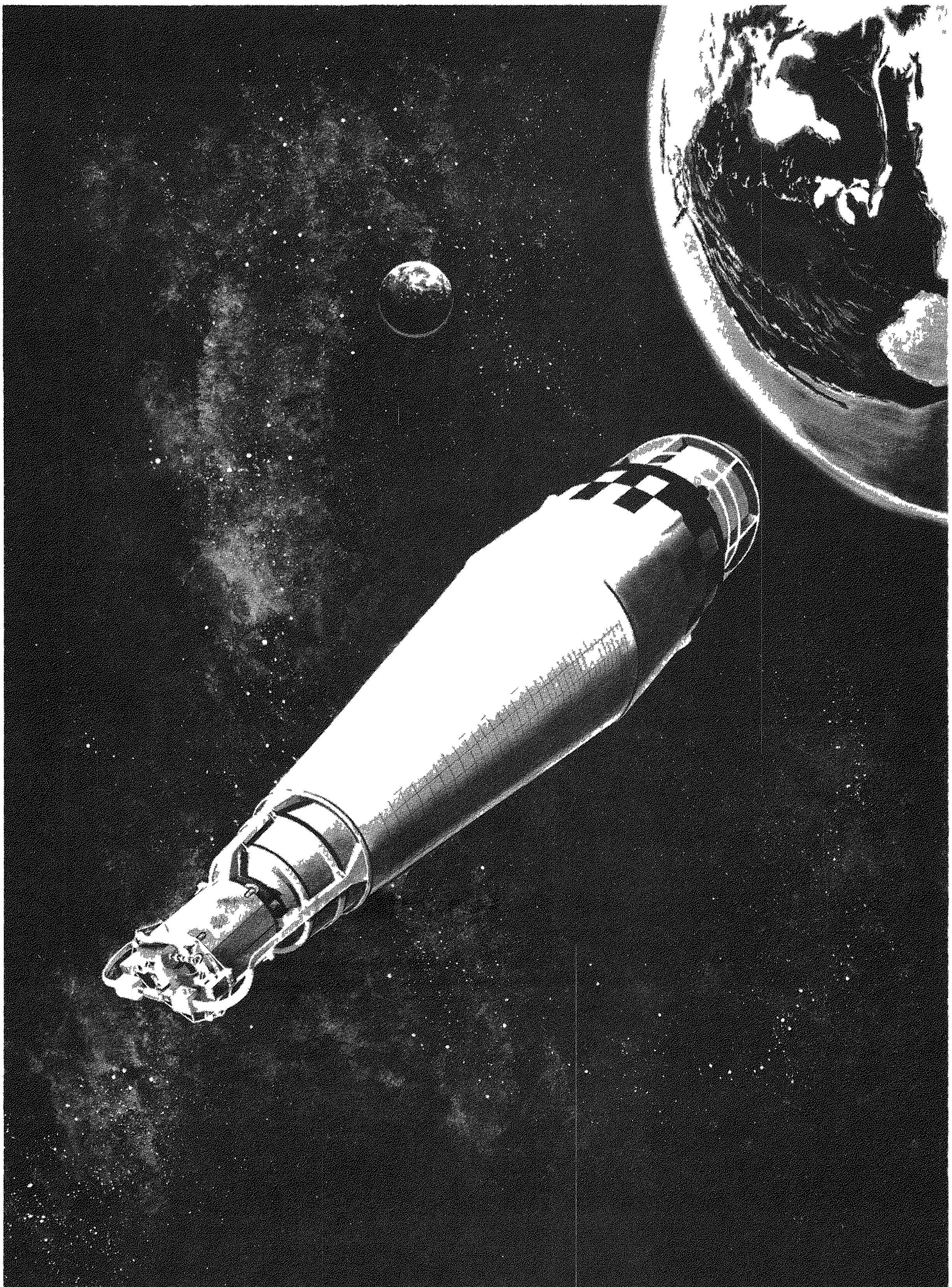
CONTRACT: AT(11-1)-GEN-8
ISSUED: MARCH 14, 1961

UNCLASSIFIED

[redacted]

[redacted]

[redacted]



SNAP 10A

[redacted]

[redacted]

CONTENTS

CONTENTS

TABLES

FIGURES

[redacted] UNCLASSIFIED

FIGURES

SUMMARY AND RECOMMENDATIONS

The estimated achieved reliability of SNAP 10A space nuclear power units will be relatively low at the time of the first SNAPSHOT flight test in April, 1963, and the existing R & D program does not provide a significant reliability growth thereafter. While such a low value for the achieved reliability is acceptable in the feasibility program, the economics of launching and maintaining a number of operational satellites will necessitate a much higher value of achieved reliability for the essential electrical power supply. Such application of SNAP 10A units then demands that an additional reliability improvement program be undertaken at the earliest possible time; this report provides a basis for the planning of such a program.

To obtain necessary economic information on the cost of achieving a given reliability, three different programs are considered in addition to the existing R & D program. These programs are identified as Program I, II, and III. Each program differs only in level of effort in addition to the current program, as indicated in Table I and by the chart in Figure 1, and result in different reliabili-

TABLE I

TESTING LEVEL AND ACHIEVED RELIABILITY FOR SEVERAL POTENTIAL PROGRAMS

Program	Equivalent Number of SNAP 10A Systems Under Simultaneous and Continuous Life Test During Government Fiscal Year						Reliability Achieved† by End of GFY 1967	
	1962*	1963	1964	1965	1966	1967	1-Year Operation (R)	Launch Survival and Startup (R_e)
Present R & D	0.7	1.0	0.8	0.3	0.0	0.0	0.43	0.63
Present R & D + Program I	1.4	1.8	2.3	2.3	2.0	2.0	0.79	0.85
Present R & D + Program II	1.7	2.5	3.6	3.9	3.7	3.7	0.86	0.85
Present R & D + Program III	1.7	2.7	5.7	6.3	6.0	6.0	0.90	0.88

*Last half of GFY 1962 only.
†For reliability engineering and product improvement efforts carried out at a rate approximately proportional to life test effort.

ties being achieved at given points in time as shown in Figures 2 and 3. The information shown in Figures 2 and 3 is based on the assumption that no reliability contribution is provided by use of SNAP 10A units in a satellite system; the estimated achieved reliabilities shown are thus somewhat conservative. The effects of including operational data in the estimation of reliability growth is discussed in this report; it is concluded that its major contribution will be to the improvement of launch survival and startup reliability due to the nature of the failure information that is expected to be telemetered. The influence on 1-year reliability will be less marked because weight limitations will confine diagnostic instrumentation to that which indicates only the fact and not the mode of subsystem failure. The probable component and mode of failure must then be deduced via extensive study and laboratory experimentation. Structural failure during launch or failure during startup, both occurring in relatively short periods of time, is much more susceptible to such deductions than is an endurance failure.

The total costs of an 8-satellite network using SNAP 10A units over a 5 year period has been approximated for the case where the total cost of a single satellite launched is 8 million dollars. The results are summarized in Table II. Although the satellite network costs presented are only approximate, they indicate the large savings that can result from even a small reliability improvement program.

TABLE II

APPROXIMATE TOTAL 5-YEAR COST OF AN 8-SATELLITE NETWORK USING SNAP 10A UNITS*
(Assumed 8 Million Dollars per Satellite Launched)

	Total Cost of Reliability Improvement Program 1/62 - 6/67 (10^6 Dollars)	Approximate Total 5-Year Costs of 8-Satellite Network Including Reliability Program 7/64 - 7/69 (10^6 Dollars)
Existing R & D Program	0.0	1039.6
Existing R & D Program Plus Reliability Improvement Program I	22.6	725.2
Existing R & D Program Plus Reliability Improvement Program II	31.1	710.9
Existing R & D Program Plus Reliability Improvement Program III	48.7	681.9

*Excludes any reliability improvement based on satellite operational data.

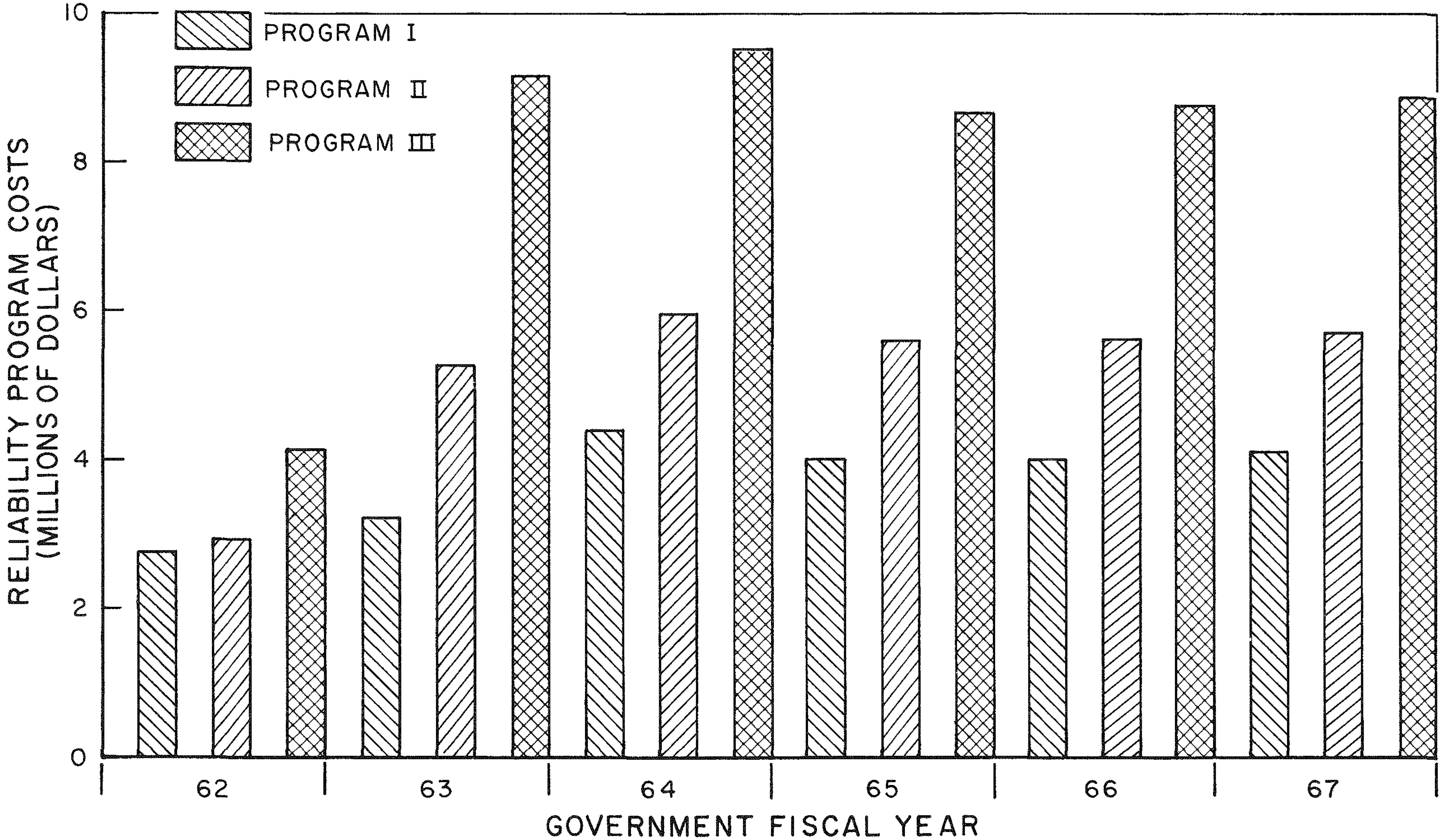


Figure 1. Estimated Annual Prices of Reliability Programs I, II, and III

UNCLASSIFIED

[redacted]

[redacted]

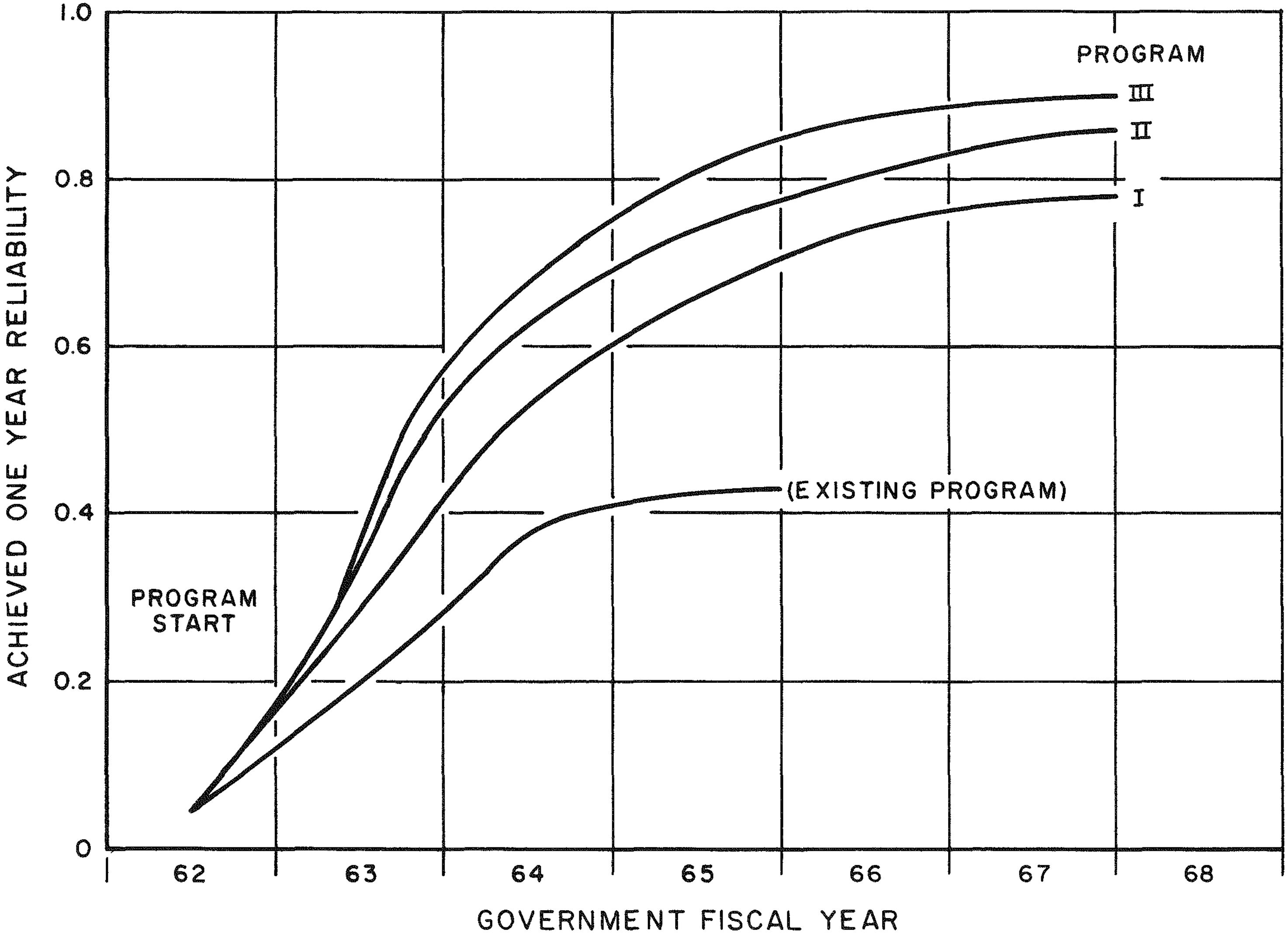


Figure 2. Achieved One-Year Reliability

[redacted]

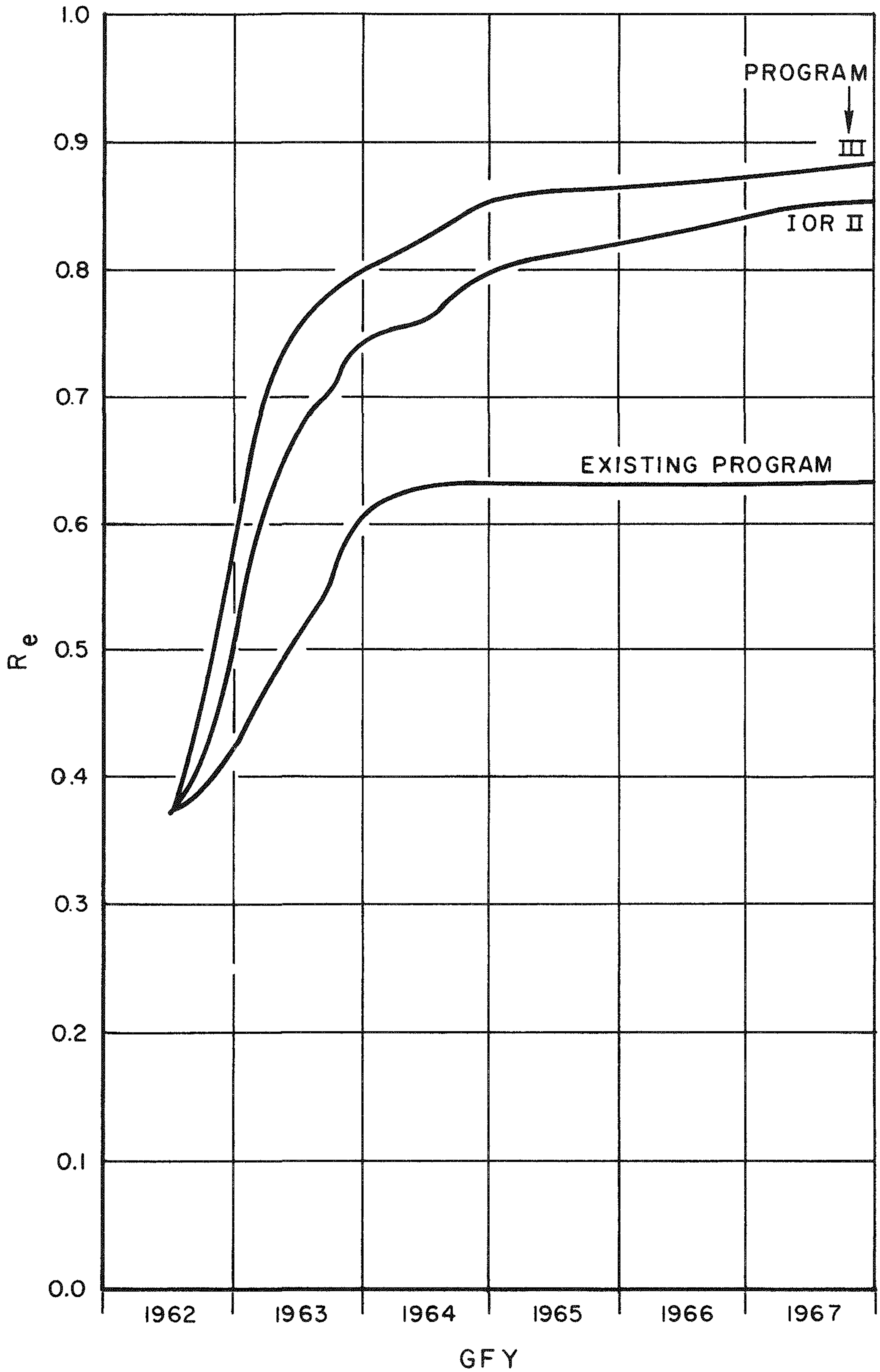


Figure 3. Achieved Launch Survival and Startup Reliability

[redacted]

The satellite replacement prices and the reliabilities not associated with SNAP 10A used in the satellite network cost analysis are not sufficiently accurate for selection between Program I, II, and III for the 8-satellite case considered. The level of the reliability improvement program should be estimated by military planners with correct factual information used in a detailed operational analysis; the SNAP 10A reliability growth estimates are presented in this report in sufficient detail so that military operations analysis personnel may readily include them in their more complete analysis. However, in view of the very large savings that will result from an improvement program, it is recommended that a program of at least the scope of Program I be undertaken immediately if operational use of SNAP 10A is being tentatively planned. A January, 1962, initiation date is considered to be consistent with the Air Force requested production plans detailed in NAA-SR-MEMO-6598. Re-evaluation of the actual rate of reliability improvement will be made continuously to revise and update the reliability growth equations to ensure that the reliability improvement is consistent with operational requirements.

The reliability values quoted in this report are the expectation (average) values, which correspond to a confidence level of ~50%.

I. INTRODUCTION

A. SNAP 10A SYSTEM DESCRIPTION

The SNAP 10A system is a 500 watt nuclear space power unit currently under development by Atomics International for the Atomic Energy Commission. The development objectives of the SNAP 10A system have been established to meet the requirements of the U.S. Air Force MIDAS weapon system. These requirements are summarized below:

1) 500-watt electrical output for 1 year of continuous operation
2) Minimum package weight (maximum allowable weight is 775 lb for the flight system, and 875 lb for the flight test systems equipped with diagnostic instrumentation)
3) Capability to withstand missile launch environment
4) Minimum hazard during all phases of missile launch and operation
5) Minimum package length (not to exceed 124 in.)
6) Shielding to give 10^{12} nvt and 10^7 r integrated one-year dose at a 5-ft diameter payload dose plane located 9 ft from the base of the power unit.
7) Maximum reliability.

The SNAP 10A system consists of a SNAP 2 reactor as a heat source, coupled to an array of integral thermoelectric converter radiator units mounted on small tubes and a d-c conduction pump which circulates a liquid metal that transfers the heat from the reactor to these tubes. A schematic of the system is shown in Figure 4. Also indicated in this Figure is the LiH shield, which is located between the reactor and the radiator converter, and the liquid metal expansion compensator.

SNAP 10A offers considerable advantage over other electric power supplies of similar output for use in satellite networks. It is compact, rugged, requires no extension or fold out, is independent of sun-shade transients, is not susceptable to space radiation damage or approximate vicinity nuclear weapons explosions, and its orientation during operation is immaterial. The space radiator tubes are potentially susceptible to damage by micrometiorites, but protection against puncture is

UNCLASSIFIED

[redacted]

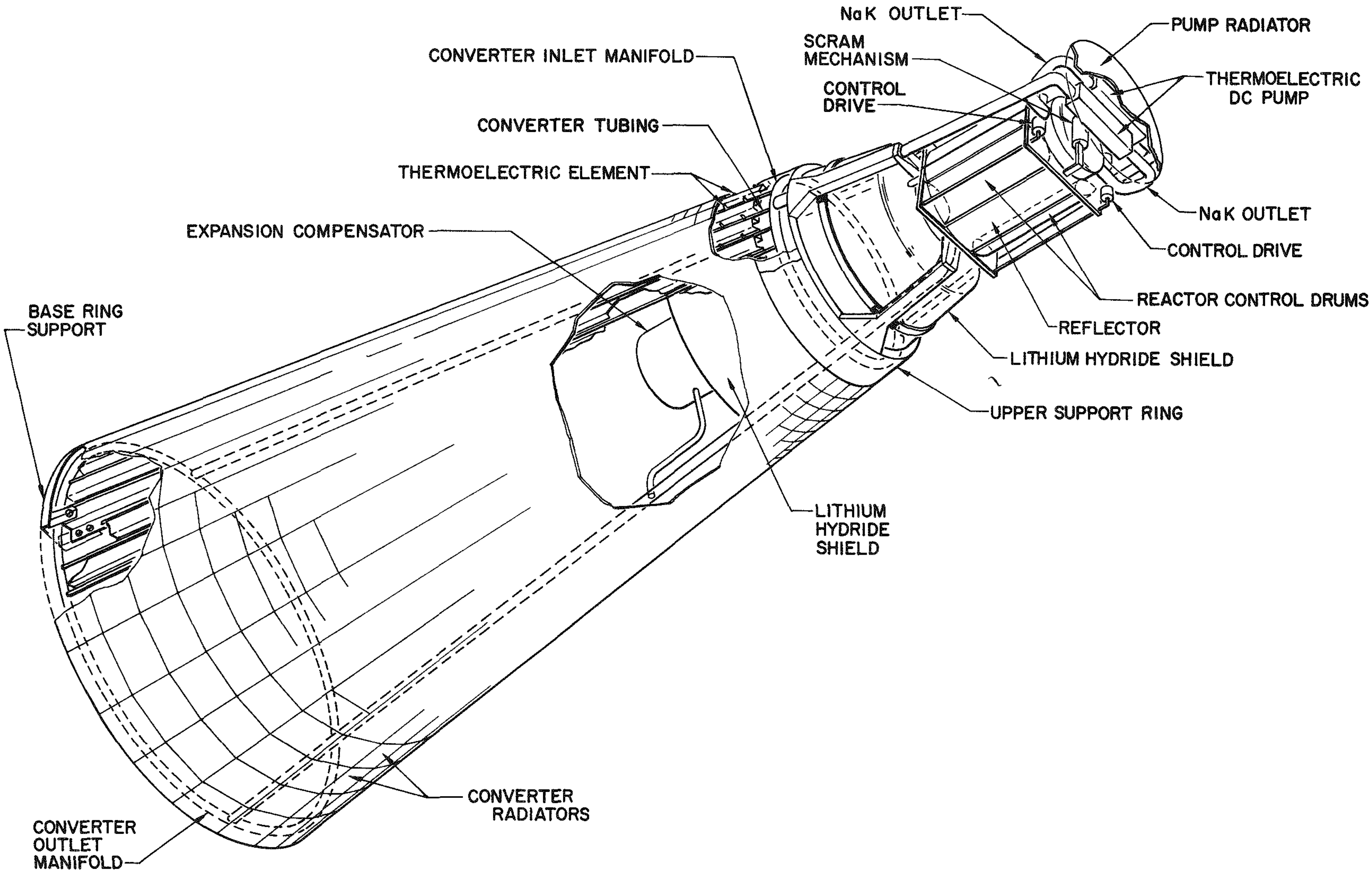


Figure 4. SNAP 10A System

UNCLASSIFIED

[redacted]

provided. There are no parts in continuous motion after startup, the only movement being the flow of electromagnetically pumped fluid in passages for heat transfer purposes. As such, the inherent reliability of the power system and the satellite is very high.

The SNAP 10A reactor, shown in Figure 5, is required to furnish $\sim$30 kw of thermal power at an outlet coolant temperature of 936°F. The heat transfer fluid is liquid metal NaK-78. Reactor and system startup will take place after a suitable orbit has been achieved; following the initial startup period the reactor will operate without external control for 1 year. At the end of the operational life ($\sim$1 year) the system will automatically shut down to allow a sufficient time for the accumulated fission product to decay before the system re-enters the earth's atmosphere.

Electrical energy is produced by the thermoelectric process which occurs when a temperature difference is maintained between opposite faces of a special class of materials. The thermoelectric materials selected for this system are the lead tellurides, N and P type. The required temperature differences are maintained by the liquid metal on the hot side and an aluminum radiator dissipating heat energy to space on the cold side. The integral thermoelectric-radiator elements are alternately connected by flexible electrical conductors as illustrated in Figure 6.

The aluminum radiator is required to dissipate $\sim$27 kw of thermal power to space, and is designed with a high fin effectiveness and high emissivity in order to minimize the required radiating area. Each radiator section is sized so that approximately the same ΔT, and therefore, the same heat flux is maintained across each thermoelectric element.

Due to an anticipated thermoelectric material degradation of about 10% and to uncertainties involved in the determination of performance changes during system operating life, the initial electrical power output will be set at 585 watts. The SNAP 10A overall conversion efficiency will be 1.7% at the end of 1 year of life.

The heat transfer system will maintain a coolant flow of about 12 gpm through the reactor with a system pressure drop of less than 1 psi. Coolant pumps are located above the reactor on each of the two NaK outlets. The type of coolant pump selected for the SNAP 10A system is a d-c conduction pump utilizing integrally mounted thermoelectric materials on the pump throat. Thermoelectric

[redacted] UNCLASSIFIED

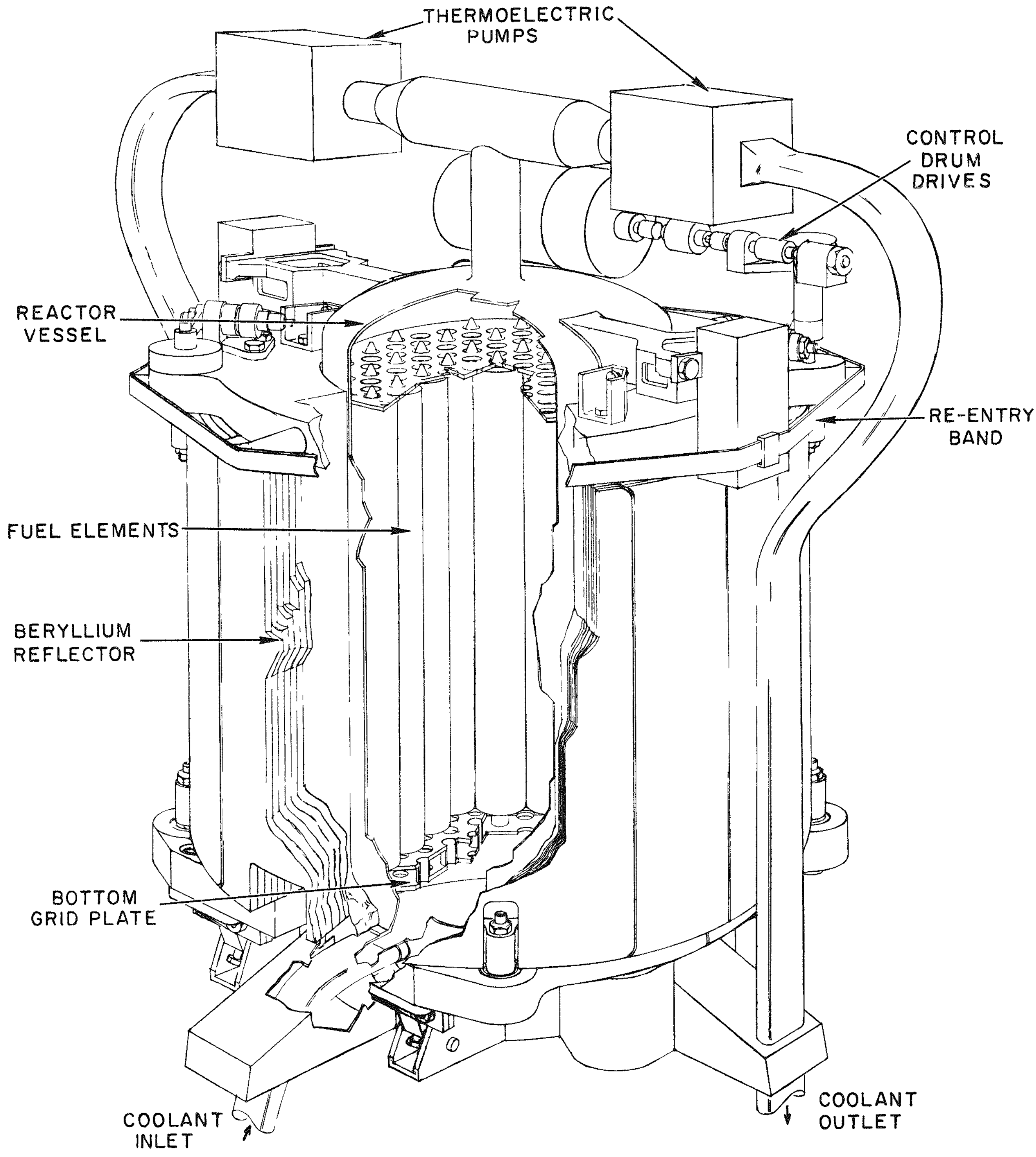


Figure 5. SNAP 10A Reactor

UNCLASSIFIED

[redacted]

[redacted]

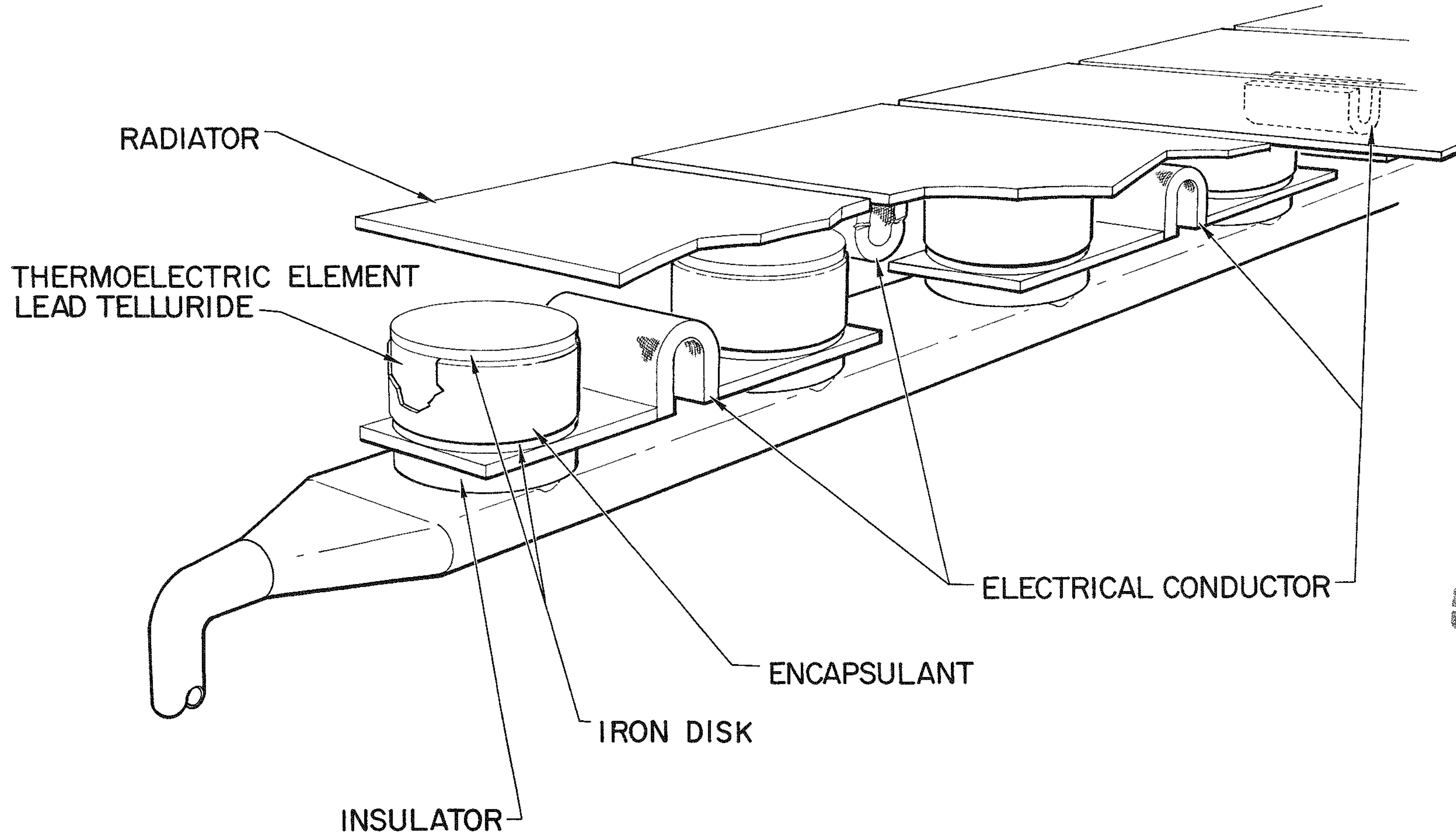


Figure 6. Primary Vacuum Thermocouple Design

UNCLASSIFIED

[redacted]

[redacted] UNCLASSIFIED

power is obtained from the temperature difference maintained between the hot coolant in the pump throat, and a cooler radiator dissipating heat energy to space. Figure 7 shows a flow-temperature schematic of the SNAP 10A system, and Table III indicates the system parameters.

TABLE III

SYSTEM PARAMETERS*

Electrical output (year-end)	500 watts
Reactor thermal power	30 kw
Efficiency (year-end)	1.7%
Temperatures	
Reactor outlet, initial	936°F
Reactor inlet	828°F
Converter hot junction	900 to 800°F
Converter cold junction	638 to 538°F
Radiator	628 to 528°F
Radiator area (converter)	62 ft^2
Radiator area (thermoelectric pumps)	2 ft^2
Flow in coolant system (NaK-78)	12 gpm
Pressure drop	1 psi
System weights	
Reactor (controls, structure, and safety devices)	250 lb
Radiator-converter	105 lb
Heat transfer system	100 lb
Structure (including meteorite protection)	65 lb
Shield	225 lb
Instrumentation, wiring, insulation, destruct, etc.	30 lb
Flight test instrumentation (for flight test models only)	50 lb
Contingency	50 lb
Total Weight	875 lb

*System components are discussed in more detail in the text.

A void-free NaK volume is maintained throughout the system by means of expansion compensators which automatically adjust according to the varying pressures and temperatures experienced during launch and system startup.

 [redacted]

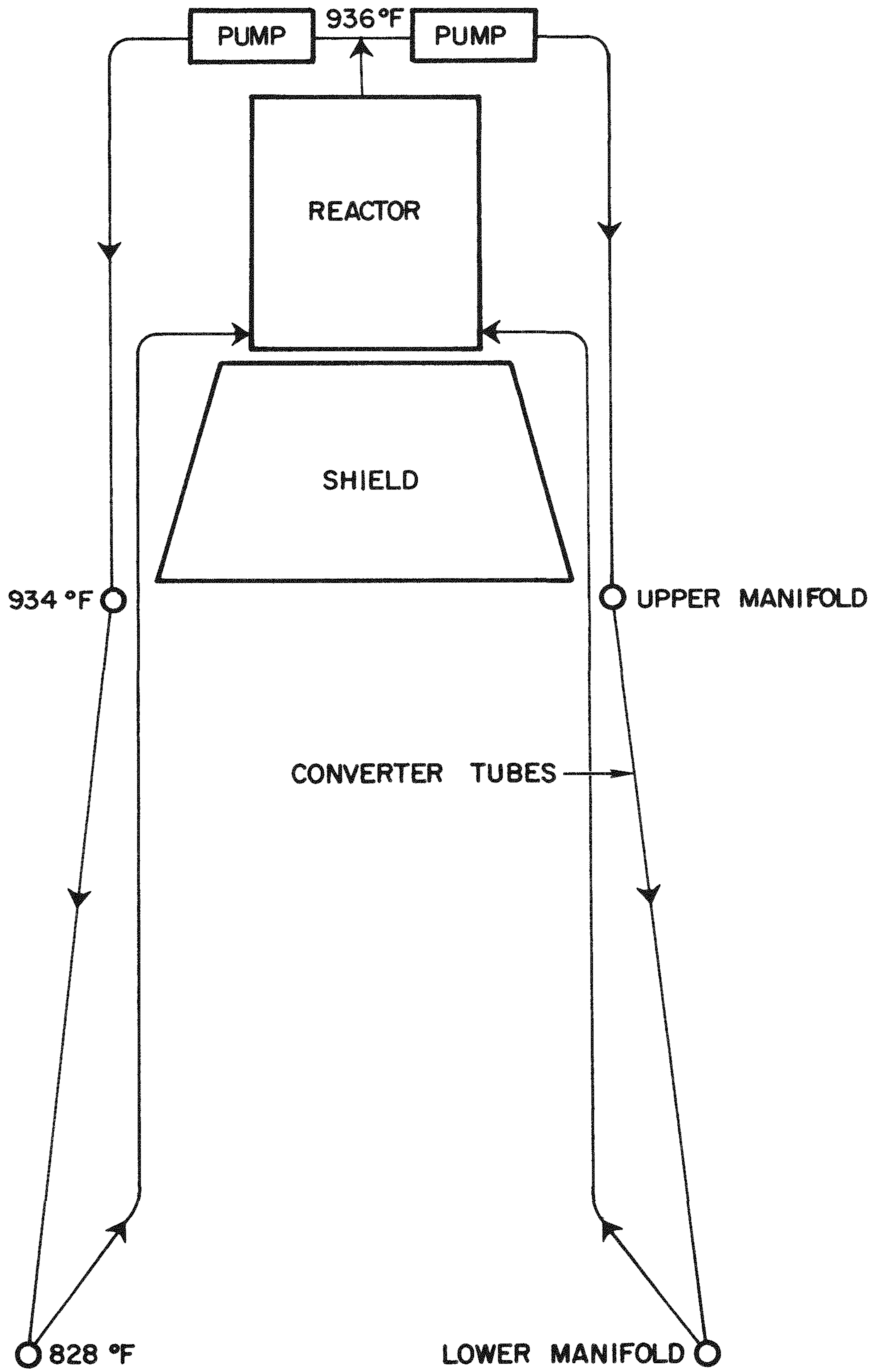


Figure 7. Temperature Flow Schematic-SNAP 10A System

[redacted]

All portions of the heat transfer system are fabricated of corrosion-resistant alloys. Meteorite protection is also provided to prevent penetration of the coolant system. Instrumentation will be provided to monitor various system parameters during launch, startup and flight, in addition to regulating the start-up sequences.

B. SUMMARY OF CURRENT DEVELOPMENT PROGRAM

The current SNAP 10A developmental program is directed toward flight tests of these units under the joint AEC-USAF SNAPSHOT program. SNAPSHOT flights are intended to establish the capabilities of nuclear auxiliary power plants so that their future use in space systems can be programmed with confidence. The sequence of flight tests for the SNAP 10A system form an integral part of this effort. These flight tests are currently scheduled for April and August, 1963, based on current launch site availability information. A third flight test is being considered for a later date.

In order to meet the objectives of the SNAP 10A program, a carefully scheduled set of development tasks and system tests must be performed. The nature of these are outlined in the paragraphs that follow.

1. System Engineering

The system performance objectives are analyzed and the requirements for the various subsystem components are established. The development necessary to meet the objectives is determined. The system package design is initiated and carried through.

2. Component Development

The development of the components is carried out to meet the performance objectives established under System Engineering. These components are tested under simulated vehicle launch as well as performance conditions. The components are associated with several major subsystems as follows:

a. Reactor

The SNAP 2 reactor will be used in this system. The SNAP 2 program will carry out the major development of the reactor and components with minimum modifications required for the SNAP 10A program.

b. Power Conversion System

A thermoelectric converter with an integral radiator will be used in this system. The converter development will be based on the utilization of current thermoelectric materials, such as lead telluride, together with an intensive effort on low resistance, mechanically sound electrical contacts, and encapsulation to suppress sublimation of the couple materials. In addition, module development to meet the weight, reliability and life objectives will be accomplished.

c. Heat Transfer System

NaK-78 will be used to transfer the heat from the reactor to the converter. A d-c electromagnetic pump as well as other system components, such as an expansion compensator, will be developed.

d. Shield

A lithium hydride radiation shield will be developed and tested to meet the nuclear and environmental requirements.

e. Structure

A structural package will be designed to provide the support for all of the components and attachment to the vehicle structure.

3. Environmental Test System (S-10-PSM-1)

The S-10-PSM-1 system will be used in performing mechanical tests on the package. It will consist of the basic structure together with the subsystems either mocked up as to mass and shape or as a developmental prototype being subjected to the localized shock and vibrational environment. The package will be subjected to the specified shock, vibration, and stress environment, and will provide structural information for the flight system design.

4. Performance Test (S-10-PSM-3)

The performance of a converter and associated heat transfer components will be studied in the S-10-PSM-3 system. The system will be operated with electrical heat in a simulated space environment. Data on efficiencies, heat losses, and long term performance will be obtained.

5. Flight System Design

The design of the flight system will be executed on the basis of the results of the component development and environmental and performance system tests.

6. Non-nuclear Qualification Tests (S-10-PSM-1)

The first system built from the flight design will be used for non-nuclear qualification tests. It will be subjected to qualification tests which will equal or exceed the expected mechanical environments of the launch conditions, after which it will undergo thermal tests in a simulated space environment.

7. Nuclear Qualification Tests (S-10-FS-1)

The nuclear qualification test system will be used to provide a final check of the flight system before delivery. S-10-FS-1 will be identical to the subsequent flight test systems, and will incorporate any modifications found to be necessary as a result of the non-nuclear qualification tests. After going through the acceptance test procedure the system will be operated under nuclear heat as a performance demonstration.

8. Flight Test (S-10-FS-2 and S-10-FS-3)

There will be at least two flight test systems. These will be identical to S-10-FS-1. Acceptance test procedures will be carried out and the systems delivered for flight test.

These tasks are coupled through the system design efforts. The preliminary design will constitute the reference system through the environmental and performance tests (S-10-PSM-1 and S-10-PSM-3) after which the flight design will be the reference system. As a result of the non-nuclear qualification tests, certain modifications may be necessary to the flight design. These modifications will be incorporated in the nuclear qualification and flight systems prior to their checkout.

In addition to the development program, two pre-flight mockups are required by the Air Force. The first is an electrical simulator mockup designated S-10-PSM-2, it will be developed to meet the vehicle contractor's requirements for a vehicle electrical load test. S-10-PSM-2 will be used in the development and testing of the vehicle electrical system.

A second system, S-10-FSM-2, will be used in the checkout of the flight vehicle. It will be integrated into the vehicle during final checkout and will go through the hot firing test of the vehicle. This test will provide a final qualification of the system for all of the vibration and shock conditions to be experienced in flight.

The schedule for the SNAP 10A program is shown in Figure 8 in terms of milestones for the developmental systems and subsystems just described.

C. ESTABLISHING OVERALL RELIABILITY GOALS

The use of the SNAP 10A power unit for an operational weapons system such as MIDAS will require an achieved reliability beyond the reliability projected for the current feasibility demonstration program which culminates in the SNAPSHOT test flights. In the feasibility demonstration the objective of 1 year life is maintained. However, it is not necessary to demonstrate before the first launch the reliability with which this endurance can be achieved. Estimates of the reliability associated with the current SNAP 10A developmental program, which are given in Section III, indicate a rather low value for the achieved system reliability at the time of the initial SNAPSHOT flight test. While a low value of reliability is acceptable in a feasibility program, the economics of launching and maintaining a number of operational satellites will demand a much higher degree of achieved reliability for the essential electrical power supply. An operational analysis of the total satellite complex must be performed to determine the required reliability to be met by the electrical power supply. The costs of an increasingly extensive ground reliability achievement program can be traded off against the costs of launching and maintaining a satellite network with a power system of lower achieved reliability. Such an operational analysis approach is given in Section IV. Much of the input information required for this type of analysis is tentative at this time, and for this reason it is presented primarily as a method to illustrate the technique.

In order to obtain the necessary economic information on the cost of achieving a given reliability, three different programs are described in Section III. These programs are identified as Program I, II, and III. Each program differs only in level of effort in addition to the current program, and result in different values of reliability being achieved at given points in time. There is also a considerable difference in funding levels and schedule of funds associated

UNCLASSIFIED

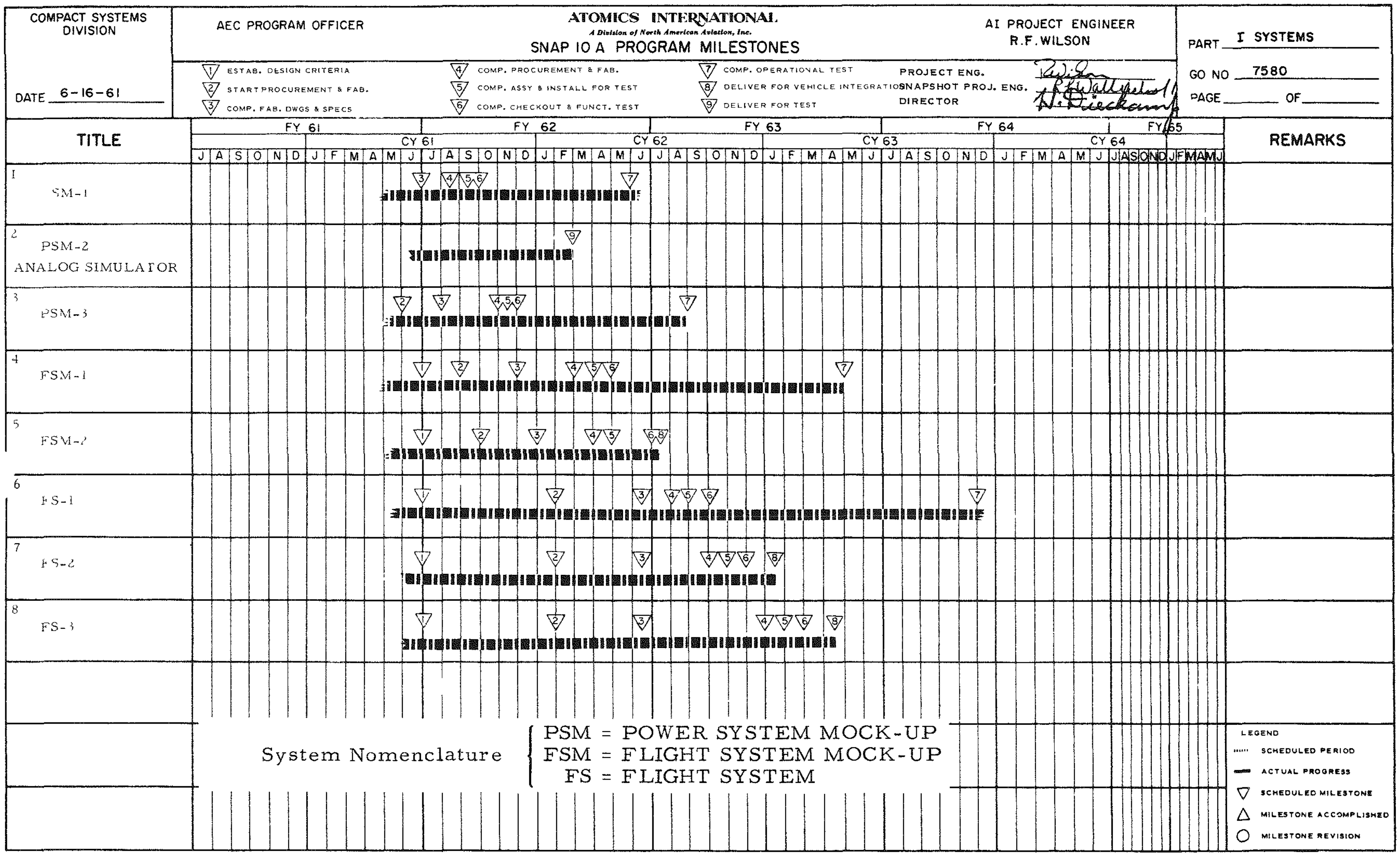


Figure 8. SNAP 10A Program Milestones

UNCLASSIFIED

with each of the three programs. This reflects the level of effort, the number and amount of concurrent tests, and the facilities required for the execution of the programs described. The information can be used to determine the relationship of achieveing a given reliability vs time and/or costs.

D. RELIABILITY IMPROVEMENT VERSUS RELIABILITY DEMONSTRATION PROGRAMS

In low-cost, short-lived systems it is frequently possible to include a reliability demonstration program with only a moderate increase in cost and which can be completed within an acceptable time period. However, for high-cost, long-life systems a reliability demonstration program often becomes unacceptably expensive and requires a prohibitively long testing period. Formal statistical reliability demonstration is fundamentally incompatible with rapid reliability growth. Statistically rigorous reliability demonstration infers that successive test systems remain constant in design and production techniques, which requires that there shall be no change or reliability improvement within the system during the reliability measurement. For the high-cost, long-life system, there must necessarily be a de-emphasis in a static reliability demonstration in preference to a major effort directed toward a dynamic reliability improvement or growth program.

A dynamic reliability growth program is one in which full emphasis is placed on methods for reduction and elimination of failure modes with component design improvements verified by accelerated component tests and incorporated into the system with a minimum time lag. The first occurrence of a failure mode initiates this closed loop system improvement effort as contrasted to static reliability programs which require a significant repetition of a particular mode of failure before an administrative decision is made to initiate the improvement process.

However, a quantitative knowledge of reliability status need not be entirely lacking in a reliability growth program. The reliability engineer may revise and update partial test data from obsolete systems and estimate reduction in failure rates achieved by improved design or production techniques. Thus, a current reliability status may be inferred which is sufficient for practical purposes; this should not be confused with statistically rigorous reliability demonstration testing. The latter demonstration is expensive and time consuming and it is questionable whether there exists any real need or utility for a rigorous knowledge of reliability status as compared to an approximate, inferred reliability status.

E. ELEMENTS OF A RELIABILITY IMPROVEMENT PROGRAM

The basic elements of a dynamic reliability growth program are: 1) reliability engineering and coordination; 2) product improvement development; 3) subsystem and system reliability developmental testing; and 4) production quality assurance.

1. Reliability Engineering and Coordination

The reliability engineering and coordination basically supplement the normal development, safety, and production engineering functions such that reliability factors receive proper emphasis as a specific system requirement.

The system reliability goals are assessed and apportioned to the different components to serve as design, development, production, and quality control guides. The modes of failure and the cause and effects of performance degradation are analyzed in terms of system performance to establish research and development requirements. The effects of redundancy and performance derating are analyzed and evaluated. The system design is analyzed to determine that the overall concept does not place unrealistic reliability objectives upon individual components. Failure reports are prepared, and development and production specifications are compiled and analyzed with appropriate corrective actions taken as required. Subcontractor reliability programs are monitored and purchased parts reliability and quality control specifications are prepared and administered.

2. Product Improvement Development

This is a major productive area of a reliability improvement program. Components or materials which are ascertained to be critical reliability areas from either failure mode analysis, statistical reliability analysis, or from occurrence of failures during the development, production, or operational testing phases are selected for detailed investigation and improvement.

a. Program Technological Support

This effort is required to establish the basic scientific foundation that will allow a rapid understanding and lead to remedial solutions for observed or anticipated failure modes to enhance component improvement. Fundamental investigations are required in areas such as: metallurgical fusion processes, diffusion rate effects, impurity phenomena, materials creep and fatigue, temperature and radiation effects, errosion, corrosion, wear, welding, bonding, high vacuum, shock, vibration, and micrometeorite effects. Failure to vigorously support these areas of effort can result in a succession of failures and quick fixes which are expensive and completely inadequate to achieve the final reliability objectives. This basic program support is required, in fact, to improve the state-of-the-art so that the effort for long-lived high-reliability systems can proceed in an orderly, economic and rapid manner.

b. Component Modification and Re-design

Functional analyses of critical parts must be performed to determine design, fabrication process, or materials required to eliminate or reduce modes of failure. Alternate solutions are compared and tested to verify that desired results have been achieved. In complex situations where direct functional analysis is inadequate to determine where failure modes exist, experiments designed to statistically isolate the failure mode will be utilized.

3. System Reliability Improvement Testing

In actual subsystem and system testing the final system failure points are obtained and are used to define the areas of concentration for the previously described product improvement development and program technological support activities.

a. Launch Environment

The simulation of shock and vibration conditions of missile launching will be imposed on complete systems and major subsystems. Detailed measurements of local component environments as effected by resonance or damping conditions will be made to guide design modifications.

b. Life Tests

Proper evaluation of the ultimate system life capability and its performance degradation properties requires life testing. Extensive life testing at the component level will have revealed the majority of the aging effects such that system testing will primarily serve to reveal interaction effects which could not be anticipated. In principle, all such system effects should be represented in the environmental component testing; however, in practice complete final system tests in the most closely simulated environment possible must be undertaken in small quantity or sample for final verification of program adequacy.

c. Startup and Safety Shutdown Testing

The system orbital startup programmer, sensors and actuators must survive the launch conditions and then successfully start up the nuclear system and eject nosecone fairings and radiator shields. This requires repetitive operation to reveal potential reliability trouble areas. The safety mechanisms and end of life shutdown devices also require environmental and repetitive testing to reveal problem areas.

4. Quality Assurance

The major quality assurance effort will be associated with the production program and is discussed in detail in the production report, NAA-SR-MEMO-6598 (SECRET).

The quality assurance effort associated with the reliability improvement program is limited to inspection and acceptance testing necessary to establish that specifications for materials, parts, and equipment used in the improvement program are met. Existing inspection techniques will be used wherever possible. Inspection data will be recorded for later use in analyses of failures which occur during the reliability improvement test work.

5. Evaluation and Usage of Production and Operational Data

Production, quality assurance, and reliability groups will work in conjunction to evaluate the influence of dimensional tolerances, materials specifications, manufacturing processes, and similar factors on both reliability and product producibility. This cooperative effort provides for determination of criticality within such areas with regard to reliability and thus provides the earliest possible indication of those specifications which can be relaxed to enhance producibility.

Limited field test and operational data as well as failure reports will be available for SNAP 10A units used in the performance of space missions. The value of such information is discussed in Section III-D.

II. RELIABILITY PROGRAM PLANNING AND ADMINISTRATION

A. PROGRAM ADMINISTRATION

The organization of the SNAP 10A reliability program within Atomics International consists of: 1) a SNAP 10A Reliability Project Engineer reporting directly to the SNAP 10A Chief Project Engineer; 2) a central grouping of specifically assigned SNAP 10A reliability engineers in the SNAP 10A Reliability Engineering Unit; and 3) assistance of reliability engineers assigned to various sybsystems or specific tasks located where needed in various parts of the organization. This type of organization is shown on Figure 9 and is consistent with the present organization of technical responsibilities on the SNAP 10A development program. The relation of the SNAP 10A reliability organization with the overall Reliability Representation at Atomics International is also illustrated in Figure 9.

The responsibilities at each level of the reliability organization are as follows:

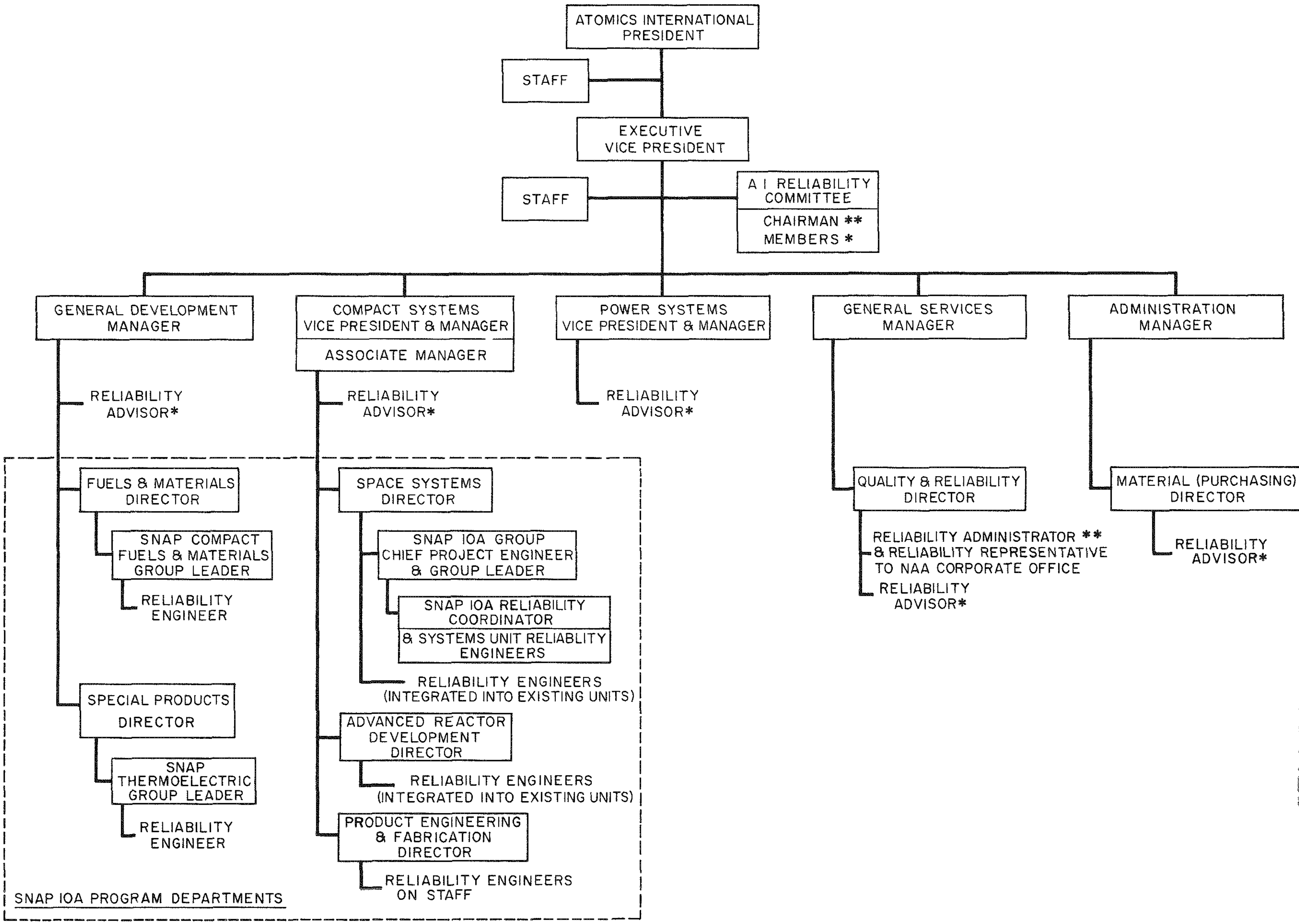
1) The Atomics International Reliability Administrator is Chairman of the Reliability Committee, and also serves as the Corporate Office Representative. He is concerned with reliability training, information exchange, and reliability policy with customers and suppliers.

2) Divisional Reliability Advisors are members of the Reliability Committee and in the case of the Compact Systems Division, are concerned with keeping the Division Head and each SNAP project reliability coordinator informed of reliability factors which have a bearing upon the Division's activities.

3) SNAP 10A Reliability Project Engineer is the focal point for SNAP 10A customer contacts pertaining to reliability, SNAP 10A subcontractor reliability program requirements, and contract reliability specifications. As a technical assistant to the SNAP 10A Chief Project Engineer, he maintains surveillance and provides direction to the complete SNAP 10A reliability program.

4) SNAP 10A Reliability Engineering Unit engineers conduct SNAP 10A system reliability activities including reliability apportionment, failure report analysis, maintain central failure report files, and prepare reliability reports for the AEC and the Air Force.

[redacted]



[redacted]

Figure 9. SNAP 10A Reliability Program Organization

5) Functionally assigned reliability engineers are organized within various groups as needed. Their duties are detailed analysis of modes of failure, effects of redundancy design, effects of component derating and design factors of safety, and assist development engineers in statistical design of experiments to determine cause of failures.

B. RELIABILITY ENGINEERING AND COORDINATION

The overall function of reliability engineering activities is to supplement and assist the normal development engineering activities so that reliability growth and measurement receive proper emphasis as a distinct system requirement. These activities range from quantitative selection of factors of safety in the design phase to post mortem analysis of failures in developed systems.

1. Design Procedures

Techniques useful in the design phase are estimation of system reliability goals, reliability apportionment to the component level, and interpretation of these goals in terms of recommendation of required safety factors for design. Alternate design approaches can be compared in terms of relative potential reliability and evaluated along with other relative performance criteria to guide design decisions. Design reviews can include reliability considerations with the aid of check lists of prior failure experience on similar components.

2. Development Procedures

The development phase, when component and system prototypes are being constructed and tested, is an important area for reliability improvement. Detailed analysis of early failures and performance malfunctions can assist the development engineer in determining the probable cause of the failure and eliminate it by design modifications. In complex situations the reliability engineer can assist by a statistical design of experiments to reveal the factors causing performance deterioration. A careful surveillance of purchased part performance observed during the development phase may yield lists of recommended suppliers. The observed failures should be recorded and analyzed in failure reports to guide current and future designs.

3. Production Procedures

In this phase the design is basically fixed and the reliability emphasis is upon fabrication process control and establishment of written specifications to detail the control. Formal reliability programs for selected subcontractors will be required with similar process control specifications. The failure reports from the development test activities, qualification tests, launch pad activity tests and telemetered orbital operation performance will be compiled and evaluated. The reports will require individual failure mode analysis and corrective recommendations as applicable. The performance and test program results will be evaluated in terms of demonstrated reliability and status reports prepared for the AEC and the Air Force.

4. Production and Performance Records for Identification of Critical Parts

Production and performance records will be maintained to follow each part from design through fabrication, inspection, assembly, acceptance testing, and final usage. Specifications and all data obtained from inspection, quality control, performance, and failure will be recorded and cataloged for use in identification and improvement of critical parts and components.

The immediate availability of this information will be useful in evaluating the relative criticality of the many parts at any time so that work can be concentrated in the most critical areas. This approach is analogous to the PERT-PEP systems used to locate the critical paths through a development program in order that effort is apportioned to best advantage.

C. METHODS FOR EVALUATION OF PROJECTED RELIABILITY PROGRAMS

1. One-Year Reliability Growth Equation

In instances where considerable accumulated experience with individual components is available, such as in the case of some electronic equipment, the reliability of the initial design may be estimated with reasonable accuracy.

After a system has been constructed and tested, the achieved reliability may be readily inferred using the techniques of probability and statistics. However, it is always very difficult to predict the reliability improvement which would result from an additional subsequent improvement effort; this difficulty arises because the relationship of reliability improvement to rate of effort is highly dependent on factors such as ability to anticipate possible failure modes, number of failure observations before redesign can be completed, skill of redesign, test down time for installation of redesigned components, and so on. In spite of the many unknowns involved, it is absolutely necessary that a relationship between reliability improvement and rate of improvement effort be predicted for use in planning and evaluating reliability improvement programs; this relationship is frequently called the reliability growth equation. The equation selected for application to the SNAP 10A system and the reason for its selection are described in the following:

Defining f as the failure rate, the reliability (R) is:

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

where T is the lifetime for which the failure rate is defined. Defining θ as the mean time between failures, then

$$R = e^{-\frac{T}{\theta}}$$

or, since T = 1 year for SNAP 10A,

$$R = e^{-\frac{1}{\theta}} .$$

For a reliability improvement program carried out at a fairly constant rate, it is reasonable to assume that information is gained and applied such that the mean time between failure increases at a constant rate; therefore, it is assumed that

$$\theta = at + \theta_o$$

where a is a constant, t is time measured from the initiation of the program, and θ_o is the initial mean time between failure at t = 0. Then

$$R = e^{-\frac{1}{at + \theta_o}} .$$

At t = 0, there exists some initial reliability based on previous work; for a reliability improvement program begun at mid-GFY 1962 this initial reliability for SNAP 10A is conservatively estimated to be 0.05 yielding an initial $\theta_o = 1/3$; hence

$$R = e^{-\frac{1}{at + 1/3}} .$$

 [redacted]

The value of the constant a, which describes the rate of increase of θ, may be estimated by comparison with reliability improvement experience on liquid rocket engines. Liquid rocket engines are mechanical and hydraulic systems and thus serve as a better model for comparison with nuclear reactor power plants than any primarily electronic system. An observed reliability growth equation that has been used to fit reliability growth experience at Rocketdyne is:

$$R = e^{-\frac{1.3}{Y^{1.5} + 1.3}}$$

where

Y = number of rocket engine firing duration tests in groups of 20.

This equation is shown on Figure 10 in comparison with the 1-year reliability growth equation proposed for SNAP 10A. A value of $a = m/3$, where m is the number of equivalent simultaneous SNAP system tests being conducted, is selected in view of the differences in rocket engine testing and reactor system testing. Rocket engine test firings are conducted at a rate of about 100 firings per year on a given engine, while SNAP system tests will average only 2 to 6 per year. With such closely spaced rocket engine tests it is difficult to incorporate design changes for reliability improvement into the next following engines tested. In a SNAP 10A system reliability improvement program scheduling will allow each new system tested to be modified and improved based on all prior test experience. From such considerations it is estimated that 10 rocket engine firings yield approximately the same reliability improvement as 1 year of SNAP system testing in terms of resultant learning and reliability growth. This equivalence is indicated on the abscicca of Figure 10, and the proposed SNAP 10A 1-year reliability growth equation is seen to approximate the slope of the Rocketdyne equation.

The implications of, and some insight into the proposed SNAP reliability growth curve are represented in Figures 11 and 12. Basically, the mean time between failures, θ, increases linearly with test effort time, t. In practice various physical limitations will form an upper limit on the rate of increase in mean time between failure; however, this limitation is expected to be beyond the limitations of funding. In Figure 12, the reliability growth is shown with real program time as abscicca and various values of multiplicity m in the level of concurrent equivalent tests as a parameter.

[redacted]

[redacted]

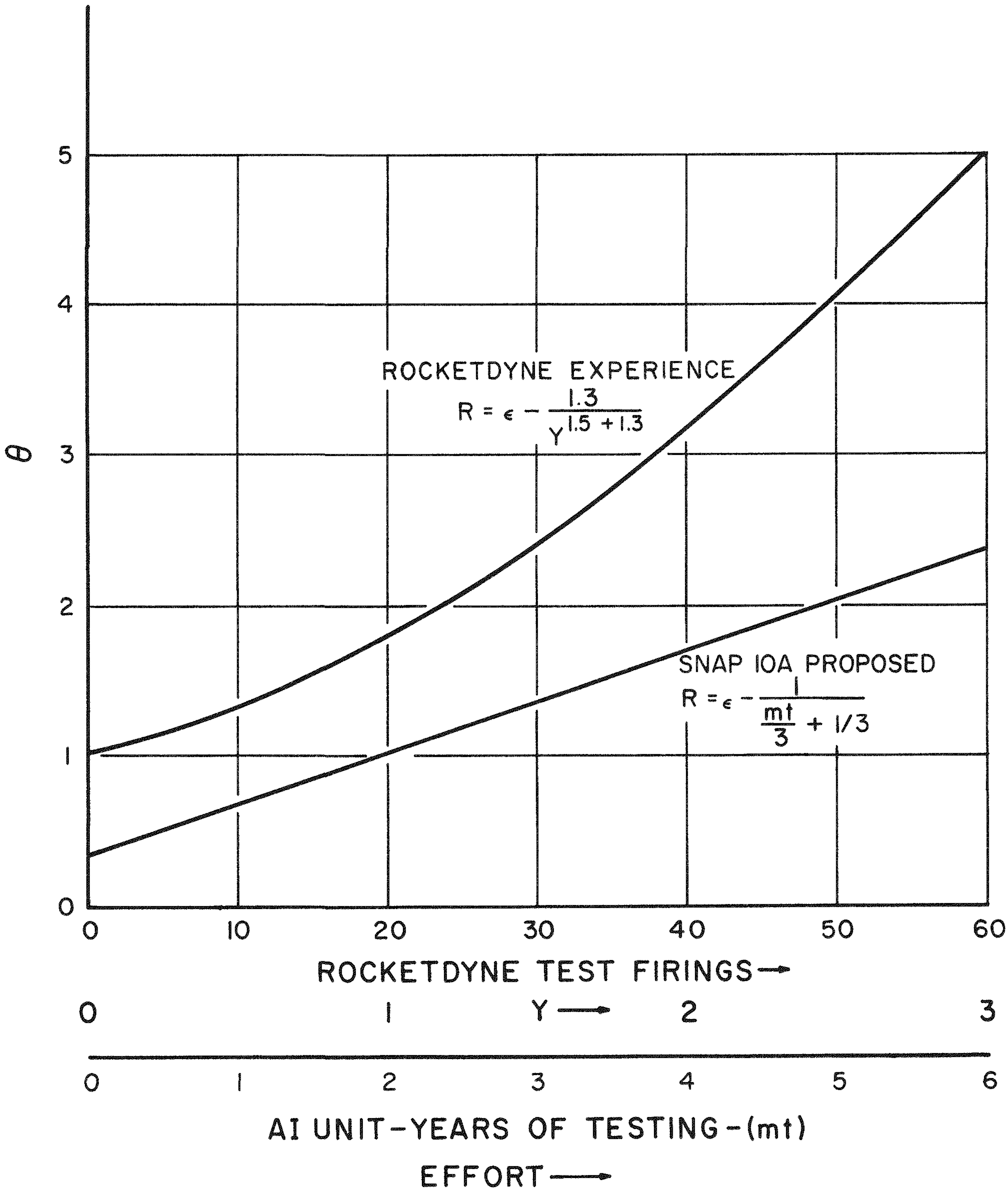


Figure 10. Relation Between Engineering Test Effort and Achieved Reliability

[redacted]

[redacted]

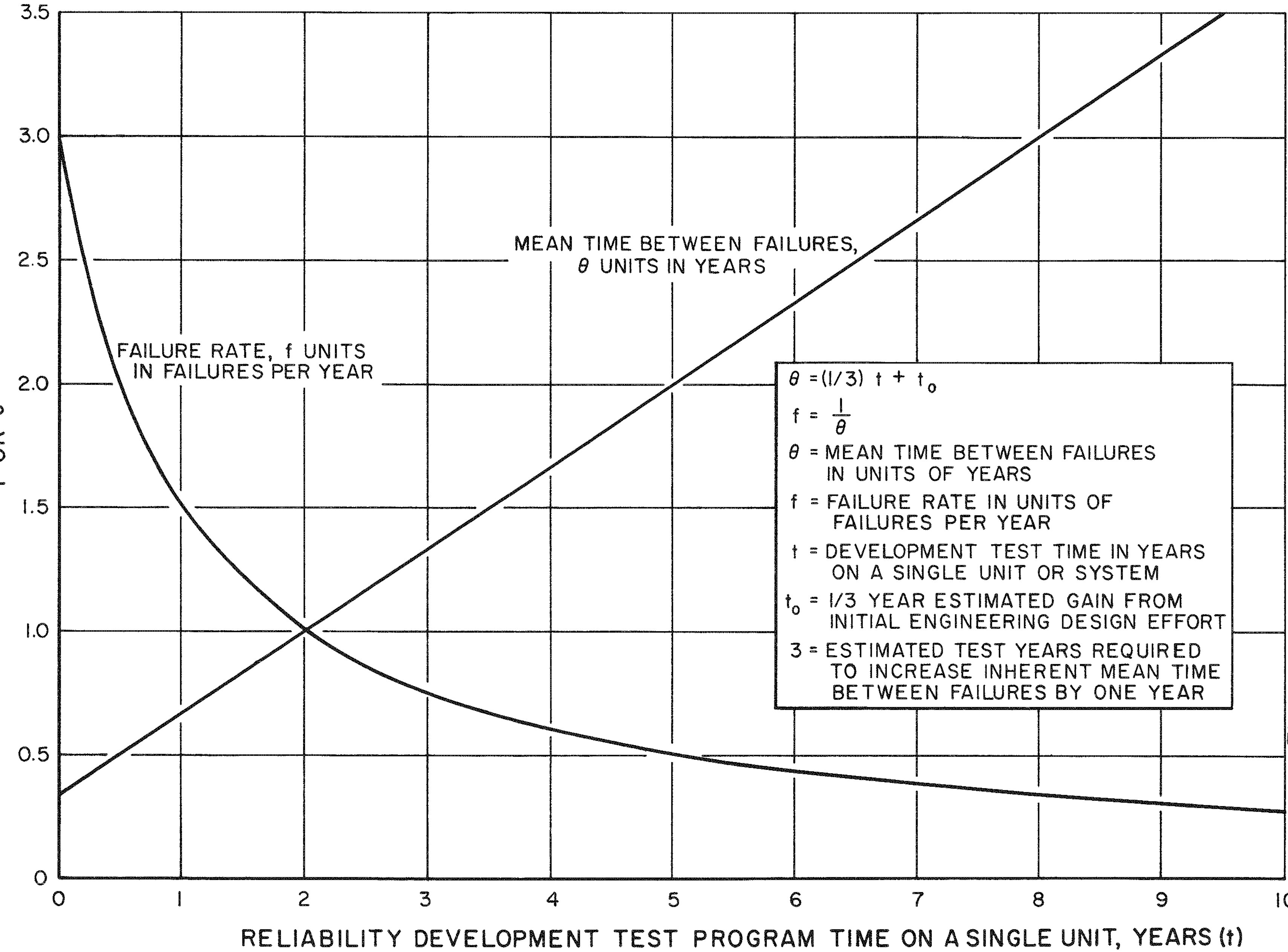


Figure 11. Proposed Learning Curves

[redacted]

[redacted]

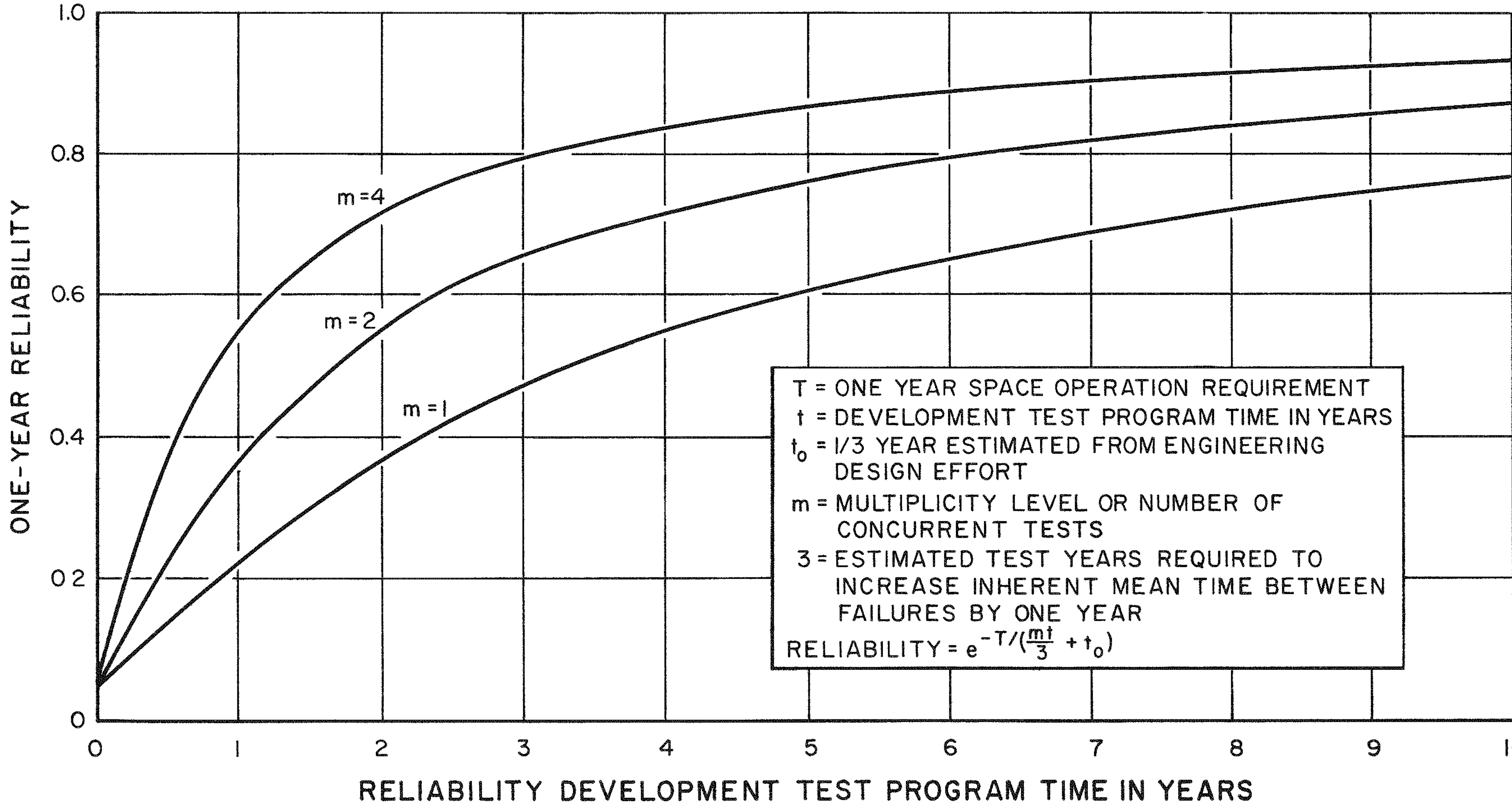


Figure 12. One-Year Reliability Growth Curves

[redacted]

2. Launch Survival and Startup Reliability Growth Equation

Since this portion of the program will be carried out at a rate proportional to the 1-year reliability improvement effort, the launch survival and startup reliability growth equation should be of the same general form as the 1-year reliability growth equation just defined.

In this case the reliability at the beginning of the improvement program is estimated to be 0.37; the growth equation is then

$$R_e = e^{-\frac{1}{bX + 1}}$$

where R_e is the launch survival and startup reliability, b is a constant, and X is the number of tests completed.

Performance of a single launch environment test of a system, analysis of results, and modification in line with the results will require about 3 months; testing, analysis, and modification of startup and safety subsystems will proceed on the average at a comparable rate. By planning the program such that the instantaneous ratio of systems being subjected to launch environment testing, to systems in startup and safety tests, remains fairly constant during the program, the number of launch environment tests completed is an index to reliability growth. Therefore, X in the growth equation is taken to be the number of launch environment tests completed.

It is now necessary to estimate a value for the constant b. The failure of a single part can terminate a launch environment test so that information regarding other critical parts can be gained only via additional tests. In life testing, a failed part can usually be replaced so that testing can be continued and other critical parts can be identified. Therefore, it is estimated that one launch environment test is equivalent in result to one-half of a 1-year life test. Hence, by comparison with the 1-year reliability growth equation,

$$b \cdot 1 = \frac{1}{2} \cdot \frac{1 \cdot 1}{3}$$

from which

$$b = \frac{1}{6} .$$

Then

$$R_e = e^{-\frac{1}{\frac{X}{6} + 1}} .$$

This equation is plotted in Figure 13.

3. Statistical Methods

a. General

In the preceding discussion a reliability growth equation was defined in terms of complete system tests. However, good engineering development practice involves a mixture of component, subsystem and system testing. A method of properly assessing the worth of component and subsystem testing in terms of equivalent system testing is thus required. Some degree of guidance in planning may be obtained by first considering the equations to be used for evaluating test results on components in terms of system performance.

In a series system of n components and independent failures it is generally stated that failure rates are additive; however, it is frequently forgotten that only the mean or expectation values of failure rate may be added. Statistical terms like median failure rate,, most likely failure rate, or failure rate at some confidence level are interesting terms when properly used, but in general none of these have the desired additive property.

In life tests in which failure rates are assumed to remain constant, Poisson statistics are applicable and it may be rigorously stated for a failure truncated test with replacement that the expectation (average) value of i^{th} component failure rate is:

$$\overline{\lambda}_i = \frac{x_i + 1}{T_i}$$

where x_i is the observed number of failures in time T_i.

If all component tests are of same duration, T_n, then the expectation (average) value of system failure rate is

[redacted]

UNCLASSIFIED

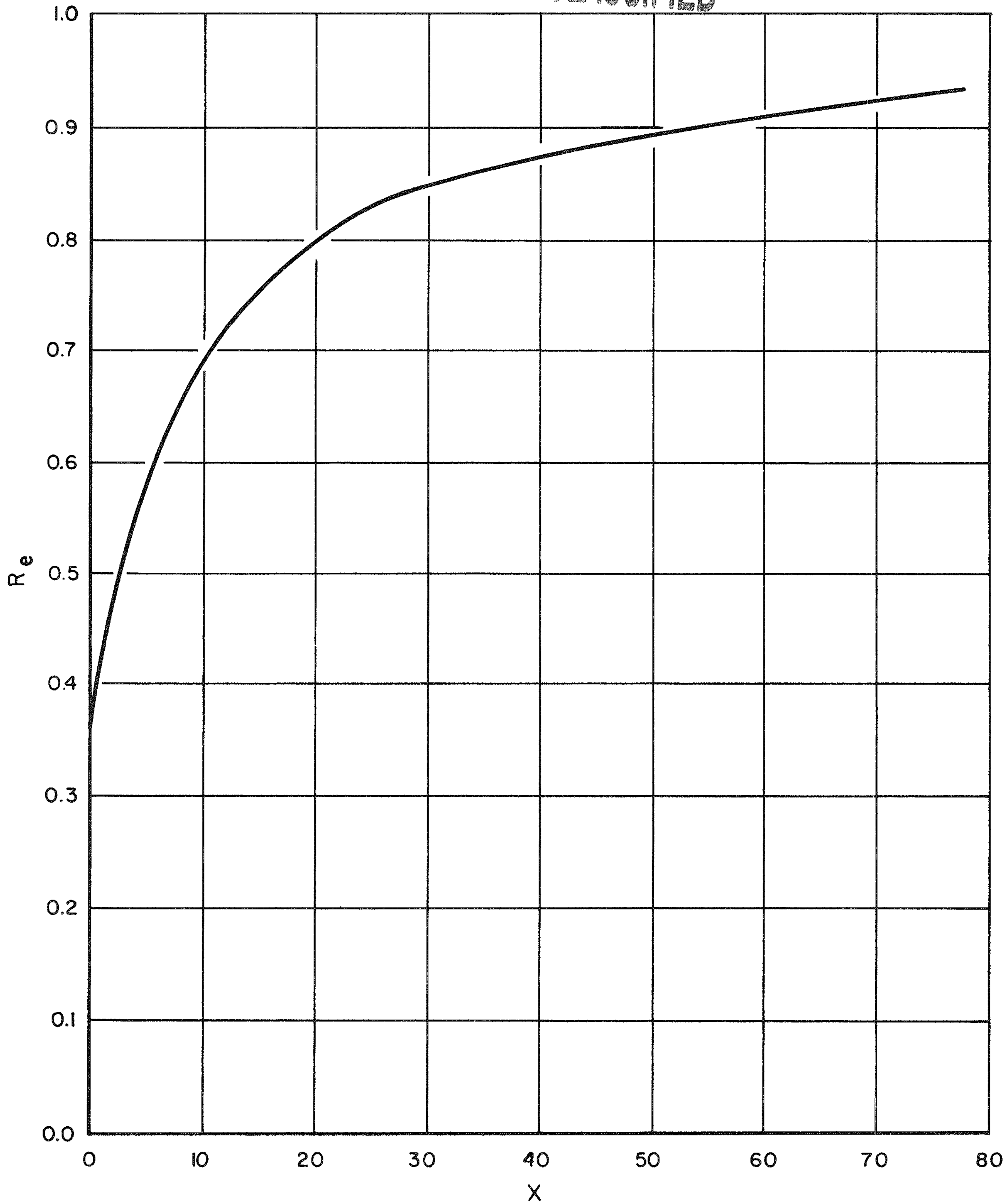


Figure 13. Growth of Launch Survival and Startup Reliability (R_e) as a Function of Tests Completed (x)

UNCLASSIFIED

[redacted]

$$\overline{\lambda}_n = \frac{\sum^{i} (x_i) + 1}{T_n} .$$

A necessary modification required to make these equations consistent when component failure rates are added is for the general case in which component test times are unequal,

$$\overline{\lambda}_n = \sum^{i} \left(\frac{x_i + 1}{T_i} \right) - \frac{n - 1}{T_w}$$

where

$$T_w = \frac{\sum^{i} (1 - f_i) T_i}{\sum^{i} (1 - f_i)}$$

and f_i = estimated fraction of system failure rate due to i^{th} component. The T_w term has been designed to maintain consistency when $T_i = T_n$ and yield reasonable values of system failure rate for unequal component test times. A rigorous statistical treatment of this type of problem for a system consisting of more than two components requires extensive digital machine calculation. This action is not warranted at this stage of planning but would be undertaken as part of the reliability program to assess reliability status.

b. <u>Worth of Various Tests</u>

The worth of a set of unequal time tests on system components may be expressed in terms of an equivalent system test time, T_E, as

$$T_E = \frac{1 + \sum^{i} x_i}{\overline{\lambda}_n}$$

where $\overline{\lambda}_n$ is obtained as described in the preceding. A useful approximation that is reasonably satisfactory for program planning purposes is:

[redacted]

$$T_E \approx \frac{\sum^{i} f_i T_i}{\sum^{i} f_i}.$$

In the specific case of SNAP 10A a preliminary estimate is that about 2/3 of the system failure rate will be due to the non-nuclear power conversion subsystem while 1/3 will be due to the reactor sybsystem. On this basis, a non-nuclear subsystem test is counted as the equivalent of 2/3 of a system in accumulating reliability experience. Similarly, all nuclear SNAP 2 life tests are counted as 1/3 of an equivalent SNAP 10A system in accumulating reliability experience applicable to SNAP 10A.

The reliability growth equation is based upon an assumed level of learning from system tests. When a ground test system malfunctions or fails, the parts are available for detailed examination and reliability experience accumulates. In the case of the initial SNAPSHOTS, the operating systems will be provided with extensive telemetry which will provide additional system performance experience. Since the parts will not become available for examination, a space test has been arbitrarily counted as 1/4 as effective as an equivalent ground system test in terms of accumulation of reliability growth experience. Of course, operation of systems in space will be a much larger factor in terms of demonstrating reliability.

c. Optimum Apportionment of Effort for Minimum Cost

The preceding section indicates that optimum reliability growth is achieved by applying developmental testing effort on a particular subsystem in proportion to its estimated fractional contribution to the total system failure rate. However, an economic optimum apportionment of effort must include the factors of relative cost of development testing effort on various subsystems. One method of apportioning effort within a system composed of two major subsystems is as follows: consider the SNAP 10A nuclear subsystem with fraction, f, of the system failure rate tested for time T_1 and the non-nuclear subsystem tested for time T_2 and assume the case of zero failures.

The expectation of system failure rate is:

[redacted]

$$\overline{\lambda}_s = \frac{1}{T_1} + \frac{1}{T_2} - \frac{1}{(1 - f)T_1 + fT_2}$$

$$= \frac{1}{T_1}\left[1 + \frac{1}{r} - \frac{1/f}{r + (1 - f)/f}\right]$$

where

$$r = T_2/T_1$$

and the system test cost is:

$$C_s = C_1T_1 + C_2T_2 = T_1(C_1 + rC_2).$$

Simultaneous solution of these equations to eliminate T_1 yields

$$\overline{\lambda}_s = \left[\frac{C_1 + rC_2}{C_s}\right]\left[1 + \frac{1}{r} - \frac{1/f}{r + (1 - f)/f}\right].$$

For

$$\frac{d\overline{\lambda}s}{dr} = 0,$$

$$\frac{C_1}{C_2} = \frac{\left[1 + \frac{1}{r} - \frac{1/f}{r + (1 - f)/f}\right] - r\left[\frac{1}{r^2} - \frac{1/f}{\left\{r + (1 - f)/f\right\}^2}\right]}{\frac{1}{r^2} - \frac{1/f}{\left\{r + (1 - f)/f\right\}^2}}.$$

This relation is presented in Figure 14 for various assumed values of f and is seen to be relatively insensitive to this parameter. At an estimated ratio of $C_1/C_2 = 4$ for reactor subsystem to non-nuclear subsystem testing costs, the optimum time ratio ranges from $T_2/T_1 = 1.4$ to 1.8 for the ratio of non-nuclear subsystem test time to reactor subsystem test time for f ranging from 1/4 to 1/2. A figure of 1.5 was used in apportioning the testing levels in Reliability Programs I, II, and III described in a later section.

[redacted]

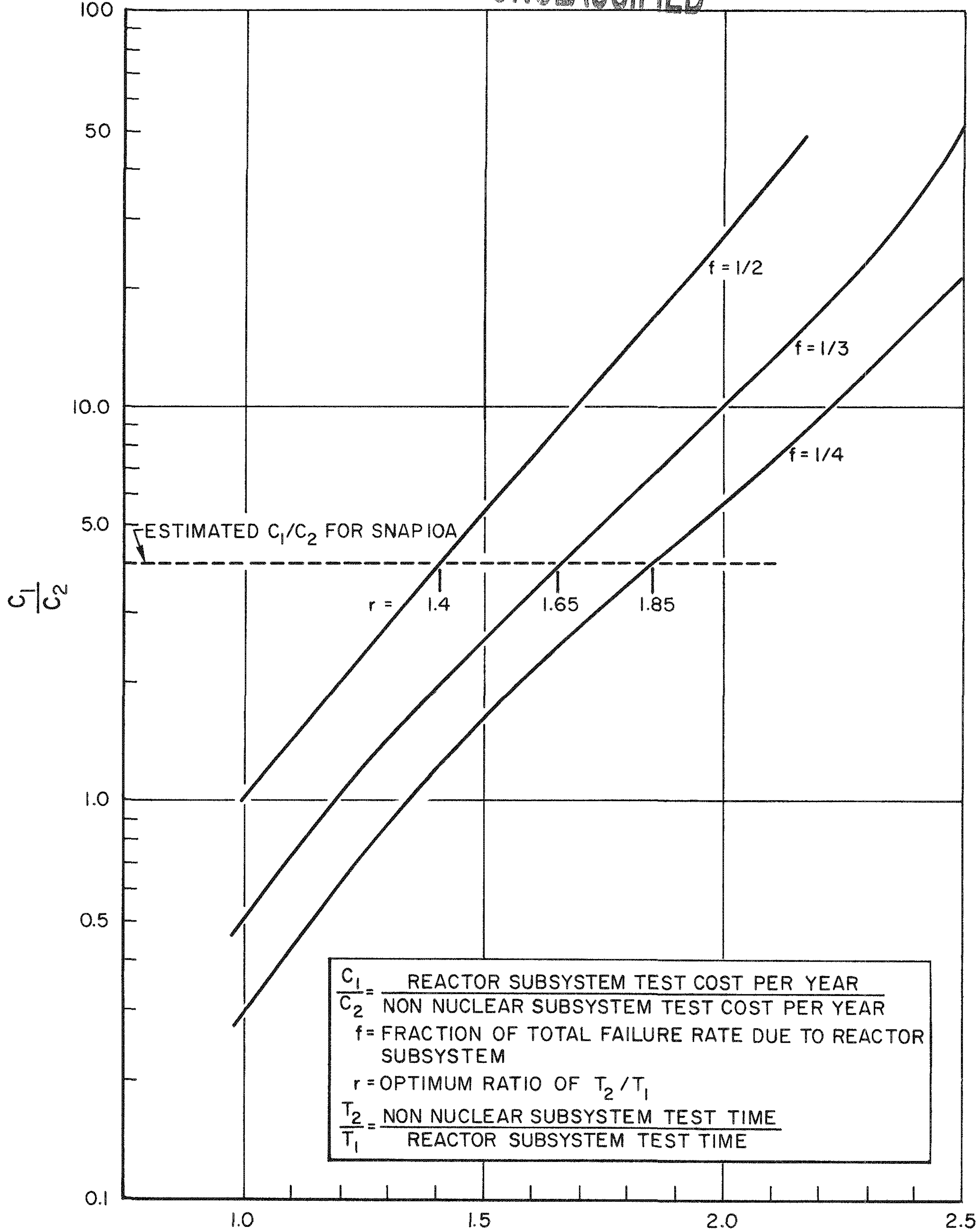


Figure 14. Optimum Apportionment of SNAP 10A Reliability Development Test Program

[redacted]

[redacted]

d. Statistical Design of Experiments

In many cases of component testing it is possible to apply the techniques of statistical design of experiments. This technique is applicable when reliability may be defined in terms of some critical performance output parameter which must stay within a particular set of limits for the system not to fail. An example in the case of SNAP 10A is the voltage output of the thermoelectric circuits. The voltage output must stay within particular limits for the payload to function as intended.

The physical variables that affect thermoelectric voltage output deterioration with time are parameters such as temperature, braze material composition, and compressive loading. If the output is assumed to be a linear function of the magnitudes of each physical variable, then all constants in the assumed output equation may be calculated after performing one replicate of a statistically designed set of experiments. This full replicate set of experiments merely insures that each physical variable has been varied sufficiently for its individual effect to be calculated. If desired, only the most important of the variables are changed to yield a partial replicate. If it is desired to determine particular constants more precisely than others, some experimental conditions may be repeated, yielding a confounded partial replicate.

Despite the imposing terminology, statistical design is a useful tool in orderly experimentation. This type of effort to determine the cause of performance deterioration at the component level is expected to yield most significant contributions to achievement of high reliability system designs. It is for this reason that significant amounts of funding for component development activities and supporting research are included in Reliability Programs I, II, and III. It is at the component development level that high reliability is achieved. The subsystem and system testing serves primarily to reveal more complex modes of failure that are not apparent in an analysis nor at the component level.

[redacted]

III. DESCRIPTION, RESULTS, AND COSTS OF POTENTIAL RELIABILITY IMPROVEMENT PROGRAMS

A. GENERAL

Three different programs in addition to the present R & D program are outlined in this section; these are denoted as Programs I, II, and III. These programs are all potential additions to the existing R & D program and differ only in rate of effort. Planning, evaluation, and pricing are based on the following:

1) Program start time is mid-GFY 62.
2) Existing launch environment test facilities and equipment are adequate to handle Program I, II, or III in addition to the existing R & D program.
3) Startup and safety subsystem testing can be carried out with facilities and equipment used for life and launch environment testing.
4) The quality assurance effort associated with the reliability improvement program is limited to inspection and acceptance testing necessary to establish that specifications for materials, parts, and equipment used in the improvement program are met.
5) All tests are conducted in an environment approximating that which will be encountered in actual operational usage (pressure, temperature, etc).
6) Reliability growth is as previously described.
7) Funding of the present R & D program is provided separately and is not included as reliability improvement cost.

The functions and tests specified in the schedule for each program are described in Sections I-B and I-E. When possible, tests are planned at the component level so that the component failure modes may be studied and corrected with greatest ease when interaction effects are not present. Sufficient work at the subsystem and system levels is included for determination of interaction effects and elimination of failure modes not inherent in the separated components.

B. PRESENT R & D PROGRAM

The present SNAP 10A developmental program is described in Section I-B, and the program schedule is shown in Figure 8. There are, of course, parts of

[redacted]

UNCLASSIFIED

this program which will lend to reliability improvement. Since the SNAP 10A system employs the basic SNAP 2 reactor, there is an additional contribution derived from the SNAP 2 program. The materials and component research being conducted in the SNAP 8 program will provide additional technology to aid in failure analysis and in product improvement.

1. One-Year Reliability

The portions of the SNAP 10A and SNAP 2 developmental program which will contribute to improved 1-year reliability of the SNAP 10A unit are depicted in the top portion of Figure 15. These are evaluated in terms of multiplicity of equivalent SNAP 10A systems undergoing simultaneous life tests, and the net result is shown in the center portion of Figure 15. Evaluation of the 1-year reliability resulting from these rates of effort by means of the growth equation (Section II-B) is illustrated in the lower portion of Figure 15.

The existing program represents a 1-year reliability improvement effort at an average testing multiplicity of about 0.7 for 3-1/2 years.

2. Launch Survival and Startup Reliability

The current SNAP 10A and SNAP 2 developmental programs also contribute to improved launch survival and startup reliability. Pertinent parts of these programs have been evaluated in terms of tests completed as noted in Figure 16. Allowing three months for operation, analysis, and elimination of failure modes in a single test of an equivalent system, the resulting launch survival and startup reliability evaluated by means of the appropriate growth evaluation (Section II-C) is also shown in Figure 16.

3. Cost

The present developmental programs are funded separate from any formal reliability program. The results are then assumed to be available to a reliability improvement program at no cost.

UNCLASSIFIED

[redacted]

[redacted]

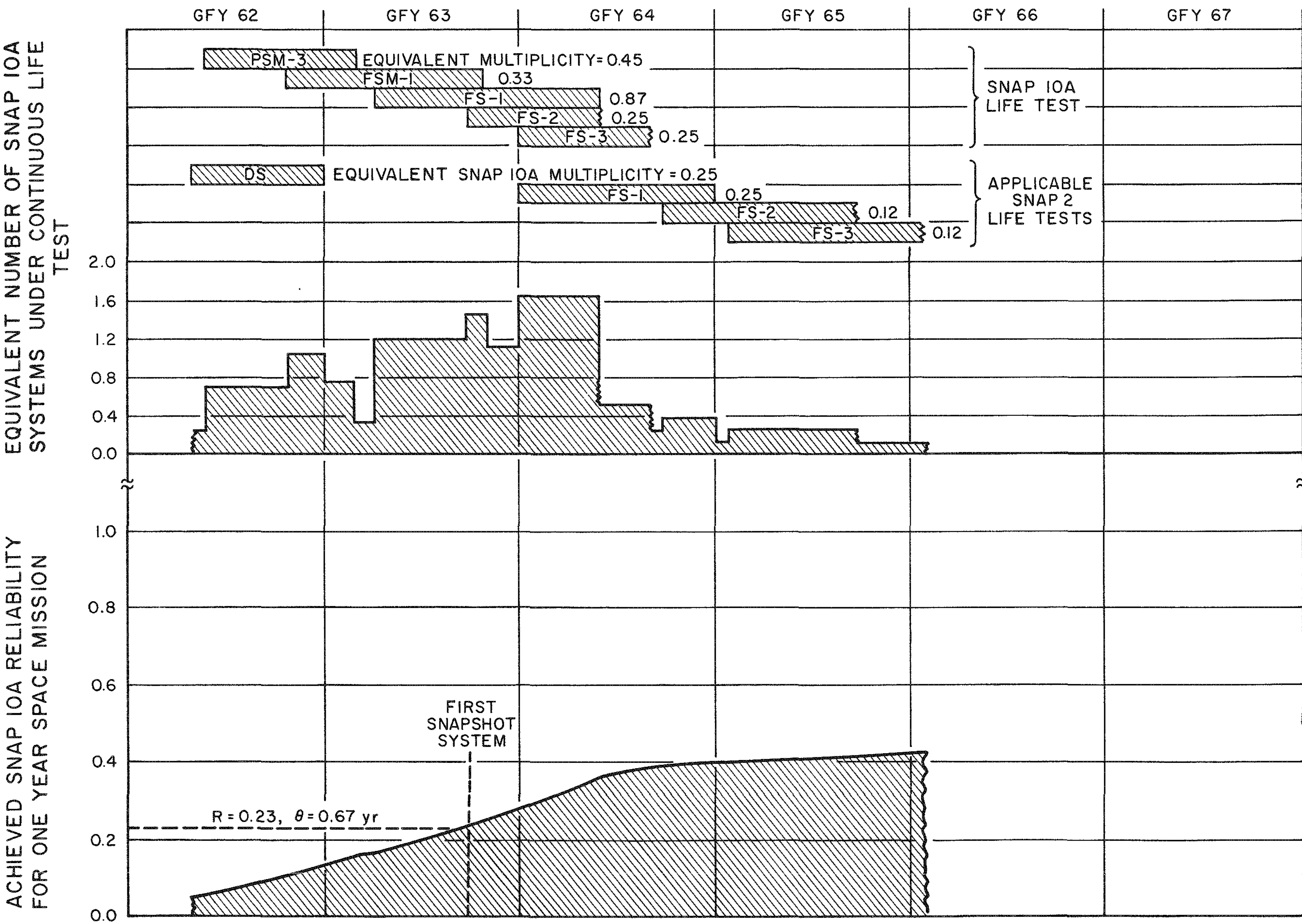


Figure 15. Level of Life Testing Effort and Resultant One-Year Reliability, Present Program

[redacted]

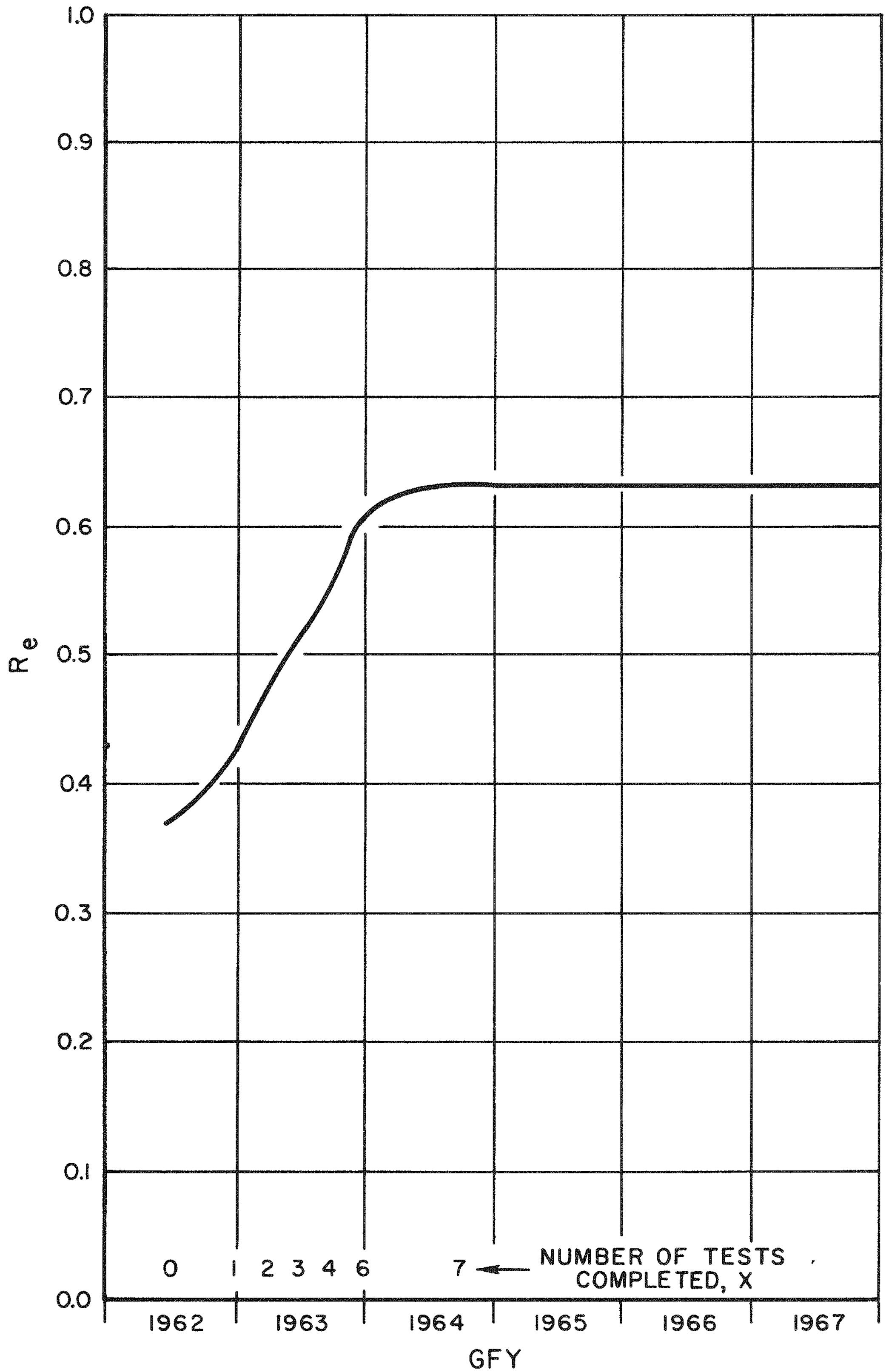


Figure 16. Launch Survival and Startup Reliability, Present Program

 [redacted]

C. PRESENT R & D PROGRAM PLUS POTENTIAL RELIABILITY IMPROVEMENT PROGRAMS

1. Present R & D Program Plus Program I

Program I, detailed and scheduled as shown in Figure 17, is designed to add a very moderate reliability improvement effort to the presently planned developmental program and extends for 5-1/2 years beyond the initiation date of January 1, 1962.

a. One-Year Reliability

The total multiplicity of the 1-year endurance reliability improvement effort, including the present R & D program, is summarized in the top half of Figure 18. Evaluation of the resultant 1-year reliability via the appropriate growth equation (Section II-B) yields the results shown in the lower half of Figure 18.

b. Launch Survival and Startup Reliability

Launch survival and startup reliability work will approximately double that of the present R & D program and will extend this phase for the full 5-1/2 years during which 1-year reliability effort is also to be made. The total number of tests with subsequent analysis and correction of failure modes at various points in time are shown in Figure 19. The resultant reliability predicted using the appropriate growth equation (Section II-C) is also shown in that Figure.

c. Cost

Total informal estimated cost of Program I is 22.6 million dollars over a 5-1/2 year period. A breakdown of Program I annual costs is presented in Table IV. These costs do not include the funding of the present R & Dprogram.

[redacted]

[redacted]

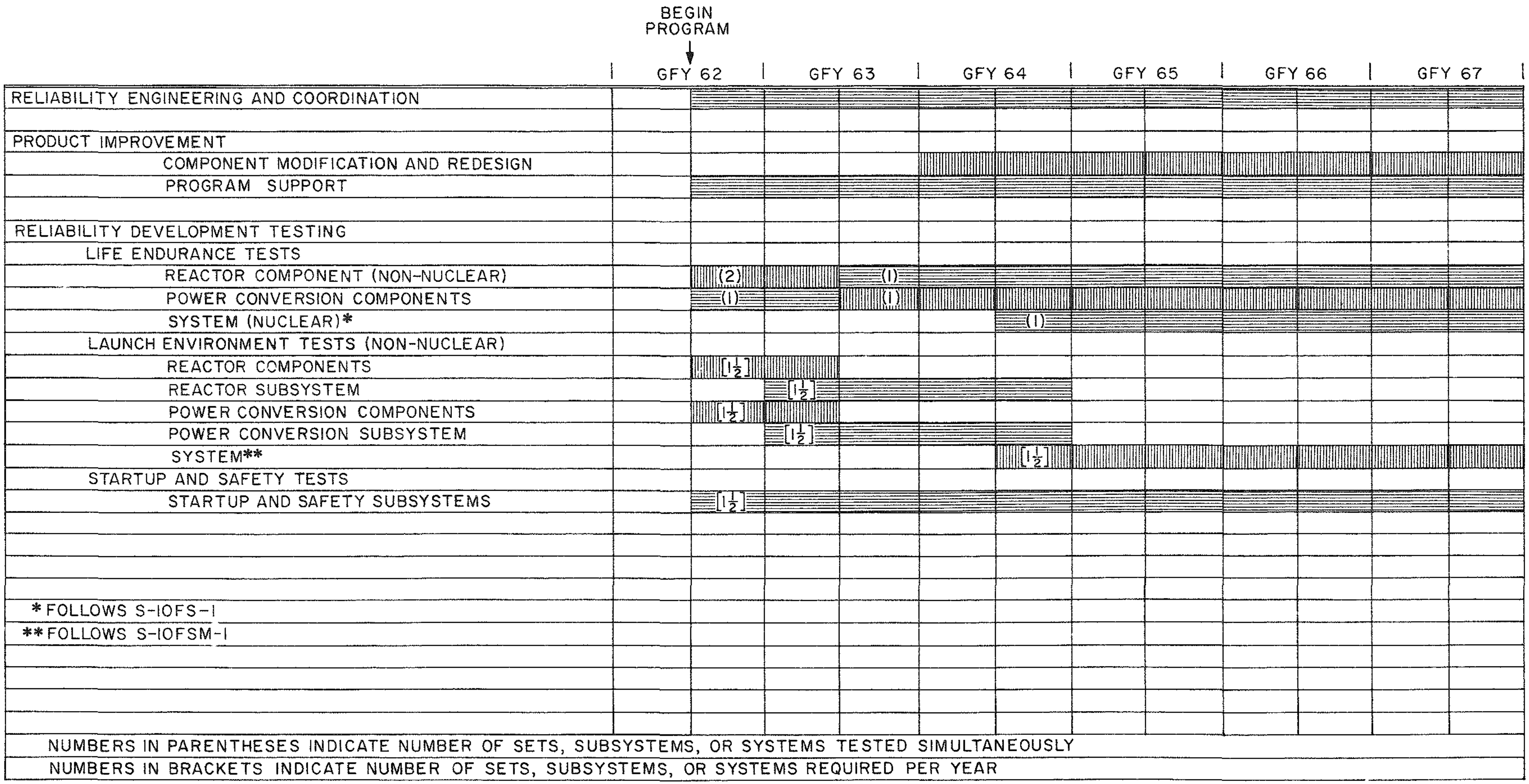


Figure 17. Schedule for Program I

UNCLASSIFIED

[redacted]

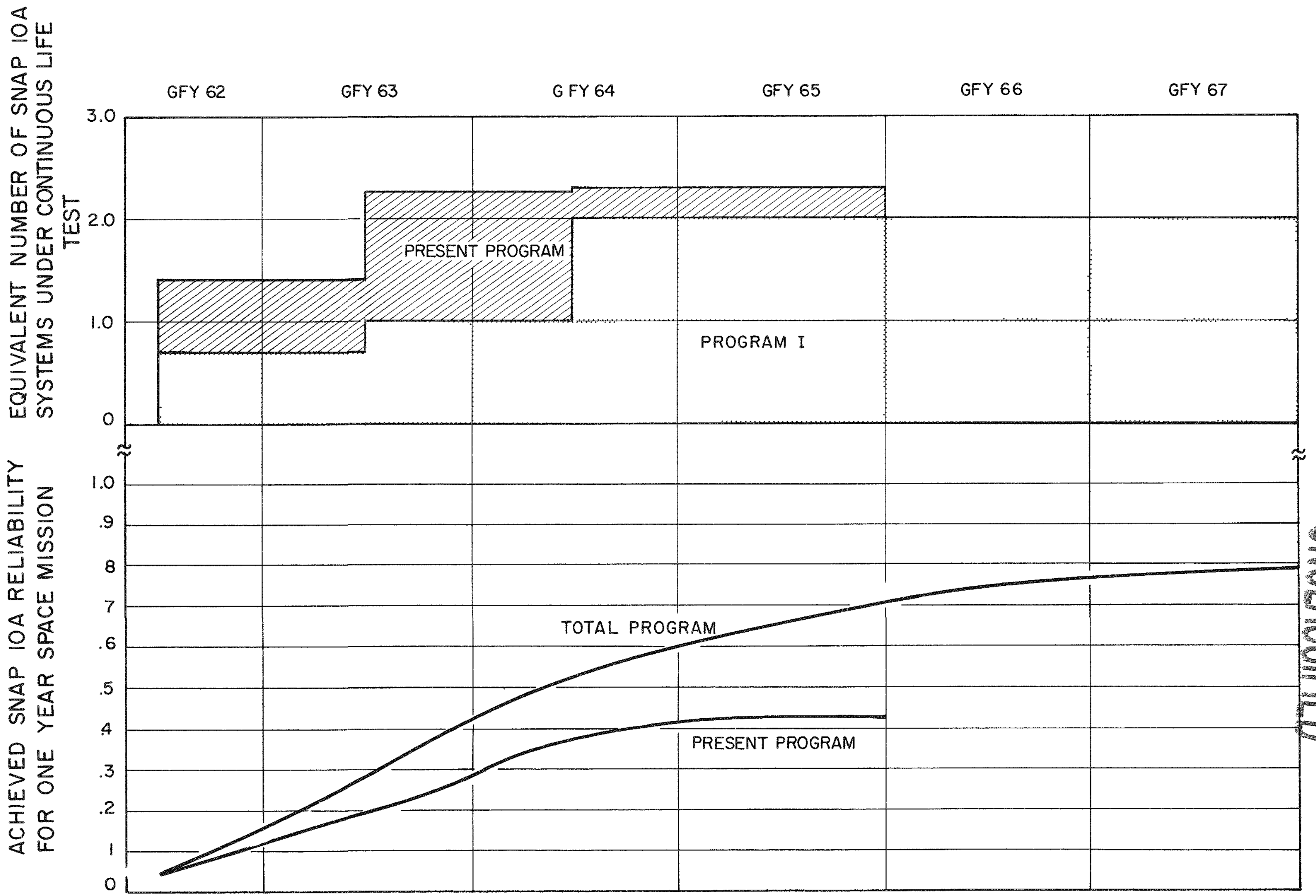


Figure 18. Level of Life Testing Effort and Resultant One-Year Reliability, Present Progrem Plus Program I

[redacted]

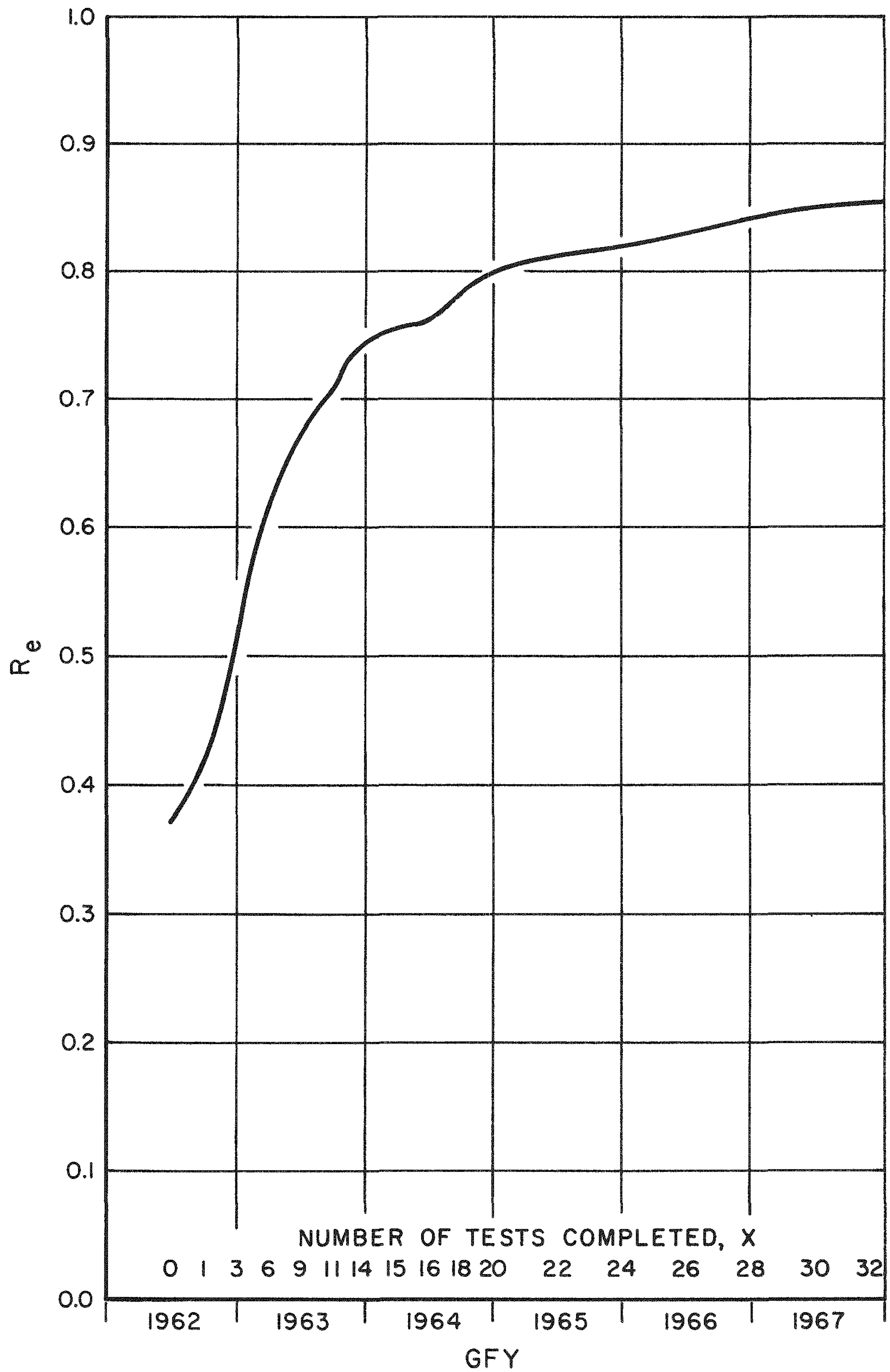


Figure 19. Launch Survival and Startup Reliability, Present Program Plus Program I or II

[redacted]

[redacted]

UNCLASSIFIED

TABLE

INFORMAL PRICING ESTIMATE FOR SNAP 10A RELIABILITY IMPROVEMENT PROGRAM I
(Prices in Thousands of Dollars)

	FY62	FY63	FY64	FY65	FY66	FY67	Subtotal
Reliability Engineering and Coordination	35	170	177	184	190	199	955
Product Improvement							
Component Modification and Redesign	-	-	531	551	569	600	2,251
Program Support	35	170	354	367	380	399	1,705
Reliability Development Testing							
Life Endurance Tests							
Reactor Components (Non-Nuclear)	861	431	431	431	431	431	3,016
Reactor Sybsystems	-	-	-	-	-	-	-
Power Conversion Components	615	307	307	307	307	307	2,150
Power Conversion Subsystem	-	-	-	-	-	-	-
System Nuclear Test	-	-	1,046	1,046	1,046	1,046	4,184
Launch Environment Testing							
Reactor Components	431	150	-	-	-	-	581
Reactor Subsystem	231	462	231	-	-	-	924
Power Conversion Components	308	102	-	-	-	-	410
Power Conversion Subsystem	159	318	159	-	-	-	636
System	-	-	1,046	1,046	1,046	1,046	4,184
Startup and Safety Tests							
Startup and Safety Subsystem	98	98	98	98	98	98	588
Facilities and Equipment	-	978	-	-	-	-	978
TOTAL ESTIMATED PRICE	2,273	3,186	4,380	4,030	4,067	4,126	22,562

UNCLASSIFIED

[redacted]

2. Present R & D Program Plus Program II

Program II, detailed and scheduled as shown in Figure 20, represents a 1-year reliability improvement testing effort about twice that of Program I. The launch survival and startup reliability improvement work is the same as for Program I. The reliability engineering and coordination and the product improvement efforts are expanded accordingly.

a. One-Year Reliability

The total multiplicity of the 1-year reliability improvement effort, including the present R & D program, is summarized in the top half of Figure 21. Results of such a program, evaluated using the 1-year endurance reliability growth equation (Section II-C), are shown in the lower half of that Figure.

b. Launch Survival and Startup Reliability

This phase is the same as for Program I and, therefore, has the same results as illustrated in Figure 19.

c. Cost

Total informal estimated cost of Program II is 31.1 million dollars over a 5-1/2 year period. A breakdown of Program II annual costs is presented in Table V. These costs do not include the funding of the present R & D program.

[redacted]

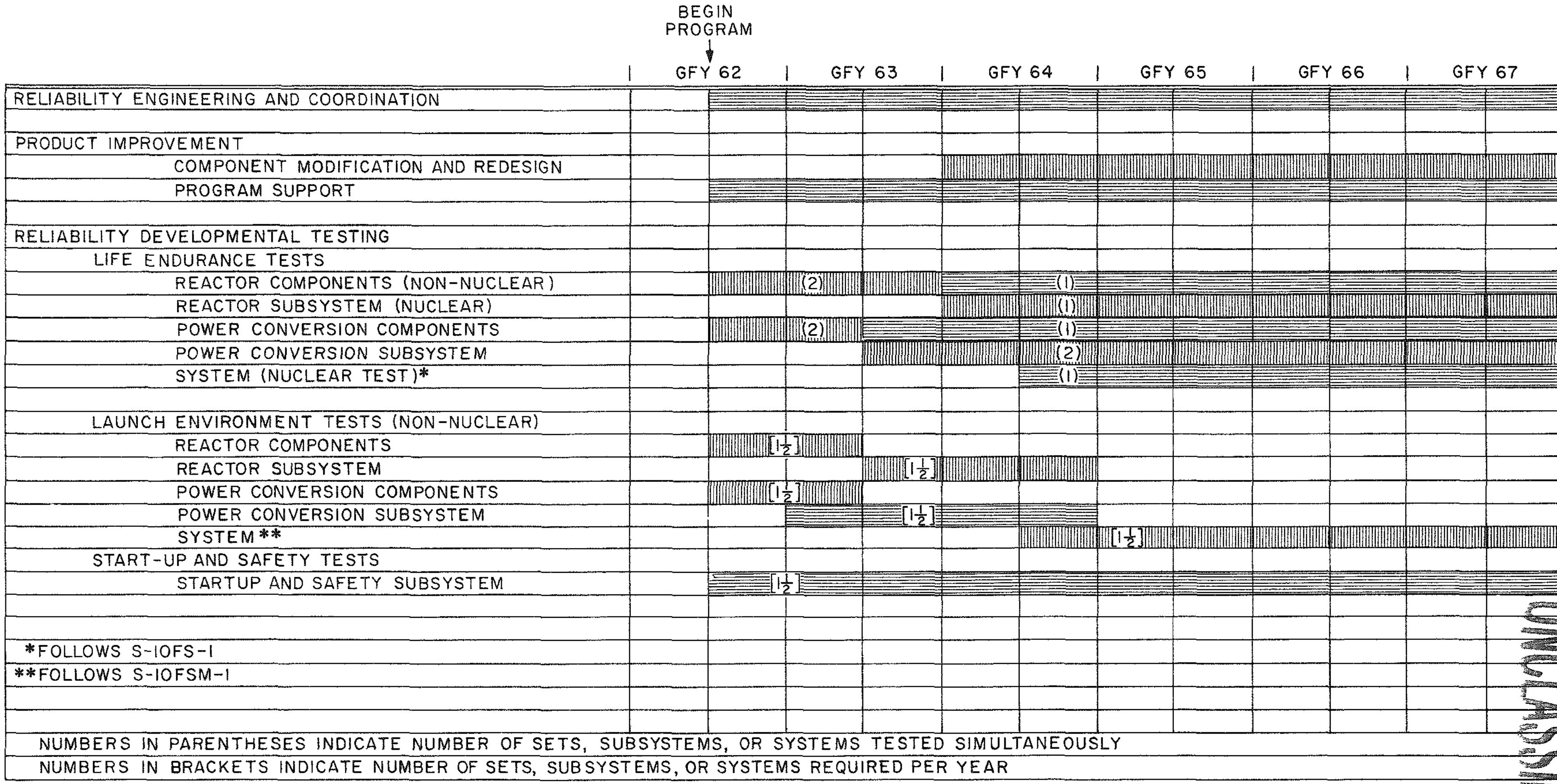


Figure 20. Schedule for Program II

[redacted]

UNCLASSIFIED

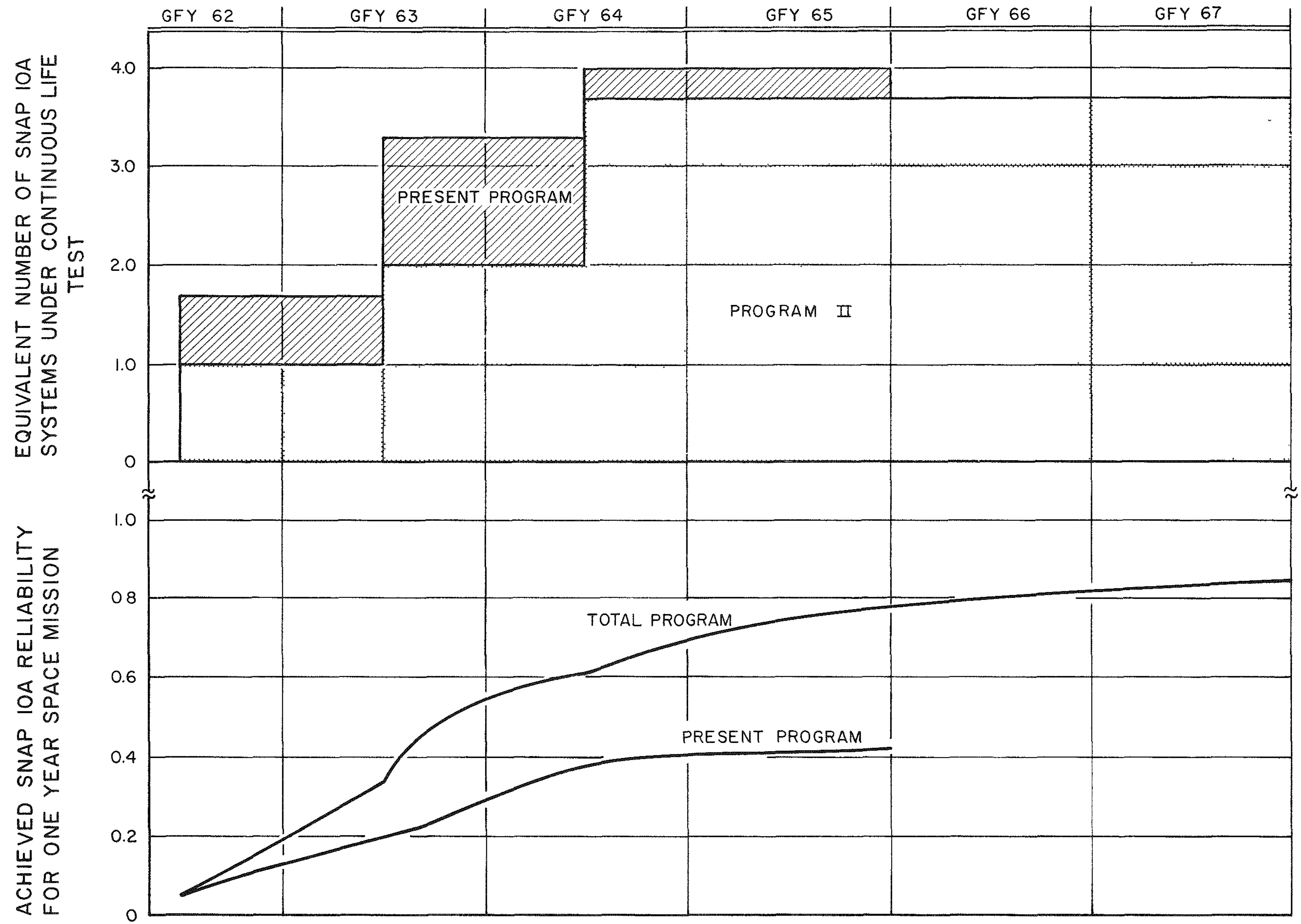


Figure 21. Level of Life Testing Effort and Resultant One-Year Reliability, Present Program Plus Program II

UNCLASSIFIED

[redacted]

UNCLASSIFIED

TABLE V

INFORMAL PRICING ESTIMATE FOR SNAP 10A RELIABILITY IMPROVEMENT PROGRAM II

(Prices in Thousands of Dollars)

	FY62	FY63	FY64	FY65	FY66	FY67	Subtotal
Reliability Engineering and Coordination	59	243	253	263	271	285	1,374
Product Improvement							
Component Modification and Redesign	-	-	759	787	813	855	3,216
Program Support	59	243	506	526	542	570	2,446
Reliability Development Testing							
Life Endurance Tests							
Reactor Components (Non-Nuclear)	861	431	431	431	431	431	3,016
Reactor Subsystems	-	468	468	468	468	468	2,340
Power Conversion Components	615	307	307	307	307	307	2,150
Power Conversion Subsystem	-	636	636	636	636	636	3,180
System Nuclear Test	-	-	1,046	1,046	1,046	1,046	4,184
Launch Environment Testing							
Reactor Components	431	150	-	-	-	-	581
Reactor Subsystem	231	462	231	-	-	-	924
Power Conversion Components	308	102	-	-	-	-	410
Power Conversion Subsystem	159	318	159	-	-	-	636
System	-	-	1,046	1,046	1,046	1,046	4,184
Startup and Safety Tests							
Startup and Safety Subsystem	98	98	98	98	98	98	588
Facilities and Equipment	-	1,835	-	-	-	-	1,835
TOTAL ESTIMATED PRICE	2,821	5,293	5,940	5,610	5,658	5,742	31,064

[redacted]

UNCLASSIFIED

3. Present R & D Program Plus Program III

Program III, detailed and scheduled as shown in Figure 22, represents a 1-year reliability improvement testing effort about three times that of Program I. The launch survial and startup reliability improvement work is about twice that of Programs I and II. The reliability engineering and coordination and the product improvement efforts are expanded accordingly.

a. One-Year Reliability

The total multiplicity of the 1-year reliability improvement effort, including the present R & D program, is summarized in the top half of Figure 23. Results of such a program, evaluated using the 1-year reliability growth equation (Section II-C), are shown in the bottom half of Figure 23.

b. Launch Survival and Startup Reliability

Including the tests run in the present R & D program, the total number of tests with subsequent analysis and corrections of failure modes at various points in the program are shown in Figure 24. The resultant reliability predicted using the growth equation (Section II-C) is also shown in that Figure.

c. Cost

Total informal estimated price of Program III is 48.7 million dollars over a 5-1/2 year period. A breakdown of Program III annual prices is presented in Table VI. These prices do not include the funding of the present R & D program.

D. POTENTIAL ADDITIONAL RELIABILITY IMPROVEMENT RESULTING FROM USE OF SNAP 10A UNITS IN A SATELLITE SYSTEM.

Up to this point, the influence on reliability of actual flights of SNAP 10A units other than SNAPSHOT has been excluded. This was done for two reasons:

1) Operational flights will not carry the complete diagnostic instrumentation that will be used for SNAPSHOTS, although the region of failure will be reported and can then be investigated in laboratory tests; this infers that operational units will serve to demonstrate reliability, but will not lead as directly to reliability improvement.

2) The influence on reliability is a strong function of the number of operating units existing simultaneously and of the rate at which units are being launched.

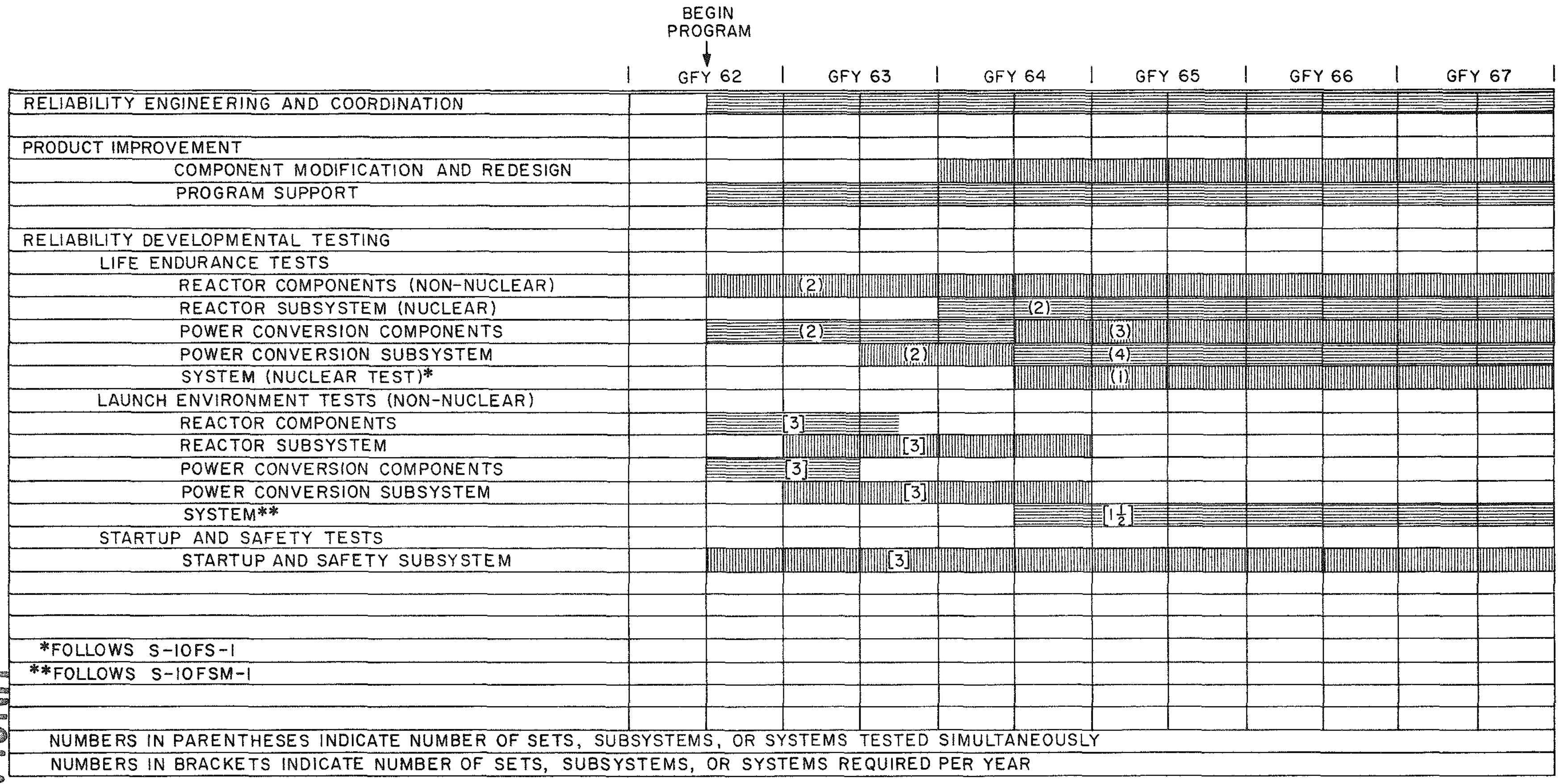


Figure 22. Schedule for Program III

[redacted]

UNCLASSIFIED

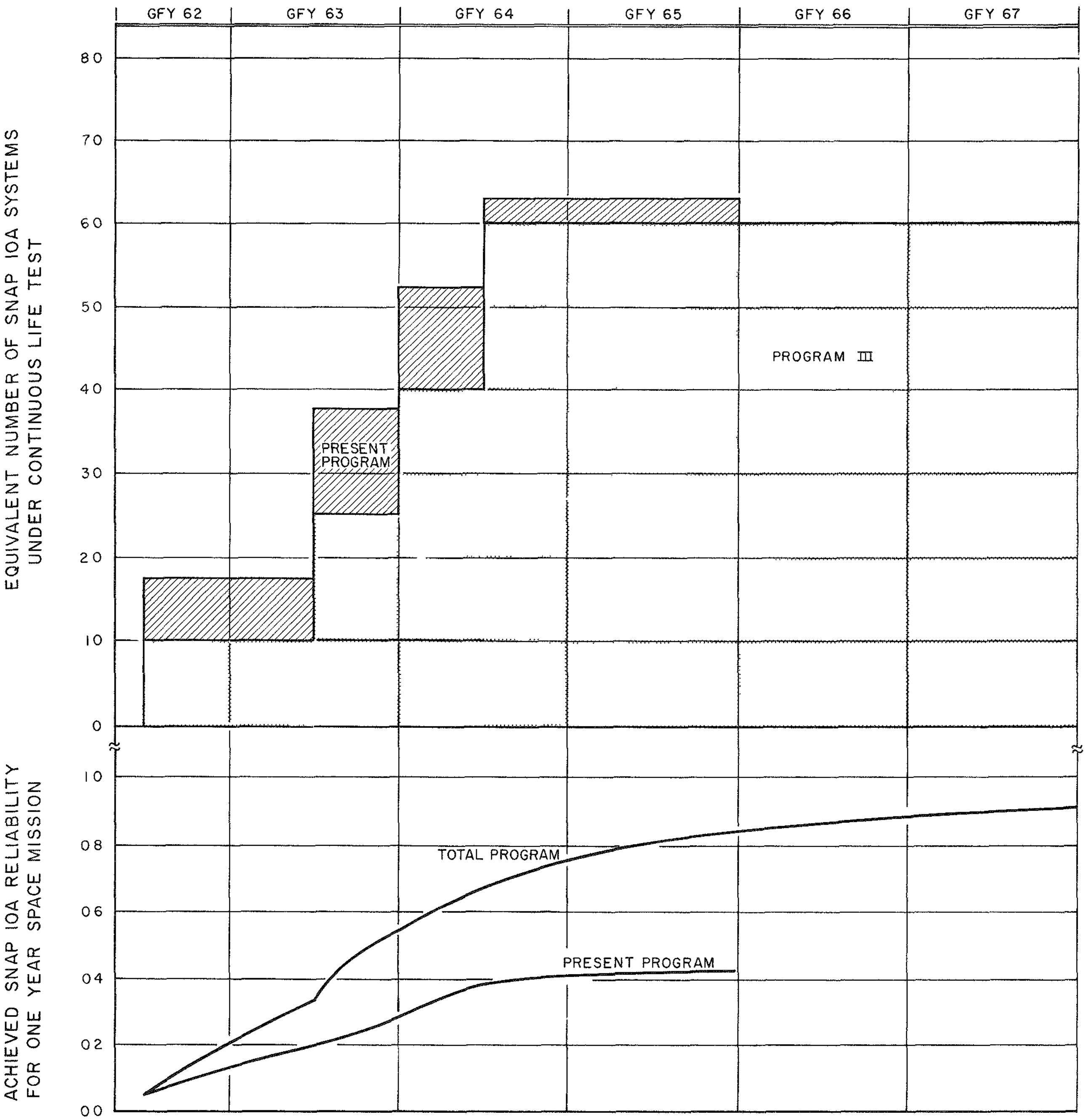


Figure 23. Level of Life Testing Effort and Resultant One-Year Reliability, Present Program Plus Program III

UNCLASSIFIED

[redacted]

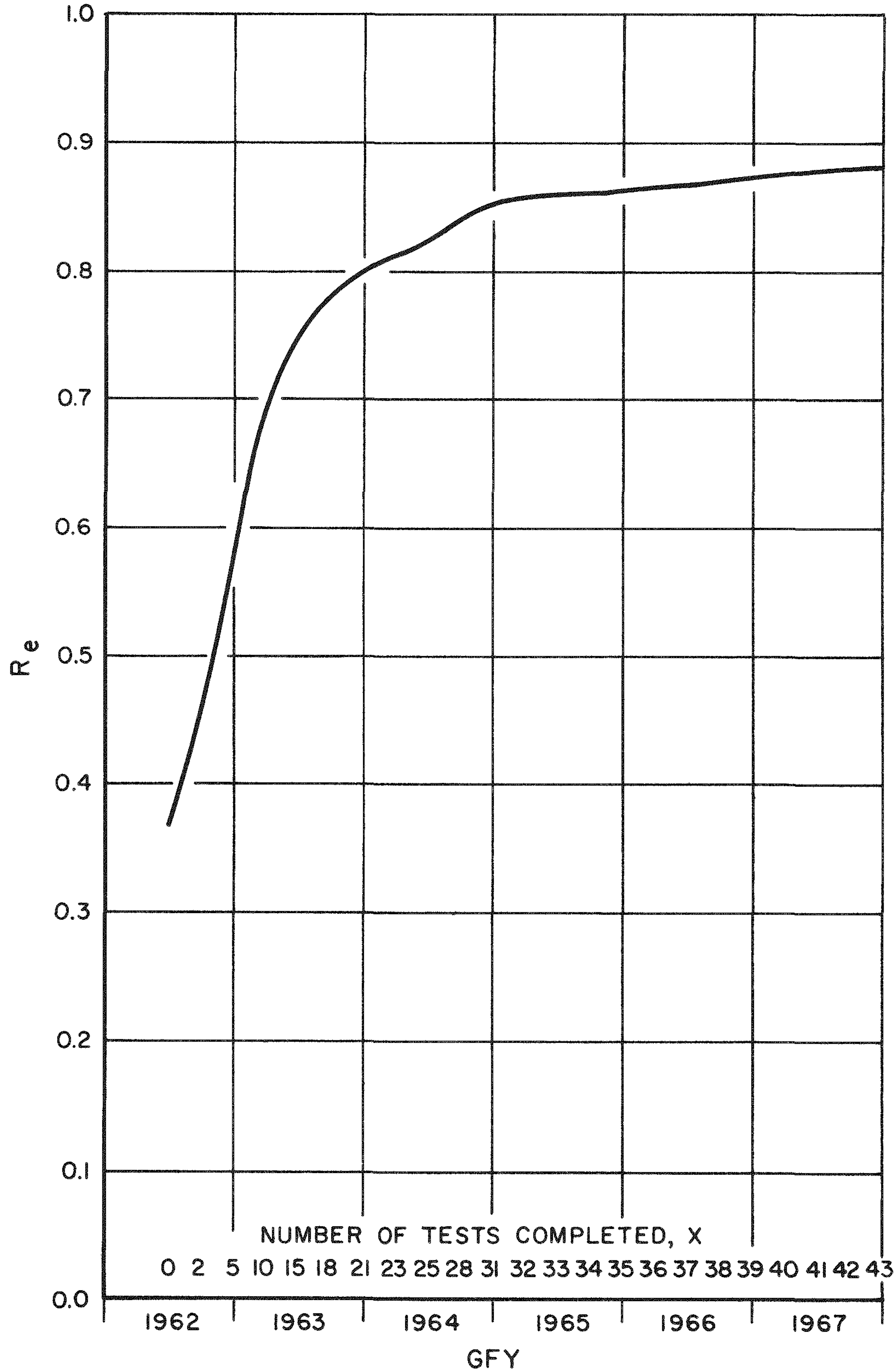


Figure 24. Launch Survival and Startup Reliability, Present Program Plus Program III

[redacted]

UNCLASSIFIED

TABLE VI

INFORMAL PRICING ESTIMATE FOR SNAP 10A RELIABILITY IMPROVEMENT PROGRAM III
(Prices in Thousands of Dollars)

	FY62	FY63	FY64	FY65	FY66	FY67	Subtotal
Reliability Engineering and Coordination	59	364	379	394	407	427	2,030
Product Improvement							
Component Modification and Redesign	-	-	1,137	1,182	1,221	1,281	4,821
Program Support	59	364	758	788	814	854	3,637
Reliability Development Testing							
Life Endurance Tests							
Reactor Components (Non-Nuclear)	861	861	861	861	861	861	5,166
Reactor Subsystems	-	936	936	936	936	936	4,680
Power Conversion Components	615	615	922	922	922	922	4,918
Power Conversion Subsystem	-	636	1,272	1,272	1,272	1,272	5,724
System Nuclear Test	-	-	1,046	1,046	1,046	1,046	4,184
Launch Environment Testing							
Reactor Components	861	290	-	-	-	-	1,151
Reactor Subsystem	462	924	462	-	-	-	1,848
Power Conversion Components	616	205	-	-	-	-	821
Power Conversion Subsystem	318	636	318	-	-	-	1,272
System	-	-	1,046	1,046	1,046	1,046	4,184
Startup and Safety Tests							
Startup and Safety Subsystem	195	195	195	195	195	195	1,170
Facilities and Equipment	-	3,125	-	-	-	-	3,125
TOTAL ESTIMATED PRICE	4,046	9,151	9,332	8,642	8,720	8,840	48,731

UNCLASSIFIED

[redacted]

However, information gained during launch and operation can be used in a reliability improvement program as described in the following.

1. One-Year Reliability

As in the case of SNAPSHOT flights, the failed SNAP 10A units will not be available for examination and determination of the sequence of events leading to failure. Unlike SNAPSHOTS, failure information telemetered from operational satellites is expected to indicate only the more general region in which failure occurred after operation for a certain number of hours. A pre-planned sequence of laboratory tests on parts and components in that region will then be carried out to reveal the probable cause of failure. On this basis it is estimated that the worth of information from an operational satellite is about 1/3 that from a SNAPSHOT. Simultaneous operation of SNAP 10A units in a system of N satellites then adds a factor of 0.04 N to the multiplicity m in the 1 year reliability growth equation. The influence of this addition on 1-year reliability resulting from the existing Program I, is shown in Figure 25 for the 8-satellite system considered in a later example (Section IV). As shown, inclusion of operational data and failure reports in the analysis indicates reliability improvement slightly greater than that when it is excluded; the effect on the results of Program II and III would be even less. Therefore, exclusion of this information from the analysis does not cause a significant error in prediction of 1-year reliability resulting from the potential reliability improvement programs described previously.

2. Launch Survival and Startup Reliability

Again, the SNAP 10A units that fail during launch or startup will not be available for examination, and it is expected that information regarding only the fact and not the mode of failure will be telemetered for flights other than SNAPSHOTS. The probable cause will have to be determined by laboratory testing. The worth of launch and startup of an operational SNAP 10A unit is then estimated to be 1/2 that of an identical ground test unit. Each launch and startup attempt then adds 1/2 to X in the equation for launch survival and startup reliability. If a launch or startup fails this factor should not be added to X until approximately 3 months; this interval of time will be required to deduce the exact cause of failure and initiate corrective measures.

[redacted]

UNCLASSIFIED

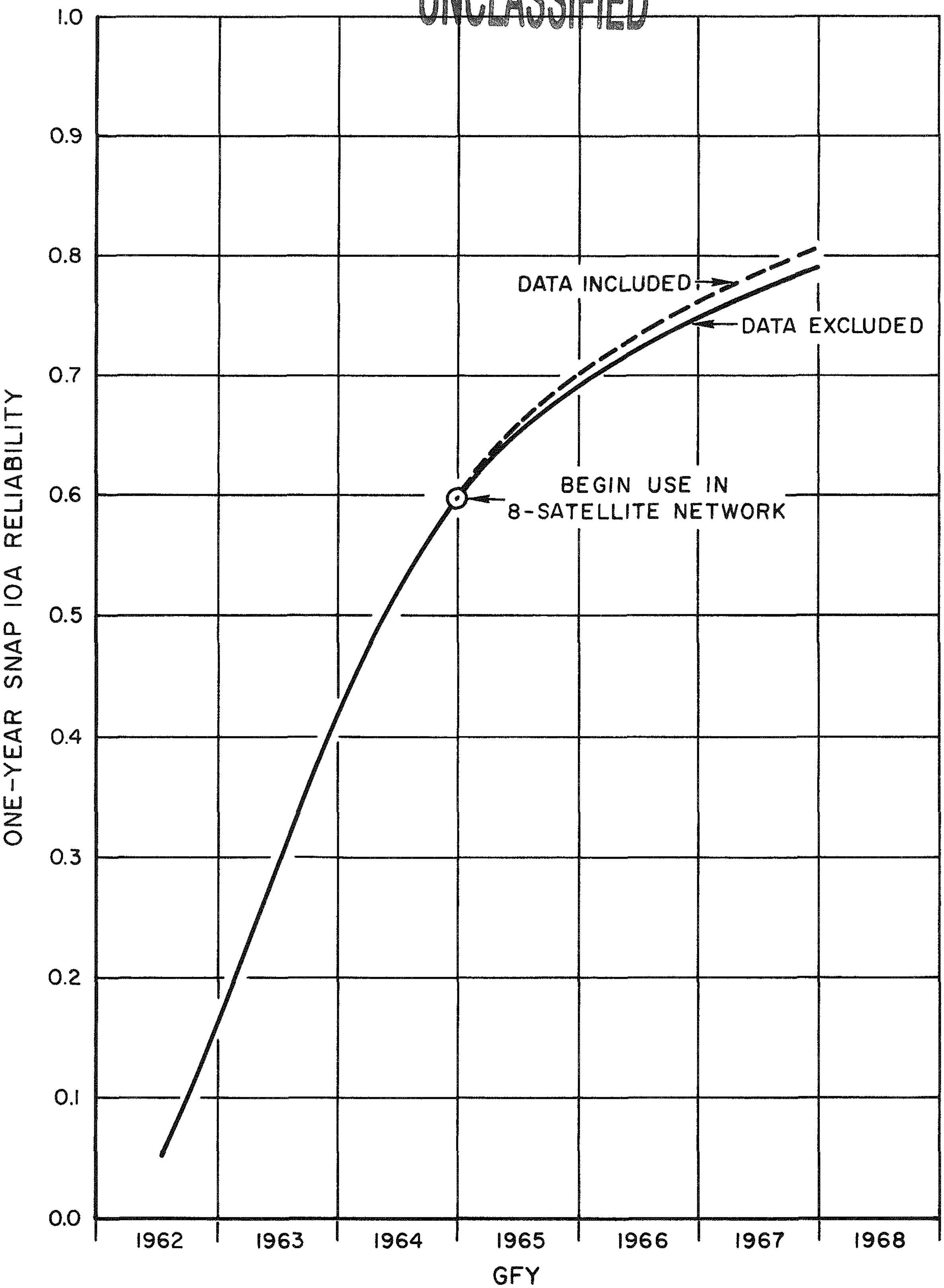


Figure 25. Influence of Use of Operational Data From 8-Satellite System on One-Year Reliability

UNCLASSIFIED

[redacted]

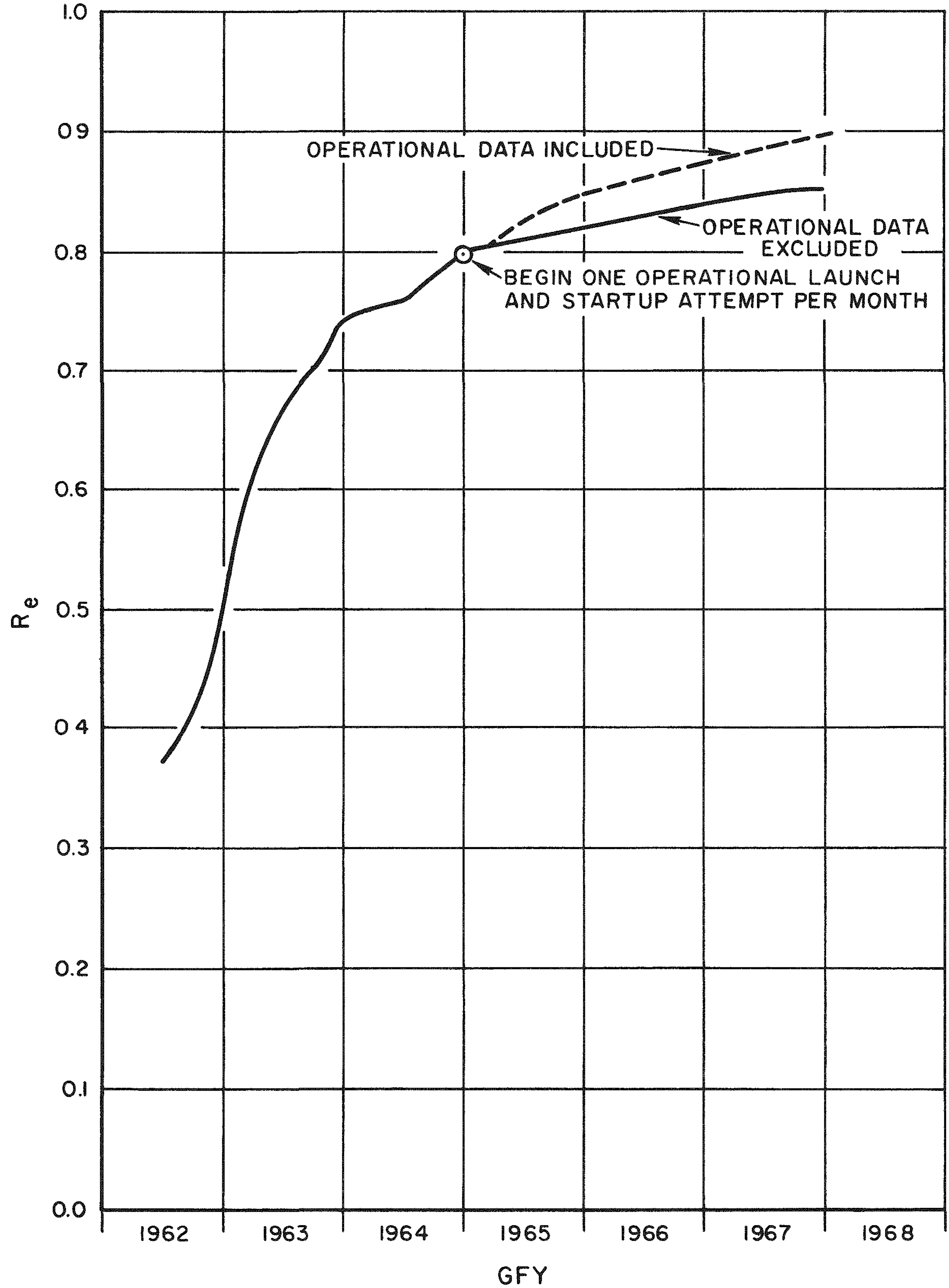


Figure 26. Influence of Use of Operational Data on Launch Survival and Startup Reliability, One Operational Launch and Startup Attempt Per Month

The influence of operational usage on launch survival and startup reliability improvement is highly dependent on the numbers and dates of launch and startup attempts and is, therefore, a strong function of both number and overall 1-year reliability of the satellites in orbit. Figure 26 is presented as a simple illustration of the improvement that can result from use of operational launch and startup data. This Figure shows the launch survival and startup reliability achieved when data from one operational launch and startup attempt per month in addition to Program I is considered, the operational launch and startup attempts commencing at the beginning of GFY 1964. The effect in conjunction with Program II would be the same, while that in conjunction with Program III would be less.

After specification of a satellite network mission and selection of a 1-year reliability improvement program, the influence of operational data on launch survival and startup reliability growth can be determined in detail.

IV. THE SELECTION OF A RELIABILITY PROGRAM

A. GENERAL METHOD

The selection of a particular level of effort in a reliability improvement program for a satellite surveillance system may be guided by an economic analysis to minimize total system cost. To simplify the analysis let the total unattended system consist of a missile booster to achieve orbit, a SNAP power supply and a payload that requires power. The logistics of establishing an $\underline{N}$ satellite station network is a function of the maximum permissible rate of initial launchings and will not be estimated here. The frame of reference that will be considered is the logistics of maintaining a constant level of $\underline{N}$ satellites on station and the influence of various reliability factors. Let the payload have a failure rate of f_c failures per year, and the SNAP power supply have f_o failures per year. In addition, let the SNAP power supply have some maximum lifetime, T, determined by the particular design limitations. The number of replacement launchings required per year, N_T, is then approximately,

$$N_T = \frac{N\left(f_c + f_o + e^{-f_o T}\right)}{R_a R_b} .$$

The term R_a is the reliability of the satellite reaching an acceptable orbit. The term R_b is the reliability of the satellite to survive launch, achieve proper orientation, and successfully start up.

If the cost of a missile launching is C_L per launch, the satellite replacement cost can be represented by the equation:

$$C = C_L \frac{N\left(f_c + f_o + e^{-f_o T}\right)}{R_a R_b} .$$

The annual cost C_r of reliability improvement programs, (vehicle, payload, power supply), is included in the calculation of the approximate estimated total annual cost, C_T, as follows:

$$C_T = C_L \frac{N\left(f_c + f_o + e^{-f_o T}\right)}{R_a R_b} + C_r.$$

The effect of a reliability improvement program on operating cost may be included by defining each reliability parameter in terms of a reliability growth equation. Several criteria may now be applied to determine an optimum level of a reliability improvement program. The most direct criterion is to minimize the total satellite system cost over the tactical life of the system.

The actual level of a reliability program should be estimated by military planners with correct factual information to be used in the operational analysis. The SNAP 10A reliability growth estimates have been presented in this report in sufficient detail so that military operations analysis personnel may readily include them in their more complete analysis.

B. EXAMPLE FOR AN 8-SATELLITE SYSTEM

In the special case of an 8-satellite system, the total operating expenses over a 5 year tactical mission time may be estimated as a function of level of reliability program effort.

The total prices of the SNAP reliability improvement programs were evaluated in Section III and are included in this example; the present R & D program funding is excluded.

This example represents the following conditions:

1) Total cost of a missile, payload, and SNAP 10A power supply plus launch and tracking costs is 8 million dollars.

2) Reliability R_a of satellite reaching an acceptable orbit is a constant 0.9.

3) By the time SNAP 10A is used as the power supply the <u>payload</u> launch survival, orientation, and startup reliability is 0.9 and remains constant after that time.

4) Payload 1-year reliability is a constant 0.9.

5) Reliability growth equations previously described for SNAP 10A system are applicable, effects of operational data being excluded from calculations.

6) All SNAP 10A systems used during a given GFY were manufactured the previous GFY and have corresponding reliabilities.

7) Design changes to enhance SNAP 10A reliability are introduced into production at the first of each GFY beginning with the GFY in which production is started.

8) All SNAP 10A systems have a maximum lifetime of 1 year.

9) Production of SNAP 10A units begins in GFY 1963 and utilization in an 8-satellite system starts at the beginning of GFY 1964.

10) The reliability improvement program, if any, is initiated as scheduled at mid-GFY 1962.

11) Tactical use time of the satellite system is 5 years. The equation representing the approximate total annual cost of utilization is then:

$$C_i = \frac{64\left(0.105 + f_{o,i-1} + e^{-f_{o,i-1}}\right)}{0.81\ R_{e,i-1}} + C_{r,i}$$

where the index i indicates the year of usage and i-1 indicates that the units were manufactured the preceding GFY with corresponding reliabilities.

An additional cost not included in this equation is the cost of initial establishment of the satellite system. Denoting this cost by C_o,

$$C_o = \frac{64}{0.81\ R_{eo}}$$

where R_{eo} is the launch survival and startup reliability of the SNAP 10A units used for the initial satellites. This equation infers that all attempts to orbit the satellites are made simultaneously and that a failure is immediately rectified; the value of C_o calculated using this equation is then somewhat less than the actual value, but it is adequate for comparison of potential reliability improvement programs.

Failure rates and launch survival and startup reliabilities resulting from the existing R & D program, and from the existing R & D program plus additional Programs I, II, and III, are shown in Table VII as functions of years SNAP 10A units are produced.

[redacted]

TABLE VII

FAILURE RATE, f_o, AND LAUNCH SURVAL AND STARTUP RELIABILITY, R_e, OF SNAP 10A PRODUCTION UNITS

	Year of SNAP 10A Unit Manufacture				
	1964	1965	1966	1967	1968
Present R & D Program					
Failure rate, f_o (units/yr)	1.27	0.88	0.85	0.85	0.85
Launch survival and startup reliability, R_e	0.61	0.63	0.63	0.63	0.63
Present R & D Program and Program I					
Failure rate, f_o (units/yr)	0.89	0.52	0.37	0.29	0.24
Launch survival and startup reliability, R_e	0.74	0.80	0.82	0.84	0.85
Present R & D Program and Program II					
Failure rate, f_o (units/yr)	0.70	0.38	0.25	0.19	0.15
Launch survival and startup reliability, R_e	0.74	0.80	0.82	0.84	0.85
Present R & D Program and Program III					
Failure rate, f_o (units/yr)	0.62	0.28	0.18	0.13	0.10
Launch survival and startup reliability, R_e	0.80	0.85	0.86	0.87	0.88

Substitution of these values into the cost equations yields the annual and 5-year total satellite system costs presented in Table VIII. These estimated costs indicate there is little difference between the results of Programs I, II, and III, under the conditions of this particular example. However, the performance of any one of these reliability improvement programs would reduce the average annual cost of the satellite program from over 200 million dollars to about 150 million dollars. Such a large savings certainly provides great incentive for undertaking of a reliability program.

The apparent optimum program selection would appear to occur where the total cost goes through a minimum. However, there exist other considerations such as: the probability of early system obsolescence, military necessity or strategy, etc., so that it is not necessarily desirable to be guided entirely by the minimum cost solution obtained from a tactical analysis of only one satellite system. Thus, more extensive considerations could lead to a decision to accept a higher apparent cost solution.

[redacted]

TABLE VIII

5-YEAR TOTAL SATELLITE SYSTEM COSTS
(In Millions of Dollars)

GFY	SNAP 10A Reliability Improvement Program Cost	Satellite Replacement Cost	Cumulative Total Cost
With Existing R & D Program			
1962	--	--	--
1963	--	--	--
1964	--	--	--
1965	--	214.498	214.948
1966	--	175.582	390.080
1967	--	175.325	563.405
1968	--	175.325	736.730
1969	--	175.325	910.055
		Cost of Initial Satellite System =	129.528
		Grand Total =	1039.583
With Existing R & D Program Plus Program I			
1962	2.773	--	2.773
1963	3.186	--	5.959
1964	4.380	--	10.339
1965	4.030	150.123	164.492
1966	4.067	120.493	289.052
1967	4.126	112.352	405.530
1968	--	107.513	513.043
1969	--	105.412	618.455
		Cost of Initial 8-Satellite System =	106.773
		Grand Total =	725.228
With Existing R & D Program Plus Program II			
1962	2.821	--	2.821
1963	5.293	--	8.114
1964	5.940	--	14.054
1965	5.610	139.018	158.682
1966	5.658	115.456	279.796
1967	5.742	109.269	394.807
1968	--	105.538	500.345
1969	--	103.739	604.084
		Cost of Initial 8-Satellite System =	106.773
		Grand Total =	710.857
With Existing R & D Program Plus Program III			
1962	4.046	--	4.046
1963	9.151	--	13.197
1964	9.332	--	22.529
1965	8.642	124.740	155.911
1966	8.720	106.063	270.694
1967	8.840	102.900	382.434
1968	--	101.082	483.516
1969	--	99.664	583.180
		Cost of Initial 8-Satellite System =	98.765
		Grand Total =	681.945