RELIABILITY CONSIDERATIONS FOR COMMUNICATION SATELLITES

BY

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ABSTRACT

A detailed program covering all phases of reliability for a communication satellite was presented. In long mission programs such as this one, reliability is the prime consideration in assuring a successful accomplishment of the stringent goals set forth. Reliability principles and methods were incorporated in delineating each major task in the program. These principles and methods not only aided the reliability personnel in performing their duties better, but also assisted the design group, manufacturing personnel, and the testing and evaluation group in performing their jobs efficiently by being aware and knowledgeable of reliability engineering.

Various reliability disciplines were imposed, as requirements, on the different groups assigned to the high reliability program. As each group in the program organization became aware of the many problems encountered in this type of program, the reliability personnel worked with each one, incorporating the methods and controls of reliability. These methods and controls aided the design group in designing a system with reliability as the prime consideration. The manufacturing personnel received training and indoctrination instructions in reliability practices, thus enabling them to build a system at the highest level of reliability. The testing and evaluation group used reliability and statistical analysis techniques in their testing programs to check out the design and manufacturing of the satellite.

The results and accomplishments speak for themselves. Checking the record to date shows a very successful phase of communications by way of satellite. The feasibility of satellite communications has been proven and the future for more sophisticated techniques looks excellent.

APPROVAL OF THESIS

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PREFACE

Communication by means of satellite has come of age. A decade ago this method of communicating was not feasible basically because of the severe requirements imposed on the various electronic components. Parts were needed that could last for many years without maintenance. Our technology had not advanced that far at that time. Another way of putting it: the methods and techniques of obtaining high reliable components for the satellite were not fully developed. This paper presents one way of designing, manufacturing, and testing a communication satellite, with reliability being the primary objective.

Chapter 1 is concerned with the historical background of communication satellites, detailing the progress achieved since the first successful launching of Score in December, 1958. Also discussed in this chapter are the merits of passive communication satellites and active communication satellites. Reliability was introduced at this point to establish the necessary goals in achieving a communication satellite of high reliability for mission times of up to 5 years.

Reliability was the main concern during the stages of design. This was accomplished by setting up an organization with the reliability function as one of the main disciplines. A reliability program was set up specifically to monitor and control all aspects of the reliability tasks. Such tasks as reliability analysis and assessments; control of processes, material, and parts; reliability control of suppliers; failure reporting, analysis, and corrective action feedback of all failures; reliability indoctrination and training; reliability testing programs; and program review are covered in some detail in Chapters 3 and 4.

In Chapter 5 are the conclusions, findings, and recommendations of the reliability program developed for the communication satellite system. These conclusions and recommendations are based on present state-of-the-art techniques and methods.

I would like to express my appreciation to my advisor, Dr. Salvatore R. Calabro, Department of Industrial and Management Engineering, Newark College of Engineering for his suggestions and guidance while writing this thesis; also to Mr. Anthony J. Finocchi, Staff Consultant for Reliability and Quality Control at ITT Avionics, a division of International Telephone and Telegraph Corporation and Mr. Fred T. Kallet, Chief Engineer, Reliability Engineering, Kearfott Products, a division of General Precision Systems Incorporated, for their critical reviews and suggestions. Many thanks are also in order to Mrs. Edward Schley, who typed the thesis most efficiently.

Most of all I wish to express my sincere thanks to my wife, Gloria, who's encouragement inspired me in writing this thesis.

Frank Polizzi

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CHAPTER 1

HISTORY AND INTRODUCTION OF COMMUNICATION SATELLITES

HISTORICAL BACKGROUND

In this fast moving and complex world we live in today, the need for long distance, real-time communications has developed. One solution to this problem is the use of a communication satellite. To this end the National Aeronautics and Space Administration, in 1959, initiated a program developing the technology and feasibility of such a system.

Passive Communication Satellites

Earth satellites could either be passive or active. The passive satellites are orbiting reflectors that return a signal from a transmitter on the primary body. The most common configuration used is the balloon. Examples of the passive satellites are the Echo I, Echo II (Rebound), and West Ford.

Echo I is a 100-foot diameter balloon made of aluminized plastic film (Mylar) only 0.005 inches thick. It was launched into orbit on August 12, 1960. The important significance of Echo I was it proved that it was practical to reflect two-way telephone conversations by using a manmade passive satellite. It also confirmed the design requirements for future ground stations and that satellite tracking by the use of radar and telescope was very reliable.

The Echo II was launched from the Pacific Missile Range on January 25, 1964. The satellite had a novel controlled inflation and pressurization system. This came about because it was indicated in the Echo I configuration that the balloon had not been pressurized significantly to remove the wrinkles from the skin surface. This increase in pressure provided a great improvement in balloon sphericity and RF reflectivity characteristics. It should be noted that during this time a cooperative experimental program was implemented between the USSR and the U.S. The USSR supplied the U.S. the results of their optical and photographic observations from Soviet sites taken in the early life of Echo II.

The last type of passive satellite is the West Ford which was conceived in 1959. It was originated and developed by Massachusetts Institute of Technology's Lincoln Laboratory. The satellite was made up of a belt of millions of hair-thin orbiting reflective "needles". It was successfully launched in the summer of 1963 with the following results noted:

- A few of these belts could provide worldwide, reliable, low data rate communications almost immune from physical destruction.
- Predictions of non-interference with radio astronomy were valid.
- The method used of dispensing a belt of millions of tiny fine wires was workable and feasible.

Active Communication Satellites

The other type of satellite being used for communications is the active type. The active satellites receive and amplify a signal before retransmitting it to the ground. There is therefore some electronics involved in the configuration of these active satellites.

The first active communications satellite was Score, standing for "Signal Communications by Orbiting Relay Equipment". It was launched on December 18, 1958 with the capability of real-time relay of voice, code and teletype. Although short lived, only 13 days, it demonstrated its capabilities extremely well. The satellite was powered by battery, being the most feasible in 1958.

Another active satellite was the Army Signal Corps' Courier I-B. It was launched on October 4, 1960 being powered by 20,000 solar cells. The electronic package consisted of four receivers, four transmitters, and five tape recorders. In this way signals were received from the ground, stored on the tapes and transmitted back to the ground at a later time. It transmitted some 118 million words during its active but short life (only 17 days in orbit).

Telstar I, proposed by the Bell System in 1960, was another type of active satellite used for communications. It was launched into an elliptical orbit on July 10, 1962 having an apogee of 3503 miles and a perigee of 593 miles. It weighed only 170 pounds and had a 34 inch diameter.

The following objectives were the reason for the Telstar project:

- To prove that a broadband communications satellite could be used to relay telephone messages, data, and television programs.
- To measure the radiation that the satellite encountered while in space.
- To test the electronic equipment used in the communications satellite under launch and space stresses.
- To find the most efficient means to track the satellite accurately.
- To provide life test for the antennas and other ground station equipment.

The satellite performed more than 300 technical tests all with successful results. The electronic equipment performed just as it was expected, encountering no damage from vibration or shock during the launch phase. The only unexpected thing that was encountered was the extreme manmade radiation levels in space. These were estimated to be more than 100 times than expected. As a result the transistors in the command circuit encountered difficulties. The malfunctioning satellite was diagnosed from the ground and successfully commanded back "on". This was a first in space communications.

On May 7, 1963 Telstar II was launched into an elliptical orbit having an apogee of 6713 miles and a perigee of 604 miles. The higher altitude (almost twice that of Telstar I) provided Telstar II with longer visibility periods at the ground station in Andover, Maine and several ground stations in Europe. Most important it kept the satellite out of the high radiation regions of space for a much longer time.

The major differences in Telstar I and Telstar II were the following:

- Telstar II had a greater range of sensitivity when radiation measurements were taken.
- Six new measurements were taken and reported back to earth.
- Telemetry could be sent on both the microwave beacon and on the 136 megahertz beacon.
- Telstar II used different types of transistors in the command decoder circuit, one from which the gasses had been removed from the cap enclosures that surround the elements of the transistor. In this instance we see where reliability is an over-riding consideration in satellite design to provide longer life by proper choice of components.

Relay I was another in the series of active communication satellites. It was launched by NASA on December 13, 1962 and provided the first satellite communications link between the United States and South America, Japan, Germany, and Scandinavia. Relay I was designed to receive and transmit one television broadcast or 12 simultaneous two-way telephone conversations. It used nickel-cadmium storage batteries charged by more than 800 solar cells. Each satellite had two transponders delivering 10 watts each. The transponders consisted of a receiving, amplifying, and transmitting system.

Relay I was successful in carrying live television broadcasts between the United States and Europe and continued to operate for more than twice its design life of 1 year. This is another example of designing a reliable satellite and using reliability and all its important considerations in the program for long life electronics.

Relay II was launched on January 21, 1964. It was modified basically to improve its reliability and increase its resistance to radiation damage. It performed its intended function and experiments were conducted until September 26, 1965.

The Syncom Project was an undertaking in the field of active communications satellites that started with the launching of Syncom I on February 14, 1963. The objective was to place active repeater satellites into synchronous orbit.

There were two advantages of a synchronous satellite. The first advantage of synchronous orbits is that fewer satellites are needed to cover most of the earth's surface. The second advantage is that simpler ground stations are needed, despite its greater distance from the earth.

Since low altitude satellites move very fast through the field of view of the ground station, two antennas were needed for uninterrupted service, one to track the satellite and the other ready to acquire the next satellite as it comes into the field of view. These very large antennas had bandwidths of 0.1 degree. Using and pointing these large antennas with their narrow bandwidth beams at fast moving satellites was not an easy assignment. The equipment used during this operation was very expensive.

Synchronous satellites, like the Syncom series of active communications satellites, were quite satisfactorily used with nearly fixed antennas.

The Syncom satellites carried within their structure an apogee kick rocket motor. This motor added the capabilities of the existing launching vehicle to place the 75-pound satellite in a near synchronous orbit. Additional propulsion subsystems must perform to successfully complete the intended mission.

As was mentioned previously, the first experimental Syncom satellite, Syncom I, was launched on February 14, 1963. Its peak altitude was approximately 22,300 statute miles. After the on-board rocket was fired, all signals ceased. Up to this point, however, the communications equipment functioned satisfactorily. It was established at a later time that Syncom I achieved a 33° inclined orbit with a period of almost 24 hours.

Syncom II, launched on July 26, 1963, achieved first successful synchronous orbit with full spacecraft capability. It had many "firsts" to its credit. Among them were:

- Provided first television, voice, and facsimile experience with a satellite in 24 hour orbit.
- Became the first satellite maneuvered to a specific longitude (55° West).

- Period and attitude control was achieved for the first time in order to station Syncom II and provided the world with demonstrations between North America, Europe, and Africa.
- Carried first telephone conference between heads of state via satellite.
- The first press conference was successfully completed by using the Syncom II communication facilities in 1963.

In addition to these achievements Syncom II supplied useful data to scientifically determine the shape of the earth and to learn more about drift behaviour of synchronous satellites. Accurate observations were made of anomalies in the earth's gravitational field. It was also learned that it took less energy to keep a synchronous satellite on station than was originally surmised.

Syncom III was launched on August 19, 1964. It was the first attempt to place a satellite in geostationary orbit. The ground track of a geostationary satellite is a point instead of a figure 8. Zero inclination of Syncom III was possible by using the Thrust Augmented Delta (TAD). This was a more powerful X-258 third stage with the thrust of the second hydrogen peroxide spacecraft control system.

Syncom III provided increased capability for maneuvering and station keeping. Also greater radiation protection and longer useful life expectancy was realized by shielding the solar cells with 12 mil glass.

A summary of the space communication satellite projects is given in Table 1.1.

LAUNCH DATA				INITIAL ORBITAL DATA					
NAME	DATE	SITE	VEHICLE	WEIGHT POUNDS	PERIOD MINUTES	PERIGEE MILES	APOGEE MILES	INCL. DEGREES	STATUS
Score	12/18/58	ETR	Atlas B	8750	101.5	115	914	32.3	Decayed, 1/21/59; first comsat, transmitted messages for 13 days.
Echo I	8/12/60	ETR	Delta	166	118.2	941	1,052	47.2	In orbit, first passive comsat; relayed voice and TV signals.
Courier 1B	10/4/60	ETR	Thor-Able Star	500	106.9	586	767	28.3	In orbit; first active repeater comsat; operated 17 days.
Telstar I	7/10/62	ETR	Delta	170	157.8	593	3,503	44.8	In orbit, active repeater comsat; transmitted until 2/21/63.
Relay I	12/13/62	ETR	Delta	172	185.9	819	4,612	47.5	In orbit; comsat, experiments conducted until 2/65.
Syncom I	2/14/63	ETR	Delta	86	1426.6	21,195	22,953	33.5	In orbit; communication lost at orbital injection.

TABLE 1.1 SPACE LOG OF COMMUNICATION SATELLITES

	LAUNCH DATA			INITIAL ORBITAL DATA					
NAME	DATE	SITE	VEHICLE	WEIGHT POUNDS	PERIOD MINUTES	PERIGEE MILES	APOGEE MILES	INCL. DEGREES	STATUS
Telstar II	5/7/63	ETR	Delta	175	225.0	604	6,713	42.7	In orbit; active repeater comsat; transmitted until 5/65.
Syncom II	7/26/63	ETR	Delta	86	1454.0	22,062	22,750	33.1	In orbit; synchronous comsat over Indian Ocean, used by DOD.
Relay II	1/21/64	ETR	Delta	172	194.7	1,298	4,606	46.0	In orbit, comsat, experiments conducted until 9/26/65.
Echo II	1/25/64	WTR	Thor-Agena B	547	108.8	642	816	81.5	In orbit, passive comsat, first joint program with USSR.
Syncom III	8/19/64	ETR	TAD	86	1436.2	22,164	22,312	0.1	In orbit; synchronous comsat at 180°W.
Early Bird Intelsat I	4/6/65	ETR	TAD	85	1436.4	21,748	22,733	0.1	In orbit; commercial communication service initiated 6/28/65.
IDCSP-1	6/16/66	ETR	Titan IIIC	100	1334.7	20,923	21,053	0.1	In orbit; one of 7 initial defense communication satellites.

TABLE 1.1 Continued

LAUNCH DATA				INITIAL ORBITAL DATA					
NAME	DATE	SITE	VEHICLE	WEIGHT POUNDS	PERIOD MINUTES	PERIGEE MILES	APOGEE MILES	INCL. DEGREES	STATUS
IDCSP-2	6/16/66	ETR	Titan IIIC	100	1335.3	20,927	21,066	0.1	In orbit; initial defense comsat; all successfully operated.
IDCSP-3	6/16/66	ETR	Titan IIIC	100	1336.6	20,936	21,088	0.1	In orbit; initial defense comsat.
IDCSP-4	6/16/66	ETR	Titan IIIC	100	1340.8	20,935	21,194	0.0	In orbit; initial defense comsat.
IDCSP-5	6/16/66	ETR	Titan IIIC	100	1344.0	20,949	21,258	0.1	In orbit; initial defense comsat.
IDCSP-6	6/16/66	ETR	Titan IIIC	100	1338.6	20,936	21,139	0.2	In orbit; initial defense comsat.
IDCSP-7	6/16/66	ETR	Titan IIIC	100	1347.6	20,948	21,350	0.0	In orbit; initial defense comsat.
Intelsat 2A	10/26/66	ETR	TAD	192	730.1	2,088	23,014	17.2	In orbit; active comsat, 12 hour orbit rather than planned 24 hour orbit.
Pacific 1	1/11/67	ETR	TAD	192	1436.1	22,244	22,257	1.3	In orbit; trans-pacific communication service initiated 1/11/67.

TABLE 1.1 Continued

LAUNCH DATA				INITIAL ORBITAL DATA					
NAME	DATE	SITE	VEHICLE	WEIGHT POUNDS	PERIOD MINUTES	PERIGEE MILES	APOGEE MILES	INCL. DEGREES	STATUS
IDCSP-8	1/18/67	ETR	Titan IIIC	100	1330.0	20,835	21,038	0.1	In orbit; initial defense comsat.
IDCSP-9	1/18/67	ETR	Titan IIIC	100	1331.0	20,854	21,031	0.0	In orbit; initial defense comsat.
IDCSP-10	1/18/67	ETR	Titan IIIC	100	1332.0	20,867	21,036	0.0	In orbit; initial defense comsat.
IDCSP-11	1/18/67	ETR	Titan IIIC	100	1333.0	20,875	21,063	0.0	In orbit; initial defense comsat.
IDCSP-12	1/18/67	ETR	Titan IIIC	100	1335.0	20,901	21,089	0.0	In orbit; initial defense comsat.
IDCSP-13	1/18/67	ETR	Titan IIIC	100	1337.0	20,923	21,128	0.1	In orbit; initial defense comsat.
IDCSP-14	1/18/67	ETR	Titan IIIC	100	1340.0	20,932	21,192	0.1	In orbit; initial defense comsat.
IDCSP-15	1/18/67	ETR	Titan IIIC	100	1343.0	20,935	21,275	0.0	In orbit; initial defense comsat.
Atlantic 2	5/22/67	ETR	TAD	192	1436.1	22,246	22,254	2.0	In orbit; third Intelsat II, stationed above Atlantic.

TABLE 1.1 Continued

ETR = Eastern Test Range
WTR = Western Test Range
TAD = Thrust Augmented Delta

INTRODUCTORY REMARKS

We now come to the main subject of this paper: Reliability. Just what is reliability? Webster defines reliability as being suitable or fit to be relied on, trustworthy, honesty. These are all in the category of abstract concepts. In the engineering world and in mathematical statistics, reliability has a real and exact meaning. In its simplest and general form, reliability is a probability of success. Stated in formal terms: Reliability is the probability of performing without failure a specified function under given conditions for a specified period of time.

Reliability is viewed as one of the essential engineering technologies and is characterized as concerning itself with:

- The probability of performance over a specified period of time.
- The analysis of available strength against probable stress.
- The trade-off of reliability against other qualities that are desired.
- The cost needed to achieve the given reliability goal.
- The optimum usefulness of the product after it has been sent into service.

Military reliability considerations have become very important in the last ten years. With increasingly wide use of electronic equipment and its growing complexity reliability found its way into every phase of the concept, design, development, manufacturing, test, and delivery cycle. By 1952 the Research and Development Board of the Department of Defense had created an Advisory Group on the Reliability of Electronic Equipment. As a result of their studies the reliability activity grew and culminated in the 1957 AGREE report, on the work of nine task groups in the Reliability of Electronic Equipment.

Reliability becomes an ever-increasing factor in the military business. The main specifications and documents listed in the bibliography are an indication of the importance of reliability requirements.

In the design of communication satellites, reliability is a most important consideration. In order for the system, using satellites for communications, not to become prohibitively expensive the satellite has to be extremely reliable, with a lifetime of at least one year or more. Presently for space electronics used in communication satellites, the term long life connotes mean-time-to-failures or mean-time-between failures (MTBF) of at least five years.

For a typical communication satellite the following reliability requirements will have to be met.

- The mission time - ten years.
- The probability of success - at least 50%.
- The Mean-Time-Between Failure, MTBF - 5,250 days or approximately 1,916,250 hours.
- The number of discrete electronic components - 2500 to 5000.
- The average failure rate per part - 1.6×10^{-9} to 3.2×10^{-9}.

These reliability requirements will have to be achieved by designing reliability into the communication satellite system. By proper selection of component parts, by use of redundancy in certain sections of the electronics package, and by having a tight control on manufacturing, testing, failure reporting, training of personnel, it is then possible to achieve the reliability for a successful satellite system.

Before delineating on the main tasks of reliability to assure a reliable satellite let's describe in detail the advantages and disadvantages of some of the satellite systems mentioned in the previous section.

When considering the advantages and disadvantages of the different communication satellite systems, there are certain points which should be remembered. First, distinction must be made between a disadvantage that is relative in nature and a disadvantage of a system that might prevent the satellite from operating satisfactorily. Thus if the satellite system was of the synchronous orbit type, the station keeping equipment would be more complex thus reducing the reliability (which is of prime importance in long life communication satellites). The launch weight would be greater and a more powerful vehicle would be required to launch the satellite. Looking at it from another point of view, ground station antenna costs are reduced considerably, tracking requirements are lessened, fewer satellites are needed to cover the same area, and that of knowing where the next satellite will appear is reduced. Thus only a complete analysis will tell if one type of system is better than another. All of the factors must be examined thoroughly and weighed against the attributes of other competing systems.

If several satellite systems are feasible a decision must be made as to which one should be chosen. There are a few criteria in making the selection. They are:

- Location in the radio spectrum of the bands of frequencies needed for the proposed service. Usually the transmit frequency bands are different from the receiver frequency bands.
- The required bandwidth needed to transmit and receive communication messages.
- Any interference that might be encountered to the system, thus not providing the optimum requirements for communications.
- The cost of building such a satellite system.
- Obtaining approval for frequency allocations.

Advantages and Disadvantages of Passive Satellites

As we recall passive satellites are metallized spheres that reflect ground radio signals from one point to another ground point. There are no active parts in the passive satellite and therefore the signal is not amplified in anyway. Some of the important advantages of passive satellite systems offered are as follows:

- Simplicity and reliability because, as mentioned above, there are no active components in the system.
- Satellite stabilization is not a requirement unless the system uses a reflector that is directive.
- Since the satellites are linear, they are broad-bandwidth devices and can be used at various power levels and frequencies without problems in cross-talk.

- The feasibility of such a satellite system has been demonstrated, as in Projects Echo and West Ford.
- The required payload weight is very modest.
- The satellite cannot cause any radio interference once it becomes obsolete.
- By adding terminal facilities new channels can be added thus increasing the flexibility of the system.
- Changes in the state-of-the-art can be made even if the satellite is in orbit. These changes might be a change in frequency, increase in power, and use of different modulation techniques.

The disadvantages or limitations of a passive satellite system are:

- The need for high transmitter power for isotropic designs, usually ranging from 10 kilowatts to 10 megawatts. This high power is likely to cause interference to other services, due to antenna and side-lobe radiation and radiation of harmonic power.
- The signals received are not amplified in any way in the process of being reflected from the sphere or balloon.
- The returned signals will fluctuate unless the sphere is rigid.
- The maximum range at which the passive satellite can be used is restricted due to the poor signal-to-noise ratio at the altitudes at which the satellite is placed in orbit.
- The large size makes it very susceptible to puncture and to orbital deviation due to radiation pressure.

Advantages and Disadvantages of Active Satellites

Recalling that active satellites are complex electronic devices capable of receiving a signal, amplifying it, and returning it to the ground (this is an instantaneous repeater) or storing it and returning it at a different location (this is a delayed repeater), let us discuss some of the advantages and limitations of this device.

The advantages may be stated as follows:

- Smaller ground antennas and transmitter powers can be used, as compared to the passive satellite system. The power requirements are usually 1 kilowatt or less. This low power reduces the interference to other services from antenna side lobes and harmonic radiation.
- The signal-to-noise ratio is adequate for high-altitude orbits.

Some limitations or disadvantages of active satellites are as follows:

- Once the satellite is in orbit, state-of-the-art changes cannot be made in the improvement of system characteristics.
- The equipment used is more complex, thus giving a satellite system which is inherently less reliable than a passive satellite system. Due to this complexity more effort in design and development is required to achieve long lifetimes (usually five years or more) for the satellite.
- There are limitations on the power supplies and transmitter power in the satellite for the time being. This will improve as larger payloads become possible, and as nuclear power sources become available.

- In order not to be a source of interference, the satellite system must be destroyed or its transmission terminated once it becomes obsolete.
- Antenna stabilization would be needed to minimize any fluctuation of signals.
- The satellite might be susceptible to interference from high-power ground sources such as radars.
- To transmit and receive a message over a long distance, say 45,000 miles (from earth to satellite and back), involves a time lag of about 0.55 seconds. This delay is very annoying and makes two-way conversation difficult. Figure 1.1 shows the time delay which will be present in space systems.

In the chapters to follow attention will be given to every phase and task deemed necessary for reliability considerations in designing, building, and launching a successful communication satellite. First of all let us talk about the problem we are faced with. We begin this in the next chapter by giving a statement of the problem.

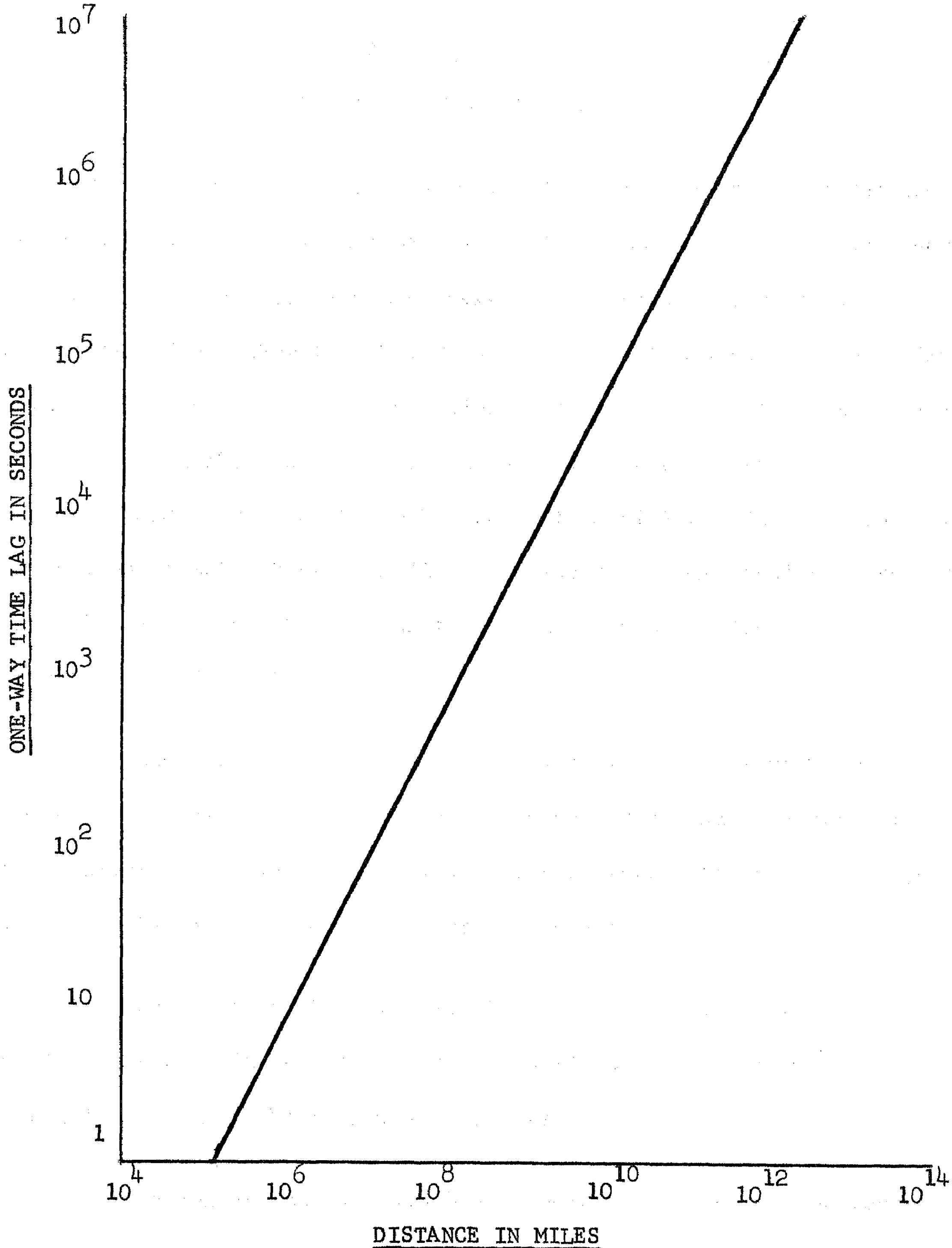


FIGURE 1.1 Communication Time Lag

CHAPTER 2

STATEMENT OF THE PROBLEM

As can be seen from the discussion in Chapter 1 and by reviewing Table 1.1, Space Log of Communication Satellites, a very large percentage of satellites that were launched were successful and as a matter of fact still operating perfectly. The questions now are asked: Why have there been so many successful communications satellites? Was it just a matter of chance? On the contrary! It was no accident that caused a very successful phase in communication by means of satellite. It could be stated in just one simple phrase: Reliability was the prime consideration from initial system concept, through manufacturing and testing, and finally into launch and orbit.

How does one go about implementing a reliability program for a communication satellite to be reasonably confident that the satellite will perform its mission satisfactorily for periods in excess of 3 years? This then is the problem that we are faced with.

The rest of this chapter will discuss in some detail the necessary reliability considerations and tasks needed to obtain a communication satellite that must be extremely reliable.

Bell Telephone Laboratories have developed a numerical procedure for predicting the mean time to failure of complex electromechanical systems. For instance, in designing a 24 hour synchronous communication satellite, the mean time before failure of 1.5 years was calculated. If the satellite, whose orbit control had to last for only 30 days, a mean time before failure of 1.8 years is possible. This would be the case for satellites in a polar orbit. A theoretical mean time before failure of 3 years would be required for uncontrolled active satellites.

High reliability in a communication satellite requires intensive planning during its design and construction. Reliability must be considered during the initial design studies and continued throughout the entire program. Reliability cannot be overlooked until the testing program is started in hopes that testing will improve the system reliability. One very important fact must be stated at this point: Reliability cannot be tested into a system, it must be designed in very early in the program.

In obtaining a high reliable communication satellite certain approaches must be followed:

- Reliability must be pursued in every phase of the program as an end in itself.
- Components used in the system must be used at a small fraction of the designed or rated capacity. This is known as derating.
- Wide design margins must be used in all subsystems when considering environmental conditions and operating parameters.
- Consider the use of redundant components or units which will offer the highest potential for increasing the overall reliability. Redundancy is the existence of more than one way for doing a given task where a system failure is defined only if all the ways to

perform the given task have failed. We will discuss redundancy and types of redundant configurations under the task of reliability assessments, apportionment, and analysis.

- All phases of the mechanical design and fabrication must be understood and designed with adequate margins.
- The testing program must be performed at three levels - component, subsystem, and system.

At this point a review will be made of a system description and some of the requirements for a typical communication satellite system in order to point out the characteristics of not only the satellite itself but also of the ground station from which full communications capacity is obtained. The review will consider one of the project Syncom satellites. This project was assigned the synchronous orbit, active repeater satellite investigations.

The advanced Syncom, or Syncom II has a voice communication capacity of 600 two-way telephone conversations for each of the transponders in the satellite. The Syncom II system had four transponders, giving a total capability of 2400 two-way telephone channels. The system was also capable of providing television or other wide-bandwidth signals, using the same transponders. The solar cells which were used for electrical power provided the satellite with 135 watts.

The communications requirements for the Syncom II are as follows:

Capacity: The satellite should be designed to accommodate 600 two-way telephone channels or one monochrome or color television station in each of the four frequency bands. The 600 telephone channels could start from as many as 100 ground station terminals simultaneously and should accommodate multiplexed teletype signals.

Quality: The communication links should be of such quality so as to exceed the standards set by the International Radio Consultative Committee (CCIR) of the International Telecommunication Union (ITU).

Table 2.1 lists the characteristics of the ground station for which the full communications capacity is achieved.

Transmitter (For Each Frequency Assignment)	
Saturated Power	10 kilowatts
Frequency Band	6 gigahertz
Bandwidth	25 megahertz
Diplexer Loss	-1 db
Frequency Stability	1 part in 10^{10} for short term
	1 part in 10^7 for long term
Antenna	
Diameter	85 feet
Efficiency (receiving and transmitting)	54 percent
Receiver	
Noise temperature (all sources including antenna)	80°K

TABLE 2.1 Characteristics of Ground Station

The standards used for the Syncom II are given in Table 2.2.

Television Signal-to-Noise Ratio	
Peak-to-peak signal to weighted noise	51 db
Television Video Bandwidth	
Monochrome	4 megahertz
Color	4.5 megahertz
Voice Channels	
Test tone/noise ratio	50 db
Total channel bandwidth	4 kilohertz
Voice portion of bandwidth	3.1 kilohertz
Multiplexed Teletype Signals	
Maximum error in frequency	2 hertz

TABLE 2.2 Standards for Communication System

The signal and noise levels for the system at several points are given in Tables 2.3 and 2.4. It should be noted that these parameters are for the system when used for monochrome television signals.

Transmitter Power	33.0 dbw
Diplexer Loss	-1.0 db
Ground Antenna Gain	62.1 db
Space Attenuation	-200.8 db
Receiver Antenna Gain	8.0 db

Off Beam Center Allowance	-1.5 db
Receiver Carrier Power	-101.2 dbw
Receiver Noise Power Density	-195.3 dbw/hertz
Receiver Noise Bandwidth	74.0 db
Receiver Noise Power	-121.3 dbw
Carrier/Noise Ratio	20.1 db

TABLE 2.3 Frequency Modulation (TV), Ground to Spacecraft

Spacecraft Transmitter Power	6 dbw
Diplexer and Phase Shifter	
Losses	-3 db
Spacecraft Antenna Gain	18 db
Space Attenuation	-197.1 db
Off Beam Center Allowance	2 db
Ground Antenna Gain	58.4 db
Receiver Carrier Power	-119.7 db
Receiver Noise Power Density	
(80°K)	-209.6 dbw/hertz
Receiver Bandwidth	74.0 db
Receiver Noise Power	-135.6 dbw
Carrier/Noise Ratio	15.9 db
Carrier/Noise Ratio - UP Link	20.1 db
Carrier/Total Noise Ratio	14.5 db
Top Modulation Frequency	4 megahertz
Modulation Index, M	2.5

Improvement Factor	17.7 db
Average Signal-to-Noise Ratio	32.3 db
Noise Weighting Factor	14.5 db
Peak-to-Peak Signal/Weighted Noise	55.2 db

TABLE 2.4 Frequency Modulation (TV), Spacecraft to Ground

Tables 2.5 and 2.6 list the signal and noise levels at points in the system for the condition of full channel useage, or when 600 two-way telephone circuits are in use in each frequency band.

Transmitter Peak Power Capability	40 dbw
Transmitter Average Power	31.7 dbw
Channel Test Tone Power	18.9 dbw
Diplexer Loss	-1.0 db
Ground Antenna Gain	62.1 db
Space Attenuation	-200.8 db
Receiving Antenna Gain	8.0 db
Off Beam Center Allowance	-1.5 db
Received Test Tone Power	-115.3 dbw
Receiver Noise Power Density	-195.3 dbw/hertz
Channel Bandwidth	34.9 db
Psophometric Noise Weighting Factor	-2.5 db

Receiver Channel Noise (Weighted)	-162.9 dbw
Test Tone/Fluctuation Noise Ratio	47.6 db
Test Tone/Intermodulation Noise Ratio	50.5 db
Test Tone/Noise Ratio	45.8 db

TABLE 2.5 Single Sideband Modulation (Voice) Ground to Spacecraft

Spacecraft Transmitter Power	6 dbw
Diplexer and Phase Shifter Losses	-3 db
Spacecraft Antenna Gain	18 db
Space Attenuation	-197.1 db
Off Beam Center Allowance	-2 db
Ground Antenna Gain	58.4 db
Received Carrier Power	-119.7 dbw
Receiver Noise Power Density (80°K)	-209.6 dbw/hertz
Receiver Noise Bandwidth (25 megahertz)	74.0 db
Receiver Noise Power - Total	-135.6 dbw
Carrier/Total Noise Ratio	15.9 db
Weighted Channel Noise Power	-177.2 dbw
Carrier/Channel Noise Ratio	57.5 db
Channel Test Tone Modulation Index	0.35

Test Tone/Noise Ratio	48.5 db
Overall Link Test Tone/Noise Ratio	43.9 db
Compander Improvement Factor	15 db
Overall Link Test Tone/Effective Noise Ratio	58.9 db

TABLE 2.6 Phase Modulation (Voice) Spacecraft to Ground

The spacecraft reliability requirements will now be presented for the Syncom II Communication satellite. The two mission functions for the satellite are communications and telemetry, each having its own reliability characteristics. The reliability requirements for each of these mission functions are shown in Table 2.7, including the probability of survival of boost and synchronization-orientation. As can be seen from the table the transponder may operate in either a multiple access mode or frequency translation mode during the communication phase.

Phase of Operation	Boost Reliability	50% Lifetime, Years
Communications		
Multiple Access Mode		
Four Quadrants	0.96	1.0
Three Quadrants	0.99	2.0
Two Quadrants	0.99	2.5
One Quadrant	0.99	3.0

Frequency Translation Mode		
Four Quadrants	0.96	0.5
Three Quadrants	0.99	1.0
Two Quadrants	0.99	1.5
One Quadrant	0.99	2.5
Telemetry		
Four Quadrants	0.98	2.0
Three Quadrants	0.99	3.0
Two Quadrants	0.99	4.0
One Quadrant	0.99	5.0

TABLE 2.7 Spacecraft Reliability Requirements

The various subsystem reliability requirements are shown in Table 2.8. These estimates are the reliability goals or objectives for each subsystem used in the satellite.

Subsystem and Unit	Reliability Objective
Transponder Subsystem	
Transmitter	
TWT and Electronics	0.615
Antenna and Diplexer	0.970
Receiver	
Frequency Translation Mode	0.762
Multiple-access Mode	0.762
Antenna and Diplexer	0.958
Antenna Control Electronics Subsystem	0.842

Command Subsystem	
Receiver and Diplexer	0.950
Decoder A and B	0.962
Antenna and Hybrid	0.988
Telemetry Subsystem	
Transmitter and Diplexer	0.886
Encoder	0.748
Power Supply Subsystem	
Battery and Changing Circuit	0.896
Solar Panel	0.998
Reaction Control Subsystem	
Solar Sensors	0.998
Apogee Motor	0.999
Structure	0.999

TABLE 2.8 Reliability Objectives

The reliability program plan will now be presented in some detail. This plan is to be implemented to assure the attainment of the reliability goals and objectives for a communication satellite. The reliability tasks to be discussed are as follows:

- Reliability Program Organization
- Reliability Program Plan
- Design Review Program
- Reliability Apportionment, Assessment, and Analysis
- Parts Material and Process Control

- Supplier Reliability Control
- Failure Reporting and Analysis and Corrective Action
- Reliability Indoctrination and Training
- Reliability Testing Program
- Reliability Program Review

<u>Reliability Program Organization</u>

The main purpose of this task is to define the organization responsible for implementation of the communication satellite reliability program plan. The program organization should show the relationship between the reliability engineering department to all other departments assigned to the program. It should also outline all responsibilities of the reliability engineering group. The main points for a comprehensive organization reliability program call for the following action:

- Institute and maintain an agressive program to improve and control reliability.
- Assign responsibilities to each department for product reliability.
- Establish reliability goals and objectives with measurable values assigned to elements affecting customer satisfaction.
- Develop and formally review conceptual product designs to ensure they reflect and incorporate: a) customer reliability requirements; b) simplicity of design and standardized components; and, c) outcome of performance data as a result of feedback from the field.

- Verify the design and performance of the end items and processes. Consider installation conditions, use and service. Include accurate instructions on installing, operating, and servicing the end item.
- Maintain a control on specifications and drawings to assure manufacture to current design information.
- Establish and operate quality assurance procedures to assure conformance with engineering specifications.
- Audit the reliability program by: a) conducting the reliability testing on each component to substantiate continued conformance with original verification programs; b) evaluating the effectiveness of the reliability programs; and, c) gathering, interpreting, and transmitting significant product performance data from the field.
- Train each one in the reliability control technique important to his job.

Reliability Program Plan

A reliability program plan is to be formulated and defined as to what individual tasks will be planned to conform with the requirements of the applicable specifications. In order to implement the individual tasks, procedures will be prepared delineating all the steps necessary to carry out the particular task. Certain milestones and program schedules for each task compatible with the communication satellite program schedule must be defined. The program plan, to be effective, must be revised and updated as needed.

The reliability program plan should provide the necessary program elements and procedures listed below.

- Reliability Program Organization
- Reliability Design Review Program
- Reliability Apportionment, Assessment, and Analysis
- Parts, Material, and Process Control
- Supplier Reliability Control
- Failure Reporting and Analysis, and Corrective Action
- Reliability Indoctrination and Training
- Reliability Testing Program
- Reliability Program Review

Reliability Design Review Program

The best way for controlling reliability is through design and review. The basic philosophy includes early program use of reliable design techniques plus formal design reviews throughout the program. There are generally three phases in the sequence of a reliability design review: a) conceptual or preliminary review; b) detail or major review; and, c) improvement or verification review. A more detailed description of each of these phases will be made in the subsequent chapters covering the solution mentioned at the beginning of this chapter.

The design review board should be composed of the following personnel, as required:

- The electrical design engineer
- The physical (packaging) design engineer
- The systems engineer
- The product design engineer
- The cognizant reliability engineer
- The project engineer
- The parts application engineer
- The test engineer

These board members are responsible for the review and approval or disapproval of the applicable design presented.

Reliability Apportionment, Assessment, and Analysis

The reliability program provides for the prediction and analysis of the communication satellite system. Inherent reliability is an engineering design parameter in the same sense as performance and weight. Procedures for the prediction of reliability are based on the stresses anticipated in the actual application. The method used for reliability prediction and analysis of the satellite is compatible with the military specification, MIL-STD-756A, Reliability Prediction.

Prediction and analysis procedures apply in each phase of the life cycle of the system; feasibility, detail design, manufacturing, and service use. The feasibility prediction is used in the conceptual phase of the system design which covers development of the satellite system from its initial design concept to and including the preliminary design. During the detail design phase, a prediction is made based on accurate parts lists, application data, environmental conditions, and mission profiles. The prediction made in the detail design phase is updated during manufacturing as new data becomes available.

Mathematical models are used to describe the satellite reliability allocation, internal component reliability apportionment and relationship of the respective equipment to the overall system. The mathematical model serves as a basis for reliability reassessment, reallocation, design tradeoffs, logistics, and deployment.

Reliability prediction and analysis serves as a basis to accomplish the following: quantify system reliability, conduct design tradeoffs, determine problem areas, evaluate redundancy techniques, plan test programs, and a guide for failure mode and effect analysis studies.

The general sequence of steps followed in the implementation of the reliability prediction and analysis is shown below:

- Define the reliability specifications and requirements.
- Determine the environmental conditions and mission profiles.
- Establish the reliability mathematical model(s).
- Determine the component population for each functional element.
- Determine appropriate stress factors for each component.
- Conduct design analyses on component application.
- Assign applicable failure rate to each component.
- Compute numerical probability of success.

The primary sources of failure rate data are: MIL-HDBK-217A, Reliability Stress and Failure Rate Data for Electronic Equipment, IDEP (Interservice Data Exchange Program), customer supplied information, manufacturers' data, and information published in engineering journals.

An initial assumption is made that the time to failure distribution is exponential. As sufficient operating time and failure information becomes available, analyses are performed to determine the actual failure distribution. Use is made of the three parameter Weibull distribution which considers constant, increasing and decreasing failure rates.

Parts Material and Process Control

The main purpose of this task will deal with the reliability of parts, material, and processes in the communication satellite system. Part failure modes, mechanisms, and causes will be discussed as well as those materials and processing factors needed to assure reliability of the system.

The reliability function will be responsible for the following:

- Review part requirements and specifications.
- Collect parts application information for use in system tradeoffs to maximize reliability.
- Measure reliability of each part so the reliability of the system can be predicted.
- To maintain surveillance over all parts during the production and manufacturing phase to assure their continuing reliability.

Specifications for all parts will have to be prepared and should include as a minimum the following:

- Required part parameters
- Service conditions
- Type and vendor approval requirements
- Requirements for packaging and marking of each component
- Requirements for lot qualification
- Screening and acceptance requirements
- Approved sources of procurement
- Qualification requirements.

In some cases special fabrication processes will occur which have not been dealt with previously by others or by manufacturers. It should be the responsibility of reliability engineering to ensure that such processes are recognized early in the design, are thoroughly investigated and evaluated, and are covered by a process specification and a manufacturing procedure. A more detailed discussion will be presented in the "solution" portion of this paper.

Supplier Reliability Control

Supplier reliability control provides assurance of delivery of components, parts and materials that meet the reliability requirements for the communication satellite. Supplier reliability controls are implemented in order to effectively monitor a supplier's conformance to stipulated reliability requirements. Requirements for supplier control are specified in the reliability work statement.

Each supplier is provided with guidelines upon which to base the reliability program. These guidelines are formal documents and include information on the following: supplier organization for reliability, reliability program planning, design review, prediction and analysis, test program, failure reporting system, indoctrination and training, mathematical methods, lower tier supplier controls, and documentation.

Reliability personnel represent the reliability function and provide services and support to the following activities:

- Make or buy team
- Survey team
- Source evaluation team
- Weighting team
- Source selection board

Liaison is maintained with the cognizant reliability representatives of the supplier's facility. Personnel are assigned when required as resident representatives to monitor the supplier's performance.

Periodic supplier facility surveys are made to assure that the supplier possesses the requisite capabilities to provide the necessary materials, equipment or services that meet the reliability requirements. Reliability personnel are members of the facility survey along with quality control, engineering production, and procurement.

Reliability personnel review the records of supplier performance for indications of performance trends that could affect the reliability of the communication system. Early failure mode analyses are made and investigation performed to determine causes of failures. Corrective measures are instituted, and the effectiveness of these measures monitored by reliability personnel.

Failure Reporting and Analysis and Corrective Action

A failure reporting system will be established to provide for the detection of failure modes, causes of failure, and the feedback of information for corrective action during the satellite program. A failure is normally defined as operation outside the tolerance limits given in the performance specification.

The following elements form the basis of the failure reporting system:

- Detection of system failure
- Recording of all pertinent data
- Information on data processing record cards
- Store information for reference
- Retrieve information as required
- Analyze data for determination of basic failure modes and causes of failure
- Summarize the generated information
- Recommend corrective action to prevent recurrence of failure
- Report the final results to cognizant personnel.

The purpose of the failed parts analysis is to determine the basic cause of failure and evaluate the need for changes in design, material, workmanship, manufacturing, inspection, testing and handling. Recommendations for corrective actions designed to prevent recurrence of the experienced failure are a part of failure analysis.

Failed parts will be subjected to the following procedure as required:

- Review all test data and system performance requirements.
- Review description of failure and failure symptoms.
- Examine physical unit and associated equipment.
- Review all previous failure data on similar systems.
- Conduct verification and diagnostic testing.
- Submit samples to special tests, such as radiographic, and infra-red examination as required.
- Perform dissection analysis.
- Prepare drawings, illustrations, and photographs.
- Determine mode of failure and recommend corrective action.

Reliability Indoctrination and Training

Reliability indoctrination and training courses will be conducted for all personnel assigned to the program. The object of the training is the motivation of personnel in the utilization of reliability concepts and the importance of each person's contribution to the reliability of the final system.

Recognizing the high reliability performance required, these courses will thoroughly familiarize each individual on the program with his duties. A continuous program will provide an attitude of reliability consciousness in all personnel. The reliability engineering staff will coordinate with the training supervisor on reliability training of all program personnel. Coincident with this training will be instructions to operating personnel regarding their particular work functions.

There are a few levels for which the reliability courses will be prepared. One level is management, engineering, and supervision, where detail definitions, concepts and the philosophy of reliability will be presented. Another level is the operating personnel, including manufacturing, assembly, inspection and test groups.

Indoctrination courses for the assembly and test personnel will be conducted to acquaint them with reliability concepts and goals. After an initial general lecture on reliability concepts, specific training will be keyed to the particular job function. This specific training will consist of delineating the reliability requirements for the communication satellite system and presenting them in a clear and enlightening manner to the operating personnel. All personnel assigned to the satellite program will be made to recognize the concept that building a high reliable communication system is an exercise in perfection. Visual aids will be prepared for parameters difficult to describe in familiar or technical terms.

Human factors will be a consideration in reliability training, and will be integrated into each training course. In order to insure the integration of human factors into the overall training program, it is necessary not only that they be valid, but that they be timely. This study will take into account the learning ability, sensory ability and experience of each group. The necessity for maintaining a consistently high level of workmanship will be impressed upon all personnel. Requirements of the work functions will be specifically delineated, with special attention to the interaction between operating personnel and the designed system.

Motivation incentives will be oriented to provide the proper mental "set" for the exacting requirements of each job function. As a necessary adjunct, reward and motivation activities will be established. Voluntary honesty in reporting all discrepancies will be encouraged. The prevailing work attitude and conditions will provide an atmosphere in which inherent reliability of design is not degraded during production.

Reliability Testing Program

This is one of the most important tasks to be performed on a high reliability program such as this one proposed here. The main objective will be to describe the special testing required on parts and assemblies to assure reliability achievement.

The reliability engineering department will be responsible for planning and implementation of special parts and assembly tests as required per specifications. The tests to be performed and their milestones will have to be delineated in the test plans. There test plans will detail the test procedures and should be approved by design engineering and all other personnel involved directly.

Any additional testing that may be required to assure compliance with the program requirements should be implemented by reliability engineering. For a communications satellite program special testing might be made on the following components and/or units:

- Tunnel Diodes
- Tunnel Diode Amplifiers (TDA)
- Tunnel Diode Amplifier Circulators
- Traveling Wave Tube Amplifiers (TWTA)

Reliability Program Review

This task is to review the effectiveness of the reliability program. Special required reports will be prepared and reviewed with responsible personnel. These reports could include the following, as required:

- Reliability Program Plan
- Minutes of Design Reviews
- Reliability Assessments and Analysis
- Failure Mode and Effect Analysis
- Parts Specifications
- Failure Reports and Analysis with Corrective Actions
- Monthly Status Reports

Regular meetings will also be held with the program manager to discuss outstanding problems as related to the reliability tasks for the program.

CHAPTER 3

SOLUTION TO THE PROBLEM

The next two chapters will be devoted to the solution of the problem: the implementation of a reliability program for a communication satellite possessing a high degree of reliability. This chapter will cover the following reliability program tasks in detail:

- Reliability Program Organization
- Reliability Program Plan
- Reliability Design Review
- Reliability Apportionment, Assessment, and Analysis.

Chapter 4 will be devoted entirely to the remaining reliability program tasks,

- Parts, Material and Process Control
- Supplier Reliability Control
- Failure Reporting and Analysis, and Corrective Action
- Reliability Indoctrination and Training
- Reliability Testing Program
- Reliability Program Review.

Reliability Program Organization

In organizing for high product reliability the program must be placed under the direction of a manager who is technically competent and thoroughly familiar with all avenues of reliability. The reliability organization must report to top management thus making top management aware and conscious of reliability as well as of manufacturing, purchasing, engineering, and marketing. In addition to being technically competent, the reliability manager must have knowledge of his company's product. He should also have managerial skills and talents for organizing and planning for reliability tasks. Experience in manufacturing and marketing and some knowledge of statistics will also help. It should be noted and emphasized that responsibility for reliability remains with the line organization. The task of the reliability program manager is in planning, monitoring, and coordinating the reliability effort.

There is no specific organization chart or structure that will fit all divisions or meet all product lines. It is very desirable to coordinate the reliability effort with the line functions. A suggested organization chart is shown in Figure 3.1.

Let us look a little closer at the reliability structure. Shown in Figure 3.2 is a functional organization chart of a typical reliability engineering department. The Parts Reliability section is responsible for the following tasks:

- Writing of parts procurement specifications.
- Writing of specifications for parts testing.
- Surveillance of parts testing.
- Writing of test reports for parts testing program.
- Document and publish standard parts lists.

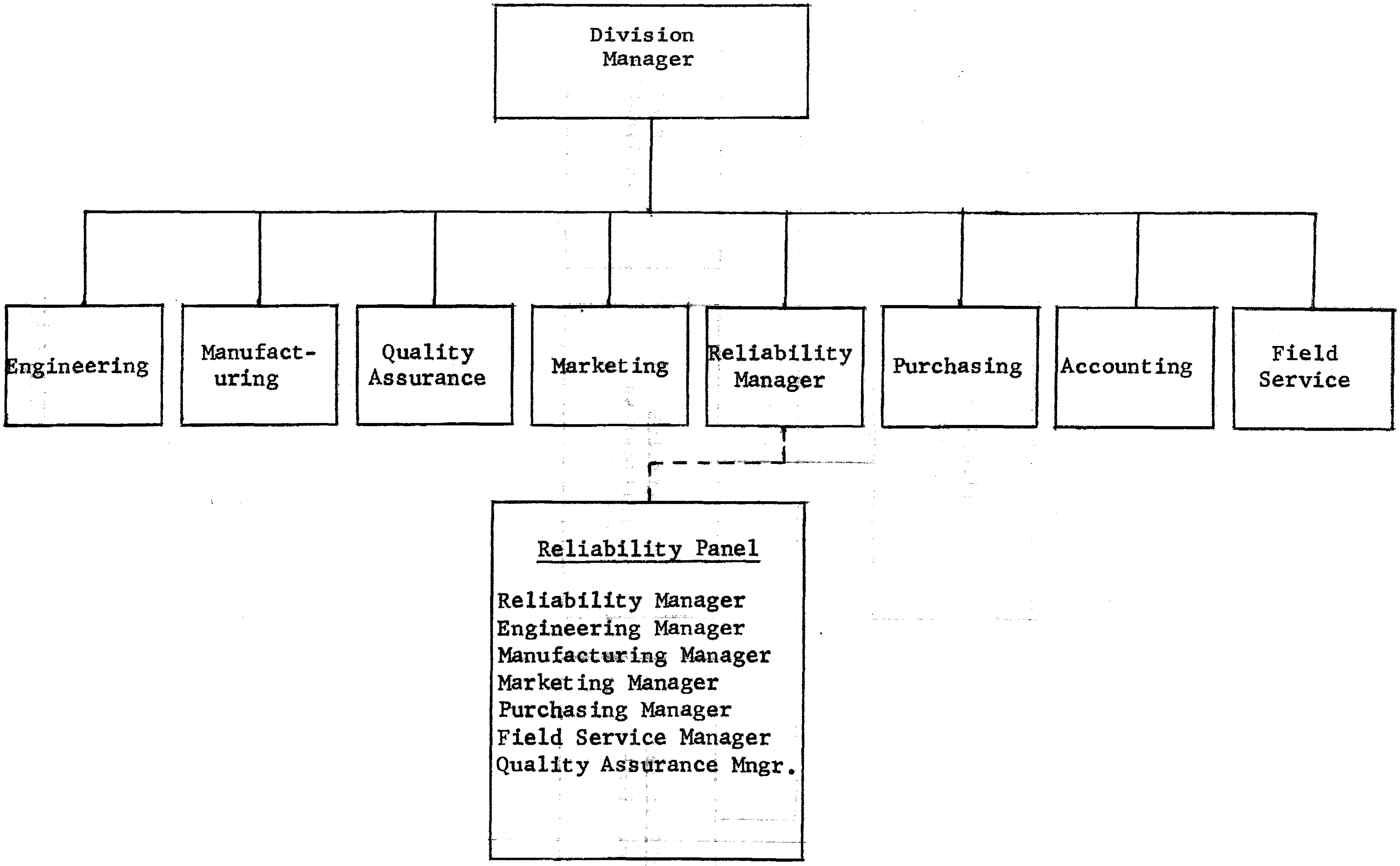


FIGURE 3.1 Reliability Organization Chart

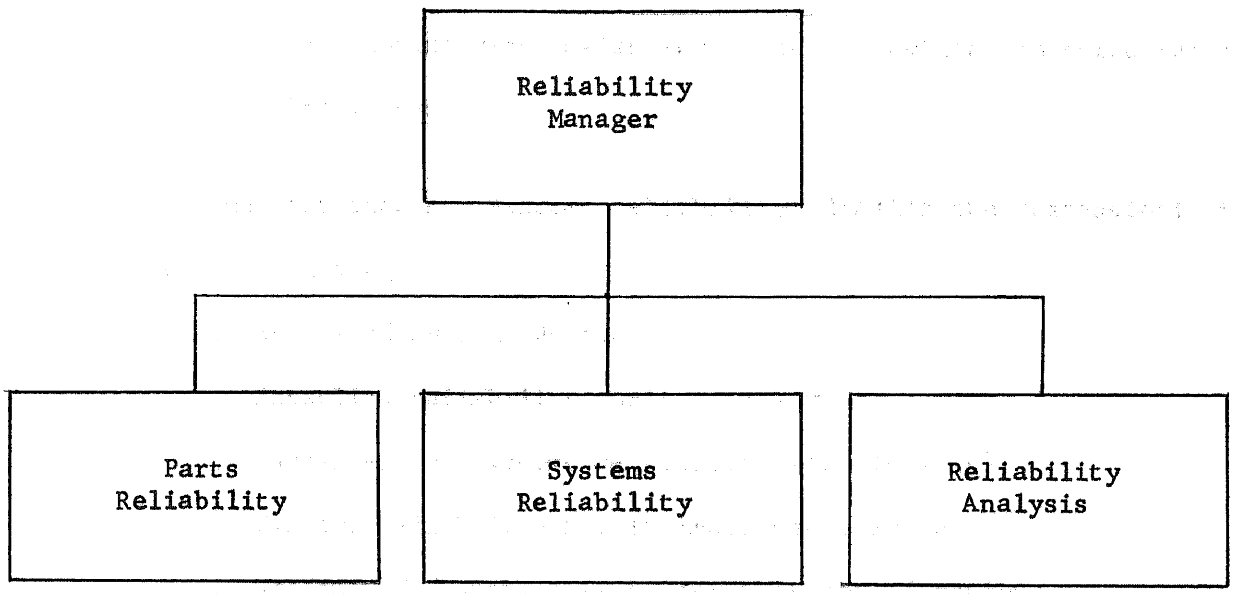


FIGURE 3.2 Reliability Engineering Functional Organization Chart

- Assist in parts selection and application.
- Investigate failed parts and follow up action.
- Review parts documents for use and requirements.
- Survey suppliers' facilities before procurement of parts.
- Participate in data exchange programs of parts.
- Monitor parts handling, transportation and storage techniques.
- Assist engineering design and drafting sections in selection of reliable parts.

The next section, Systems Reliability, details the responsibilities for the following:

- Review of systems designs.
- Establish reliability audit points.
- Assessment of systems reliability (predictions).
- Systems reliability requirements established.
- Writing of systems reliability test specifications.
- Surveillance of systems reliability tests.
- Writing of systems reliability test reports.
- Survey sub-contractor facilities.
- Systems failures and malfunctions investigated and corrective action written.
- Aid in statistical analysis as required.

The last section in the functional organization chart is Reliability Analysis. This section is responsible for performing the following tasks:

- Establish and monitor failure reporting and corrective action.
- Establish and monitor operate time accumulation system.
- Train and indoctrinate personnel by preparing and conducting reliability training and indoctrination programs.
- Prepare procedures for statistical and mathematical methodology.

In a program such as a communications satellite, reliability should be organized to provide the tasks delineated above in a most efficient manner. The reliability department should be so organized that their decisions should not be compromised by other departments which are primarily interested in the cost of producing the unit and its delivery schedule. Too often this is the case where it seems, for a while anyway, that money and on time delivery will solve all of the program's problems. But because of a component or unit that was purchased without adequate screening and testing, the reliability of the complete system will be in jeopardy. In this type of program, where reliability is of the utmost importance, this cannot and should not be allowed to take place. A proper reliability organization as described above should be set up to prevent this type of operation from happening. The organization should be able to establish policies as well as have the means to carry their policies out. The reliability organization, to be effective, should not be static but must adjust and correct in response to operating experience and advances in the technology of the state-of-the-art. The organization described in this section will obtain maximum return from the money invested in the communications satellite reliability program where the program is programmed and managed maturely. The time phasing of the reliability program with each of its stages with the corresponding stages of development, production, and field use will help accomplish this.

Reliability Program Plan

The main purpose of a reliability program plan is to define management decisions on all of the reliability tasks in a way that represents the best judgement of the customer and the contractor. The program plan should define what activities will constitute a reliability program and how each activity will be carried out to a successful completion. The plan should also define which items or pieces of equipment will be subjected to which disciplines, how much effort will be expended on the application of each task discipline to each piece of equipment, and when these reliability tasks will be performed. The plan also describes the related reliability activities of other departments or organizations in order that effective and sound coverage is maintained throughout the program.

The reliability program plan describes all reliability procedures and methods needed to carry out the required reliability tasks. It should be written in such a manner as to permit the customer or its representatives to determine the adequacy of the reliability program for the system.

The reliability plan for the communications satellite should delineate all areas of reliability work that is required during development and production of the complete system. It must include, as described in the previous section, reliability technical and administrative concepts, all operational details of the program, and necessary documentation needed to carry out the required tasks in the operational phase.

The reliability program plan should be reviewed for updating as required to reflect the latest program requirements. The reliability department is responsible for coordinating and disseminating these changes, whether they be additions or deletions.

A satellite reliability program of the type discussed here is best viewed in terms of the types of malfunctions or failures that must be predicted, detected, prevented, and corrected during the design and development phase of the program.

The following failure contributors must be recognized, all of which will determine the reliability levels achieved by the communications satellite:

- Random failures (a random failure is any catastrophic failure whose probability of happening is stationary with respect to time, and whose occurrence within any given interval of time is, consequently, unpredictable, or alternatively, failures which are individually unpredictable).
- Degradation failures (this is a failure that results from a gradual change in performance characteristics of an equipment or part with time).

- Part and unit environmental failures.
- Packaging inadequacy failures.
- Poor workmanship failures.
- Fabrication process failures.
- Checkout procedure failures.
- Storing and shipping failures.

The main difference in a reliability program for a non-maintainable satellite such as this is that almost all tasks are basically irreversible. It is like a trapeze artist who completes 999 good swings on the bar (out of a possible 1000) and makes one bad swing. As far as the audience is concerned the trapeze artist tried his best and was 99.9 percent perfect. But looking at it from a more practical view, the artist had zero reliability (remembering that reliability is defined as the probability of mission success without any failures).

Some of the key objectives to consider in planning a reliability program plan are as follows:

- The customer should present the manufacturer with an operational analysis of the system, such as delineating all modes of operation used in the communications satellite (as detailed in TABLE 2.7 Spacecraft Reliability Requirements in Chapter 2.) Also, the numerical reliability requirements, such as probability of completing the given mission, failure rates for the various components, and application factors should be made available.

- Make sure that the basic definition of component failures and system failures is clearly understood by all concerned. This is very important when the Reliability Testing phase of the program is initiated.
- The methods and reasons used to derive the reliability assessments and predictions should be clearly explained. Any assumptions made while preparing the estimate, such as use of redundancy in certain portions of the electronics, should be stated and justified to customer satisfaction.
- An explicit definition of the accuracy of instrumentation that will be used during certain portions of the program.
- Any data reduction techniques that are initiated and considered necessary should be delineated to the fullest.

It is believed that the reliability program plan as described in Chapter 2 will be sufficient in attaining the required reliability requirements for a communications satellite. This requirement can be stated as successful operation of an extremely complex system in a space environment for periods of up to 5 years.

The elements of the reliability program plan will now be discussed in some detail, starting with the Reliability Design Review tasks, then Reliability Apportionment, Assessment, and Analysis, followed by Parts Material and Process Control. The remaining tasks will be discussed in the following chapter.

Reliability Design Review

A formal definition of a design review can be stated as follows: A reliability design review is an evaluation of a system and/or the components making up the system for the purpose of recommending design changes which will ultimately improve its reliability. The design review gives consideration to other design criteria such as producibility, schedules, weight, size, cost, performance, and maintainability in order to achieve the optimum reliability compatible with the other criteria. The main objectives of a reliability design review are, a) to review the progress of the design; b) to monitor reliability growth and achievements; c) to assure the reliability requirements will be met in an optimum manner; and, d) to provide feedback information to all concerned groups involved in the program.

The system should be reviewed by personnel not directly associated with its design and development. A well organized reliability department will have reliability engineers who are qualified in performing this task. A very important point should be made here. A reliability design review is not considered as a duplication of effort of the design engineering group. A design review committee or board will evaluate the performance objectives with the methods and techniques of reliability design review, performed as an independent effort of the design engineer, in order to assure a more effective system design.

Figure 3.3 shows the general areas for which design reviews are scheduled.

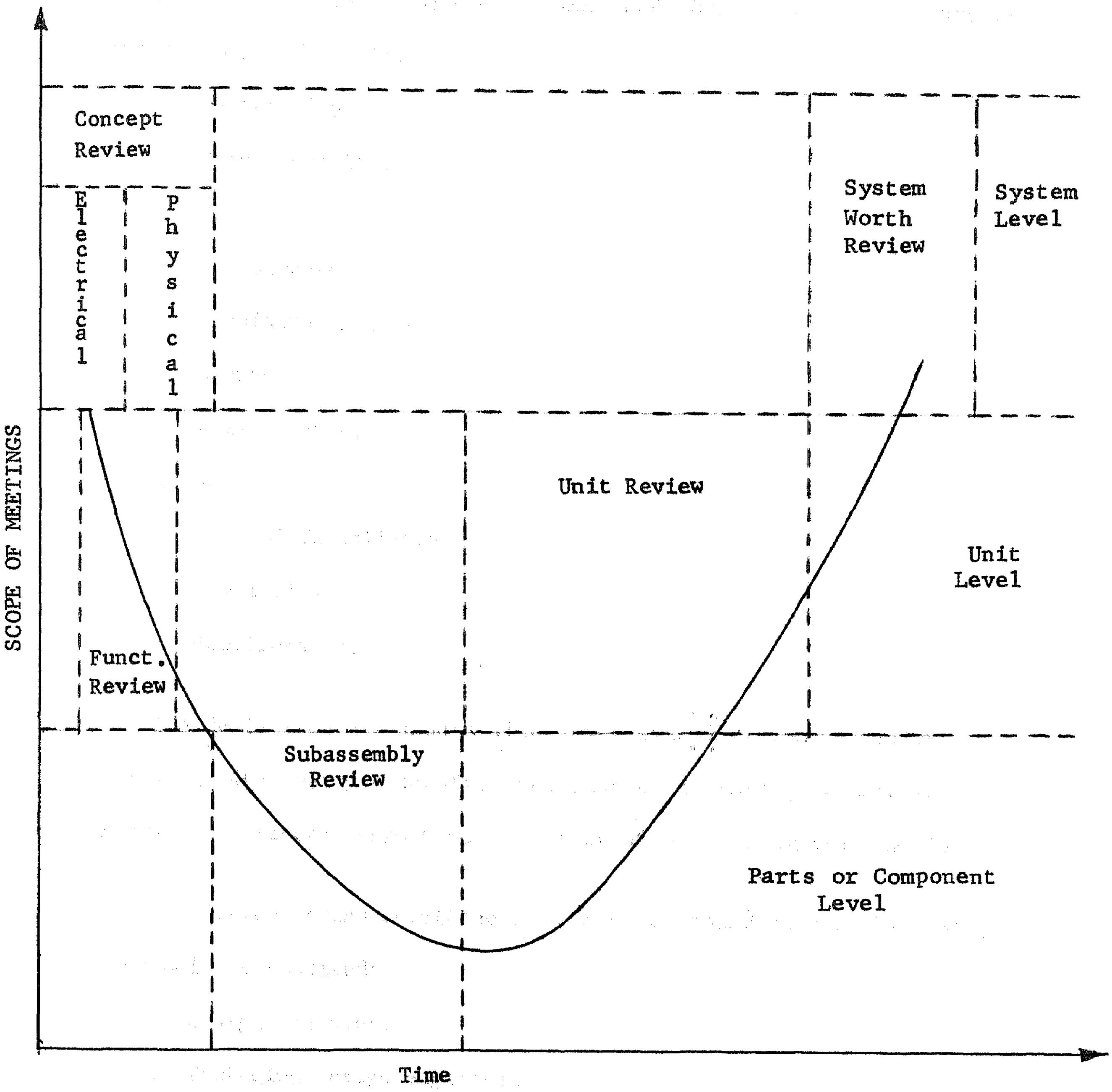


FIGURE 3.3 Scope of Design Reviews vs. Phase of Development

Effective design reviews are held when all aspects of the design are examined in detail. The areas examined should include but are not limited to the following:

- Reliability
- Maintainability
- Cost
- Performance
- Manufacturability
- Operability
- Human Factors
- Safety
- Ease of Installation
- Simplicity
- Requirements.

The design reviews should also cover system concept, design philosophy when using tradeoffs, application of parts, materials, circuits, processes, structures, configuration, and thermal design.

The design review committee should be composed of the following personnel, as required:

- Design engineer.
- Packaging design engineer.
- Systems engineer.
- Product design engineer.
- Reliability engineer.

. Project engineer.

. Parts application engineer.

. Test engineer.

. Quality Assurance engineer.

. Manufacturing.

Each design review member should be experienced in his particular area to assume all responsibilities for his decisions. Each member should have the ability to criticize another member's work area by suggesting changes or alternates for product improvement.

To be effective, design reviews should be conducted at several different stages during the program. These stages can be divided into the following:

. Conceptual Design.

. Developmental Design.

. Final Design.

The first review or conceptual design review should be held at the time the new design is in the planning stage and before the detailed design efforts began to consider the design philosophy and approaches required to meet the required specification and to assure that the specifications contain realistic requirements.

The next review or developmental design review is made to verify the adequacy of final designs based on the approved conceptual design and any changes made up to this time, to establish the requirements for future purchasing, to establish initial reliability efforts such as assessments and predictions, and to identify problem areas. This review will be held early in the development phase of the program.

Before the final review, an interface review should be held. This review is held at a subsystem level in which the operational characteristics for each subsystem are checked for proper interfaces between each subsystem within the system.

The last review, the final design review, is a release of the review for preproduction. This review will verify the function and a configuration with the requirements of the system, provide final parts, materials, and process approvals, provide a final reliability review, and equipment specifications and reliability test procedure review. All detailed drawings will be released at this time to provide manufacturing with suitable information to build the system.

Some of the key tasks that should be performed during the design review stages can be stated as: a) circuit analysis, b) reliability stress analysis, and c) failure mode and effect analysis.

Circuit analysis. The operating life of the circuit is decreased due to drifting of part values in many cases, thus causing unacceptable degradation in the performance of the circuit. There are several techniques that should be used to determine the acceptable usable tolerances. The computer technique is one of these. The following procedure is generally used: Equivalent circuits are drawn of the system, unit, or module; circuit equations are written in terms of parts parameters (includes rating of parts, end-of-life tolerances, and circuit failure criteria); a computer program is written based on the circuit equations, requirements, and expected part parameter drift; the computer program is run and the output reviewed and analyzed. The computer aided design program is being used at an increasing rate throughout the industry and has proven very useful as well as time saving. Another method used is the analog tester method. Drift effects are checked by sequentially switching in every combination of high and low end point tolerance-limit values and evaluating the effects on the circuit performance. This method has the advantage of not needing a complete mathematical equation of the circuit to perform the analysis of tolerance limits.

Reliability stress analysis. Reliability stress analysis is performed to assure the proper application of component parts and to determine the actual stresses to which each component part is subjected. Stress analysis is therefore an essential element in the Reliability Program for newly designed electronic equipment.

The reliability of component parts is directly related to the stress that is imposed in the application. In most instances this relationship is inversely proportional, the higher the stress the lower the reliability. This shows that the design safety factor (ratio of maximum allowable stress to actual part stress) is a prime consideration. The safety factor must be determined by tradeoffs between volume, cost and reliability. In order to predict the reliability of newly designed equipment it is essential that applied stresses be known. In most design and development activities, breadboard models are built to verify electrical performance characteristics. To demonstrate a reliability performance value requires prohibitively long periods of time. It therefore becomes necessary that reliability efforts are utilized in the design phase to provide assurances that the reliability design goals are being met.

Applied part stresses are computed by means of a circuit analysis. Such an analysis is performed by examination on a functional circuit. The circuit is separated into several sub-functions to allow for ease of mathematical calculations. Care is exercised in the sub-divisions to account for all interacting impedances and/or generators. The sub-functional circuit is then analyzed to determine all voltages and/or currents that the individual parts are subjected to. This is accomplished by drawing an equivalent circuit of the actual circuit in terms of equivalent generators and impedances. The analysis is then put on a form which contains a description of each part, its maximum rated stress, applied temperature and electrical stresses, failure rate and failure effect upon the circuit. Three component part failure modes are assumed, open, short, and degraded. Each failure mode is classified as to the severity of its effect upon the circuit performance. The purpose of the failure effects analysis is to ascertain the degree of degradation resulting from the occurrence of one or more of the failure modes determined in the failure mode assumption.

Failure mode and effect analysis. A failure mode and effect analysis will identify the principal functions of the part, component or subsystem and the possible modes of failure. The areas in which failures are most likely to occur will be identified and their effect upon the functions of the system will be presented. The proposed measures to eliminate the effects of such failures will be delineated. Comprehensive study to ascertain the component's ability to withstand functional stresses or combinations of environmental stresses will be conducted. Reliability hazards resulting from such anticipated stresses such as thermal, electrical and vibration will be specifically assessed in terms of component integrity.

The failure mode and effect analysis will contain the following:

- Part name and number.
- Specific individual functions.
- Failure mode description - from analytical considerations and from test experiences.
- Probability of occurrence - high, low and insignificant.
- Failure effect - actual and potential on component function.
- Action to be taken to remedy or prevent the failure occurrence or effect.
- Revisions as required by significant changes and corrective action affecting design.

A detailed check list is a most useful tool to be used in design reviews. It should be prepared jointly by design and reliability personnel. A typical check list is given in Table 3.1 showing typical areas of investigation that are looked into during a design review.

TABLE 3.1 Reliability Design Review Check List

1. Are the requirements for performance, signals, environment, life, and reliability established for each component?
2. Are the specific design criteria for reliability and safety of each component specified?
3. Are maintenance requirements and maintainability goals established?
4. Have acceptance, qualification, sampling, and reliability assurance tests been established?
5. Are standardized high-reliability parts being used?
6. Are unreliable parts identified?
7. Has the required failure rate for each part or part class been established?
8. Are component parts selected to meet reliability requirements?
9. Have "below-state-of-the-art" parts or problems been identified?
10. Has shelf life of parts chosen for final design been determined?
11. Have limited-life parts been identified, and inspection and replacement requirements specified?
12. Have critical parts which require special procurement, testing, and handling been identified?
13. Are derating factors being used in the application of parts? (Indicate level.)
14. Are safety factors being used in the application of parts?
15. Are circuit safety margins ample?
16. Are standard and proven circuits utilized wherever possible?
17. Has the need for the selection of parts (matching) been eliminated?
18. Have circuit studies been made considering variability and degradation of electrical parameters of parts?
19. Have adjustments been minimized?

TABLE 3.1 (Continued)

20. Have all vital adjustments been classified as to factory, preoperational, or operator types?

21. Have stability requirements of all circuits or components associated with each adjustment been established?

22. Have specification limits for each adjustment - such as "no adjustment," "readjustment to nominal," or "classify as failure" - been established?

23. Is feedback being used wherever required to maintain constant gain of circuits?

24. Are regulated power supplies used for critical circuits?

25. Are similar plugs and connectors adequately protected against insertion in wrong sockets?

26. Are solid-state devices being used where practicable?

27. Are malfunction-indicating circuits or devices being used extensively?

28. Are self-monitoring or self-calibration devices installed in major systems where possible?

29. Are mechanical support structures adequate?

30. Are heat transfer devices or designs efficient?

31. Is there a concentrated effort to make the developmental model as near to the production model as possible?

32. Has equipment been designed for the elimination of shock mounts and vibration isolators where possible?

33. Are elapsed time indicators installed in major components?

34. Are fungus-inert materials and fungus-proofing techniques being used?

35. Has packaging and mechanical layout been designed to facilitate maintenance?

TABLE 3.1 (Continued)

36. Has the theoretical reliabiliry or MTBF of the component based on the actual application of the parts been determined?

    (a) Comparison made with reliability goal.
    (b) Provision for necessary design adjustments.

37. Are the best available methods for reducing the adverse effects of operational environments on critical parts being utilized?

38. Has provision been made for the use of electronic failure prediction techniques, including marginal testing?

39. Does the basic design provide for the system to meet serviceability goals established for field test operations?

40. Is there provision for improvements to eliminate any design inadequacies observed in engineering tests?

41. Have normal modes of failure and the magnitude of each mode for each component or critical part been identified?

42. In the application of failure rates of components to reliability equations, have the following effects been considered?

    (a) External effects on the system or branch in which the component is located.
    (b) Internal effects on the component.
    (c) Common effects, or direct effect of one component on another component, because of mechanical or electromechanical linkage.

43. Has redundancy been provided where needed to meet reliability goals?

In conclusion, the design review is a very important task of the complete reliability program and is one of the essentials in the communication satellite design e ffort. It is the responsibility of the reliability engineering department to work with and supply those tools necessary to bring objective evidence of their results into the design review. As a result, optimum decisions will be provided in designing, at lowest cost, the most reliable communication satellite system possible.

Reliability Apportionment, Assessment, and Analysis

The major factors in the design and development phase of the communication satellite are the reliability apportionment, assessment, and analysis. These are very useful analytical tools to provide a realistic basis upon which tradeoff studies can be evaluated.

In Table 2.8, the reliability objectives were presented for the Syncom II communication satellite. In a way one could say that this is the reliability apportionment or reliability budget for the system. In the apportionment numerical reliability objectives or goals have been apportioned to the various modules and subsystems throughout the satellite. This reliability model will be continually up-dated as changes are made resulting from design reviews or changes in scope on the overall program. This model will be used in the reliability assessments or estimates for each element of the system.

Typical failure rates in percent per 1000 hours are shown in Table 3.2. These failure rates give approximate estimates of potential reliability only. For high population parts these failure rates were obtained from Mil-Handbook-217, Reliability Stress and Failure Rate Data for Electronic Equipment. The test conditions were assumed to be at an environmental temperature of 55°C and a stress derating of 90 percent (stress level of 10 percent of rating). The failure rates for low population parts that were not available from Mil-Handbook-217 were taken from secondary sources in the industry.

The reliability of nonredundant systems is found by assuming all elements in a series and summing the individual parts failure rates. We are assuming here the exponential case of chance or random failures and there the expected number of failures is the same for equally long operating periods. In this case the reliability is mathematically defined by the exponential formula

$$R(t) = e^{-\lambda t}$$

In this formula e is the base of the natural logarithm (2.71828 - - -), λ (lamda) is a constant defined as the chance failure rate, and t is an arbitrary operating time for which the reliability R of the system is wanted. Both the failure rate and the operating time have to be expressed in the same time units - usually in hours.

It should also be pointed out this formula is correct for systems or devices which have been debugged which are not subject

COMPONENT	DERATING TO 0.10
Antenna	0.0200
Capacitors	
Ceramic	0.0010
Ceramic, variable	0.0010
Electrolytic	0.1400
Glass	0.0030
Mica	0.0010
Mica, button	0.0010
Mica, dipped	0.0010
Paper	0.0010
Tantalum	0.0100
Tantalum, foil	0.0150
Tantalum, slug	0.0010
Crystals	0.0200
Coaxial connectors	0.0200
Coaxial relay	0.0250
Coupler, direction	0.0100
Diodes	0.0100
Switching	0.0020
Varacter	0.0210
Zener	0.0150
Filters	0.0160
Ferrite phase shifter	0.0200
Junction box	0.0010
Inductors	0.0020
Mixers	0.0300
Resistors	
Composition	0.0020
Film	0.0290
Film, power	0.1080
Wire wound	0.0170
Wire wound, power	0.0006
RFC	0.0010
Transformers	0.0500
Transistors	0.0200
Traveling wave tube	5.0

TABLE 3.2 Typical Failure Rates - Failures/10^5 Hours

to early failures, and which have not yet suffered any wearout damage or performance degradation because of age. This is shown in Figure 3.4, Component Failure Rate as a Function of Age, and is known as the "bathtub curve."

The reciprocal of the failure rate is called the mean time between failures, or MTBF. It is usually written as a lower case letter m. Then by definition, in the exponential case, the mean time between failures, or MTBF is

$$m = \frac{1}{\lambda}$$

and the reliability function R(t) can be also written in the form

$$R(t) = e^{-t/m}$$

The derivation of the exponential formula for reliability is presented here because of its importance in the reliability discipline. Assume a fixed number of components are repeatedly tested. Let N_o = the total number of components tested, N_s = the total number of components surviving, N_f = the total number of components failed. Therefore $N_o = N_s + N_f$ is a constant during the whole test because as the test is being performed, the number of failed components increases exactly as the number of surviving components decreases. Reliability is defined as the probability of survival and is expressed as a fraction

$$R = N_s/N_o = N_s/(N_s + N_f) \qquad (3.1)$$

where N_s and N_f are counted at a specific time t.

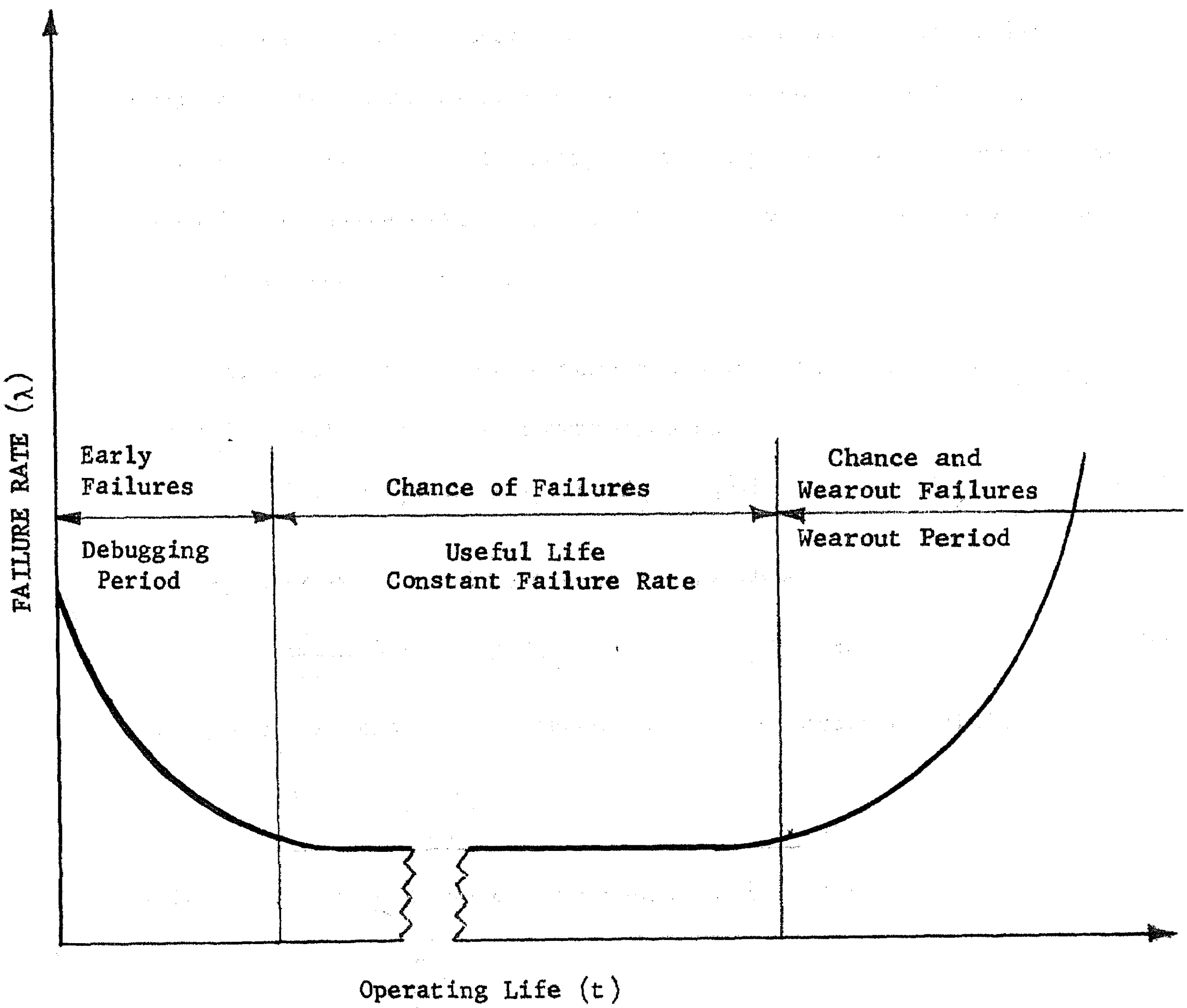


FIGURE 3.4 Component Failure Rate as a Function of Age

Unreliability, or probability of failure is defined as

$$Q = {}^{N}f/N_o = {}^{N}f/(N_s + N_f) \tag{3.2}$$

As can be seen at once R + Q = 1. These events are called complementary events because each of the components will either survive or fail. In probability terms they are also referred to as mutually exclusive events because if one component survives, it has not failed, and vice versa.

The number of surviving components in a test is $N_s = N_o - N_f$ and reliability can also be expressed as

$$R(t) = N_s/(N_s + N_f) = (N_o - N_f)/N_o = 1 - N_f/N_o \tag{3.3}$$

By differention of this equation we obtain

$$\frac{dR(t)}{dt} = d(1 - N_f/N_o)/dt = - 1/N_o \, {}^{dN}f/dt \tag{3.4}$$

because N_o is constant. Rearranging the differential yields

$$\frac{dN_f}{dt} = - N_o \frac{dR}{dt} \tag{3.5}$$

which is the rate at which components fail. Also

$$\frac{dN_f}{dt} = - \frac{dN_s}{dt}$$

which is the negative rate at which components survive.

At any time t there are still N_s components in test; therefore $\frac{dN_f}{dt}$ components will fail out of these N_s components.

Dividing both sides of equation (3.5) by N_s yields on the left the rate of failure or the instantaneous probability of failure per one component, which is called the failure rate λ:

$$\lambda = \frac{1}{N_s}\ \frac{dN_f}{dt} = -\frac{N_o}{N_s}\ \frac{dR}{dt} \tag{3.6}$$

But from equation (3.1) the following is obtained:

$\frac{1}{R} = \frac{N_o}{N_s}$. Substituting this on the right side of equation (3.6) yields

$$\lambda = -\frac{1}{R}\ \frac{dR}{dt} \tag{3.7}$$

which is the general expression for the failure rate that applies to any type of reliability function, either exponential or non-exponential. By rearrangement and integration of (3.7) the general equation for reliability is obtained

$$\lambda dt = -\frac{dR}{R}$$

$$\int_o^t \lambda dt = -\int_1^R \frac{dR}{R} = -\ln R$$

$$\ln R = -\int_o^t \lambda dt$$

Solving for R assuming that at time t=o, R=1

$$R(t) = e^{-\int_o^t \lambda dt} = \exp\left(-\int_o^t \lambda dt\right) \tag{3.8}$$

Now if λ is constant in equation (3.8), the exponent becomes

$$-\int_0^t \lambda dt = -\lambda t$$

and the well known exponential reliability equation for constant failure rate results,

$$R(t) = e^{-\lambda t}$$

This elaborate derivation of the exponential reliability formula was presented because the derivation can help to measure the failure rate of a component population. For a complete detailed discussion on this subject see reference, Igor Bazovsky, "Reliability Theory and Practice."

The satellite reliability model should be based on the following phases of the mission:

- Boost and Launch Phase
- Acquisition Phase
- Orbital Phase.

The boost and launch phase includes that phase in which the spacecraft equipment satisfactorily completes the liftoff and final booster turnoff. All necessary operations from booster turnoff until final satellite orbit positioning is the acquisition phase. The orbital phase includes all operations after successful satellite deployment. This phase is based on the mission time, usually 5 years or 43,800 hours.

When performing a reliability prediction, a degradation factor has to be used in conjunction with each part failure rate to take account of the actual environment seen by the satellite. Typical degradation factors for various environments have been measured over long periods of time and are shown here.

1.0	Laboratory
0.9	Military Ground Station
0.13	Shipborne
0.07	Trailer-mounted
0.04	Manned Aircraft

The value of 0.33 is the degradation factor for satellite environment in that part of space outside of the lower Van Allen radiation belt.

It should be a general rule that no component part in the communication satellite be operated at a higher level than 25 percent of rated use. This practice is essential for long-lived operation such as a five year life for the satellite. It is a known fact that the failure rates of components are a function of some power of the ratio of applied stress to rated stress. There are some general rules to follow for determining failure rates for various components. Let us review some here.

For semiconductors an application analysis should be performed to determine that none of the maximum ratings will be exceeded. A classification according to type of material (germanium or silicon) used should be made. Next determine the ambient temperature and power dissipation at operating conditions. Finally determine the component failure rates from families of curves as shown in Figures 3.5 and 3.6.

For resistors the procedure is similar. Classify component according to specific type. Determine the ambient temperature and power dissipation and wattage rating, including derating and voltage limitation. Find part failure rate based on temperature and percent of rating. Typical curves are shown in Figures 3.7 and 3.8.

The next components are capacitors. It is known that the expected life of capacitors varies as the fifth power of the ratio of rated to applied voltage. After the capacitor has been classified determine the peak voltage, including AC, ripple and pulse voltage. Determine the ambient temperature, then find the failure rate from curves as shown in Figures 3.9 through 3.12. Adjust the failure rate found by multiplying it by one for DC applied voltage, by two for sine wave AC voltage, or by three for narrow pulses.

The failure rates for transformers and coils are calculated based on the type of insulation used and the hot-spot temperature of the device. The hot-spot temperature is defined as the ambient temperature plus the temperature rise inside the device. The failure rates are given in Figure 3.13. Also used is a multiplying factor depending on the application as follows:

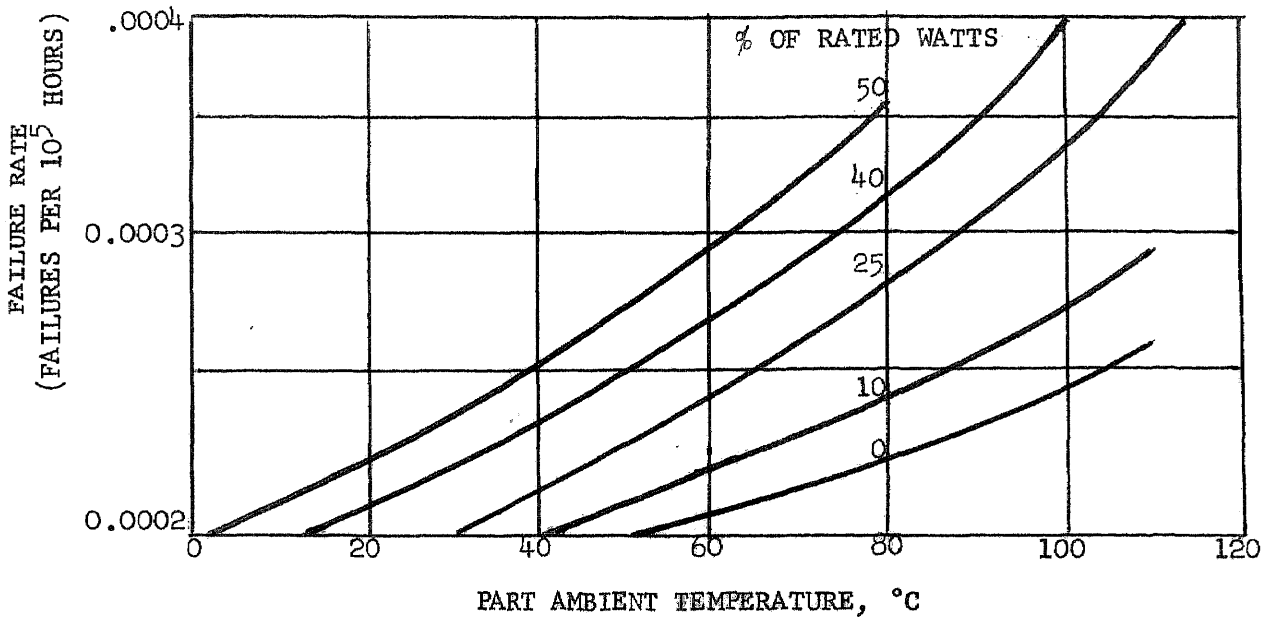
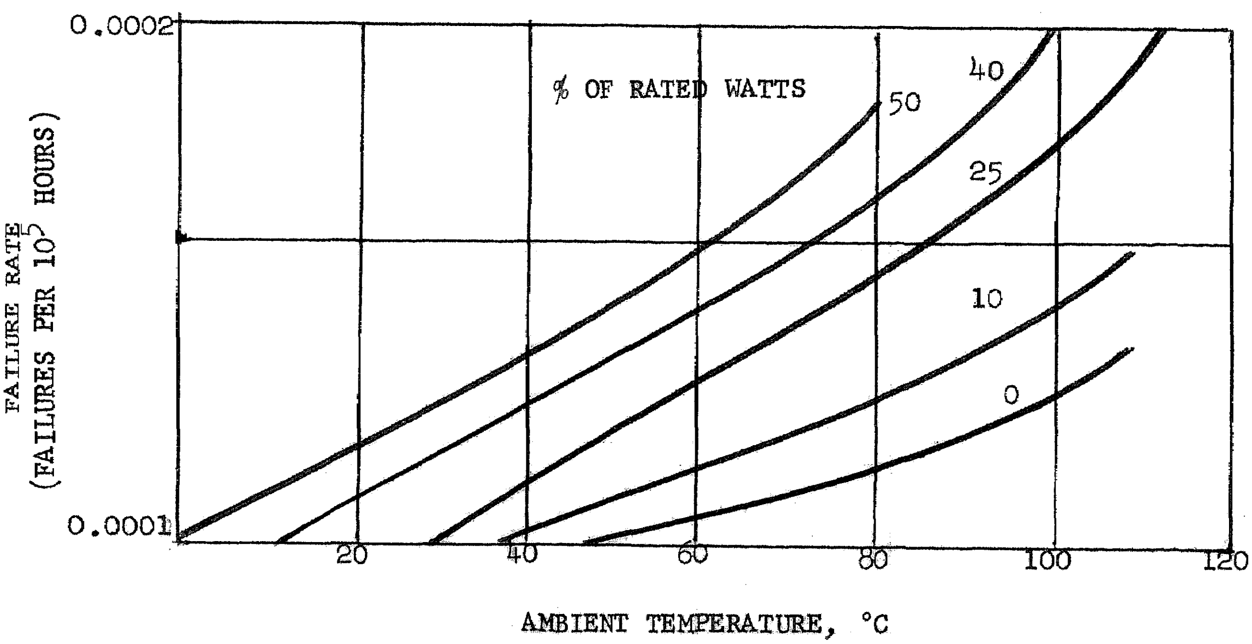


Figure 3.5 Failure Rates for Silicon Transistors



NOTE:
For Power Diodes (>1 watt) multiply by 2.0
For Computer Application Divide by 2.5
For Zener (Reference) Diodes Multiply by 7

FIGURE 3.6 Failure Rates for Silicon Diodes

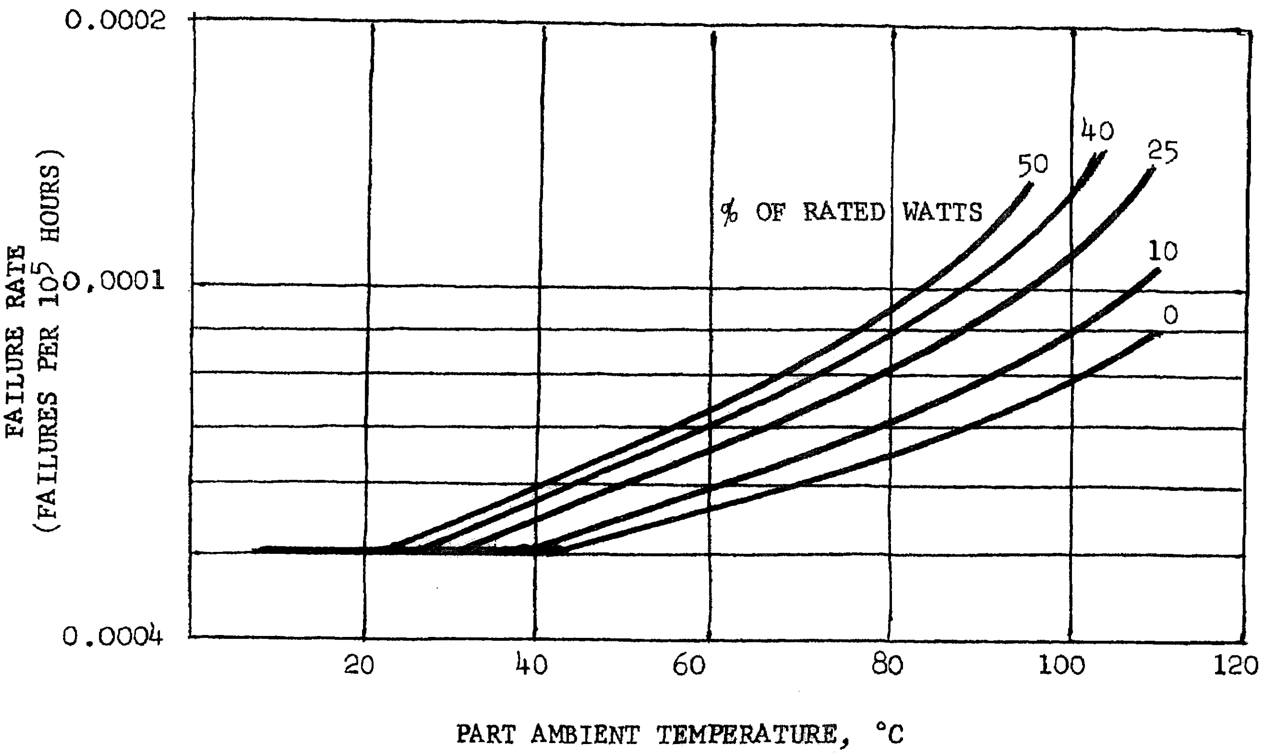


FIGURE 3.7 Failure Rates for Composition Resistors

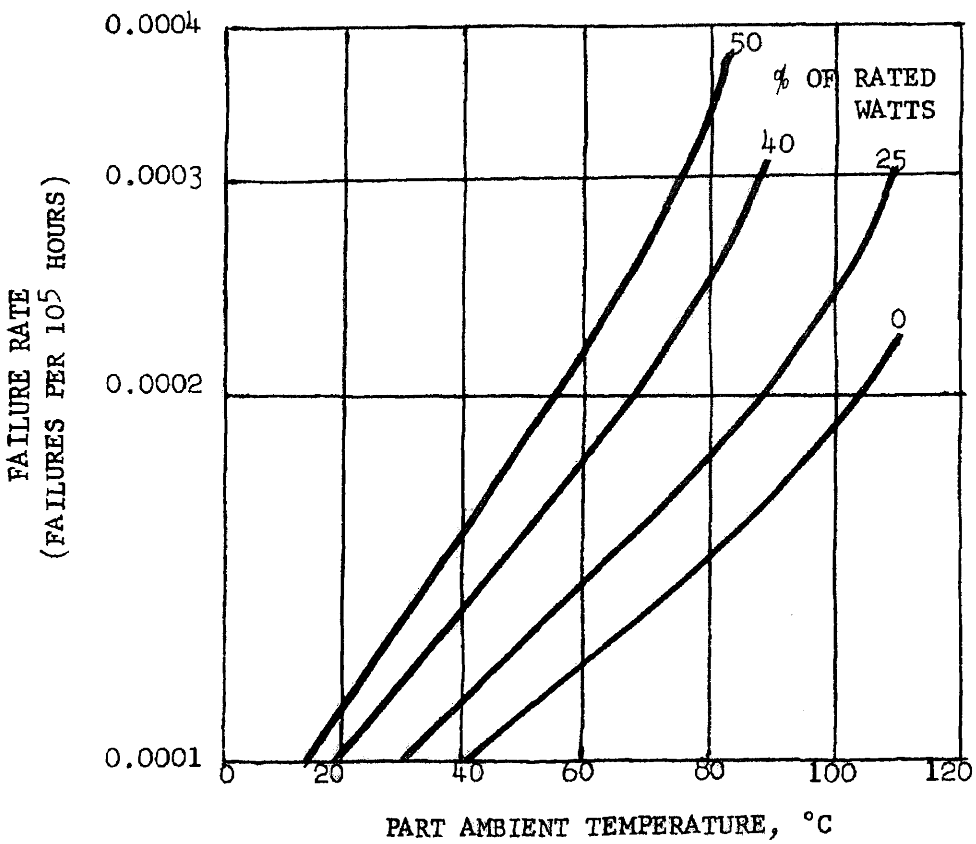


FIGURE 3.8 Failure Rates for Film Resistors

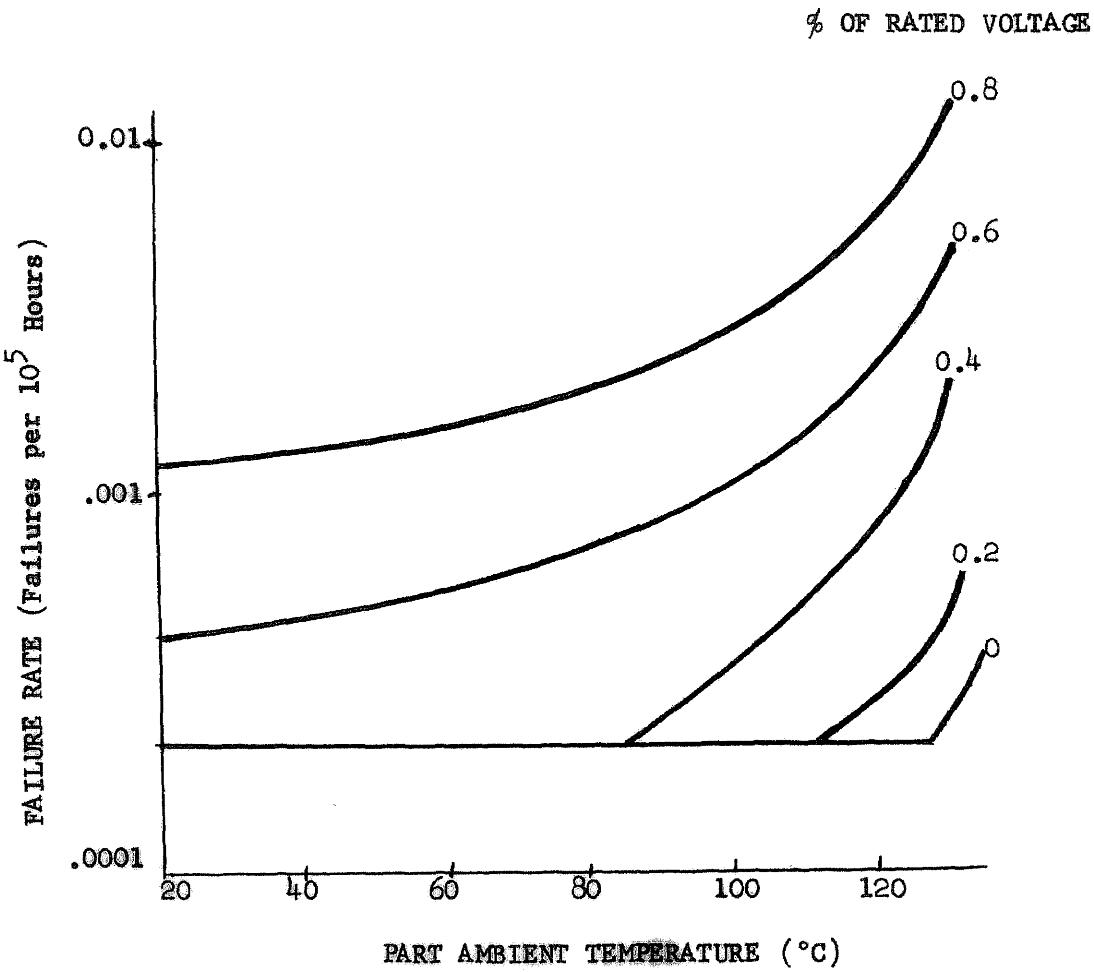


FIGURE 3.9 Failure Rates for Paper Capacitors

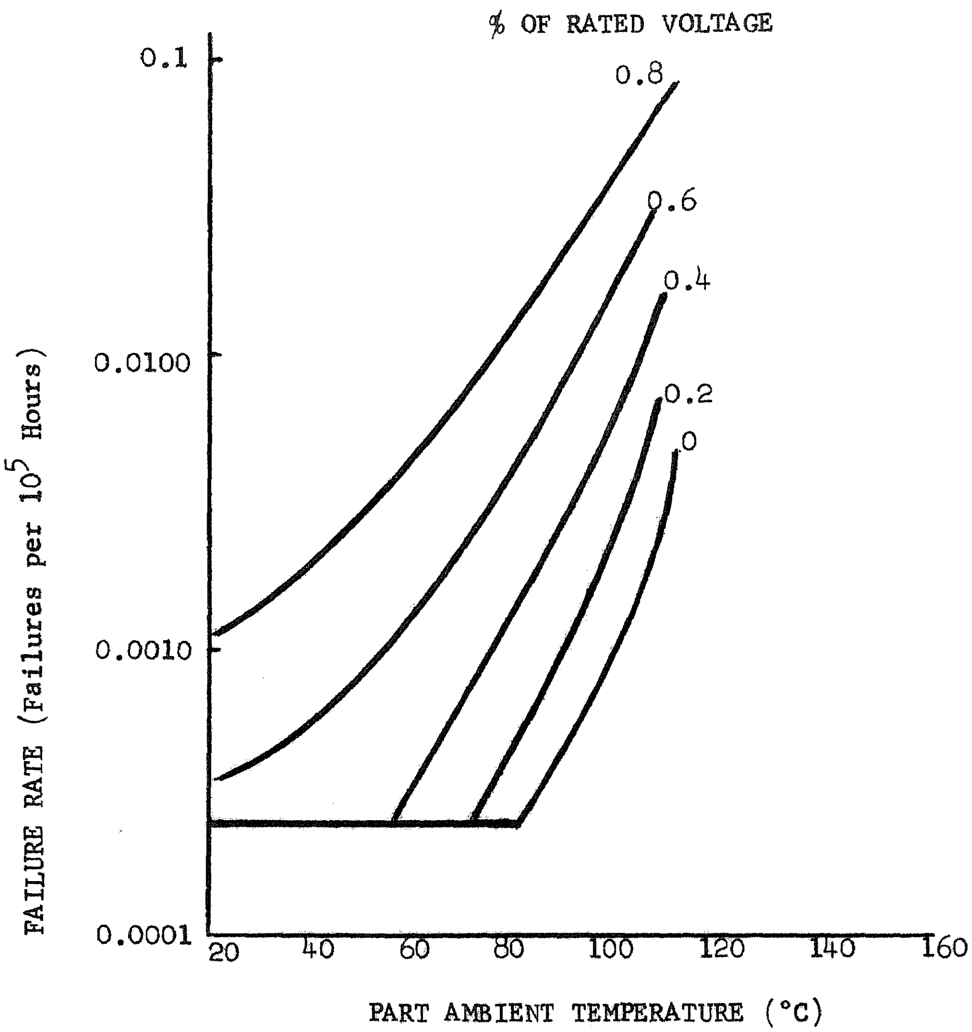


FIGURE 3.10 Failure Rates for Mica Capacitors

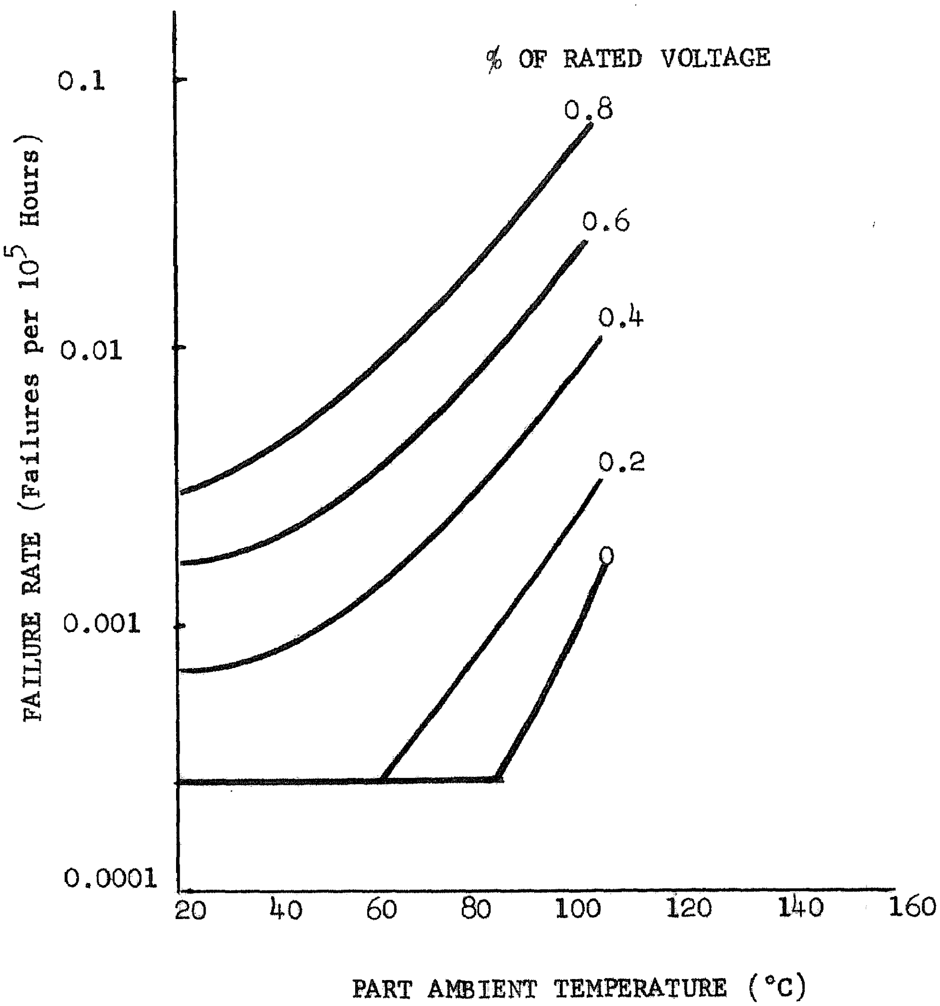


FIGURE 3.11 Failure Rates for Ceramic or Glass Capacitors

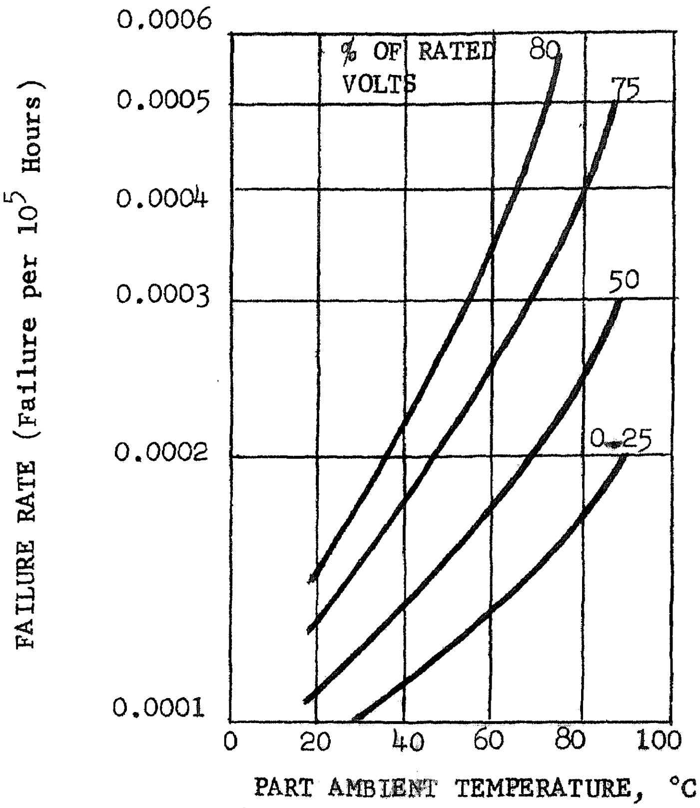


FIGURE 3.12 Failure Rates for Tantalum Capacitors

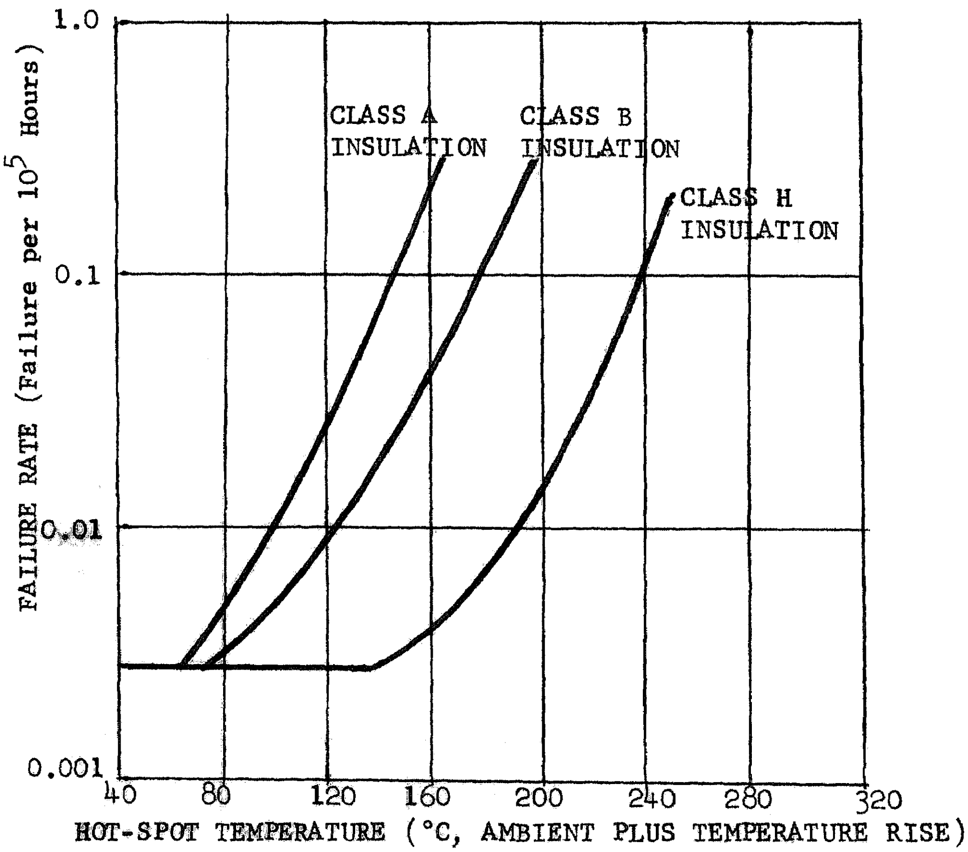


FIGURE 3.13 Failure Rates for Transformers and Coils

FAILURE RATE MULTIPLYING FACTOR	APPLICATION
1.0	Plate and power transformers, filter chokes, motor windings, filament and audio transformers.
0.3	Tuning inductances (low voltage devices).
1.5	Pulse transformers, IF transformers, tuning inductances (high voltage devices).

Rotary components' failure rates are obtained by using Figure 3.14. The stresses are similar to the transformers and coils. Rotary devices include motors, blowers, generators, dynamotors, synchros, and resolvers. There are two major areas of failure: mechanical and electrical. Mechanical failures are usually associated with bearings and brushes and are due to frictional effects. The windings are basically insulated wire wrapped around a magnetic core therefore analogous to a transformer and can be rated in the same way as far as electrical failures are concerned.

In determining the failure rate for relays the steps listed below should be followed.

- From Table 3.3 find the base failure rate based on relay classification, contact rating and coil power.
- Determine the life expectancy (operations causing 10 percent failures) of contact mechanisms.
- From Table 3.4 find the failure rate per contact set based on total actuations.

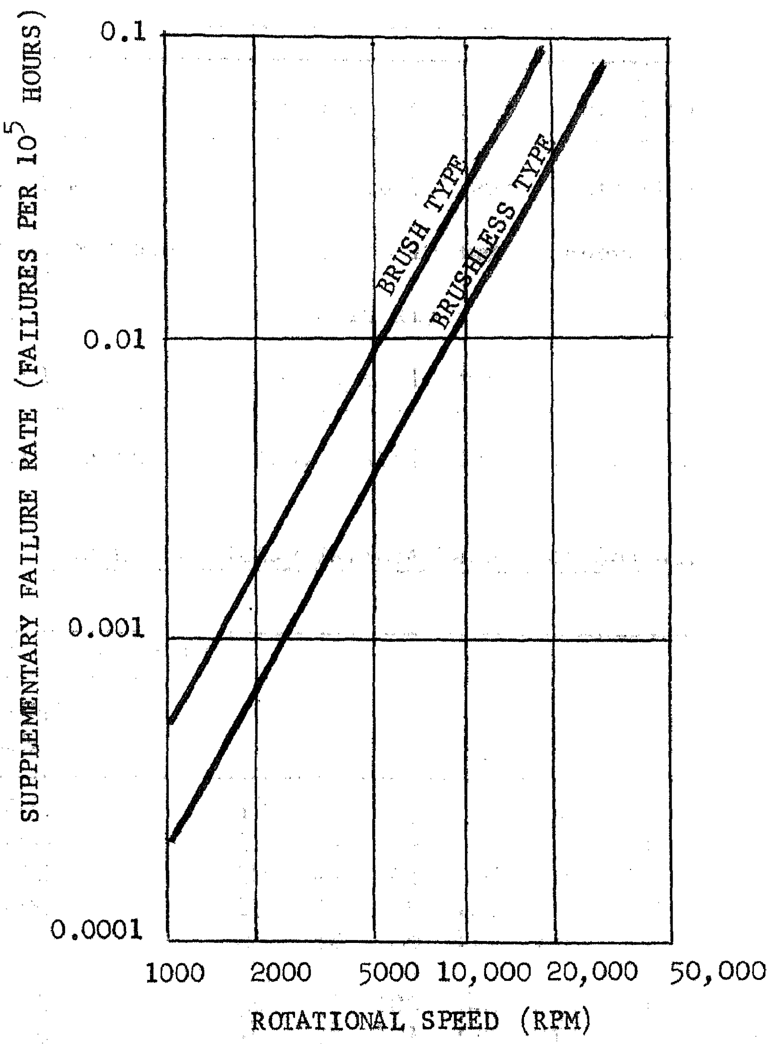


FIGURE 3.14 Failure Rates for Rotary Devices

- From circuit data calculate contact load in percent of rated current. From Table 3.5 select the proper load factor and multiply by failure rate found above.
- To obtain the final relay failure rate add contact supplementary failure rates to the base failure rates.

TABLE 3.3 Relay Base Failure Rate

Relay Class	Contact Rating	Coil Power	Base Failure Rate
Sensitive	100 μa to 1.5 amp	Less than 0.1 watt	400
General purpose	100 μa to 10 amp	Above 0.1 watt	250
Power	Above 10 amp	*	40
Thermal	100 μa to 10 amp	-	400

*In this class of relay, restrictions of coil power are not normal.

TABLE 3.4 Relay Failure Rates per Contact Set

Total Actuations for 90 Percent Survival Probability										
100,000	18	35	53	70	88	105	123	140	158	175
90,000	20	39	59	78	98	117	137	156	175	195
80,000	22	44	66	88	109	131	153	175	197	219
70,000	25	50	75	100	125	150	175	200	225	250
60,000	29	58	88	117	146	175	204	233	263	292
50,000	35	70	105	140	175	210	245	280	315	350
40,000	44	88	131	175	219	262	306	350	394	437
30,000	58	117	175	233	292	350	408	466	515	583
20,000	88	175	262	350	437	525	612	700	787	875
10,000	175	350	525	700	875	1050	1225	1400	1575	1750

NOTES: 1. For manual switches, the chart applies directly.

2. For relays, apply chart and add the following supplementary failure rates:

Sensitive and thermal delay relays	400
General purpose relays	250
Power relays	40

3. Class differences:

Sensitive: Less than 100 milliwatts coil power
General purpose: Contact rating of 10 amperes or less
Power: Contact rating greater than 10 amperes

TABLE 3.5 Load Factor for Contact Current Rating*

Percent of Rated Current	Multiply By	Percent of Rated Current	Multiply By
100	1.00	40	0.44
90	0.90	30	0.36
80	0.80	20	0.30
70	0.70	10	0.25
60	0.61	dry circuit	**
50	0.52	(Not used)	0

*Proper arc suppression required.

**"Dry" circuit conditions (current less than 50 microamperes) constitutes a special case. If gold or paladium contacts are used, multiply by 1.0. Other contact materials in dry circuits are not recommended for general use.

Failure rates for low population parts are given in Table 3.6.

Reliability analysis can be classified into several different categories. First, a reliability analysis can be made soon after the design concept has been established by considering a rough estimate of the system reliability. This estimate can be used as design goals

TABLE 3.6 Average Failure Rates for Low Population Parts

PART TYPE AND CLASSIFICATION	AVERAGE FAILURE RATE IN FAILURES/10^5 HOURS
Accelerometers	1.0
Batteries	0.01/cell
Cells, Solar	0.001
Crystals, quartz (MIL-C-3098B)	0.0076
Gyros	5
Heaters (crystal oven)	0.01
Joints, solder (per connection)	0.00005
Microwave elements (coaxial and waveguide)	
Elements, fixed	
Directional Couplers	Negligible
Fixed studs	(less than 0.001)
Cavities	
Elements, variable	
Tuned cavities	0.001
Tuned studs	0.001
Loads	Determine electrical
Attenuators	and temperature stresses
Fixed	and use Figure 3.5
Variable	
Thermistors	0.02

NOTE: These failure rates are applicable only if the parts are replaced before their respective wearout periods.

for future analysis. Next, a reliability analysis can be made as the design becomes more definite as a result of a more accurate parts count. The next category of reliability estimates is when the pre-production and prototype units have been started to be built. An evaluation of the reliability could then be made of this particular design showing any weak areas that could be improved. A reliability estimate could be made as a result of laboratory and/or field test data, thus giving an estimate based on the test program. The last category could be a reliability analysis by using actual test data of the unit in the environment for which it is intended.

An example will be given to demonstrate the methods used in obtaining a reliability prediction. The problem can be stated as follows: A communication satellite system is to operate for one full year in a synchronous orbit having a probability of success of 0.96. What is the optimum configuration if the basic elements in the system are as shown in Figure 3.15? The failure rates for each element are shown in Table 3.7.

First all requirements must be defined. They are as follows:

a) The physical environment - Van Allen radiation belt, ambient temperature, acceleration and vibration at launch.

b) Continuous operation of the communication satellite.

c) The satellite must operate without maintenance.

d) Burn-in of 200 hours of satellite before launch.

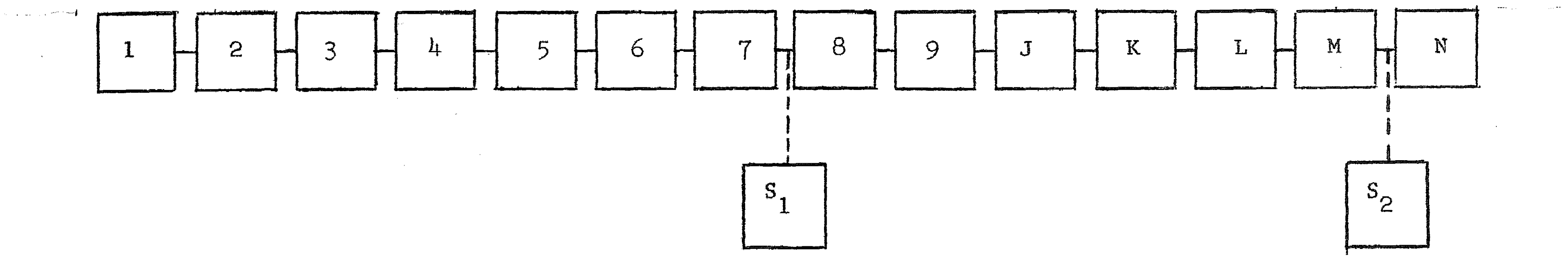


FIGURE 3.15 Basic Configuration of Communication Satellite

BLOCKS	FAILURE RATES (λ) FAILURES/10^5 HOURS
1	0.152
2	0.142
3	0.112
4	0.045
5	0.055
6	0.262
7	0.459
8	0.266
9	0.459
J	0.065
K	0.074
L	0.067
M	0.007
N	0.155
S_1	0.583
S_2	0.148

TABLE 3.7 Failure Rates for Communication Satellite System

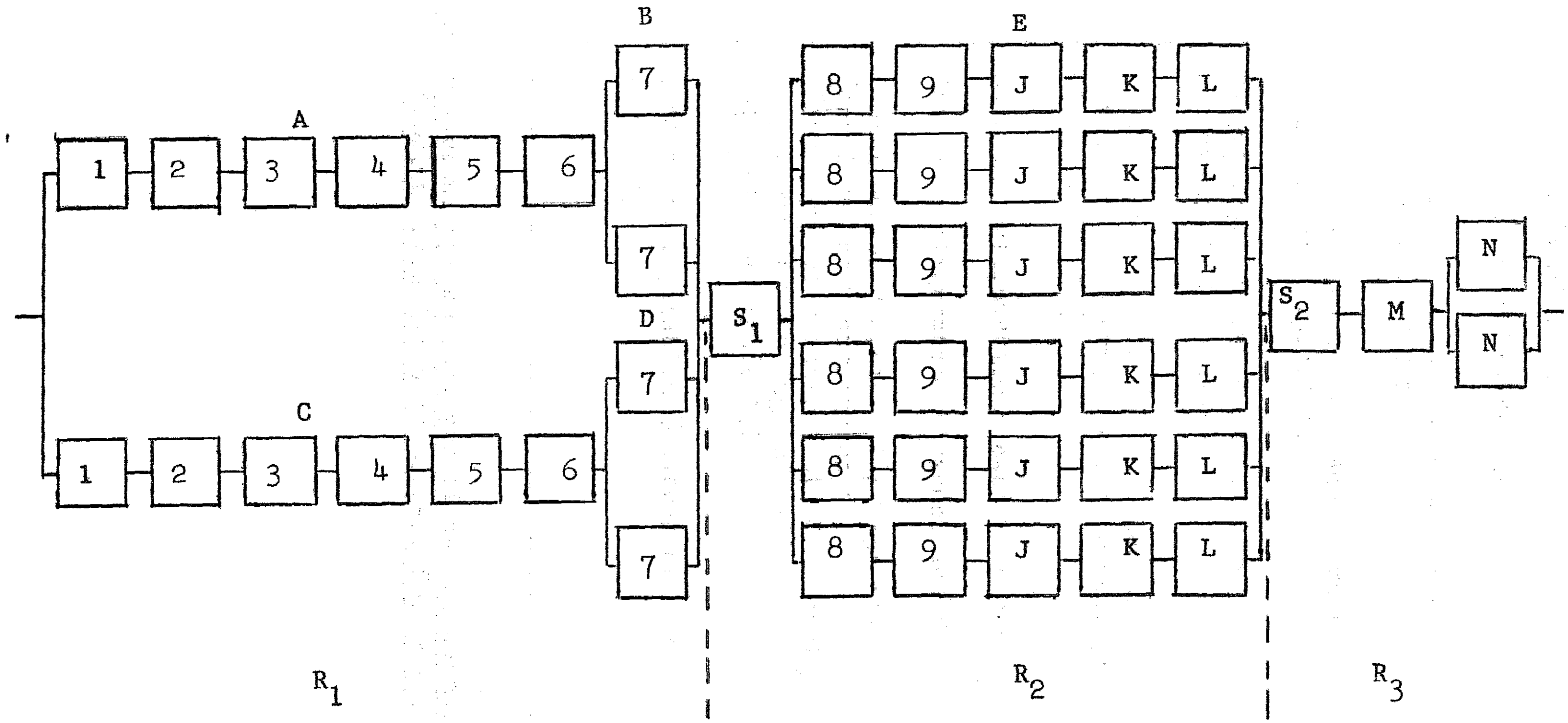


FIGURE 3.16 Redundant Configuration of Communication Satellite

CONFIGURATION	SYSTEM CONFIGURATION	PROBABILITY OF SUCCESS
1	(1·2·3·4·5·6·7·8·9·J·K·L·M·N)	0.637
2	[1.2.3.4.5.6.7.M.N] [any 5 out of 6 strings of (8·9·J·K·L)]	0.875
3	[1·2·3·4·5·6·7·M·N·6S_1] [any 5 out of 6 strings of (8·9·J·K·L)]	0.648
4	[1·2·3·4·5·6·7·M·N·6S_2] [any 5 out of 6 strings of (8·9·J·K·L)]	0.810
5	[1·2·3·4·5·6·M·N·6S_2] [any 1 out of 2 strings of (7)] [any 5 out of 6 strings of (8·9·J·K·L)]	0.842
6	Same as configuration 5 except delete S_2	0.897
7	Same as configuration 6 except add N	0.908
8	[Any 1 out of 2 strings {[1·2·3·4·5·6] [any 1 out of 2 strings of (7)] }[any 5 out of 6 strings of (8·9·J·K·L] [any 1 out of 2 strings of (N)] [S_1·S_2·M] see Figure 3.16	0.886
9	Same as configuration 8 except delete S_1 and S_2	0.973

TABLE 3.8 Different System Configurations for Satellite System Showing Probability of Success for One Year

e) Pressure, humidity, and temperature to be controlled.

f) Minimum power output to be used to provide longer life of the satellite.

g) The frequency is to be specified.

The next step is to develop a reliability model. This is shown in Figure 3.15 as a series string of elements. Then apply the reliability data to the model and find out if the design requirements have been met. Study various levels of redundancy so that the requirement could be met.

By looking at Table 3.7, block 7 has the highest probability of failure (highest failure rate). A way must be found to reduce this failure rate. One way is to add another block 7 in parallel redundancy as shown in Figure 3.16 along with other elements in redundancy. Table 3.8 shows the reliability calculations for 9 different configurations.

It appears that configuration 9 is the optimum design. The reliability calculations are shown below using the configuration as shown in Figure 3.16 deleting S_1 and S_2.

First calculate the reliability of branch A for six elements functionally in series. The reliability is

$$R_A = R_1 R_2 R_3 R_4 R_5 R_6$$

R_A = reliability of branch A

$R_1, R_2, \ldots, R_6$ = reliability of each element.

Since for a constant failure rate $R = e^{-\lambda t}$ where λ is the failure rate and t is the mission time the equation for R_A becomes:

$$R_A = e^{-(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6)t}$$

Since branch A is in series with branch B which consists of two like elements "7" in parallel redundancy we must first calculate the reliability of this redundant configuration. The reliability of branch B is

$$R_B = 1 - (1 - e^{-\lambda_7 t})^2$$

The reliability of branches A and B is therefore

$$R_{AB} = [e^{-(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6)t}]\ [1 - (1-e^{-\lambda_7 t})^2\ ]$$

Branches C and D are identical to branches A and B respectively and are in parallel redundancy. Either A and B or C and D must operate. Therefore, the reliability of branches A and B or C and D is

$$R_1 = 1 - (1 - R_{AB})^2$$

$$= 1 - \{1 - [2e^{-(\lambda_1 + \cdots + \lambda_7)t} - e^{-(\lambda_1 + \cdots + \lambda_6 + 2\lambda_7)}\ ]\}^2$$

$$= 4e^{-(\lambda_1 + \cdots + \lambda_7)t} - 2e^{-(\lambda_1 + \cdots + \lambda_6 + 2\lambda_7)t}$$

$$+4e^{-(\lambda_1 + \cdots + \lambda_7 + \lambda_1 + \cdots + \lambda_6 + 2\lambda_7)t}$$

$$- 4e^{-2(\lambda_1 + \cdots + \lambda_7)t} - e^{-2(\lambda_1 + \cdots + \lambda_6 + 2\lambda_7)t}$$

Substituting the failure rates found in Table 3.7

$R_1 = 0.99562$

Next calculate the probability of success for branch E or R_2. For one string of this branch

$$R_{8...L} = e^{-(\lambda_8 + \lambda_9 + \lambda_J + \lambda_K + \lambda_L)t}$$

Now any 5 out of 6 strings must operate, therefore

$$R_2 = R^6_{8...L} + 6R^5_{8...L}\, Q_{8...L} \text{ where } Q_{8...L} = 1 - R_{8...L}$$

$$R_2 = e^{-6(\lambda_8 + \cdots + \lambda_K + \lambda_L)t} + 6e^{-5(\lambda_8 + \cdots + \lambda_K + \lambda_L)t}\left[1 - e^{-(\lambda_8 + \cdots + \lambda_L)t}\right]$$

Again substituting the failure rates found in Table 3.7

$R_2 = 0.97774$

Now calculate the probability of success for elements M and N, R_3. For element M,

$$R_M = e^{-\lambda_M t}$$

For element N one out of two must operate. The combined probability of failure Q_N is equal to

$$Q_N = (1 - e^{-\lambda_N t})^2$$

$$R_N = 1 - Q_N = 1 - (1 - e^{-\lambda_N t})^2$$

$$R_3 = R_M R_N = e^{-\lambda_M t}\left[1 - (1 - e^{-\lambda_N t})^2\right]$$

Substitute the failure rates found in Table 3.7

$R_3 = 0.99922$

Now the reliability of the complete system is simply

$R_S = R_1 R_2 R_3$

$= 0.973$

Presented in this section was a way to perform reliability predictions and estimates. Actually there are several techniques that could be used. They will just be mentioned here for reference.

- Predictions based on typical equipment classification.
- Predictions using active element groups (AEG) count.
- Predictions by part count and nominal failure rate assignment.
- Predictions by part count and assignment of failure rates as a function of stress levels.
- Prediction methods based on MIL-R-26474, MIL-HDBK-217A, NAV SHIPS 93820, RADC Reliability Notebook, and MIL-STD-756.
- Steady-state methods using algebra and matrix multiplication.
- Transient methods using Markov chain method and Markov processes.
- Monte Carlo Techniques of simulation.
- Predictions by digital computer using the block diagram and the probability of success for each block as the input (also known as computer aided analysis).

- Predictions based on figure-of-merit (FOM) or amount of experimental information received from the satellite while in orbit.
- Predictions through determination and the adaptation of complexity factor ratings.

These techniques while not precise are effective in reducing failures and increasing system reliability and are therefore an essential part in a reliability program such as this.

CHAPTER 4

SOLUTION TO THE PROBLEM

This chapter will delineate the following reliability tasks as a continuation to the solution of the problem as stated in Chapter 3:

- Parts, Material and Process Control.
- Supplier Reliability Control.
- Failure Reporting and Analysis, and Corrective Action.
- Reliability Indoctrination and Training.
- Reliability Testing Program.
- Reliability Program Review.

Parts, Material, and Process Control

This task is essentially dealing with the reliability of parts, materials, and processes in the communication satellite system. Part failure modes and effects, mechanisms, and causes should be delineated in detail along with those factors in material and processing that are needed to assure a high degree of system reliability. It is the responsibility of the reliability department to have overall cognizance of this task. The department should supply necessary services to aid in the selection of component parts, establishing a preferred parts list, aid in the preparation of procurement specifications, analysis of component part reliability data, take part in vendor evaluation, and aid in reviews of a design and value analysis nature.

The preferred parts list should identify all parts by a detailed procurement specification. This specification should include provisions for reliability, quality control, and packaging. Component parts needed for a system such as a communication satellite are obtained by achievement of the following principles:

- Design the component part for the specific environment. This includes choosing parts whose wear-out point is well beyond the required useful life. Limitations on the life of the component are effected by the space environment. The environment is divided into the following five major effects: magnetic fields, gravitational fields, vacuum, micrometeorites, and radiation.
- Control of the manufacturing process. This includes control on three phases of product life: a) prevent marginal product from extending the period of early failures into the useful life region (see Figure 3.4); b) assure lowest failure rate during the useful life period; and, c) assure wear-out failures do not occur in the region of useful life.
- Eliminate potential early failures by initiating screening tests. This will include all forms of environmental testing and operating tests under the expected conditions of the system. Table 4.1 shows some typical screening conditions.
- Selection of most stable component parts as a result of the extensive and intensive testing program.

The choice of component types should be selected on the following basis:

MECHANICAL
Acceleration
Temperature/Humidity Cycle
Vibration (sinusoidal and random)
Shock
Radiographic inspection (x-ray)
Temperature cycle
RELIABILITY
Accelerated Tests
High Temperature processing

TABLE 4.1 Typical Screening Conditions

- Do not use new or untried types. This also applies to materials used in the manufacturing of the components. Use only those parts that have a sufficient background of proven part performance.
- Adjustable components should be avoided due to severe vibration, mechanical shock, and acceleration seen during launch.
- Avoid use of hermetically sealed parts filled with oils or electrolytes. These materials gas and build up very destructive pressures under the severe radiation environment seen in space. Materials for housing and structural use as well as coatings should also be chosen carefully for resistance to deterioration under electron and proton radiation.

. Such components as resistors, capacitors, and power transformers, on which low pressure might have an effect were chosen so that they would operate under extremely low pressure (vacuum of space) without high temperature rise or other detrimental effects encountered in space.

Table 4.2 shows the types of passive components used and their typical uses for a communication satellite.

USE	TYPE
	CAPACITORS
General purpose, temperature compensation	Ceramic
Precision in low values	Glass
Precision in high values	Mylar
High values, small size	Tantalum solid
Precise tuning	Glass and quartz tubular trimmers
	RESISTORS
General purpose, low precision	Carbon composition
General purpose, moderate precision	Pyrolytic carbon film
High precision, high frequency	Metal film
High precision	Wire wound
Power dissipation	Vitreous enameled wire wound
	INDUCTORS
High frequency, general purpose	(Nonmagnetic core, fixed) (Nonmagnetic slug, adjustable)
Power frequency	Permalloy dust core toroid
Memory coils	Ferrite core

	TRANSFORMERS
Narrow-band high frequency (tuned)	(Nonmagnetic core, adjustable inductance) (Magnetic core toroid)
Broadband high frequency	(Closed ferrite core) (Ferrite cup core) (Laminated magnetic core)
Power frequency	(Magnetic tape core toroid) (Permalloy dust core toroid)

TABLE 4.2 Types and Typical Uses of Communication Satellite Passive Components

One of the principles for selection of components was stated as to design the component for the specific environment because of the limitations of useful life imposed on the components due to the space environment. Delineated below are definitions of the major space environmental effects.

Magnetic fields - The earth's magnetic field at the magnetic equator has a maximum horizontal flux component of 0.3 gauss. It is presumed that this field varies inversely as the cube of the distance from the center of the earth. As the distance increases, the earth's magnetic field becomes irregular, probably due to reaction with the magnetic component of the solar wind and plasma clouds. The magnetic flux densities of the order of magnitude found in the space environment will not have any noticeable affect on the mechanical properties of materials. However, sensitive meter movements and other devices which operate with low magnetic flux densities are affected.

Gravitational fields - The acceleration of gravity, g, may be calculated at any altitude, h, above the earth's surface by the equation

$$g = g_o \left(\frac{r_o}{r_o + h}\right)^2$$

where r_o is the radius of the earth, and g_o is the acceleration of gravity at a distance r_o from the center of the earth. The absence or reduction of the force produced by the earth's gravitational field, while having no affect upon electronic components or equipment, may have an appreciable affect on the operation of certain mechanical or electromechanical systems. For manned space flights, the physiological effects would require the greatest amount of consideration.

Vacuum - The gas pressure in space is extremely low and measuring it is not feasible at the present time. Generally, the pressure at various altitudes is determined by calculations based on the ideal gas law and values of pressure at low altitudes where direct measurement is possible. Latest models of the atmosphere indicate approximate pressures of 10^{-5} mm mercury at 100 miles altitude and 6×10^{-11} mm mercury at 1000 miles. It is estimated that the pressure outside the solar system may be as low as 10^{-16} mm mercury.

Low atmospheric pressure sublimates solids and evaporates liquids. Sublimation of metals may result in the condensation of these metals on electrical contacts and terminals causing arcing and short circuits. Plasticizers with high vapor pressures (used in many plastic materials) may lose a great deal of mass due to evaporation, with resulting changes in structural properties. Moving metal parts operating in direct contact will lose their oxide coating, and in the vacuum of space these coatings will not re-form. Uncontaminated metal surfaces in direct contact may gall and seize.

Micrometeorites - Micrometeorites are small particles of matter existing in outer space. They are considered to be debris from other bodies in the solar system. These particles are considerably larger than molecular size, and, generally are approximately a few microns in diameter. Most of these particles are thought to be of cometary origin, although some are believed to be fragments of asteroids. The velocity of the particles relative to the earth varies from about 11 to 72 kilometers per second; however, accurate data concerning the density and mass of the particles and the number of particles impinging per unit area per unit time of a given mass are not available. The impingment of micrometeorites upon any solid surface will result in sputtering, erosion, and a general roughening of the surface. This change of surface characteristic will have its greatest affect on the thermal and optical properties of materials.

Radiation - Radiation is defined as the combined processes of emission, transmission, and absorbtion of radiant energy. Radiant energy is composed of particle radiation and electromagnetic radiation and consists of the following:

Particle radiation

Electrons

Protons

Neutrons

Alpha particles

Electromagnetic radiation

X rays

Gamma rays (photons)

The penetrating radiation environment of space may be due to a variety of sources, the most important of which follow:

Cosmic radiation

Trapped radiation

Auroral radiation

Solar flare radiation

The effects of the space environment on electronic components that would be used in communication satellites are listed below.

Semiconductor devices - The relatively low radiation tolerance of semiconductor devices sets them apart from other electronic components. With few exceptions, most transistors fail completely when subjected to an integrated dose of approximately 10^{13} neutrons/cm^2 and 10^7 roentgens gamma radiation. Significant differences have been conclusively observed between the behavior of germanium and silicon transistors in radiation fields, with germanium showing slightly more radiation resistance than silicon. Semiconductor diodes exhibit a greater neutron tolerance than do transistors; however, the gamma tolerance is about the same. Infrared detectors (PbS cells) have been tested at 10^{12} neutrons/cm^2 and 10^6 roentgens gamma radiation and were found to operate satisfactorily after irradiation. However, like most other semiconductor devices, permanent damage was clearly evident when these dose rates were increased by a factor of ten. Thermistors, which are also semiconductor devices, have been reported to survive an integrated dose of 10^{13} neutrons/cm^2 and 10^6 roentgens gamma radiation. The useful life of a semiconductor device in a radiation field will depend on the circuit application or function required. Failure because of radiation does not usually appear as a sudden or abrupt change but rather a gradual change in characteristics. The following characteristics have been noted in the irradiation of semiconductor devices.

Transistors - Gamma radiation may cause permanent as well as temporary degradation if the total exposure becomes high enough. Current gain is decreased. Germanium devices are less sensitive to damage than silicon devices. Diffused-junction structures are less sensitive than alloyed-junction types.

Diodes - Not affected to the same extent as transistors. Thin based-width devices are less sensitive than thick based width devices. Forward voltage at constant current increases and reverse resistance decreases. Diffused-junction structures are less sensitive than alloyed-junction structures. Germanium devices are less sensitive than silicon devices.

Controlled Rectifiers - Data available indicates that these units can be used in a radiation environment of integrated fast-neutron flux on the order of 10^{14} neutron/cm^{2}.

Failures experienced are not catastrophic in nature but result from the increase in gate current required to fire until the gate-cathode junction heating becomes excessive.

<u>Capacitors</u> - Capacitors that use inorganic materials, such as glass, mica, and ceramic have exhibited the greatest resistance to radiation. Organic dielectric capacitors, polystyrene, polyethylene, and mylar are less satisfactory than the inorganics by about a factor of ten; however, they do offer a better capacitance-to-volume ratio.

Paper - A 20 to 30 percent change in capacitance and minor changes in dissipation factor can be expected when exposed to a radiation of fast-neutron flux of 10^{15} n/cm^{-2} and gamma exposure of 3×10^{8} roentgens. The combined effect of pressure build-up by high temperatures and radiation and the evaporation of the solder material used in the seal due to high vacuum could accelerate a failure condition.

Ceramic - Available data for all types of ceramic capacitors indicates that no extensive degradation of electrical and physical characteristics can be expected from a fast-neutron flux of 2 x 10^{15} n/cm^{-2} and gamma exposure of 3 x 10^{8} roentgens. However, it is believed, that other environments such as ambient temperature and high vacuum may be more important for design considerations.

Glass and Porcelain - The threshold of radiation damage has been estimated to be 10^{15} n/cm^{-2} fast-neutron flux and a gamma exposure of 10^{9} roentgens. These types show more resistance to nuclear radiation than others; however, the effect of ambient temperature and high vacuum may be more important.

Plastic - When this type of capacitor is irradiated in a fast-neutron flux of 10^{15} n/cm^{-2} and a gamma exposure of 3 x 10^{8} roentgens a 10 to 14 percent change in capacitance and a 3 percent change in dissipation factor can be expected. Teflon is not recommended as a dielectric, regardless of whether it is immersed in silicone oil. The limited information that is available concerning life expectancy and reactions to ionizing radiation fluxes indicates that polystyrene dielectric units will not perform satisfactorily. Existing data indicates that a mylar capacitor would perform better.

Mica - When exposed to a fast-neutron flux of 10^{15} n/cm^{-2} and gamma energy of 3 x 10^{8} roentgens a capacity decrease of approximately

5 percent or less can be expected. However, the reliability of mica capacitors is approaching the level of ceramic and glass capacitors.

Tantalum - Solid electrolyte tantalum capacitors are not expected to be impaired to any great extent in a combined environment of 100°C ambient temperature, high vacuum, and radiation levels of 5×10^{13} n/cm^{-2} fast-neutron flux, and 7×10^{8} roentgens gamma energy. The wet-foil tantalum capacitor has the same characteristics as the wet-slug tantalum capacitor and appears to be ideal for use in a high ambient temperature. Further study is required to determine the effects of nuclear radiation and high vacuum. Teflon is definitely not recommended for sealing purposes.

Mylar - There is very little information available concerning effects of radiation, temperature, and high vacuum on the reliability of mylar capacitors; however, some advantages may be gained in place of paper capacitors. The effects of exposure to high vacuum would depend to a great extent on the quality of the glass seal.

Oil impregnated - A 30 percent increase in capacitance and an increase in the dissipation factor can be expected in a radiation environment of fast-neutron flux of 10^{15} n/cm^{-2} and gamma energy of 5×10^{8} roentgens.

<u>Connectors</u> (Miniature) - The construction materials of connectors will determine their susceptibility to the effects of a

combined environment of radiation, high vacuum, and temperature. Elastomeric inserts, nylon boots, epoxy potting compounds, and compression glass-seal receptacles are organic materials which react unfavorably. When used in a high-vacuum environment, consideration must be given to the terminal spacing and the effect of corona ignition and extinction voltages.

(Subminiature) - The same considerations as outlined above for miniature connectors apply; except that the effect of the reduced terminal spacing will present a greater design problem.

Relays (Miniature and Subminiature) - The materials of construction will determine the reliability of relays in a combined space environment. Hermetically sealed units would be unsuitable for use in a high vacuum in view of the difficulties experienced with epoxy sealants. Since contact clearances are relatively small, corona ignition and extinction should also be considered.

Inductors - The available information is incomplete to provide a reasonable estimate of the reliability of inductors in a combined space environment. However, the information that is available indicates that various inductors will remain reliable in a fast-neutron flux of 10^{14} n/cm^{-2} and gamma energy of 10^{10} roentgens.

Transformers - The threshold of radiation damage to transformers is high in comparison to the effects on other components and materials.

The high-temperature environment imposes rigid requirements that preclude many insulation materials used in conventional transformers. The problem of high-vacuum effect and material diffusion should be given consideration.

Resistors (Metal-Film) - In the construction of metal-film resistors, the film is deposited on the outer surface of a steatite tube and molded solid in a high-temperature plastic such as diallyl phthalate. As such, excellent reliability can be expected when exposed to an environment of high temperature and radiation. However, some units are constructed by depositing the film on the inner surface of a steatite tube and it appears that damage could be expected due to ionization of the trapped air.

Carbon-Film - Basically similar in construction to metal-film resistors but differs mainly in resistive element materials. Because of the carbon-film, degradation becomes more a function of temperature. Carbon-film resistors are generally more sensitive to exposure than metal-film resistors. The effects of high vacuum on carbon-film resistors have not been thoroughly explored; however, a study of the basic materials indicate a better performance could be expected from metal-film resistors.

Carbon Composition - This type of resistor is considered to be more susceptable to radiation damage than carbon-film. The threshold of radiation at which significant changes in resistance occur have been estimated at 10^{14} n/cm^{-2} fast-neutron flux and 10^{9} roentgens gamma energy. Some types of resistors are constructed with a pyrex glass which contains boron and is very susceptible to nuclear radiation. It would appear, however, that the construction of this type of resistor favors their use in a high-vacuum environment.

Wire-wound - Power wire-wound resistors that are protected by vitreous enamel and subjected to an integrated fast-neutron flux of 6×10^{13} n/cm^{-2} and gamma energy of 10^{8} roentgens have not been damaged. Units that are encased and/or coated with silicone resins are expected to operate satisfactorily at the same radiation levels although no information on the subject is presently available.

Wire-wound accurate - These resistors, if used for accuracy and stability rather than to dissipate power, can be expected to perform well under a combined environment of radiation, temperature, and high vacuum.

Thermistors - A limited amount of research has been conducted to determine the extent of radiation damage to thermistors during exposure to nuclear radiation. The results of some experiments have indicated that as far as voltage-current relations are concerned practically no measurable effects were noted after exposure to fast-neutron fluxes up to 10^{16} n/cm^{-2}.

Varistors - Information concerning the effect of radiation on varistors or voltage-sensitive elements is not available. However, since most of the varistors currently used are selenium or copper-oxide rectifiers, information of these elements can be substituted. In general, the semiconductor types of varistors can withstand nuclear radiation up to 10^{14} n/cm^{-2} without serious changes in their forward or reverse characteristics. Diodes fabricated from silicon carbide were found to be most radiation resistant, and it is hypothesized that these elements hold great promise for use in nuclear environments up to total integrated exposures of 10^{17} n/cm^{-2}.

Sensitive Microswitches - On the basis of available data it appears that the inorganic materials of which microswitches are constructed would not be seriously affected by nuclear radiation. However, the organic materials would be degraded in a vacuum where sublimation and evaporation would occur and the threshold of gamma radiation is estimated to be approximately 10^{10} roentgens. It is believed that a greater assurance of good performance in a combined environment will be achieved provided the organic materials used for insulation and plungers are fabricated from synthetic mica. Consideration should also be given to the corona ignition and extinction voltages when operated in a high vacuum.

Thermostats - An examination of the basic construction materials from the point of view of radiation tolerance does not indicate rapid deterioration. Little information is available on the effects of high vacuum; however, it is believed that if thermostats with silver contacts are required to interrupt a reactive load, the metal spray may reach prohibitive proportions. Palladium or platinum should be considered for such applications.

Coaxial Cables and Wire - Coaxial cables containing the polyethylene dielectric materials are believed to be satisfactory for the combined environment of 100°C temperature, high vacuum, and nuclear radiation. In a radiation environment above 10^{10} roentgens of gamma energy the polyvinyl chloride jacket will become hard and decrease in flexing capability. At high radiation levels and operation at high radio frequencies a slight increase in dielectric constant and a decrease in characteristic impedance can be expected. It is not considered advisable to use teflon dielectric cables because of their poor performance in a nuclear radiation and high-vacuum environment. It has been strongly recommended by most system application and design engineers that polyethylene-insulated hook-up wire be used wherever a combined environment is anticipated.

Electron Tubes - These components fail when exposed to high-intensity radiation fields due to damage to the glass envelope or glass-to-metal seals. Boron-free glasses show more resistance to radiation damage and can withstand integrated mixed fluxes as high as 10^{18} n/cm^{-2}; however, there are indications that an increase in fragility can be expected which might shorten the life of an electronic device. The envelopes of subminiature and miniature vacuum tubes exhibit more resistance to nuclear damage than other glass-type tubes. This is mainly due to the reduction in bulk of the glass envelope and the size of metal-to-glass seals.

The correct operation of gas tubes depends on maintenance of proper potentials and voltage drops across the tubes. The elements normally used in gas tubes react to nuclear bombardment in a manner similar to that encountered in vacuum-tube elements. The major cause of malfunction for gas tubes, excluding damage to glass-envelopes, is related to radiation effects on the gas. The gas is affected by gamma ionization and proton recoil ionization which often cause structural transmutation.

Gamma radiation of 10^{10} roentgens causes appreciable physical damage only to electron tubes that depend for their main function upon light transmission through the envelope. Discoloration of glass greatly affects the operation of light-sensing devices. Radiation-induced currents have been detected and these currents frequently exceed the photomultiplier's rated current. Tube sensitivities are greatly affected and can be attributed to glass discoloration.

The use of magnetrons in a nuclear environment is limited by radiation damage to the glass-to-metal seals used in their construction. In applications involving ultra-high frequency principles, the dielectric constant of the various insulating materials greatly influences the operational characteristics.

If nuclear damage results in complete failure as would be encountered when the glass envelope of a tube fails, there is no point in considering the changes that occur in electrical operating characteristics. However, electrical changes, such as decreases in plate current, reduction of emission current, increases in control grid current, and changes in transconductance are design considerations.

Coatings - The interest in coatings is a result of the need to develop more stable temperature-control coatings for satellites and space vehicles. Additives such as pigments, plasticizers, and other coating ingredients, as well as the type of surface on which the coating is applied, influences the radiation resistance of the coating. Table 4.3 gives radiation resistance of some coatings.

COATING	GAMMA RADIATION RESISTANCE
Phenolic	5×10^9 roentgens
Silicone-Alkyd	$1-5 \times 10^9$ roentgens
Alkyd Enamels	
40% Phthalic Anhydride (MIL-D-5557)	$1-5 \times 10^9$ roentgens
32% Phthalic Anhydride (MIL-E-7729)	$7-10 \times 10^8$ roentgens
Epoxy	$5-10 \times 10^8$ roentgens
Fluorinated Vinyl	$5-10 \times 10^8$ roentgens
Nitrocellulose Lacquers	$5-7 \times 10^8$ roentgens

TABLE 4.3 Limits of Radiation Resistance of Selected Organic Coatings

The reliable application of component parts, materials, and process control in space application such as a communication satellite system, shows a present capability of withstanding the effects of space environment. As more sophisticated space missions are encountered for extended useful missions, more stringent requirements will be placed on the reliability of components and materials used in the space environment.

Supplier Reliability Control

This program task includes controlling vendor and subcontractor activities to assure their capability of furnishing components having the required reliability requirements. Some of the specific tasks included under this phase of the program are:

- Supplier plant surveys
- Supplier rating systems
- Requiring suppliers to prepare written reliability program plans.

Reliability personnel have the responsibility for the surveillance of the supplier reliability performance in the design and manufacturing of the end item. This surveillance is continued by participation in all design reviews at the supplier's facility and reviewing all activities that will have an impact on reliability.

In order to perform an effective and timely supplier evaluation many factors come into play. Of prime consideration are the following:

- The supplier should have a well defined manufacturing setup, readily adaptable to fabrication of the high reliable product.
- The supplier should have adequate personnel who are technically knowledgeable in designing, manufacturing and testing the product in accordance with the high reliability standards and specifications necessary for end product reliability integration.
- The supplier should have adequate capacity for manufacturing and testing the product without the danger of slippage in delivery schedule.
- The supplier should be able to supply sufficient test data, particularly life test and field test results, verifying the product's capabilities or limitations, and therefore enabling the criteria for failure rates.

The supplier, in addition to the above considerations, must be willing to participate in a high reliability program financially. This will enhance his future programs in the space area as he becomes a qualified supplier for space environmental projects.

The supplier rating system is a very useful tool to aid purchasing in maintaining and upgrading the quality of the product delivered from the supplier. As an example of the rating system let's consider the following: A rating of 75 would occur when the sample fraction defectives are equal to the specified acceptable quality level (AQL), with a maximum of 1 in 25 lots rejected. A rating of 60 would occur when the sample fraction defectives equal 0.5 times the specified AQL's, with a maximum of 1 in 156 lots rejected. The AQL is defined as a nominal value expressed in terms of percent defective or defects per hundred units for a given group of defects of a product.

The supplier's reliability program plan that is required by the prime contractor should include those items necessary for manufacturing the item so as to meet all of the high reliability requirements. It should include but not be limited to the following tasks.

Design Reviews - held at supplier's facility with the responsible prime contractor personnel present.

Production Control - to assure that the reliability achieved in design is maintained during manufacture.

Reliability Test Program - tests should be designed to give confidence in the end item to meet expected environments.

Reliability Analysis - made on a periodic basis of reliability achievement of the technical progress evaluations.

Failure Reporting, Analysis, and Feedback - formalize a system for reporting, analyzing, and recommending corrective actions on all failures.

Reliability Monitoring - to insure adequate development of reliability by analyzing the reliability status relative to the requirements; by determining the corrective action needs; and by setting up a follow-up procedure on all corrective actions initiated.

Only through a tight supplier reliability control program will the assurance be given that the items received from that supplier are indeed those items needed for a successful completion of the proposed mission. For a mission such as communications by satellite for periods in excess of 3 to 5 years, this task cannot be overemphasized enough.

Failure Reporting, Analysis, and Corrective Action

This next phase of the program plan is an integral part of the reliability effort for spacecraft systems. Although successful operation of the complete system is the ultimate goal that is sought, it adds very little feedback and information on which design improvements can be made. If failures are encountered during manufacturing or qualification, acceptance, or reliability testing, these add much data necessary for an effort of improvement to the design. This feedback information of failure reporting, failure analysis, and corrective action is one of the essential ingredients of reliable product improvement.

The failure reporting phase of this task should provide a closed loop system that is well monitored. It should report all failures on a timely basis so that failure analysis can be performed quickly, defining the cause of failure. As a result of the analysis, corrective action is instituted to assure against this type of failure recurring on the system. Time is of the utmost importance in performing this task so as to implement necessary changes or rework on the system, thus increasing the probability of a more reliable system.

A well formulated failure reporting system should have failure history records. These records serve two main purposes. First, the chances of the same problems occurring in future systems are minimized. (Solutions already obtained from part system failures should be incorporated into design review checklists as outlined in Figure 3.1 under the task of Reliability Design Reviews). Second, an estimate of the reliability of the new system can be made realistically. For example, actual failure rates obtained under field or use conditions could be used in predicting or estimating the system reliability of similar units.

The failure reporting system should provide the following information as a minimum:

- Component description, type
- Serial number
- Date entered production
- Circuit reference number
- Operational test time
- Cumulative operational test time
- On-off cycles
- Cumulative on-off cycles
- Serial numbers of next higher assembly

- Part number and serial number of components
- Description of failure
- Corrective action initiated and due date

There are many types of failure reporting forms in use today. The features of some of these are described below:

- Development Form. This gives detailed reporting of the failure that is at system detection, unit rework, and part failure analysis levels. This form is basically useful for low volume, detailed analysis, and manual data processing.
- Flight Test Form. Similar to the development form for specialized subsystem field flight use. It is not as detailed in coverage as the development form but is suitable for low volume manual data processing.
- Production Reliability Test Form. Specifically set up for reliability test failure reporting. This form features numerous combinations of cause-of-failure codes. Also corrective action follow-up is provided for timely feedback.
- Field Failure Report Form. Designed for high volume military reporting where machine data processing is essential. One form is used per failure.
- Industry Electronic Field Failure Report. This form classifies type of failure at system, subsystem, unit, and part levels. The type of failure code is stated on each form. Also field and supplier repairs and replacements could be documented on each form generated.

To simplify failure reporting a coding system should be set up and utilized. One such system could use a coding category as follows:

- Parts classification code
- Manufacturer's code
- Part condition code
- Symptom code
- Mode of operation code
- Environment code
- Corrective action code
- Cause of failure code
- Responsibility code

A failure analysis system is an essential part of the task and requires the reporting of all failures occurring during system production. Of primary interest during failure analysis are the following:

- The failure cause should be identified for proper analysis and corrective action.
- Determine overstress on other components due to the primary failure and to find out the effects of the overstress.
- Initiate repair of failure and corrective action as necessary.

All failure analysis should take into account the following procedures:

- Appropriate system specifications and test data should be reviewed.

- Physical examination of the failed unit should be made before proceeding with failure analysis. Visual evidence will save time before analysis begins.
- A verification of the reported failure should be made as soon as practical.
- If necessary, extended tests should be made, such as radiographic and/or infra-red.
- The piece part should be dissected for further analysis if deemed necessary. Photographs or drawings should be prepared for clarification of the analysis.
- Mode of failure should be determined at this point in time and corrective action recommended.

The information requested for each failure analysis should include enough information for a complete description of the failure and corrective action. As a minimum the following is required:

- Failure analysis report number
- Failed part description
- Program name
- Date of failure
- Major system and serial number
- Major subsystem, serial number, and drawing number
- Major module and serial number, drawing number and manufacturer
- Failure verified/not verified
- Lot quantity

- Department reporting failure
- Classification of failure (critical, major, minor)
- Failed part environment (temperature, humidity, etc.)
- Description of failure
- Photographs and radiograph, file number, if any
- Name of personnel preparing form and date
- Name of personnel approving form and date
- Corrective action instituted and date
- Tests performed to confirm failure
- Failure analysis
- Corrective action and recommendations made.

A flow diagram of a failure reporting, analysis, and corrective action system is shown in Figure 4.1.

The depth of failure analysis could vary from somewhat trivial to a sophisticated and detailed one. During the period of a high reliability program such as the communication satellite system, many failures might occur which need to be analyzed, and corrective action implemented as required. Therefore, a well organized program is required to implement a failure reporting, analysis, and corrective action task on a timely basis.

Reliability Indoctrination and Training

The reliability of the communication satellite system will be enhanced if a comprehensive training and indoctrination program is

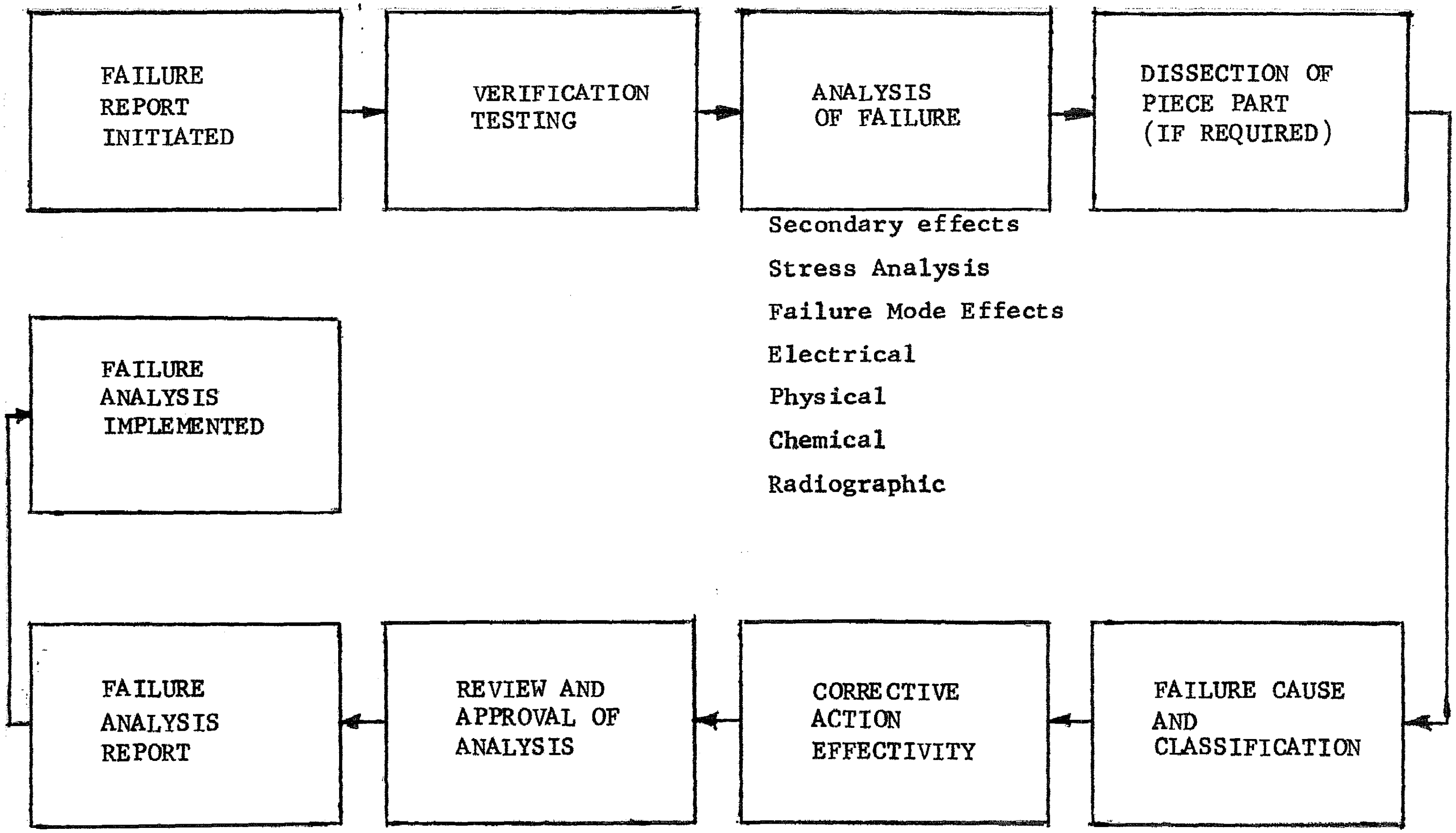


FIGURE 4.1 Summary of Flow Failure Reporting, Analysis & Corrective Action System

initiated early in the program. Each functional group such as design engineering, production, procurement, quality control, and test engineering will contribute greatly to the reliability of the satellite system if each group knows the nature of its contribution and is so motivated to carry it out. The indoctrination and training program could consist of lectures, motion pictures, periodic bulletins, posters and displays, and a reliability training manual. Regardless of what method is used and training program is a continuing education process.

The implementation of a reliability training program is based on many factors which are delineated below.

First, who should be told about the importance of reliability and its effects on long-life systems such as a communication satellite? Every branch of the organization responsible for an effort in the high reliability requirements of the system should be made aware of the principles and practices of reliability fundamentals. Remember, it will be easier for a group to accept something new and helpful only if the group has a full understanding of the basic problem and an insight to its solution. A proper training program will make each group aware of the need, the methods, and the effect on themselves and their jobs.

Secondly, why start a reliability training program? Basically, the reason is to develop an understanding of, and a desire to, achieve the fundamentals of reliability. There are many more reasons for starting a training program. They can be summarized as follows:

- To make groups aware of the meaning and important significance of reliability and methods for its control.
- To make known to management the problems others are faced with in attempting to achieve a high level of reliability.
- To emphasize the differences between short term and long term program goals, as far as the achievement of reliability is concerned.
- To aid design personnel in diagnosing system and design problems. This can be worked in conjunction with the reliability design review task previously discussed.
- To unify the entire organization into a team to achieve the goals set up in the reliability program.

Thirdly, the question of what should be taught in the training programs must be answered. This depends on what level in the organization the training program is given. For top management personnel, the program should show the accomplishment of improving the company profit, reducing manufacturing costs, saving time, keeping up with schedule objectives and goals, and improving the customer-seller relationship. Top management is not interested primarily in the technical aspects of the program, but rather in the economic and financial phases. Middle management training courses should help the group in performing better on the job, supply them with new techniques to aid their advancement, defining their responsibilities in the program for achieving the reliability objectives, help reduce costs and meet schedules better, and help in training their subordinates. The middle management personnel will understand the technical problems far better than top management personnel. Members of the technical staff such as design, industrial, production, and laboratory engineers should be trained emphasizing the following:

- The technical, scientific and mathematical techniques to solve problems as encountered in reliability.
- All the fine points and details with alternatives should be presented depending on the group taking the training.
- Need for simplification of technical ideas when communicating with higher management who are not well versed in the technical aspects of the program.

The training and indoctrination classes for the operating personnel, which includes manufacturing, assembly, inspection and test groups, should stress the following points:

- Those opportunities which will be available after working on a high reliability satellite program.
- Simplification of the job as a result of the training program.
- Contribution of the training program to the job security.

Sophisticated technical language should be avoided, if possible, when presenting a topic. Moreover, when it is feasible, calculations should be simplified utilizing well known mathematical procedures.

For a high reliability program such as the one for the communication satellite, training and indoctrination plans should be developed for the different levels of the organization involved. The following plans are presented as illustrative of what should be covered at the different organizational levels and the approximate time needed.

For top management, the course should run for 8 to 10 hours spread out over 4 or 5 weeks (this is equivalent to one day per week for 2 hours per class). The general plan should cover the following subjects:

- Need for the training program.
- Principles of reliability.
- Typical class problems and solutions.
- Program organization.

The middle management personnel course should run for approximately 12 to 16 hours spread out over 6 or 8 weeks (this is equivalent to 2 days per week for one hour per class). The general plan should cover the same subjects as for top management only in more detail, especially the principles of reliability and class problems.

The staff technical course should run for 20 to 40 hours spread over 10 or 20 weeks (this is equivalent to 2 days per week for one hour per class). The plan should include the following reliability disciplines:

- Need for the training program.
- Principles of reliability.
- Theory, methods, techniques, and class problems.
- Program organization.

For the operating personnel the training program should run for 8 hours spread over 4 weeks (this is equivalent to 1 day per week for 2 hours per class). The topics should include the need for a training program, general principles of reliability, and how the program will affect each one on the job.

The classroom meetings could be supplemented by other techniques such as visual aids, blackboard work, charts, recordings, trips, plant tours, and training film. Training films seem to be most effective. The following is a partial list of films having a bearing on reliability that should be shown to the personnel working on high reliability programs.

- "The Search for Reliability" - Standard Pressed Steel Co. - Primarily treats of fastener reliability and highlights the product rule. Standard Pressed Steel Co., Jenkintown, Pa.
- "The Art of Soldering" - Boeing Airplane Co. - Reliability improvement through correct soldering techniques for printed circuits. Boeing Airplane Co., Seattle, Washington.
- "10-9-8 Hold" - Boeing Airplane Co. - The abortion of a Bomark interceptor mission resulting from a single solder connection failure. - Boeing Airplane Co., Seattle, Washington.

- "Tremendous Trifles" (Confidential) - Lockheed Aircraft Corp. - The high cost of poor workmanship and quality control. - Space Technology Laboratories, Los Angeles, California.
- "The Closed Loop of Reliability" - Martin Co. - The need for failure reporting accuracy and an approach by the Martin Co., Denver. - Space Technology Laboratories, Los Angeles, California.
- "Talos, Deadly Where Reliable" (Confidential) - Bendix Aviation - The importance of superior workmanship standards as an approach to reliability. - Chief, Technical Publications, Bendix Products Division - Missiles, Bendix Aviation Corp., Mishawaka, Indiana.
- "Talos, Flight 440" (Confidential) - Bendix Aviation - A true case history of a flight failure. - Chief, Technical Publications, Bendix Products Division - Missiles, Bendix Aviation Corp., Mishawaka, Indiana.
- "Rascal Project MX-776" (Confidential) - Bell Aircraft Corp. - Flight tests, both successful and unsuccessful, of the Rascal weapon system - Bell Aircraft Corp., Manager, Photographic Dept., Buffalo 5, New York.
- "No Margin for Error" - Bell Aircraft Corp. - Designed for production workers, showing importance of each worker's contribution to overall system reliability. - Bell Aircraft Corp., Manager, Photographic Dept., Buffalo 5, New York.
- "No Second Chance" - The story of how one weapon system - an interceptor missile - has been made reliable. - Air Force Film Library Center, Air Photographic - Charter Service, St. Louis 25, Mo. - Film #DO-59-41SEP456.

- "A Life in Your Hands" - Hughes Aircraft Co. - The importance of the indivual component part in a failure that caused a mission abort. - Public Relations & Advertising, Hughes Aircraft Co., Culver City, California.
- "The Prime Dimension" - Hughes Aircraft Co. - How a modern weapon producing organization engineers and builds reliability into its product. - Public Relations & Advertising, Hughes Aircraft Co., Culver City, California.
- "A Synthesis of Standards" - Convair - The importance of standards and the strict adherence thereto as a means of obtaining high reliability. - Convair Division of General Dynamics, Pomona, California.
- "The Price of a Goof" - Redstone Arsenal - The failure of a missile flight is traced from a solder joint to the abort. - U. S. Army Ordnance District, Dallas Regional Office, Dallas 2, Texas.
- "The Priceless Component" - Hughes Aircraft Co. - The importance of the individual component parts to quality and reliability. - Public Relations Department., Hughes Aircraft Co., Culver City, California.

Reliability Testing Program

Reliability of the communication satellite system is an attribute that must be designed into it. As stated previously, reliability cannot be tested into the system, but rather testing could be used to evaluate the design. Testing could be considered a design tool to find and eliminate the weak areas in the satellite system and thereby upgrade its quality. Reliability testing is necessary for the following reasons:

- To verify that the design meets the performance requirements and has the required life expectancy.
- To verify that hardware used previously is suitable in the new application.
- Detecting and correcting failure modes as a result of the tests performed.
- Monitoring reliability trends and evaluating the results of any changes.
- Train personnel who will be responsible for the system during its launch and for data analysis and reduction.

The environments that the satellite will encounter could be stated as: (a) prelaunch; (b) launch; and, (c) orbit. The environmental conditions experienced by the communication satellite are shown in Table 4.4.

PRELAUNCH	LAUNCH	ORBIT
. Temperature & Humidity	. Shock & Vibration	. Space Vacuum
. Shock & Vibration	. Acceleration-Thurst, Guidance, Wind Shear	. Solar Radiation
. Handling	. Aerodynamic Noise	. 3°K Heat Sink
. Sterilization	. Aerodynamic Heating	. Earth Radiation and Albedo

. R-F Radiation	. Pressure Decrease	. Radiation Belt & Solar Flares
. Storage Duration	. Corona	. Temperature Extremes
		. Cyclic Variation
		. Separation & Despin
		. Weightlessness
		. Attitude Control
		. No Air Daming
		. Magnetic Torques
		. Meteoroids

TABLE 4.4 Environmental Conditions Experienced by Communication Satellites

Testing has many concepts depending on the type of test being performed. Some of the more general concepts of the testing phase are given in Table 4.5.

TEST TYPE	GENERAL PURPOSE
Environmental	Performance of system under environmental stresses.
Failure	Failure mode determination, design margins.
Life	Fatigue limit, time-to-failure.
Special	Special conditions investigated.
Specification	Qualification, Acceptance, Production.
Functional	Performance of system over short period under specified conditions.

Reliability	Performance of system for a specified time under specified environmental conditions.

TABLE 4.5 Concepts of Testing

For the communication satellite system all parts will be electrically and environmentally tested. All critical items used in the system will be screened for parameter drift. The high reliability testing program to be performed for the various components will now be delineated. The specific environments and various testing parameters are given in Table 4.6.

Semiconductors - All parts to be burned-in for 1000 hours at maximum power.

Electrical parameter drift measurements to be performed on all components, before, during, and after burn-in. For transistors, collector-base cutoff current, and DC current transfer ratio are measured. Measurements of emitter-base cutoff current, collector-emitter saturation voltage, and a breakdown voltage parameter are required. For diodes, leakage, forward voltage, and breakdown voltage are to be screened.

Samples from each type are subjected to environmental, life, and temperature cycling tests in accordance with the applicable component specification.

	Mechanical & electrical Characteristics	Terminal Strength	Shock	Vibration	Temperature Cycling	Immersion Cycling	Dielectric Strength	Moisture Resistance	Temperature Coefficient	Corrosion	High Vacuum	Resistance to Soldering Heat	Low Temperature Operation	Short Time Overload	Solderability	High and/or Low Temperature Storage	Aging	Thermal Shock	Acceleration	Phase Jitter	Seal	Resistance After Firing	Overload Blowing	Magnetic Testing	Burn-in	Test Data
Capacitors																										
Tantalum	X	X	X	X	X	X	X	X		X	X				X									X	X	X
Glass	X	X	X	X	X	X	X	X	X	X					X									X	X	X
Ceramic	X	X		X	X	X	X	X							X									X	X	X
Resistors																										
Composition	X	X	X	X	X		X	X	X			X	X	X	X									X	X	X
Metal film	X	X	X	X	X		X	X	X			X	X	X	X									X	X	X
Wirewound	X	X	X	X	X		X	X	X				X	X										X	X	X
Crystals	X	X	X	X	X											X	X			X	X			X		X
Chokes and Transformers	X		X	X			X	X				X						X						X		X
Relays	X	X	X	X															X		X			X	X	X
Fuses	X	X	X	X			X	X			X					X	X	X	X		X	X	X	X	X	X
Transistors	X	X	X	X	X			X			X	X			X	X		X						X	X	X
Diodes	X	X	X	X	X			X	X		X	X			X	X	X	X						X	X	X
Wire and cable	X					X	X	X							X		X									X
Connectors	X	X	X	X			X			X					X		X		X					X		X

TABLE 4.6 Environments and Testing Parameters of Satellite Components

Capacitors - All capacitors receive a load life (burn-in) test for a specified voltage, temperature, and time. Specifications to be similar to the following:

Tantalum	Rated voltage, 25°C, 250 hours
Ceramics & Glass	Rated voltage, 25°C, 100 hours
Mylar Foil	Rated voltage, 85°C, 100 hours
Mica	Rated voltage, 150°C, 50 hours

Capacitance, dissipation factor, and leakage (or dielectric resistance) measurements are made before and after burn-in tests. The parameters must meet the original specification requirements when measured after burn-in and capacitance and dissipation factor must remain within specified limits.

Sample capacitors taken from each lot are subjected to temperature and immersion cycling, vibration, shock, moisture resistance, corrosion, high vacuum, and temperature storage.

Resistors - All components require a 100-hour load life (burn-in) at an ambient temperature of 25 ± 5°C and at a wattage dissipation that raises the resistor hot spot temperature to its maximum rated value.

Resistance measurements are made before and after burn-in test. The resistant value after burn-in must be within the original tolerance limits of the specification and the resistance must not exceed a specified value.

Samples of each type are subjected to the following tests: over-load test, resistance temperature characteristics, temperature cycling.

Special reliability testing will be conducted on selected components to derive failure rates, failure modes and effects, and any parameter variations. The critical components to be tested are the tunnel diode amplifier and the traveling wave tubes, both essential units used in a communication satellite.

The reliability testing program for the tunnel diode amplifier will now be given. Basically, the tunnel diode amplifier uses germanium tunnel diodes, an impedance matching and biasing circuit, and a microwave circulator. The reliability testing program is composed of tests, screening procedures, and analysis to assure the reliability goals have been met. The necessary steps in performing the tunnel diode amplifier tests are as follows:

- Diode Matrix Test. Reveal the potential failure modes by using screened assemblies to determine the diode's response to temperature and power with high stress. This will generate data useful in the parameter drift screening sequence and give valuable information on failure rate estimates.
- Microwave Circulator Stress Test. Determine the circulator response to temperature extremes thus revealing potential failure modes.
- Germanium Diode Life Test. Test under operational conditions for a specified time period thus obtaining an estimate of the required failure rate.

- Parameter Drift Screening. Screening of parts on a 100 percent basis to reveal potential failures in the unit. This is to be performed on all diodes undergoing the life test and all amplifiers to be used in the satellite.
- Qualification Test. The tunnel diode amplifier will be evaluated under the actual space environment to give confidence in the reliability performance under launch and orbit conditions (vibration, shock, radiation, high vacuum, humidity, and acceleration).

The tunnel diode screening procedure will entail measuring the diodes for peak current, peak voltage, valley current, series resistance, and resistive cutoff frequency. The criteria for failure will be if the peak-current, peak voltage, or series resistance changes more than 10 percent or the resistive cutoff frequency changes more than 15 percent.

The tunnel diodes will be temperature cycled from 25°C for twenty-four hours to -20°C for twenty-four hours. Next the diodes will be vibrated ultrasonically for approximately 10 minutes for the purpose of accelerating imperfections in the junction. Electrical measurements are then made of peak current, peak voltage, series resistance, and resistive cutoff frequency. A second temperature cycling test is next performed at 80°C for twenty-four hours, 25°C for twenty-four hours, and -20°C at twenty-four hours. A second ultrasonic vibration is conducted to stress all components associated with support of the diode.

A temperature cycling and burn-in test is then performed over a temperature range of +60°C to -20°C, holding at +60°C for twenty-four hours, at 25°C for twenty-four hours, and at -20°C for an additional twenty-four hours. Measurements of the peak current will be made at each temperature stated above. This temperature cycling test will continue for a period of 3 months. At the conclusion of the test final measurements will be taken of the peak current, peak voltage, valley current, series resistance, and resistive cutoff frequency.

The tunnel diode amplifier qualification test procedure will now be given in accordance with the detailed environmental specification.

Pre-environmental tests - Each amplifier will be checked per test specification for noise figure, gain and bandwidth measurement, saturation level, mismatch, VSWR (voltage standing wave ratio), and DC current drain. Each unit shall meet the requirements of the tunnel diode amplifier specification.

Temperature tests - The tunnel diode amplifiers will be placed in temperature chambers and subjected to three temperature cycles.

A temperature cycle will consist of a low temperature exposure of 24 hours and a high temperature exposure of 24 hours. The transitions between temperatures shall take three hours and the rate of change of temperature shall be no greater than one degree per minute. The low temperature shall be -30°F, and the high temperature +140°F.

Post temperature electrical test - The test described in Pre-environmental tests above shall be repeated at room ambient temperature.

Humidity test - The tunnel diode amplifiers shall be placed in a humidity chamber and subjected to five twenty-four hour cycles. The cycles shall consist of raising the temperature over a two-hour period to 120°F, holding it at 120°F for six hours, and lowering the temperature over a 16-hour period to 68°F. The relative humidity shall be held at 95% + 0% - 10% over the cycle. Post humidity electrical tests described in Pre-environmental tests shall be repeated on the units immediately after the completion of the fifth humidity cycle in room ambient temperature.

Launch vibration test - The tunnel diode amplifiers shall be subjected to a random vibration test to simulate launch conditions. The sweep rate shall be 1-1/4 octaves per minute. The amplifiers shall be mounted as they normally would be and vibrated in each of the three mutually perpendicular axes.

Launch shock test - Each of the amplifiers shall be shock tested once in one plane. The shock shall be 100G ± 10G, for 6.5 millisecond, half sine shock wave. Electrical test after vibration and shock as described in Pre-environmental tests shall be repeated on each of the amplifiers.

Launch vibration and shock endurance - The tests described in Launch vibration test and Launch shock test are considered to simulate one launching of the satellite on the tunnel diode amplifier. These tests will be repeated on each amplifier ten times. The units will then be electrically tested per Electrical test after vibration and shock after each launch simulation.

Orbital environment stress test - This test will check the ability of the tunnel diode amplifiers to operate in a vacuum and with the temperature cycling expected in orbit.

Criteria for failure - The tunnel diode amplifier shall be considered to have failed if the following parameters are not met:

Noise figure	5.0 db maximum
Bandwidth	± 5 mc
Gain variation	± 0.1 db over any 60-mc range within 250-mc bandwidth
Gain stability	± 0.4 db
Maximum slope at any frequency over the bandwidth	± 0.1 db/mc
Departure from linearity	1 db max at -22 dbm output
DC current	± 10% initial value.

The following test data for orbital environmental stress test shall be recorded for each tunnel diode amplifier:

Noise Figure

NF at center frequency -125 mc _____ db

NF at center frequency -75 mc _____ db

NF at center frequency -25 mc _____ db

NF at center frequency +25 mc _____ db

NF at center frequency +75 mc _____ db

NF at center frequency +125 mc _____ db

Gain at Center Frequency _____ db

Bandwidth

Lower 3-db point _____ mc

Upper 3-db point _____ mc

Gain Variation

Maximum variation over 60 mc _____ db

Place over scope face and trace response

0.1 db

0.1 db

-125 mc

Center Frequency

-125 mc

Saturation Level

Point of departure of -1 db output level ______ dbm

Mismatch

Stable over range ______

VSWR	Input	Output
VSWR at center frequency -125 mc		
VSWR at center frequency -50 mc		
VSWR at center frequency +50 mc		
VSWR at center frequency +125 mc		

Pre-environmental test - Each amplifier will be checked per test procedures for noise figure, gain and bandwidth, saturation level, mismatch, VSWR, and DC current drain.

Vacuum test - Install feedthroughs and cables for the amplifiers in the vacuum chamber using 50-ohm bulkhead feedthroughs. Check the resulting cable assemblies for VSWR, a maximum of 1.05 is allowable. The DC power is brought out through a suitable bulkhead fitting. Install the tunnel diode amplifiers in the chamber, mounting the amplifiers on temperature controlled panels. Perform on each tunnel diode amplifier the noise figure, gain, bandwidth, gain variation, saturation level, and DC current tests. Start the pump down to 1×10^{-5} mm Hg and maintain the temperature control panel at +70°F with all amplifiers operating. As the chamber pressure is reduced the gain shall be monitored and measured at 5-minute intervals using the output indications of the crystal detectors. After the chamber pressure has been reached 1×10^{-5} mm Hg, measure the noise figure, gain, bandwidth, gain variation, saturation level, and DC current. Continue operating the amplifiers at 1×10^{-5} mm Hg with a base plate temperature of 70°F. Monitor the gain except when amplifier is being electrically tested. Measure the noise figure, gain, bandwidth, gain variation, saturation level, and DC current on each amplifier on an hourly basis. Continue this test for 24 hours or until any instability of amplifier characteristics have stabilized.

Thermal vacuum temperature cycling - Continue operating the amplifiers at 1×10^{-5} mm Hg while temperature cycling the base plate temperature. The base plate temperature shall be cycled over a temperature range of +30°F to 90°F. The temperature shall be changed at a rate of 1 degree per minute, being increased to 90°F in one hour and reduced in one hour to 30°F. This cycle shall be repeated throughout this test. Monitor the gain of each amplifier. During the first temperature cycle, monitor and measure the noise figure of the number one tunnel diode amplifier over the temperature cycle. On the second cycle repeat the same measurement on number two tunnel diode amplifier. In similar fashion measure the remaining amplifiers.

During the second cycle measure the gain, saturation level on the number one amplifier over the temperature cycle. On the third cycle repeat the same measurement on the number two tunnel diode amplifier.

In similar fashion measure three on the next cycle and onto the last amplifier.

This test will give a set of data on how the tunnel diode amplifiers are affected by temperature while in a vacuum. From the data the most meaningful point in the temperature cycle will be determined for electrical testing of the tunnel diode amplifiers.

The test will be continued through 1000 temperature cycles. The gain of the amplifiers will be monitored throughout the test when other measurements are not being made. On a weekly basis measurements of noise figure, gain, gain variation, bandwidth, saturation level, and DC current shall be made on each amplifier. At 250 cycles, 500 cycles, 750 cycles, and 1000 cycles the noise figure, gain saturation level, bandwidth, gain variation shall be measured over a complete temperature cycle on each tunnel diode amplifier. Use the same procedure as used on the first one to thirteen cycles of this paragraph. Throughout this test check for any change in electrical response or temperature response. Any small change should be studied for early indication of an unknown failure mode.

The traveling wave tube is used to generate output power in the communication satellite and is required to function without failure for a much longer period of time than the life of ordinary tubes. It is also expected to withstand the severe mechanical stresses during the launch of the satellite.

The characteristics of a typical traveling wave tube are given in Table 4.7.

Anode voltage	1770 volts
Cathode current	17 ma
Cathode current density	85 ma/cm^2
Collector power, including helix and anode	12.5 watts
Collector voltage	740 volts
Gain, at saturation	35.5 db
Gain, low level	41 db
Heater power	1.5 watts
Helix voltage	1540 volts
Operation point	0 dbm input saturated output
Output power, minimum	3.5 watts
Weight	7.1 pounds

TABLE 4.7 Satellite Traveling Wave Tube Characteristics

The reasons for using traveling wave tubes to generate output power in the satellite are as follows:

- The efficiency of the traveling wave tube is much higher than solid-state devices for generating power at frequencies of a few thousand megahertz.

- The weight of the solar cells needed to give power for the solid-state device would offset the decrease in weight from that of the traveling wave tube.
- The traveling wave tube has a higher gain over other tubes such as triodes, which would require two or more stages to generate the same power output as the traveling wave tube.

The cathode of the traveling wave tube usually operates at a temperature of between 725°C and 800°C. Every 20°C reduction in cathode temperature doubles the life of the tube. The tubes used in the satellite have been estimated to have mean time between failures of 7 or 8 years. Past experience revealed a peculiar thermal problem of the tube in space. When the tube was put in a vacuum to simulate space environment it developed characteristics that were unfavorable for reliable operation. There was presence of output ticks less than 1 db in amplitude and 1 millisecond in duration. No knowledge was known at the time of what effect the ticks would have on the useful life of the tube. Extensive research on the problem related the cause with hot spots which resulted in the emission of gas to such an extent that the gas became ionized, thus producing a low impedance path, forming an arc. This was eliminated by a pressurized design in which all high voltage points outside the traveling wave tube were operated at atmospheric pressure in an enclosed chamber.

The reliability testing program on the traveling wave tubes is delineated below. It is designed to accumulate data which will provide the required confidence needed in the communication satellite design.

Prelaunch and launch environmental tests - Prelaunch and launch environmental tests will be conducted on both the high-level and low-level traveling wave tubes to verify the ceramic-to-metal seal and end cap design, and the capabilities of the tubes to survive all launch environments.

Accelerated cathode life tests - This test will provide confidence in the estimated cathode wearout life estimate of over 100,000 hours. This test is designed to obtain data at several points on the acceleration wearout life curve which will allow extrapolation at normal operating conditions. The test is based on cathode temperature and the general rule that cathode life is doubled for each 20°C decrease in temperature.

Each of the low-level and high-level cathodes in the gun structure will be connected such as to allow diode operation of the cathodes. Each of the cathodes will be operated at three different temperatures to obtain three points on the wearout curve. The data will then be extrapolated to the normal operating conditions. The test duration is for one year.

Traveling wave tube reliability test - A qualitative reliability test will be run on the low-level tubes and on the high-level tubes. This test will be a multiple purpose test. The first purpose will be to parameter drift screen flight traveling wave tubes. The second will be to generate reliability data for failure rate demonstration.

All traveling wave tubes will be placed in life test racks and will be electrical performance tested every 200 hours. The data will be analyzed for the parameter drift, population trends, and individual trends. As tubes are needed for the flight program those which are closest to the population norm and exhibit the least drift will be chosen. The flight tubes selected will have a minimum of 3,000 hours of operation and a maximum of 12,000 hours. Twenty tubes of each type tube plus the flight tubes, the engineering model tubes and the critical item environmental test tubes will be placed in this qualitative reliability test. Operating this phase of the test in this manner has the advantage of allowing the selection of the best tubes from a large population of space qualified tubes for the flight satellites.

Reliability life tests will also be performed on other critical components and subsystems in the satellite system. One of the subsystems is the despin subsystem. Reliability life testing of the despin subsystem will be conducted on the two subsystem elements separately: the electronics unit and the pneumatic assembly. Tests will be performed on two electronics units containing the rate gyros and on one pneumatic assembly consisting of the pressure regulator and relief valve, two solenoid valves, high and low pressure transducers and associated plumbing.

The two electronics units will both be subjected to acceptance level vibration tests and functionally tested before and after vibration.

The two units will then be subjected to a vacuum environment for a period of 6 weeks. One unit will be operated once each day simulating flight requirements of 20 minutes despin time followed by 10 minutes venting time. The second unit will be vacuum soaked for 3 weeks, then operated once each day for the remaining 3 weeks. These tests will provide a confidence level for the operational capability of the units.

The acceptance test vibration level is shown below:

Frequency Range	Vibration Level
10 to 300 hertz	2g
300 to 2000 hertz	3g

The vibration shall be in the 3 mutual perpendicular axes of the unit and the displacement shall be 0.4 inch double amplitude maximum. The input vibration sweep rate shall vary at a rate of 4 octaves per minute.

The components of the pneumatic assembly will be tested to verify the operational requirements. This assembly will be placed in a vacuum environment for a period of 2 months. Leakage of the assembly will be monitored for one month. The assembly will then be operated to simulate operational flow requirements of 20 minutes despin time followed by 10 minutes of venting time, once each day for the second month. System parameters of flow, regulated pressure and leakage will be monitored for this period.

Reliability testing of the combined power control assembly and traveling wave tube converters will be performed. Two power supplies will be used to simulate the tapped solar array. One of the power supplies will be programmed to reduce its output periodically to simulate solar eclipses and exercise the traveling wave tube undervoltage protection circuits. These simulated eclipses will be repeated at two-hour intervals to approximate the total number of eclipses during five years in orbit within the first six months of testing. Resistive loads will be used to simulate the traveling wave tube converter loads.

The test setups will be energized and operated continuously for six months with mounting plate temperatures maintained at nominal satellite operational conditions. The periodic test measurements will be performed on a weekly basis. Daily checks will be made to verify continuous system operation. After the initial six months, step-stress testing with 10°C mounting plate temperature increases at one-month intervals will be performed until failures occur.

Qualification tests will be conducted on all spacecraft assemblies. Five major environmental exposures are planned for assembly qualification.

- Humidity. Humidity tests will be conducted on those assemblies which will not be protected from a damp atmosphere during handling, shipping and storage, or which may be adversely affected by high humidity during launch operations. After stabilization in a temperature and humidity chamber the assembly will be exposed to the specified humidity conditions for 50 hours. Subsequently the performance of the assembly will be checked.

- Vibration. Assemblies will be vibrated in each of three orthogonal directions, with one direction parallel to the thrust axes. Attachment of the assembly to the test apparatus will simulate the actual attachment of the assembly to the spacecraft structure. The assembly will be tested in the operational condition normal for the launch phase of the mission. The vibration tests will include sinusoidal and random motion vibration (complex wave) and sinusoidal sweep mode response tests.
- Acceleration. The assemblies will be attached to a mounting fixture simulating attachment to the spacecraft structure and attached to the acceleration equipment such that the acceleration is in the direction of the resultant of the thrust and spin accelerations applied to the assemblies. The acceleration levels will be maintained for at least 3 minutes for each assembly. The assembly will be in the operational condition occurring during boost.
- Thermal-vacuum. Thermal-vacuum tests will be performed with the assembly mounted in a manner thermally simulating the attachment of the assembly to the spacecraft structure.

During evacuation the assembly will be operated in the condition typical of the launch phase; corona effects will be monitored throughout the evacuation period. Tests will be conducted under stabilized exposure of 48 hours with the assembly operating. For cyclically-operated assemblies cold start capability will be demonstrated during the 48-hour exposure. Performance of the assembly will be verified throughout and after the exposure.

- Shock. Nine shocks (three shocks along each of the three coordinate axes) will be applied to each assembly through the normal mounting provisions of the assembly.

After successful integration, the satellite will be subjected to specified environmental conditions. The spacecraft environmental qualification phase of the test program commences with mass properties determination and concludes with the acceptance. The mass properties and magnetic properties of the spacecraft will be measured as part of the environmental qualification test program. Five major environmental conditions for the spacecraft are as follows:

- Vibration. While in the launch mode, the spacecraft will be subjected to separately applied sinusoidal and random vibrations in each of the three orthogonal directions. The vibration will be applied and measured at the spacecraft separation plane. Equipment performance will be monitored. After the test, the spacecraft will be subjected to a post-vibration functional check to search for failure, malfunction, or out-of-tolerance performance degradation.

- Humidity. The spacecraft will be installed in a temperature and humidity chamber. After stabilization the spacecraft will be exposed to the conditions for 24 hours. The spacecraft will then be removed and its operational performance checked.
- Spin. The spacecraft in its launch configuration will be subjected to a spin test, including spin-up and de-spin tests. The spacecraft will be in an operational status normal for powered flight. While in its orbital injection flight configuration and operational mode, the satellite will be subjected to a spin rate of 12 rpm and maintained at this rate for sufficient time to exercise all functional subsystems.
- Temperature. While in a nonoperating condition, the spacecraft will be exposed to the temperature range specified by the design margins. After the spacecraft is returned to ambient conditions, it will be tested for failure or out-of-tolerance conditions.
- Thermal-vacuum. Thermal-vacuum tests will be performed to verify the thermal design and to demonstrate performance capability beyond the temperature range to be encountered in flight. Tests will be conducted under stabilized pressure conditions with simulated solar illumination of the spacecraft and with the chamber walls cooled. The spacecraft will be operated in all modes of normal operation which are controlled by ground command. During the test all operable equipment will be cycled through its maximum thermal excursion. The spacecraft will be rotated at a rate sufficient to stabilize the temperature of the solar array. The test will last for 2 weeks.

The following tests are also to be performed to qualify the design of the satellite.

- Balance. The spacecraft will be balanced before environmental tests so that the effect of balance weights is included.
- Weight, Center of Gravity, and Moment of Inertia. While non-operative, the spacecraft weight, center of gravity, and moments of inertia (about the spin axis and the maximum and minimum moments about the transverse axes) will be determined and compared with design requirements.
- Magnetic Properties. Magnetic measurements of the fully assembled and operating prototype spacecraft will be made.
- Electromagnetic Compatibility. Electro-magnetic compatibility tests will be performed as a part of systems performance tests to verify that all subsystems are capable of compatible operation. RF susceptibility tests will be made on a concurrent basis to provide information on the interference profile of the spacecraft.

Acceptance tests will be performed on all flight spacecraft to see that performance requirements have been met, that the equipment is free from workmanship defects, and that it will survive the flight environments.

Acceptance tests for subsystems consist of environmental exposures at those levels considered adequate to detect workmanship defects and provide a simulation of the launch and orbital environment.

The environmental exposures during the acceptance tests differ from qualifications tests in that only two stresses are considered, vibration and thermal-vacuum.

. Vibration. Only sinusoidal vibrations will be applied.

. Thermal-vacuum. Thermal-vacuum tests will be performed with the assembly mounted in a manner thermally simulating the attachment of the assembly to the spacecraft structure. Tests will be conducted at maximum and minimum predicted assembly temperatures. During evacuation the assembly will be operated in the condition typical of the launch phase; corona effects will be monitored throughout evacuation. Tests will be conducted under stabilized temperature and pressure conditions for a minimum exposure of 24 hours with the assembly operating. For cyclically-operated assemblies cold start capability will be demonstrated during the 24-hour exposure. Performance of the assembly will be verified throughout and after the exposure period.

After successful integration, the satellite will be subjected to specified environmental conditions. Two major environmental exposures for satellite acceptance are as scheduled below. In addition, the mass and magnetic properties of the satellite will be determined as part of the acceptance program.

. Vibration. The flight spacecraft will be vibrated in each of three orthogonal directions, with one direction parallel to the thrust axis. The control accelerometer for these tests will be tested in the operational condition normal for the launch phase of the mission. Separate sinusoidal and random excitation will be applied in sequence.

- Thermal-vacuum. The spacecraft will be placed in the space simulation chamber and while it is being operated in the normal space mode will be exposed to an environment simulating that expected during the mission. Vacuum, solar radiation, and the heat-sink condition of space will be approximated. These conditions will be maintained sufficiently long to permit complete testing of the spacecraft.

As can be seen from the extensive testing program, much effort goes into a satellite system which requires a high degree of reliability. The testing phase is an activity of qualifying the system by means of space environmental simulation. This simulation is used to answer many questions and give solutions to numerous problems encountered during the design and development of the communication satellite.

To be effective, the reliability testing program must be completely integrated. This is best obtained by a single engineering group. Since the methods and techniques used are those associated with the reliability discipline, the reliability group seems the logical choice.

One approach that satisfies most of the test planning requirements is based on two analyses. These are pretest analysis and test emphasis analysis. The pretest analysis determines the needs of the program, such as the different types of tests needed to be performed on components, subsystems, and the complete system. The test emphasis analysis determines the elements of the testing program, such as requirements for test sample size, scheduling requirement and cost requirement constraints.

In addition to the types of tests mentioned in Table 4.5, there is another type: step-stress testing. The main reasons for this testing technique are as follows:

- To detect process change measurements of process improvement.
- To determine maximum ratings of the device being tested.
- To determine maximum application stresses.
- To establish the necessary levels of screening.

The step-stress method of testing is ideal for devices that are prone to fail because of threshold (as opposed to time dependent) failure mechanisms. The stress is applied to the device to which the failure mechanism is most likely to occur in equal steps until failure. A frequency distribution is then plotted of stress levels versus devices that failed. From this the process average and process control can be determined.

It should be noted that in applying this technique of testing, consideration must be given as to whether the failures that occur at any step are ascribable to the same failure mechanism. To accomplish this a detailed failure analysis is required as described previously. Consideration must also be given as to whether the failure mechanisms change with increasing stress levels.

The saving of time and money is realized by employing the step-stress technique as compared to life testing. For instance, in testing 10,000 transistors at a high reliability level, a 10,000 hour life test would be required with one failure. If the step-stress testing technique were used only 100 transistors need be tested for approximately 100 hours with 100 failures. If failures did occur, by employing a timely failure analysis to each failure, information would become available for improving the devices being tested, its applicability to the next level of assembly, and the screening methods used in remaining irregularities.

A method used extensively today in finding components that are prone to failure is nondestructive testing. This type of reliability testing is designed to identify devices that are likely to fail when put into operation without destroying or harming the device. The nondestructive tests are classified into several categories: mechanical, electrical, thermal, visual, and radiographic.

The mechanical tests include the following:

- Vibration. Check weak parts of structure, resonance points, and intermittent conditions.

- Shock and Acceleration. Evaluate physical integrity of devices by subjecting it to stresses that could occur in operation, handling, and transportation.
- Helium Leak. Detect package or seal defects.
- Fluid Leak. Detect gross leaks not detectable by helium leak test. Devices put in solution of ethylene glycal and inspected for bubbles.
- Radiflo. Radioactive tracer gas is put into device, and the rate of leakage is measured by a radiation counter.
- Moisture-Resistance. Device under varying temperature and humidity conditions to check deterioration of seals and packaging.
- Pressure. Evaluate device package and seals and the ability of the device to withstand pressure differentials.
- Ultrasonic. Evaluate bond strength and detect variations in the density of materials.

The electrical nondestructive tests encompass the following:

- Power (Burn-in). Operating component for long period of time at rated conditions to weed out marginal components.
- Current-noise. Check noise (voltage fluctuation) in resistors by passing direct current through them. There is a direct relationship between defective resistors and those that are noisy.

- Infrared scanning. Voids and contamination are revealed as hot spots in the component when current is passed through it. This technique is used in checking resistors and integrated circuits.
- Thermographic mapping. Evaluates semiconductor devices and printed circuit assemblies. Cholesteric compounds (liquid crystals) are used to plot hot spots when a component is subjected to changes in temperature environment due to overstressing.
- Dielectric strength. Sometimes called hi-pot, this test detects flaws in insulation or workmanship.
- Radio frequency noise. Detects poor contact or voids in solder joints, splices, or connectors.

The thermal tests include the following:

- High temperature storage. Screens parts not capable of high temperatures and stabilizes electrical characteristics of solid state devices by baking out contaminants and moisture.
- Temperature cycling. Detects poor connections and bonds, inadequate strain relief, and thermal mismatch by exposing components to high and low temperatures.

The following nondestructive test falls under the category of visual test:

- Microscopic examination. Detect imperfections in the component before encapsulation. Integrated circuits require 80X magnification inspection while resistors may often be inspected with only 10X or 15X magnification.

The radiographic tests or x-ray radiography detects any foreign material, loose particles, solder, and other imperfections in the component.

In designing a nondestructive testing program the failure mode of each component must be considered. The application requirements must be studied such as parameter drift tolerances, loads, operating time, on-off times, radiation, heat oxidizing, pressure, reducing, and corrosive environments. The part construction is also an important factor - the materials, interfaces, structural elements, contamination, process controls, and processes.

Reliability Program Review

The reliability program review is basically an evaluation procedure used to assure the effectiveness of the reliability program for the communication satellite by evaluation of reliability controls and procedures. The objectives could be stated as follows:

- Initiate standard procedures for evaluating the degree and effectiveness of reliability controls and practices.
- To evaluate methods of controlling specific tasks leading to reliability improvement and higher safety margins.
- Identify problems encountered during the reliability phase of the program and finding solutions to these problems using the reliability disciplines and techniques developed in this thesis.

The reliability program tasks considered in this thesis consisted of the 10 major activity areas, each having a separate and distinct relationship to the program. The reliability evaluation phase is conducted with the following objectives in mind:

- To determine if effective coverage for each phase of the reliability program is obtained and kept up to date in accordance with specified requirements.
- To find out the weaknesses and strengths in each of the reliability tasks that are to be performed throughout the program.
- If there are weaknesses in the reliability tasks, the evaluation phase will make necessary recommendations for improving and strengthening each task.

An evaluation of the degree of coverage for each task will now be given. The basic steps to follow in the reliability program evaluation are stated below.

Step A. The relative importance (usually in percent) of each reliability task is established.

Step B. The relative importance (from 1 to 10) of the individual work elements within each reliability task is then determined.

Step C. The degree of effective coverage (in percent) of the individual work elements is established for each task.

Step D. All related specification and requirement numbers for each work element are recorded.

Step E. The functional or departmental responsibility for each work element is determined next.

Step F. A weighted effective rating for each work element is found by the product of the relative importance factor (Step A) and the degree of effective coverage (Step C).

Step G. Determine for each work element the need for priority and action to be taken by subtracting the weighted effective coverage (Step C) from the relative importance factor (Step A). The need is greatest when the number obtained is highest.

Step H. Repeat Steps F and G for each reliability major task.

Each reliability task has a separate and distinct contribution in the communication satellite program. They are not independent of each other in that the weakness of one task can have a decided effect upon the other tasks of the program. Relative importance factors (Step A) must be established for each task. A set of these factors has been established as shown in Table 4.8, column A. The work elements of each reliability task are given relative importance factors in the same way as where given to the major task. It should be noted each factor is subject to revision based on experience as the program progresses.

	Relative Importance Factor A	Degree of Effective Coverage (%) B	Weighted Effective Coverage (A) (B) C	Relative Need (A - C) D	Functional Responsibility E
Reliability Program Organization	10	40	4.0	6.0	Rel.
Reliability Program Plan	7	60	4.2	2.8	Rel.
Design Review Program	18	80	14.4	3.6	Rel.
Reliability Apportionment, Assessment, and Analysis	10	40	4.0	6.0	Rel.
Parts, Materials, and Process Control	10	80	8.0	2.0	Rel.
Supplier Reliability Control	10	60	6.0	4.0	Rel.
Failure Reporting and Analysis and Corrective Action	13	60	7.8	5.2	Rel.
Reliability Indoctrination and Training	10	80	8.0	2.0	Rel.
Reliability Testing Program	12	80	9.6	2.4	Rel.
TOTAL	100	---	66.0	---	---

TABLE 4.8 Reliability Program Evaluation Summary

In Column B of Table 4.8 is given the degree of effective coverage. This coverage rating of each major reliability task is based on surveys conducted by program personnel. Coverage that is satisfactory is given a rating of 100 percent.

The weighted effective coverage is given in Column C of Table 4.8. This quantity is the product of Column A and Column B.

When recommending corrective action and need for priority, it is necessary to find the lack of coverage for each major task or individual work element and to include at the same time the relative importance factors for each task or work element. This is accomplished by subtracting the weighted effective coverage from the relative importance factor (Column C from Column A). This gives Column D in Table 4.8. The higher the number in Column D, the greater is the need for action.

Column E is to be filled in to indicate the functional responsibility for the task. In this instance Reliability Engineering is the responsible function.

The overall degree of effective coverage for the reliability program is established directly from the relative importance factor of each task and their associated degree of effective coverage. The sum of the weighted effective coverage (Column C) is then totaled (in this case 66 percent) and is the percent representing the degree of overall program coverage for the reliability phase of the program.

It should be noted that the numbers used in the evaluation of the program were not actual figures but rather figures used for illustration purposes only. What was shown was a method that could be used in reviewing and evaluating the reliability tasks necessary in establishing a high reliable communication satellite.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The achievement of communication by means of satellites has required the development of many technical innovations. Most important was the technique of improving the reliability of each system as it was placed in orbit. The use of large spherical passive reflectors such as Echo I and II was shown to be feasible as a first step in satellite communication. The Echo project verified that total communications system calculations agreed with theory to within one decibel. The project also demonstrated the feasibility of placing large structures into a space environment without any detrimental effects.

The next step in developing a more flexible communication operation was the use of the active satellite. Here we see the communication capacity of the satellite transponders increased from narrowband (teletype, voice, and facsimile) to wideband television, or many telephone channels. The design of the transponders has been a fruitful arena for the application of a growing field within electronics such as the design of very reliable traveling wave tubes, tunnel diode amplifiers, components, circuits, and subsystems.

The initial phase of operational communication satellites has left a number of important questions unanswered relating to, namely:

- Frequency Allocation
- Time Delay and Echo
- Multiple Access

It is imperative that these questions be resolved in the near future to facilitate the resolution of problems which are expected in the initial phase. The following discussion is presented to provide an appreciation of the factors involved.

It has been apparent since 1959 that frequency allocation with surface systems be mandatory for communication satellites, since the 1-10 GHz region, which is best suited for space communications, was already fully allocated to terrestrial services. Studies conducted in the early 1960's concluded that frequency allocation would be feasible. In 1963, the International Telecommunications Union allocated 2800 MHz of spectrum space for satellite communications systems on the basis of sharing with terrestrial systems. Sharing criteria are conservative, and further experience may well provide a basis for desirable relaxation, desirable since flux densities at the earth's surface required for operation of small and inexpensive ground terminals are higher than allowed by the present criteria.

A second technical problem is the time delay inherent in synchronous altitude satellite systems in which the round trip delay is about 6/10 of a second. This delay by itself is not usually detectable by a telephone user. When terminations are imperfect, however, an echo occurs, and acceptability and usability of the circuit decreases rapidly with increasing echo amplitude. Echo suppressors are used to eliminate the echo, but echo suppressors are voice-operated switches and they introduce undesirable side effects. The adverse effects of long-delayed echo led to a tentative international agreement in 1960 that round-trip delays should not exceed 300 milliseconds.

Additional laboratory and subjective tests of user reaction to time delays and echo were conducted for three years, 1962-1964, but with inconclusive results. The last in this group of tests was conducted by American Telephone and Telegraph in collaboration with Federal Communications Commission, National Aeronautics and Space Administration, and the Communications Satellite Corporation. The most important results of these tests were submitted by the United States in 1964. Based on these results and on information submitted by other administrations, the following limitations on mean one-way propagation times when echo sources exist and echo suppressors are used was recommended.

- Acceptable without reservation, 0 to 150 ms.
- Provisionally acceptable, 150 to 400 ms. In this range, connections may be permitted, in particular, when compensating advantages are obtained.

- Provisionally unacceptable, 400 ms and higher. Connections with these delays should not be used except under exceptional circumstances.

The problem of time delay and echo is not limited to voice communications. In fact, the conclusions may well be different when considered in connection with high speed data communications, particularly if automatic error detection, querying, and correction is included. Certain high speed automatic signalling and routing systems may be sensitive to the amount of delay.

The successful application of satellite-borne repeaters for global telecommunications provides the potential for extending high quality telephone communications service to many points now served poorly or not at all. However, to realize this potential, a number of technical problems must be solved.

One of the most significant problems is called "multiple access" or how to employ a single satellite-borne repeater simultaneously for communication among a number of ground stations, each communicating with one or more of the others.

Various methods of modulation and multiplexing can be employed to provide a multiple access capability. However, each scheme is sensitive to the configuration of the satellite system, the number of participating ground stations, the traffic demands of each, and the required flexibility of routing.

Much has been discussed on the general attributes of the four principal categories of multiple access technology (multiple FM carriers, SSB in the up-link, time division multiplex, and common spectrum). An assessment of their relative merits was also made and evidence exists that efforts regarding the problem of multiple access will continue until a suitable and successful solution is found.

The future of satellite communications is very optimistic indeed. As the traffic increases in satellite communications systems there will be a tendency to install more ground stations to give a greater flexibility to service. This greater flexibility could result if a higher power satellite could be achieved. The type and capacity of the power supply is the greatest factor to be considered in achieving this higher power. A power supply developing several kilowatts of power for long periods of time is needed. At the present time there are two possibilities. One is the use of solar power and the other is the utilization of power developed in the nuclear-fission reactor. There have been several programs under way for nuclear reactors. These programs are known as the SNAP-10A, SNAP-2, and the SNAP-8 and develop 1, 3, and 30 kilowatts of electric power respectively. The SNAP-8 can develop 60 kilowatts of power with duel power converters.

A preliminary design has been made of a nuclear-powered satellite vehicle. While a number of difficult design problems have been uncovered it appears that if sufficient effort is applied to their solution the satellite could be demonstrated in flight in the very near future.

For this preliminary design several decisions were made based on experience gained in the design of other satellites that have been successfully launched and operated in space:

- A modular design consisting of a power unit and an electronic payload unit appears to be advantageous. This permits design of the two units to proceed independently, except for interfaces. This is particularly desirable in view of the special handling required for nuclear reactors.
- Heat dissipation is a major problem, and the radiators required for this purpose are a major mass item. While the radiators could be deployed after launching and continuously orientated with respect to the sun to minimize mass this would complicate the mechanical design and place additional burdens on the orientation system. Thus, it was decided that the vehicle would be earth orientated, with the nose up, and that the radiators would be integral with the body in both modules to conserve structural mass. The resultant simplicity enhances the vehicle reliability.
- The electronics payload module should be as far removed from the reactor as possible to reduce radiation flux hazards to a minimum.

It has been estimated that the high power communication satellite would have a capacity of 27,000 two-way voice channels. There is plenty of margin for growth in the traffic since only 6,000 two-way voice channels are required of the Atlantic satellite by mid-1970. For this type of future service, design for reliability and provisions for continuous service are of prime importance.

From the viewpoint of continuity of service the salient characteristic of the high-power-satellite-communications system, is that it takes about 75 days to place a satellite into operating position. If only one non-redundant satellite is at any one of the three stations its failure will interrupt service for at least 75 days even if several launch pads, boosters and replacement satellites are kept in constant readiness. To maintain a sufficiently high probability of uninterrupted service a higher order of redundancy in satellites and repeaters must be provided at each station. To evaluate this probability quantitatively a reliability model of the satellite must first be established.

It is assumed that each satellite will have a single reactor, but that other vital equipment will be at least in duplicate form. The present 60 kW SNAP-8 unit already consists of two duplicate 30 kW turbine-electric converters, each with its own turbine, electric alternator, radiator, pumps and liquid-flow loop. The output of each 30 kW converter is sufficient for 13,600 two-way voice channels which, according to the predictions, will not be reached until about 1980 for the Atlantic station. Hence, duplicate power capacity for communications purposes is available in each satellite at each station. The present SNAP-8 reactor loop contains a heat exchanger, to transfer heat to the converter loops, a pump and a pump motor. This loop design might be reconfigured to provide for complete duplicate loops or to include units whose design permits replacement of functions without blocking the entire loop or failure of the entire unit. Concerning the electronics equipment, multiple communications repeaters and power supplies should present no difficult technical problems. Non-rotating microwave plumbing such as waveguides and antennae will probably not need any duplication. Antennae are fixed to the satellite, presently designed to be three-axis stabilized. The station-keeping and attitude-control system will present design problems for long life, and a design with duplication of critical components will undoubtedly be necessary. The resulting mass penalty is estimated to be about 250 lb. Telemetry and control equipment should lend themselves to long life or duplication with relatively small mass penalties. It is seen that the mass increase from redundant design does not result in any major increase in the overall mass distribution, owing primarily to two reasons:

- The major mass increases over a single 30 kW unit are already included in the 60 kW SNAP-8 duplicate converter-radiator design.
- The power capacity is considerably more than twice the communications requirement (at least until 1980) which

should permit mass-power trade-offs in design. In summary, the reliability model specifies two independent communications repeater sub-systems per satellite, each capable of handling the entire traffic load.

The results of detailed calculations for the probability of continuous service using the reliability model described earlier are summarized as follows:

a. Based upon a reasonable 90 percent probability of successful launch and injection into orbit by 1972 and thereafter, the overall probability of success of at least one out of three such successive attempts is 99.9 percent. This would be considered an acceptable risk, whereas one out of two attempts would provide a probability of success of 99 percent a marginal risk.

b. Because of (a), at most 225 days must be allocated to replace a satellite failure as a result of three successive attempts, each up to 75 days in length. This is an upper limit on replacement time and provides at least a 99.9 percent confidence of replacement. A lower limit (90 percent confidence) on replacement time is 75 days for a single attempt.

c. It is necessary to maintain two satellites at ecah station. If only one satellite (two repeaters) is kept on station the following risks are incurred (considered to be unacceptable):

- A premature or unforeseen failure of the single nuclear power supply.
- Upon failure of one repeater the probability of continuous service (non-failure) of the other repeater depends upon the repeater mean life (M.T.B.F.). Figure 5.1 shows this probability for the curves labelled P_s (1/1). For an M.T.B.F. of 3 years this probability ranges from 81 to 93 percent for the upper and lower limits established earlier.

d. When two satellites are on station there are four repeaters, one in operation, and three as spares. This provides the following levels of confidence in continuous service:

- Two independent nuclear power supplies are on station, one in each satellite.
- Upon failure of the operating repeater, the probability of continuous service during replacement time for an M.T.B.F. of 3 years ranges from 99.4 to 99.97 percent. Figure 5.1 shows this probability, labelled P_s (1/3). This is considered to be acceptable.

Communication by means of satellites has proven to be both feasible and reliable over the past decade. To help maintain the required high reliability requirements needed for such an undertaking a reliability program has been presented. By using the reliability techniques and statistical methods as presented, a successful communication satellite

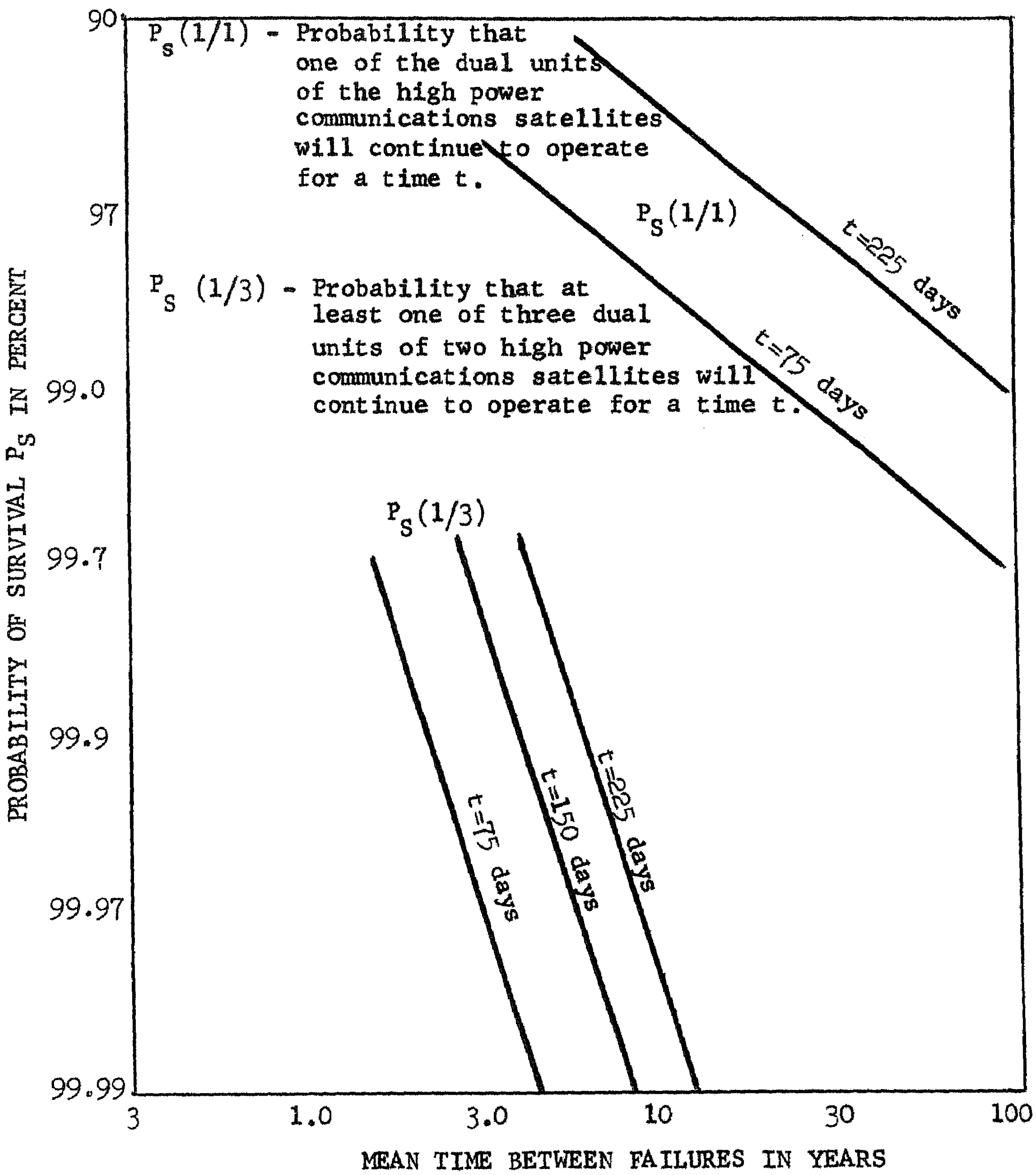


FIGURE 5.1 Probability of Survival High-power Communications Satellite

system could be realized. Reliability must be the prime consideration for such a non-maintained system. Reliability must be introduced early in the design studies and continued throughout the entire program. As was stated previously, reliability cannot be tested into the satellite system (more testing does not improve the reliability of the system), but it must be designed in the system at the outset.

In conclusion, it is therefore recommended that the reliability considerations set forth in this thesis be followed in detail, thus assuring a communication satellite system of successfully completing its intended mission for the period of time specified. To cite an example of the usefulness of communication satellites the following was noted recently. Two existing Atlantic telephone cables broke and went out of operation. The odds of this happening are approximately 1000 to 1. One cable was from New Jersey to St. Hilaire-de-Riez, France and the other was from New Jersey to Cornwall, England. Both failures occurred off the United States coast. It was the Intelsat communication satellites Early Bird and Atlantic II that provided 177 circuits as temporary assistance for the transatlantic operation.

Both of the satellites and satellite earth stations functioned precisely as required. It was also noted that the reliability of the satellite system during 1967 was outstanding. There were no service failures attributable to either satellite. The reliability for earth-station operations was 99.37 percent, and the reliability for land lines between earth-stations and international switching centers was 99.14 percent.

With the continuation of growth in the techniques and disciplines of reliability engineering, the future of more elaborate and complex satellites for the purpose of communications is excellent.

APPENDIX I

SATELLITES REMAINING AS A FUNCTION OF TIME

APPENDIX I

SATELLITES REMAINING AS A FUNCTION OF TIME

If satellites having a given mean time to failure and a constant failure rate over the lifetime of the system are launched at a uniform rate, the average number still functioning at any time, is given by (A-1)

$$N(t) = e^{-(t/MTF)} \sum_{i \leq t} e^{(i/MTF)} \quad \text{or} \qquad \text{(A-1)}$$

$$= e^{-\mu t} \sum_{i \leq t} e^{\mu i}$$

where

MTF is mean time to failure in months

μ is reciprocal of MTF or failure rate

i is the number of launches per month.

Table A-1 gives N(t) for satellites having two-year mean time to failure and a launch rate of one per month. Note that although one satellite is launched each month, the number operating does not increase by one each month. Specifically, at about two years, the number of operating satellites is increasing at a rate of less than a half of a satellite per month. It can be shown that the limit of this process is a number less than thirty. A-1 represents a geometric progression whose sum is given by (A-2).

$$S = a \frac{(r^n - 1)}{(r - 1)} \qquad \text{(A-2)}$$

where

a is the first term

r is the ratio between terms

n is the number of terms

Applying this relationship to (A-1):

$$S = e^{(1/MTF)} e^{-(t/MTF)} \frac{e^{(t/MTF)} - 1}{e^{(1/MTF)} - 1} \quad \text{(A-3)}$$

$$= e^{(1/MTF)} \frac{1 - e^{-(t/MTF)}}{e^{(1/MTF)} - 1}$$

In the limit,

$$\lim_{t \to \infty} S = \frac{1}{1 - e^{-(1/MTF)}} \quad \text{(A-4)}$$

If 30 operating satellites are desired:

$$30 = \frac{1}{1 - e^{-(1/MTF)}} \quad \text{(A-5)}$$

$$MTF = 29.1$$

which shows that the minimum mean time to failure must be 29 months. If the mean time to failure is taken as 60 months (five years), and satellites are launched at the same one-per-month rate, Table A-2 gives the number operating at any time. Note that it takes 42 months to place an average of 30 working satellites in orbit.

TABLE A-1

SATELLITES REMAINING AS A FUNCTION OF TIME

(MTF = 24 MONTHS)

i (Months)	$e^{-\mu t}$	Σe^{ui}	N(t)
1	0.958	1.04	1.0
2	0.9198	2.13	2.0
3	0.883	3.26	2.8
4	0.8446	4.45	3.8
5	0.812	5.68	4.8
6	0.7788	6.96	5.4
7	0.7468	8.30	6.2
8	0.716	9.70	6.9
9	0.687	11.15	7.6
10	0.659	12.67	8.3
11	0.632	14.25	9.0
12	0.606	15.90	9.6
13	0.581	17.62	10.2
14	0.559	19.41	10.8
15	0.535	21.28	11.3
16	0.518	23.21	12.0
17	0.493	25.24	12.4
18	0.471	27.36	12.9
19	0.453	29.57	13.4
20	0.435	31.87	13.9
21	0.416	34.27	14.3
22	0.400	36.77	14.7
23	0.384	39.38	15.1
24	0.368	42.10	15.5
25	0.352	44.94	15.8
26	0.338	47.90	16.2
27	0.324	50.98	16.5
28	0.310	54.20	16.8
29	0.298	57.56	17.1
30	0.286	61.05	17.5

TABLE A-II

SATELLITES REMAINING AS A FUNCTION OF TIME

(MTF = 60 MONTHS)

i (Months)	$e^{-\mu t}$	$\Sigma e^{\mu i}$	N(t)
1	0.985	1.02	1.00
2	0.97	2.05	1.99
3	0.953	3.10	2.95
4	0.937	4.17	3.9
5	0.92	5.26	4.8
6	0.905	6.36	5.8
7	0.89	7.48	6.6
8	0.875	8.62	7.5
9	0.861	9.78	8.4
10	0.845	10.96	9.26
11	0.832	12.16	10.1
12	0.818	13.38	10.9
13	0.806	14.62	11.8
14	0.792	15.88	12.6
15	0.779	17.16	13.4
16	0.766	18.47	14.2
17	0.754	19.80	14.9
18	0.741	21.15	15.7
19	0.729	22.52	16.4
20	0.717	23.91	17.1
21	0.705	25.33	17.9
22	0.694	26.77	18.6
23	0.684	28.24	19.3
24	0.670	29.73	19.9

TABLE A-II (Continued)

i (Months)	$e^{-\mu t}$	$\Sigma\, e^{\mu i}$	N(t)
25	0.660	31.25	20.6
26	0.648	32.79	21.2
27	0.638	34.36	21.9
28	0.627	35.95	22.5
29	0.617	37.57	23.2
30	0.607	39.22	23.8
31	0.597	40.89	24.4
32	0.587	42.59	25.0
33	0.577	44.32	25.6
34	0.568	46.08	26.2
35	0.558	47.87	26.7
36	0.549	49.69	27.3
37	0.541	51.54	27.9
38	0.532	53.42	28.4
39	0.521	55.34	28.8
40	0.513	57.29	29.4
41	0.505	59.27	29.9
42	0.497	61.28	30.4
43	0.488	63.33	30.9
44	0.48	65.41	31.4
45	0.472	67.53	31.9
46	0.465	69.68	32.4
47	0.456	71.87	32.8
48	0.448	74.10	33.2

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APPENDIX II

LETTERS OF CRITICAL EVALUATION

ITT

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390 Washington Avenue
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May 8, 1968

Mr. Frank Polizzi
23 Ellis Street
Lincoln Park, New Jersey 07035

SUBJECT: LETTER OF CRITICAL EVALUATION

Dear Mr. Polizzi:

I have completed the review of the document you wrote on the topic of "Reliability Considerations for Communications Satellites." I find the general outline and organization to be logically put together and in good order. The technical content of this paper is in good agreement with reliability principles and practices. The specific applications and examples cited should make this volume of interest to many people in the communication field.

I was indeed happy to read this paper which brought information to me not particularly available before, as well as the satisfied feeling I received when I realize that finally the topic of reliability has become of sufficient importance to be considered as thesis material.

Congratulations on this effort and I hope to be invited to review your next paper, which perhaps will lead to your doctorate.

Very truly yours,

Anthony J. Finocchi
Quality and Reliability
Staff Consultant

GENERAL PRECISION INC.
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KEARFOTT DIVISION

May 10, 1968

Mr. F. Polizzi
23 Ellis Street
Lincoln Park, N.J. 07035

Dear Frank,

I have reviewed your thesis entitled "Reliability Considerations for Communication Satellites" which you have written in fulfillment of your Master's Degree. I found the thesis very enlightening and note that you treat the discipline of Reliability in a very comprehensive manner.

I have noted however, that you indicate, in a few places, that Reliability of these satellites is "the" most important function. Since you are in the Reliability business I think you were somewhat carried away with the subject, as you probably should be, but I suggest you change these inferences to read that Reliability is one of the more important functions.

I might further suggest that the abstract be reviewed giving a bit more detail as to what the reader might expect when reading the entire paper. The abstract omitted some complete chapters relating to the technical and statistical parts of the thesis and deals mainly with the organizational, administrative, and narrative part.

There are some other minor comments which I have written across various pages of the draft which you will see as you go through it.

I wish you the best of luck in your endeavors.

Sincerely,

FTK/dp

F. T. Kallet
Product Assurance Mgr.