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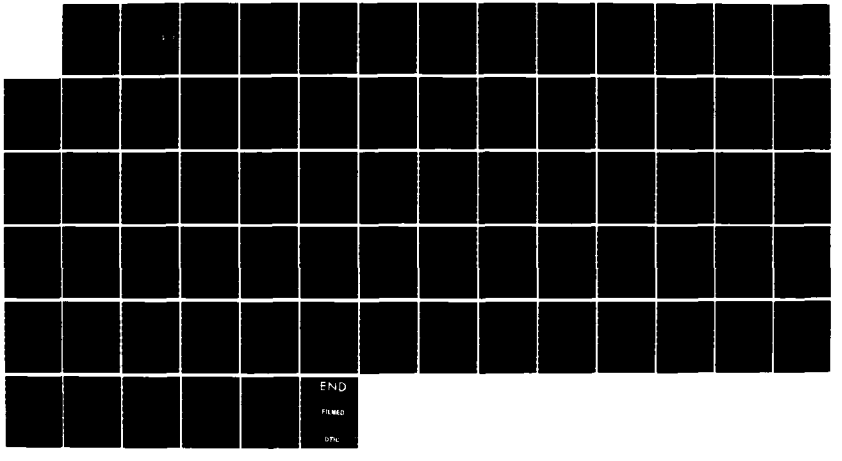

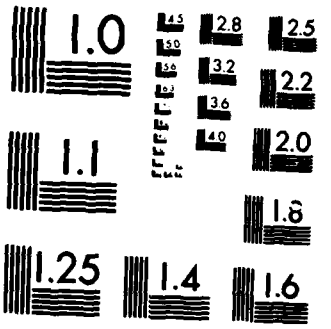

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Analysis of Orbital Satellite Storage

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November 1985

Interim Report

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Prepared for

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This interim report was submitted by the Aerospace Corporation, El Segundo, CA 90245, under Contract F04701-83-C-0084 with the Space Division (AFSC), Los Angeles Air Force Station, P. O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by H. E. McDonnell, Programs Group. Col. L. C. Young, SD/CGX was the project engineer for Space Communications Systems.

This report has been reviewed by the Office of Information (OIS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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FOR THE COMMANDER

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This study addresses whether service of sufficient duration can be expected from a satellite that has been stored on orbit for significant periods of time. The question was approached in two ways. First, an extensive review of the research on orbital storage was conducted. While there has not been a great deal of published analysis on the subject, the records of those efforts are consistent in their conclusions that orbital storage does not appear to have any adverse impact on satellites or their redundant components.

The second approach was empirical. A data set was collected, consisting of the dormant and post-dormant characteristics of redundant electronic boxes from 155 NASA, DoD and commercial satellites. Three separate investigations examined length of dormancy and subsequent length of activity of redundant units to statistically determine any relationship. The first investigation considered only the units which failed during operation, and, using regression analysis, probed for a statistical relation between the duration of dormancy and the length of activity. The second investigation divided the boxes into two groups: those which operated until the mission's termination and those which failed. Using Chi Square analysis, these subpopulations were examined with respect to the length of their dormant periods to see if there were any effects on the mission duration. The technique of "censored testing" was employed in the third analysis where an effort was made to include all of the redundant activation data by separately estimating the active lifetimes of boxes with long dormant times and those with short periods of dormancy.

From the thousands of boxes residing in the 155 satellites sampled, we found that primary boxes (having identical redundant back-ups) rarely fail (N=93). Only ten redundant boxes failed. One failed at activation; the remaining boxes provided service of varying durations. Unknown factors accounted for most of the variation in the operation time of failed redundant boxes. The causes may be idiosyncratic, or that a failed redundant box may have a similar predisposition as its primary box to fail. The results of the statistical analysis led to the conclusion that length of dormancy is not a significant contributor to electronic box failure. Any degrading effects which can be attributed to the dormancy experience will be mild. The relatively successful orbital operation of dormant redundant boxes suggests that satisfactory operation may be expected of electronic boxes in satellites stored on orbit.

Keywords: Statistical analysis; Chi Square method; regression analysis; censored testing ←

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SECTION I

BACKGROUND OF ORBITAL STORAGE ISSUE

Man-made satellites have been orbiting the earth since Sputnik was launched in 1957. These satellites have evolved from scientific experiments to a position of service for both civil and military organizations. As their usefulness has increased, so too has our dependence on the services that satellites provide. Consequently, an emphasis is placed on satellite designers and decision-makers to assure service.

The consequences of the loss of service, while always deleterious to mission objectives, takes many forms. For commercial satellite programs, loss of service is tantamount to loss of revenue. Loss of service for the National Aeronautics and Space Agency's (NASA) scientific and experimental satellite programs usually means missed opportunities for data acquisition. Interrupted or lost service of the Department of Defense (DoD) space activities, could, in its extreme form, significantly weaken our defense posture. As a result, design philosophies have been driven by the need to minimize reduced or lost service.

Procurement agencies have been debating the merits of on-orbit storage for twenty years. It has always been an attractive idea, since orbital storage nearly guarantees uninterrupted service. Although in the last decade, circumstances have resulted in several occasions of satellite storage for DoD users, it has not been until recently, that DoD satellites were launched and placed immediately into storage as a result of strategic and/or analytic aforethought. The question of the potential negative effects from orbital storage has nagged defense decision makers throughout their experience in the procurement and operation of spacecraft -- even when events in the past prompted decisions to deactivate operational spacecraft and place them into storage. Part of the problem has been that while the technical analysts have

sought to provide the statistical support and associated confidence factors to enable a decision regarding orbital storage, isolating the explicit causes of operational failures is difficult. Satellites on orbit, are seldom sufficiently instrumented to discern the failure of a specific piecepart; often, it is only possible to uncover a failure at the box level. Reliability experts have tried attacking the question through the determination of the actual operational lifetimes of piece parts, boxes and systems. However, before complete empirical lifetime data is collected, users often terminate the mission when the satellite has outlived its usefulness so that little definitive statistical confidence about the behavior of redundant components and pieceparts stored in orbit for extensive periods is available. Consequently, decision-makers in the military and commercial arenas have relied on their "intuition" that on-orbit storage is not significantly deleterious to the duration of the function subsequently required by satellites and their electronic equipment.

The questions of what is the actual operating lifetime and do indefinite periods of orbital storage affect that lifetime, are difficult to answer. One reason for this is that Defense satellite procurement agencies must guarantee that a satellite will provide service of sufficient duration to satisfy the users' mission, not provide a satellite that will last indefinitely. Satellite orbital storage may satisfy the user's pragmatic requirement of "sufficient duration" by assuring uninterrupted military service, especially if it can be determined that long periods of orbital dormancy will not significantly affect the necessary length of service once the dormant spacecraft is reactivated.

This study addresses whether the user can expect sufficient service from a spacecraft that has been stored on orbit for significant periods of time. We do not attempt to evaluate mitigating circumstances such as the use of unreliable parts, poor workmanship, and marginal design which likely affect reliability whether or not storage is employed. Instead, this study takes the

viewpoint that, somehow, despite the greatest of care, all these aspects in varying degrees may exist in any given satellite. The focus of this work, therefore, is to learn what twenty years of experience can teach us with regard to the total impact on electronic[1] components in satellites that have been dormant in orbit for extended periods.

Additionally, this study is not an attempt to evaluate the merits of ground versus orbital satellite storage. We believe that each storage mode offers benefits; and that it is within the authority of the satellite program offices to determine which mode is most advantageous to program objectives. Rather, the statement this study makes is that our on-orbit experience to date has been excellent, and is largely attributable to careful and conservative engineering design, stringent reliability requirements and the like. Thus, it is due to these technical achievements that we believe on-orbit satellite storage can be used as a mechanism for allowing more flexibility in the attainment of satellite program objectives.

We approached the question of the viability of orbital storage in two ways. First, an extensive review of the research on orbital storage was conducted. While there has not been a great deal of published analysis on the subject, the record of those efforts are consistent in their conclusions that orbital storage does not appear to have any adverse impact on satellites or their redundant components.

The second approach was empirical and asked whether satellites which have experienced a period of orbital storage, without maintenance, are able to satisfy their mission requirements. Since on-orbit storage is not currently

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1 The examination of mechanical failures due to orbital storage is excluded in the study. In the early days of space flight, mechanical devices received a great deal of attention due to concerns about wear-out. Materials and lubricants have since been discovered which address much of the mechanical wear-out problems. However, new designs which are sophisticated and intricate do warrant attention until the design is proven.

utilized to any significant extent, there is little data from orbitally stored satellites with which to study the question directly. However, an approach to the issue can be made using data from satellites in which certain subsystems have been orbitally "stored" prior to their activation. These "stored" subsystems are the backup units in certain redundant systems. Until the primary unit fails the backup unit is nonoperational, in some sort of "stored" condition. That the environmental conditions may not be exactly the same as for a truly stored satellite is granted, and this must be borne in mind when interpreting the study. On the other hand, this data is the only empirical, space-based information available.

A data set was collected which is more comprehensive than all recorded previous studies that examined post-dormant behavior of redundant boxes. The data is comprised of the dormant and post-dormant characteristics of redundant electronic boxes from 155 NASA, DoD and commercial satellites. The major analytical question we addressed was NOT how long these redundant components last after periods of dormancy, but rather do they last LONG ENOUGH to satisfy the user's mission requirements. Hence, the question is a practical one where the answer may allow the user to change paths or priorities at any time in the procurement, launch and operation of a constellation of spacecraft[2]. If the total experience for all types of satellites -- be they military, commercial or NASA -- indicates that electronic redundant components are not harmed by on-orbit storage, and that they function properly when required, it may indicate that on-orbit storage of satellites is not only an intuitively satisfying course of action, but is also a pragmatically successful way to maintain service.

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2 One important caveat is that the orbital storage of satellites is viable once design-related problems are understood and resolved.

SECTION II

EXPLANATION OF TERMS

A number of terms and phrases, while commonly used by engineers and others, nonetheless can evoke confusion and ambiguity when used in different contexts. This section provides explanations how certain terms and phrases are used in the context of this study.

1. Orbital satellite storage: satellites which have not completed their effective mission duration but are deactivated, except for part of the bus (usually Telemetry, Tracking and Command Subsystem and attitude control); not providing service to the user for a period of time determined by the user.

2. Orbital satellite spares: satellites which have served their mission and are, for the most part, no longer needed. However, the mission elements remain active or partially dormant, and are capable of providing all or partial service.

3. Dormancy: the state in which a subsystem or box is not in operation, yet is presumed operable.

4. Mission duration: a period of time, determined by the user, during which the satellite is needed to fulfill the mission's objective. While this is a somewhat subjective determination, it nevertheless provides guidance to the engineers in the satellite's design and development.

5. "Lifetime" or "life" of a satellite, subsystem, box, etc.: the actual, measured length of active service. (However, what usually occurs is that expendables are exhausted, or, for some other reason, the user terminates a satellite before the lifetime can be measured; the system, for the most part, has already served its purpose and is no longer needed.)

6. Primary box/unit: that piece of electronic hardware slated for operation from the start of the mission.

7. Redundant box/unit: electronic hardware, identical to the primary one, which is used in the event the primary box fails.

8. Box, unit, component: in this paper, these terms are treated synonymously, and refer to electronic rather than mechanical equipment.

SECTION III

A REVIEW OF EXPERIENCE REGARDING ORBITAL SATELLITE STORAGE

Introduction

Twenty years and more have passed since we began launching satellites. This experience has reached a point where we can now empirically test some of the assumptions underlying our strategies with respect to design, launch and programmatics, especially as they pertain to on-orbit satellite storage. This section reviews the DoD, NASA and commercial satellites' experiences with orbital storage, followed by the small body of literature which has analyzed data accumulated from that experience. While this paper is concerned with the degrading effects of the orbital environment on unactivated space systems, much can be learned from the reliability and orbital performance of spacecraft, in general. Therefore, this section will conclude with a discussion on the performance of activated systems, as it bears on the issue of orbital storage.

Orbital Storage Experience

Orbital storage is not a new idea. A NATO IIIB satellite,[1] launched in 1977, was used to provide short term service to the Defense Communications Agency (DCA) users until their DSCS II satellite could provide service. After 27 months, a DSCS II satellite was launched and replaced the NATO satellite. The NATO satellite was moved to another location and then deactivated except for its Power, TT & C and Attitude Control. The satellite was subsequently stored for 43 months before being reactivated. With the

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1 Communication with Messrs. Ray Berg, Program Director, and Frank Strubel, NATO III Program Office, October 3, 1984.

exception of one TWTA which failed at activation[2] and was replaced by a redundant one, the satellite has been providing continuous service to the user for over two years.

In 1978, a DSCS II[3] satellite was launched and partially activated for 18 months. Since no service was required by the user[4], it was deactivated in the same fashion as the NATO IIIB satellite to become a spare for another DSCS II. After 42 months of on-orbit storage, the satellite was reactivated with no failures. The system has been successfully operating for approximately 20 months. Due to this success, the program office felt confident to launch another DSCS II satellite late in 1982 and place it immediately in a stored condition.

The commercial satellite companies do not launch and then immediately store their satellites on orbit, but rather utilize on-orbit spares for a number of purposes (outlined later in this section). The distinctions between

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2 This storage/reactivation experience turned out to be very instructional with respect to TWTAs. It suggested that the orbital activation, deactivation and reactivation of TWTAs which have seen several thousand hours of operations, has a deleterious effect on the performance of the TWTA. Discussion with Ralph Smith, Director, FLTSATCOM/DSCS II Program Office, and Ben Thompson, TWTA Program Office, October 5, 1984.

3 Communications with Messrs. Ralph Smith, and Fred Kahn, FLTSATCOM/DSCS II Program Office, and Ben Thompson, TWTA Program Office, October 4, 1984.

4 It has been predicted that the older DSCS II satellite occupying this location would be nearing its end-of-life. Instead, it operated for almost twice its expected lifetime which meant the DSCS II just launched was redundant. This long operation time turned out to be the rule rather than the exception for the later DSCS II System. While this point will be addressed more fully later in the paper, it is interesting to note that orbital storage became a reality for DSCS II because its satellites outlived its predicted lifetimes by a considerable extent.

orbital storing and sparing for the commercial businesses[5] are, first of all, that satellite spares have usually spent the majority of their useful mission life whereas stored satellites have not. Spares may or may not be deactivated whereas stored satellites have the payload and part of the housekeeping function turned off. Commercial companies often lease out the remaining capacity of the spare so as to maximize profit, or have it serve in a standby mode (either active or inactive) should a back-up payload capability be necessary. Orbital storage is simply what it purports; namely, a satellite moved to an unobtrusive location and, for the most part, deactivated until placed into service.

To confuse the issue slightly, the DoD does not often diligently adhere to this lexical distinction between the terms "storing" and "sparing"[6]. "Spare satellites" is often used synonymously with the term "stored satellites". Moreover, the DoD also engages in the practice of sparing in the same context as the commercial world. That is, satellites which have served much of their mission are maintained in an active state for use in case part of a younger satellite's payload malfunctions. Once the propellant is almost depleted, however, the spare spacecraft may be propelled to a higher or lower orbit, where it is no longer used or in the way.

The policy of the commercial satellite company INTELSAT is "to provide spare capability in-orbit above each ocean, not on the ground"[7]. Profit is enhanced because this policy virtually ensures uninterrupted service. Consequently, years of useful information have accumulated on the

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5 Correspondence from Mr. Joseph H. O'Connor, COMSAT General Corporation to RAdm. Earl Fowler, Commander, Naval Electronics System Command. 8 May 1978; telecommunication with Mr. Jim Owens, General Manager, INTELSAT, August 30, 1984.

6 From communications with DSP, DMSP, GPS, DSCS II/III Program Offices. August, 1984.

7 Correspondence from Mr. Joseph H. O'Conner, op. cit.

performance of spare satellites and on redundant equipment. For example, in 1977, prior to using the remaining fuel to propel their orbits above synchronous altitude, seven obsolete satellite spares were reactivated so as to test all subsystems and redundant electronic equipment, "some of which had been off for almost ten years"[8]. All performed "satisfactorily" with no anomalies or failures.

As a general practice, tests are performed on all operational, spare and retired INTELSAT and COMSAT satellites. According to O'Conner, these tests have indicated "satisfactory operation of units following long term in-orbit storage". He goes on to report that "there has never been a case where a unit which has been in long term on-orbit storage and which has been thought to be in satisfactory condition failed to come on or any other unusual occurrence"[9].

NASA has no explicit sparing policy for its spacecraft programs. Rather, dormancy data is obtained from activated redundant equipment, from spacecraft which have been deactivated due to unsolvable problems with the on-board experiments, or from spacecraft which have been retired and tested years later. In one study[10], dormancy data were examined for nine NASA spacecraft, and 84 components and 39 piece parts. In effect, no reliability problems occurred that could be attributed to dormancy. The following is a synopsis of the dormancy experience from those NASA spacecraft examined.

The experiments aboard the SERT II spacecraft exhibited problems for a year after launch. The decision was made, consequently, to deactivate it and place it into storage. Two years later (1973) SERT II was reactivated to

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8 Ibid., p. 8.

9 Ibid., p. 9-10.

10 Planning Research Corporation, On-Orbit Spacecraft Reliability. Prepared for NASA, Headquarters, NASA-CR-157427. 30 September 1978.

examine its multiple restart capability and to evaluate the thruster components. Each thruster successfully started 112 times. In addition, no anomalies or failures were discovered in any of the basic subsystems. The satellite was deactivated and stored. This exercise was repeated again each year for the next five years with no failures or anomalies showing up. Not only did dormancy appear to have no affect on components, but the yearly start-ups and deactivations also demonstrated no deleterious effect. OSO-5 (Orbiting Solar Observatory) was deactivated December 31, 1972 until July 1974 at which point it was reactivated and tested. After 1 1/2 years of dormancy, no failures or anomalies were discovered in any of its subsystems. Likewise, the experiments on board GEOS-2, after 28 months of dormancy, were "found to be in good condition and operable"[11]. SAS-B was dormant for 18 months. Upon reactivation, all basic systems were reported to be normal.

Two experiments and the TV subsystem were dormant for significant periods during the mission of the Mariner 10. No parts failures were experienced at any time these systems were turned on or off.

Redundant equipment were examined on LANDSAT-I and the SMS/GOES satellites. After two years of dormancy, LANDSAT's two redundant equipment groups exhibited no anomalies or failures. Redundant boxes in SMS/GOES, after four to six months of dormancy, were also found to operate normally.

The analysis of dormant components and piece parts uncovered no failures or anomalies. The study concluded that the experience during orbital "dormancy is probably no worse than general on-orbit experience"[12].

What is interesting to note is that none of the above experiences with orbital storage were a consequence of decisions based on the relative

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11 Ibid., p. 93.

12 Ibid., p. 98.

merits of ground or orbital storage (or sparing). Instead, it was serendipidous circumstances (as in the case with NASA satellites), profit (the purpose for commercial satellites) or a defense user need which resulted in the storing or sparing of spacecraft on orbit. Specific considerations of either design or operations of orbital storage based on empirical evidence is sparse. On the one hand, the majority of those studies which do exist seem dated, since they evaluate information from satellites with late 1960's/early 1970's designs. On the other hand, their relevance may nonetheless be current since many of today's candidate satellites for orbital storage (or at least some of their components and subsystems) have designs[13] which are similar to or better than the vintage of the data analyzed. Moreover, viability of the assumption that the effects of the orbital environment on electronic equipment varies with design and complexity changes has not, as yet, been established. We will return to this point later in this section. Now, a review of studies which provided the first empirical insights into the potential effects of orbital storage will be presented.

Hammerand[14] evaluated redundant boxes from the Space and Missile Systems Organization (SAMSO, the predecessor of Space Division) satellite programs and found that, after an average of three years of on-orbit dormancy, redundant boxes experienced no failures at activation. A TRW study[15] examined activated redundant boxes from 29 of their spacecraft. None of the 14 redundant boxes failed at activation. Bean and Bloomquist[16] examined dormant components from 34 spacecraft, and found no failures to have occurred

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13 See MIL-HDBK-217D, 15 January 1982.

14 Hammerand, Roy On-Orbit and In-Plant Satellite Storage. SAMSO-TR-76-111. 19 May 1976.

15 TRW Systems, Definition of Potential and Identification of Problems for Silent Spares. Prepared for SAMSO Contract No. F04701-74-C-0044. October 1973.

16 Bean, I.E. and C. E. Bloomquist "Reliability Data from In-Flight Spacecraft: 1958-1970". Planning Research Corporation, 30 November 1971.

during dormancy. In a study[17] evaluating dormant and on-off cycled electronic equipment, reliability was found to be better than that predicted using the failure rates of MIL-HDBK-217 by 3 to 7 times. These studies all concluded that dormancy does not appear to affect the subsequent activation of redundant units. What they do not examine, is whether dormancy may affect the subsequent duration of the boxes' operation or that of the satellite's mission.

Anderson and Sugihara[18] attempted to address this question in their analysis of the same data set Hammerand used [19]. They proposed that the long term effects of orbital storage could be ascertained by comparing the longevity of the redundant box with that of the primary one. While they concluded that orbital storage "does not appear to adversely effect operation after turn-on"[20], the comparison may not have been the appropriate way to address the question. As Nishime pointed out[21], failed primary boxes may be "sick" boxes. Comparing the lengths of operation may only determine whether or not the redundant box has a problem similar to the primary box.

Watson and Stockwell[22] analyzed the lengths of dormancy versus activity of redundant boxes from the majority of Space Division satellite programs and, in particular, the post orbital storage performance of NATO III

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17 "Dormancy and Power On-Off Cycling Effects on Electronic Equipment and Part Reliability". RADC-TR-73-248. August 1973.

18 Anderson, H. and S. Sugihara, Satellite Storage Study. TOR-0081 (6902-07)-1. 15 September 1981.

19 See Hammerand, op.cit.

20 Anderson and Sugihara, op.cit., p. 24.

21 From meeting with Frank Nishime and H. E. McDonnell, The Aerospace Corporation, September, 1984.

22 Watson, R. and N. D. Stockwell, "Reliability of Dormant Spares". ATM 83(2072-07)-2. 18 March 1982.

and DSCS II. They concluded that on-orbit dormant spares are "extremely reliable".

All satellites examined which have had some orbital storage experience are still operating and still providing full service to their users. Both the Watson and Stockwell study and the Anderson and Sugihara Study found that over 90% of activated redundant boxes operated until their users terminated the mission. Moreover, those redundant boxes which did fail posed no threat to the spacecrafts' operation.

Reliability and Orbital Performance

The scarcity of data on the operational behavior of satellites stored on-orbit precludes definitive statistical analysis of orbital storage effects. Therefore, as the previous section has outlined, the question has been addressed analogously through examinations of the post-dormant behavior of redundant boxes. The issue may also be addressed through evaluations of the reliability and orbital performance of active satellites which have never had orbital storage experience. This section will briefly discuss studies which evaluate the relationship between reliability predictions and actual satellite performance.

Overall, performance evaluations of active satellites suggest that much of the design assumptions and reliability predictions guiding the development of spacecraft have been cautious, resulting in an underestimation of their actual operational life[23]. In fact, as a RAND study examining reliability factors concluded, "most DoD, NASA and commercial satellites

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23 Buehl, F. W. and R. E. Hammerand, A Review of Communications Satellites and Related Spacecraft for Factors Influencing Mission Success. Aerospace Corporation TOR-0076(6792)-1. 17 November 1975.

exhibit a characteristic almost unknown in modern high-technology products -- they function much longer than expected"[24]. One study examining satellites built and launched during the 1960's and 1970's, found that "reliability of spacecraft increased significantly, even though spacecraft size and complexity and mission length also increased"[25]. Pressure on acquisition program offices for low failure rates per spacecraft may partly explain this seemingly paradoxical relationship. In fact, the impact and publicity of the few failures that did occur cannot be minimized as a primary catalyst for increasing improvements in the areas of management, design and development of hardware, electronic components and software, as well as procedures detailing testing and operations.

The caution that is fundamental to the design and production of spacecraft is also reflected in the reliability estimates regarding their performance. A study of 42 spacecraft of various vintages and complexities, developed and produced by the same manufacturer may corroborate this point. It was found that, "on the whole, spacecraft appear to serve their users longer than would be expected based on their individual reliabilities"[26]. In a later study of 44 satellites, Leonard and Nishime[27] found that the observed mission life exceeded the predicted design life. Beuhl and Hammerand's study[28] noted a similar trend.

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24 Dreyfuss, D. J., K. P. Horn, and Major A. G. Parish, An Evaluation of Reliability Related Factors that Influence Future Spacecraft Procurement Policies. RAND Corporation WN-9534-PR. August 1976 p. v.

25 Pickering Research Corporation, Development of Reliability and Safety in the U. S. Space and Missile Programs. Prepared for Aerospace Corporation, January 1981, p. A-10.

26 Barnett, E. "Demonstrated Orbital Reliability of TRW Spacecraft". TRW 74-2286.142. December 1974, p. 3-9.

27 Leonard, B. P. and F. S. Nishime "User's Guide on Satellite System Procurement Schedule and Replenishment Launch Strategy" ASR, December 1983 (Engineering Volume)

28 See Buehl and Hammerand, op.cit.

All studies noted that the usefulness of design life and reliability predictions does not lie so much in the prediction itself, but in its employment as guidelines for the design engineers. Consequently, satellites are being "overdesigned"[29] as a technique to guarantee a minimum mission time, and, naturally, are lasting much longer. DSCS II is one case in point. The satellite was designed to serve a five year mission. Several have lasted ten years, and others show every indication of operating as long. Clearly, this is indicative of the difficulty we have of estimating satellite durability.[30]

Summary

Our search uncovered no published theoretical analysis on the physical phenomenon of orbital storage. While analysts presume that deterioration as a result of constant exposure to the space environment exists to some degree,[31] there has been no proposition detailing those variables which contribute to the degradation of electronic equipment in a dormant state.[32] The benefit of theory is that it establishes a framework by which to address the problem; it serves as a strawman, if nothing else. Perhaps not enough is known so as to create such a proposition. What is "intuitively" known to spacecraft decision-makers and manufacturers, is that electronic equipment has experienced little or no adverse effects attributable to the orbital experience.

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29 MIL-HDBK-217A through D reflects a decrease in failure rates.

30 In fact, discussions are underway concerning the advisability of launching the last DSCS II spacecraft. Many feel its need diminishes with DSCS III now becoming operational.

31 The effects on solar arrays and batteries have occupied a special area of study and concern. TWTAs also may require special heating considerations.

32 "(T)here is a great deal known about the effects of radiation, vacuum, and other elements of the space environment on materials. ...It is possible to make better quantitative estimates of degradation in the dormant state than has been done in the past. The motivation has been lacking." J. L. Wittels, IOC, Aerospace Corporation 1 November 1985.

In any event, it is reasonable to conclude that whatever negative effects the space environment may have on unactivated systems, it is not sufficient to retard the minimum mission need. In other words, experience has demonstrated that spacecraft manufacturers have succeeded in designing satellites to withstand the rigors of the orbital environment for longer than the intended duration of the satellite's mission[33]. If orbital satellite storage does have a retarding effect on the satellite's actual life, it may not be significant enough to affect the time necessary to achieve the users' mission objectives despite the duration of the storage experience.

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33 An on-going Aerospace Corporation study has found that the assumptions concerning the electron environment in higher orbits were overly pessimistic: "The electron environment is less than we have typically designed to, and in some instances, dramatically so. This translates into a reduced shielding requirement from a total dose standpoint and/or a longer life expectancy for radiation critical systems and sub-systems, i.e., less vulnerability and longer satellite lifetimes". R. G. Pruett, Aerospace Corporation, Interoffice Correspondence, 24 September 1984.

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SECTION IV

RESEARCH DESIGN

Study Framework

One approach to the question as to whether orbital storage has any deleterious affect on a mission's life is to examine the history of redundant boxes on operational space systems. Since the power to the redundant units selected for the study remains off until the primary ones fail, it appears a reasonable analogy to the environment that an entire satellite might experience when stored on orbit.

That period in which the primary box was active is equal to the time the redundant one was dormant. Its service begins at the moment of activation, soon after the primary box fails. The redundant box's length of dormancy and subsequent length of service is therefore examined. Three separate analytical procedures evaluate the proposition that evidence of degradation will be seen in the failure of the redundant box to remain active throughout the duration of the mission. The null hypothesis to be tested is:

H_o = "There is no statistical association between the period of dormancy, and the ability of the redundant box to survive the mission".

Thus, the unit of analysis becomes the redundant box, NOT the primary unit, since it is the effects of dormancy (which is a characteristic only of redundant boxes) that is being evaluated.

Description of the Data

Detailed satellite data are accumulated by the Aerospace Corporation in the Orbital Data Analysis Program (ODAP) document. It contains anomaly and

failure data for nearly all the Space Division satellite programs as well as several commercial satellite programs. These data were supplemented with more commercial satellite data obtained directly from commercial satellite companies, and with data obtained from NASA Goddard for many of their space programs. In all, activated redundant units were examined from 155 satellites, broken down as follows:

Customer	Number of Satellites
DoD	68
NASA	67
Commercial	30
Total:	155

(See Appendix A for a complete description of the data base.) Only those activated redundant boxes which had remained dormant for more than six months were considered in the analyses. This was to insure that any subsequent failure would more likely be attributable to the dormant experience as opposed to an infant mortality or launch related problem.

Description of Variables

The variables to be examined which are measurable attributes of redundant units are described below:

1. Length of dormancy, in months -- equal to the period of activity of the primary unit.
2. Length of activity, in months -- on-orbit period of operation.
3. Failure --
   (a) Failed at or before activation
   (b) Failed at a measurable time after activation

4. Current status --

   (a) The box is operational

   (b) The box failed in operation

   (c) The mission terminated while the box was still operational

   (d) End-of-life tests performed at the time of mission termination to determine which of the (never activated) redundant boxes survived the long dormancy periods.

Certain variables, which we will call "context" variables, are also attributes of redundant boxes because they describe the context in which redundant boxes operate. The inclusion of these variables allows for discrimination of differential dormancy effects.

1. Box identity -- Allows discrimination of potential dormancy effects between different electronic components.

2. Subsystem identity -- Allows discrimination of potential dormancy effects between electronic components in different subsystems.

3. Satellite program identity[1] -- Allows discrimination of potential dormancy effects between different satellite programs.

4. Orbit properties (altitude and inclination) -- Engineers from satellite programs utilizing low earth orbits believe that storing at these altitudes may have harsher environmental effects than at higher altitudes. Furthermore, almost as much station keeping, maneuvering and power dissipation are required to maintain a stored satellite as it is for an activated satellite in these orbits. Thus, orbital storage itself, they propose, may reduce the duration of available active service because the satellite cannot be "as dormant" as satellites stored in higher orbits.[2]

5. User identity (DoD, NASA, Commercial) -- Even though the same contractors build satellites for all three types of customers,

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1 See Barnett, op.cit. p. 3-9, for one satellite manufacturer's experience with bias in anomaly statistics from two troubled programs with six other programs.

2 However, satellites in low orbits "could be designed for dormancy by the use of techniques such as gravity gradient stabilization, rotisserie yaw motion for thermal and power management, etc." J. L. Wittels, IOC, The Aerospace Corporation, 1 November 1985.

the specifications and requirements to which the satellites are built may vary considerably among the customers. This variation may have a discernible effect on post-dormancy performance.

Analysis

The analysis begins with a statistical description of the sample, which includes basic measures of central tendency, variation, etc. These measures are presented for the total sample as well as all pertinent subsets of the sample as described above.

Next, three separate investigations will examine length of dormancy and subsequent length of activity of redundant units to statistically determine any relationship. If long periods of dormancy are associated with early failures, then evidence of degradation from the orbital environment would be statistically demonstrated.

Redundant units actual length of life are not known for the entire sample; that is, the actual lifetime is only known for those units which failed prior to the end of the mission. In fact, the failed redundant units comprise only a small proportion of the total number of activated redundant units. The fact that the length of life of the non-failed units is unknown, led to a three-step analysis which allowed all information from the sample to be considered in the evaluation.

The first of these investigations considers only the units which fail during operation, and probes for a statistical relation between the duration of dormancy and the length of activity. In the second investigation, the units are divided into two groups: those which operate until the mission's termination and those which fail. These subpopulations were examined with respect to the length of their dormant periods to see if there are any effects on the mission duration. The technique of "censored testing" is employed in the third analysis where an effort is made to include all of the redundant activation data by separately estimating the active lifetimes of boxes with

long dormant times and those with short periods of dormancy. The two estimates are compared to determine if any difference exists between units having long dormancy experiences and those with short dormancy times.

Limitations of the Study

To definitively address the question of the effects of dormancy on subsequent operation would require knowing the actual survival time of redundant boxes. The majority of redundant boxes in our data are still operating, and a considerable number were operating when the satellite was deactivated by the user. Indeed, the user's needs often intervene before data can be acquired for analyses such as these. This is a frequent limitation on empirical analyses, that real-life and programmatic requirements take precedence over scientific ones. However, the scope of this study has addressed this limitation by only ascertaining whether dormancy affects the redundant box's activity through the necessary mission duration, a period of time specified by the user. In other words, we are only interested in acquiring from those redundant boxes as much service as is needed; we are not asking how much life is ultimately available from those boxes.

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SECTION V

SUMMARY OF RESULTS

A summary of the results is presented in this section. A detailed account of the calculations and findings is provided in Appendix B.

Descriptive Statistics

From the 155 DoD, NASA and Commercial satellites examined, only 93 redundant electronic boxes were activated after a minimum of six months of dormancy[1], usually due to the failure of their identical primary box.[2] Considering the thousands upon thousands of redundant units that constitute the 155 spacecraft,[3] this finding alone is a significant statement regarding the durability, in general, of electronic boxes.

Redundant boxes were activated across eleven different subsystems, and represent 49 different categories of electronic boxes (see Table 1). There was too little data to do a box-by-box comparison so as to determine if dormancy contributed to the failure of a particular box. Table 2 shows that the Communications and TT&C subsystems had more redundant boxes activated than

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1 In order to test the effects of dormancy, redundant boxes were included in the sample only if they had experienced a minimum of six months of dormancy. Failure of primary boxes earlier than six months of operation may be attributable to systematic problems with both the primary and redundant components.

2 Actually, nine of the 93 redundant boxes never operated; instead they were tested at their mission's end and found to be operable.

3 Not all satellites in our sample had extensive one-for-one redundancy throughout their subsystems.

Table 1. General Breakdown of Sample

1. Different Categories of:	Numbers
Programs	16
Subsystem types	11
Boxes	49

2. Status of Boxes	Number of Boxes
Operational	55
Failed	10
Operated Until Mission Terminated (MT)	19
Never Operated, but tested at End of Mission (EMT)	9
N=	93

3. Organization	Number of Boxes
DoD	69
NASA	16
Commercial	8
N=	93

Table 2. Description of Subsystem

Subsystem	Number Activated Redundant Boxes	Months Dormant Mean	Months Dormant Std Dev	Months Operating Mean	Months Operating Std Dev	Number Failures
Attitude Control	8	40	28	35	25	1
Communications	38	34	16	25	25	5
Data Handling	1	11		25		0
Data Management	9	48	41	16	28	3
Electrical Power	8	33	25	19	15	0
Guidance & Control	5	48	34	31	48	0
MSS	1	45		8		0
Navigation	2	49	65	23	4	0
NASA Payload	3	45	27	4	2	1
Primary Sensor	1	26		4		0
TT & C	17	44	36	31	30	0

any of the others. There were five redundant box failures in the Comm subsystem (all TWTAs) and no failures in the TT&C. Again, the sample is too small to determine if dormancy statistically contributes to failure across particular subsystems.

Only one program experienced more than one redundant box failure, and that was the NATO II/III program. Four out of the 21 activated redundant boxes failed (all TWTAs). However, there is not a large enough difference between failures in boxes across satellite programs to determine the effects of dormancy.

The majority of activated redundant boxes are from satellites flying in a high earth orbit. The orbital location is classified for 20% of the boxes. Consequently, dormancy's effect on satellites' located across different orbits cannot be tested.

Eight redundant boxes failed in DoD satellites, two from NASA programs and no redundant box failures were found in commercial spacecraft. Again, the data are too sparse to determine if the dormancy experience contributes to a propensity towards failure across any type of spacecraft.

All boxes are characterized as either (a) still operating, (b) operated until mission terminated by the user (MT), (c) never operated, but at mission termination functioned normally when tested (EMT), or (d) failed, either at activation or some time later (see Table 3). Over half the boxes (n = 55) are currently in operation. 30% of the boxes either operated until their satellite's mission was terminated or were tested and found operable. This means that almost 90% of the sample are boxes that never had the opportunity to operate to the point of failure. Thus, to test whether dormancy has any influence on the propensity for a box to fail, could only be performed on the ten boxes which did fail. From the group of failures, one box failed at activation, and the others at varying times later. This very small sample size presented severe limitations on the types of analyses which could be performed in order to test the effects of orbital dormancy. To

Table 3. Description of Subsystem

Subsystem	Total Boxes	Failures	Operating	MT	EMT
Attitude Control	8	1	6	1	-
Communications	38	5	28	5	-
Data Handling	1	-	1	-	-
Data Management	9	3	-	3	3
Electrical Power	8	-	4	2	2
Guidance & Control	5	-	1	1	3
MSS	1	-	1	-	-
Navigation	2	-	2	-	-
NASA Payload	3	1	1	1	-
Primary Sensor	1	-	-	1	-
TT & C	17	-	11	5	1
TOTAL	93	10	55	19	9
(% of Total)	(100%)	(11%)	(59%)	(20%)	(10%)

NOTES:

MT - Redundant boxes were operating when mission was terminated by user.

EMT - Redundant boxes never were activated. After mission termination, redundant boxes were tested. All boxes were successfully activated.

compensate for this, we performed two other statistical techniques utilizing the information on the remaining boxes to present a more complete picture of the effects, if any, from orbital dormancy.

An assumption in the study is that dormancy will affect all the electronic boxes more or less equally. The assumption is a pragmatic one both in terms of preserving the sample size, and in the sense that satellites are launched with the general presumption that all boxes will last as long as needed. The one notable exception to this rule, however, may be TWTAs. Of the 38 activated redundant boxes in the communications subsystem, 19 were TWTAs and five of those failed. Four of the failed TWTAs were from early NATO satellites, and one resided in a DSCS II spacecraft. As mentioned earlier, it was learned that some of the TWTA failures were more likely a result of being

turned on, off, and on again rather than their dormant experience. Despite their infamy, we have included the TWTAs in the sample to allow for worse case analyses.[4]

Regression Analysis of Failed Redundant Units

In testing the association between length of dormancy and subsequent length of activity, Regression Analysis was chosen because it could take into account the small amount of information available on the failed boxes, as well as test the null hypothesis of months active as a function of months dormant. Regressions were run for the entire sample of ten failed boxes, and for two subsets of the sample: one group of the five TWTAs, and one group consisting of the remaining five boxes. This division of the sample was done to either underscore or allay concerns about the reliability of TWTAs after significant periods of dormancy.

Table 4 presents the results of the analysis for the entire sample of failed units. The average length of dormancy was about a year and a half. The subsequent average duration of operation was a little over one year. A weak, although significant relationship between length of operation as a function of dormancy was demonstrated. This means that dormancy accounts for approximately 10% of the total variation in length of operation of the failed units. In other words, there are other unknown factors which contribute to failures. Since there were so few failures, however, uncovering these other contributing factors may prove to be a very difficult exercise.

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[4] Unlike ground storage conditions, the space environment is considered a benign, as well as a prefered, environment for the storage of Traveling Wave Tubes. In fact, the major TWT manufacturers have specified to the DoD that, given the proper thermal conditions, no testing is required for TWTs orbitally stored. (They do recommend, however, that TWTs stored on the ground be tested periodically before launch.)

Table 4. Regression Analysis of Activated Redundant Units Which Failed

Months Dormant	Months Active		
N = 10	10	Degrees of Freedom (N-2) =	8.00
Mean = 17.66	15.40	Slope =	-0.61
SD = 10.77	14.41	Intercept =	15.40
		Est Var =	205.49
		Std Err of Est =	0.42
		T Statistic =	-1.45
		Cor Coeff =	0.34
		R^2 =	.1156
		Level of Significance =	90%

The regressions run on the two subgroups of failures were not statistically significant (see Tables 5 and 6), meaning that a relationship between length of dormancy and length of subsequent operation for TWTAs or the other subgroup of boxes has not been demonstrated. However, the sample sizes were too small (n = 5) to allow for any definitive conclusion at this point.

Table 5. Regression Analysis of Activated Redundant TWTAs Which Failed

Months Dormant	Months Active		
N = 5.00	5.00	Degrees of Freedom (N-2) =	3.00
Mean = 19.00	17.00	Slope =	-0.62
SD = 12.60	14.75	Intercept =	17.00
		Est Var =	259.80
		Std Err of Est =	0.57
		T Statistic =	-1.09
		Cor Coeff =	0.23
		R^2 =	.0529
		Level of Significance =	85%

Table 6. Regression Analysis of Activated Redundant Non-TWTA Units Which Failed

Months Dormant	Months Active		
N = 5.00	5.00	Degrees of Freedom (N-2) =	3.00
Mean = 16.20	13.80	Slope =	-0.68
SD = 8.33	13.88	Intercept =	13.80
		Est Var =	267.49
		Std Err of Est =	0.88
		T Statistic =	-0.77
		Cor Coeff =	-0.12
		R^2 =	.0144
		Level of Significance =	75%

Test Between Dormancy and Subsequent Mission Life Satisfaction

The preceding analysis indicates that a small amount of lifetime degradation may be attributable to length of dormancy. However, it is not clear whether such degradation seriously affects the mission duration. Here, it is necessary to reiterate our distinction between the potential lifetime of the box, and that period of time necessary to complete the mission. The former is not always measurable because all but the failed boxes are terminated before their life is spent. Since the user defines the length of the mission, it is assumed that the potential lifetime of a box will, in general, exceed the time needed for completion of the user's mission. For the most part, the experience to date[5] substantiates this assumption.

To determine whether the mission duration is affected by dormancy, two smaller subgroups were extracted from the population of 93 redundant boxes: those which operated until the mission was terminated by the user, and those which failed prior to mission termination. Excluding those units which

5 See Section III.

are still operating reduced the sample size to 38 redundant boxes. These two subgroups were further dichotomized into groups experiencing either long or short periods of dormancy. A chi-square test was performed to determine whether length of dormancy was statistically associated with success in meeting the mission's life requirements. (See Appendix B for the mechanics of this procedure.)

With a confidence level of > .995, long dormancy periods and mission satisfaction were found to be significantly related. This means that, in effect, the longer the primary unit lasts, the less operating time is required for the redundant unit to complete the mission. Hence, the likelihood of completing the mission is extremely high.

This finding complements the regression results in that mission duration does not appear to be affected by dormancy. However, while the two preceding analyses are leading in the direction to accept the null hypothesis, there is still no definitive conclusion regarding the effects of dormancy on subsequent active operation. The primary reason is that the test data are "censored." This means that we have different kinds of information on the boxes with respect to their potential time of operation. Only ten redundant boxes operated until failure, while the remaining 83 are either still operating or were terminated at the mission's end. Therefore, to maximally utilize the information available on the data, a mathematical treatment of censored data had to be performed. This led to the next and final analysis.

Estimation of Active Lifetime Using Censored Testing[6]

The data are divided into two groups, one having long periods of dormancy, and the other with short dormant experiences. An estimate of the mean active lifetime is performed for the two groups to determine whether

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[6] See D. J. Bartholomew, "The Sampling Distribution of an Estimate Arising in Life Testing," in Technometrics, Vol. 5, No. 3, August, 1963, for the approach used in this analysis.

differential dormancy times affect redundant units subsequent operational life expectancy. (Again, Appendix B provides detail of this analysis.)

The estimated mean lifetime for redundant boxes which were dormant for short time periods was 172.5 months with a standard deviation of 62.2 months. This means that redundant boxes which were dormant for less than two years can mathematically be expected to operate between 110 and 242 months. In other words, users can feel confident that redundant boxes, dormant for short time periods, will operate until the mission is terminated.

Those boxes which were dormant for over three and one half years had a mean lifetime estimate of 420 months, with a standard deviation of 421.4 months. Because of the large standard deviation, it is not possible to say much about the central tendency of active operation. This high dispersion in the estimate is due to only one of the units failing, indicating that insufficient time had elapsed for a definitive test to be performed. This, therefore, leads to the acceptance of the null hypothesis, meaning that it can not be demonstrated that dormancy significantly affects the subsequent operation of redundant boxes to the end of the mission.

Conclusion

From the thousands of boxes residing in the 155 satellites sampled, we found that primary electronic boxes (having identical redundant back-ups) rarely fail. While this reduced our analysis options by limiting the size of the data set of activated redundant boxes, it makes a pleasing contribution to the growing recognition that satellites are, for the most part, highly reliable and durable.

Only ten redundant electronic boxes failed. One failed at activation; the remaining boxes provided service of varying durations. This small number of failures indicates several things with respect to orbital storage. First, the incidence of failure of both the primary box and its back-up is very small. This in itself should provide confidence to

decision-makers as to the viability of orbital storage on electronic equipment. Our analysis also indicated that unknown factors accounted for most of the variation in the operation time of failed redundant boxes. The causes may be idiosyncratic; or it may be, as Nishime points out, that a failed redundant box may have a similar predisposition as its primary box to fail.[7]

Any degrading effects which can be attributed to the dormancy experience will be mild; and, in fact, has posed no hindrance to the completion of a satellite's mission, to date. The relatively successful orbital operation of dormant redundant boxes suggests that satisfactory operation may be expected of electronic boxes in satellites stored on orbit.

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7 Communications with Nishime and McDonnell, op-cit.

SECTION VI

DISCUSSION AND IMPLICATIONS

Introduction

The challenge of the past two decades was to develop technology so that satellites would, first of all operate, and second of all, endure for the time required. The new challenge is one which creatively applies and modifies that knowledge so that satellite users may be served in an efficient and cost effective manner. The implications of the findings in this study point to the heart of strategic planning and decision-making regarding the procurement, launch and operation of spacecraft. Orbital storage is an option which addresses several programmatic needs of the user, part of which includes when and how long the service is needed. World events, national elections, changing technology and the like, all may intervene causing user needs to be more dynamic in character than absolute. Hence, flexibility, overall, needs to be built into the procurement, launch and operation of spacecraft in order to meet the challenging and dynamic requirements of the user community. Orbital storage is one means for achieving this goal.

Programmatics

Since orbital storage does not appear to be detrimental to the satellites' mission, programmatic planning is consequently affected in two significant ways. First, orbital storage can influence the satellite development cycle and second, it can strongly affect program costs related to launch. The latter impact is amplified by shuttle manifesting considerations.

In the early phase of the acquisition process satellites are designed and developed to establish a constellation that will provide full service for the users. Subsequent production is planned to replace retired or failed satellites in the constellation. If orbital storage is viewed by

decision-makers as safe and viable, as the study indicates it to be, then the production and launch of these spacecraft do not need to be driven by predicted need dates. Efficiencies could be built into the manufacturing process which may allow simultaneous production, rather than extended sequential production. Subsequent storage on orbit after scheduled launch, would minimize launch costs, as well as optimize service availability.

In the last decade, the DoD has utilized a myriad of launch strategies. They range from low priorities "getting in the queue" for a DoD or NASA launch vehicle, to "launch on demand" for which a launch vehicle and satellite are held at the ready. Both extremes incur additional expenses. "Getting in the queue" causes the satellite program to maintain a satellite "standing army" for periods the length of which are forced by higher priority programs. "Launch on demand" is the most expensive in that it ties up satellites as well as launch vehicles and launch facilities. Satellite development schedules can be planned in a cost effective manner if decision makers can be confident that on-orbit storage is viable.

Acceptance of on-orbit storage will allow acquisition managers to concentrate on the technical trades between potential obsolescence resulting from on-orbit storage if the duration is too long, versus on ground storage which allows for the up-grading of the spacecraft. This trade is within the decision-making bounds of the acquisition manager and need not be driven by outside (other program priority) forces.

The findings of the study provide confidence for another type of strategy which may assure uninterrupted service. The data shows that satellites do not completely fail; portions fail. The commercial satellite businesses have benefited from this by leasing to customers the residual capability of payloads from older satellites. The use of partial satellites, that is, part of the payload from the older satellite and its complementary payload part from the newer satellite, can work together to provide full service to the military user. For the DoD, this may serve as another method of maximizing the total utility of a spacecraft.

Future Areas of Study

This study has sought to assimilate twenty years of satellite experience as it bears on the question of orbital storage. The data reflects the performance of current and past technology. Newer technologies may not do as well. On the other hand, perhaps they can be made to do better, which is the real point. Our space systems are reliable, whether active or dormant, because we have learned how to design them to be reliable. Therefore, further study and specific documentation in other areas are recommended to assure that the implementation of satellite orbital storage sucessfully meets users' needs.

Satellite Design Considerations:

The data described in this study are restricted to the failure experience of redundant electronic boxes. Examination of the effect of orbital storage on other spacecraft elements which have demonstrable life-degrading modes is necessary. Included in this group are batteries, solar arrays, radiation sensitive components, and items using finite expendable sources such as propellent. Should orbital storage be a part of a satellite program strategy, design engineers will need to be sensitive to those areas as well as to thermal control surfaces, optics adhesives, coatings, seals, wire insulation and the like.

The number of satellite electronic equipment located at low earth orbits were too few to permit any statistical conclusions regarding the effects of dormancy. The question of greater radiation damage to components, whether active or not, at lower altitudes is an open and important issue which design engineers need to address.

More data must be accumulated on the operational and post-dormant operational behavior of microelectronics before the conclusions of this study can be extended to all electronic equipment. While our knowledge of the radiation environment has improved over the years, the designers, nonetheless must protect against an infrequent worst case. In particular, prompt and total dose impacts require further examination in the field of microelectronics.

Analysts need to specify which subsystems and boxes should be deactivated and which need to remain operational, especially during eclipse season. Testing is another issue which requires investigation and documentation, not only with respect to which components need testing but also documentation as to how much testing is required.

The design criteria of mechanical parts and electro-mechanical equipment often has enough reserve to assure meeting requirements. Electronic equipment have wear-out patterns which are different and which are accommodated in design through derating by larger percentages. Since satellites are never totally dormant when stored on orbit, design criteria needs to be re-evaluated to allow for the longer life expected from equipment which will always be operational.

Programmatic Considerations:

For DoD satellites, there is the issue of how to bring orbitally stored and spare satellites into service during a crisis situation. The Satellite Control Network would presumably be inoperable requiring a greater emphasis on the survivability of mobile mission control segments.

On-orbit storage will be needed for any program which must maintain a high degree of mission availability. Therefore, the actual strategic and cost benefits of orbital storage for DoD satellites need to be quantified. Trade-offs between orbital storage and other methods for assuring service need to be considered. DCA, for example, has performed studies on the use of partial satellites for assuring uninterrupted service. The use of partial satellites in conjunction with orbital storage should be evaluated. Other areas which warrant consideration are designs that permit soft degradation in user service.

SECTION VII

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APPENDIX A

Tables A-1 and A-2 list all the satellite programs we examined in compiling our data base of activated redundant units. Not all spacecraft, especially the non-DoD ones, had one-for-one redundancy throughout their systems. In addition, activated redundant boxes were selected only if they had been dormant for at least six months.

Table A-3 specifies all the information available to us for our data set of redundant boxes. The boxes are sorted alphabetically. The satellite type, program and subsystem is identified for each box. Also, each box's length of dormancy, operation, and status at the time of compilation is shown. Finally, the mean and standard deviation of dormant and active time for each category of box is listed.

Table A-1. Air Force Satellite Programs

OADAP Code	Program
CL1	--
CL2	--
DMSP	DMSP (Meteorological)
DSCS 2	DSCS II (Communications)
DSCS 3	DSCS III (Communications)
FLTSATCOM	FLTSATCOM (Communications)
GPS	GPS (Navigation)
IDCSP	IDCSP (Communications)
NATO 2	NATO II (Communications)
NATO 3	NATO III (Communications)
NUCL DTECT	VELA (Nuclear Detection)
SKYNET 1	Skynet 1 (British Communications)
SKYNET 2	Skynet 2 (British Communications)
SPACE TEST	Space Test Program
TAC COMSAT	Tactical Communications Satellite

Table A-2. Non-Air Force Satellite Programs

OADAP Code	Program
AE	Atmosphere Explorer (NASA Scientific)
AEM	Applications Explorer Mission (NASA Scientific)
ANIK	Anik (Telesat Canada Communications)
ANNA	Anna (Army-Navy-AF-NASA Geodetic)
APOLLO	Apollo (NASA) (MOON MISSION)
APPLE	Apple (India Communications Experiment)
ARIEL	Ariel (British) (Space Experiments)
ATS	Applications Technology Satellite (NASA)
BEACON	NASA (AIR DENSITY)
BIOSAT	Biosatellite (NASA)
BS	Japanese TV Broadcasting
COMMSAT	Commercial Communications Satellite
COURIER	Communication (Army)
DE	Dynamics Explorer (NASA) (Solar Energy)
DISCOVERER	ADVANCED RESEARCH PROJECTS AGENCY (ARPA)
DODGE	Dodge (Navy)
EARLY BIRD	EARLY BIRD (Commercial Communications) (Also known as INTELSAT01)
ECS	Japanese Experimental Communications
ESAA	European Space Agency Astronomical (Also known as TD)
ESSA	Environmental Science Services Administration (Commerce Department)
EXPLORER	Explorer (NASA) (ARMY)
GEMINI	Gemini (NASA)
GEODETIC	Geodetic Explorer (NASA)
GEOS	GEOS (ESA) (Geodynamic Experimental Ocean Satellite)
GMS	Weather (JAPAN)
HEAO	High Energy Astronomy Observatory (NASA)
HELIOS	German Solar Probe

Table A-2. Non-Air Force Satellite Programs (Continued)

OADAP Code	Program
HEOS	Highly Eccentric Orbit Satellite (ESA) (Scientific)
HERMES	Hermes (Experimental Communications) (NASA-CANADA)
IMP	Interplanetary Monitoring Platforms (NASA)
INJUN	Injun (Navy Scientific)
INSAT	Insat (India Communications, meteorological, TV Broadcast)
INTELSAT	Intelsat (Commercial Communications)
IRAS	Infrared Astronomical (European)
ISEE	International Sun-Earth Explorer (NASA)
ISS	Japanese Ionospheric
TTOS	Improved TIROS (NASA) (Operational Weather)
IUE	International Ultraviolet Explorer (Astronomical)
LANDSAT	Landsat Earth Resources (NASA) (Also known as ERTS)
LES	Lincoln Lab/MIT Experimental Satellite
LUNAR ORB	Lunar Orbiter (NASA)
MAGSAT	NASA Scientific
MARECS	Marecs (ESA) (Maritime Communications)
MARINER	NASA (Mars)
MARISAT	Commercial Communications
MERCURY	NASA
METEOSAT	Meteosat (ESA) (Weather)
NIMBUS	Nimbus (NASA) (Meteorological)
NOAA	National Oceanic and Atmospheric Administration Advanced TIROS-N (Weather)
NTS	Navigation Technology Satellite (NAVY)
OAO	Orbiting Astronomical Observatory (NASA)
OGO	Orbiting Geodetic Observatory
OSCAR	Oscar (Communications for Radio Operators)
OSO	Orbiting Solar Observatory
OTS	Orbital Test Satellite (ESA Communications)

Table A-2. Non-Air Force Satellite Programs (Continued)

OADAP Code	Program
OV	Orbiting Vehicle
PAF	Particles and Fields (NASA) (Moon)
PALAPA	Indonesian Communications
PEGASUS	Meteoroid Detection (NASA)
PIONEER	Pioneer (NASA) (Planetary Mission)
PIONEVENUS	Pioneer Venus Probe (NASA)
RANGER	Lunar Probe (NASA)
RELAY	Relay (NASA) Experimental Communications
SAS	Small Astronomy Satellite (NASA)
SATCOM	RCA Communications
SEASAT	SEASAT (NASA) (Oceanographics)
SCORE	ARPA Communications
SKYLAB	Skylab (NASA)
SME	Solar Meosphere Explorer (NASA Scientific)
SMS	Synchronous Meteorological Satellite (Also known as GOES) (Geostationary Operational Environmental Satellite)
SOLMAX	Solar Maximum Mission (NASA)
SOLRAD	Solar Radiation (NAVY)
SPAS	German Commercial For Science and Technology Work
SPACELAB	European Scientific
SURVEYOR	Surveyor (NASA Lunar Probe)
SYMPHONIE	Franco-German Telecommunication
SYNCOM	Syncom (NASA Communications)
TDRS	Tracking and Data Relay Satellite (NASA)
TELSTAR	Telstar (Commercial Communications) (Bell Lab)
TIROS	Weather (NASA)
TIROS-N	See ITOS, Flight 15
TRANSIT	Transit (NAVY) Navigation

Table A-2. Non-Air Force Satellite Programs (Continued)

OADAP Code	Program
UOSAT	English Scientific Educational
VANGUARD	(Revealed Pear-Shaped Earth) (NAVY)
VIKING	Viking (NASA) (MARS)
VOYAGER	Voyager (NASA) (Planetary Mission)
WESTAR	Western Union Communication
Z1	NASA Unidentified Spacecraft (1972-1976) Study

Table A-3. Characteristics of Activated Redundant Units (Broken Down by Unit and by Status)

Program	Subsystem	Unit	Orbit	Months Dormant	Months Active	Status	Type	Statistics by Unit		
CL-1	Data Manag.	9 REDUN UNITS	S	113	0	EMT	D	Count = 1		
DMSP	ELEC POWER	BAT. CHARGE REG	LEO	52	0	EMT	D	Count = 1		
GPS	NAVIG	BB PROC	LEO	56	19	0	D	Count = 1		
Nato III	Comm	Beacon Transm.	GEO	24	73	0	D	Count = 1		
DMSP	DATA MANAG.	CENTRAL PROC	LEO	31	1	F	D	Count = 3	MeanD = 32.	sdD = 4.6
DMSP	DATA MANAG.	CENTRAL PROC	LEO	39	18	MT	D		MeanA = 9.3	sdD = 6.9
DMSP	DATA MANAGE.	CENTRAL PROC	LEO	28	9	MT	D			
GOES 4	TT&C	CENTRAL TELEMETRY	GEO	9	14	0	N	Count = 1		
DMSP	ELEC POWER	CHARGE CONTROL	LEO	2	0	EMT	D	Count = 1		
LANDSAT 2	ELEC POWER	COM CLK POW SPLY	LEO	86	4	MT	N	Count = 1		
FLTSAT	ELEC POWER	COMM CONVERTER	GEO	32	31	0	D	Count = 3	MeanD = 32.	sdD = 7.3
FLTSAT	ELEC POWER	COMM CONVERTER	GEO	42	35	0	D		MeanA = 29	sdA = 5.8
FLTSAT	ELEC POWER	COMM CONVERTER	GEO	24	21	0	D			
SBS	TT&C	COMMAND RECEIVER	GEO	18	35	0	C	Count = 1		
CL-1	GUID & CONT	CONT ELEC ASS'Y	S	28	31	MT	D	Count = 1		
GOES 5	TT&C	CONTROL TELEMETRY	GEO	11	3	0	N	Count = 1		
CL-1	DATA MANAG.	DATA COMPRESSOR	S	10	27	F	D	Count = 1		
SPACE TEST	DATA MANAG.	DATA PROC	S	7	5	F	D	Count = 1		
COMSTAR 101	ATTITUDE CONTROL	DESPIN CONT ELEC	GEO	83	17	0	C	Count = 1		
COMSTAR 102	ATTITUDE CONTROL	DESPIN CONTROL	GEO	15	76	0	C	Count = 1		
CL-1	TT&C	DIG TELE	S	75	23	0	D	Count = 1		
NOAA III	DATA HANDLING	DIGITAL TAPE REC	LEO	11	25	0	N	Count = 1		
Nato III	Comm	Down Converter	GEO	43	20	0	D	Count = 3	MeanD = 43	sdD = N/A
Nato III	Comm	Down Converter	GEO	43	20	0	D		MeanA = 20	sdA = N/A
Nato III	Comm	Down Converter	GEO	43	20	0	D			
Nato III	Comm	Driver .	GEO	43	20	0	D	Count = 2	MeanD = 43	sdD = N/A
Nato III	Comm	Driver	GEO	43	20	0	D		MeanA = 20	sdA = N/A
IUE	ATTITUDE CONTROL	GYRO 1	HEO	15	34	F	N	Count = 2	MeanD = 34.	sdD = 19
IUE	ATTITUDE CONTROL	GYRO 2	HEO	54	1	0	N		MeanA = 17.	sdA = 16
GPS	NAVIG	HIGH POWER AMP	LEO	43	27	0	D	Count = 1		
CL-1	TT&C	KGE 28A	S	113	0	EMT	D	Count = 1		
Nato III	Comm	Limiter	GEO	43	20	0	D	Count = 3	MeanD = 43	sdD = N/A
Nato III	Comm	Limiter	GEO	43	20	0	D		MeanA = 20	sdD = N/A
Nato III	Comm	Limiter	GEO	43	20	0	D			
Nato III	Comm	Local Oscillator	GEO	43	20	0	D	Count = 3	MeanD = 43	sdD = N/A
Nato III	Comm	Local Oscillator	GEO	43	20	0	D		MeanA = 20	sdA = N/A
Nato III	Comm	Local Oscillator	GEO	43	20	0	D			
COMSTAR 102	ATTITUDE CONTROL	MOTOR DRIVER	GEO	15	76	0	C	Count = 2	MeanD = 49	sdD = 34
COMSTAR 101	ATTITUDE CONTROL	MOTOR DRIVER	GEO	83	17	0	C		MeanA = 46.	sdA = 29

Table A-3. Characteristics of Activated Redundant Units (Broken Down by Unit and by Status) (Continued)

Program	Subsystem	Unit	Orbit	Months Dormant	Months Active	Status	Type	Statistics by Unit		
LANDSAT 2	SPACECRAFT	MAR. BD TAPE REC	LEO	48	42	MT	N	Count = 1		
DSCS II	TT&C	PCM ENCODER	GEO	78	1	MT	D	Count = 1		
Nato III	TT&C	PCM MULTIPLEXER	GEO	8	61	0	D	Count = 1		
DMSP	ELEC POWER	POWER COND.	LEO	13	24	MT	D	Count = 2	MeanD = 14	sdD = 1
DSCS II	ELEC POWER	POWER COND.	GEO	15	42	0	D		MeanA = 33	sdA = 9
Nato III	Comm	Preamp.	GEO	43	20	0	D	Count = 1		
CL-1	GUID & CONT	RATE GYRO ASS'Y	S	113	0	EMT	D	Count = 1		
MARISAT 202	Comm	RECEIVER 3	GEO	60	24	0	C	Count = 2	MeanD = 58.	sdD = 1.5
MARISAT 203	Comm	RECEIVER 3	GEO	57	14	0	C		MeanA = 1.5	sdA = 5
LANDSAT 2	ATTITUDE CONTROL	RMP MOTOR 1	LEO	51	29	MT	N	Count = 1		
DMSP	GUID & CONT	ROLL-YAW COIL	LEO	53	0	EMT	D	Count = 1		
GOES 2	Comm	S-BAND	GEO	52	7	0	N	Count = 1		
LANDSAT 3	MSS	SCAN MONITOR	LEO	45	8	0	N	Count = 1		
GOES 3	ATTITUDE CONTROL	SIDE 1	GEO	11	36	0	N	Count = 1		
SPACE TEST	GUID & CONT	SPIN COIL	S	16	126	0	D	Count = 1		
NOAA 5	PRI SENSOR	TAPE RECORDER	LEO	26	4	MT	N	Count = 1		
GOES 1	TT&C	TELEMETRY ENCODER	GEO	31	48	0	N	Count = 1		
CL-1	DATA MANAG.	THRESHOLD MEM	S	113	0	EMT	D	Count = 3	MeanD = 68.	sdD = 13
CL-1	DATA MANAG.	THRESHOLD MEM	S	86	0	EMT	D		MeanA = 0	sdA = 0
CL-1	DATA MANAG.	THRESHOLD MEM	S	7	92	MT	D			
CL-1	TT&C	TRANSMITTER	S	34	0	MT	D	Count = 9	MeanD = 45.	sdD = 35
Nato II	TT&C	TRANSMITTER	GEO	12	97	MT	D		MeanA = 38.	sdA = 34
DMSP	TT&C	TRANSMITTER	LEO	48	9	MT	D			
CL-1	TT&C	TRANSMITTER	S	31	9	MT	D			
FLTSAT	TT&C	TRANSMITTER	GEO	13	32	0	D			
DSCS II	TT&C	TRANSMITTER	GEO	32	95	0	D			
CL-1	TT&C	TRANSMITTER	S	103	50	0	D			
CL-1	TT&C	TRANSMITTER	S	113	12	0	D			
SPACE TEST	TT&C	TRANSMITTER	GEO	22	44	0	D			
Nato II	Comm	TWTA	GEO	7	18	F	D	Count = 19	MeanD = 29	sdD = 17
Nato III	Comm	TWTA	GEO	11	18	F	D		MeanA = 29.	sdA = 29
Nato II	Comm	TWTA	GEO	16	43	F	D			
Nato III	Comm	TWTA	GEO	43	0	F	D			
Nato III	Comm	TWTA	GEO	43	20	0	D			
Nato III	Comm	TWTA	GEO	43	20	0	D			
CPX	Comm	TWTA	S	11	24	0	D			
CPX	Comm	TWTA	S	35	61	0	D			
DSCS II	Comm	TWTA ECHL	GEO	58	21	MT	D			
DSCS II	Comm	TWTA ECHL	GEO	14	5	MT	D			

Table A-3. Characteristics of Activated Redundant Units (Broken Down by Unit and by Status) (Continued)

Program	Subsystem	Unit	Orbit	Months Dormant	Months Active	Status	Type	Statistics by Unit		
DSCS II	Comm	TWTA ECHL	GEO	8	127	O	D			
DSCS II	Comm	TWTA ECLL	GEO	56	23	MT	D			
DSCS II	Comm	TWTA ECLL	GEO	32	35	O	D			
DSCS II	Comm	TWTA ECLLC	GEO	35	22	O	D			
DSCS II	Comm	TWTA MCHL	GEO	18	6	F	D			
DSCS II	Comm	TWTA MCHL	GEO	41	86	O	D			
DSCS II	Comm	TWTA MCHL	GEO	13	54	O	D			
DSCS II	Comm	TWTA MCHL	GEO	14	43	O	D			
DSCS II	Comm	TWTA MCLL	GEO	56	23	MT	D			
DSCS II	Comm	Tunnel Diode AmpGEO	GEO	28	51	MT	D	Count = 1		
COMSTAR 101	Comm	UHF AMP 3	GEO	18	81	O	C	Count = 1		
GOES 4	Comm	UHF RECEIVER	GEO	7	16	O	N	Count = 1		
GOES 2	PAYLOAD	VISSR ENCODER	GEO	18	2	F	N	Count = 2	MeanD = 45	sdD = 27
SMS 2	PAYLOAD	VISSR ENCODER	GEO	72	6	O	N		MeanA = 4	sdA = 2
CL-1	GUID & CONT	VLV DRIV ASS'Y	S	34	0	EMT	D	Count = 1		
		N = 93	Mean =	39.3	27.7					
			SD =	27.6	27.6					

NOTES:

1. TYPE:
   - D = DoD
   - N = NASA
   - C = COMMERCIAL

2. STATUS:
   - O = OPERATIONAL
   - F = FAILURE
   - MT = MISSION TERMINATED
   - EMT = END OF MISSION TESTING
   - (Dormant redundant units tested to see if working; no failures.)

3. ORBIT:
   - GEO = GEOSYNCHRONOUS
   - LEO = LOW EARTH ORBIT
   - S = CLASSIFIED
   - HEO = HIGH EARTH ORBIT

4. STATISTICS:
   - MeanD = AVERAGE MONTHS DORMANT
   - MeanA = AVERAGE MONTHS ACTIVE
   - sdD = STANDARD DEVIATION OF MONTHS DORMANT
   - sdA = STANDARD DEVIATION OF MONTHS ACTIVE
   - Count = UNIT COUNT

APPENDIX B

Regression Analysis

Regression analysis was employed to test the degree of association between months active and months dormant. Tables B-1, B-2 and B-3 provide the details of the analysis for the entire sample of failed redundant units, and for the subsets of failed TWTAs and failed non-TWTAs.

Table B-1. Regression Analysis of Months Active as a Function of Months Dormant (All Failed Units)

Program	Subsystem	Unit	Orbit	Months (D) Dormant	Months (A) Active	Type	d (D-MEAN)	a (A-MEAN)	ad (a*d)	ae (est. a)	a^2 ((a-ae)^2)
NATO II	Comm	TWTA	GEO	16.00	43.00	D	1.60	27.60	-44.16	16.38	708.80
NATO II	Comm	TWTA	GEO	7.00	18.00	D	-10.60	2.60	-27.56	21.87	14.99
NATO III	Comm	TWTA	GEO	11.00	18.00	D	-6.60	2.60	-17.16	19.43	2.04
CL-1	DATA MANAG.	DATA COMPRESSOR	S	10.00	27.00	D	-7.60	11.60	-88.16	20.04	48.45
GOES 2	PAYLOAD	VISSR ENCODER	GEO	18.00	2.00	M	0.40	-13.40	-5.36	15.16	173.08
SPACE TEST	DATA MANAG.	DATA PROC	S	7.00	5.00	D	-10.60	-10.40	110.24	21.87	284.63
IUE	ATTITUDE CONTROL	GYRO 1	MEO	15.00	34.00	M	-2.60	18.60	-48.36	16.99	289.43
DMSP	DATA MANAG.	CENTRAL PROC	LEO	31.00	1.00	D	13.40	-14.40	-192.96	7.22	38.68
DSCS II	Comm	TWTA MCHL	GEO	18.00	6.00	D	0.40	-9.40	3.76	15.16	83.83
NATO III	Comm	TWTA	GEO	43.00	0.00	D	25.40	-15.40	-391.16	-0.11	0.01
			N =	10.00	10.00			SUM a*d =	-708.4	SUM a^2 =	1643.94
			MEAN =	17.60	15.40			SUM a^2 =	2076.40	SUM d^2 =	1160.40
			STD DEV =	10.77	14.41						

NOTES:

1. TYPE: D = DOD
   M = NASA
   C = COMMERCIAL

2. ORBIT: GEO = GEOSYNCHRONOUS
   LEO = LOW EARTH ORBIT
   S = CLASSIFIED
   MEO = HIGH EARTH ORBIT

3. D = MONTHS DORMANT
   A = MONTHS ACTIVE

DEGREES OF FREEDOM (N-2) =	8.00
SLOPE =	-0.61
INTERCEPT =	15.40
EST VAR =	205.49
STD ERR OF EST =	0.42
T STATISTIC =	-1.45
COR COEFF =	-0.34
LEVEL OF SIGNIFICANCE =	90%

Table B-2. Regression Analysis of Months Active as a Function of Months Dormant (Failed TWTAs Only)

Program	Subsystem	Unit	Orbit	Months (D) Dormant	Months (A) Active	Type	d (D-MEAN)	a (A-MEAN)	ad (a*d)	ae (est. a)	a^2 ((a-ae)^2)
NATO II	Comm	TWTA	GEO	16.00	43.00	D	-3.00	26.00	-78.00	18.87	582.24
NATO II	Comm	TWTA	GEO	7.00	18.00	D	-12.00	1.00	-12.00	24.48	42.00
NATO III	Comm	TWTA	GEO	11.00	18.00	D	-8.00	1.00	-8.00	21.99	15.90
DSCS II	Comm	TWTA MCHL	GEO	18.00	6.00	D	-1.00	-11.00	11.00	17.62	135.10
NATO III	Comm	TWTA	GEO	43.00	0.00	D	24.00	-17.00	-408.00	2.04	4.15
			N =	5.00	5.00			SUM a*d =	-495.0	SUM a^2 =	779.40
			MEAN =	19.00	17.00			SUM a^2 =	794.00	SUM d^2 =	2176.00
			STD DEV =	12.60	14.75						

NOTES:

1. TYPE: D = DOD
   M = NASA
   C = COMMERCIAL

2. ORBIT: GEO = GEOSYNCHRONOUS
   LEO = LOW EARTH ORBIT
   S = CLASSIFIED
   MEO = HIGH EARTH ORBIT

3. D = MONTHS DORMANT
   A = MONTHS ACTIVE

DEGREES OF FREEDOM (N-2) =	3.00
SLOPE =	-0.62
INTERCEPT =	17.00
EST VAR =	259.80
STD ERR OF EST =	0.57
T STATISTIC =	1.09
COR COEF =	-0.23
LEVEL OF SIGNIFICANCE =	85%

Table B-3. Regression Analysis of Months Active as a Function of Months Dormant (Non-TWTA Failed Units)

Program	Subsystem	Unit	Orbit	Months (D) Dormant	Months (A) Active	Type	d (D-MEAN)	a (A-MEAN)	ad (a*d)	ae (est. a)	a^2 $((a-ae)^2)$
CL-1	DATA MANAG.	DATA COMPRESSOR	S	10.00	27.00	D	6.20	13.20	81.84	18.02	80.72
GOES 2	PAYLOAD	VISSR ENCODER	GEO	18.00	2.00	N	1.80	-11.80	-21.24	12.58	111.85
SPACE TEST	DATA MANAG.	DATA PROC	S	7.00	5.00	D	-9.20	-8.80	80.96	20.06	226.66
IUE	ATTITUDE CONTROL	GYRO 1	MEO	15.00	34.00	N	-1.20	20.20	-24.24	14.62	375.74
DMSP	DATA MANAG.	CENTRAL PROC	LEO	31.00	1.00	D	14.80	-12.80	-189.44	3.74	7.49
			N =	5.00	5.00			SUM a*d =	-235.80	SUM a^2 =	802.47
			MEAN =	16.20	13.80			SUM a^2 =	346.80	SUM d^2 =	1925.60
			STD DEV =	8.33	13.88						

NOTES:

1. TYPE: D = DOD
   N = NASA
   C = COMMERCIAL

2. ORBIT: GEO = GEOSYNCHRONOUS
   LEO = LOW EARTH ORBIT
   S = CLASSIFIED
   MEO = MIGH EARTH ORBIT

3. D = MONTHS DORMANT
   A = MONTHS ACTIVE

DEGREES OF FREEDOM (N-2) =	3.00
SLOPE =	-0.68
INTERCEP =	13.80
EST VAR =	267.49
STD ERR OF EST =	0.88
T STATISTIC =	-0.77
COR COEFF =	-0.12
LEVEL OF SIGNIFICANCE =	75%

Chi-Square Test Between Dormancy and Mission Life Satisfaction

The hypothesis tested is whether mission life satisfaction is affected by length of dormancy. Table B-4 depicts those boxes which operated until the mission was terminated ("Pass") and those which did not ("Fail"). They are further dichotomized as having long dormant times or short (long = 1, short = 0)

Table B-4. Description of Test Data

MISSION "PASS"			MISSION "FAIL"		
Length of Dormancy Group	Mos. Dormant	Mos. Active	Length of Dormancy Group	Mos. Dormant	Mos. Active
1	113	0	1	43	0
1	113	0	0	31	1
1	113	0	0	18	2
1	113	0	0	18	6
1	86	4	0	16	43
1	86	0	0	15	34
1	78	1	0	11	18
1	58	21	0	10	27
1	56	23	0	7	5
1	56	23	0	7	18
1	53	0			
1	52	0			
1	51	29			
1	48	42	Long = 1		
1	48	9	Short = 0		
1	39	18			
1	34	0			
1	34	0			
0	31	9			
0	28	51			
0	28	9			
0	28	31			
0	26	4			
0	14	5			
0	13	24			
0	12	97			
0	7	92			
0	2	0			

The Chi-square analysis assumes that if n_1, n_2, ...n_k and e_1, e_2 ...e_k represent actual and expected frequencies respectively, for the K possible outcomes that are to be performed n times; then as n becomes infinite, the distribution of the random variable

$$\sum_{i=1}^{k} \frac{(n_i - e_i)^2}{e_i} \tag{1}$$

will approach that of a χ^2 variable with k-1 degrees of freedom.[1]

Contingency tables were constructed (see Tables B-5 and B6) to study the relationship between the two variables of classification; that is dormancy length (long, short) and mission satisfaction (pass, fail). Chi-square tests the hypothesis as to whether dormancy is related to mission satisfaction. Let p_{ij} be the probability that a box selected at random from the data (see Table B-4) will be a member of the cell in the i^{th} row and j^{th} column of the contingency table. Let $p_i.$ be the probability that the box will be a member of the i^{th} row and let $p._j$ be the probability that the box will be a member of the j^{th} column

$$H_o: P_{ij} = P_i \cdot P_j, \qquad \begin{matrix} i=1,\ldots,r \\ j=1,\ldots,c \end{matrix} \tag{2}$$

By applying (1), χ^2 will assume the form under the hypothesis H_o

$$\chi^2 = \sum_{i=1}^{r} \sum_{j=1}^{c} \frac{(n_{ij} - np_i.p._j)^2}{np_i.p._j} \tag{3}$$

---

1 Hoel, Paul G. Introduction to Mathematical Statistics, John Wiley & Sons, Inc., 4th Edition, p.228.

Table B-5. Distribution of Data with Regard to Null Hypothesis

	"Long" Dormant Times	"Short" Dormant Times
Pass:	14	14
Fail:	5	5
	19 boxes	19 boxes

Table B-6. Actual Distribution of Data

	"Long" Dormant Times	"Short" Dormant Times	Total
Pass:	18	10	28
Fail:	1	9	10
	19 boxes	19 boxes	38 boxes

Table B-7. Chi-Square Analysis

	"Long" Dormant Time	"Short" Dormant Time
Pass:	1.143	1.143
Fail:	3.2	3.2

$\chi^2 = 8.686$
(1 degree of freedom)

Confidence level > .995

Estimation of Active Lifetime Using Censored Testing

The technique of censored testing is used when the underlying distribution of the failures of the redundant boxes follows an exponential density function

$$f(t) = \frac{1}{\theta} e^{-t/\theta}, \quad 0 \leq t < \infty, \quad 0 \leq \theta < \infty$$

where t is time, θ is the expected lifetime and the following restrictions on the observations apply: the t_i are known only if $t_i \leq T_i$ (i<1, ..., n).

Our failure data falls into this category since the only redundant boxes for which the actual lifetimes, t_i, are known, are those that failed before the end of the mission or before the cutoff date of the study. The end constraint is represented by observations on the variable, T_i, which is the observed period of active operation for non-failed units.

Under the circumstances that relatively few of the units have actually failed, an estimator of the expected life, θ, of the redundant boxes and an estimator of the variance of θ is available (see Bartholomew, op cit, Section 4). The estimator θ for θ is implicitly defined by the following equation:

$$\sum_{i=1}^{n} \frac{a_i T_i}{1-e^{-T/\hat{\theta}}} = \sum_{i=1}^{n} T_i \qquad \text{where } a_i = \begin{cases} 1 & \text{if } t_i < T_i \\ 0 & \text{otherwise} \end{cases}$$

Although there is no general closed form solution to this equation, the left hand side of the equation is monotonic in $\hat{\theta}$, and the right hand side is constant for a given set of data; therefore, it is a simple matter to solve for $\hat{\theta}$ numerically. The variance for θ is given by:

$$\text{VAR}(\hat{\theta}) = \theta^2 / \sum \frac{Q_i}{1-Q_i} \log^2 Q_i$$

The way this estimator was used was to divide the sample into two groups, those redundant boxes which were activated after relatively short dormancy periods, i.e., less than two years, and those which were turned on after periods longer than two years. Next, the estimated lifetime for boxes in each group was calculated using the equations above. The results were statistically tested to determine if there were significant differences in the estimated lifetimes for the two groups.

Table B-8 presents the data on the redundant boxes for both groups along with the calculations and results of the statistics.

Table B-8. Estimate of Lifetime in Short and Long Dormancy Groups

Short Dormancy Group					Long Dormancy Group				
Months Dormant	T_i	t_i	Q_i		Months Dormant	T_i	t_i	Q_i	
7	92		0.59	0.3915	43	20	0	0.95	0.0461
7	102	18	0.55	0.4211	43	20		0.95	0.0461
7	59	5	0.71	0.2769	43	20		0.95	0.0461
7	16		0.91	0.0849	45	8		0.98	0.0187
8	61		0.70	0.2847	48	42		0.90	0.0944
8	127		0.48	0.4856	48	9		0.98	0.0210
9	14		0.92	0.0747	51	29		0.93	0.0662
10	103	27	0.55	0.4240	52	0		1	0
11	3		0.98	0.0165	52	7		0.98	0.0164
11	36		0.81	0.1806	53	0		1	0
11	24		0.87	0.1246	54	1		1.00	0.0023
11	52	18	0.74	0.2491	56	19		0.96	0.0439
11	25		0.87	0.1294	56	23		0.95	0.0529
12	97		0.57	0.4066	56	23		0.95	0.0529
13	32		0.83	0.1624	57	14		0.97	0.0325
13	54		0.73	0.2572	58	21		0.95	0.0484
13	24		0.87	0.1246	60	24		0.94	0.0551
14	5		0.97	0.0273	72	6		0.99	0.0140
14	43		0.78	0.2114	75	23		0.95	0.0529
15	42		0.78	0.2071	78	1		1.00	0.0023
15	76		0.64	0.3393	83	17		0.96	0.0393
15	40	34	0.79	0.1984	83	17		0.96	0.0393
15	76		0.64	0.3393	86	0		1	0
16	126		0.48	0.4833	86	4		0.99	0.0094
16	93	43	0.58	0.3946	103	50		0.89	0.1113
18	81		0.63	0.3563	113	12		0.97	0.0279
18	41	2	0.79	0.2028	113	0		1	0
18	39	6	0.80	0.1940	113	0		1	0
18	35		0.82	0.1761	113	0		1	0
22	44		0.77	0.2157	113	0		1	0
	172.5 = θ'_L					420 = θ'_M			
	3868.7 = VAR					177558.5 = VAR			
	62.2 = STDEV					421.4 = STDEV			
	# observations = 30					# observations = 31			
	# failures = 8					# failures = 1			
	$\sum T_i$ = 1662					$\sum T_i$ = 430			

where:

T_i = { observed period of active operation for non-failed units.
{ time failed units would have been under observation.

t_i = active lifetime of failed units

Q_i = { $\exp\{ - T_i/\theta'_L\}$ for short dormancy group
{ $\exp\{ - T_i/\theta'_M\}$ for long dormancy group

$$\theta'_L = \frac{\frac{1}{N}\sum_{i=1}^{N} T_i}{-\ln\left(1 - \frac{n}{N}\right)}$$

$$\theta'_M = \frac{\frac{1}{M}\sum_{i=1}^{M} T_i}{-\ln\left(1 - \frac{m}{M}\right)}$$

} estimates of "lifetime" where

N = # units in short dormancy group
n = # failed in short dormancy group
M = # units in long dormancy group
m = # failed units in long dormancy group

$$VAR = \frac{\theta'^2_L}{\sum_{i=1}^{N} \frac{Q_i}{1-Q_i} \times \ln^2 Q_i}$$ for short dormancy group

$$VAR = \frac{\theta'^2_M}{\sum_{i=1}^{M} \frac{Q_i}{1-Q_i} \times \ln^2 Q_i}$$ for long dormancy group

} estimator variance

St Dev = $\sqrt{VAR}$

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