A Reliability Driven Mission For Space Station

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SUMMARY & CONCLUSIONS

The repair of the Hubble Space Telescope has validated the feasibility of repair in space. This paper proposes that the International Space Station be used as a repair base for the many communication, scientific and military satellites, in Low Earth Orbit, and that the Space Shuttle be used to retrieve such satellites. It is shown that the lifetime of such a satellite is primarily limited by the amount of propellant provided. Other major systems such as batteries and solar panels are designed so that there is a small probability of them failing before the satellite lifetime is reached. The primary components which fail infrequently before the end of design lifetime are the electromechanical components of the attitude control system. The electronics are shown to have a decreasing failure rate and a low probability of failure within the lifetime. It is proposed that the shuttle, (or in the future a space tug), be used to move any repairable satellite at the end of its mission to the Space Station. The cost for operating a satellite for one lifetime plus replenishment of propellant and replacement of electromechanical attitude control components, batteries, and solar panels for a second lifetime is considerably less then launch of one satellite and launch of a replacement satellite. The cost per year of operation for replenishment/replacement can in the limit approach one half of the cost per year for the initial orbit boost plus a replacement orbit boost.

1. INTRODUCTION

The current missions of the International Space Station (ISS) are space science and studies of life in space, but in the future, manned travel to Mars and other planets may be added. Another important mission which we propose adding in the immediate future is replacement of key satellite components with high failure rates in order to significantly increase the lifetime and decrease the cost of maintaining a satellite system. Early studies of this concept by NASA and DOD took place in 1986 and 1987 as part of the effort called Space Assembly, Maintenance, and Servicing (SAMS) [1]. The Department of Defense has recognized that re-supply of consumables, repair/replacement of components, and reconfiguration of spacecraft" are key items to plan for in satellite operations [2]. The space insurance industry has recently experienced mounting claims for satellite failures, indicating recent decreases in satellite reliability, and suggests that "reliable ways to replace or salvage failed spacecraft" is one possible solution. [3]. Cost effective repair involves replacing components that fail frequently but are light enough so that boost cost into space is low compared to a new satellite. Typical candidates for replacement are gyros, solar panels, batteries, and fuel supplies for attitude control and station keeping. There have been three satellite repair missions, the first was the April 1-11, 1984 repair of the Solar Maximum Satellite via a Shuttle extra-vehicular activity (EVA). The second and third missions were repairs, also by EVAs from the Shuttle, of the Hubble Space Telescope (HST) in an orbit 331 nautical miles above the earth. The HST, launched on April 25, 1990, experienced the first repair on December 2-13, 1993 and the second Shuttle repair on February 11-21, 1997 [1]. In addition there have been numerous repairs and resupply of the American Space Station Skylab and the Russian Salyut and Mir Space Stations and periodic building, re-supply, and repair missions have been carried out and are planned for the International Space Station.

Many satellites are classified as being in Geosynchronous Earth Orbit (GEO), that is, a circular orbit at an altitude of 23,300 miles having the same period as the earth's spin rate, thus causing the satellite to appear stationary above a point on the earth. Most other satellites occupy Low Earth Orbit (LEO), situated several hundred miles above the earth and characterized by an orbit period of about 90 minutes. A few satellites are in elongated elliptical orbits. There are many satellite populations which can benefit from repair: military, commercial, and scientific (NASA). The most accessible ones are those in LEO. The largest population is current and planned mobile communication systems, e.g. Table 1. [4]. In the next decade, about 213 satellites worth $23 billion will be launched [3].

Study of Table 1 reveals two important facts: there should be over a hundred satellites which are initial candidates for repair, and the planned lifetime is short (5-8) years. The 1999 bankruptcy of Iridium relieved the new owners of much of the debt incurred in building the $5 billion system. The new service is now returning a profit, but this may not be sufficient to cover the costs of launching new satellites as the current ones age [5]. Thus repairs that extend the lifetime of such satellites may be vital to making the refinanced system a commercial success. Information on a GEO military communication satellite, DCS, first launched in 1982, can be found at a FAS web site, [6]. A number of launches occurred during the 1980's and 1990's and launches are scheduled in 2002 and 2003.

Table 1 Typical Mobile Communications Satellites Planned or in Place

System	Iridium	Globestar	Ellipso
Operator	Iridium Wash. DC	Globestar San Jose, CA	Mobil Comm. Wash. DC
Satellites	66	48	14
Satellite Life yr.	5-8	7.5	5-7
Orbit	780 km 485 m	1400 km 870 m	520-7846 km 323-4875 m
Attitude Control System	Momentum bias system	3-Axis control	?
Power	Solar array and batteries	Solar array and batteries	Solar array and batteries

There seems to be three approaches for improvement of satellite reliability:

1. Improve reliability of spacecraft to reduce the failure rate.
2. Reduce the manufacture and boost cost of spacecraft, making an improved success rate moot
3. Extend the lifetime of spacecraft, thereby increasing return on investment.

The global investment in the International Space Station, ISS, was originally based on the concept of industrializing space by exploiting the unique characteristics of the space environment for commercial purposes. It soon became apparent that ventures envisioned for the ISS could not produce the return on investment common to other commercial space ventures like communications, weather, and Earth observation satellites. As a result the ISS mission was changed to one of science, since there need be no expectation of any commercial return from basic scientific research within typical corporate time scales. However, there may be a role for the ISS that could directly and substantially affect the economics of typical commercial space businesses, and it involves the approach suggested in item 3 mentioned above.

The reliability of typical major components of a commercial satellite will be assessed in Section 2 of this paper. Results obtained illustrate the fact that some components are more reliable than they need be because failure is more likely to occur first in others. The quantity of propellant stored in the satellite to counteract the effects of drag forces to maintain a stable orbit and the amount of propellant used by reaction control systems for accurate stationkeeping are of great importance in establishing satellite lifetime. All satellites currently in use depend upon the on-board propellant supply. No matter how reliable the mechanical or electronic components of the satellite, when the propellant runs out, the satellite fails. If all the other components of the satellite have additional life left, the mere replenishing of propellant can extend the productive life of the satellite.

A properly designed satellite has a high probability of lasting for its design lifetime. However, the probability of success decreases rapidly thereafter since the satellite runs out of sufficient power, either through the depletion of propellant or degradation of solar panels or exhaustion of batteries. Propellant is necessary for precise orbit maintenance and in many designs it is used in the attitude control system. Because running out of propellant causes the satellite to fail, even with all systems operative, the reliability of those systems generally does not fix the time of satellite overhaul. Thus, we can equate the overhaul time with the lifetime and compute the major satellite components that need to be replaced during overhaul. In general, batteries and solar panels are sized to last for the mission lifetime as dictated by the propellant supply. This leaves the electromechanical elements in the attitude control system and the satellite electronics to be considered. In Section 2 we shall show that these failure rates are in most cases modest so that substantial capital cost is completely lost because of the inequities in component reliability. The intent of this paper is to illustrate how those losses can be minimized by prudent application of in-space replenishment and overhaul.

A productive role for the ISS in the commercial satellite industry is twofold: to provide a means to replenish satellite propellant supplies, and, ultimately, to overhaul satellites. The Space Shuttle is capable of reaching LEO satellites in orbits up to 650 miles, such as IRIDIUM and ELLIPSO (at closest approach) satellites but not GLOBESTAR (see Table 1). However, the Shuttle is too expensive to employ merely for such retrieval missions . As an alternative, an Orbital Maneuvering Vehicle (or OMV, as first suggested by NASA a dozen years ago when such a vehicle's capabilities were considered important for Space Shuttle activities [7], not to mention those of space stations) could be employed to capture, return and re-launch ailing or spent satellites. Though development of robotic OMV's has been suggested for on-orbit servicing of satellites, the presence of skilled personnel aboard the ISS make such complicated development programs quite unnecessary. Thus, a simple robotic OMV, or "space tug" will suffice. Furthermore, as part of an international cooperative effort, the broad-based replenishment and overhaul of commercial satellites is exactly the kind of (fee-paid) service the ISS partner governments should be providing to commercial, government, and military satellites to ameliorate the costs of space access and occupation.

Actually the list of candidates for overhaul in space is somewhat larger than the categories discussed above. There are many satellites problems, such as placement in useless orbits, stuck solar panels, and so on, which could probably be remedied in space if the satellites are retrieved to the Space Station for servicing.

2. SATELLITE RELIABILITY MODELS

This paper focuses on generic methods for assessing the advantages of using the ISS for repair of satellites in low Earth orbit (LEO). The most likely candidates for repair are communications satellites, (notwithstanding the poor financial health of some LEO communication constellations); however, weather satellites, military satellites and other scientific satellites may also qualify. In the next decade, about 213 satellites worth $23 billion will be launched [3]. In essence, a viable candidate for a space repair mission is any satellite designed for a long term mission, e.g., greater than 5 years, that requires replacement by another satellite if it fails in service.

The possibility of satellite repair does not at present apply to higher altitude GEO satellites because they are too high for the Space shuttle to reach. However, the OMV mentioned previously would be capable of reaching these higher altitude satellites. The significant amounts of fuel necessary to reach GEO altitude in a short period of time need not be a barrier. Low thrust ion engines, for example, could be used to provide a slow ascent to GEO altitude (22,300 miles) and a slow descent to the ISS altitude (237 miles). In the case of a long life satellite (15 years or more), technology may have changed sufficiently that repair of the older technology is not attractive, whereas in other cases gradual improvements in technology may be accommodated by replacement of key upgraded components. Such upgrades have already taken place and more are planned for the Hubble Space telescope (HST) [1]. There is also some possibility that ion thrusters might be incorporated in the future design of higher altitude LEO or GEO satellites to slowly lower such satellites into a more accessible orbit for capture and servicing.

2.1 System Failure Rates

The purpose of this section is to estimate the overall failure rate of a LEO satellite and to determine which subsystems are potential candidates for replacement at the end of satellite life, i.e., when propellant must be replaced and the satellite repaired or overhauled. Access to a large database of modern satellite failures would allow an analysis of *specific* satellite failure rates and subsystems or line replaceable units (LRUs) that are candidates for replacement. Unfortunately, such data is not available to the authors and much of the calculations in this section are based on typical ranges for representative satellites. The four main repositories of spacecraft failure data are: JPL's Payload Flight Anomaly Database (PFAD), NASA Goddard's Spacecraft Orbital Anomaly Report (SOAR), the Air Forces's Orbital Data Acquisition Program (ODAP) and the Air Forces's Space Systems Engineering Database (SSED). (ODAP and SSED databases are maintained for the Air Force by the Aerospace Corporation).

Caceres [8] presents the *average* success rate for various commercial payloads over the past decade. He reports the number of launches, launch failures, payloads, and on-orbit failures for all satellites in years 1990 - 2000 for all countries. The data for on orbit failures is given in Table 2 during the three periods reported in the Caceres paper. The reliability shown in the 5th column is given by the ratio of successful payloads to payloads launched. For our purposes, we can deal with the composite data shown on the 4th line of the table. Note that it is not uncommon for some problems to occur immediately after a satellite launch and for some to be fixed by signals sent from ground control. For example, the data reported for year 1999-2000 actually included 8 incidents of malfunction, however, 4 of these were remedied over a period of weeks or months and are not classified as failures.

Table 2 Failure Rates of Newly Launched Satellite Payloads, Caceres [8].

Period orbit	Time yrs.	Failed	Pay-loads	Reliab. R(t)	Fail Rate λ	R(5)	R(7)
1990–1994	5	45	486	0.907	0.0195	0.907	0.872
1995–1999	5	60	409	0.853	0.0318	0.853	0.800
1999–2000	1	4	132	0.970	0.0305	0.970	0.808
1990–2000	----	109	1027	------	0.0273	0.873	0.826

The simplest reliability model is to assume that the failure rate (hazard) is constant ($z(t) = \lambda$) yielding the reliability model given in Eq. (1).

$$R(t) = e^{-\lambda t} \tag{1}$$

Solving for the failure rate λ yields

$$\lambda = - \ln\{R(t)\}/t \tag{2}$$

If we substitute the reliability data from Table 2 into Eq. 2 we may solve for the failure rate λ given in 6th column of the table. Substitution of these two failure rates into Eq. (1) yields the reliabilities given in the last two columns. The failure rate, λ, for the composite data is the average of the three failure rates, and the resulting reliability for 7 years, 0.826, can be used as our representative figure. Thus, for the 64 satellite IRIDIUM constellation we would expect about 11 failures in 7 years of operation. Even if the reliability for 7 years of IRIDIUM were as high as 0.95, one would still expect 3 failures in 7 years.

To supplement the Caceres data we can examine the reliability of two other satellites. An RCA GEO communications satellite designed for 7.5 years of operation had a design reliability of 0.56 if one assumed that all of the

24 communications channels are operating. Substitution into Eq. 2, $\lambda = -\ln\{0.56\}/7.5$, yields $\lambda = 0.0773$. [9]. This failure rate is somewhat higher than that of Table 2; however, this is an older satellite and extra channels were incorporated to assure reasonable operation even with a few failed channels. Another study [10] shows that the equivalent constant failure rate for a GEO communications satellite is 2.4×10^{-6} failures/hr. Multiplication by 8,766 hours per year yields $\lambda = 0.0210$, and the 7 year reliability is exp (-0.0210 x 7) = 0.86, which agrees quite well with the reliability values given in Table 2.

The following sections examine failure rates for particular components or classes of components. In general the data can be categorized as describing electronics boards, attitude control components, and power system components. Clearly both attitude control systems and power systems have electronics boards, so these are lumped in with the category electronic boards, leaving mainly electrical and electromechanical components.

2.2 Satellite Electronics Failure Rates

Hecht [11,12] conducted a comprehensive study of *electronics* failures in over 300 satellites for which approximately 2,500 malfunctions were reported. Although much of this data is 20 years old, it is still useful. The overall finding was that satellite electronics failure data showed a decreasing failure rate with time. One of Hecht's explanations for this was the fact that many satellites had redundant components and even if one unit failed, the failure was detected but the satellite continued to operate. The data used in the report did not reduce the number of components in such a case, thus the failure rate (hazard) decreased. Another explanation (proposed by the authors of this paper, but not proposed by Hecht) is that most of the units reported on were electronic boards and their components were probably preponderantly integrated circuits. Most available data on integrated circuits shows a decreasing failure rate with time [13]. In any event, Hecht fitted a Weibull failure rate model of the form given in Eq. (3a,b) to the decreasing data, as follows:

$$z(t) = \beta t^{\beta-1} / \alpha \qquad (3a)$$

$$R(t) = \exp(-t^{\beta} / \alpha) \qquad (3b)$$

in which t = hours in orbit. Hecht found the best fit to the data was for $\alpha = 255$ hours and $\beta = 0.28$. The reliability values corresponding to this model are given in Table 3.

The conclusion is that electronics failures are not the primary elements limiting satellite lifetime, and other items, such as the components of the attitude control and power systems, must dominate the computation of satellite lifetime. Furthermore, the slowly decreasing nature of the reliability function given in Table 3 is helpful to our overall goal. The probability of electronics lasting for 14 years is calculated to be 0.901. We assume that any satellites diagnosed with electronic board failure during the 7 year overhaul will not be renewed. At this stage the differences and complexity of electronic boards makes their replacement in space too complex but future designs carried out with overhaul in mind may change this. This means that any satellites with electronic failures in the first 7 years will not be overhauled and the probability of electronics surviving another 7 years is actually 0.901/0.918 = 0.982. Thus, if we assume Hecht's data is still applicable, the probability of an electronics failure during the second 7 years for a satellite that has not had one in the first 7 years is quite small.

Table 3 Satellite Electronics Reliability Based on Hecht's Weibull Model, [11,12].

Weibull Model	P(survive 1 yr.)	P(surv. 5 yr.)	P(surv. 7 yr.)
R(t)= $\exp(-t^{-0.28}/255)$	0.951	0.925	0.918

The conclusions that may be drawn from a decreasing electronics failure rate such as that demonstrated are quite intriguing. If a satellite were fitted with electronics boards designed for space replacement during an overhaul, then the replacement parts *should not be new ones*! It would be better to have the boards operating on the ground in a 7-year burn-in so that only the survivors would be sent into space as replacement parts. These burned-in components could be individual boards or complete satellites depending on the economics. An even better alternative would be to scavenge electronic parts that remain good from any satellites that experienced an electronics failure during the first 7 years, (these parts have been burned-in in a real environment, the actual orbit in space).

Our example of an overall 7-year reliability of 0.826 predicts 11 failures in an IRIDIUM constellation of 64 satellites. However, the 7-year electronics reliability in Table 3, 0.918, only predicts 5 electronics failures. It is likely that by identifying and swapping failed boards in the 5 with electronics failures we would expect to renew the electronics on 3 or 4 of these satellites. Thus, with new propellant and new electromechanical components, one could overhaul 9 or 10 of the failed satellites. There is clearly great potential for overhauling satellites on the ISS.

2.3 Attitude Control Components

A satellite is guided into orbit by a navigation or orbit injection system that places the center of gravity in an acceptable orbit around the earth. LEO satellites are placed in a stationary orbit several hundred miles above Earth, whereas GEO satellites are placed in an orbit 23,300 miles high. Once in orbit, the satellite attitude control system takes control and any tumbling in orbit is removed. The second task is to point the satellite in a particular direction and stabilize the pointing. The purpose of pointing the satellite in a particular direction is one or more of the following: point the solar cells toward the sun, point directional communication antennas toward a region of the earth, point a sensor or a telescope toward a region of the earth or a target in space, etc. Attitude control systems vary in design and some typical architectures are summarized in Table 2.

Table 4 Typical Satellite Attitude Control Systems [4].

System Name	Iridium	Globestar	Ellipso
Attitude control	Momentum bias system	3-axis control	?
Power	Solar array + batteries	Solar array + batteries	Solar array + batteries

A 3-axis attitude control system has three orthogonal rate gyros (older systems "iron" gyros, newer ones laser gyros) whose rate information is integrated to obtain angular information. Sometimes sun sensors, earth horizon sensors, star trackers, earth magnetic field sensors, and other position sensors are used to provide additional angular information.

Momentum wheels are often used to provide torques about three mutually orthogonal axes for angular actuation. A speed-up of the momentum wheel provides an equal and opposite torque applied to the spacecraft. During an orbital period, the satellite is exposed to various cyclic torques such as the variations in earth gravity, solar radiation pressure, etc. which speed up and slow down the momentum wheels during an orbit. Sometimes magnetic field torquers pushing against the magnetic field of the earth are used as actuators to cancel out some of these effects. Some disturbance torques, such as those arising from solar pressure, are secular (in the same direction) and over several weeks the momentum wheels reach their maximum speed. This is called saturation of the momentum wheel and control about this spin axis is lost. Thus, an additional system, a reaction control system (RCS) composed of orthogonal gas jets (generally hydrazine) is used to de-spin (unload) the momentum wheels. Often 3-axis systems have one or more gyros and reaction wheels pointed at an angle(s) to the three axes so that components are produced along each axis and these redundant gyro(s)/wheel(s) serve as a backup should one of the primary components fail. The attitude control system generally fails soon after the gas is expended.

A momentum bias system is simpler and cheaper than a 3-axis control system and employs a single momentum wheel spun up to a constant speed of about 5,000 rpm. A reaction control system counters the torque on the satellite while this spin-up takes place. Magnetometers can also be used for sensing the magnetic field of the earth and magnetic torquers can be used to "push" against this magnetic field to steer the spin axis of the momentum wheel.

Other techniques of attitude control are in use or have been proposed, such as gravity gradient systems, where the elongated shape of the satellite is such that there is a larger gravity force on the lower part of the satellite than the upper and the lower points toward the earth. Also, some authors propose that instead of a battery to store energy gathered by solar cells, the energy should be used to speed up a pair(s) of counter rotating momentum wheels in a momentum bias or 3-axis configuration. Thus, the momentum wheel system is used to provide control torques and electric generators on the shafts convert the stored momentum into electrical power.

Gyroscope Failure Rates. Gyroscopes are components that may be considered candidates for replacement in space. Typical failure rates for so-called "iron gyros" can be obtained from handbooks and previous space projects and some values typical values appear in Table 5

Table 5 Failure Rate of Typical Satellite Gyroscopes

Component	Application	Point Estimate Of Failure Rate
Gyroscope, General	Satellite (1)	3.503×10^{-6} failures / hr.
Gyroscope, Rate Integrating	Satellite (2)	1.908×10^{-6} failures / hr.
Gyroscope	Compton Gamma Ray Observatory (3)	4.225×10^{-6} failures/hr.
Gyroscope	Hubble (4)	7.843×10^{-6} failures/hr
	average	4.3947×10^{-6} failures/hr.

Data Sources: (1),(2) NPRD-3, [14]; (3) Wilford [15]; (4) Leary [16]; (note the shuttle replaced Hubble gyroscopes).

Converting the average gyroscope failure rates into failures per year yields: $\lambda_g = 0.0385$ failures per year. The probability of a single gyro surviving 7 years, as given by Eq. (1), is 0.764. If there are three gyros, the probability of all three surviving seven years is only 0.446. Clearly redundant iron gyros are needed, and the first service mission of Hubble replaced the package of 4 gyros since two had failed. Obviously other position sensors are present so that HST was still operable (but its redundancy was compromised) by the two gyro failures. The reliability of a two out of four system [17] is given by

$$R(2:4) = p^4 + 4p^3(1 - p) + 6p^2(1 - p)^2 \qquad (4)$$

in which p is the probability of a single gyro surviving. Substitution of p = 0.764 in Eq. (4) yields R(2:4) = 0.957, which is an acceptable reliability. Returning to our example of an IRIDIUM constellation of 64 satellites, and assuming a 2:4 gyro system, we would expect about 3 gyro system failures in 7 years. Another approach is to use the newer more reliable laser ring gyros.

Magnetometer and Magnetic Torquer Failure Rates. The reliability of magnetometers used in satellite control was calculated to be 0.9995 for the seven year IRIDIUM lifetime. Substitution in Eq. (2) yields a failure rate of 7.144×10^{-5} failures per year or 8.15×10^{-9} failure/hr [18] and perhaps magnetic torquers have a similar reliability. The number of survivors for the 64 satellites due to one of 3 magnetic torquer failures is 0.9995x3 x 64 = 63.90, thus magnetometer failures should be negligible. We assume similar failure rates for magnetic torquers.

Momentum Wheel Failure Rates. The failure rate of momentum wheels is about 250×10^{-9} failures per hour, or 2.192×10^{-3} failures per year [19]. Substitution into Eq. (1) for 7 years yields a reliability of 0.985 for a single wheel and $0.985^3 = 0.956$ for 3 wheels, resulting in 3 failures for our constellation of 64 satellites.

2.4 Power System Components

The power system of a satellite has two main components, the batteries and the solar panels. In most satellites, the solar panels are pointed toward the sun by a positioning system that derives position information from the attitude control system, thus electronics and some electromechanical actuators are also involved. However, we will focus on the batteries and solar panels.

Battery Failure Rates. Satellite battery systems are designed with a number of high quality NiH_2 cells connected in parallel and designed to withstand the numerous charge-discharge cycles which occur in LEO (about every 90 minutes). Although the battery capacity decreases over the nominal 7-year lifetime of the mission, the design is such that sufficient capacity is still available after 7 years. Thus the failure probability we are interested in is the rare occurrence of a total battery failure within the 7-year period.

One of the leading makers of space batteries, Eagle Pitcher, had accumulated 400,000,000 cell hours in space by Sept. 2001. Three cells were lost: on two different occasions by micrometeriote collisions and on a third by a piece of debris within the satellite falling on and shorting out cell contacts, [20]. A typical battery is composed of 22 cells and will operate even if one cell fails. Thus, these three instances of individual cell failures did not result in battery failures. To compute the hazard for the case of zero failures, we assume an equivalent failure number = 1/3, for the numerator. We divide the 400,000,000 cell hours by the 22 cells in a typical battery, to obtain 18,181,818 battery hours. Dividing by the 8,766 hours in a year we obtain 2074 battery years for the denominator. The ratio of numerator to denominator yields 1.6×10^{-4} failures / year. Substitution of this failure rate into Eq. (1) for a 7 year period yields: R(7) = 0.999. Multiplying this by the 64 satellites in our example we predict we predict a negligible number of failures of 0.064.

As a check on this battery failure rate, an estimate was made of the reliability for the 3 Li/SO2 batteries on the Galileo spacecraft that had to endure the flight for 6 years from Earth to Jupiter and then operate for a 51 minute mission. The analysis of battery reliability revealed a 98.5% probability of success for 6 years, [21]. Assuming the same reliability number for our example constellation of 64 satellites and a 7-year lifetime predicts about 1 failure.

Another paper on Lithium/Iodine cells for implanted heart pacemakers shows a failure probability of 0.0005% per month which is equivalent to a failure rate per year of 0.0005 x 0.01 x 12 = 0.00006 failures/year, [22]. The pacemaker data predicts a negligible failure probability in our application.

Solar Panel Failure Rates. Solar panels are large "wings" covered with many solar cells that extend from a spacecraft and power the spacecraft and recharge the batteries during a sun cycle. During the dark portion of the orbit, battery power is used. There have been several recorded instances of one or more stuck solar panels which could not open on orbit insertion and therefore would not point at or track the sun. For our purposes, we consider panel extension part of the launch and orbit insertion process and only consider the reliability of satellites placed in orbit in operating condition. It is well known that proton and electron radiation in spaces reduces the lifetime of solar cells. In addition, it also degrades power output by about 5% per year. Thus, solar panels designed for a 7-year lifetime would have to be sized so that 65% of their initial power output is still sufficient to achieve mission goals. With thousands of individual solar cells on a panel, it is not uncommon for individual cells to short or open or sustain damage by micrometeorites during the satellite lifetime. The cells are arranged in a complex series-parallel arrangement to guard against any such failures having much impact on the electrical output of the panel. Furthermore, the series-parallel circuits are organized into a large number of "strings" which are paralleled to charge the battery. It is anticipated that a number of strings will fail during a mission, however, the generous initial design capacity will insure that the mission can still be accomplished. Although it is difficult to obtain data on solar panel failure rates, it is unlikely that failure of properly deployed panels will be significant during the mission lifetime, however, because of degradation, it will be necessary to replace solar panels during overhaul.

Summary of Failure Rates.

Table 6 Reliability of Typical Satellite Components

Component	Point Estimate Of Failure Rate	Expected Failures In 7 Years For A Constellation Of 64
Electronics	R(7) = 0.918	5
Gyroscope Average	7.843 x 10^{-6} fail/hr and a 2:4 gyro system [see Eq. (4)]	3
Magnetometer, Magnetic Torquer	Negligible	--
Momentum Wheels	R(7) = 0.956	3
Battery	R(7) = 0.985	1 ?
Solar Panel	Negligible	--
Other	?	?
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Complete Satellite		12?

Table 6 illustrates the distribution of satellite failures among components for a typical LEO satellite constellation of 64 satellites.. Note the agreement between the overall system reliability (number of failures) in Table 6, (12), and the number of expected failures based on the Table 2 data, (11).

3. REPAIR COST MODELS

We compare the costs of launching a satellite and repairing it at the end of its design lifetime, Y, with the cost of launching an initial satellite and replacing it with a second launch at time Y. The capital cost of one satellite is assumed to be Cs and the cost of launching this satellite is assumed to be C1. Launch costs are currently in the range of $5000 to $10,000 per pound [23]. Therefore the total cost of N launches is N(Cs+Cl). The service period of the payload, as determined solely by the propellant budget arising from launch mass and volume constraints is taken as Y years. The dollar cost for a replenishment of propellant is likewise set at Cr and includes the cost of the propellant and its launch into orbit.

To achieve an operating lifetime of 2Y using a second replacement launch, (assuming that none of the components fail in 2Y years), N = 2 and the cost would be 2(Cs+Cl). Thus, two separate satellites would be needed, one launched at time zero and one at time Y, respectively. On the other hand, with replenishment, and still assuming no failures of the components, the total cost is (Cs+Cl+Cr) since just one satellite is used. The cost difference between the two cases is given by:

$$\text{Cost advantage} = [2(Cs+Cl)] - [Cs+Cl+Cr] = Cs+Cl - Cr \quad (5)$$

Thus, if replenishment could be carried out at a significantly lower cost than a separate complete launch of an additional satellite, the concept would be economically attractive.

We can include the effect of component failures in our comparison and develop an more comprehensive cost comparison than Eq. (5). We now compute the cost of the satellite per year of life for the two cases, N =2 and N = 1 plus replenishment. The expected number (statistical average) number of years of life for a Y year mission is given by R(Y)* Y. For the case where N=2 and Y=7, the expected lifetime is [R(7)*7 + R(7)*7] = 2R(7)*7. For the case where the original satellite is merely replenished, the expected years are [R(7)*7+ R(7|r)*7], where R(7|r) is the reliability for 7 years, given replenishment. Then, the cost per year for a total system life of 14 years for our two cases is as follows:

Model 1 – 2 launches, no replenishment: Cost per year = 2(Cs+C1)/2R(7)*7

Model 2 – 1 launch + replenishment: Cost per year = (Cs+Cl+Cr)/7*[R(7)+R(7|r)]

The ratio of costs per year with replenishment in space to those without it is given by the following:

$$\frac{yearly\ cost\ Model2}{yearly\ cost\ Model1} = \frac{(Cs + Cl + Cr)}{[R(7) + R(7|r)]7} \div \frac{2(Cs + Cl)}{2R(7)7} \quad (6a)$$

If replenishment/overhaul makes the satellite "as good as new" then R(7|r) = R(7) and Eq. (6a) becomes

$$\frac{yearly\ cost\ Model2}{yearly\ cost\ Model1} = \frac{1}{2}\left[1 + \frac{Cr}{Cs + Cl}\right] \quad (6b)$$

This cost ratio can be quite close to 50% if the cost of replenishment/overhaul is much less than the cost of a new satellite and its launch.

4. CONCLUSIONS

We have shown that the use of replenishment/replacement could reduce the yearly cost of a satellite system by as much as 50% in the limit. The actual cost reduction might be as large as 40%. The boost cost to orbit of most items exceeds the item manufacturer cost. In the case of propellant replacement, a significant portion of the weight is the tank and boosting a larger quantity of gas into orbit to serve for several satellite replenishments requires a larger tank where the weight of the tank per pound of propellant decreases, thus one would hope that we could actually realize a ratio of say 60% for Eq. (6b).

If overhaul in space were adopted, a number of significant goals might be achieved:

Cost Reduction for Space Access. It has been demonstrated that in-space overhaul at the ISS has a distinct commercial potential for increasing the lifetime of expensive space assets and thereby reducing the annual costs of commercial space operations.

Governmental Investment and Cost Reimbursement. The achievement of this new space industry would be initiated by multi-national government support of the development of an OMV. This vehicle has a multitude of uses, with satellite retrieval being only one. Satellite operators would reimburse the general fund for ISS operations for costs incurred by the use of the OMV to retrieve ailing satellites to the ISS and for replenishment and overhaul.

Clearing Space Debris. Clearly, the ability of an OMV to retrieve failed satellites and place them in an orbit easily reachable from the ISS contributes to debris clearing in space. At present, failed GEO satellites are boosted to a higher, graveyard, orbit to remain circling the globe. With the use of slow, low cost propulsion, one should be able to lower these satellites to a high-tech junkyard of expensive satellites that could be salvaged for repair parts. LEO satellites can be retrieved more quickly. This retrieval capability will also serve to reduce the likelihood of additional debris being added to the important commercial real estate of space.

Spare Parts and Salvage. If renewable satellite components such as solar panels, batteries, and attitude control components were built of interchangeable components, the entire overhaul process would be greatly improved. Furthermore, the creation of standard series of such components should increase the annual number that are manufactured and thus decrease the cost.

Satellite Assembly in Space. Satellites must withstand two different regimes, boost into space and orbit in space. The latter has special considerations of weightlessness, radiation, long duration, etc., however, the stresses of the boost phase are particularly difficult and many components must be designed to withstand boost requiring increased weight, cost, and ruggedness which is not needed in orbit. Thus, eventually we may contemplate satellite assembly in space from modular assemblies which are lighter and lower in cost than those in present components. If such is the case, overhaul in space may be a prelude to assembly in space.

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