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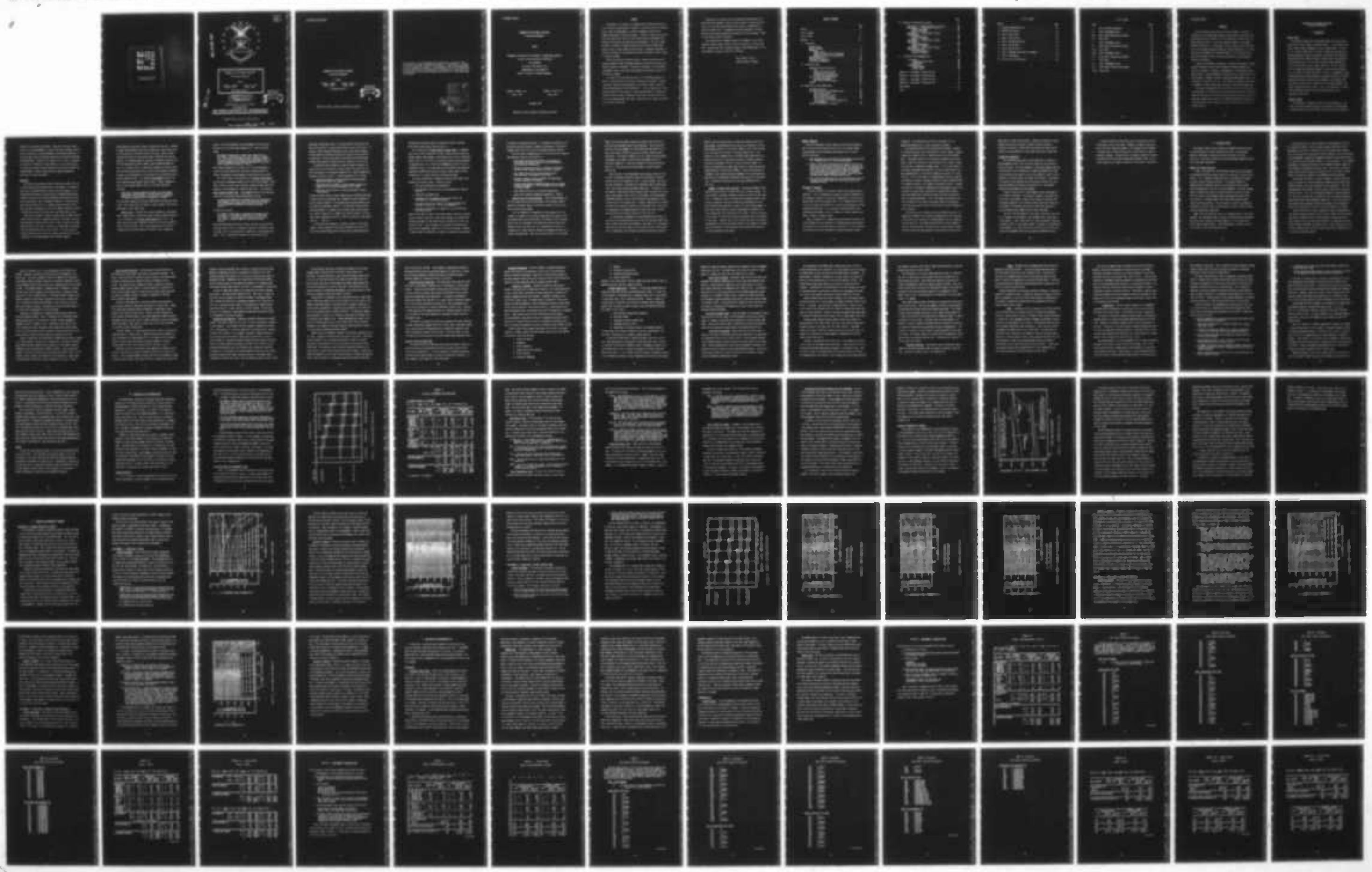

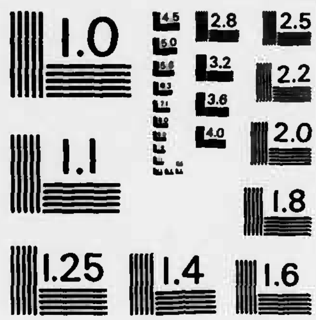

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AD-A148 447

PLANNING FOR THE ON-ORBIT SERVICING

OF MILITARY SPACECRAFT

THESIS

Michael E. Russell
Captain, USAF

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Major, USAF

AFIT/GSM/LSY/84S-27

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AFIT/GSM/LSY/84S-27

PLANNING FOR THE ON-ORBIT SERVICING OF MILITARY SPACECRAFT

THESIS

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Systems Management

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September 1984

Approved for public release; distribution unlimited

Preface

The purpose of this study is to examine on-orbit spacecraft servicing from a military program manager's viewpoint. We believe that the increasing pace of servicing developments is worthy of managerial attention and possible application to military programs. To assist in application evaluation, this study first looks at military servicing policy background and surveys civilian servicing technology and developments. During our study, the body of available literature concerning servicing and related areas began to grow at a much faster pace than before. Subsequent researchers in the servicing area will have much more available information, both in terms of breadth and depth.

After the policy and literature survey, a model which may be used to evaluate economic trade-offs between different non-servicing and servicing mission scenarios is presented. The model is developed in a microcomputer spreadsheet format to facilitate rapid adaption and alteration as well as easy use by a manager.

In light of the fact that servicing is in its formative stages, no specific program evaluations have been conducted with the model. Instead, its general properties and assumptions are outlined in detail along with some candidate methods of data presentation. It is our feeling that it will be more valuable for the manager to conduct program-specific analyses with the most current economic information at the time of analyses rather than for us to examine economic data which, at the time of this study, exist just as preliminary projections.

Concurrent to our study, an Air Force Spacecraft Maintenance Policy Review was being conducted. We did not have access to a study draft until late in our own study and the status of that study's recommendations is currently unknown to us. We suggest that anyone interested in military servicing policy should ascertain the status of this Policy Review in order to have the most current information.

We are particularly indebted to Major Eric Sundberg for the initial comparative model concept formulation and his assistance in further model work. We would also like to thank our advisor, Major Rodney Byler, for his encouragement and supply of pertinent information.

Major Robert M. Tayloe

Captain Michael E. Russell

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Abstract

On-orbit spacecraft servicing for military programs is examined. A foundation is first established through a brief review of past significant servicing policy and a survey of civilian literature to outline servicing technologies and status. The military community appears to be somewhat reticent to embrace or, in some cases, to even consider on-orbit servicing. The civilian community appears enthusiastic about the potential of on-orbit servicing and the majority of economic studies of civilian missions show servicing strategies to be an attractive alternative to most expendable spacecraft strategies.

A model called SATSERV is presented. This model can be used to conduct economic comparisons from an overall standpoint between expendable and servicing strategies. The model is implemented in a microcomputer spreadsheet format for rapid implementation and application along with ease of use by the manager. SATSERV is based on normalized program segment costs as a percentage of spacecraft unit cost. Total program cost between alternatives is compared on a delta change basis and also on a percentage change basis.

Four basic spreadsheet and mission scenarios are outlined and assumptions examined: two low earth orbit mission profiles within the current STS operations envelope, one low earth orbit mission profile outside current STS operations capability and requiring a Teleoperator Maneuvering System, and one geosynchronous mission scenario involving a space station and orbital transfer vehicle.

PLANNING FOR THE ON-ORBIT SERVICING OF MILITARY SPACECRAFT

I. Introduction

General Issue

Since Sputnik became the first man-made object to orbit the Earth, satellites have been viewed as expendable assets -- to be forgotten once they no longer function adequately for the intended mission. In order to fully use the capabilities of the Space Transportation System and to achieve projected long-term cost benefits, the National Aeronautics and Space Administration (NASA) has begun to develop satellites designed to be serviced while still in orbit (34:7) and has already performed its first on-orbit repair mission in May of 1984 (23). The Air Force has yet to introduce any deliberate features of on-orbit servicing design into its current or planned satellites. To date, no comprehensive trade studies have been performed regarding the potential benefits of on-orbit spacecraft servicing in terms of force readiness, force capabilities, and program life-cycle costs of specific Air Force space systems. The issue of importance then is "should -- and if so, when should -- the Air Force take steps to ensure the on-orbit serviceability of its operational satellites?"

Specific Problem

The Department of Defense as a whole and Program Managers in particular are under increasing pressure from Congress and the Department of Defense administration to hold down costs while delivering systems on schedule with acceptable performance. These short term goals make it difficult for Program Managers to justify the large investment costs for what is perceived as a risky development of serviceable spacecraft unless the longer range cost/benefit objectives are thoroughly understood and substantiated. Therefore, this research will provide a representative survey of literature in areas related to on-orbit servicing and will describe an analysis model and decision tool which can assist the Program Manager in making a timely decision regarding spacecraft servicing for a specific program.

Background

Well before the operational Space Transportation System (STS) and its Space Shuttle Orbiter became reality, the potential of spacecraft servicing for extending mission duration was being discussed. Early discussions were primarily linked to plans for manned missions where astronauts would perform routine and emergency maintenance activities during long duration lunar or planetary missions or on earth-orbiting space stations (60:6;17:6.1.2). Unmanned "remote maneuvering units" were also under investigation at this time. However, these were limited to sensing and retrieval functions near a host manned vehicle (95).

While much literature is readily available detailing NASA's current interest and activities in spacecraft servicing, relatively little has been published concerning plans of the Air Force to exploit the growing technology base in this area, and there is no established and accepted policy concerning DoD plans for such activity. In order to meet an expanding operational military role in space, some sources urge strong consideration of the human capabilities to perform numerous mission-enhancing functions in space including servicing (62). Although it appears that spacecraft servicing is beginning to receive high-level Air Force attention (57:39; 46:V-5; 30:10-1 and 10-2), there are other indications that the Air Force may be taking a definite "wait and see" approach. Dr. Eberhardt Rechtin, president of Aerospace Corporation (an Air Force sponsored non-profit research center supporting Space Division), in a lecture before an international symposium on military space policy and the future applications of military space systems included no reference to the development of (or the need for) on-orbit servicing of military spacecraft (85). In a 1983 Air Force Magazine review of Air Force research and development, General Robert T. Marsh, Commander of the Air Force Systems Command, had this to say about spacecraft servicing:

> Later along, such man-in-space activities as on-orbit repair, construction, reconfiguration, and modification of satellites, perhaps using plug-in modules, may turn out to be advisable for reasons of economy as well as capability. [22:40]

This placing of spacecraft servicing considerations at some time "later along" in the future does not indicate a strong interest in the current development of such capabilities.

General Policy. The definitive guidance document for the development of capabilities in space which support national defense objectives is Air Force Manual 1-6, Military Space Doctrine (31:iii-iv). This manual points out several responsibilities which have been assigned to the Air Force by the DoD. One of these responsibilities is that of "managing military space operations including: launch, command and control, on-orbit sustainment, and refurbishment of military space vehicles for all military space systems (31:7)." AFM 1-6 further states:

> An integral responsibility to deploying a space force is maintaining it and ensuring that it has an enduring capability. Thus, the Air Force must develop a logistical capability to sustain forces that are based in the space medium. This logistics system should be developed and deployed concurrently with an operational capability. [31:12]

While these statements do not directly call for the development of on-orbit servicing capabilities, they have provided the basis for further investigation and development of space logistics activities.

As a direct result of the publication of Military Space Doctrine and the nearly simultaneous formation of Air Force Space Command in late 1982, an effort to define space logistics concepts was begun under the auspices of the Sacramento Air Logistics Center (46). The resulting Space Logistics Concept Study -- Final Report has this to say about the current Air Force posture regarding spacecraft servicing:

> In today's environment, the inaccessibility of the operational space segment is the major factor which precludes application of logistics support concepts and utilization of the traditional logistics infrastructure to sustain operations. [46:V-1]

It goes on to say that

> The present infrastructure of program office managed contractor support, in the present technological and operational environment, is the most practical, mission and cost effective, and will probably remain so into the near future. [46:V-2]

The study draws these conclusions from the fact that unclassified DoD payloads currently orbit at altitudes of from 400 to 22,000 miles while the upper limit of the Space Shuttle's capability is approximately 300 miles. Thus, a transportation capability to take the servicing mechanism to these satellites or to retrieve them for servicing at the Space Shuttle Orbiter is required which does not exist at this time. In the past, rapidly changing technology has led to the current research and development environment surrounding the acquisition and operations of satellites. This has contributed to the logistics problem through program-unique spacecraft designs and small production runs (46:V-2).

In projecting future systems and logistics support concepts, the study points to the development of several capabilities which will enhance the potential of serviceable spacecraft as a viable alternative to expendable satellites (46:V-3). These developments are as follows:

- o Space Shuttle Orbiter altitude extension with more powerful engines and larger fuel capacity.
- o Manned Spaceflight Engineers to ensure shuttle payloads are compatible with (and take advantage of) man in space.
- o NASA Orbit Transfer Vehicle to retrieve payloads for return to the shuttle.

As these and other logistics support capabilities are attained the study recognizes that the Space-Based Laser represents the best candidate for on-orbit support because of its projected high cost and currently planned refueling requirements. (46:V-4). The study also points out that the establishment of a permanent orbiting space station offers significant logistics potential for "command post, spares warehouse, orbiting repair depot, manufacturing facility, satellite launch pad, (and) weapon platform. . . (46:V-4)."

In concluding its discussion of logistics support for the space segment of space systems the study panel recommends that "Space Division, ESD and Space Command should evaluate space system architecture alternatives and conduct feasibility/trade/cost studies to develop future space system support concepts (46:V-5)."

As a follow-on to the Space Logistics Concept Study, in September 1983, the Air Staff directed AFLC to lead a study with participation by Systems Command, Space Command, and Secretariat activities to "determine whether (and if so, how) the Air Force should pursue planned maintenance of spacecraft and, if so, provide the recommended policies for its implementation (29:1)." The study team received briefings from spacecraft contractors and NASA that outlined a range of issues relative to the consideration of on-orbit servicing for DoD space systems.

The costs and benefits of spacecraft servicing were found to vary dependent upon several factors. These are (29:16):

- The age and complexity of the spacecraft.
- The function(s) and criticality of the spacecraft to national security.
- Spacecraft replacement cost.
- Availability of new technology which could improve the performance of a replacement spacecraft.
- The type of servicing or repair to be done and whether the spacecraft has been built to easily accommodate it.
- The added life expectancy or capability to be realized from servicing actions.

Benefits were found in areas of pre-launch anomaly correction, minimized mission downtime, indefinite on-orbit spare storage, and reduced costs through procurement of fewer satellites and ride-sharing of servicing missions (29:16). Costs increases were projected for purchasing and storing spare subsystems, acquisition of servicing equipment, changeover to modular design of spacecraft, and means of transportation and support for access to the satellite (29:16). An intangible cost might also be generated through the potential premature obsolescence of the mission hardware late in the life of a still serviceable satellite (29:16).

The review team's recommendations call for policies to be issued by the Secretary of the Air Force which will:

- o Ensure satellite maintenance options are considered in requirements definition, acquisition program management, and contractual documentation.
- o Continue to examine the utility of spacecraft maintenance options as their economic benefits continue to expand.
- o Avoid design actions which would preclude on-orbit servicing later in the satellite life cycle.
- o Continue to pursue, jointly with NASA, the technologies related to spacecraft maintenance.
- o Conduct trade studies to determine feasibility of including spacecraft maintenance on future programs and block changes to present systems.
- o Apply these policies on an individual program basis.
- o Develop the necessary implementing regulations. [29:23]

Tentative Plans for Servicing/Repair. Three program managers at Air Force Space Division were interviewed on 15-17 February 1984 to determine the general status of planning for spacecraft servicing on both new and evolving systems.

LtCol Bill McDermott is responsible for the preparation of the request for proposal for the current concept definition phase of the Space-Based Space Surveillance System. He pointed out that the statement of work for this phase of the acquisition does not specifically address on-orbit servicing since it is considered the contractor's responsibility to make trade-off studies and recommend the best way to support the system (68). While the operational details of the system remain to be defined, several areas offer potential applications for servicing the Space-Based Surveillance Spacecraft. The size and complexity of the space segment will likely mean that each satellite will cost on the order of $250 million and will occupy an entire shuttle payload bay. Since sensor component life is a concern area and product improvements are planned, on-orbit repair/replacement activity is attractive, especially if more than one satellite can be serviced per mission or if the servicing can be performed as a partial shuttle mission (68).

Major John Wert of the Space-Based Laser program office and Loren Corriston of Aerospace Corporation spoke of the prominent role which on-orbit servicing is expected to fulfill in their program. Servicing has been considered a requirement for space-based lasers from the beginning of the current concept development phase (111). The need for replenishment of operating and station-keeping fuels, the high cost of the assets (approximately $150 billion for the system), and the deployment timeframe of 2000+ all point to the availability and benefits of on-orbit servicing for this system (111). The major issues which will effect the design of the servicing capability are the sensitivity of the optics to contamination, the hazardous nature of some of the fuels, and the need to minimize the downtime required for servicing (111).

Col Steve McElroy addressed the issues regarding the potential of servicing for the Defense Meteorological Satellite Program's (DMSP) next block of satellites which, when deployed in the 1990's, will incorporate additional survivability features not available with the current design (70). Although early cost analyses indicate that designing a modular

"DMSP-II" would not significantly increase the projected cost of the space segment, the DMSP satellites are and will be relatively low cost (approximately $100 million per copy for DMSP-II) and no clear information is available for the cost of a servicing mission (70). This, coupled with the incompatibility of the DMSP system constellation for multiple servicing on a single shuttle mission, indicates a generally unfavorable cost/benefit ratio for on-orbit servicing of DMSP. Col McElroy indicated that two issues remain which will govern the decision regarding the use of servicing for DMSP-II. They are the possible development of more compatible mission parameters for the new system and the maturing of transportation technology and policy which could either lower or drastically raise the cost of placing a DMSP satellite in orbit (70).

Summary of Current Policy and Plans. The sources reviewed did not indicate any active use of on-orbit servicing in current programs. The future presents a guardedly optimistic picture for both policy and capability. Although only one of the three future systems reviewed is specifically planning for the use of servicing, the presence of an Air Staff sponsored study team shows interest in the early establishment of policy which should lead to an orderly development of capability for those systems where servicing makes the most sense. No overt resistance to the concept of on-orbit servicing was encountered during the research for this paper. However, where initial analysis has shown only marginal cost benefits for on-orbit servicing, there is a willingness to let NASA work out the details of both technology and costing before committing Air Force resources to the concept.

Research Questions

With this background in mind, answers to the following questions shall be used to provide decision tools for Air Force space systems program managers who are considering the possible use of on-orbit satellite servicing:

1. What spacecraft servicing technology developments are available for consideration by Air Force program managers?
2. Based on three orbit configurations with general military application (low-earth polar orbit within shuttle altitude, low-earth polar orbit outside of shuttle reach, and geosynchronous orbit), what does an available cost estimating and analysis tool reveal about the relationship of costs for candidate on-orbit servicing approaches as compared to baseline systems (planned and/or generic expendable satellites)?
3. What other advantages might arise from designing and constructing satellites for serviceability which would improve the cost/benefit ratio?

Philosophy of Approach

A two-part approach will be used to explore the proposed research questions. First, a representative survey of available literature will be presented in Chapter II to serve as a determinant of current and projected satellite servicing capabilities. It is intended that this survey and its lengthy bibliography will provide program managers and other interested parties with: (1) an overview of recent space servicing technologies and studies, and (2) a resource for further research into specific issues of program interest.

Next, in Chapter III, a spacecraft servicing decision analysis tool called SATSERV, which was developed in the Manned Spaceflight Engineering Program at Air Force Space Division (100;30:8-2), will be introduced and explained to provide a mechanism for generating decision support information. The flexibility and utility of the model will be demonstrated through use of a basic two-satellite example.

Four program scenarios will be developed using SATSERV in Chapter IV to explore the basic cost relationships for a small number of defense related orbit scenarios and to illustrate the utility of the SATSERV model. The graphic results will be analyzed to determine the relative merit of satellite servicing for these scenarios over a range of launch and inter-orbit transportation segment costs. It is not the intent of the scenario development and analysis to arrive at either specific program recommendations or to provide an exhaustive analysis of all possibilities. In fact, the creators of SATSERV eschew its use for detailed cost analysis of specific programs, choosing to reflect normalized costs for parametric studies of cost element relationships (30:8-3). Instead, the scenarios are intended to demonstrate the development of basic relationships in a manner easily understood by program decision makers. These relationships and the model can then be tailored and applied to specific program requirements. Also, since generalized scenarios and cost information will be used for the study, detailed (and possibly classified) cost data and orbital configurations of current systems will not be required.

The results of the literature survey and SATSERV analyses will be summarized in Chapter V and conclusions presented which will highlight the availability of resources for Program Managers who are considering on-orbit servicing. This study should serve as an initial departure point for those involved in the acquisition of space systems to become familiar with the cost relationships of satellite servicing and how to apply them in a useful analysis model. Students and analysts of space systems can also use this study to expand the model and explore additional scenarios to further define and analyze the governing cost factors in the consideration of the on-orbit servicing of satellites.

Constraining Assumptions

The relationships described by the SATSERV model are subject to three assumptions which limit its direct translation into real-world dollars and cents. The first assumption is that space segment costs can be partitioned into cost elements and related sub-elements which then can be normalized with respect to one of the elements in order to draw parametric conclusions about cost element relationships. The accuracy of the model is then dependent upon the accuracy with which cost elements/sub-elements are defined and the stability of relationships between the sub-elements and cost elements.

A second limiting factor is that emergency repair/replacement is not included in the model. Since there is currently no recovery capability from a catastrophic on-orbit failure short of launching a new replacement spacecraft, this limitation should enhance the objectivity of the model by eliminating the costing of additional spacecraft or Orbit Replaceable Units (ORUs) above the basic requirement.

The third limiting assumption of the model is that the launch vehicle is assumed to be the same for each strategy within a given operational scenario. Thus, launch costs for a purely expendable system are the same as that for a serviceable system. By default, this defines the launch segment in all cases as the STS, and does not allow direct comparison with expendable satellites launched on expendable boosters.

It must be pointed out that these last two limitations only apply to the model as used in this study. SATSERV is extremely flexible and can be tailored to expand the number of cost elements and sub-elements or otherwise add in factors which may be of significance to a specific program or strategy. The description of the model in Chapter III should be studied with the view toward understanding SATSERV's basic utility without regard to any inherent limitations of this specific application.

II. Literature Survey

This chapter reviews current literature to determine the broad reasons for and the effects of on-orbit spacecraft servicing. Servicing here applies to maintenance, refueling, and other traditional servicing activities. Also briefly covered are existing maintenance capabilities and future technology requirements.

Reasons for On-orbit Servicing

In 1981, Frank Cepollina, the multimission spacecraft project manager at the Goddard Spaceflight Center, stated "if we can pull off the servicing mission, it will completely change the course of how spacecraft programs have been planned in the past (25:138)." His comments exemplify an apparent positive sentiment toward on-orbit spacecraft servicing which exists throughout most of the civilian space community. Four major reasons appear to underlie this desire to perform spacecraft servicing in space. The first reason is the estimated economic advantage associated with on-orbit service. The second reason is the trend toward larger and more complex orbiting structures. The third reason is a need for autonomy and survivability, and the fourth is the validation of the in-flight servicing concept through actual experience.

Cost. The first motivator, cost, is an important aspect of any public program. Since the general public can easily misconstrue space programs as being frivolous in nature, cost effectiveness is of vital importance to public sector program survival. Cost effectiveness, of course, is also a vital concern of any profit-making activity.

On-orbit servicing is a possible method of saving money over the life of a spacecraft program. Several economic analyses (16:247-249; 35:237; 36:492-493; 53:8,11; 65; 77; 97:29; 99:7; 101:30; 108:757) have indicated that on-orbit servicing is economically worthy. Compared to the current method of using expendable launchers and expendable spacecraft, the studies found on-orbit servicing to be consistently superior in cost advantages. In the studies, percentages of program costs saved over the expendable approach ranged from 5-70% depending on spacecraft and mission type. Dollar value of savings for direct on-orbit servicing could be as high as 13 billion dollars for about 80-90% of the missions planned for the 1985-2000 period (16:247-249).

Cost savings occur due to a variety of reasons. One cost-saving strategy is the reuse of an existing spacecraft through servicing and/or refurbishment instead of building a completely new one (96:160-61). Short-life subsystems which would normally limit the overall spacecraft life could be replaced (43:5-6). Also, the corresponding spacecraft life-span extension will lower unit costs per year, and spacecraft can be treated as cumulative assets rather than one-shot expendable items (18:1). Long life is also now considered attractive because the space environment is not considered as hostile over long periods of time as it once was thought to be (8:479).

On-orbit servicing can reduce transportation costs through sharing of STS missions and space-available travel of parts, spares, and replenishables which would increase STS Orbiter load percentages. Basing servicers on-orbit appears to be a very attractive alternative to ground basing (56:4,6; 64:261; 67:59-60; 98:94-95; 104:148-49; 105:19). With a space station as an on-orbit operations base, on-orbit servicing could have a payback period of as little as four years (44:130).

Design of spacecraft for in-flight maintenance yields further cost-savings. Spacecraft reliability has historically been addressed in two costly ways: very high (estimated) reliability components and redundancy. The extreme reliability normally required for spacecraft components could be relaxed somewhat (35:237; 43:5-6) since faulty components may now be replaced on-orbit. The excessive amount of redundancy used in attempts to increase reliability may also be reduced, and less duplication of spacecraft component cost will occur (36:493; 43:5-6). Since most reliability models do not address transient failure rates, the models do not provide a accurate picture of reliability (40:194) and problems will most likely be occur more often than normally estimated. The desirability and cost effectiveness of an on-orbit servicing capability is thus increased.

Modularity is recognized as a spacecraft design feature required to permit maintenance (35:240). Also, if spacecraft can be designed to make maximum possible use of "off the shelf" or generic modular components, component costs will decrease, as will construction costs (35:237; 53:2; 99:3-5). Modularity would also permit faster checkout and launch preparations since faulty modules could be replaced without wasting previous integration efforts, greatly reducing lengthy tear-down/build-up costs.

Design of spacecraft with standardized, reuseable payload support elements (e.g. power supplies, attitude control systems, etc.) and modular interface buses enables payload change-out and eliminates building expensive support elements for each unique payload (7:550-551; 58:245). Several spacecraft designs on the drawing board such as the European Retrievable Carrier (73:33), Olympus (12:250), Proteus, and Leasecraft (33:21) make use of common buses and standardized interfaces for payload changeouts on Earth or in space.

Larger Orbiting Structures. The second major reason motivating on-orbit servicing is the overall trend toward larger space structures. This trend is occurring primarily because the space program (in the United States at least) is shifting toward industrialization and commercialization (47:23). The relative cost of commercial efforts is generally lowered by grouping together several missions in larger spacecraft or producing products in more economic product lot sizes which also means larger spacecraft to handle the probable increase in production equipment size (58:247; 59:171; 69:50-51; 82:41-42,46).

The term "larger spacecraft" as used here denotes those spacecraft which cannot be currently transported into space by a single launch. Therefore, these larger spacecraft must be assembled or constructed in space (58:245; 73:45; 83:615; 84:279) and will require on-orbit maintenance to reach planned life-times because of the greater spacecraft complexity and/or expendable resource use (59; 73:45). Planned life-times are very long (decades rather than years) in most cases to recover high initial costs (32:48-49; 54:1; 63:274; 78:30-31; 82:46; 92:4).

A perfect example of a large structure which will need all the services mentioned above is a space station. Assembly/construction and checkout on-orbit, maintenance, and replenishment will all be needed along with modular design to permit evolutionary growth and payload changes as currently planned (9:289; 21:472; 33:18; 56:4,6; 69:50-51; 96:160-61; 113:14).

Throughout the rest of this century, most commercially important activities will continue to be located in geosynchronous earth orbit (GEO) (43:1; 92:3-4). This is because commercial space activities are predominantly communications related and GEO is the prime location for communications satellites.

Crowding in the most desirable orbit locations is already occurring and the demand for communications service is expected to continue to rise. GEO crowding increases the probability of collision by as much as two orders of magnitude (to about .00006/year) over normal Earth orbit hazards (19:490), and this increase does not even address the potential for increased signal interference through either physical occlusion or electromagnetic interference.

One way to lessen GEO crowding is to group multiple missions together as previously mentioned (83:614; 86:625; 92:3-4). Other ways to lessen the collision risk and crowding are reducing the number of replacement spacecraft inserted into GEO orbit by lengthening spacecraft life (4:30; 92:3-4; 107:1-2) or reducing the total number of GEO spacecraft by removing those spacecraft that are no longer functional (4:25-27; 86:625). On-orbit servicing will be important to these methods through activities such as refueling, maintenance, and payload changeout.

<u>Autonomy and Survivability</u>. Spacecraft autonomy is desirable for several reasons. One reason, common with the idea of on-orbit maintenance in general, is cost reduction. The overhead involved in keeping a spacecraft alive and well is high because it is currently human labor and ground control intensive (13:393; 20:31; 109:216). As an example, the support overhead required for the relatively short STS Orbiter flights would be prohibitive in cost for similar support of long-duration space platforms with many complex activities without increased autonomy and automation (26:189; 78:31; 105:104; 113:23). During Skylab operations, just the attitude control system alone required the support of five engineers and related computers around the clock (15:267). As space structures grow larger, the sheer enormity of the support task, if conducted as currently done, may not even be reasonably possible (14:51; 78:30).

For the reasons listed above, autonomy and automation will be high-leverage items in reducing initial and overall space station cost (10:37,39). The prime functions of space station autonomous capabilities will be to off-load routine and trivial tasks from the human crew in an effort to save crew time for tasks deserving uniquely human capabilities. Crew activity planning will be one of the keys to effectiveness and efficiency and should be accomplished autonomously on the space station to best provide an economical working environment (72:224-5).

A space station is expected to be an evolutionary effort to take advantage of technology advances over the long planned life of the station. This imposes unique requirements on the space station information system as it must be readily upgradeable in technology while possessing a core which will last for the planned station lifetime (21:473-77). To effectively support manned habitation of space, the information system must be extremely reliable and easily serviceable as well. These requirements also apply to the station's autonomy capabilities (3:165; 15:268; 69:16; 74:101; 104:152). Autonomy is also needed for the space station to most effectively function as a servicing and transportation base (26:185).

Another reason for spacecraft autonomy is particularly important to the Air Force: spacecraft survivability during conflict (27:15-16). Since most current spacecraft rely on frequent ground station contact for mission operations, the spacecraft are only as survivable as the ground stations (48:167-68). The reduction of this reliance on the ground stations is of high priority to the Air Force (41:342; 57:40; 94:6; 109:216). Additionally, when the spacecraft is out of view of ground stations, on-board autonomy may help in surviving hostile or threatening conditions by enabling the spacecraft to help itself (13:393). Since commercial communications systems in the United States are used by government agencies for some traffic, studies are also being conducted to determine the most cost effective means of enhancing commercial systems survivability (11:674-76).

Previous Servicing Experience. The fourth major reason behind on-orbit servicing is the successful demonstration of maintenance on a manned space vehicle. In both the United States' Skylab and the Soviet Union's Salyut orbiting laboratory programs, both planned and unplanned on-orbit maintenance was accomplished on the laboratories. The amount of maintenance required was higher than predicted in all cases. These circumstances substantially verified that long-duration missions will require maintenance and that on-orbit maintenance is feasible (36:492-493; 42:381; 91:20). Spacelab 1 flight experience also demonstrated that all contingency possibilities can not be planned for and that systems must be designed to permit effective maintenance (5:16).

The concept of spacecraft servicing was validated with actual experience on Space Transportation System Flight 41-C in April 1984. Astronauts successfully restored the Solar Maximum satellite to operational capability after repairing spacecraft system failures (23:18). Plans are already in place for servicing of other spacecraft such as the Hubble Space Telescope (24:51).

On-orbit Servicing Capabilities

Since most studies have determined that there are potential benefits of on-orbit servicing, the technologies required to actually carry out the servicing are examined next. Two broad categories, autonomous maintenance and servicing by external agent, are used to delineate the literature. In each category, future needs will also be discussed.

Autonomous Maintenance. The first category, autonomous maintenance, refers to the ability of an spacecraft to carry out its own maintenance without any external assistance. Historically, earth-orbiting spacecraft have been designed without this ability and have relied on ground operations centers for routine maintenance and for problem recovery (66:1).

Categories of Autonomy. Spacecraft autonomy has been defined (40:191) as "the ability of a satellite to function, for a stipulated period of time, without human intervention or ground support but to accept valid external commands when they are available." Spacecraft autonomy can be classified in several ways. One method uses two categories: welfare maintenance and health maintenance. Welfare maintenance consists of those tasks which are more preventive in nature and are part of a normal mission plan. Health maintenance tasks, on the other hand, arise from anomolies or unplanned events. These anomolies must be first identified and then corrected. Health maintenance is much more difficult to implement than welfare maintenance since it requires both the ability to recognize the problem and the ability to select and undertake a course of corrective action (35:240; 41:343).

Another classification scheme concentrates on the levels of autonomy present in a system, ranging from least complex (level one) to most complex and difficult (level ten) (26:182):

1. Closed loop control
2. Redundancy
3. Failure detection
4. Sequencing and error checking
5. Fault tolerance
6. Functional commanding

7. Adaption
8. Tolerance of design errors
9. Inference and decision-making
10. Mission optimization

Generally, the current state of the art ranges from level three to level six depending upon the particular system's function.

Autonomy Capabilities. In general, no technology breakthroughs are required to meet near-term welfare maintenance goals (94:8). In fact, the current absence of wide-spread use of autonomy is more due to a past absence of need rather than a lack of technology (40:191). However, to meet the long-term goal of spacecraft with high-level autonomous health maintenance capabilities, advances are needed in several areas (41:344-346; 48:169-70; 66:v,29-30; 71:1.21; 94:8):

a. Fault-tolerant on-board data processors.
b. Mass data storage.
c. Autonomous navigation capabilities.
d. Autonomous function control.
e. Methodology for design/validation of autonomous spacecraft

Of these areas, fault-tolerant computing is the key to achievement of all the rest of the areas and to autonomy in general (40:193).

To reach the ultimate goal of complete autonomy, some form of artificial intelligence must be incorporated into the spacecraft (14:iii; 94:18). In relatively controlled environments on Earth, programming a machine to do even simple tasks is still a complex job because all possible situations must be provided for. In the complex space environment, programming a machine for all potential situations is nearly impossible and artificial intelligence methods can reduce the machine preparation and computation task to manageable proportions (14:70-71). The technology for this type of artificial intelligence will probably not exist until the 1990s (2:3.1.2; 94:18).

Space Station Autonomy. Autonomous capabilities and the underlying computation/information system may well be the single most important determinant of a space station's capability since a space station will be the most complex spacecraft yet attempted by man (3:168; 61:157). No technology gaps exist for an initial space station utilizing 1985 technology; however, advances will be needed in several areas to support the required autonomy and information system requirements perceived for later space station stages (74:104,108; 113:22). As the space station capability grows, the crew role can change to increasingly allow machines to do more of the routine and repetitive tasks (26:186-89).

Servicing by External Agent. Since achievement of true spacecraft autonomy may be well into the future, on-orbit spacecraft servicing by external agent will probably be used much more extensively in the next decade (1985-1995). Servicing by external agent is defined here to mean that something other than the spacecraft needing service is performing the servicing.

Servicing Policy/Concept. Before servicing by external agent is used on a wide scale, servicing policies and concepts need to be established and standardized (33:21; 45:1-2; 54:24; 112:8). Widely-accepted standards would increase chances of effective satellite service capability and reduce costs. Without standardization, unique servicing methods, procedures, and materials would proliferate for each unique spacecraft design. Each service mission would therefore also have to be unique, and uniqueness increases costs and decreases responsiveness (33:18).

The development of the Hubble Space Telescope may help to initially provide standardization for spacecraft, as a high program priority was placed on investigating on-orbit servicing and associated design requirements. The establishment of potential standards was a primary reason for program cost growth, but the problems solved will help future spacecraft (33:18). The planned United States space station may also help in setting servicing standards. Standardization and maintainability are high leverage cost items for the space station, and failure to consider the requirements and issues could nullify any potential space station economic benefits (10:37,39).

Another important servicing issue is whether or not the external agent doing the servicing will involve humans or automation (6:82-83; 35:237; 47:23; 101:30). In general, the high costs of human operations in space are partially offset by the extreme flexibility inherent in human beings (when compared to current machines). However, the space environment poses great potential hazards to people and places an upper limit on human capabilities (1:2).

Extending human presence through remotely controlled servicers will become possible in the latter 1980's, but use of true robotics technology to accomplish tasks will not begin until the 1990's (55:114). Some human capabilities (such as high-level reasoning and tactile touch abilities, for example) will continue to be unreproduceable in machines until the 21st century (63:274-275; 90:23).

Therefore, the best plan from a cost point of view appears to be use of a mix of human and non-human service activities. Exactly how this mix is to be apportioned between human being and machine is not entirely clear. Also not clear is which of the agents best suits different types of activities. This human/machine role confusion is not limited just to servicing operations, but extends to the basic broad roles of human being and machine on board the proposed space station as well (69:16).

The challenge will be to plan a human-machine mix which will make the best use of a human being's unique capabilities and the capabilities of existing machines (90:23). Human beings and machines can and should be viewed as complementary rather than competing agents (6:82-83). Due to the current uncertainties surrounding the human-machine question, the remaining discussion on servicing by external agent will be predominantly from a generic point of view. The constitution of the servicer will not be stated unless it is germane.

Where human beings are used, the question of appropriate training and qualifications arises. Servicing and assembly activities are more manually-oriented than those tasks currently performed by astronauts. The increase of space activity may make utilization of only highly trained experts for all tasks, particularly for the tasks that are intensively manual in nature, prohibitive in cost and time. The usual trend for earth systems is for experts to initially accomplish procedures and then transition the activity to less-skilled technicians using extensive technical documentation. This transition is feasible for space tasks but some documentation hurdles must be overcome. The present concept is to use electronic documentation aids to serve as servicing guides/instruction aids. Further study is required in this area (87:171-2,175-6).

<u>Servicing Technology</u>. Three general areas of technology requirements for servicing by external agent are used for literature classification. The areas are design, tools, and transportation.

Design. Effective servicing demands that the spacecraft be designed for servicing (84:279). The servicing agent must have room to work and perform the service as well as maneuver parts. Access must be provided to the elements being serviced and the servicer must have some means of mating to the spacecraft to be serviced (36:493; 89:4). The servicing recipient must be stabilized and the mated servicer-recipient pair will have to be controlled (57:39; 89:4).

Another prerequisite for servicing, previously discussed, is the use of modularity in spacecraft design. Modularity permits easy change of function-specific components in orbit and forces planning ahead for maintenance by the necessity of modularity considerations and accomodations during the design process (35:240; 37:292).

Tools. A spectrum of tools is required for on-orbit servicing (10:27; 69:34-35) just as a variety of tools is required for earthbound servicing. Hatch covers will have to be removed, module restraining devices will need to be first disengaged and then re-engaged, and methods of module extraction and replacement will be required. The experience gained through previous manned spaceflights helps considerably in this area, but further advancements are needed (32:42; 51:32; 78:30; 89:4). One study (45:4.2) identified 21 new or modified tools needed for effective astronaut maintenance work in the next decade. Actual flight experience with the first few tools designed for space servicing demonstrated the great increases in effectiveness and efficiency that could be achieved (23:20). Highly developed general purpose handling mechanisms are a vital prerequisite for future space maintenance activities (35:240; 47:23-24; 56:2).

Servicing also demands support equipment such as EVA work stations, methods of moving servicing materials (modules and fuel, for example), spacecraft sustainment provisions, and a stable foundation for the spacecraft while the work is being done (10:27; 56:1-2; 75:4-1). EVAs use large quantities of expendable items and regeneration processes may be cost effective for long term manned facilities such as a space station (50:86). Contamination-sensitive payloads may require support equipment to maintain cleanliness of detector surfaces (113:20-21). Additionally, there are many simularities between servicing and assembly/construction equipment so good designs could allow tool and equipment usage for both types of tasks, reducing storage and cost (84:279).

Transportation. On-orbit transfer capability is a fundamental requirement when the spacecraft to be serviced is too far away from the servicer's orbit (57:39; 93:30). This situation can occur in many ways. In the case of the Space Transportion System Orbiter, the Orbiter was designed primarily for shuttling payloads between the Earth and low Earth orbit. Because of this design, problems arise in use of the Orbiter for servicing. The Orbiter is not agile enough to permit efficient maneuvering for servicing rendezvous with many spacecraft in different orbits. Extensive servicing operations with the Orbiter will require some sort of supplementary orbital transportation (32:42-43; 34:7; 76:1.1).

One proposed method is to use an atmospheric sail at lower altitude and attached to the orbiter to obtain orbital plane changes. Use of a sail would be more efficient, although slower, than synergistic or propulsive plane changes (80:172,175). Another method is to not change the Orbiter's orbit but to use a Proximity Operations Module (POM) for operations within one kilometer of the Orbiter. Use of the POM would reduce spacecraft contamination, reduce Orbiter fuel use, and enable the capture of spacecraft spinning at a higher rate than the RMS (56:3-4).

For longer range operations, either a teleoperator maneuvering system (TMS) or a larger orbital transfer vehicle (OTV) could be used to retrieve and return the spacecraft for servicing at the Orbiter or carry servicing equipment to perform the service at the spacecraft. This is especially important for servicing operations outside the Orbiter's normal operation upper altitude of 220 miles or its maximum altitude capability of 300 miles (34:7; 52; 53:11). Seventy percent of the projected 1985-1995 low altitude spacecraft missions will range from 220-1500 miles in altitude (106:1).

Currently, the best cost advantages may be associated with the co-use of an Orbiter mission by a communications satellite deployment and then servicing an existing operational spacecraft on-orbit (28:3). Several key mission points are (28:3-7):

a. Both the communications and servicee satellites place orbital plane launch constraints on the Orbiter.

b. The Orbiter has essentially no propulsion capability to change planes after launch.

c. A servicee with propulsion capability to return to the Orbiter altitude can provide some orbital plane matching assistance.

d. The launch/deployment/servicing windows have limited portions of overlap (5 days at most).

e. Launch delays can result in a 22 or 44 day wait until the next launch/deployment/servicing window overlap.

f. The number of payloads to deploy impacts the number of days delay on a combined deploy/service mission, depending on the time required between deployments.

g. Certain rendezvous orbits and adroit use of servicee maneuvers can ease the phasing problems.

h. An Orbiter direct ascent profile may offer potential benefits and merits additional study.

i. Orbiter payload bay space probably can not be used twice on missions (a like spacecraft exchange operation may be an exception).

In the case of a space station or platform, a prime mission will be on-orbit assembly/servicing (44:66-67; 49:264; 63:274-5; 64:15,261; 69:14; 90:26; 104:148-49; 105:31,33,49). A relatively fixed orbital servicing base such as a space station would have the same orbital maneuvering problems as the Orbiter. Therefore, some form of orbital transfer capability will be required to deploy/retrieve/service spacecraft as in the Orbiter's case (10:27; 63:275; 64:261; 69:34-35; 78:30-31; 84:280-81; 90:20; 92:5; 93:30).

A space-based OTV/servicer appears to be economically and operationally advantageous compared to ground/Orbiter basing (38:1.1,1.2,3.7,3.8; 39:1.1,1.3; 44:54-55,130; 64:235,237; 67:59-60; 79:52; 88:77; 98:12,94-95,97,99; 105:19; 110:43). For rapid response or as a preferable method of basing, OTVs or the servicers themselves could be parked on-orbit until needed (35:240).

Not only is some sort of orbital transportation required, but advances in guidance technology will also be needed. The complex problem of achieving rendezvous between spacecraft in different orbits is still a difficult one to solve and is exaggerated when the target spacecraft is unable to manuever. Even a means for a STS Orbiter crew to determine, without ground assistance, the most efficient means of rendezvous is still a few years away (81:174-75). The more autonomous a maintenance vehicle is, the more pronounced the problem of guidance (35:237; 47:25-32; 103).

Rendezvous appears to be initially simpler overall in GEO versus LEO due to the constant communications available between a ground controlled servicer and the ground controller. After a demonstration in LEO, ESA plans to demonstrate docking and rendezvous in GEO in the early 1990's (86:625-26). NASA's Geostationary Communications Platform Program plan calls for launch of an experimental GEO platform by the 1993-94 timeframe and would present an excellent opportunity for GEO servicing tests (83:618-19).

Once a spacecraft in need of maintenance has been reached, another problem is encountered -- docking (78:30-31). It is difficult enough to accomplish docking between two spacecraft under ideal conditions, but if the target spacecraft is unstable the problems are enormous. The target spacecraft must somehow be stablilized before docking can begin (57:39). Once that is accomplished, docking is still difficult for un-manned and/or autonomous servicers (35:237; 47:25-32). Recent tests have shown an ability of video systems to handle target tumble rates of at least 1000 degree/hour and test results have indicated that with artificial intelligence techniques and other changes, performance will improve even more (102:III.1).

Summary

A broad overview has been provided of on-orbit servicing technologies and related issues. The technologies and advances needed are not just restricted to a few areas, but span the spaceflight technology spectrum. The potential advantages of considering and, if advantageous, providing for on-orbit servicing in a spacecraft program are many and outweigh the costs. The next chapter outlines a model for quick analysis of the potential economic advantages of servicing versus expendable strategies.

III. Description of the SATSERV Model

The SATSERV model, developed by the Manned Spaceflight Engineering Program at Air Force Space Division (100;30:8-2), provides a means for program managers to visualize the effect of risk on normalized total program cost. As used in this report, all costs will be normalized against the nominal cost of one complete expendable (i.e. current technology) space vehicle (SV). That is to say, the cost of the baseline expendable satellite for each scenario under consideration is assumed to be 100 percent, and all other costs are reflected as percentages of SV cost. The model is implemented in a computer spreadsheet format that allows easy replication and manipulation.

SATSERV is a three step process which leads to a graphical representation of the relative change in total program cost as specified elements of space and launch segment costs are varied over a relevant range. The three steps in the process are (1) the definition of alternative servicing strategies for a specific mission requirement, (2) the partition of space vehicle, launch segment, and satellite servicer costs into meaningful cost elements and sub-elements for insertion into the computerized spreadsheet, and (3) the display of the results of spreadsheet manipulations in a graphic format to show the effects of cost uncertainty on normalized total program cost (30:8-1 to 8-15).

Strategy Definition

It is in the area of program strategy definition that the orbit and mission requirements of the space segment first are described and the strategies developed which will govern the layout of the spreadsheet in step 2. The primary inputs to this step of the process are as follows:

- o The number of satellites required to perform the basic mission.
- o The number of nominal satellite lifetimes required to fulfill the planned lifecycle of the program. As used in the study a "cycle" will be defined as one satellite lifetime or, in the case of serviceable satellites, the normal period of time between servicing. For example, a program expected to last 15 years and using satellites with a mean orbit lifetime of three years would require 5 cycles to perform the mission for the program lifecycle.
- o The orbit parameters required to perform the program mission (eg. Can two or more satellites be launched on the same booster? Is the mission orbit within direct reach of the Shuttle? Etc.).
- o The servicing strategies appropriate to the mission (eg. expend after one cycle, service after one cycle and expend after the second cycle, service for two cycles and expend after the third, etc.).

A format developed at Space Division (100) to display the alternative strategies is shown in Figure 1. In this example, two satellites are required for the basic mission, and six cycles comprise the program lifetime (note that a cycle can represent any number of years since specific years are not relevant to the goal of the model). The orbits are assumed to be non-coplaner and are, therefore, not compatible for dual servicing (i.e. servicing both satellites on the same mission). Also, separate launches are required for each satellite for the same reason of orbit incompatibility.

Cost Partitioning and Spreadsheet Layout

Table 1 is a spreadsheet layout which shows the cost partitioning for the scenarios outlined in Figure 1. The major space segment cost elements have been defined as Space Vehicle (SV) related costs, Space Transportation (ST) related costs, and Satellite Servicer (SS) related

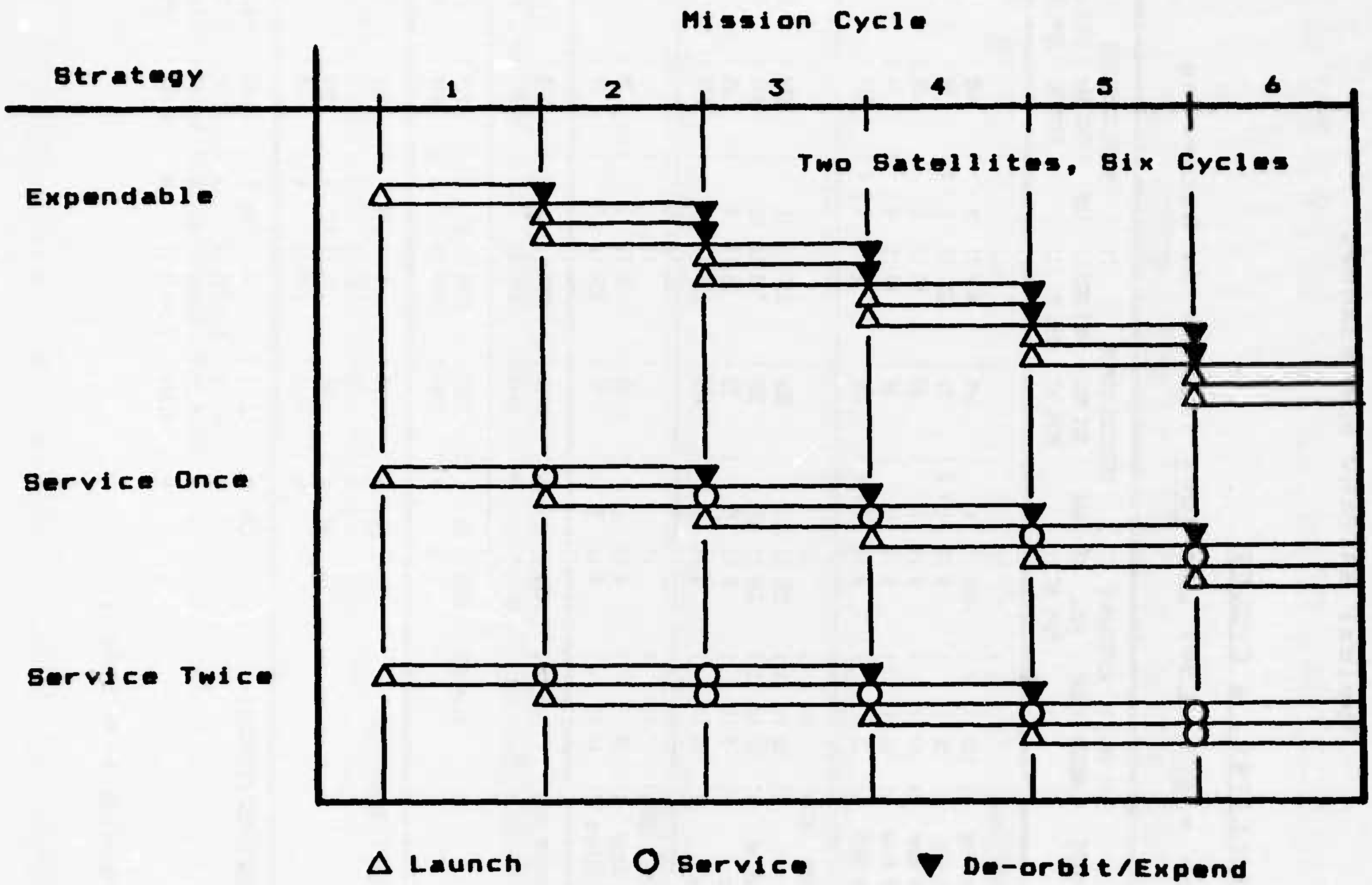


Figure 1. Program Strategy Definition

TABLE I

Typical SATSERV Spreadsheet

<u>2 SATELLITES, 6 CYCLES</u>

ST Lch = <u>50%</u> (Low) and <u>100%</u> (Hi) of SV Recurring

COST ELEMENTS	% SV RECUR	EXPENDABLE USE	EXPENDABLE FULL REPL'MT	SERVICE1/EXPEND USE	SERVICE1/EXPEND 50% ORU REPL'MT	SERVICE1/EXPEND 100% ORU REPL'MT	SERVICE2/EXPEND USE	SERVICE2/EXPEND 50% ORU REPL'MT	SERVICE2/EXPEND 100% ORU REPL'MT
SPACE VEHICLE(SV)									
SV Recurring	100	11	1100	6	600	600	4	400	400
SATSERV ORU	50		0	1 / 5	50	250	1 / 7	50	350
SATSERV Nonr	50		0	1	50	50	1	50	50
SATSERV Mods	10		0	6	60	60	4	40	40
SATSERV ORUR	25		0	4 / 0	100	0	6 / 0	150	0
SPACE TRANS (ST)									
Launch	50	11	550	11	550	550	11	550	550
Integration	30	11	330	11	330	330	11	330	330
Service	5		0	5	25	25	7	35	35
Credits	-25		0	5	-125	-125	7	-175	-175
SAT SERVICER (SS)									
SS ASE Recur	30		0	1	30	90	1	30	60
SS ASE Refurb	10		0	5	50	150	7	70	140
TOTAL PROGRAM COST	Low ST		1980	LOW R*	1720	1980	LOW R	1530	1780
				N*	1845	2105	N	1705	1955
	High ST		2860	HI R	2500	2760	HI R	2270	2520
				N	2750	3010	N	2620	2870
DELTAS FROM EXPENDABLE TPC				LOW R	-260	0	LOW R	-450	-200
				N	-135	125	N	-275	-25
				HI R	-360	-100	HI R	-590	-340
				N	-110	150	N	-240	10
% DIFFERENCE FROM EXPENDABLE				LOW R	-13.13	0	LOW R	-22.73	-10.101
				N	-6.818	6.31313	N	-13.89	-1.2626
				HI R	-12.59	-3.4965	HI R	-20.63	-11.888
				N	-3.846	5.24476	N	-8.392	.349650

* R = Ridesharing; N = No ridesharing

costs. The values of the sub-elements (listed in column 2, % SV RECUR) are multiplied by "USE" factors for each strategy (obtained from analysis of Figure 1) and then summed to arrive at a total program cost. Recall that the costs are not in dollars but rather are percentages relative to baseline space vehicle cost (SV Recurring always equals 100%). The cost factors used in this chapter and Case Number 1 of Chapter 4 are based on acceptable planning figures used at Space Division as of February 1984 (100).

Space Vehicle Costs. The sub-elements of SV costs are those directly related to recurring and development costs for the program's space segment. Development costs for the baseline expendable satellite are not included since it would be the same base factor for all strategies. The base SV cost and the cost of adding serviceability to the baseline are reflected in five sub-elements as follows:

SV Recurring -- the per-satellite cost of a complete baseline spacecraft. This is the cost for the satellite that would be built if servicing were not a consideration.

ORU -- the cost of one full set of Orbit Replaceable Units (ORUs); all of the ORUs required to service one satellite (assumed to cost 50% of SV Recurring).

Nonr -- the one-time cost of developing the ORU designs and modifying the design of the baseline SV for serviceability.

Mods -- the per satellite cost of adding maintainability to the baseline SV.

ORUR -- the cost of one half set of ORUs. This provides the factor related to the planned replacement of 50% of the ORUs on a routine servicing mission.

Space Transportation Costs. As used in this study ST costs are variables which can be altered to show their impact on total program cost for the various servicing scenarios. The ST cost sub-elements for the example are as follows:

Launch -- the normalized full cost of a full STS mission. This is the primary input variable, and all other Space Transportation costs are related to it on a percentage basis in the spreadsheet calculations. The USE factors reflect the requirement for one launch cost for each launch and/or servicing mission. In Table 1, ST launch cost has been input as 50 percent of the baseline SV cost (this might be representative of a $200 million spacecraft launched on a $100 million space shuttle mission).

Integration -- the "per launch" cargo integration cost of each STS mission (100). This study uses a figure of 60 percent of basic ST launch cost, a figure currently used at Air Force Space Division for planning.

Service -- the "orbit-time" cost of performing a servicing mission to pay for Extra-Vehicular Activity and shuttle maneuvering time and fuel; 10 percent of basic ST launch cost (100).

Credits -- reductions to basic ST launch costs to allow for launch ridesharing opportunities where the program being studied does not have to pay the full cost of the shuttle launch but, rather, can share the cost of the servicing missions with some other unrelated program (the example shows ridesharing for the servicing missions only). The credit of 50 percent of ST launch cost reflects a one-half share of the launch cost.

Satellite Servicer Costs. These costs are for the Aerospace Support Equipment (ASE) required to enable the servicing of the SV in orbit. For the bulk of this study, SS costs are assumed to hold a constant relationship to the cost of the SV. However, they can be made variable to allow their manipulation in determining overall cost risk relationships to total program cost as will be illustrated later is this example. It is assumed that the basic hardware is generic in nature so development cost is not included. The following SS ASE costs are pertinent to the study:

Recur -- a one-time cost for any program specific additions to the basic servicing capability (specialized tools, etc.). If given a greater multiplication factor than the 30% shown, this could reflect the cost of a program dedicated set of servicer hardware.

Refurb -- the cost of preparing the servicing equipment for subsequent missions and/or to add minor additional hardware to the servicing capability as needed for a specific mission. The factor of one third of basic servicer costs is arbitrary but reasonably conservative for the purpose of this study and it is consistent with previous SATSERV analyses performed at Space Division (100).

Total Program Cost Summary. A summary of total program costs is provided which shows the expected cost of the program (Low ST refers to the input ST cost factor). The summary also shows the computed total program cost if ST costs should be twice that which is anticipated (High ST). The effects on total program cost of ridesharing (R) on servicing missions vs no ridesharing (N) on any missions are also indicated by summing with and without the rideshare credits.

In order to display the flexibility of the computer spreadsheet technique, two additional cost summaries are shown in Table 1 which have not been used prior to this study. In the first, "Deltas from Expendable TPC," the difference between the normalized total program cost (TPC) for the servicing alternatives and that for the expendable baseline program are displayed. The second, "% Difference from Expendable," displays the same information in terms of percentage of cost growth or reduction (-) from the baseline expendable program.

Incorporating Servicing Strategies Into the Spreadsheet. The servicing strategies from Figure 1 are translated into the "USE" factors on the spreadsheet to reflect the number of times a particular sub-element is required for each strategy. The sub-element cost factors (percent of SV recurring) are then multiplied by the "USE" factors and summed to yield the normalized total program cost for each strategy. To illustrate, in the expendable satellite USE column in Table 1, the number of SVs is eleven. Each SV requires a separate launch and integration and, being expendable, there are no servicing related charges.

In addition to the two servicing strategies (service once or service twice), two servicing cost risk alternatives are also provided for in the example under columns labeled "50% ORU REPL'MT" and "100% ORU REPL'MT." The first alternative would reflect the planned ORU replacement schedule for the servicing missions and the expected cost of the SS ASE sub-elements. The example shows a nominal replacement of only 50 percent of the available ORUs on a satellite during any one servicing mission. The second alternative illustrates the cost risk if it becomes necessary to replace all ORUs on each servicing mission and if SS ASE costs should grow by some multiple factor. In the example, SS ASE costs are tripled to show cost growth risk for the service once strategy but only doubled for the service twice strategy in order to show the flexibility of the model. In the "USE" factor column, the second factor is used where appropriate to incorporate the risk alternatives.

It is important to note at this point that the basic concept of SATSERV is to provide a means of rapidly generating tabular and graphical information for comparison of basic cost relationships and not absolute cost numbers. Therefore, the model must be tailored to provide the most meaningful information for the specific program of interest. That is to say, the model must be constructed to provide the greatest variability in those cost elements or sub-elements where the risk of deviation from expected cost is greatest. The version of the model described in this study is only representative of one possible comparison table. In this case, Space Transportation costs are deemed to offer the highest risk of variability and ORU plans and SS ASE costs a secondary risk.

Graphical Presentation of Results

The originator of the SATSERV model limited the graphical results of the spreadsheet calculations to a basic plot of total program cost on the vertical axis (ordinate) versus strategy-dependent program risk (i.e. risk which the program manager cannot control after having made a basic strategy decision) on the horizontal axis (abscissa). The total program risk was determined to be the reasonable range of cost growth for the serviceable elements of the model superimposed upon the range of potential growth in launch costs (100). As used in this example, the elements of risk induced by selecting a servicing strategy are the average level of ORU replacement required (i.e. 50% vs 100%) and the potential growth of SS ASE costs. A typical plot of this type is shown in Figure 2 reflecting the results of the example in Table 1 and comparing the expendable strategy with the service once strategy.

TWO SATELLITES, SIX CYCLES, SERVICE ONCE

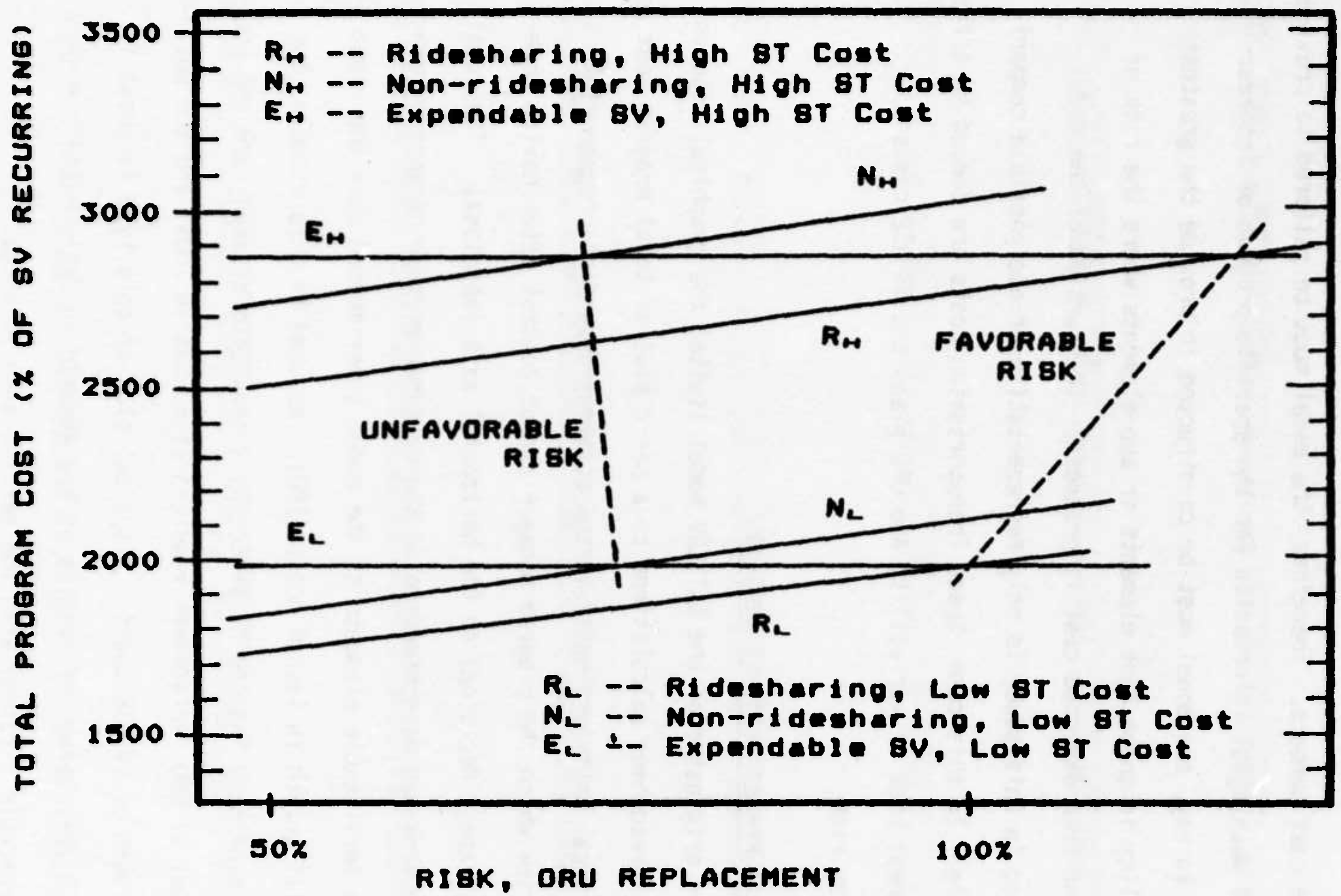


Figure 2. SATSERV Risk Analysis

To interpret Figure 2, note that the lines depicting the total program cost for an expendable strategy are horizontal for both Low and High values of ST cost (having no serviceable components, an expendable strategy would have no cost variability due to servicing cost growth). The lines depicting total program cost for the serviceable system have a positive slope indicative of the potential for cost growth (i.e. risk) with these strategies. The point at which the line for a servicing strategy crosses the expendable line defines the point at which that servicing strategy would become more expensive than the expendable strategy and, therefore, the point at which the program manager would desire to change from serviceable to expendable strategies (assuming a no cost change).

The most important features of the graph (30:8-3) are the dashed lines which approximate the locus of crossing points as ST Launch cost grows from 50 percent of SV Recurring to 100 percent of SV Recurring for servicing with ridesharing and servicing without ridesharing. The negative slope of the dashed line for the non-ridesharing case indicates that as ST Launch cost grows the servicing scenario becomes less favorable because marginal costs for the serviceable system without ridesharing are greater than marginal costs for the expendable system, as servicing costs and launch costs rise. Thus, the program manager can tolerate less risk in the serviceable strategy as ST Launch costs grow. The positive slope of the dashed line for the ridesharing case indicates a favorable marginal cost situation for servicing when ridesharing is available, and the program manager would be able to tolerate more risk in the serviceable strategy as ST Launch costs grow. A program manager/decision-maker would be less inclined to select a "service once" strategy in this case if ridesharing could not be guaranteed and the possibility of launch cost growth was high. However, if ridesharing were available, the program manager could select the servicing strategy and be assured that it would continue to be the lowest cost strategy even if launch and SS ASE costs grew and more ORU replacements were required.

This description of this SATSERV risk analysis technique has been provided for the sake of completeness in introducing the model as designed by its originator. However, a shortcoming of the technique illustrated above is that it requires some span within the range of potential ST Launch cost growth where the strategy being investigated goes from being the less expensive strategy (at its low-cost risk level) to the more expensive strategy (at its high-cost risk level). Where there are no such crossing points, the locus of decision points cannot be determined and the graph would be meaningless. Such is the case over most of the range of data for the service twice strategy where crossing points occur (i.e the "50% ORU REPL'MT" column is negative and the "100% . . . " column is positive) only for the non-ridesharing case at ST Launch values greater than 100% of SV Recurring.

In addition to a review of the example scenario, three cases will be investigated in Chapter IV where there are no crossing points available with which to perform risk analysis. Because of the shortcoming in the SATSERV risk analysis technique and in order to explore the potential of the SATSERV model in revealing underlying relationships between cost elements and total program cost, a different method of presenting

SATSERV information will be used. In each case, the ordinate will represent two factors: (1) the deviation from expendable total program cost and (2) the percentage of deviation from expendable total program cost. This means of presentation, which will be described in detail in the following chapter, should provide an easily understandable tool for interpretive use by program managers who may have little time to become familiar with the details of the SATSERV model.

IV. Analysis of Hypothetical Programs

Description of Programs Selected for Analysis

Four hypothetical programs, representing potential mission profiles of use to the military space community, were selected to provide a means of displaying the capabilities of the SATSERV model. The first case is that of a mission requiring two satellites in low orbit (ie. within direct reach of the Space Shuttle) where the orbits of each satellite are in different planes. Thus, launch and/or servicing of both satellites on the same Space Shuttle mission is not possible. In addition to expendable satellites, strategies are evaluated which would service each satellite once or service each twice during its orbit life. This scenario, the same as in the preceding chapter, also provides an opportunity to expand the method of graphical data presentation.

A second case explores the potential for maintaining a spare satellite in orbit by means of servicing. The baseline program uses one expendable satellite (again in low orbit within reach of the Space Shuttle) to perform the mission with a replacement being launched at the end of each cycle. Three alternative servicing strategies are offered involving the use of two serviceable satellites in the same orbit.

The third case involves the use of a Teleoperator Maneuvering System (TMS) for launching and servicing two satellites in low orbit (less than 1000 miles) but outside the reach of the Space Shuttle. The program mission profile and proposed servicing schedules are the same as for Case Number 1. However, use of the TMS requires other cost risk factors in the area of Space Transportation, and their impact on total program cost must be evaluated.

The fourth and final case evaluated in this report is that of a two satellite system in Geosynchronous Earth Orbit (GEO). To demonstrate the potential of SATSERV in evaluating long-range plans, it is assumed that launch and servicing missions will be staged through an Orbiting Space Station (OSS) and will require an Orbit Transfer Vehicle (OTV) to carry the satellites and servicing hardware to GEO. The servicing schedules evaluated are also the same as for Case Number 1.

Case Number 1: 2 Satellites, 6 Cycles

SATSERV Development. This is the basic two-satellite-separate-orbit scenario discussed in Chapter III to explain the SATSERV model (refer to Figure 1 for strategy development). The spreadsheet was run to compute total program cost figures for values of ST Launch of 10, 20, 50, 100, 200, and 400 percent of SV Recurring. From the results, a graph was drawn (Figure 3) for the "service once" strategy to show the variation in Total Program Cost (expressed as the delta from the expendable baseline and the percentage difference from the expendable baseline) with growth in ST Launch. This was plotted for four risk conditions as follows:

- Ridesharing on all servicing missions with SS ASE Recurring cost equal to 30% of SV Recurring and replacement of 50% of available ORUs on each servicing mission (i.e. low cost servicing)
- Ridesharing on all servicing missions with SS ASE Recurring cost equal to 90% of SV Recurring and replacement of 100% of available ORUs on each servicing mission (i.e. high cost servicing)
- No ridesharing with low cost servicing
- No ridesharing with high cost servicing

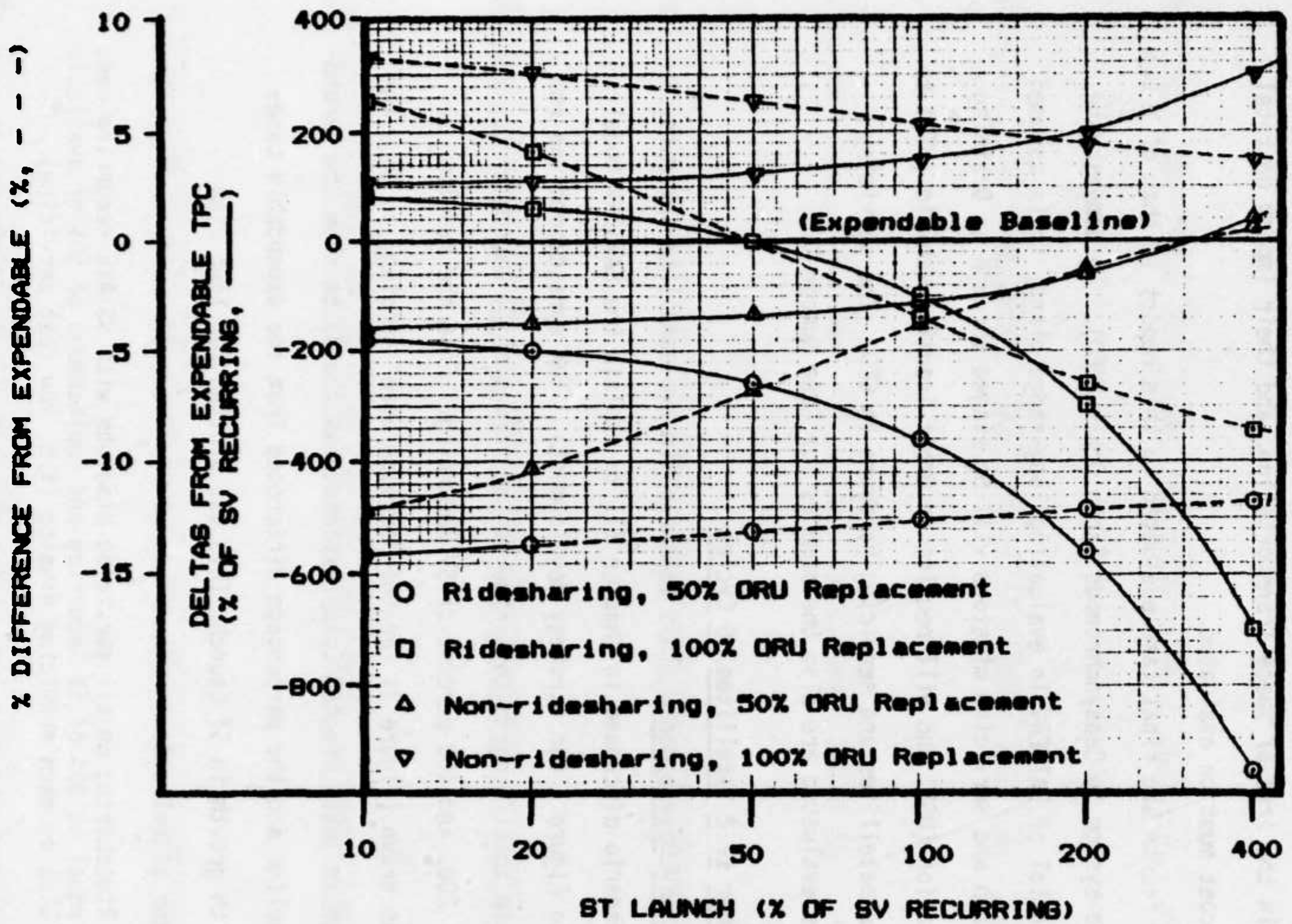


Figure 3. Case 1, Service Once

A second graphical presentation was drawn (Figure 4) showing the same four risk conditions for the strategy where the satellites are serviced twice during their lifetime. In this strategy, however, SS ASE Recurring cost only grew to 60% of SV Recurring for the high cost limit for servicing. Refer to Appendix A for a summary of governing assumptions, a representative layout of the spreadsheet, a table of the formulas and constants used in developing the spreadsheet, and a table of the data used to plot the graphs.

Analysis of Results. From the risk analysis graph in Chapter III, the impact of ridesharing on the servicing decision was made apparent. The graphs in Figures 3 and 4 further highlight this relationsnip. In terms of Total Program Cost differences for the "service once" strategy (Figure 3), the non-ridesharing band (between the low cost and high cost of servicing limits) straddles the zero line for low values of ST Launch (roughly 10% to 100%) and trends higher for larger values of ST Launch (being completely above the zero line by the time ST Launch reaches 400%). On the other hand, the ridesharing band begins at nearly the same level for low ST Launch values but trends quickly lower than the expendable strategy, falling completely below the zero delta line at ST Launch values greater than 50%. In terms of percentage relationships, the rise in cost for the non-ridesharing band does not appear to be significant since at its highest (at low ST values) it is approximately eight percent above the expendable strategy and narrows to between four percent and one half percent at ST Launch value of 400%. The ridesharing band narrows to around ten percent lower than expendable at the high end of ST Launch values. The results show that for this scenario a

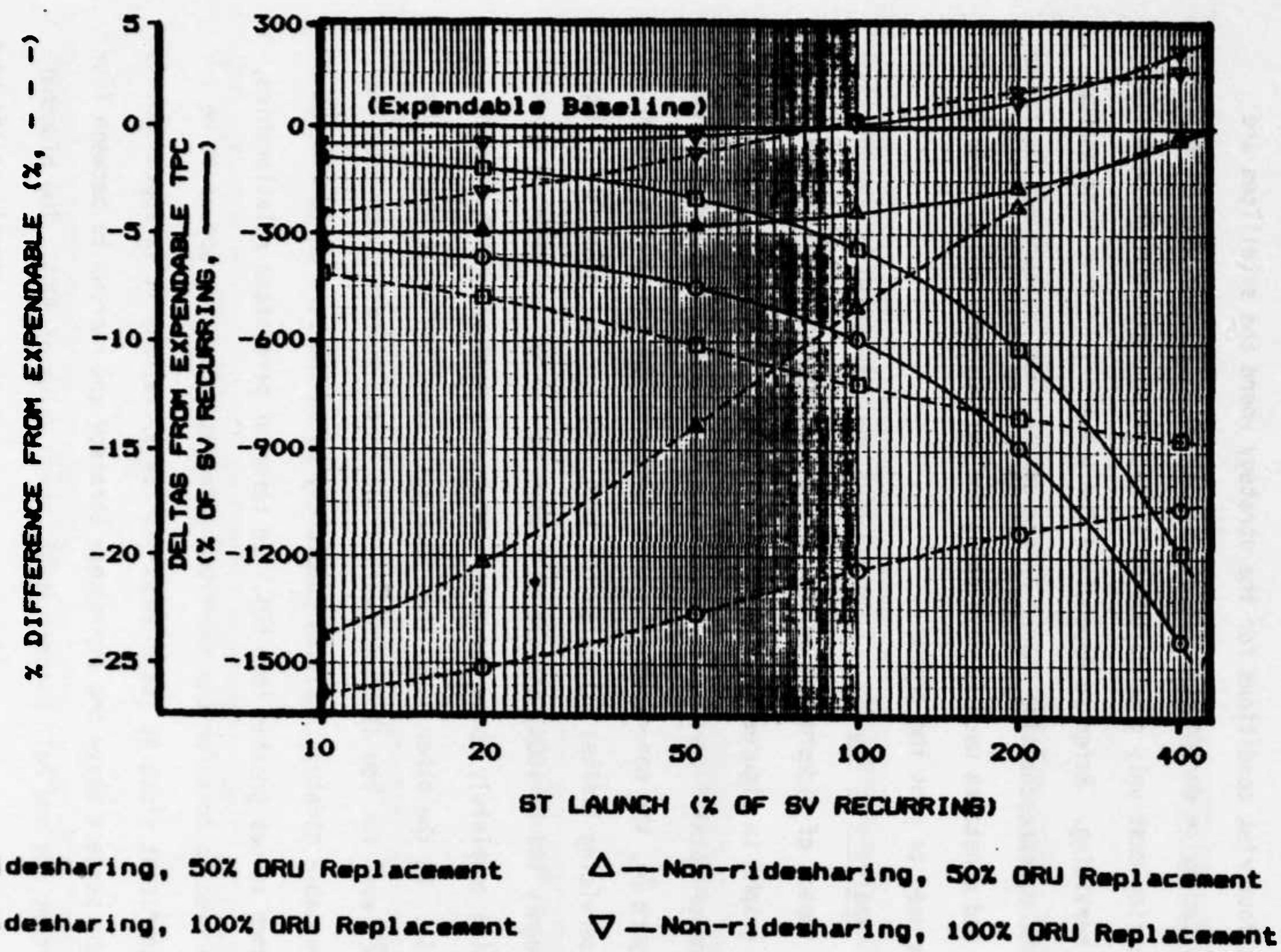


Figure 4. Case 1, Service Twice

decision in favor of servicing would tend to be a sound one for most values of ST Launch unless ridesharing were completely ruled out for all launch and servicing missions. The accuracy of the model is, of course, only as good as the input data; therefore, generalization to existing programs cannot be inferred.

As would be expected, the "service twice" strategy displays results that are even more favorable to a decision for servicing than the results from the "service once" approach. In this case the Total Program Cost and percentage differences all fall below the expendable strategy until ST Launch value exceeds approximately 85 percent with the maximum leveling off at less than five percent above the zero line. The percentage savings that would result from this strategy could be as high as 15 to 17 percent where the ST costs are high relative to the satellite value and where ridesharing is assured.

<u>Case Number 2: 2 Satellites, 6 Cycles, On-Orbit Spare</u>

<u>SATSERV Development</u>. This variation of the basic two-satellite-separate-orbit scenario was chosen to show the relative cost of maintaining a "hot spare" satellite in the same orbit as the prime mission satellite. Here the comparison is between a baseline expendable system with only a single satellite in orbit vs three different satellite servicing strategies. The strategies chosen were as follows:

- o Service once with launch and servicing of both prime and spare SVs on the same missions (i.e. dual launch and dual servicing)
- o Service twice with launch and servicing of both prime and spare SVs on the same missions

- Service twice with launch and servicing of the spare SV lagging launch and servicing of the prime by one cycle, but being performed on the same missions. This would involve some dual servicing missions and some launch/servicing missions but no dual launch missions.

From the strategy definition layout in Figure 5, it was determined to treat each launch without regard to ridesharing. The assumption is made that a dual launch, dual servicing, or launch/service mission would completely fill one STS mission and ridesharing was not included in the expendable strategy to simplify the computations and graphics. Therefore, the ridesharing "Credits" line was deleted from the spreadsheet. Also, in this and all subsequent cases in this study, the risk multiplier term in the SS ASE sub-element has been eliminated in order to simplify the model and focus attention to the ORU replacement strategy effects on servicing costs. The spreadsheet layout, along with a summary of assumptions and the data table used to set up Case 2, can be found in Appendix B.

The spreadsheet was run to compute total program cost figures for values of ST Launch of 10, 20, 50, 100, 200, and 400 percent of SV Recurring with SS ASE held constant at 30 percent of SV Recurring. From the results, graphs were drawn showing the variation in Total Program Cost (expressed as the delta from the expendable baseline and the percentage difference from the expendable baseline) with growth in ST Launch. This was plotted for both 50 percent and 100 percent ORU replacement strategies and for servicing once (Figure 6), servicing twice (Figure 7), and servicing twice with a staggered launch/service sequence (Figure 8).

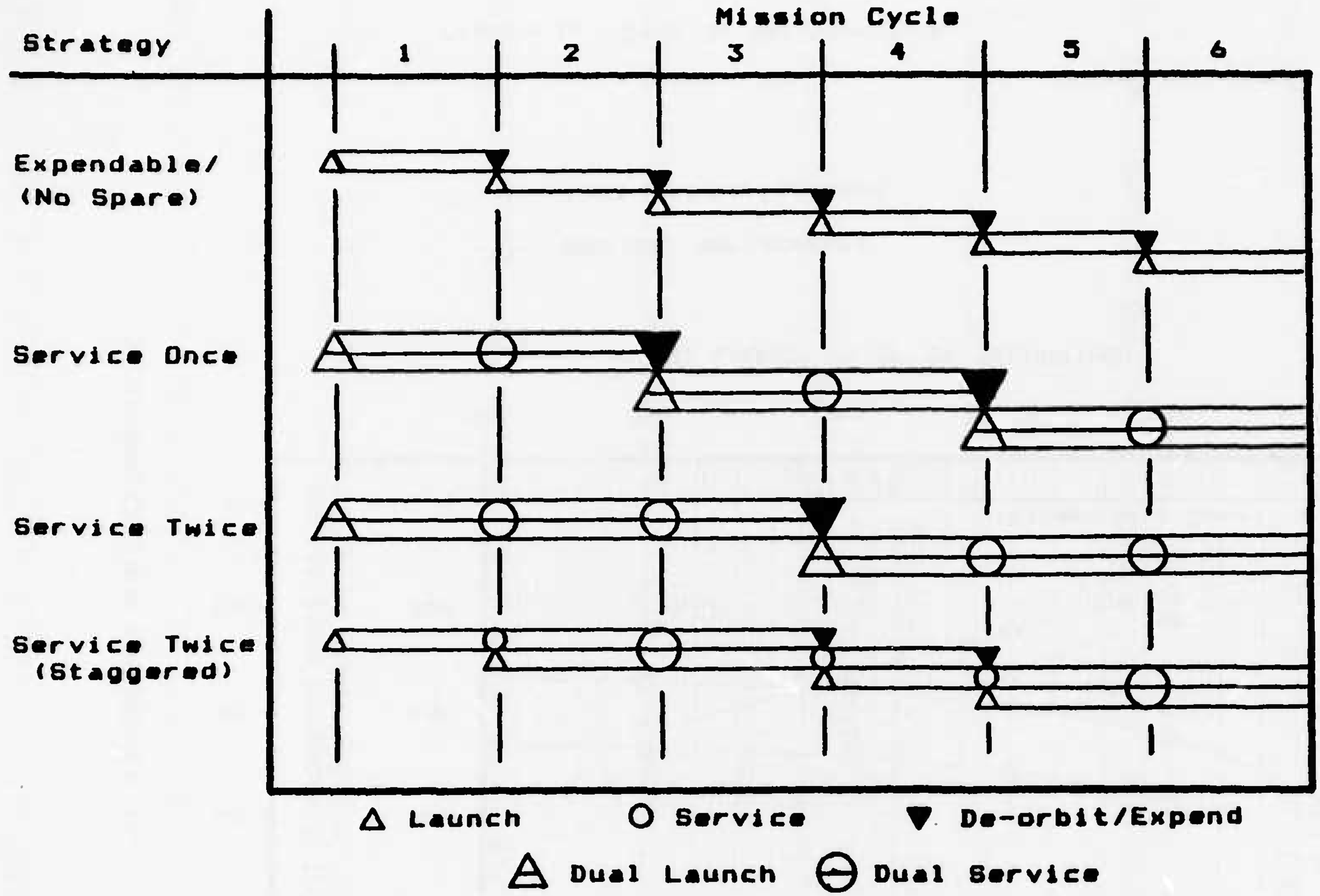


Figure 5. Case 2, Strategy Definition

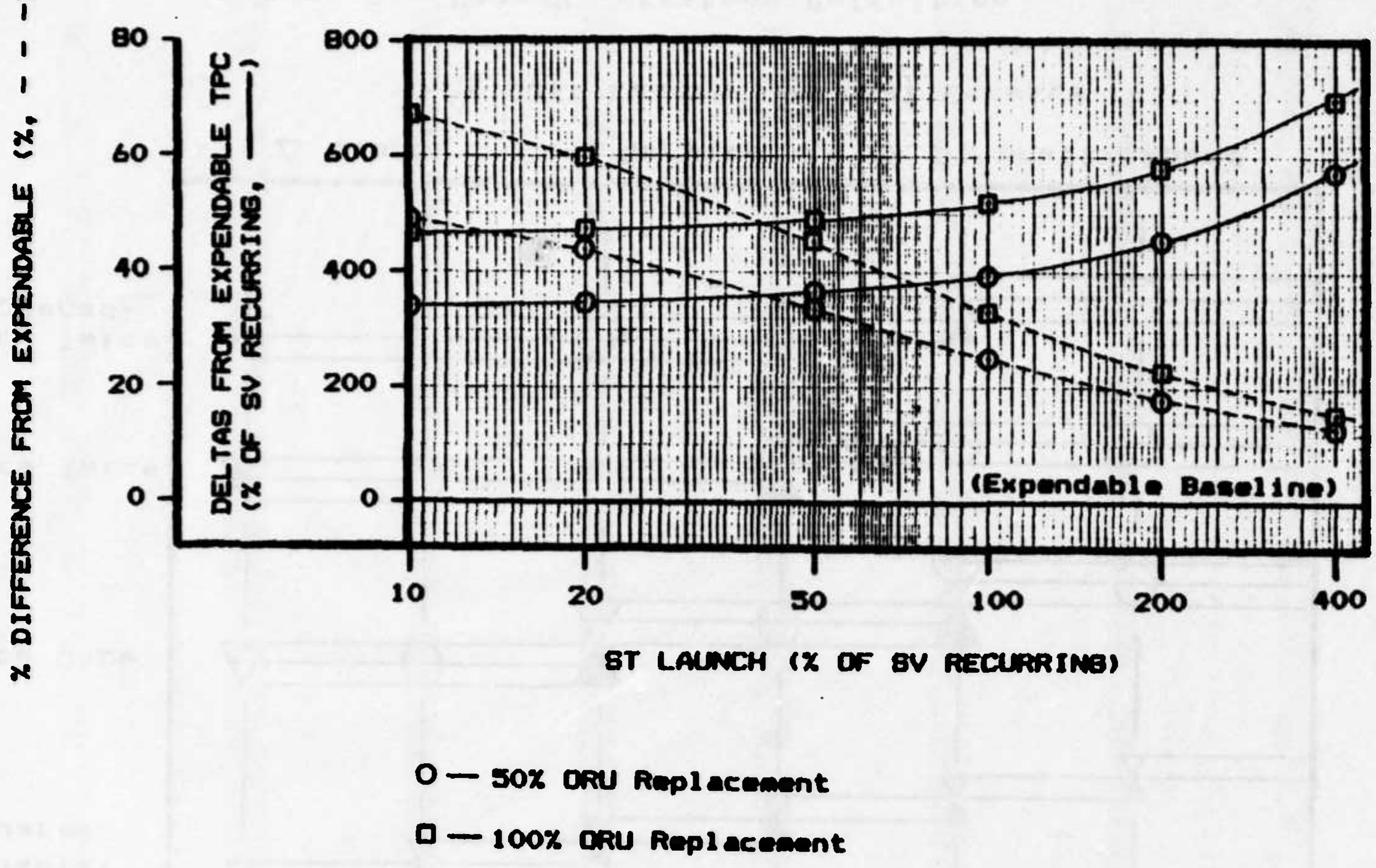


Figure 6. Case 2, Service Once

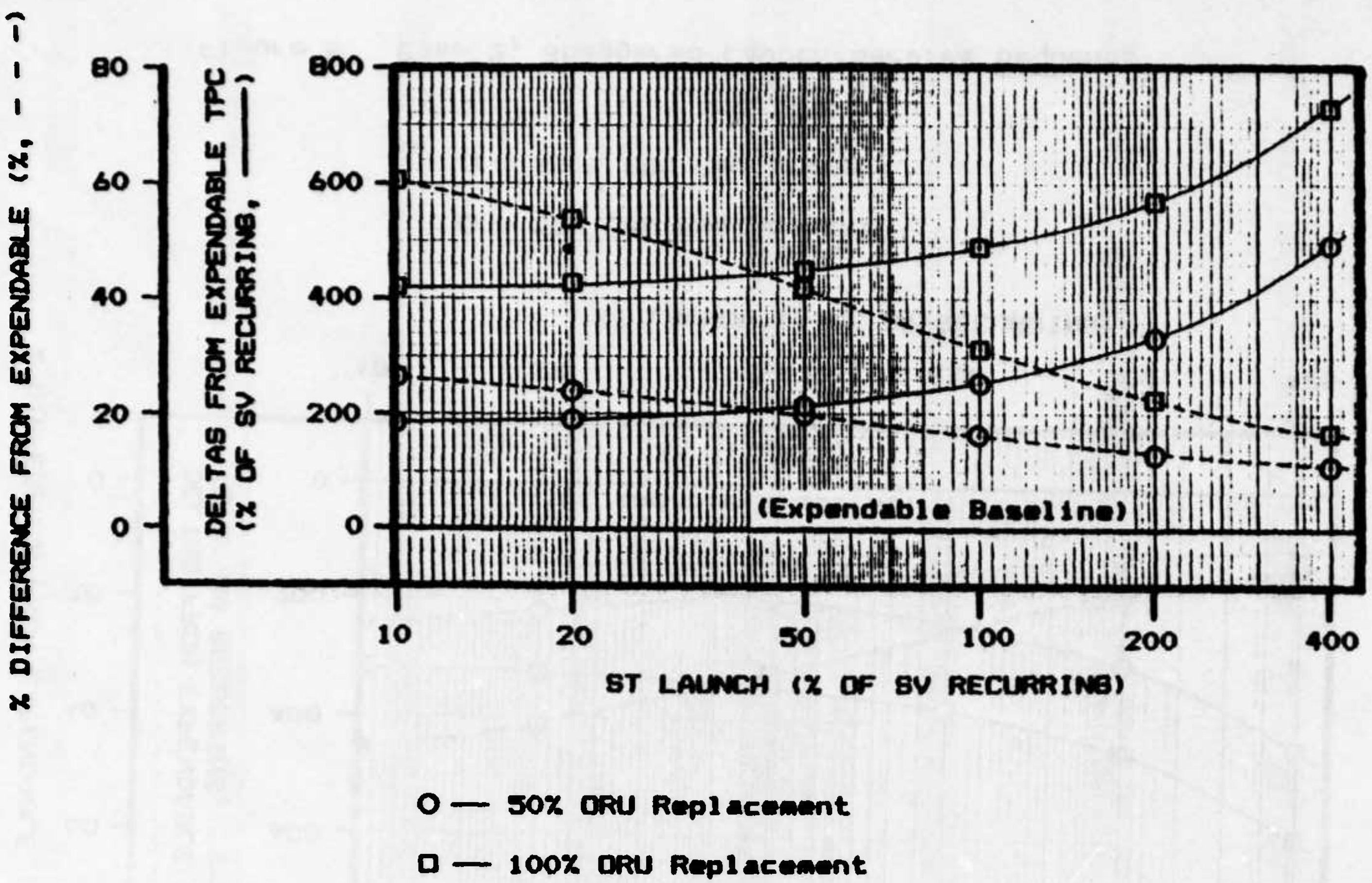
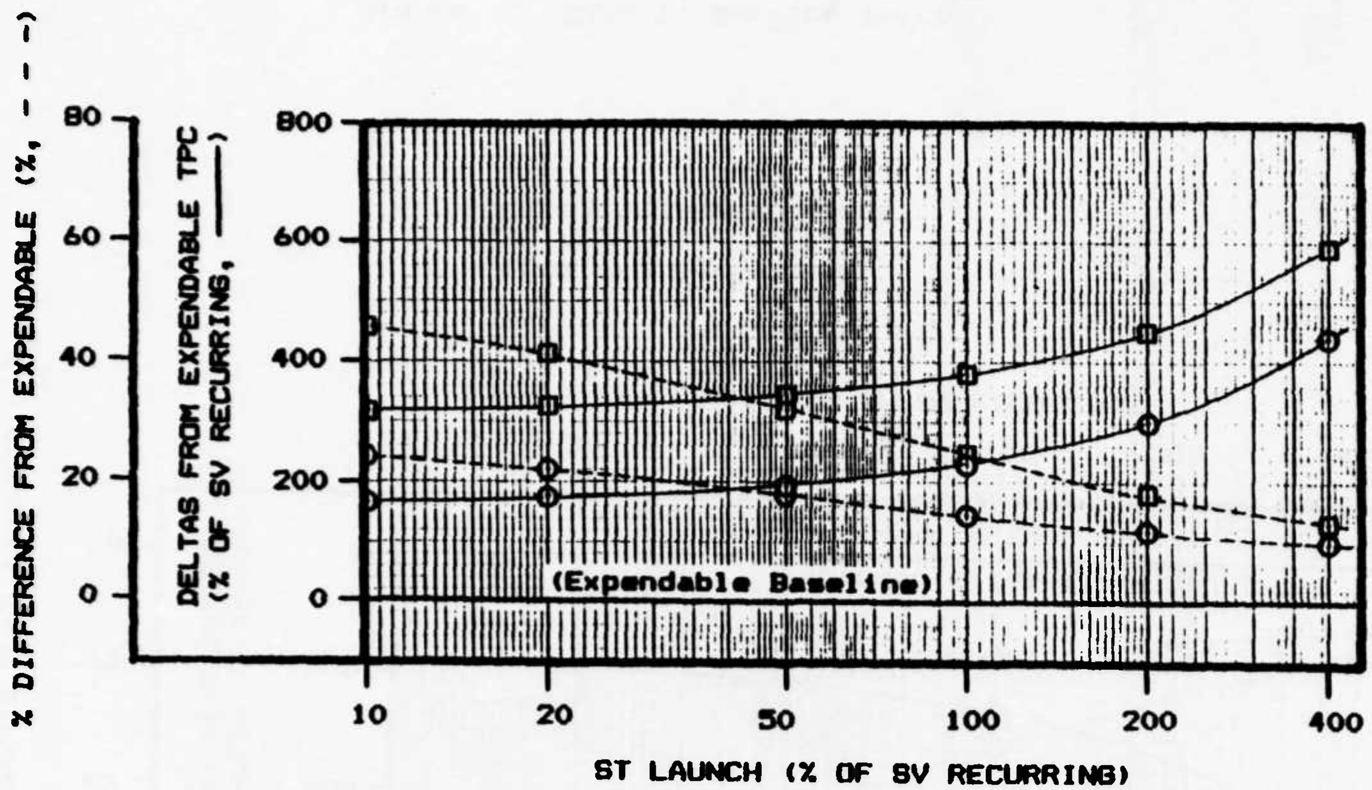


Figure 7. Case 2, Service Twice



O — 50% ORU Replacement

□ — 100% ORU Replacement

Figure 8. Case 2, Staggered Launch/Service Sequence

Analysis of Results. The graphs illustrate that there are no points at which the on-orbit spare with servicing strategies provide a lower program cost than the single expendable satellite strategy (because there are no crossing points, the type of risk analysis performed in Chapter III is not possible). Although the same number of launches are used for each strategy, the additional cost of incorporating servicing into the spacecraft and mission designs apparently outweighs the fact that fewer satellites are required for both "service twice" strategies. It must be recognized however that the utility of a "hot spare" is more of a mission survivability issue than it is a cost effectiveness issue. In view of this, it is significant to note that, where ST Launch cost is high relative to SV cost (i.e. greater than 200%), the cost of a system with an on-orbit spare using servicing falls to less than 20 percent above the cost for a single satellite system. Again program specific costs cannot be inferred; but, these results indicate that where mission criticality is an issue, on-orbit servicing might offset the increased costs of keeping a backup satellite ready for immediate call-up.

Case Number 3: 2 Satellites, 6 Cycles, TMS Required

SATSERV Development. This case involves the same basic program mission requirements and alternative servicing strategies as for Case Number 1. The difference is that the satellite orbit altitude is assumed to be outside the direct reach of the Space Shuttle. Therefore, a Teleoperator Maneuvering System is required for launching the satellites to the higher orbit from the Space Shuttle as well as for carrying the unmanned servicing capability to the satellites.

While the strategy definition layout is the same as that shown in Figure 1 of Chapter III, the use of the TMS requires that some additions be made to the cost sub-elements of the spreadsheet. The following Space Transportation sub-elements are added to the basic spreadsheet layout in Table 1 of Chapter III:

TMS Recurring -- this represents the cost to fuel the TMS and prepare it for a mission by adding any program peculiar electrical or physical interfaces. No TMS development costs are included since the TMS is assumed to be a generic addition to the STS capability. The USE factors reflect the requirement for a full TMS for each individual satellite launch or servicing activity. This is assumed to be 10 percent of the basic ST Launch cost.

TMS Ops -- this is the cost of the orbit operations time for each TMS mission and includes the cost of additional Shuttle Orbiter "on-station" time plus any ground control requirements for the mission. It is also figured at 10 percent of ST Launch cost.

SV Credits -- this is the same as the "Credits" line from the example in Chapter III. In this case, however, SV Credits (50 percent of ST Launch) are used to reflect ridesharing on a SV launch mission (as opposed to a servicing mission). As discussed in Chapter II, a primary reason for the TMS is to provide increased mission utility for the STS. Activities which currently cannot be manifested on the same shuttle mission will be possible because of the TMSs out-of-plane maneuver capability. Thus, ridesharing is assumed to be available for each SV launch activity.

ORU Credits -- this credit line reflects the assumption that a TMS service mission, carrying ORUs instead of a full SV, will use less room in the Space Shuttle and that the extra space will be used by some other program. This allows an 80 percent rideshare credit for each servicing activity rather than the 50 percent credit given for an SV launch.

The spreadsheet was run to compute total program cost figures for values of ST Launch of 10, 20, 50, 100, 200, and 400 percent of SV Recurring with SS ASE held constant at 30 percent of SV Recurring. From the results, a graph was drawn (Figure 9) showing the variation in Total Program Cost (expressed as the delta from the expendable baseline and

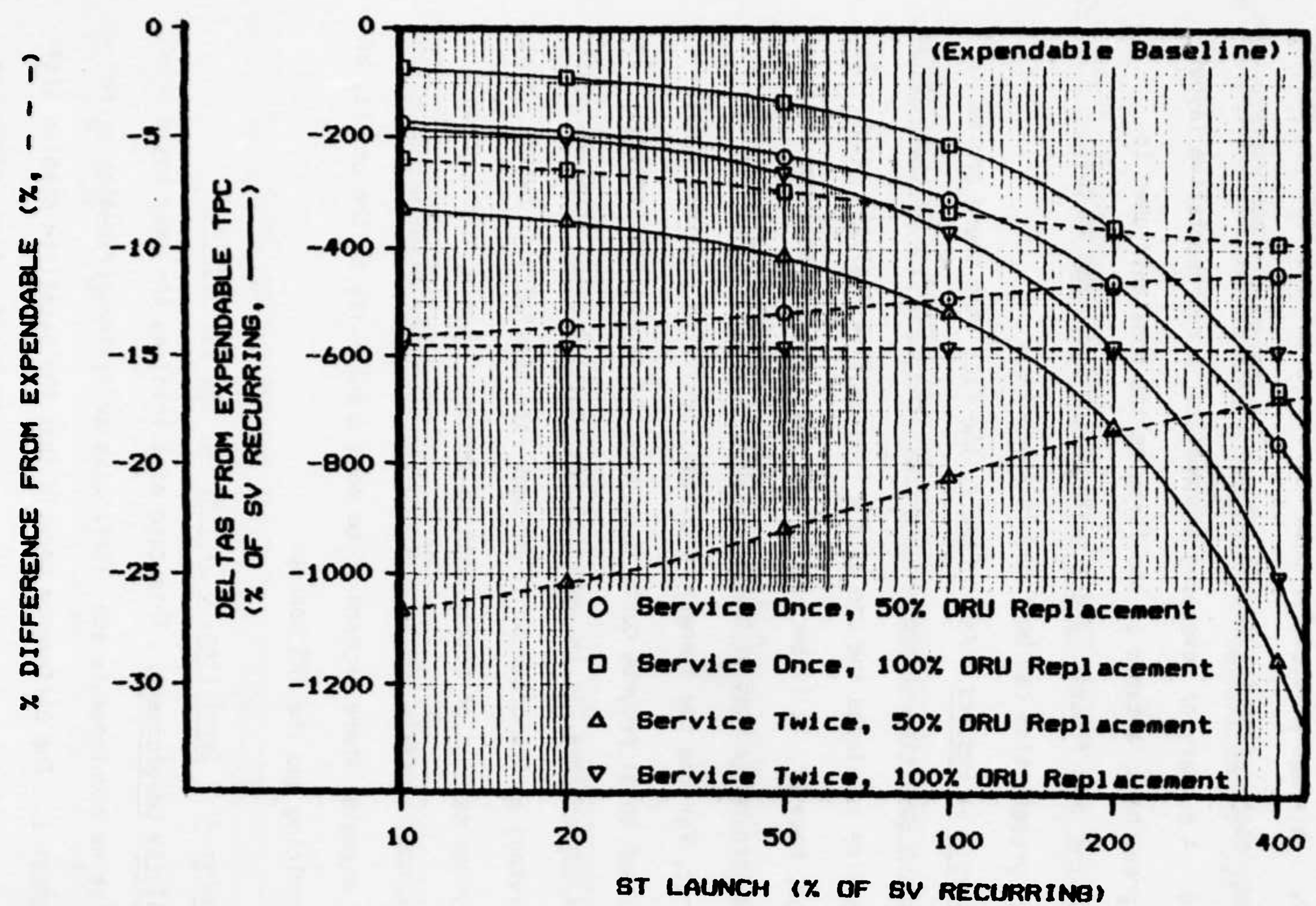


Figure 9. Case 3, TMS Required

the percentage difference from the expendable baseline) with growth in ST Launch. This was plotted for both "service once" and "service twice" strategies, each reflecting the 50 percent to 100 percent ORU replacement band. A summary of governing assumptions, a representative layout of the spreadsheet, a table of the formulas and constants used in computing the cost figures, and a table of the data used in the graphical presentation can be found in Appendix C.

Analysis of Results. As in Case 2, the fact that there are no points where servicing strategy costs cross the zero line of the expendable baseline precludes the use of the Program Risk Analysis graph. In this case, however, it is because all of the servicing strategy cost estimates are below that of the expendable strategy. The graph indicates that, for the the scenario provided, servicing provides consistently lower total program costs than does the expendable strategy. In terms of percentages, it is seen that the "service once" strategy provides savings on the order of 10 percent, and the "service twice" strategy provides savings of better than 15 percent. Again, although more specific cost criteria would be needed to extend the results beyond this limited example, there appears to be some credibility to the utility of both servicing and the TMS concept.

Case Number 4: 2 Satellites, 6 Cycles, OSS and OTV Required

SATSERV Development. This case also involves the same basic program mission requirements and alternative servicing strategies as for Case Number 1. The difference here is that the satellite mission altitude is assumed to be at Geosynchronous Earth Orbit. Also, since the intent of this scenario is to demonstrate the capability of SATSERV to support long-range planning, it is assumed that the satellites and ORUs will be carried into space by the STS to an Orbiting Space Station. At the OSS the satellites (or ORUs and Servicer) will be integrated onto a space-based Orbit Transfer Vehicle for the transfer to GEO.

As in Case 3, the strategy definition layout is the same as that shown in Figure 1. of Chapter III, and changes are required to the basic spreadsheet format to allow for additional Space Transportation sub-elements as follows:

Integration -- the USE factor is used here to reflect STS integration costs for the SV only, since it is assumed that integration costs to haul the ORUs will be minimal.

I&C/O @ OSS -- this factor reflects the cost of Integration with the OTV and Check-Out of the SV or ORU/Servicer ASE at the Orbiting Space Station. While hard cost factors are not currently available, a factor of 10 percent of the basic STS mission is used for this example.

OTV Recurring and OTV Ops -- these sub-elements equate to those used for the TMS example from Case 3.

SV RS and ORU RS Credits -- these sub-elements also equate to those used in Case 3. As discussed in Chapter II, a primary consideration for the OSS is that it will enable the STS to be used in its most efficient manner to haul cargo on a "packaged freight" basis to and from orbit. This means that load factors will be high and integration and mission costs lower for each individual program. However, since hard cost figures are not currently available, the same cost factors as used in Case 3 are used here even though they are probably conservative when considered with OSS operations.

The spreadsheet was run to compute total program cost figures for values of ST Launch of 10, 20, 50, 100, 200, and 400 percent of SV Recurring with SS ASE held constant at 30 percent of SV Recurring. From the results, a graph was drawn (Figure 10) showing the variation in Total Program Cost (expressed as the delta from the expendable baseline and the percentage difference from the expendable baseline) with growth

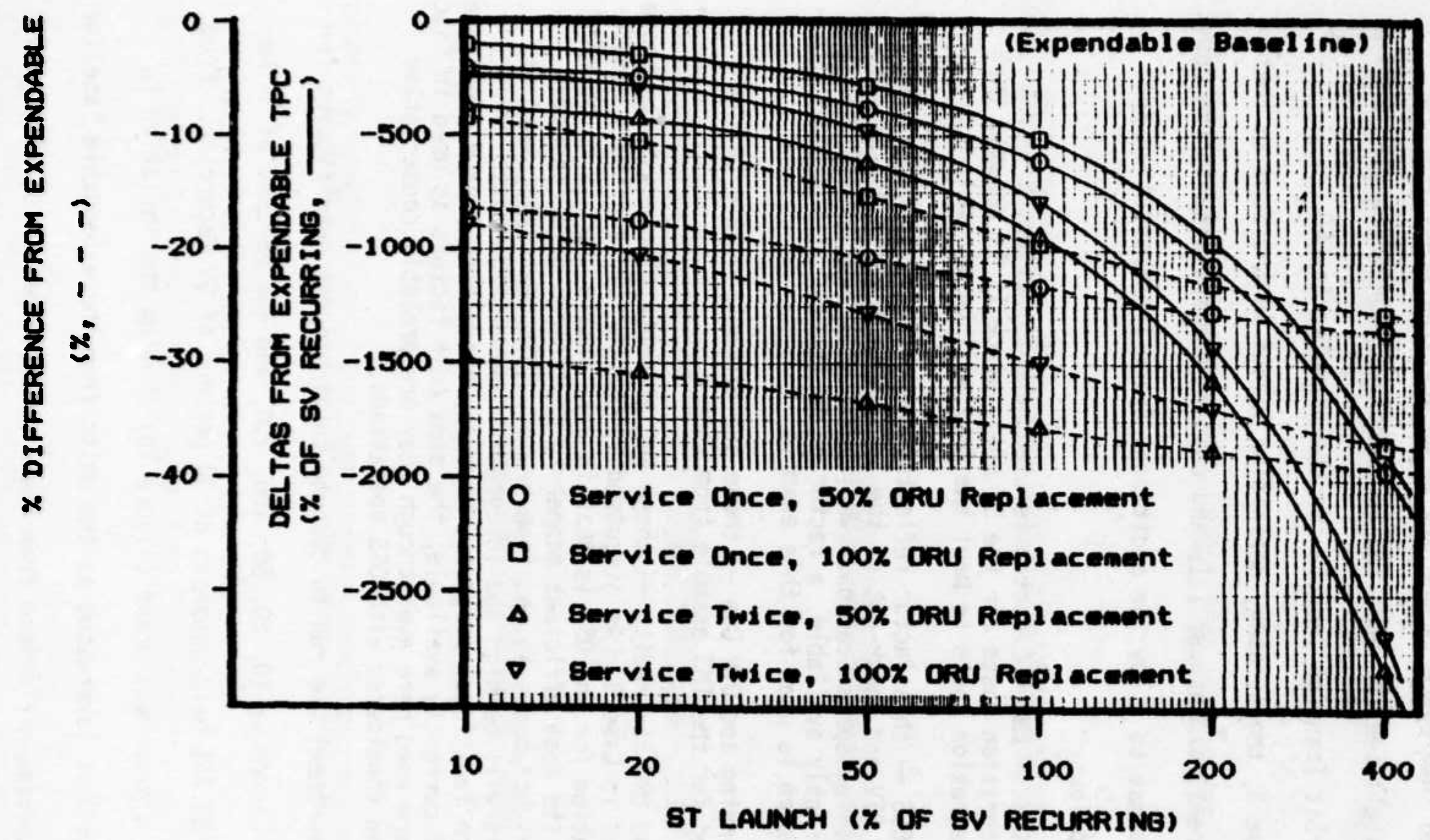


Figure 10. Case 4, OSS and OTV Required

in ST Launch. Since the satellites and ORUs will be carried aboard the Space Shuttle with other OSS support items ridesharing is assumed for both. This was plotted for servicing both once and twice with each showing the 50 percent to 100 percent ORU replacement band. A summary of governing assumptions, a representative layout of the spreadsheet, and a table of the formulas and constants used in computing the cost figures can be found in Appendix D.

Analysis of Results. Program Risk Analysis graphing is precluded for the same reason stated in Case 3 (i.e. there are no zero line crossings because all of the servicing strategy cost estimates are below that of the expendable strategy). Also, as was the situation in Case 3, the graph indicates that, for the the scenario provided, servicing provides consistently lower total program costs than does the expendable strategy. In terms of percentages, it is seen that the "service once" strategy provides savings on the order of 15 percent at low values of ST Launch to 25 percent for high values of ST Launch. The "service twice" strategy provides savings of about 20 to 25 percent for low ST Launch values and better than 35 percent for higher ST Launch values. Again, although more specific cost criteria would be needed to extend the results beyond this limited example, there appears to be substantial savings potential (over the expendable strategy) of using on-orbit servicing in conjunction with the Orbiting Space Station and an Orbit Transfer Vehicle.

V. Conclusions and Recommendations

To this point, a survey has been conducted of military policy and civilian literature concerning on-orbit spacecraft servicing. The SATSERV model has been introduced and discussed in the context of four general sample scenarios. Some conclusions based upon the foregoing material will now be drawn and some recommendations for program managers and further study will be made.

Conclusions

Literature Survey Trends. The military space community has historically taken a "wait and see" attitude toward on-orbit servicing. This hesitation is born of a genuine desire on the part of program managers to reduce the program risk and, thereby, limit potential cost to the public. In addition, until recently there has been no readily useable servicing technology in spite of much speculation on the benefits of servicing. Recently, however, military policies are being examined in light of increased space activity and servicing technology availability, along with the increased need for spacecraft survivability. The civilian space community, however, continues to advocate a much stronger stance in favor of on-orbit servicing for reasons of both cost savings and necessity (larger structures, for example). Previous experience has indicated the effectiveness of spacecraft servicing.

If current United States efforts toward establishing an operational space station in the 1990s continue, then one by-product will be technology critical to the expansion of servicing capability. Specifically, on-orbit transportation such as Orbital Transfer Vehicles, tools for space assembly and servicing tasks, and advances in automation will be developed. Additionally, the existance of an orbital transportation node will reduce transportation costs which currently limit economical servicing ability.

SATSERV Model. The SATSERV model is a useful estimation and comparison tool which enables a program manager to readily analyze underlying cost relationships and to determine sensitivities to cost factor growth. The model's chief advantage is its simple spreadsheet format which makes it ideal for use on any of the new microcomputers being purchased by the Air Force (for example, an International Business Machines Personal Computer was used for this study). In this format, the model can be easily implemented to rapidly generate a large number of alternatives for investigation. The extreme flexibility that SATSERV offers can also be a shortcoming in that the results obtained from it cannot be generalized to cover a broad range of programs. The setup of the model and its results must be tailored to provide information for each specific program, and the most current economic information should always be used.

The model, as developed initially and as used in this study, provides an output based on normalized costs relative to spacecraft recurring cost, implying that spacecraft recurring costs are known with a greater degree of certainty than any other program cost element. Within the program management environment at Space Division, this is currently perceived as an appropriate assumption because of two unsettled questions: (1) what, if any, will be the role of the expendable launch vehicle in the future of military space systems? and (2) if the STS or a future derivative is to be the sole U. S. space launch capability, how much is it going to cost? While the civilian space community may answer these questions with a degree of certainty on their part, the early track record of the STS with unforeseen integration costs, cargo rate changes, and launch delays (many of which are rightfully due to system complexity born of crew safety considerations) leaves the military space program manager with more confidence in defining space segment related costs (i.e. risk) than space transportation costs. Even the ultimate availability of servicing hardware and systems was not really doubted, only "when?" and "how much will it cost?" unresolved questions prevented low risk forecasts based upon servicing factors. Thus, the use of spacecraft cost as the primary normalization factor is the currently most acceptable method, but the emergence of some other factor or combination of factors should not be ruled out for the future.

As has been noted earlier, generally applicable conclusions cannot be drawn from the four scenarios examined with SATSERV in this study. There are, however, some interesting observations which arise that should be examined more closely to see if generalization would be appropriate. For instance, the only situation where serviceable system cost was both greater than and still rising compared to expendable system cost as ST cost grew was when ridesharing was not available and an entire STS mission was required to launch a relatively low cost spacecraft into a unique orbit. The potential requirement for just such a mission for a military system which might find enhanced survivability in not living in a crowd argues strongly for a continued expendable spacecraft and launch capability.

On the other hand, in each situation where ridesharing was available or where orbit compatability allowed dual launch and/or servicing missions, total program cost (again, relative to the expendable system on a percentage basis) fell, or was falling, or had stabilized at a point below that of the expendable system as ST launch cost grew to the upper extreme. This indicates potential significant benefits to the total space community of servicing where military mission orbit requirements overlap those of other military missions or of civilian missions.

The potential benefits of designing spacecraft for servicing when similar orbit requirements exist go beyond the sharing of transportation costs. Since spacecraft with similar orbits often have similar missions (e.g. military and civilian communications satellites at GEO), the potential for standardizing servicing hardware/methods and ORUs is substantial, leading to additional savings due to economies of scale. Even where orbit compatability may not enhance the opportunity for servicing, increased modularity in spacecraft designs should lead to lower spacecraft construction costs as well as reduced problem correction time when prelaunch anomalies occur. These are areas where further study is needed to review past experience and to define similarities that are conducive to common modularity in systems.

Recommendations

Program Managers. As was recommended in the Spacecraft Maintenace Policy Review (29:23), program managers should at least consider on-orbit servicing scenarios at the outset of a program. As servicing technology becomes more pervasive in actual missions, risks of using servicing should diminish as well as the costs, increasing the potential program life-cycle cost savings. Additionally, design of a spacecraft for servicing may be beneficial in other ways as discussed above and earlier in the study and will hold open the option for future servicing.

The SATSERV model will provide a good overall look at competing scenarios and can be used prior to or in conjuction with the use of a more detailed costing model. The time to adapt and use the SATSERV model should be more than offset by the increase in conceptualization ability and the potential servicing savings.

<u>Further Study</u>. The utility and nature of the SATSERV model could be modified in several ways. Reliability considerations could be included in the model to reflect the impacts of serviceablity and servicing in terms of overall life-cycle cost. More capable spreadsheet software could be used to automatically graph alternatives in desired formats. Links could be used with other computers to use accurate and current project data in the model and reduce manual factor updating.

With regard to the model scenarios, populations and orbit characteristics different from the basic ones used in the study should be examined. Also, as servicing technology becomes more defined, costs and effects will become more defined and the model could be used for more precise and definitive analysis of scenarios and comparisons. If costs for a different program element other than spacecraft vehicle recurring cost are known with a greater degree of confidence, then the model could be modified to use normalized costs based on the higher confidence element. Servicer/servicing costs in particular should be explored over a broad range to determine servicing cost risk effects on the program. Additionally, non-STS transportation options can be considered as well as mixes to include emerging space launch capabilities.

Appendix A: Case Number 1 Supporting Data

The following is a list of basic assumptions and inputs for Case 1:

- o Two Satellites, Six Cycles
- o Non-coplaner orbits, both Satellites cannot be serviced/launched on the same STS mission
- o Three Strategies

  Expendable
  Service once and expend
  Service twice and expend

- o Primary input variable is ST Launch cost which is input as 10%, 20%, 50%, 100%, 200%, and 400% of basic SV recurring cost.
- o Costs for two ORU replacement levels are computed to provide a band for analysis of planning risk.

  Replacement of 50% of available ORU's and
  Replacement of 100% of available ORU's

Table II provides a spreadsheet layout for Case 1 which includes the column letters and row numbers for use in interpreting the formulas and constants provided in Table III. The data used in drawing the graphs for Case 1 are provided in Table IV.

TABLE II

Case 1 Spreadsheet Layout

```
|      A       | | C || D||E||F|| G || H||I||    |L|| M ||N|| O || P||Q|   |T|| U ||V|| W |
```

Row	Cost Elements	% SV Recur	Expendable Use	Expendable Full Repl'mt	Service1/Expend Use	Service1/Expend 50% ORU Repl'mt	Service1/Expend 100% ORU Repl'mt	Service2/Expend Use	Service2/Expend 50% ORU Repl'mt	Service2/Expend 100% ORU Repl'mt
1	CASE 2, 2 SATELLITES, 6 CYCLES									
2	ST Lch = 100% SV Recur									
3										
4										
5		% SV	EXPENDABLE		SERVICE1/EXPEND			SERVICE2/EXPEND		
6	COST ELEMENTS	RECUR	USE	FULL	USE	50% ORU	100% ORU	USE	50% ORU	100% ORU
7				REPL'MT		REPL'MT	REPL'MT		REPL'MT	REPL'MT
8										
9	SPACE VEHICLE(SV)									
10	SV Recurring	100	11	1100	6	600	600	4	400	400
11	SATSERV ORU	50		0	1 / 5	50	250	1 / 7	50	350
12	SATSERV Nonr	50		0	1	50	50	1	50	50
13	SATSERV Mods	10		0	6	60	60	4	40	40
14	SATSERV ORUR	25		0	4 / 0	100	0	6 / 0	150	0
15										
16	SPACE TRANS (ST)									
17	Launch	100	11	1100	11	1100	1100	11	1100	1100
18	Integration	60	11	660	11	660	660	11	660	660
19	Service	10		0	5	50	50	7	70	70
20	Credits	-50		0	5	-250	-250	7	-350	-350
21										
22	SAT SERVICER (SS)									
23	SS ASE Recur	30		0	1	30	90	1	30	60
24	SS ASE Refurb	10		0	5	50	150	7	70	140
25										
26	TOTAL PROGRAM COST									
27	Low ST		E1	2860	LOW R*	2500	2760	LOW R	2270	2520
28					N*	2750	3010	N	2620	2870
29										
30	High ST		E2	4620	HI R	4060	4320	HI R	3750	4000
31					N	4560	4820	N	4450	4700
32	* R = Ridesharing; N = No ridesharing									
33										
34	DELTAS FROM EXPENDABLE TPC									
35					LOW R	-360	-100		-590	-340
36					N	-110	150		-240	10
37					HI R	-560	-300		-870	-620
38					N	-60	200		-170	80
39										
40	% DIFFERENCE FROM EXPENDABLE									
41					LOW R	-12.59	-3.4965		-20.63	-11.888
42					N	-3.846	5.24476		-8.392	.349650
43					HI R	-12.12	-6.4935		-18.83	-13.420
44					N	-1.299	4.32900		-3.680	1.73160

TABLE III

Case 1 Basic Formulas and Constants

The table that follows is a list of the formulas and constants used to build the spreadsheet for Case 1. The left side of the equation indicates the location of the item in Table II, by column letter and row number. The right side of the equation displays the value of a constant or the arithmetic operation to be performed ("*" for multiplication, "/" for division, and "SUM" to total the inclusive elements indicated) on the data from the locations shown.

Basic Input Parameter

C2 = NA (NA is used by the spreadsheet to reserve the location for an input variable

Space Vehicle (SV) Costs

C10 = 100
E10 = 11
G10 = C10*E10
I10 = 6
M10 = C10*I10
O10 = C10*I10
Q10 = 4
U10 = C10*Q10
W10 = C10*Q10
C11 = 50
G11 = C11*E11
I11 = 1
K11 = 5
M11 = C11*I11
O11 = C11*K11
Q11 = 1
S11 = 7
U11 = C11*Q11
W11 = C11*S11
C12 = 50
G12 = C12*E12
I12 = 1
M12 = C12*I12
O12 = C12*I12
Q12 = 1
U12 = C12*Q12
W12 = C12*Q12
C13 = 10
G13 = C13*E13
I13 = 6

(continued)

TABLE III (continued)

Case 1 Basic Formulas and Constants

M13	= C13*I13
O13	= C13*I13
Q13	= Q10
U13	= C13*Q13
W13	= C13*Q13
C14	= 25
G14	= C14*E14
I14	= 4
K14	= 0
M14	= C14*I14
O14	= C14*K14
Q14	= 6
S14	= 0
U14	= C14*Q14
W14	= C14*S14

Space Transportation (ST) Costs

C17	= C2
E17	= 11
G17	= C17*E17
I17	= 11
M17	= C17*I17
O17	= C17*I17
Q17	= 11
U17	= C17*Q17
W17	= C17*Q17
C18	= C17*.6
E18	= 11
G18	= C18*E18
I18	= 11
M18	= C18*I18
O18	= C18*I18
Q18	= 11
U18	= C18*Q18
W18	= C18*Q18
C19	= C17/10
G19	= C19*E19
I19	= 5
M19	= C19*I19
O19	= C19*I19
Q19	= 7
U19	= C19*Q19
W19	= C19*Q19
C20	= -C17/2
G20	= C20*E20

(continued)

TABLE III (continued)

Case 1 Basic Formulas and Constants

```
I20     = 5
M20     = C20*I20
O20     = C20*I20
Q20     = 7
U20     = C20*Q20
W20     = C20*Q20
```

Satellite Servicer (SS) Costs

```
C23     = 30
G23     = C23*E23
I23     = 1
M23     = C23*I23
O23     = C23*I23*3
Q23     = 1
U23     = C23*Q23
W23     = C23*Q23*2
C24     = C23/3
G24     = C24*E24
I24     = 5
M24     = C24*I24
O24     = C24*I24*3
Q24     = 7
U24     = C24*Q24
W24     = C24*Q24*2
```

Total Cost Summary

```
G27     = SUM(G10:G20)
M27     = SUM(M10:M24)
O27     = SUM(O10:O24)
U27     = SUM(U10:U24)
W27     = SUM(W10:W24)
M28     = M27-M20
O28     = O27-O20
U28     = U27-U20
W28     = W27-W20
G30     = G27+SUM(G17:G20)
M30     = M27+SUM(M17:M20)
O30     = O27+SUM(O17:O20)
U30     = U27+SUM(U17:U20)
W30     = W27+SUM(W17:W20)
M31     = M30-2*M20
O31     = O30-2*O20
U31     = U30-2*U20
W31     = W30-2*W20
```

(continued)

TABLE III (continued)

Case 1 Basic Formulas and Constants

DELTAS FROM EXPENDABLE TPC

M35	= M27-G27
035	= 027-G27
U35	= U27-G27
W35	= W27-G27
M36	= M28-G27
036	= 028-G27
U36	= U28-G27
W36	= W28-G27
M37	= M30-G30
037	= 030-G30
U37	= U30-G30
W37	= W30-G30
M38	= M31-G30
038	= 031-G30
U38	= U31-G30
W38	= W31-G30

% DIFFERENCE FROM EXPENDABLE TPC

M41	= 100*M35/G27
041	= 100*035/G27
U41	= 100*U35/G27
W41	= 100*W35/G27
M42	= 100*M36/G27
042	= 100*036/G27
U42	= 100*U36/G27
W42	= 100*W36/G27
M43	= 100*M37/G30
043	= 100*037/G30
U43	= 100*U37/G30
W43	= 100*W37/G30
M44	= 100*M38/G30
044	= 100*038/G30
U44	= 100*U38/G30
W44	= 100*W38/G30

TABLE IV

Case 1 Data

ST Lch = 10% (Low) and 20% (Hi) SV Recurring

COST ELEMENTS	% SV RECUR	EXPENDABLE USE	EXPENDABLE FULL REPL'MT	SERVICE1/EXPEND USE	SERVICE1/EXPEND 50% ORU REPL'MT	SERVICE1/EXPEND 100% ORU REPL'MT	SERVICE2/EXPEND USE	SERVICE2/EXPEND 50% ORU REPL'MT	SERVICE2/EXPEND 100% ORU REPL'MT
SPACE VEHICLE(SV)									
SV Recurring	100	11	1100	6	600	600	4	400	400
SATSERV ORU	50		0	1 / 5	50	250	1 / 7	50	350
SATSERV Nonr	50		0	1	50	50	1	50	50
SATSERV Mods	10		0	6	60	60	4	40	40
SATSERV ORUR	25		0	4 / 0	100	0	6 / 0	150	0
SPACE TRANS (ST)									
Launch	10	11	110	11	110	110	11	110	110
Integration	6	11	66	11	66	66	11	66	66
Service	1		0	5	5	5	7	7	7
Credits	-5		0	5	-25	-25	7	-35	-35
SAT SERVICER (SS)									
SS AGE Recur	30		0	1	30	90	1	30	60
SS AGE Refurb	10		0	5	50	150	7	70	140
TOTAL PROGRAM COST		Low ST	1276	LOW R*	1096	1336	LOW R	938	1188
				N*	1121	1381	N	973	1223
		High ST	1452	HI R	1252	1512	HI R	1086	1336
				N	1302	1562	N	1156	1406
DELTAS FROM EXPENDABLE TPC				LOW R	-180	80	LOW R	-338	-88
				N	-155	105	N	-303	-53
				HI R	-200	60	HI R	-366	-116
				N	-150	110	N	-296	-46
% DIFFERENCE FROM EXPENDABLE				LOW R	-14.11	6.26959	LOW R	-26.49	-6.8966
				N	-12.15	8.22884	N	-23.75	-4.1536
				HI R	-13.77	4.13223	HI R	-25.21	-7.9890
				N	-10.33	7.57576	N	-20.39	-3.1680

* R = Ridesharing; N = No ridesharing

(continued)

TABLE IV (continued)

Case 1 Data

ST Lch = 50% (Low) and 100% (Hi) SV Recurring

TOTAL PROGRAM COST	Low ST	1980	LOW	R	1720	1980	LOW	R	1530	1780
				N	1845	2105		N	1705	1955
	High ST	2860	HI	R	2500	2760	HI	R	2270	2520
				N	2750	3010		N	2620	2870
DELTAS FROM EXPENDABLE TPC			LOW	R	-260	0	LOW	R	-450	-200
				N	-135	125		N	-275	-25
			HI	R	-360	-100	HI	R	-590	-340
				N	-110	150		N	-240	10
% DIFFERENCE FROM EXPENDABLE										
			LOW	R	-13.13	0	LOW	R	-22.73	-10.101
				N	-6.818	6.31313		N	-13.89	-1.2626
			HI	R	-12.59	-3.4965	HI	R	-20.63	-11.888
				N	-3.846	5.24476		N	-8.392	.349650

ST Lch = 200% (Low) and 400% (Hi) SV Recurring

TOTAL PROGRAM COST	Low ST	4620	LOW	R	4060	4320	LOW	R	3750	4000
	!!			N	4560	4820		N	4450	4700
	High ST	8140	HI	R	7180	7440	HI	R	6710	6960
	!!			N	8180	8440		N	8110	8360
DELTAS FROM EXPENDABLE TPC			LOW	R	-560	-300	LOW	R	-870	-620
				N	-60	200		N	-170	80
			HI	R	-960	-700	HI	R	-1430	-1180
				N	40	300		N	-30	220
% DIFFERENCE FROM EXPENDABLE			LOW	R	-12.12	-6.4935	LOW	R	-18.83	-13.420
				N	-1.299	4.32900		N	-3.680	1.73160
			HI	R	-11.79	-8.5995	HI	R	-17.57	-14.496
				N	.49140	3.68550		N	-.3686	2.70270

Appendix B: Case Number 2 Supporting Data

The following is a list of basic assumptions and inputs for Case 2:

- One Expendable or Two Serviceable Satellites, Six Cycles
- Both satellites are in the same orbit plane at the same altitude, and and one serves as the mission backup to the other.
- Four Strategies

  Single SV, Expendable
  Service each SV once
  Service each SV twice
  Service each SV twice, Launch the second SV at the time of servicing the first

- Primary variable is ST Launch cost (reflected as percentage of basic SV Recurring cost). Input values are 10%, 20%, 50%, 100%, 200%, and 400%.
- Two ORU replacement levels provide a range of planning risk.

  Replace 50% of available ORUs on each mission
  Replace 100% of available ORUs on each mission

- This model is used to project the relative cost of maintaining a "hot spare" on orbit by means of satellite servicing. It assumes that both satellites are launched and subsequently serviced on dedicated shuttle missions. Therefore, ridesharing is not available with other users.

Table V provides a spreadsheet layout for Case 2 which includes the column letters and row numbers for use in interpreting the formulas and constants provided in Table VI. The data used in drawing the graphs for Case 2 are provided in Table VII.

TABLE V

Case 2 Spreadsheet Layout

	A	C	E	G	I	M	O
1	CASE 2: 2 SATELLITES, 6 CYCLES, "ON-ORBIT SPARE"						
2	ST Lch = 100% SV Recurring						
3							
4							
5		% SV	EXPENDABLE		SERVICE1/EXPEND		
6	COST ELEMENTS	RECUR	USE	FULL	USE	50% ORU	100% ORU
7				REPL'MT		REPL'MT	REPL'MT
8							
9	SPACE VEHICLE(SV)						
10	SV Recurring	100	6	600	6	600	600
11	SATSERV ORU	50		0	1 / 6	50	300
12	SATSERV Nonr	50		0	1	50	50
13	SATSERV Mods	10		0	6	60	60
14	SATSERV ORUR	25		0	5 / 0	125	0
15							
16	SPACE TRANS (ST)						
17	Launch	100	6	600	6	600	600
18	Integration	60	6	360	6	360	360
19	Service	10		0	6	60	60
20							
21	SAT SERVICER (SS)						
22	SS ASE Recur	30		0	1	30	30
23	SS ASE Refurb	10		0	2	20	20
24							
25	TOTAL PROGRAM COST						
26	Low ST			1560	LOW	1955	2080
27	High ST			2520	HI	2975	3100
28							
29	TPC DELTAS FROM EXPENDABLE				LOW	395	520
30					HI	455	580
31							
32	% DIFFERENCE FROM EXPENDABLE TPC				LOW	25.321	33.3333
33					HI	18.056	23.0159

(continued)

TABLE V (continued)

Case 2 Spreadsheet Layout

	Q	T	U	V W	Y	AC	AE
1							
2							
3							
4	====================================			STAGGERED LAUNCH ========			
5		SERVICE2/EXPEND			SERVICE2/EXPEND		
6		USE	50% ORU	100% ORU	USE	50% ORU	100% ORU
7			REPL'MT	REPL'MT		REPL'MT	REPL'MT
8	=	============	============	============	============	============	============
9							
10		4	400	400	4	400	400
11		1 / 8	50	400	1 / 7	50	350
12		1	50	50	1	50	50
13		4	40	40	4	40	40
14		7 / 0	175	0	6 / 0	150	0
15	-	------------	------------	------------	------------	------------	------------
16							
17		6	600	600	6	600	600
18		6	360	360	6	360	360
19		8	80	80	7	70	70
20	-	------------	------------	------------	------------	------------	------------
21							
22		1	30	30	1	30	30
23		3	30	30	4	40	40
24	=	============	============	============	============	============	============
25							
26		LOW	1815	1990	LOW	1790	1940
27		HI	2855	3030	HI	2820	2970
28	============	============	============	============	============	============	============
29		LOW	255	430	LOW	230	380
30		HI	335	510	HI	300	450
31	============	============	============	============	============	============	============
32		LOW	16.346	27.5641	LOW	14.744	24.3590
33		HI	13.294	20.2381	HI	11.905	17.8571

TABLE VI

Case 2 Basic Formulas and Constants

The table that follows is a list of the formulas and constants used to build the spreadsheet for Case 2. The left side of the equation indicates the location of the item in Table V, by column letter and row number. The right side of the equation displays the value of a constant or the arithmetic operation to be performed ("*" for multiplication, "/" for division, and "SUM" to total the inclusive elements indicated) on the data from the locations shown.

Basic Input Parameter

C2 = NA (NA is used to by the spreadsheet to reserve the location for an input variable)

Space Vehicle (SV) Costs

C10 = 100
E10 = 6
G10 = C10*E10
I10 = 6
M10 = C10*I10
O10 = C10*I10
Q10 = 4
U10 = C10*Q10
W10 = C10*Q10
Y10 = 4
AC10 = C10*Y10
AE10 = C10*Y10
C11 = 50
G11 = C11*E11
I11 = 1
K11 = 6
M11 = C11*I11
O11 = C11*K11
Q11 = 1
S11 = 8
U11 = C11*Q11
W11 = C11*S11
Y11 = 1
AA11 = 7
AC11 = C11*Y11
AE11 = C11*AA11
C12 = 50
G12 = C12*E12
I12 = 1
M12 = C12*I12
O12 = C12*I12

(continued)

TABLE VI (continued)

Case 2 Basic Formulas and Constants

Q12	= 1
U12	= C12*Q12
W12	= C12*Q12
Y12	= 1
AC12	= C12*Y12
AE12	= C12*Y12
C13	= 10
G13	= C13*E13
I13	= 6
M13	= C13*I13
O13	= C13*I13
Q13	= 4
U13	= C13*Q13
W13	= C13*Q13
Y13	= 4
AC13	= C13*Y13
AE13	= C13*Y13
C14	= 25
G14	= C14*E14
I14	= 5
K14	= 0
M14	= C14*I14
O14	= C14*K14
Q14	= 7
S14	= 0
U14	= C14*Q14
W14	= C14*S14
Y14	= 6
AA14	= 0
AC14	= C14*Y14
AE14	= C14*AA14

Space Transportation (ST) Costs

C17	= C2
E17	= 6
G17	= C17*E17
I17	= 6
M17	= C17*I17
O17	= C17*I17
Q17	= 6
U17	= C17*Q17
W17	= C17*Q17
Y17	= 6
AC17	= C17*Y17

(continued)

TABLE VI (continued)

Case 2 Basic Formulas and Constants

AE17	= C17*Y17
C18	= C17*.6
E18	= 6
G18	= C18*E18
I18	= 6
M18	= C18*I18
O18	= C18*I18
Q18	= 6
U18	= C18*Q18
W18	= C18*Q18
Y18	= 6
AC18	= C18*Y18
AE18	= C18*Y18
C19	= C17/10
G19	= C19*E19
I19	= 6
M19	= C19*I19
O19	= C19*I19
Q19	= 8
U19	= C19*Q19
W19	= C19*Q19
Y19	= 7
AC19	= C19*Y19
AE19	= C19*Y19

Satellite Servicer (SS) Costs

C22	= 30
G22	= C22*E22
I22	= 1
M22	= C22*I22
O22	= C22*I22
Q22	= 1
U22	= C22*Q22
W22	= C22*Q22
Y22	= 1
AC22	= C22*Y22
AE22	= C22*Y22
C23	= C22/3
G23	= C23*E23
I23	= 2
M23	= C23*I23
O23	= C23*I23
Q23	= 3
U23	= C23*Q23

(continued)

TABLE VI (continued)

Case 2 Basic Formulas and Constants

W23	=	C23*Q23
Y23	=	4
AC23	=	C23*Y23
AE23	=	C23*Y23

<u>Total Program Cost (TPC)</u>

G26	=	SUM(G10:G23)
M26	=	SUM(M10:M23)
O26	=	SUM(O10:O23)
U26	=	SUM(U10:U23)
W26	=	SUM(W10:W23)
AC26	=	SUM(AC10:AC23)
AE26	=	SUM(AE10:AE23)
G27	=	G26+SUM(G17:G19)
M27	=	M26+SUM(M17:M19)
O27	=	O26+SUM(O17:O19)
U27	=	U26+SUM(U17:U19)
W27	=	W26+SUM(W17:W19)
AC27	=	AC26+SUM(AC17:AC19)
AE27	=	AE26+SUM(AE17:AE19)

<u>Deltas from Expendable TPC</u>

M29	=	M26-G26
O29	=	O26-G26
U29	=	U26-G26
W29	=	W26-G26
AC29	=	AC26-G26
AE29	=	AE26-G26
M30	=	M27-G27
O30	=	O27-G27
U30	=	U27-G27
W30	=	W27-G27
AC30	=	AC27-G27
AE30	=	AE27-G27

(continued)

TABLE VI (continued)

Case 2 Basic Formulas and Constants

% Difference from Expendable TPC

M32	=	100*M29/G26
O32	=	100*O29/G26
U32	=	100*U29/G26
W32	=	100*W29/G26
AC32	=	100*AC29/G26
AE32	=	100*AE29/G26
M33	=	100*M30/G27
O33	=	100*O30/G27
U33	=	100*U30/G27
W33	=	100*W30/G27
AC33	=	100*AC30/G27
AE33	=	100*AE30/G27

TABLE VII

Case 2 Data

ST Lch = 10% (Low) and 20% (Hi) SV Recurring

COST ELEMENTS	% SV RECUR	EXPENDABLE USE	EXPENDABLE FULL REPL'MT	SERVICE1/EXPEND USE	SERVICE1/EXPEND 50% ORU REPL'MT	SERVICE1/EXPEND 100% ORU REPL'MT
TOTAL PROGRAM COST						
Low ST			696	LOW	1037	1162
High ST			792	HI	1139	1264
TPC DELTAS FROM EXPENDABLE				LOW	341	466
				HI	347	472
% DIFFERENCE FROM EXPENDABLE TPC				LOW	48.994	66.9540
				HI	43.813	59.5960

SERVICE2/EXPEND USE	SERVICE2/EXPEND 50% ORU REPL'MT	SERVICE2/EXPEND 100% ORU REPL'MT	STAGGERED LAUNCH SERVICE2/EXPEND USE	STAGGERED LAUNCH SERVICE2/EXPEND 50% ORU REPL'MT	STAGGERED LAUNCH SERVICE2/EXPEND 100% ORU REPL'MT
LOW	879	1054	LOW	863	1013
HI	983	1158	HI	966	1116
LOW	183	358	LOW	167	317
HI	191	366	HI	174	324
LOW	26.293	51.4368	LOW	23.994	45.5460
HI	24.116	46.2121	HI	21.970	40.9091

(continued)

TABLE VII (continued)

Case 2 Data

ST Lch = 50% (Low) and 100% (Hi) SV Recurring

COST ELEMENTS	% SV RECUR	EXPENDABLE USE	EXPENDABLE FULL REPL'MT	SERVICE1/EXPEND USE	SERVICE1/EXPEND 50% ORU REPL'MT	SERVICE1/EXPEND 100% ORU REPL'MT
TOTAL PROGRAM COST						
Low ST			1080	LOW	1445	1570
High ST			1560	HI	1955	2080
TPC DELTAS FROM EXPENDABLE				LOW	365	490
				HI	395	520
% DIFFERENCE FROM EXPENDABLE TPC				LOW	33.796	45.3704
				HI	25.321	33.3333

SERVICE2/EXPEND USE	SERVICE2/EXPEND 50% ORU REPL'MT	SERVICE2/EXPEND 100% ORU REPL'MT	STAGGERED LAUNCH SERVICE2/EXPEND USE	STAGGERED LAUNCH SERVICE2/EXPEND 50% ORU REPL'MT	STAGGERED LAUNCH SERVICE2/EXPEND 100% ORU REPL'MT
LOW	1295	1470	LOW	1275	1425
HI	1815	1990	HI	1790	1940
LOW	215	390	LOW	195	345
HI	255	430	HI	230	380
LOW	19.907	36.1111	LOW	18.056	31.9444
HI	16.346	27.5641	HI	14.744	24.3590

(continued)

TABLE VII (continued)

Case 2 Data

ST Lch = <u>200%</u> (Low) and <u>400%</u> (Hi) SV Recurring

COST ELEMENTS	% SV RECUR	EXPENDABLE USE	EXPENDABLE FULL REPL'MT	SERVICE1/EXPEND USE	SERVICE1/EXPEND 50% ORU REPL'MT	SERVICE1/EXPEND 100% ORU REPL'MT
TOTAL PROGRAM COST						
Low ST			2520	LOW	2975	3100
High ST			4440	HI	5015	5140
TPC DELTAS FROM EXPENDABLE				LOW	455	580
				HI	575	700
% DIFFERENCE FROM EXPENDABLE TPC				LOW	18.056	23.0159
				HI	12.950	15.7658

SERVICE2/EXPEND USE	SERVICE2/EXPEND 50% ORU REPL'MT	SERVICE2/EXPEND 100% ORU REPL'MT	STAGGERED LAUNCH SERVICE2/EXPEND USE	STAGGERED LAUNCH SERVICE2/EXPEND 50% ORU REPL'MT	STAGGERED LAUNCH SERVICE2/EXPEND 100% ORU REPL'MT
LOW	2855	3030	LOW	2820	2970
HI	4935	5110	HI	4880	5030
LOW	335	510	LOW	300	450
HI	495	670	HI	440	590
LOW	13.294	20.2381	LOW	11.905	17.8571
HI	11.149	15.0901	HI	9.9099	13.2883

AD-A148 447 PLANNING FOR THE ON-ORBIT SERVICING OF MILITARY SPACECRAFT(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB OH SCHOOL OF ENGINEERING M E RUSSELL ET AL. SEP 84 2/2

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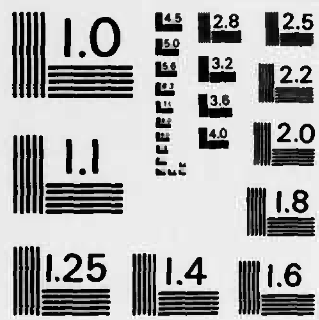

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Appendix C: Case Number 3 Supporting Data

The following is a list of basic assumptions and inputs for Case 3:

- o Two Satellites, Six Cycles
- o Mission orbits are above or out of plane of the Space Shuttle mission orbit and require TMS for both initial launch and servicing missions.
- o Three Strategies:

  Expendable satellite
  Service once and expend
  Service twice and expend

- o Primary variable is ST Launch cost (reflected as percentage of basic SV Recurring cost). Input values are 10%, 20%, 50%, 100%, 200%, and 400%.
- o Two ORU replacement levels provide a range of planning risk.

  Replace 50% of available ORUs on each mission
  Replace 100% of available ORUs on each mission

- o All missions for both expendable and serviceable satellites require the use of the TMS. Ridesharing is assumed on all missions.

Table VIII provides a spreadsheet layout for Case 3 which includes the column letters and row numbers for use in interpreting the formulas and constants provided in Table IX. The data used in drawing the graphs for Case 3 are provided in Table X.

TABLE VIII

Case 3 Spreadsheet Layout

Row	A	C	D E	F G	H I	L M	N O	P Q	T U	V W
1	CASE 3, 2 SATELLITES, 6 CYCLES, TMS REQUIRED									
2	ST Lch = 100% SV Recurring									
3										
4										
5		% SV	EXPENDABLE		SERVICE1/EXPEND			SERVICE2/EXPEND		
6	COST ELEMENTS	RECUR	USE	FULL	USE	50% ORU	100% ORU	USE	50% ORU	100% ORU
7				REPL'MT		REPL'MT	REPL'MT		REPL'MT	REPL'MT
8										
9	SPACE VEHICLE(SV)									
10	SV Recurring	100	11	1100	6	600	600	4	400	400
11	SATSERV ORU	50		0	1 / 5	50	250	1 / 7	50	350
12	SATSERV Nonr	50		0	1	50	50	1	50	50
13	SATSERV Mods	10		0	6	60	60	4	40	40
14	SATSERV ORUR	25		0	4 / 0	100	0	6 / 0	150	0
15										
16	SPACE TRANS (ST)									
17	Launch	100	11	1100	11	1100	1100	11	1100	1100
18	Integration	60	11	660	11	660	660	11	660	660
19	TMS Recurring	10	11	110	11	110	110	11	110	110
20	TMS Ops	10	11	110	11	110	110	11	110	110
21	SV Credits	-50		0	6	-300	-300	4	-200	-200
22	ORU Credits	-80		0	5	-400	-400	7	-560	-560
23										
24	SAT SERVICER (SS)									
25	SS AGE Recur	30		0	1	30	30	1	30	30
26	SS AGE Refurb	10		0	5	50	50	7	70	70
27										
28	TOTAL PGM COST									
29	Low ST			3080	LOW	2220	2320	LOW	2010	2160
30	High ST			5060	HI	3500	3600	HI	3230	3380
31										
32	DELTAS FROM EXPENDABLE TPC				LOW	-860	-760	LOW	-1070	-920
33					HI	-1560	-1460	HI	-1830	-1680
34										
35	% DIFFERENCE FROM EXPENDABLE				LOW	-27.92	-24.675	LOW	-34.74	-29.870
36					HI	-30.83	-28.854	HI	-36.17	-33.202

TABLE IX

Case 3 Basic Formulas and Constants

The table that follows is a list of the formulas and constants used to build the spreadsheet for Case 3. The left side of the equation indicates the location of the item in Table VIII, by column letter and row number. The right side of the equation displays the value of a constant or the arithmetic operation to be performed ("*" for multiplication, "/" for division, and "SUM" to total the inclusive elements indicated) on the data from the locations shown.

<u>Basic Input Parameter</u>

C2 = NA (NA is used to by the spreadsheet to reserve the location for an input variable)

<u>Space Vehicle (SV) Costs</u>

C10	= 100
E10	= 11
G10	= C10*E10
I10	= 6
M10	= C10*I10
O10	= C10*I10
Q10	= 4
U10	= C10*Q10
W10	= C10*Q10
C11	= 50
G11	= C11*E11
I11	= 1
K11	= 5
M11	= C11*I11
O11	= C11*K11
Q11	= 1
S11	= 7
U11	= C11*Q11
W11	= C11*S11
C12	= 50
G12	= C12*E12
I12	= 1
M12	= C12*I12
O12	= C12*I12
Q12	= 1
U12	= C12*Q12
W12	= C12*Q12
C13	= 10
G13	= C13*E13
I13	= 6

(continued)

TABLE IX (continued)

Case 3 Basic Formulas and Constants

M13	= C13*I13
O13	= C13*I13
Q13	= Q10
U13	= C13*Q13
W13	= C13*Q13
C14	= 25
G14	= C14*E14
I14	= 4
K14	= 0
M14	= C14*I14
O14	= C14*K14
Q14	= 6
S14	= 0
U14	= C14*Q14
W14	= C14*S14

<u>Space Transportation (ST) Costs</u>

C17	= C2
E17	= 11
G17	= C17*E17
I17	= 11
M17	= C17*I17
O17	= C17*I17
Q17	= 11
U17	= C17*Q17
W17	= C17*Q17
C18	= C17*.6
E18	= 11
G18	= C18*E18
I18	= 11
M18	= C18*I18
O18	= C18*I18
Q18	= 11
U18	= C18*Q18
W18	= C18*Q18
C19	= C17/10
E19	= 11
G19	= C19*E19
I19	= 11
M19	= C19*I19
O19	= C19*I19
Q19	= 11
U19	= C19*Q19
W19	= C19*Q19

(continued)

TABLE IX (continued)

Case 3 Basic Formulas and Constants

C20	=	C17/10
E20	=	11
G20	=	C20*E20
I20	=	11
M20	=	C20*I20
O20	=	C20*I20
Q20	=	11
U20	=	C20*Q20
W20	=	C20*Q20
C21	=	-C17/2
G21	=	C21*E21
I21	=	6
M21	=	C21*I21
O21	=	C21*I21
Q21	=	4
U21	=	C21*Q21
W21	=	C21*Q21
C22	=	-.8*C17
G22	=	C22*E22
I22	=	5
M22	=	C22*I22
O22	=	C22*I22
Q22	=	7
U22	=	C22*Q22
W22	=	C22*Q22

Satellite Servicer (SS) Costs

C25	=	30
G25	=	C25*E25
I25	=	1
M25	=	C25*I25
O25	=	C25*I25
Q25	=	1
U25	=	C25*Q25
W25	=	C25*Q25
C26	=	C25/3
G26	=	C26*E26
I26	=	5
M26	=	C26*I26
O26	=	C26*I26
Q26	=	7
U26	=	C26*Q26
W26	=	C26*Q26

(continued)

TABLE IX (continued)

Case 3 Basic Formulas and Constants

Total Program Cost TPC

G29	= SUM(G10:G22)
M29	= SUM(M10:M26)
O29	= SUM(O10:O26)
U29	= SUM(U10:U26)
W29	= SUM(W10:W26)
G30	= G29+SUM(G17:G22)
M30	= M29+SUM(M17:M22)
O30	= O29+SUM(O17:O22)
U30	= U29+SUM(U17:U22)
W30	= W29+SUM(W17:W22)

Deltas from Expendable TPC

M32	= M29-G29
O32	= O29-G29
U32	= U29-G29
W32	= W29-G29
M33	= M30-G30
O33	= O30-G30
U33	= U30-G30
W33	= W30-G30

% Difference from Expendable TPC

M35	= 100*M32/G29
O35	= 100*O32/G29
U35	= 100*U32/G29
W35	= W32*100/G29
M36	= 100*M33/G30
O36	= 100*O33/G30
U36	= 100*U33/G30
W36	= W33*100/G30

TABLE X

Case 3 Data

ST Lch = <u>10%</u> (Low) and <u>20%</u> (Hi) SV Recurring

COST ELEMENTS	% SV RECUR	EXPENDABLE USE	EXPENDABLE FULL REPL'MT	SERVICE1/EXPEND USE	SERVICE1/EXPEND 50% ORU REPL'MT	SERVICE1/EXPEND 100% ORU REPL'MT	SERVICE2/EXPEND USE	SERVICE2/EXPEND 50% ORU REPL'MT	SERVICE2/EXPEND 100% ORU REPL'MT
SPACE VEHICLE(SV)									
SV Recurring	100	11	1100	6	600	600	4	400	400
SATSERV ORU	50		0	1 / 5	50	250	1 / 7	50	350
SATSERV Nonr	50		0	1	50	50	1	50	50
SATSERV Mods	10		0	6	60	60	4	40	40
SATSERV ORUR	25		0	4 / 0	100	0	6 / 0	150	0
SPACE TRANS (ST)									
Launch	10	11	110	11	110	110	11	110	110
Integration	6	11	66	11	66	66	11	66	66
TMS Recurring	1	11	11	11	11	11	11	11	11
TMS Ops	1	11	11	11	11	11	11	11	11
SV Credits	-5	11	-55	6	-30	-30	4	-20	-20
ORU Credits	-8		0	5	-40	-40	7	-56	-56
SAT SERVICER (SS)									
SS AGE Recur	30		0	1	30	30	1	30	30
SS AGE Refurb	10		0	5	50	50	7	70	70
TOTAL PGM COST									
Low ST			1243	LOW	1068	1168	LOW	912	1062
High ST			1386	HI	1196	1296	HI	1034	1184
DELTAS FROM EXPENDABLE TPC				LOW	-175	-75	LOW	-331	-181
				HI	-190	-90	HI	-352	-202
% DIFFERENCE FROM EXPENDABLE				LOW	-14.08	-6.0338	LOW	-26.63	-14.562
				HI	-13.71	-6.4935	HI	-25.40	-14.574

(continued)

TABLE X (continued)

Case 3 Data

ST Lch = 50% (Low) and 100% (Hi) SV Recurring

TOTAL PGM COST							
Low ST	1815	LOW	1580	1680	LOW	1400	1550
High ST	2530	HI	2220	2320	HI	2010	2160
DELTAS FROM EXPENDABLE TPC		LOW	-235	-135	LOW	-415	-265
		HI	-310	-210	HI	-520	-370
% DIFFERENCE FROM EXPENDABLE		LOW	-12.95	-7.4380	LOW	-22.87	-14.601
		HI	-12.25	-8.3004	HI	-20.55	-14.625

ST Lch = 200% (Low) and 400% (Hi) SV Recurring

TOTAL PGM COST							
Low ST	3960	LOW	3500	3600	LOW	3230	3380
High ST	6820	HI	6060	6160	HI	5670	5820
DELTAS FROM EXPENDABLE TPC		LOW	-460	-360	LOW	-730	-580
		HI	-760	-660	HI	-1150	-1000
% DIFFERENCE FROM EXPENDABLE		LOW	-11.62	-9.0909	LOW	-18.43	-14.646
		HI	-11.14	-9.6774	HI	-16.86	-14.663

Appendix D: Case Number 4 Supporting Data

The following is a list of basic assumptions and inputs for Case 4:

- o Two Satellites, Six Cycles
- o Mission orbits are at geosynchronous altitude (GEO).
- o All launch and servicing missions (including launch of expendable SVs) are assumed to be staged through an Orbiting Space Station (OSS) using an Orbit Transfer Vehicle (OTV) to carry the SV or Servicer ASE to GEO.
- o Three Strategies:

  Expendable satellite
  Service once and expend
  Service twice and expend

- o Primary variable is ST Launch cost (reflected as percentage of basic SV Recurring cost). Input values are 10%, 20%, 50%, 100%, 200%, and 400%.
- o Two ORU replacement levels provide a range of planning risk.

  Replace 50% of available ORUs on each mission
  Replace 100% of available ORUs on each mission

- o STS missions to the OSS are assumed to have high load factors. Therefore, ridesharing is assumed on all missions.

Table XI provides a spreadsheet layout for Case 4 which includes the column letters and row numbers for use in interpreting the formulas and constants provided in Table XII. The data used in drawing the graphs for Case 4 are provided in Table XIII.

TABLE XI

Case 4 Spreadsheet Layout

1 CASE 4, 2 SATELLITES, 6 CYCLES, GEO SERVICING FROM ORBITING SPACE STATION (OSS)
2 ST Lch = 100% SV Recurring
3

Row	A	C	D/E	F/G	H/I	L/M	N/O	P/Q	T/U	V/W
5		% SV	EXPENDABLE		SERVICE1/EXPEND			SERVICE2/EXPEND		
6	COST ELEMENTS	RECUR	USE	FULL	USE	50% ORU	100% ORU	USE	50% ORU	100% ORU
7				REPL'MT		REPL'MT	REPL'MT		REPL'MT	REPL'MT
9	SPACE VEHICLE(SV)									
10	SV Recurring	100	11	1100	6	600	600	4	400	400
11	SATSERV ORU	50		0	1 / 5	50	250	1 / 7	50	350
12	SATSERV Nonr	50		0	1	50	50	1	50	50
13	SATSERV Mods	10		0	6	60	60	4	40	40
14	SATSERV ORUR	25		0	4 / 0	100	0	6 / 0	150	0
16	SPACE TRANS (ST)									
17	Launch	100	11	1100	11	1100	1100	11	1100	1100
18	Integration	60	11	660	6	360	360	4	240	240
19	I&C/O @ OSS	10	11	110	11	110	110	11	110	110
20	OTV Recurring	10	11	110	11	110	110	11	110	110
21	OTV Ops	10	11	110	11	110	110	11	110	110
22	SV RS Credits	-50	11	-550	6	-300	-300	4	-200	-200
23	ORU RS Credits	-80		0	5	-400	-400	7	-560	-560
25	SAT SERVICER (SS)									
26	SS AGE Recur	30		0	1	30	30	1	30	30
27	SS AGE Refurb	10		0	5	50	50	7	70	70
29	TOTAL PGM COST									
30	Low ST		E1	2640	LOW	2030	2130	LOW	1700	1850
31	High ST		E2	4180	HI	3120	3220	HI	2610	2760
33	DELTAS FROM EXPENDABLE TPC				LOW	-610	-510	LOW	-940	-790
34					HI	-1060	-960	HI	-1570	-1420
36	% DIFFERENCE FROM EXPENDABLE				LOW	-23.11	-19.318	LOW	-35.61	-29.924
37					HI	-25.36	-22.967	HI	-37.56	-33.971

TABLE XII

Case 4 Basic Formulas and Constants

The table that follows is a list of the formulas and constants used to build the spreadsheet for Case 4. The left side of the equation indicates the location of the item in Table XI, by column letter and row number. The right side of the equation displays the value of a constant or the arithmetic operation to be performed ("*" for multiplication, "/" for division, and "SUM" to total the inclusive elements indicated) on the data from the locations shown.

<u>Basic Input Parameter</u>

C2 = NA (NA is used to by the spreadsheet to reserve the location for an input variable)

<u>Space Vehicle (SV) Costs</u>

C10	= 100
E10	= 11
G10	= C10*E10
I10	= 6
M10	= C10*I10
O10	= C10*I10
Q10	= 4
U10	= C10*Q10
W10	= C10*Q10
C11	= 50
G11	= C11*E11
I11	= 1
K11	= 5
M11	= C11*I11
O11	= C11*K11
Q11	= 1
S11	= 7
U11	= C11*Q11
W11	= C11*S11
C12	= 50
G12	= C12*E12
I12	= 1
M12	= C12*I12
O12	= C12*I12
Q12	= 1
U12	= C12*Q12
W12	= C12*Q12
C13	= 10
G13	= C13*E13
I13	= 6

(continued)

TABLE XII (continued)

Case 4 Basic Formulas and Constants

M13	= C13*I13
O13	= C13*I13
Q13	= Q10
U13	= C13*Q13
W13	= C13*Q13
C14	= 25
G14	= C14*E14
I14	= 4
K14	= 0
M14	= C14*I14
O14	= C14*K14
Q14	= 6
S14	= 0
U14	= C14*Q14
W14	= C14*S14

Space Transportation (ST) Costs

C17	= C2
E17	= 11
G17	= C17*E17
I17	= 11
M17	= C17*I17
O17	= C17*I17
Q17	= 11
U17	= C17*Q17
W17	= C17*Q17
C18	= C17*.6
E18	= 11
G18	= C18*E18
I18	= 6
M18	= C18*I18
O18	= C18*I18
Q18	= 4
U18	= C18*Q18
W18	= C18*Q18
C19	= C17/10
E19	= 11
G19	= C19*E19
I19	= 11
M19	= C19*I19
O19	= C19*I19
Q19	= 11
U19	= C19*Q19
W19	= C19*Q19

(continued)

TABLE XII (continued)

Case 4 Basic Formulas and Constants

C20	=	C17/10
E20	=	11
G20	=	C20*E20
I20	=	11
M20	=	C20*I20
O20	=	C20*I20
Q20	=	11
U20	=	C20*Q20
W20	=	C20*Q20
C21	=	C17/10
E21	=	11
G21	=	C21*E21
I21	=	11
M21	=	C21*I21
O21	=	C21*I21
Q21	=	11
U21	=	C21*Q21
W21	=	C21*Q21
C22	=	-C17/2
E22	=	11
G22	=	C22*E22
I22	=	6
M22	=	C22*I22
O22	=	C22*I22
Q22	=	4
U22	=	C22*Q22
W22	=	C22*Q22
C23	=	-4*C17/5
G23	=	C23*E23
I23	=	5
M23	=	C23*I23
O23	=	C23*I23
Q23	=	7
U23	=	C23*Q23
W23	=	C23*Q23

Satellite Servicer (SS) Costs

C26	=	30
G26	=	C26*E26
I26	=	1
M26	=	C26*I26
O26	=	C26*I26
Q26	=	1
U26	=	C26*Q26

(continued)

TABLE XII (continued)

Case 4 Basic Formulas and Constants

W26	= C26*Q26
C27	= C26/3
G27	= C27*E27
I27	= 5
M27	= C27*I27
O27	= C27*I27
Q27	= 7
U27	= C27*Q27
W27	= C27*Q27

Total Program Cost (TPC)

G30	= SUM(G10:G27)
M30	= SUM(M10:M27)
O30	= SUM(O10:O27)
U30	= SUM(U10:U27)
W30	= SUM(W10:W27)
G31	= G30+SUM(G17:G23)
M31	= M30+SUM(M17:M23)
O31	= O30+SUM(O17:O23)
U31	= U30+SUM(U17:U23)
W31	= W30+SUM(W17:W23)

Deltas from Expendable TPC

M33	= M30-G30
O33	= O30-G30
U33	= U30-G30
W33	= W30-G30
M34	= M31-G31
O34	= O31-G31
U34	= U31-G31
W34	= W31-G31

% Difference from Expendable TPC

M36	= 100*M33/G30
O36	= 100*O33/G30
U36	= 100*U33/G30
W36	= 100*W33/G30
M37	= 100*M34/G31
O37	= 100*O34/G31
U37	= 100*U34/G31
W37	= 100*W34/G31

TABLE XIII

Case 4 Data

ST Lch = <u>10%</u> (Low) and <u>20%</u> (Hi) SV Recurring

COST ELEMENTS	% SV RECUR	EXPENDABLE USE	EXPENDABLE FULL REPL'MT	SERVICE1/EXPEND USE	SERVICE1/EXPEND 50% ORU REPL'MT	SERVICE1/EXPEND 100% ORU REPL'MT	SERVICE2/EXPEND USE	SERVICE2/EXPEND 50% ORU REPL'MT	SERVICE2/EXPEND 100% ORU REPL'MT
SPACE VEHICLE(SV)									
SV Recurring	100	11	1100	6	600	600	4	400	400
SATSERV ORU	50		0	1 / 5	50	250	1 / 7	50	350
SATSERV Nonr	50		0	1	50	50	1	50	50
SATSERV Mods	10		0	6	60	60	4	40	40
SATSERV ORUR	25		0	4 / 0	100	0	6 / 0	150	0
SPACE TRANS (ST)									
Launch	10	11	110	11	110	110	11	110	110
Integration	6	11	66	6	36	36	4	24	24
I&C/O @ OSS	1	11	11	11	11	11	11	11	11
OTV Recurring	1	11	11	11	11	11	11	11	11
OTV Ops	1	11	11	11	11	11	11	11	11
SV RS Credits	-5	11	-55	6	-30	-30	4	-20	-20
ORU RS Credits	-8		0	5	-40	-40	7	-56	-56
SAT SERVICER (SS)									
SS ASE Recur	30		0	1	30	30	1	30	30
SS ASE Refurb	10		0	5	50	50	7	70	70
TOTAL PGM COST									
Low ST		E1	1254	LOW	1049	1149	LOW	881	1031
High ST		E2	1408	HI	1158	1258	HI	972	1122
DELTAS FROM EXPENDABLE TPC				LOW	-205	-105	LOW	-373	-223
				HI	-250	-150	HI	-436	-286
% DIFFERENCE FROM EXPENDABLE				LOW	-16.35	-8.3732	LOW	-29.74	-17.783
				HI	-17.76	-10.653	HI	-30.97	-20.313

(continued)

TABLE XIII (continued)

Case 4 Data

ST Lch = <u>50%</u> (Low) and <u>100%</u> (Hi) SV Recurring

TOTAL PGM COST								
Low ST	E1	1870	LOW	1485	1585	LOW	1245	1395
High ST	E2	2640	HI	2030	2130	HI	1700	1850
DELTAS FROM EXPENDABLE TPC			LOW	-385	-285	LOW	-625	-475
			HI	-610	-510	HI	-940	-790
% DIFFERENCE FROM EXPENDABLE			LOW	-20.59	-15.241	LOW	-33.42	-25.401
			HI	-23.11	-19.318	HI	-35.61	-29.924

ST Lch = <u>200%</u> (Low) and <u>400%</u> (Hi) SV Recurring

TOTAL PGM COST								
Low ST	E1	4180	LOW	3120	3220	LOW	2610	2760
High ST	E2	7260	HI	5300	5400	HI	4430	4580
DELTAS FROM EXPENDABLE TPC			LOW	-1060	-960	LOW	-1570	-1420
			HI	-1960	-1860	HI	-2830	-2680
% DIFFERENCE FROM EXPENDABLE			LOW	-25.36	-22.967	LOW	-37.56	-33.971
			HI	-27.00	-25.620	HI	-38.98	-36.915

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
AFIT/GSM/LSY/84S-27

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
School of Systems and Logistics

6b. OFFICE SYMBOL *(If applicable)*
AFIT/LS

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State and ZIP Code)*
Air Force Institute of Technology
Wright Patterson Air Force Base, Ohio 45433

7b. ADDRESS *(City, State and ZIP Code)*

8a. NAME OF FUNDING/SPONSORING ORGANIZATION

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State and ZIP Code)*

10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.

11. TITLE *(Include Security Classification)*
See Box 19

12. PERSONAL AUTHOR(S)
Michael E Russell, B.S., Captain, USAF & Robert M Tayloe, B.S., Major, USAF

13a. TYPE OF REPORT
MS Thesis

13b. TIME COVERED
FROM ________ TO ________

14. DATE OF REPORT *(Yr., Mo., Day)*
1984 September

15. PAGE COUNT
122

16. SUPPLEMENTARY NOTATION

Approved for public release: IAW AFR 190-17.
LYNN E. WOLAVER 14 Sept 84
Dean for Research and Professional Development
Air Force Institute of Technology (ATC)
Wright-Patterson AFB OH 45433

17. COSATI CODES

FIELD	GROUP	SUB. GR.
22	01	Space Maint.
22	02	Spacecraft

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Spacecraft, Logistics, Space Tools, Space Stations, Space Maintenance, Cost Analysis

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Title: PLANNING FOR THE ON-ORBIT SERVICING OF MILITARY SPACECRAFT

Thesis Advisor: Rodney C Byler, Major, USAF

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
Rodney C Byler, Major, USAF

22b. TELEPHONE NUMBER *(Include Area Code)*
513-255-5023

22c. OFFICE SYMBOL
AFIT/LSM

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On-orbit spacecraft servicing for military programs is examined. A foundation is first established through a brief review of past significant servicing policy and a survey of civilian literature to outline servicing technologies and status. The military community appears to be somewhat reticent to embrace or, in some cases, to even consider on-orbit servicing. The civilian community appears enthusiastic about the potential of on-orbit servicing and the majority of economic studies of civilian missions show servicing strategies to be an attractive alternative to most expendable spacecraft strategies.

A model called SATSERV is presented. This model can be used to conduct economic comparisons from an overall standpoint between expendable and servicing strategies. The model is implemented in a microcomputer spreadsheet format for rapid implementation and application along with ease of use by the manager. SATSERV is based on normalized program segment costs as a percentage of spacecraft unit cost. Total program cost between alternatives is compared on a delta change basis and also on a percentage change basis.

Four basic spreadsheet and mission scenarios are outlined and assumptions examined: two low earth orbit mission profiles within the current STS operations envelope, one low earth orbit mission profile outside current STS operations capability and requiring a Teleoperator Maneuvering System, and one geosynchronous mission scenario involving a space station and orbital transfer vehicle.

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20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION	
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22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
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