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# SPACE STATION FREEDOM ALTITUDE STRATEGY

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## ABSTRACT

The Space Station Freedom (SSF) altitude strategy provides guidelines and assumptions to determine an altitude profile for Freedom. The process for determining an altitude profile incorporates several factors such as where the Space Shuttle will rendezvous with the SSF, when reboosts must occur, and what atmospheric conditions exist causing decay.

The altitude strategy has an influence on all areas of SSF development and mission planning. The altitude strategy directly affects the micro-gravity environment for experiments, propulsion and control system sizing, and Space Shuttle delivery manifests. Indirectly the altitude strategy influences almost every system and operation within the Space Station Program.

Evolution of the SSF altitude strategy has been a very dynamic process over the past few years. Each altitude strategy in turn has emphasized a different consideration, examples include a constant Space Shuttle rendezvous altitude for mission planning simplicity, or constant micro-gravity levels with its inherent emphasis on payloads, or lifetime altitudes to provide a safety buffer to loss of control conditions.

Currently a new altitude strategy is in development. This altitude strategy will emphasize Space Shuttle delivery optimization. Since propellant is counted against Spcae Shuttle payload-to-orbit capacity, lowering the rendezvous altitude will not always increase the net payload-to-orbit, since more propellant would be required for reboost. This altitude strategy will also consider altitude biases to account for Space Shuttle launch slips and an unexpected worsening of atmospheric conditions. Safety concerns will define a lower operational altitude limit, while radiation levels will define upper altitude constraints.

This paper will discuss the evolution of past and current SSF altitude strategies and the development of a new altitude strategy which focuses on operational issues as opposed to design.

# I   INTRODUCTION

Productive utilization of the Space Station Freedom (SSF) will depend on a careful blend of many operational factors. One of the most influential of these factors is to determine what operational altitudes SSF should fly. This paper discusses the current program altitude strategy used for system design and introduces modifications to this strategy intended to transition altitude related considerations into the operational era.

The organization of the remaining portion of this paper is as follows: Section II familiarizes the reader with the background necessary for a basic understanding of SSF altitude strategies. Section III presents a historical perspective of SSF altitude strategy evolution. The primary drivers as well as advantages and disadvantages of each strategy are discussed. Section IV presents the current program altitude strategy used to design and size systems. Section V discusses considerations for an operational altitude strategy. Only through careful evaluation of such considerations can an altitude strategy be developed which optimizes the key performance parameters. Finally, Section VI presents conclusions regarding the operational altitude strategy and future altitude work.

## II   BACKGROUND

The term *altitude strategy* is used throughout this paper and must be defined at this point. An altitude strategy refers to a set of guidelines and assumptions necessary to determine where SSF will operate. Altitude planners will use the altitude strategy to generate a set of lower (Space Shuttle/SSF rendezvous) and upper (reboost) altitudes. Specifically, the guidelines presented in the altitude strategy will provide a methodology for computing both lower and upper altitudes while the assumptions provide the necessary conditions to perform the analysis. From the altitude strategy, mission planners can estimate Space Shuttle delivery capability for manifest planning and reboost requirements for propulsion system sizing and resupply.

Currently, the lower (rendezvous) altitude is constrained by lifetime to a loss of control altitude. At the loss of control altitude (assumed to be 150 nmi [278 km]), the atmospheric torques would quickly overwhelm the SSF control system, making rescue impossible and catastrophic re-entry inevitable. This lifetime altitude was chosen to give the SSF Program adequate response time (90 days) in case of a total propulsion system failure. Thus, the lowest allowable altitude at which SSF may operate is defined as 90 days of decay to 150 nmi and is herein referred to as the **lifetime altitude**. System designers use the lifetime altitude as a design point since it represents the highest atmospheric densities the SSF will encounter. During the operational era, SSF altitude planners will choose rendezvous altitudes based on numerous factors. These factors include SSF safety, life cycle costs, delivery system utilization, radiation limits, mission planning, orbital debris density, mission requirements, and launch window considerations. Even after

consideration of all previously mentioned factors, SSF altitude planners may still want to further bias the planned SSF rendezvous altitudes from the lifetime altitude to account for unpredictable, yet expected, deltas (e.g., Space Shuttle launch slips or atmospheric worsening).

The upper (reboost) altitudes are determined from the rendezvous altitudes and the Space Shuttle flight schedule. The SSF will reboost to an altitude such that at the end of the flight interval, SSF will have decayed down to the chosen rendezvous altitude by the next planned Space Shuttle visit. Figure 1 depicts a segment of an altitude profile. It is assumed SSF will reboost as soon as operationally possible after Space Shuttle departure to ensure Space Shuttle/SSF rendezvous at the lowest point possible, thus maximizing Space Shuttle delivery capability.
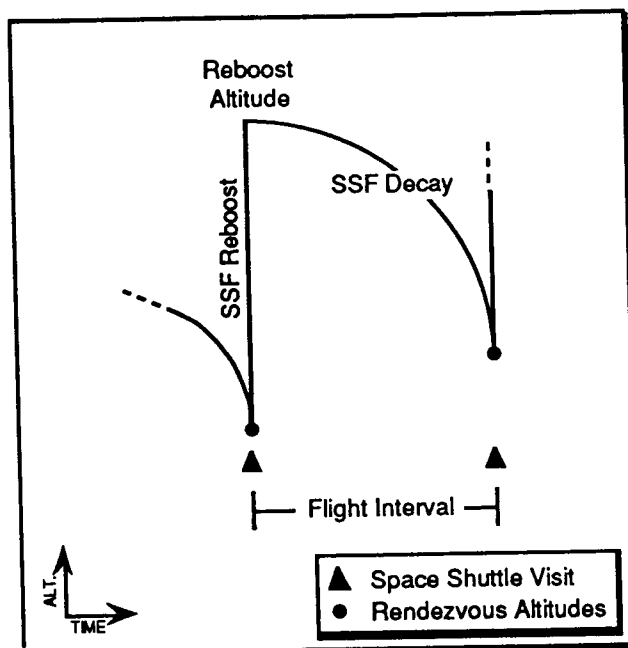


**Figure 1:** Space Shuttle/SSF Rendezvous and SSF Reboost Profile

Determining both the rendezvous and reboost SSF operating altitudes is dependent on SSF rate of decay for a specified period of time, the Space Shuttle flight interval. The rate of decay is primarily tied to two parameters: the *atmospheric density* and the *ballistic number* (BN, characterizing a vehicle's resistance to orbital decay).

## Atmospheric Density and Solar Cycle Predictions

Density is the key atmospheric parameter used by trajectory analysis programs and represents the greatest uncertainty for altitude planners. The rate of vehicle altitude decay is proportional to the atmospheric density and inversely proportional to the BN:

$$\frac{dh}{dt} = \frac{-C \rho (r+h)^{1/2}}{BN} \qquad (1)$$

where h is the SSF altitude, $\rho$ is the atmospheric density as a function of h, r is the mean radius of the earth, and C is a constant. Atmospheric density calculations are based on the energy output from the sun, which varies over an eleven year solar cycle. During peak solar energy output, the Earth's atmosphere expands outward, similar to a balloon when heated. Likewise, during minimum solar energy output, the atmosphere contracts. The net result is that any vehicle maintaining a relatively constant altitude experiences widely varying density levels during a solar cycle.

There are numerous methodologies available for determining atmospheric density. The model accepted by the SSF Program is the **Jacchia 1970 atmospheric model** (Reference 1). This model primarily uses two solar parameters to calculate density, *solar flux ($F_{10.7}$)* and *geomagnetic index ($A_p$)*. Given the variation of both measurements over a solar cycle, the Jacchia atmosphere model will predict the atmospheric density for any given date and orbital position (altitude, latitude, and longitude).

Predictions for both $F_{10.7}$ and $A_p$ are provided by the Mission Analysis Division at the Marshall Space Flight Center (MSFC) (Reference 2). Predictions for both mean (statistically, the actual value should be below the predicted value 50% of the time) and $+2\sigma$ (statistically, the actual value should be below the predicted value 97.7% of the time) atmospheres are provided by MSFC and are shown in Figure 2. Generally, the $+2\sigma$ atmospheric predictions are considered conservative, used mainly during system sizing and critical operational periods such as assembly. The mean atmospheric predictions are used when estimating resupply/return requirements during nominal SSF operations after assembly complete (AC). Solar cycle predictions have been normalized to an 11-year cycle. Actual past solar cycles have ranged from 9 to 13 years. Because actual $F_{10.7}$ and $A_p$ values
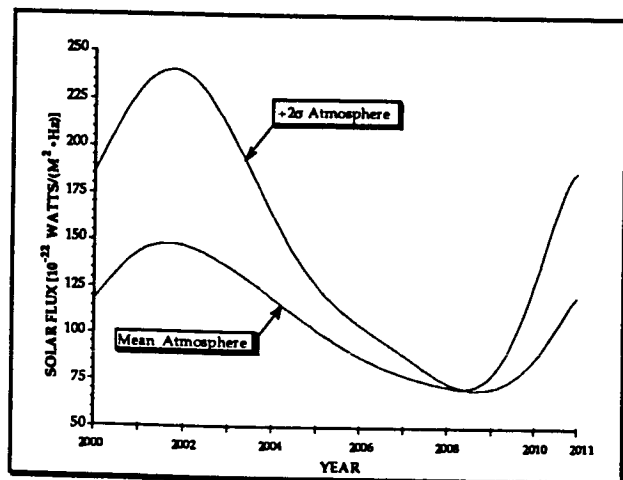


**Figure 2:** MSFC Solar Flux Predictions

may be significantly different than predicted, the operational altitude strategy must specify how and when SSF reacts to changes in atmospheric conditions.

## Ballistic Number Estimations

While the BN is a key parameter in determining SSF orbital decay, SSF configuration experts are still uncertain as to how accurate BN predictions can be at this stage of SSF development. BN is calculated using the following relationship:

$$BN = \frac{SSF \, Weight}{C_d \cdot Area} \qquad (2)$$

where Area equals the area exposed in the direction of motion($+x_{LVLH}$), and $C_d$ equals 2.3 (a typical drag coefficient for orbiting spacecraft).

The exposed area in the $+x_{LVLH}$ direction varies over an orbit due to articulating elements such as the solar arrays and thermal radiators. The exposed area also varies with SSF attitude. While torque equilibrium attitudes are maintained, the exposed area varies over an orbit since these attitudes are adjusted to account for atmospheric density changes. Therefore, even the best predictions for BN are an average for one orbit. During assembly, the BN varies significantly as SSF elements are added to the growing configuration. This fact produces uncertainty in determining SSF orbit lifetimes and precise rendezvous altitudes.

## Altitude Strategies

There are four basic approaches to defining rendezvous altitudes as part of an altitude strategy. Each approach is centered around an operational preference considered to be of paramount importance (i.e., planning simplicity, disturbance levels, safety, or life cycle costs). Development of an operational altitude strategy will consider both the virtues and failings of each approach.

1. *Constant altitude* maintenance requires varying the magnitude of the reboost with changing density levels over the course of a solar cycle. A constant rendezvous altitude has an obvious benefit, i.e., mission planning simplicity. Design of standard Space Shuttle rendezvous profiles and long range payload-to-orbit estimates for manifest planning are definite advantages. However, the rendezvous altitude selected must not violate lifetime considerations at any time during the solar cycle. This forces the altitude selection to be based on predicted conditions at the solar cycle peak. The solar cycle peak represents a relatively small segment of the entire solar cycle, lasting only 6 to 18 months. At off-peak times during the solar cycle, the rendezvous altitudes are considerably higher than dictated by lifetime considerations, thus representing a Space Shuttle delivery penalty. Therefore, a constant rendezvous altitude profile trades Space Shuttle payload-to-orbit capability for operational planning simplicity.

2. **Constant micro-gravity altitude** maintenance limits the Space Shuttle/SSF operational altitudes to a maximum micro-gravity (μg) level. Since the maximum density encountered is at the lowest point in SSF trajectory, and atmospheric acceleration is a direct function of atmospheric density, a specified μg level defines the rendezvous altitudes. This approach takes advantage of the varying atmospheric density levels over a solar cycle by lowering rendezvous altitudes when the atmosphere contracts. In this way, Space Shuttle delivery capability can be appreciably increased compared to the constant altitude strategy.

For the constant μg altitude strategy, each Space Shuttle/SSF rendezvous occurs at the same atmospheric μg level or decay rate. Therefore, the decay rate varies little over the solar cycle. Since both the rendezvous and reboost altitudes are tied to decay, any change in parameters which influences decay, such as the BN or atmospheric conditions, will cause the entire altitude profile to be biased, but result in relatively constant SSF propellant requirements. This aspect of the constant μg altitude strategy simplifies the design of the propulsion system and propellant resupply planning since requirements are not affected by major changes in SSF configuration or atmospheric predictions.

This approach has the apparent benefit of providing users with a maximum expected μg environment during nominal operations (except during planned perturbations such as Space Shuttle docking and SSF reboost). Although this strategy was accepted by the SSF Program for many years, the basic premise is very misleading. The specified μg limits the aerodynamic torques only. Gravity gradient torques are considerably higher, as much as an order of magnitude within the laboratory modules. Gravity gradient torques vary with distance from the SSF center of gravity (CG). The farther from the CG, the greater the gravity gradient torque. Only at the CG are the gravity gradient torques equal to zero and the aerodynamic torques alone determine the overall SSF μg environment. Since few, if any, experiments could be located at the CG, users should not assume maximum disturbance levels are limited by altitude.

3. **Constant lifetime altitude** maintenance sets rendezvous altitudes at the minimum allowable lifetime level. This approach attempts to maximize the Space Shuttle payload-to-orbit capability by rendezvousing as low as possible. There are two major drawbacks to this approach. First, there is no altitude margin for unplanned or unexpected events such as a Space Shuttle launch slip or atmospheric worsening. Second, any change to SSF BN or atmospheric predictions will significantly change previous estimates for Space Shuttle payload-to-orbit and propellant requirements. The rendezvous altitudes are

directly linked to the predictions for BN and atmospheric conditions.

This approach is useful, however, in defining system sizing requirements since the minimum lifetime altitudes represent the lowest allowable operating altitudes and thus the largest system requirements. This lifetime altitude strategy is discussed in detail in Section IV and currently is incorporated in the *Space Station Projects Description and Requirements Document*, JSC 31000 (Reference 3), and is a change request to the *Space Station Program Definition and Requirements Document* (PDRD), JSC 30000 (Reference 4).

4. **Optimal altitude** maintenance sets the rendezvous altitude at a point which maximizes **net** payload-to-orbit (total Space Shuttle delivery capacity minus SSF reboost propellant requirements). Both the reboost propellant usage and Space Shuttle delivery capability are directly related to altitude. The lower the Space Shuttle rendezvous with SSF, the more Space Shuttle can deliver to orbit (a rule of thumb is an additional 100 lbm/nmi). However, the lower SSF operates, the more propellant required for reboost since the atmosphere is more dense, thereby causing greater decay. The altitude which maximizes Space Shuttle **net** payload-to-orbit is called the **optimal (optimum) altitude** (shown in Figure 3). The optimal altitude defines the altitude at which flying lower would cause more additional propellant to be used than gained in Space Shuttle payload-to-orbit, and flying higher would cause more Space Shuttle payload-to-orbit lost than would be saved in reduced propellant needs.
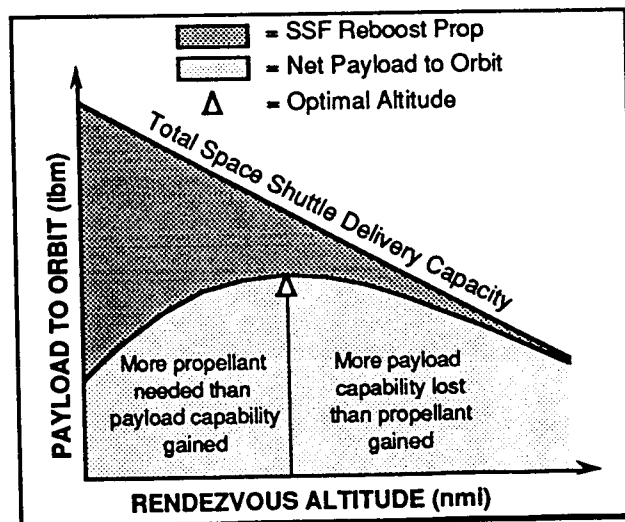


Figure 3: Optimal Altitude Definition

An altitude strategy based on optimal altitudes has the advantage of being relatively insensitive to changes in configuration and atmospheric predictions. Although these changes will cause the optimal point to move, the resultant loss in

net payload-to-orbit increases at a surprisingly slow rate as actual altitudes diverge from the optimal point. This approach will be used as a basis for an operational altitude strategy discussed in Section V.

## III    HISTORICAL VIEW

The SSF altitude strategy has evolved with program maturity over the past several years. Beginning simply with a constant altitude strategy early in Phase B, the altitude strategy has evolved to its present state where it is in transition from a system design emphasis to an operational emphasis. Although this process of change appears simple enough, it has been a long and arduous road. As the SSF Program evolved, various altitude related issues were rearranged in relative importance. Each priority change represented a new altitude philosophy or strategy. To date, altitude strategies have been used to identify operational envelopes for system design. Although these altitude strategies have been used as a basis for operational cost studies, it is understood that these altitude strategies have not adequately addressed operational issues which will ultimately drive the operational altitudes. A brief description of each altitude strategy as they evolved from early Phase B concept studies to the present is provided below.

## Constant Rendezvous Altitude

### 270 nmi (500 km) Constant Altitude

Early Phase B rendezvous altitudes for the SSF were set at a constant 270 nmi. The 270 nmi altitude served to minimize the drag and thus the propellant requirements for resupply. This was the highest the SSF could fly and maintain safe levels of crew radiation exposure. Although the 270 nmi altitude was chosen without explicit concern for the SSF lifetime, it did provide sufficient safety at the peak of the solar cycle in terms of a catastrophic re-entry into the atmosphere. Maintaining a constant lower altitude meant that the reboost sizes needed to be varied throughout the solar cycle in order to decay to the same altitude for the next Space Shuttle rendezvous. Figure 4 clearly shows the variation of the reboost sizes with the changes in the solar activity.

At this time in program history, the standards used to determine acceptable crew radiation exposure levels were re-evaluated. Radiation standards established by the Occupational Safety and Health Administration (OSHA) were adopted in lieu of more liberal NASA standards. As a result, many of the reboost altitudes violated OSHA radiation exposure levels for both the eyes and skin. This forced a program requirement which set the upper bound for SSF operations at 270 nmi. To accommodate this new requirement rendezvous altitudes were lowered to 250 nmi (463 km) which ensured that operational altitudes would remain within the 270 nmi radiation limit.

### 250 nmi (463 km) Constant Altitude

Resulting from the concerns for crew radiation exposure levels, the rendezvous altitudes were lowered to 250 nmi. This strategy resulted in an altitude profile which at no time violated radiation limits for the crew. The constant 250 nmi constant altitude strategy (Figure 5) was accepted by the Space Station Program later in Phase B (circa 1984).
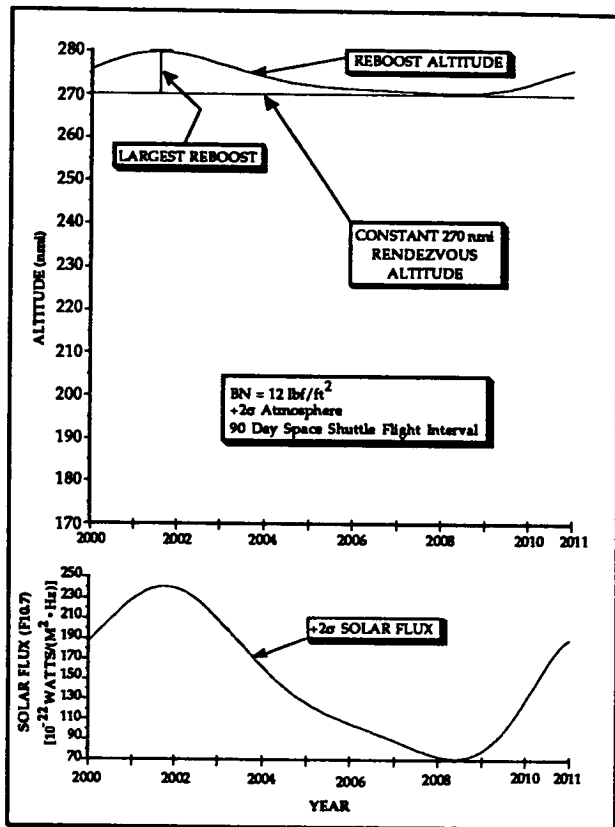


**FIGURE 4:** 270 nmi Constant Altitude Strategy with Solar Flux Data

### Advantage of a Constant Altitude Strategy

A constant altitude strategy provides mission planners with a relatively constant target altitude and thus constant payload-to-orbit capability. Standardized Space Shuttle/SSF rendezvous profiles are also possible with a constant altitude strategy, thus simplifying such planning.

### Disadvantages of a Constant Altitude Strategy

Maintaining a constant altitude profile has several disadvantages that severely impact the program. Although Space Shuttle payload-to-orbit remains constant over a solar cycle, large variations in the reboost complicate the overall Space Shuttle manifest planning. Another disadvantage is that a system designed using a constant altitude strategy severely limits operational flexibility. Several space station systems are sized based on constraints set by the

altitude strategy and Space Shuttle flight schedule. The operational altitude profile cannot be lower than the system design profile (constant rendezvous altitudes) since the systems can be sized to operate at higher altitudes. An obvious example of this would be the propulsion system; higher altitudes generally require smaller reboosts. This would result in propellant tanks inadequately sized to operate at lower altitudes.
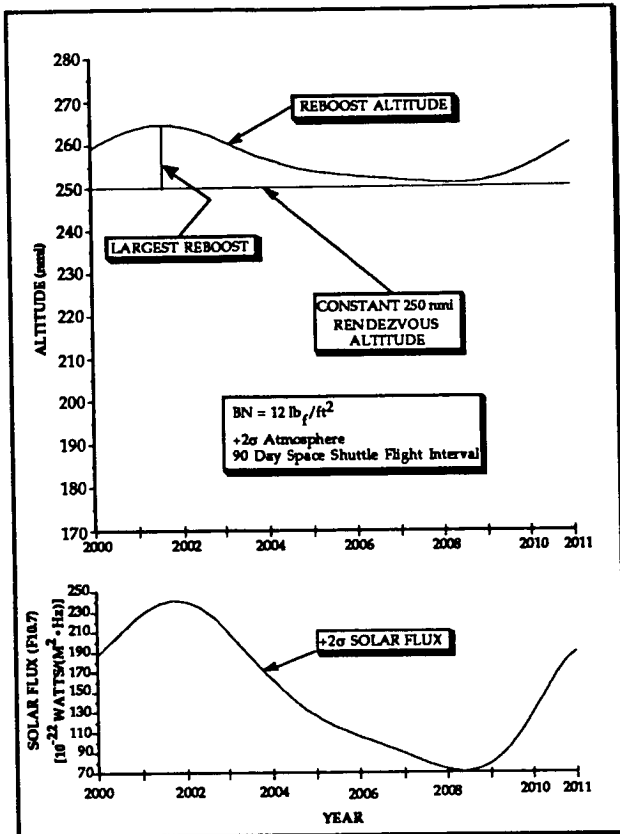


**FIGURE 5:** 250 nmi Constant Altitude Strategy with Solar Flux Data

Near the end of Phase B conceptual studies, assembly concerns began to surface. Additional assembly flights or additional payload-to-orbit are required to make assembly even possible. Since the constant altitude strategy was determined by choosing an altitude at the worst point in the solar cycle, altitudes at off-peak times could be lowered to gain significant Space Shuttle delivery performance while maintaining acceptable orbit lifetimes. At this point, payload-to-orbit was a paramount concern, and a new altitude strategy had to be developed in which the rendezvous altitude varied with the solar cycle.

## Constant Micro-Gravitational Level

The constant μg altitude strategy was developed to take advantage of solar cycle changes by defining the rendezvous altitudes at a specified constant μg. The acceleration experienced by SSF is a function of the atmospheric density; however, the atmospheric density varies over the solar cycle. For this reason, and also

so that SSF users could have an input in determining the altitude profile, a constant μg strategy became the accepted altitude strategy for SSF. The μg level represents the maximum drag acceleration SSF will experience due to atmosphere effects. This is because the SSF/Space Shuttle rendezvous occurs at the lowest point in SSF trajectory (reboost occurs shortly after Space Shuttle departs).

### Constant .3 μg Level

The PDRD (JSC 30000) baselined the constant μg level at .3 μg ($.3 \times 10^{-6}$ g) later in Phase B, around 1986. Variations in the lower altitude caused by the solar cycle can be seen in Figure 6. The .3 μg altitude strategy introduced a concept referred to as the minimum controllable altitude (the point at which SSF was deemed uncontrollable and catastrophic re-entry was inevitable). However, this altitude could not be defined because the SSF Program was unable to agree upon the conditions which would describe this point. As it turned out, several of the lower altitudes defined by this strategy did not meet acceptable orbit lifetime limits. Therefore, to alleviate this concern, the μg level was lowered from .3 to .2 μg. This change increased the safety margin or lifetime, decreased the size of the reboosts since the new altitude profile was higher in the atmosphere, decreased the atmosphere disturbance level, and also decreased Space Shuttle delivery capability.
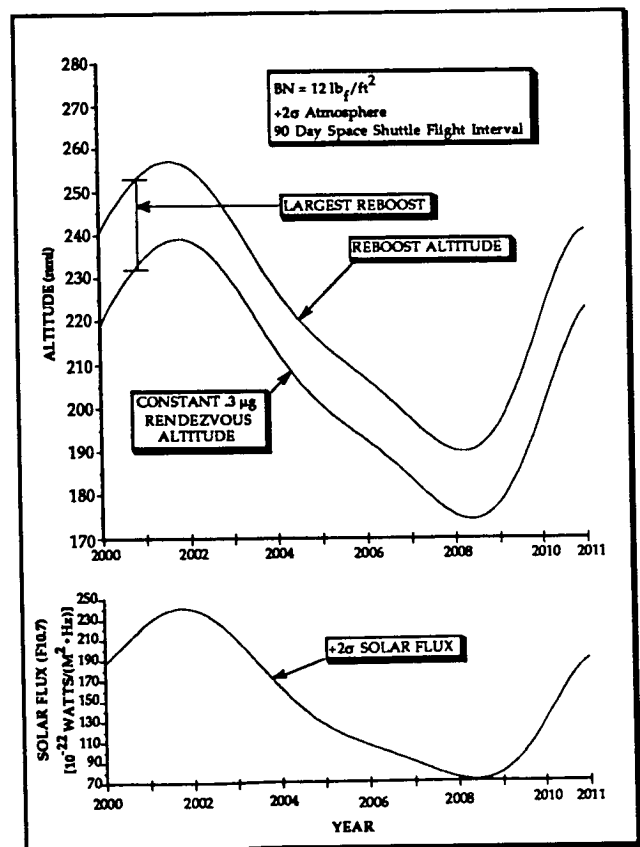


**FIGURE 6:** Constant .3 μg Altitude Strategy with Solar Flux Data

## Constant .2 µg Level

JSC 31000 (Reference 5) baselined .2 µg as the new constant µg level. This change to a .2 µg level was made for several reasons. The .3 µg level placed SSF at altitudes that were determined to have unacceptable orbit lifetimes of less than 50 days to 150 nmi. At .3 µg, the SSF was flying at altitudes that were so low that the configurations necessary to maintain control were determined to be unacceptable. Figure 7 shows the altitude profile for a .2 µg altitude strategy. While this new strategy placed SSF above the ill-defined minimum controllable altitude and had acceptable flight configurations, it had its problems as well. As the BN of SSF got worse due to a more realistic analysis of its configuration, the .2 µg strategy put SSF at altitudes that violated radiation requirements. The strategists also realized that the emphasis of an altitude strategy was really directed towards system sizing. Therefore, a strategy was needed that forced the designs to meet the maximum requirements on the station's systems. That concept evolved into the lifetime variable altitude strategy.
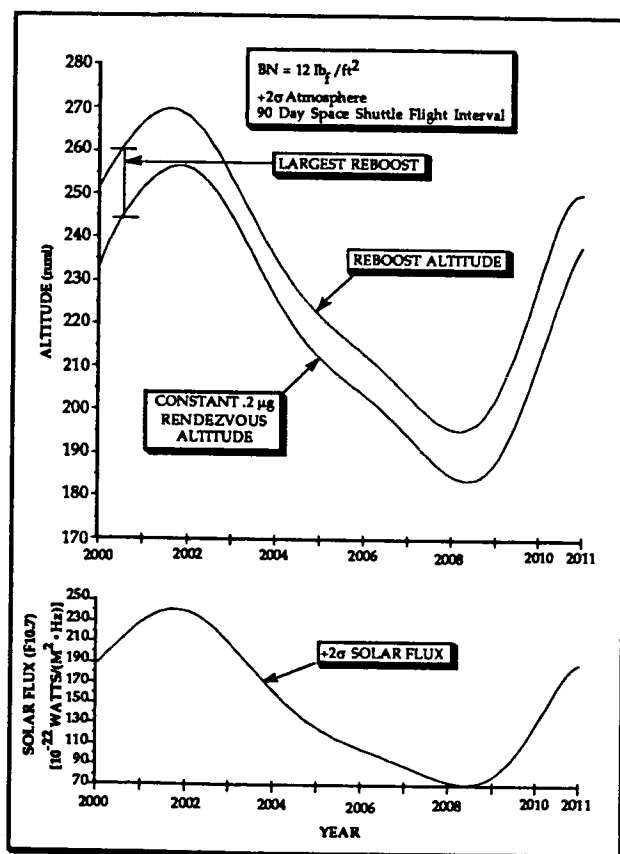


**FIGURE 7:** Constant .2 µg Altitude Strategy with Solar Flux Data

## Advantages of a Constant µg Level Strategy

By taking advantage of the changing energy output of the sun, a constant µg strategy allows for increased payload-to-orbit during times of lower solar activity. This is a significant savings in terms of payload capability not only during assembly but also in terms of life cycle costs throughout the 30-year operational lifetime of SSF. Another advantage to this strategy is that it provides a guaranteed µg environment for payloads and experiments. This is a benefit to gravity sensitive experiments. However, as mentioned earlier, this premise can be misleading since the µg level will be at the guaranteed level only at the exact SSF CG.

## Disadvantages of a Constant µg Level Strategy

The main disadvantage of the constant µg strategy is that the lifetime from the rendezvous altitudes varies significantly over a complete solar cycle. In light of the Challenger (51-L) accident, a lifetime reference has assumed greater importance for safety considerations. The need for defining a minimum operational period that SSF must be able to survive without a Space Shuttle visit was identified. Using a .3 µg level, the lifetime varied from 50 to 160 days of orbital lifetime to 150 nmi. A .2 µg level varied from 90 to 330 days of orbital lifetime to 150 nmi over a solar cycle. Although the .2 µg strategy altitudes were an improvement over the .3 µg level's lifetime, it was determined that several .2 µg altitudes had unacceptable orbit lifetime margins and thus the lifetime variable altitude strategy was developed.

## Lifetime Altitude

It was determined that the altitude strategy needed at this point in the program must emphasize system design for SSF, thus defining the *minimum design altitude*. The strategies discussed thus far all recognized the concept of minimum orbit lifetime. Although the µg strategies were aware of a minimum controllable altitude, orbital lifetime to this altitude was the underlying concern. How much time does SSF have before it decays and enters the earth's atmosphere? What time frame would a contingency scenario require to rescue SSF after a catastrophic failure? This idea of the time necessary to save SSF resulted in an altitude strategy that defined the minimum design altitude (operational altitude limit) and based it on orbit lifetime. The strategy calls for SSF to be able to survive a total failure of its propulsion system for a period of at least 90 days without a loss of attitude control. It is felt that a rescue and repair mission for saving SSF could be made ready and launched within this amount of time. Therefore, the minimum design altitudes are defined as the altitudes which give SSF 90 days of lifetime to 150 nmi. The 150 nmi loss of control altitude was determined to be the altitude where the aerodynamic torques would overwhelm the attitude control system and a loss of control would result. The altitudes resulting from the lifetime altitude strategy can be seen in Figure 8.

Presently, the lifetime strategy is incorporated in the latest revision of JSC 31000 (Reference 3). At the time of this writing, a change request submitted in 1988 to the program (Reference 6) is awaiting final approval before acceptance into the *Space Station Program Definition and Requirements Document* (PDRD) (Reference 4), JSC 30000. However, the idea of

lifetime is now widely accepted throughout the SSF Program.

## Advantages of the Lifetime Variable Altitude Strategy

The lifetime altitude strategy incorporates and corrects several of the ideas and problems identified in previous strategies. While the .3 μg strategy *mentioned* a minimum controllable altitude, the lifetime altitude strategy *defines* one. As in the μg altitude strategy, lifetime altitudes vary with the solar cycle, taking advantage of the changing energy output of the sun. Lifetime altitudes represent the lowest operating altitudes allowable, thus providing two very important parameters: maximum payload-to-orbit and system design requirements. As mentioned earlier, the minimum altitude represents the maximum requirement imposed on several SSF systems. Sizing to these altitudes provides for the most flexible operation of those systems.
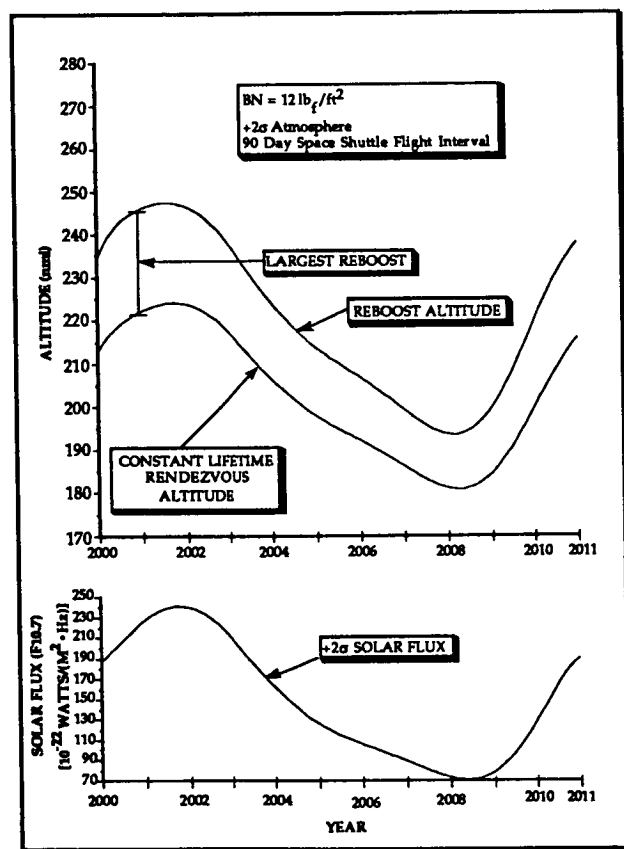


**FIGURE 8:** 90 Day Lifetime Altitude Strategy with Solar Flux Data

## Disadvantages of the Lifetime Strategy

Operationally, lifetime altitudes provide a reference to safety. However, they are difficult to plan, since they are based on SSF characteristics and solar flux predictions which both may be updated as the actual flight date approaches. Additionally, the varying μg

level experienced by flying lifetime altitudes presents difficulties to μg sensitive experimenters in both planning and data reduction.

# IV CURRENT STRATEGY

The main purpose of the current lifetime altitude strategy was to identify and provide an altitude strategy that emphasized system design while providing adequate safety margins for SSF and its crew. The current altitude strategy defines an operational altitude envelope. Since this strategy reflects operational limits, systems are designed to the extremes of this range. The current lifetime altitude strategy levies requirements on the SSF Program and has been submitted for final approval into the SSF PDRD, JSC 30000.

> *SSF shall orbit between a minimum operational altitude, defined by operational lifetime to 150 nmi, and a maximum operational altitude, defined by radiation limits.* (Reference 6, Sec. 3.1.1.1)

## Assembly

The minimum operational altitude is further divided into the two identifiable regions of SSF operations, assembly and post-AC.

> *The minimum operational altitude for assembly is defined as the altitude that provides 180 days of orbital decay to 150 nmi prior to a verified, dual fault tolerant reboost system, and 90 days of decay to 150 nmi thereafter.*
> *The decay shall be calculated using +2σ solar flux predictions.* (Reference 6, Sec 3.1.1.1.1)

Dual fault tolerance ensures that SSF has adequate lifetime prior to its propulsion system being completed. Once the system is dual fault tolerant, SSF can maintain the minimum altitude of 90 days to 150 nmi. While the present baseline assembly altitudes attempted to satisfy these minimum operational altitude requirements, they were chosen with more emphasis placed on planning simplicity. The present baseline assembly sequence is contained in the *Space Station Stage Summary Databook 12/15/89* (Reference 7). The Databook defines 220 nmi (407 km) as the rendezvous altitudes for flights 1 through 5 (MB-1 - MB-5) and 190 nmi (352 km) for flights 6 through 29 (MB-6 - L-11). These *defined* assembly rendezvous altitudes do not take advantage of the variations in the atmosphere but act as placeholders to simplify long range Space Shuttle manifest planning.

Figure 9 shows the Databook defined rendezvous altitudes and the minimum design rendezvous altitudes for the baseline assembly sequence. Recent studies have shown the 220 nmi altitudes to be conservative compared to the required 180 days to 150 nmi lifetime altitudes (~15 nmi, or 350 extra days of lifetime). However, the 220 nmi altitudes are being used as the *design-to* altitudes for Space Shuttle planning since historically it is easier to give capability back to the

program than to take it away. As the SSF design and launch schedule mature, these altitudes may be lowered to provide increased payload-to-orbit. Several lifetime violations occur at the transition from 220 nmi to 190 nmi altitudes. These violations stem from dramatic changes in SSF configuration (solar photovoltaic (PV] arrays are delivered and deployed on flight 6 [MB-6]). Lifetime violations also occur later in the sequence at flights 20 (MB-13) through flight 29 (L-11). These violations occur as a direct result of increasing solar activity. Figure 9 also depicts the solar flux values predicted for during assembly. Significant resistance to change the assembly altitudes exists in the Space Station program. However, these lifetime violations are significant and need to be addressed. The authors recommended to the Mission Planning and Analysis Division (MPAD NASA) at the Johnson Space Center (JSC), and to the Assembly Planning Review (APR), that the minimum lifetime altitudes be used as the planning altitudes for Space Shuttle manifest planning on those flights with lifetime violations. The long range planning altitudes and manifests must be reworked to correct these problems.
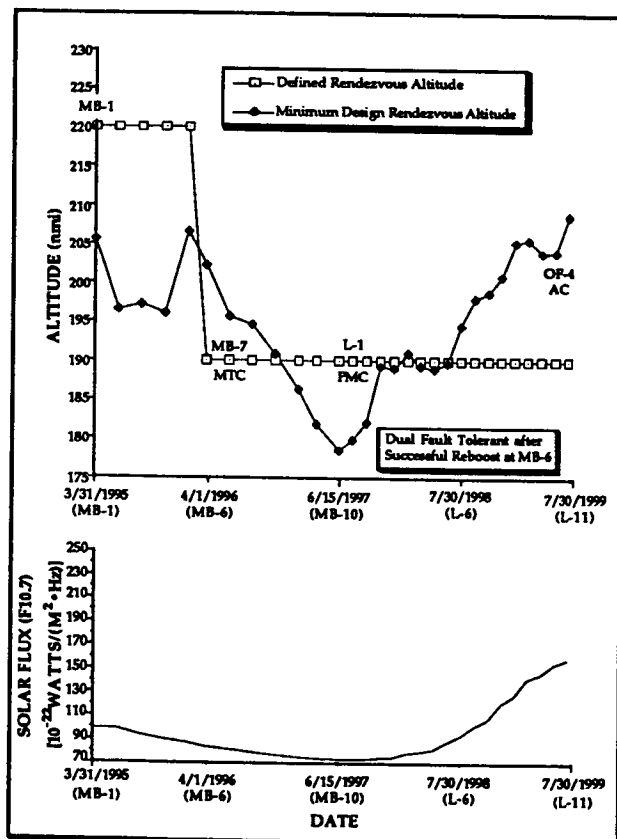
*contingency atmosphere conditions. Contingency atmosphere conditions are induced increases in solar flux values due to the effects of a +2 sigma solar flux prediction combined with a 2 year first element launch slip and a 9 year solar cycle 22.* (Reference 6, Sec 3.1.1.1.1)

Analysis of the defined assembly altitudes with a 2-year first element launch (FEL) slip in conjunction with +2σ solar flux predictions show the 220 nmi altitude to have approximately the same conservative margin, although significantly greater lifetime violations occur at flight 8 (OF-1) through flight 29 (L-11). (See Figure 10.) Analysis results show that there are 11 additional lifetime violations when compared to the results of just the +2σ atmosphere study. These additional lifetime violations arise from moving the assembly sequence forward two years into a region of higher solar flux values. The shift in the solar cycle is clearly shown in Figure 10 when compared with that in Figure 9.
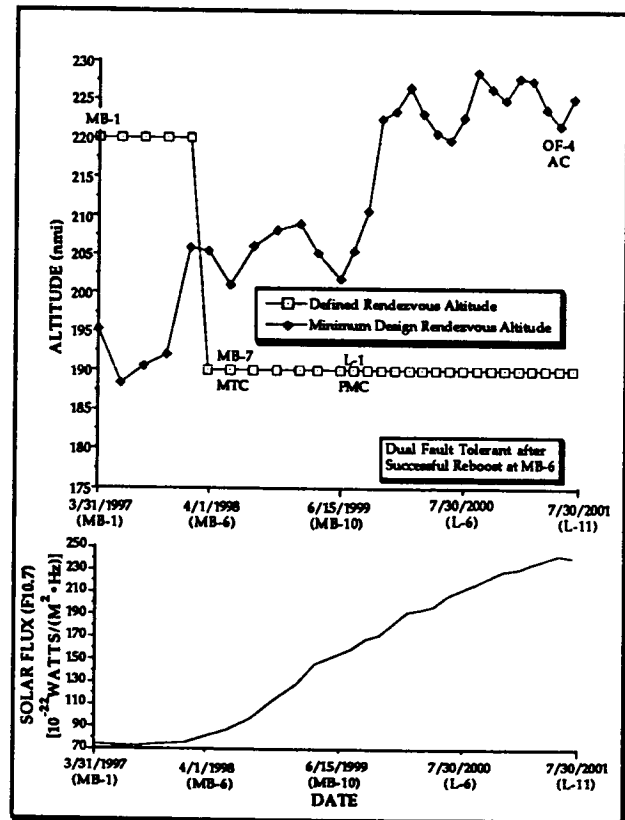


**FIGURE 9**: Minimum Design Altitude vs. the Databook Defined Altitudes with Solar Flux Data



**FIGURE 10**: Effects of a 2-Year First Element Launch Slip on the Minimum Design Altitudes Showing the Solar Cycle Shift

Additional requirements must be met by the assembly altitudes that were not considered in the previously mentioned study:

*SSF shall be capable of maintaining the minimum operational altitude under*

The requirement for a 9-year solar cycle has not yet been analyzed at the time of this publication. However, this only increases the solar flux values towards the end of assembly since the solar minimum would shift back toward the FEL point. A 9-year solar cycle analysis would result in lifetime violations of greater

magnitude due to the increased solar flux values. It needs to be determined if the two year FEL slip and 9-year solar cycle are necessary biases, and, if so, to fly the minimum design altitudes in place of defined altitudes for each assembly flight which violate the lifetime requirement.

## Assembly Complete

The altitude requirements for assembly complete (AC) are slightly different than those for assembly.

> *The minimum operational altitude for assembly complete shall be the altitude that provides 90 days of orbital decay to 150 nmi using the most current solar flux values.* (Reference 6, Sec 3.1.1.1.2)

The lifetime altitude defines the minimum altitude that the SSF can fly during post-AC. Presently, the post-AC rendezvous altitudes are set at this minimum operational altitude. The SSF will rendezvous at this altitude and SSF will reboost as soon as operationally possible after the Space Shuttle departure. SSF will reboost to an upper altitude such that it decays to the next scheduled Space Shuttle rendezvous altitude.

## System Design

The present altitude strategy has been a major driver for determining system design related requirements. The current lifetime altitude strategy represents the absolute minimum allowable altitudes for SSF operations. This will cause SSF to operate in a more dense region of the atmosphere, resulting in maximum reboosts and aerodynamic torques. Designing systems to meet the needs of SSF at this minimum altitude will ensure the most flexible system design capable of surviving a variety of real world operational contingencies.

Several influences on SSF system design are incorporated into the lifetime strategy. For example, the rendezvous altitudes follow the solar activity. This takes advantage of the solar cycle not only in terms of increasing Space Shuttle payload-to-orbit, but also in varying the SSF reboost. The current altitude strategy is employed to support design studies and size the propulsion system, specifically, the size of the on-board propellant storage tanks. In a recent trade study it was determined that the propellant tanks could be sized to reduce life cycle costs. This would be accomplished by using the largest tanks that would fit in the cargo bay of the Space Shuttle as well as fulfill the requirements for the largest reboost. The maximum reboost occurs during the rise in the solar cycle curve, six to eight months prior to peak solar activity. The propulsion system has been designed to the maximum reboost of a $+2\sigma$ atmosphere at SSF maturity, since SSF mass has a direct influence on the amount of propellant required for reboost.

Propellant specific impulse ($I_{sp}$) also has an influence on propulsion system design; the lower the $I_{sp}$, the more propellant required for a particular reboost. As a result of the SSF *Scrub* reconfiguration effort (1989), mono-methyl hydrazine propellant ($I_{sp} = 230$ sec) propulsion system was baselined for SSF. This results in larger propellant requirements and higher life cycle costs than for the previously baselined hydrogen/oxygen propellant ($I_{sp} = 370$ sec for $H_2/O_2$).

The BN affects system sizing as well. The smaller the BN, the greater the orbital decay, and thus larger reboosts are required to decay to the same point.

Other systems are indirectly influenced by the altitude selection. The electrical power system batteries are sized to provide power during orbital nighttime, a function of altitude. Some operations are also influenced by altitude: extra-vehicular activity (EVA) planning flexibility goes down as the South Atlantic Anomaly grows in size (which grows larger with increasing altitude). Many payloads are sensitive to the $\mu g$ environment induced by altitude choice. Finally, altitude selection plays a key role in the utilization efficiency of the delivery system (i.e., Space Shuttle). Decreasing Space Shuttle payload-to-orbit capability by rendezvousing higher may cause carriers to be manifested at less than 100% capacity. This indirectly affects all SSF operations since Space Shuttle will deliver all resupply requirements for SSF operations.

Operationally, the SSF must **never** violate the lifetime altitude limit. While SSF systems have been designed to operate at or above this altitude limit, the lifetime altitude represents the point where a deviation from nominal operations must occur. An operational altitude strategy will need to provide an altitude safety margin based on possible operational deviations. These deviations could include such scenarios as a Space Shuttle launch slip, missed rendezvous, atmosphere worsening, or solar cycle phase shifting. While the lifetime altitude strategy provides design-to altitudes for system sizing with inherent concerns for SSF safety, an operational altitude strategy must provide an additional lifetime margin to allow for the unpredictable yet expected real world occurrences. The operational altitude strategy must also incorporate several other operational considerations as well. These considerations as well as the factors that influence the lifetime buffer will be discussed in the next section.

## V    OPERATIONAL ALTITUDE STRATEGY

The emphasis of an Operational Altitude Strategy (OAS) is overall operations cost, whereas the emphasis of the current lifetime altitude strategy is system design. Development of an OAS must consider all aspects of SSF operations:

- On-orbit operations
  - aerodynamic disturbance levels
  - radiation exposure levels
  - contamination
  - orbital debris density
  - safety (lifetime)
  - satellite servicing

- Logistics system operations
  - delivery system (Space Shuttle) utilization
  - logistics elements utilization

- Space Shuttle mission planning
  - launch windows
  - flight profile/rendezvous
  - planning simplicity
  - payload-to-orbit capability

Developing an altitude strategy based on any one of the influences listed above would result in off-nominal altitudes for all the other influences. Therefore, one influence must be considered predominant and altitudes biased off this solution to accommodate the remaining influences. Program requirements dictate that the operational altitudes may be chosen anywhere between an upper and lower altitude limit. The upper altitude bound is defined by radiation concerns and the lower limit is defined by orbit lifetime. Flying SSF as low as possible would maximize the Space Shuttle delivery capability. However, this does not necessarily represent the most efficient use of the delivery system.

Given acceptable safety levels, delivery system utilization efficiency (in the opinion of the authors) should be considered the primary performance indicator of any OAS. The Department of Defense estimates that 35-40% of the total operational cost for the military is logistics. Delivery of resupply from the ground to SSF is a significant part of the overall logistics cost and represents an area in which operations cost could be significantly reduced through careful application of an OAS.

## Optimal Altitudes

Eventually, all operational influences will be accommodated through biasing optimal altitudes to the extent required. Initially however, optimal altitudes must be investigated and understood.

In order to reduce resupply costs, optimal altitudes must maximize Space Shuttle delivery capability. As part of resupply, propellant must be delivered. However, propellant usage is tied directly to altitude selection. Increasing rendezvous altitudes results in decreased propellant requirements (reboosts are smaller since the SSF operates in a less dense region of the atmosphere), but at the same time, the Space Shuttle delivery capabilities are also reduced. The optimal altitude is therefore a balance between SSF propellant usage and Space Shuttle delivery capability and can be defined as maximizing the net Space Shuttle delivery capability on a flight by flight basis (net = total Space Shuttle delivery capability - SSF reboost propellant requirements).

The reboost propellant requirements must include support hardware (tankage and attachments) as part of the net payload-to-orbit determination. Final propellant selection will greatly influence the support mass required. For example, a hydrogen/oxygen propulsion system has relatively small support mass requirements since propellant is delivered as water in either a simple

water tank on a fluids carrier or scavenged from the Space Shuttle fuel cell tanks (no support mass requirement). On the other hand, hydrazine has large support mass requirements. Since hydrazine is a very volatile substance, on-orbit disconnections of hydrazine fluid lines are restricted. An entire Propellant Module (PM) (consisting of propellant, propellant tanks, reaction control system [RCS] thrusters and structure) must be exchanged each time propellant is delivered.

Propellant deliveries do not necessarily occur at regular intervals. Generating optimal altitudes based on specific flight manifests of PM delivery results in a very jagged rendezvous altitude profile and may force either undesirably large reboosts or rendezvous altitudes which would require a SSF deboost to achieve. For this reason, the required support mass is evenly distributed over all flights for purposes of determining a smoother optimal altitude profile. In order to accomplish this distribution, each pound of propellant needed to perform a reboost will require some amount of support mass. The ratio of support mass to propellant is termed the mass fraction and is different for each type of propellant or PM. The currently designed PM requires approximately 0.7 lbm of supporting hardware for each pound of hydrazine delivered.

## Optimal Altitude Influences

Optimal altitudes are driven by propellant requirements which in turn are driven by the SSF BN, SSF mass, Space Shuttle flight interval, $I_{sp}$, solar flux ($F_{10.7}$) predictions, and propellant mass fraction. In general, larger propellant requirements result in higher optimal altitudes.

Currently, working values for each of these influences are baselined within the SSF Program. However, the actual value may turn out to be considerably different. An understanding of how each of these influences drives the optimal altitudes and how sensitive optimal altitudes are to these influences is essential for OAS development.

## SSF Ballistic Number

BN characterizes the aerodynamic configuration and weight of the SSF. Low BNs result in high decay rates, while high BNs imply low decay rates. Lower BNs result in higher propellant usage since SSF decay is greater. Figure 11 shows the optimal altitude sensitivity to BN changes. This figure plots altitude (x-axis) vs Space Shuttle delivery capability. The slanted line at the top represents the total Space Shuttle lift capacity. As the rendezvous altitude increases, the total Space Shuttle delivery capacity decreases. The curved lines indicate the net payload-to-orbit for three values of BN. The optimal altitude occurs at the highest point on each curve (the maximum net payload-to-orbit) and is represented with a Δ on the graph. Since net payload-to-orbit is defined as the total Space Shuttle delivery capacity minus the SSF reboost propellant requirements, the vertical distance from the total Space Shuttle lift capacity line to the net payload-to-orbit line

represents reboost propellant requirements (includes both propellant and supporting hardware). The figure shows how the optimal altitudes increase with a decrease in the BN. Additionally, rendezvous altitudes derived from the .2 µg, .3 µg and lifetime altitude strategies are also presented for comparison. On each of the parametric plots which follow, the standard case is identified by a bold line. The conditions for this standard case are:

| | |
|---|---|
| BN = | 12 lb$_f$/ft$^2$ |
| SSF Mass = | 500000 lbm |
| Flight Interval = | 90 days |
| I$_{sp}$= | 230 sec |
| Solar Flux = | Maximum (+2σ peak) |

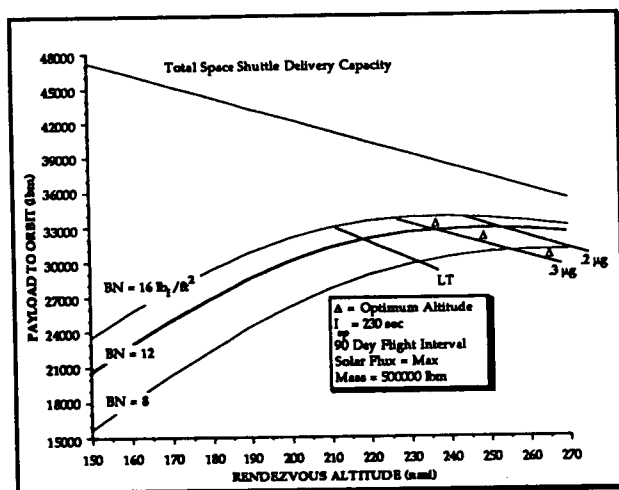and can be used as reference between the various influences.



**Figure 11**: Ballistic Number Influence on the Optimal Altitude

## SSF Mass

The more massive the SSF, the more propellant required for reboost. Although continuous low thrust burns will actually be used to reboost SSF, the propellant required to reboost SSF impulsively (infinite thrust in an instant of time) is very close (< 1%) to the propellant required using a continuous low thrust burn and is given by the following relationship:

**Prop = SSF Mass * G$_θ$ * (1 - exp(-ΔV / (G$_θ$ * Isp)))**   (3)

where G$_θ$ is the acceleration of gravity at the earth's surface, ΔV is the velocity change required to achieve a circular target orbit based on the height of the reboost, and I$_{sp}$ is the propellant specific impulse.

Figure 12 shows the optimal altitude sensitivity to SSF mass. The optimal altitude increases with mass since propellant requirements are proportional to SSF mass. Altitudes based on the .2 µg, .3 µg and lifetime altitude strategies are not affected by SSF mass changes.
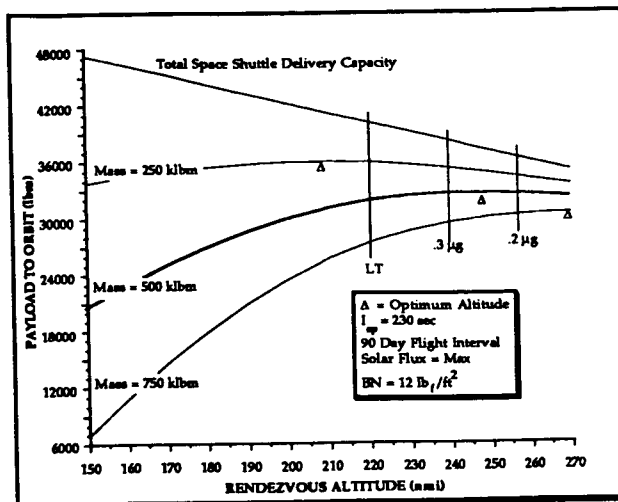


**Figure 12**: SSF Mass Influence on the Optimal Altitude

## Space Shuttle Flight Interval

Operationally, SSF is assumed to reboost soon after Space Shuttle departure. The size of the reboost is determined such that the SSF orbit will decay down to the appropriate rendezvous altitude by the next Space Shuttle visit. A longer flight interval results in a longer decay time and consequently larger reboosts. Figure 13 shows the optimal altitude sensitivity to Space Shuttle flight interval. The optimal altitude increases with flight interval. Rendezvous altitudes based on the .2 µg, .3 µg and lifetime altitude strategies are not affected by flight interval changes.

Multiple reboosts between Space Shuttle visits tend to decrease the size of each reboost, yet increase the total propellant requirements for the interval. This is a direct result of SSF spending more time at lower altitudes where the atmosphere is more dense. Multiple reboosts within a flight interval will increase the optimal altitudes as well as the operational work loads for the SSF crew and mission support teams. Therefore, a single reboost is assumed between each rendezvous.
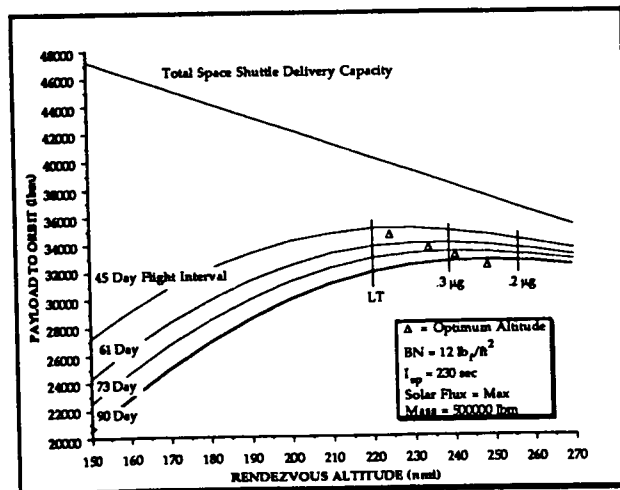


**Figure 13**: Space Shuttle Flight Interval Influence on the Optimal Altitude

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## SSF Specific Impulse

The $I_{sp}$ characterizes the efficiency of a propellant. Less propellant is required to achieve the same reboost for propellants having higher $I_{sp}$. Therefore, lower $I_{sp}$ propellants increase the optimal altitude since propellant requirements are higher. For example, hydrogen/oxygen propellant has an $I_{sp}$ of 370 sec, and hydrazine has an $I_{sp}$ of 230 sec. This translates into thousands of additional pounds of hydrazine per year as compared to water. As expected, the optimal altitude for an $I_{sp}$ of 230 sec is considerably higher than for an $I_{sp}$ of 370 sec. Reboost propellant for a given $I_{sp}$ is shown in equation (3).

Figure 14 shows the optimal altitude sensitivity to $I_{sp}$. The optimal altitude increases as $I_{sp}$ decreases. Altitudes based on the .2 µg, .3 µg and lifetime altitude strategies are not affected by $I_{sp}$ changes.
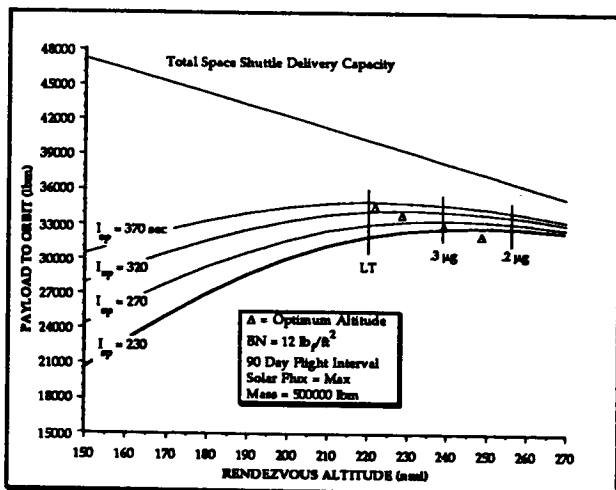


Figure 14: $I_{sp}$ Influence on the Optimal Altitude

## Solar Flux ($F_{10.7}$)

Atmospheric density is derived from $F_{10.7}$ values. Larger $F_{10.7}$ values increase the derived density and consequently increase the rate of orbital decay. $F_{10.7}$ values change with date and atmospheric predictions (+2σ or mean). If all influences discussed above were to remain constant, optimal altitudes would vary with the solar cycle.

Figure 15 shows the optimal altitude sensitivity to $F_{10.7}$. The optimal altitude increases with increasing $F_{10.7}$. Altitudes based on the .2 µg, .3 µg and lifetime altitude strategies also vary with $F_{10.7}$ changes.
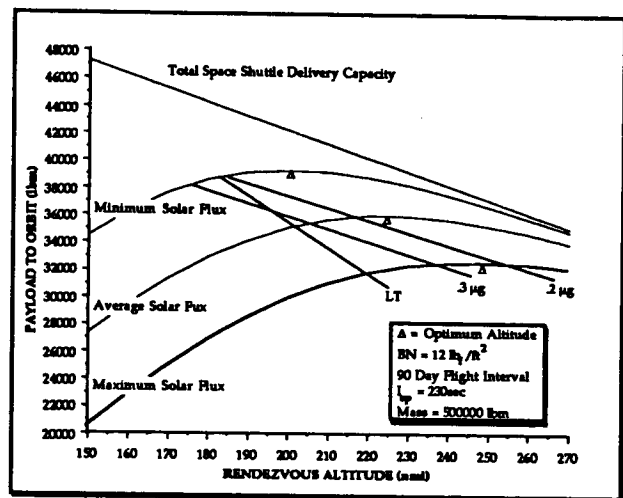


Figure 15: Solar Flux Influence on the Optimal Altitude

As shown in Figures 11 - 15, the net payload-to-orbit curves are relatively flat near the optimal points. This indicates that altitude biases due to other operational considerations could be accommodated without significantly impacting net payload-to-orbit. In fact, assuming average values for each influence, the rendezvous altitude could vary by +/- 10 nmi with a very small variance in the net payload-to-orbit. Within this 20 nmi band around the optimal altitude, less than a 500 lbm net payload loss is experienced. Given the choice of flying 10 nmi higher or 10 nmi lower, rendezvous altitudes would be adjusted upward, if possible, to increase SSF lifetime.

## Reaction to Unpredictable Events

An OAS must specify (or levy requirements on SSF operational concepts) when and how the SSF reacts to real time changes which drive altitude selection, for example, Space Shuttle launch delays. Operationally, SSF lifetime should never drop below the minimum lifetime level of 90 days to 150 nmi. Depending on the reasons for the slip, SSF may react before ever reaching this limit.

Additionally, real time changes in the solar flux could result in current altitudes with undesirable lifetimes or which are significantly off-optimal altitudes. Current thinking suggests that the operational altitudes will be determined using mean solar flux predictions. As can be seen in Table 1, recently observed solar flux data are appreciably greater than the mean predictions for those dates (Reference 8). Again, how and when should SSF react to a situation which significantly deviates from the predicted conditions?

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**TABLE 1:** Predicted vs. Observed Solar Flux Values

| DATE | MEAN | OBSERVED |
|------|------|----------|
| Dec. '88 | 113.2 | 199.8 |
| Jan. '89 | 118.4 | 235.4 |
| Feb '89 | 120.7 | 222.4 |
| Mar. '89 | 123.1 | 205.1 |
| Apr. '89 | 125.9 | 189.6 |
| May '89 | 129.2 | 190.1 |
| June '89 | 132.4 | 239.6 |
| July '89 | 135.2 | 181.9 |
| Aug. '89 | 137.5 | 217.1 |
| Sep. '89 | 139.3 | 225.9 |
| Oct. '89 | 140.8 | 208.7 |
| Nov. '89 | 142.5 | 235.1 |
| Dec. '89 | 144.1 | 213.0 |
| Jan. '90 | 145.3 | 210.1 |
| Feb. '90 | 146.4 | 178.3 |

What circumstances (SSF system failures, Space Shuttle launch slips, atmosphere worsening, etc.) will cause SSF to adjust altitude and depart from nominally planned profiles? How should SSF maintain altitude under contingency conditions? Such issues must be addressed in an OAS.

# VI CONCLUSIONS

Defining an operational altitude strategy poses significant challenges by attempting to incorporate and blend numerous operational considerations. Only recently has the SSF Program reached a maturity level to where altitude strategy planners could begin assimilating and integrating many of the influences and considerations necessary to develop an operational altitude strategy. In addition to providing the guidelines for computing nominal operational altitudes for long range and near *real time* planning, an operational altitude strategy must also be adaptive, providing procedural road maps as to how and when SSF must react to real time off-nominal conditions, such as, Space Shuttle launch slips and unexpected deviations in atmospheric parameters.

It is important to note that any altitude strategy ultimately proposed will inherently favor certain operational aspects over others. This paper has not attempted to produce a final altitude strategy to be used for the 30-year operational lifetime of SSF; rather it attempts to identify and put into perspective the associated issues and influences which will drive the development of a final operational altitude strategy.

Realistically, this process will take years of discussion and prioritization by system, element, and operations areas before mission planners are "smart" enough to implement any strategy. Unfortunately, such a strategy could be of great use in the near term to efficiently design logistics elements and estimate user and SSF core support requirements. The authors of this paper feel that *optimal* altitudes are an excellent first cut at an operational altitude strategy providing considerable flexibility to accommodate future operational considerations as they become pertinent.

# VII ACKNOWLEDGEMENTS

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