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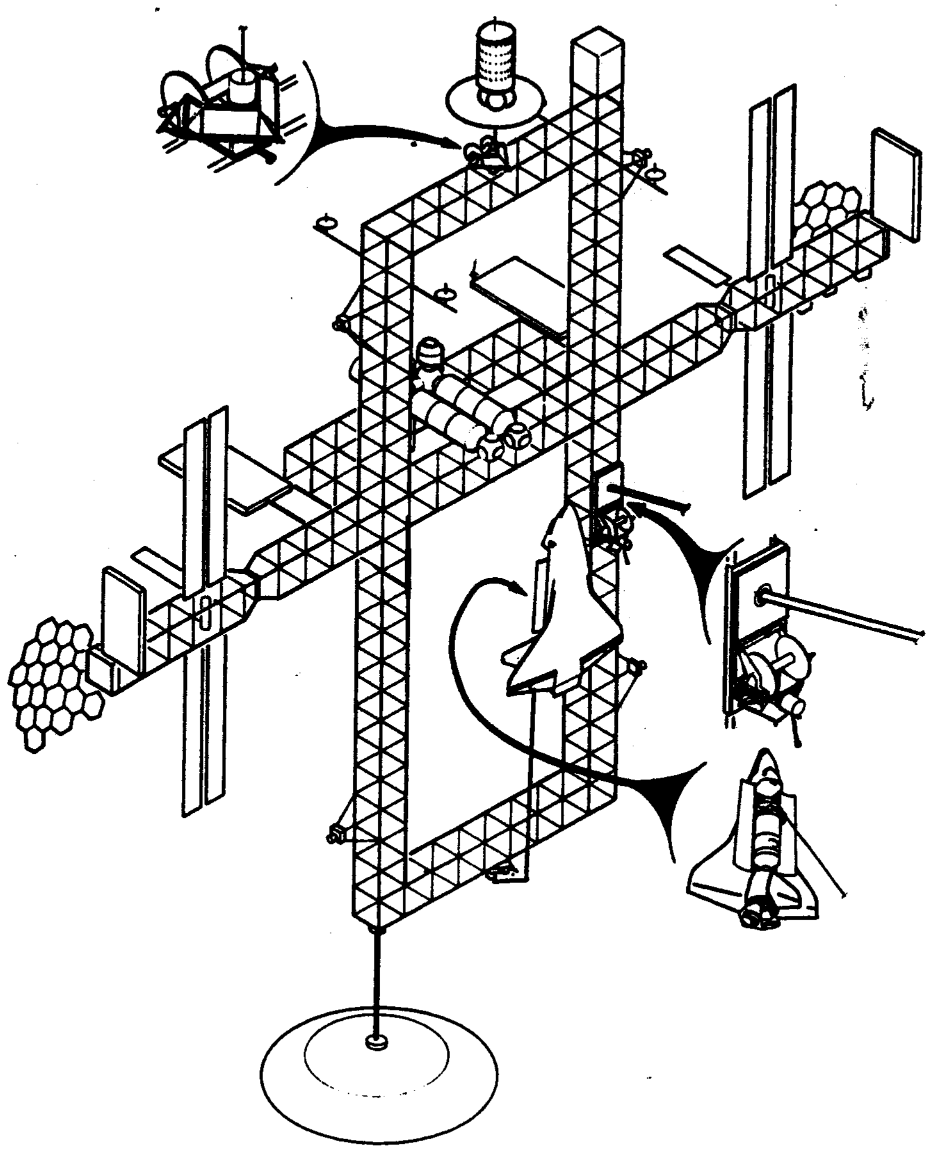
Contract NAS8-36616
MCR-86-1346

~~Executive Summary~~
Phase III

Volume I

Final Report September 1986

Selected Tether Applications in Space



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CONTRACT NO. NAS8-36616
DPD NO. 665
DR-04
MCR-86-1346 Volume I

EXECUTIVE SUMMARY

STUDY OF SELECTED TETHER APPLICATIONS IN SPACE

PHASE III

CONTRACT NAS8-36616

SEPTEMBER 1986

BY

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DENVER, COLORADO

FOR

MARSHALL SPACE FLIGHT CENTER

HUNTSVILLE, ALABAMA

FOREWORD

The study was accomplished by the Space Systems Division of Martin Marietta Denver Aerospace (MMDA) under Mr. Morris H. Thorson, and in the Spacecraft Systems Product Area under Mr. Lester J. Lippy.

The Study Manager from October through December 1985 was Mr. William O. Nobles. The Study Manager from January 1986 through the completion of the task was Mr. William R. Woodis. Mr. Jack Van Pelt was responsible for the mission performance analysis, Mr. Michael G. Keeley and Mr. Robert E. Lock generated the cost model and performed the cost benefit studies, Mr. Gilbert M. Kyrias was responsible for the mechanical design, Mr. Ed Ziehm worked the mission operations and Mr. Robert Terrazas developed the WBS. Mr. Carl Bodley and Mr. Colt Park provided support for the deployment dynamics analysis.

The Executive Summary is submitted in accordance with Contract NAS8-36616, Statement of Work paragraphs 4.1 and 5.1 and Data Procurement Document (DPD) Data Requirement (DR) Item DR-4. The study was performed under the technical direction of Mr. James K. Harrison, Marshall Space Flight Center, Huntsville, Alabama.

1.0 INTRODUCTION

This report summarizes the results of a Phase III study of Selected Tether Applications in Space (STAIS). The two applications selected for this study were:

- Tether Deorbit of Shuttle from Space Station
- Tether Assisted Launch of OTV from Space Station

The study objectives for Phase III were to: (1) perform a preliminary engineering design, (2) define operational scenarios, (3) develop a common cost model, (4) perform cost benefits analyses, and (5) develop a Work Breakdown Structure (WBS). The primary emphasis was on the cost model and benefits analyses with the other tasks worked to the depth required to support these two objectives.

The dual keel Space Station configuration shown in Figure 1 was used in this study. The Mobility System, created for moving components over one face of the Space Station, makes it possible to use a single tether deployer system for both OTV and Shuttle launches.

A balance must be established between momentum added to the Space Station through downward Shuttle deployments and momentum extracted from the Space Station through upward deployments of the OTV. Since the OTV is not scheduled to be implemented until 1999, aerodynamic drag was used to remove momentum from the Space Station during the first five years. The performance analysis identified optimum variable altitudes to achieve this balance as functions of Space Station mass and drag area and the predicted atmospheric densities for one solar cycle (1994 through 2004).

Deployer concepts ranging from a minimum capability system (weighing 2,389 kg) that can deorbit the Shuttle from a maximum altitude of 370 km to a full capability system (weighing 11,113 kg) that can deploy the OTV with 9,072 kg of payload and using 150 km of tether have been designed and are discussed in Section 3.0.

Increasing the tether length over that required for Shuttle deorbit allows the tether deployer to be used for waste disposal and External Tank (ET) deorbit. All deployer designs except the smallest (Configuration A) have incorporated this capability and the cost benefit of $3M for each waste disposal mission has been included. Benefits were not assessed for ET deorbit because no specific mission was identified.

Operational scenarios for both tethered and non-tethered Shuttle and OTV operations at the Space Station were evaluated.

Results of the cost benefits analyses are discussed in Section 4. Conclusions are presented in Section 5 and recommendations for implementing a specific design configuration and for future development and study activities are presented in Section 6.

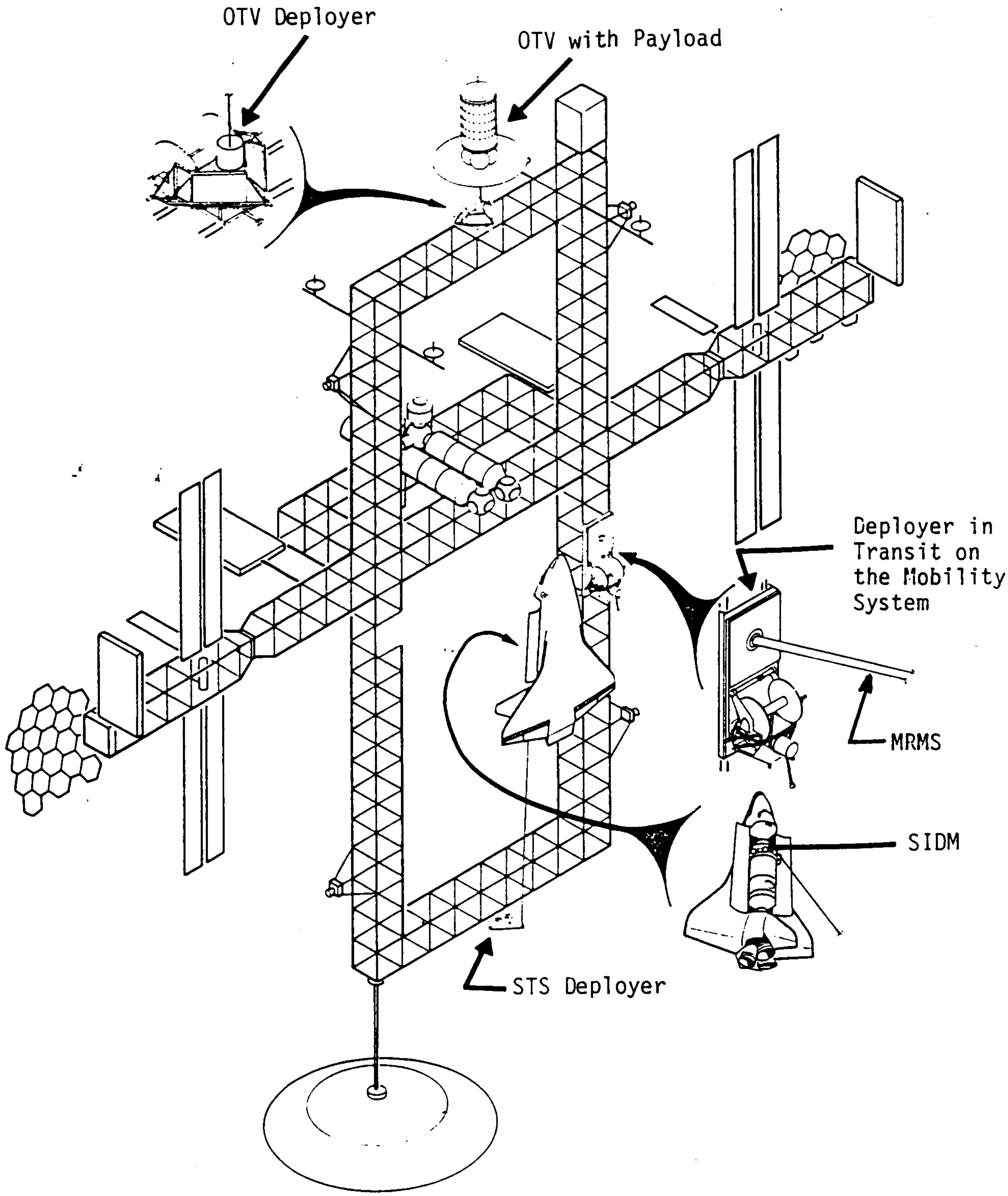

Fig. 1 Space Station with Deployer System

2.0 MISSION ANALYSIS

The mission analysis effort for this study consists of a Performance Analysis to determine benefits of tether operations at the Space Station and also a Mission Operations Analysis to determine the impact of these operations on the Space Station during the 1994-2004 time period. Several scenarios will be discussed which utilize the tether applications plus aerodynamic SS drag to balance SS angular momentum and to provide performance benefits for the Space Station.

2.1 Performance Analysis, 1994-2004. During the prior Phase II effort significant performance benefits from tethered Shuttle and OTV operations, in the form of OMS, OTV, and SS Station keeping propellant savings were identified, and resulted in a projected reduction of 10 Shuttle flights over a 10 year period.

By the time this Phase III effort began in October 1985 the Space Station baseline altitude was reduced from 500 km to 463 km and the OTV flight readiness date had moved from 1995 to 1999. As a result of these changes a variable Space Station altitude scenario was developed to utilize atmospheric drag as a momentum balancer before the arrival of the OTV in 1999. This approach significantly increases the Shuttle cargo weight delivered because it allows the Space Station to operate at appreciably lower altitudes, and provides a large benefit in addition to the propellant savings previously discussed.

In the following discussions, 5 cases are analyzed that cover the 11-year period from 1994-2004. These cases are defined as follows:

Case I — SS operates near the current baseline altitude of 463 km - no tether operations (1994-2004)

Case II — SS operates at lower variable altitudes to maximize performance benefits - no tether operations (1994-2004)

Case III — SS operates at lower variable altitudes to maximize performance benefits - tethered Shuttle operations (1994-2004)

Case IV — SS operates near the current baseline altitude of 463 km - tethered Shuttle and OTV operations (1999-2004)

Case V — SS operates at lower variable altitudes to maximize performance benefits - tethered Shuttle and OTV operations (1999-2004)

Three Space Station tether operational scenarios are considered for the 11-year study period. In all 3 scenarios the variable altitude approach (Case III) is used from 1994-1998. Beginning in 1999 three choices are available, (1) continue with Case III (no tethered OTV launches), (2) raise the SS to 463 km and use Case IV (tethered OTV launches), or (3) apply Case V (tethered OTV launches at variable altitude). Benefits for the three approaches are presented.

2.1.1 General Ground Rules. The Space Station IOC date of 1994 is used as a starting point for tether operations with an eleven year period (1994-2004) selected since it spans a full solar cycle and covers the full variation in atmospheric drag expected (varying density) at SS altitudes. Projected variations in Space Station mass, area, and atmospheric density were obtained from the Martin Marietta Space Station Study Team and were incorporated into the analysis to determine orbit drag decay rates. In all cases the SS was assumed to be at an orbit inclination of 28.5 degrees. A Space Station altitude of 463 km is used as a non-tether baseline with a 2-burn (Hydrazine system) reboost every 90 days for station keeping (Case I). The variable altitude (non-tether) approach (Case II) is used as an alternate improved baseline for final comparisons, and uses the same type of reboost as Case I. Case III (variable altitude - tether approach/no OTV) also uses a 90 day reboost cycle, but uses the tethered Shuttle deployment to raise the SS apogee to the proper altitude, followed by a single burn of the SS reboost system.

A direct insertion Shuttle cargo delivery capability of 20,729 kg was assumed for the reference altitude of 463 km with a sensitivity of -26.94 kg/km for other altitudes. The weight of the Orbiter at SS departure is assumed to be 99,750 kg in all cases and tether lengths are selected to prevent the Orbiter from descending below 185 km after tether release. The Orbiter accomplishes its deorbit OMS burn at the following apogee passage. OMS propellant scavenging benefits were determined using the methods developed in the previous Phase II study phase.

The MSFC Model 8 (low) mission model (July 1985) was used throughout the study. This model shows 6-19 Shuttle visits (average of 13) annually in the 1994-2004 time period with 6-9 OTV launches (average of 8) annually in the 1999-2004 time period at the Space Station.

For tether operations, a static release (non-swinging tether) is used with an 8-hour deployment. The tether is required to have a minimum factor of safety of 2.0 in all cases and is to be composed of braided Kevlar 49 material with a 0.25 mm Teflon jacket which provides multiple reuse capability. Tether lengths are selected to provide the capability for deorbiting 3,175 kg of waste every 90 days and also shall have the capability to deorbit an external tank (31,750 kg), in addition to its regular tethered Shuttle deployments and OTV launch operations.

Tether length requirements for Shuttle deployments vary from 33km (Case III) to a maximum of 52 km (Case IV). Corresponding tether lengths for waste disposals vary from 59 km to 73 km, respectively, with 4-6 km in length added for external tank disposals. A maximum tether length of 150 km has been selected for tethered OTV launches. Maximum tether tension values vary from 10,700 N (Case III) to 15,500 N (Case IV) for Shuttle deployments, up to 20,000 N for OTV launch assists (Cases IV and V). Tension values for tethered waste disposals and external tank deorbits are in the 1,200 N and 9,000 N range, respectively. Maximum power dissipation requirements for Case III varies from 25 kw for the tethered Shuttle deployment to 33 kw for the external tank deorbit.

Maximum power dissipation requirements for Case IV vary from 50 kw for the tethered external tank deorbit to 56 kw for the tethered Shuttle deployment. The maximum power dissipation requirement for the tether OTV launch (Cases IV and V) is approximately 220 kw. Maximum power dissipation requirements for tether waste disposals are in the 4-6 kw range. Power required to retrieve the tether after release of payloads is small (several kw) for retrievals after Shuttle deployments, waste disposals, and ET disposals. Retrieval of the tether with its end effector after OTV release would require about 26 kw of power, if accomplished in 8 hrs. The preceeding tether tension and power requirements determined by Phase II study methods, were independently checked by Tethered Satellite System personnel using the Model 1B Dynamics Program and were found to have adequate accuracy (within 5%).

2.1.2 Variable Space Station Altitude Analysis. For the variable Space Station altitude case with tethered deployments of the Shuttle every 90 days (Case III) an average atmospheric density and SS ballistic coefficient (W/C_DA) was selected for each year of the 11-year solar cycle (1994-2004). Minimum and maximum Space Station altitudes were determined for each year (using the density and ballistic coefficient data) so that the Space Station decayed from the maximum to minimum altitude in 90 days (see Case III on Fig. 2). A tether deployment of the Shuttle at minimum altitude (varies from 305-370 km) causes the Space Station to reach an apogee corresponding to the maximum altitude (Fig. 2), at which point the Space Station uses its reboost propellant to circularize the orbit (see also Fig. 3).

Case I (Space Station at 463 km - no tether operations) and Case II (Space Station at variable altitude - no tether operations) are also shown on Fig. 2 since these are the baselines which are used for comparison. For Case I, the minimum altitude is a constant 463 km with the maximum altitude varying as shown (Fig. 2) for 90 day reboosts of the Space Station. For Case II, minimum and maximum altitudes were determined in the same way as for Case III, except all reboosts use Space Station propulsion and result in higher altitudes with smaller reboosts as shown in Fig. 2. The typical variation in Space Station altitude every 90 days with Shuttles arriving at the low altitude and at intermediate altitudes would look similar to Fig. 3 (Case III) but with smaller altitude variations.

For completeness the altitude variation for Case IV (discussed in 2.1.3) for the years 1999-2004 and for Case V (also discussed in 2.1.3) for the years 1999 (low drag year) and 2003 (high drag year) are also shown in Fig. 2. Both Case IV (fixed altitude) and Case V (variable altitude) involve tethered Shuttle and OTV launches during the last 6 years of the study period.

Benefits of Case III over Case I, discussed in Section 2.1.4, are made up the direct benefit of increased cargo weight for all flights flying at lower altitudes plus integral OMS propellant scavenged on the 4 yearly tethered Shuttle deployments minus additional SS propellant required for reboost at the lower altitudes. The benefits of Case II over Case I (appreciably less than for Case III), also discussed in Section 2.1.4 are similarly determined, but do not include any OMS propellant scavenged.

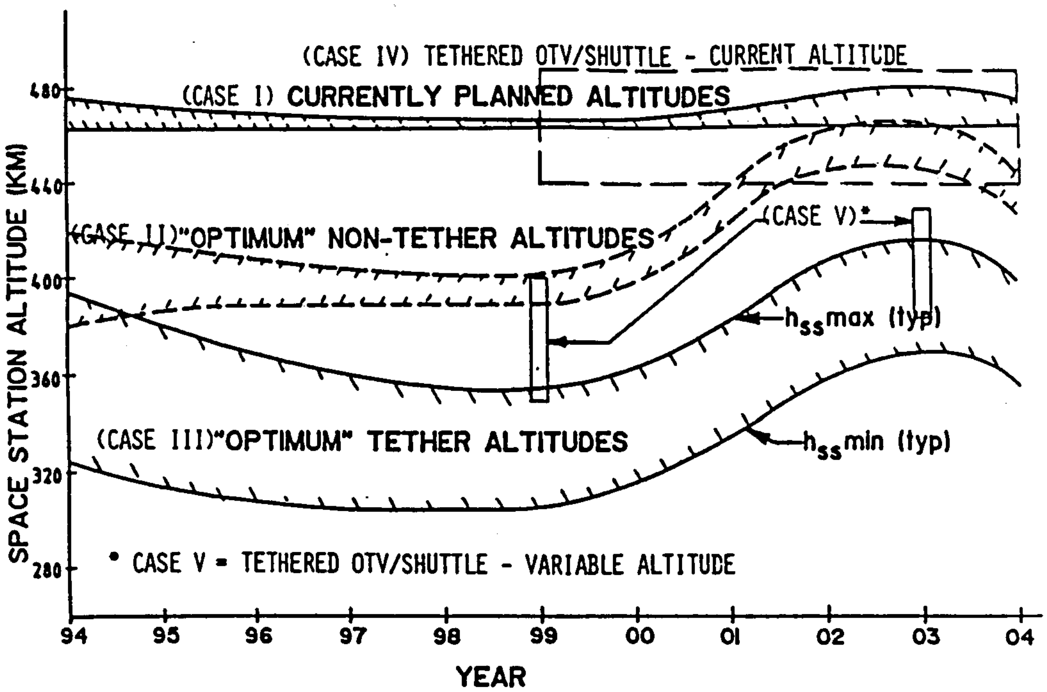

Fig. 2 Space Station Yearly Altitude Ranges

- YEARS 1994 THRU 2004
- h_{min} VARIES FROM 305 - 370 KM (165-200 NMI)
- h_{max} VARIES FROM 354 - 417 KM (191-225 NMI)
- 4 TETHERED STS DEPLOYMENTS YEARLY OUT OF 6-19 TOTAL VISITS
- (T) REFERS TO STS TETHER DEPLOYMENT FROM SS (UP TO 33 KM TETHER) TO REBOOST SS

(TYPICAL VARIATION FOR 12 STS VISITS)

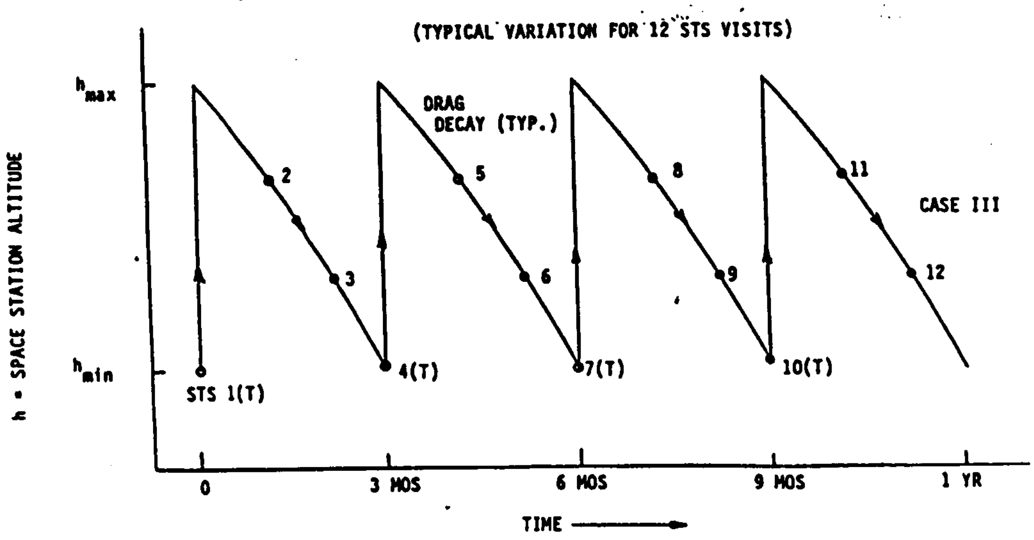

Fig. 3 Momentum Balance - Tethered Shuttle Variable Altitude Operations

2.1.3 Tether Assisted Launch of OTV, 1999-2004. Starting in 1999 tethered OTV launches are possible from the Space Station. All of these launches (an average of 8 per year for 6 years) generally go to geosynchronous orbit and would be tether-launched from the top of the Space Station.

The first approach, similar to the Phase II study, would be to tether launch the OTV with the Space Station operating near the fixed altitude of 463 km (Case IV) as shown in Fig. 3. Fig. 4 shows a typical sequence of tethered Shuttle and OTV launches to balance the Space Station momentum about this reference altitude. In this case the Space Station is left in an elliptical orbit and all of the station keeping propellant is saved. Fluctuations in the average altitude are $\pm$ 24 km about the nominal altitude of 463 km.

As shown in Fig. 4 (for a typical year of 16 Shuttle visits), 8 of the Shuttle flights have tethered deployments every 45 days alternating with 8 tethered OTV launches at about the same interval (about 22 days later), with 8 extra Shuttle flights (non-tethered) arriving at an average altitude of 463 km. Benefits of Case IV over Case I, discussed in Section 2.1.4 are made up of the direct benefit of cargo delivery weight increases for flights to lower average altitudes plus integral OMS propellant scavenged on the 8 tethered Shuttle deployments, plus OTV propellant savings from tether launches, plus SS orbit station keeping propellant saved.

The second approach combines a variable altitude scenario with tethered OTV launches (Case V) and combines some of the features and benefits of both Case III and Case IV in the 1999-2004 time period. Two years were investigated (1999 and 2003) to determine the potential benefit for this type of operation, with altitude ranges shown in Fig. 3. Altitudes and benefits are expected to show intermediate values to those shown for the two selected years. As with Case IV, the Space Station is left in an elliptical orbit and all of the station keeping propellant is saved.

As shown in Fig. 5 (for a typical year of 16 Shuttle visits), all of the Shuttle flights are used in the tether deployed mode and occur about every 23 days with 8 tethered OTV launches alternating with every 2 Shuttle deployments at 45 day intervals. This case (Case V) allows the Space Station to operate at intermediate minimum altitudes (348-383 km) where drag is also a significant contributor to the momentum balance. Benefits of Case V over Case I, discussed in Section 2.1.4, are made up of the direct benefit of increased Shuttle cargo weight at the lower altitudes plus OMS propellant scavenged on all Shuttle flights, plus OTV propellant saved on all OTV launches, plus SS orbit station keeping propellant saved. Fluctuations about an average yearly SS altitude are $\pm$ 48 km (approximately twice the variation for Case IV at the higher altitude).

- YEARS 1999 THRU 2004, 15-19 STS VISITS YEARLY
- SPACE STATION NOMINALLY AT 463 KM (250 NM) FOR ALL YEARS
- VARIATIONS UP TO ± 24 KM (± 13 NMI) TYPICAL
- 7-9 TETHERED OTV LAUNCHES YEARLY (150 KM TETHER)
- 7-11 TETHERED STS DEPLOYMENTS YEARLY TO BALANCE OTV AND DRAG (≤ 52 KM TETHER)
- TYPICAL VARIATION: S1, S2, S3, ETC. (SHUTTLE VISITS)
  (T) REFERS TO STS TETHER DEPLOYMENTS
  01, 02, 03, 04, ETC. (TETHERED OTV LAUNCHES)

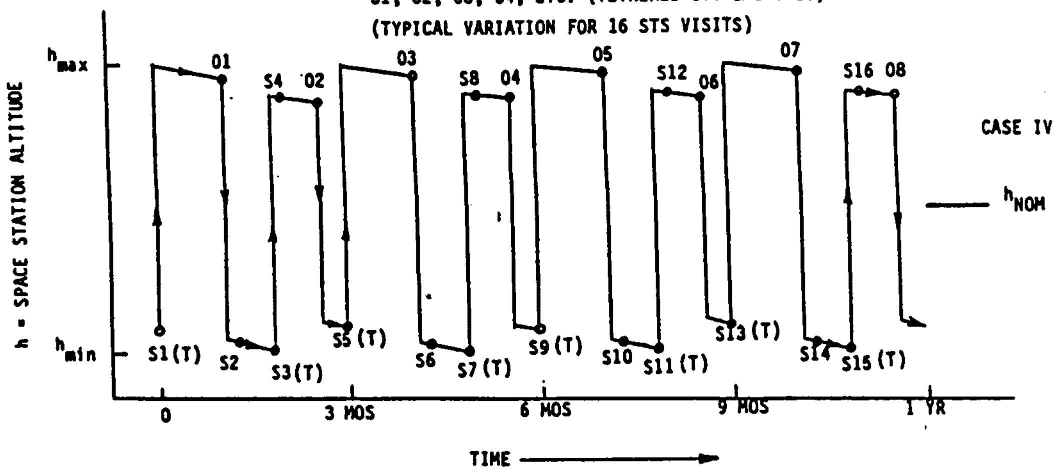

Fig. 4 Momentum Balance - Tethered OTV/STS at Current Altitude

- YEARS 1999 THRU 2004, 15-19 VISITS YEARLY
- h_{min} VARIES FROM 348 - 383 KM (188-207 NMI)
- h_{max} VARIES FROM 400 - 428 KM (216 - 231 NMI)
- 7-9 TETHERED OTV LAUNCHES YEARLY (150 KM TETHER) -01, 02, 03 ETC.
- GENERALLY, ALL STS DEPLOYMENTS ARE TETHERED (≤ 38 KM TETHER) -S1, S2, S3, ETC.

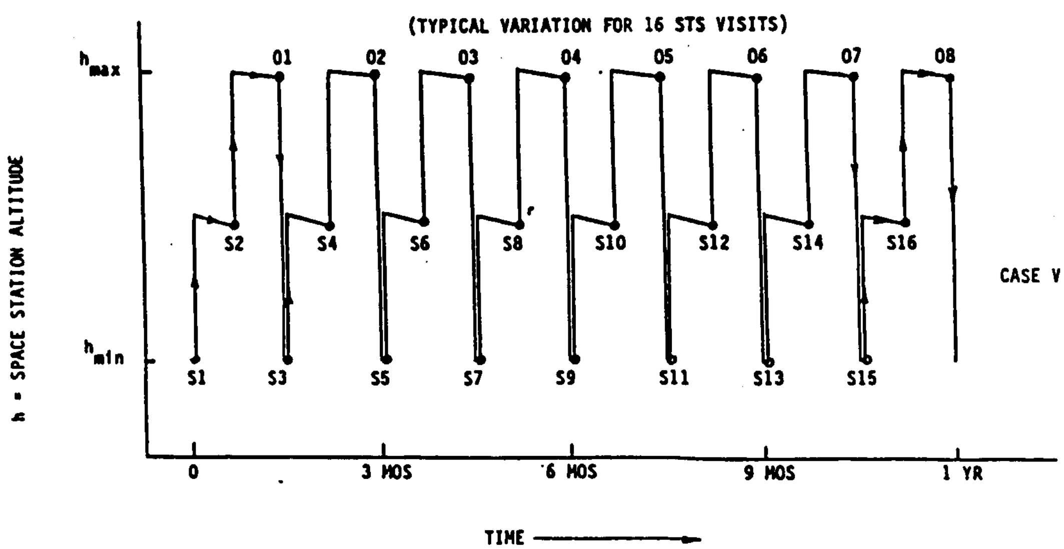

Fig. 5 Momentum Balance - Tethered OTV/STS at Variable Altitude

2.1.4 Benefits Summary. Results of the study are illustrated with the bar charts shown in Fig. 6 (Case III vs Case I) and Fig. 7 (Cases IV and V vs Case I). For comparison purposes the average benefit of Case II over Case I is 13,700 kg/yr for 11 years, with Case III over Case I showing an average benefit of 41,700 kg/yr (or 3 times the benefit). For convenience, all cases are compared to Case I, initially, and then compared to Case II in a final summary since it is assumed that the Space Station will eventually use a variable altitude scenario in either case to take advantage of the cargo savings.

For the first 5 years (1994-1998) all 3 approaches discussed in 2.1 will utilize Case III (variable altitude - no OTV). This benefit averages about 17,800 kg compared to Case II, or an average savings of 4 Shuttle flights in 5 years.

If Case IV is used for the last 6 years (1999-2004) as shown in Fig. 7, savings average about 47,100 kg compared to Case I but fall short of the average savings of 50,900 kg/yr of Case III over Case I. For this reason and the fact that an average of 21 tether operations are required annually for Case IV (compared to 8 for Case III), continuing Case III operations for the full 11 years would be recommended over the change to Case IV in 1999.

Maximum benefits are achieved if tethered Shuttle deployments and tethered OTV launches are combined in a variable altitude scenario (Case V), as shown in Fig. 7. Benefits of Case V over Case III are approximately double that shown for 1999 and about 70% higher for the year 2003. The two preferred approaches are therefore a) Case III operations from 1994-2004 and b) Case III operations from 1994-1998 and Case V operations from 1999-2004.

Maintaining the Space Station at a variable altitude for the full 11-year period, without tethered OTV operations would require an average of 8 tether operations annually (4 tethered Shuttle deployments and 4 waste disposals). Average annual benefits for Case III vs Case II would be 27,500 kg/yr and would result in a savings of 14 Shuttle flights out of a total of 143 Shuttle flights in 11 years. An OMV operation would be required for each of the non-tethered OTV launches.

If the Space Station is operated in the variable altitude mode for the first 5 years (1994-1998) with tethered Shuttle launches (Case III) and then changed to a variable altitude with tethered Shuttle and tethered OTV launches (Case V) for the last 6 years (1999-2004), the number of yearly tether operations would reach a maximum of about 30 tether operations per year (includes 4 annual waste disposals). Average annual benefits for this (Case III/Case V) vs. Case II approach would result in an average benefit of 47,200 kg per year for the 11-year period. This would result in a savings of about 22 Shuttle flights our of a total of 143 Shuttle flights compared to the optimum non-tethered approach (Case II) for the 1994-2004 time period. 48 OMV proximity operations would also be eliminated in the last 6 years by tether launching the OTV.

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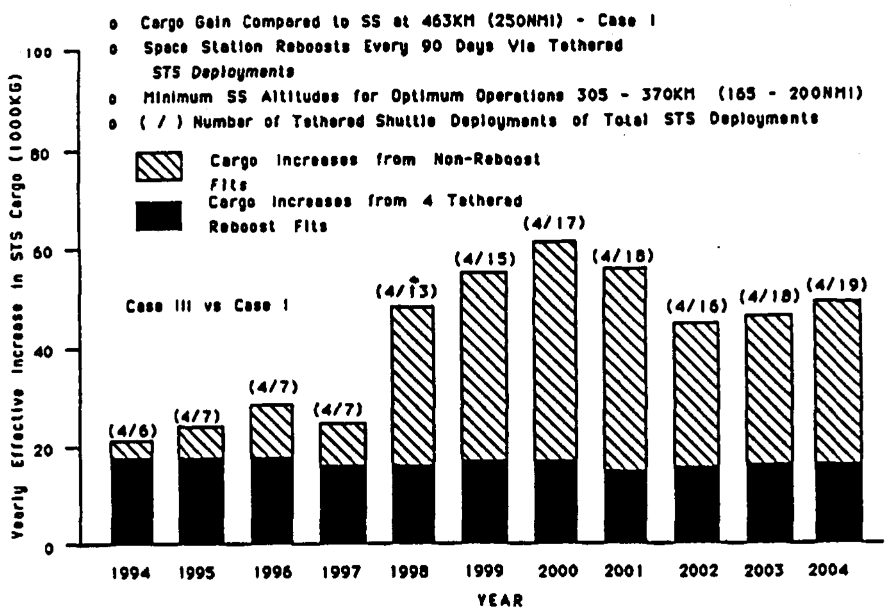

Fig. 6 - Benefit of Variable Altitude Operations - Tethered Satellite

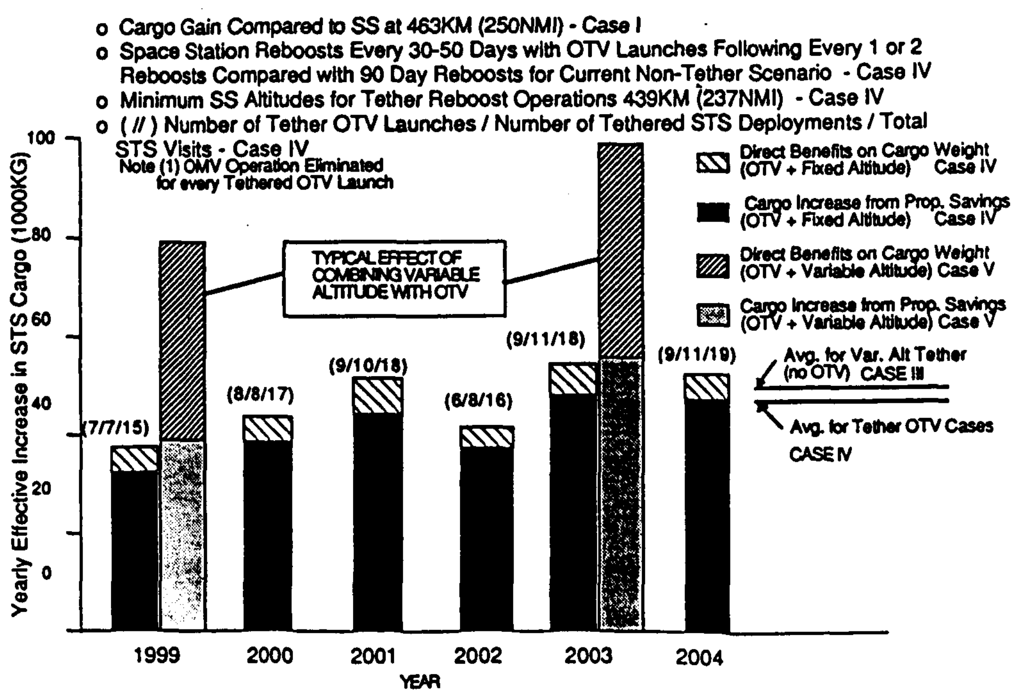

Fig. 7 - Benefit of Combining Tethered OTV and Shuttle Operations on the Space Station

2.2 Mission Operations. As previously discussed, significant benefits can be obtained by initiating tether operations on the Space Station as soon as possible. These benefits appear in the form of increases in effective cargo weight delivered, which ultimately results in the reduction of the number of Shuttle visits required (10-15%) to accomplish the missions of the Space Station over the 1994-2004 time period (and beyond). Operationally, tether operations add time to the Shuttle and OTV operations and impose a higher level of gravity (up to several milli-g's) for several hours. The anticipated non-tether (baseline) and tethered approaches are therefore compared.

A comparison between the baseline and tethered Shuttle deployments is depicted in Fig. 8. One of the prime concerns (currently being evaluated at JSC) is the effect of plume impingement and contamination from the Orbiter RCS thrusters on the Space Station. For this reason, efforts have been made to minimize those effects.

For the baseline case, the Orbiter will initiate a V bar separation rate of 0.2 FPS from the Space Station along its flight path using its low Z mode thrusters. This maneuver will move the Orbiter ahead about 120 ft in 10 minutes. At this point, another low thrust maneuver will accelerate the separation rate to 1.0 FPS along the R bar descent path which will cause the Orbiter to be about 800 ft ahead and 500 ft below the Space Station at about 25 minutes from separation. At this point, the Orbiter is far enough away to change attitude and do a 3.0 FPS retrograde burn to move into position for deorbit and reentry operations some time later, as will be discussed.

For the tethered Shuttle deployment the proximity operations are very similar, except that the Orbiter will move to a position slightly ahead and about 1 km below the Space Station after about 40 min (see Fig. 8). At this point, gravity gradient forces will be high enough to permit normal tether deployment, using the tether deployer system to control the rate of Shuttle separation from the Space Station.

A comparison between the baseline and tethered Shuttle deployments through deorbit and landing is presented in Fig. 9. Note that the total time, for the tethered approach is about 12 hrs compared to 6 hrs for the baseline case. A standard tether deployment time of 8 hrs (from separation from the Space Station to tether release) has been used throughout our studies based on a conservative approach to minimize tether librations and also to reduce heat dissipation requirements at the deployer. Retrieval times of 8 hrs have also been used throughout.

Although the 8 hr deployment period (which includes fuel scavenging operations) is a major contributor to the increased time for deployment, deorbit, and landing, almost one-half of the period is also devoted to the Orbiter cold soak and major portion of the Orbiter final preparation periods which are common to the baseline approach. The other prime contributor to increased time is the Shuttle Interface Deployment Module (SIDM) attachment and checkout operations. Other portions of the operation are similar to the non-tethered deployment.

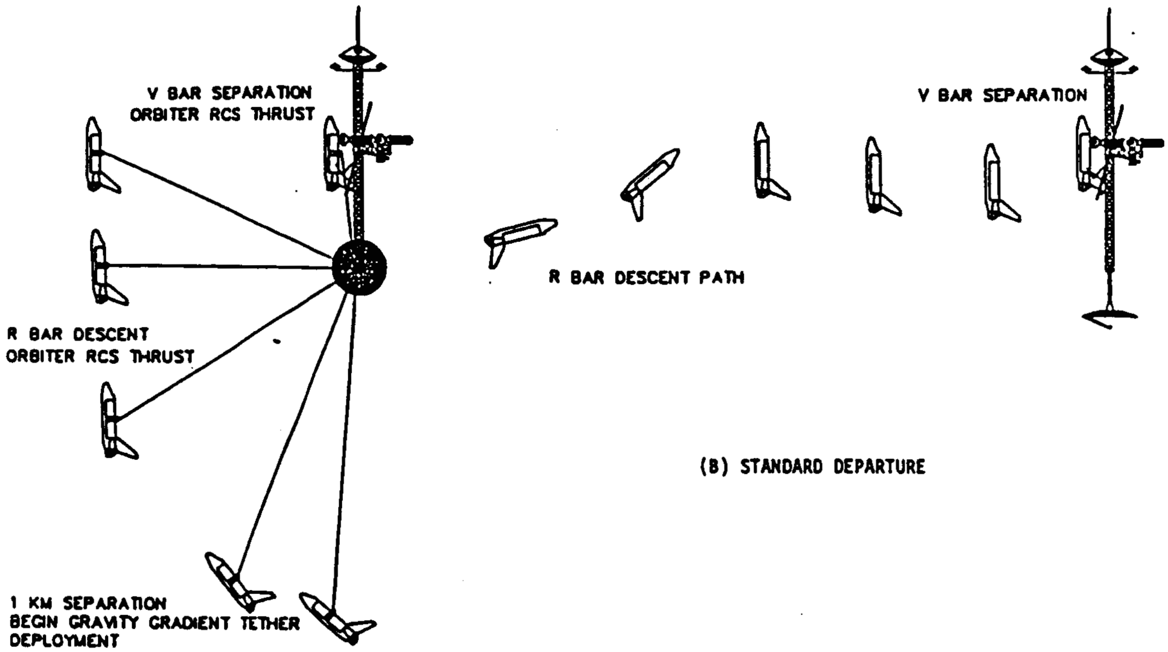

Fig. 8 Tethered and Standard Departure of Shuttle from Space Station

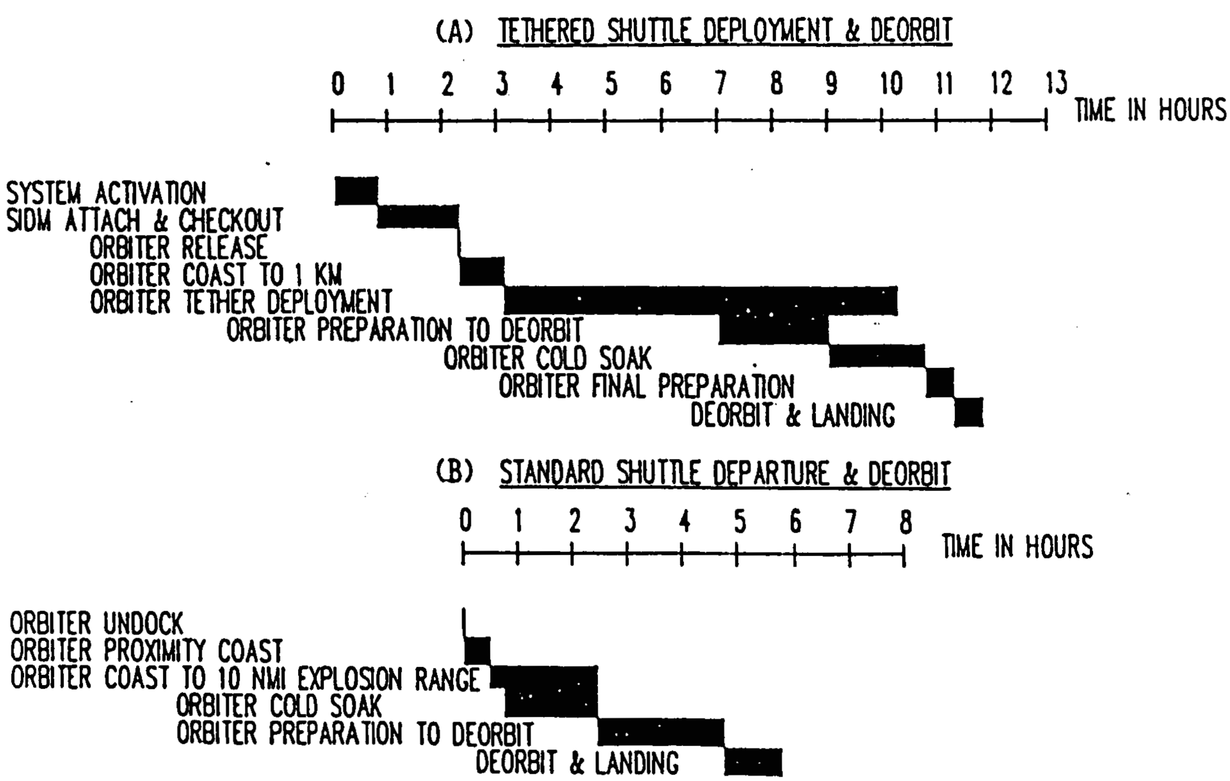

Fig. 9 Tethered and Standard Shuttle Deorbit Timelines

Overall time for tether deployment operations associated with a tethered Shuttle deorbit is slightly under 24 hrs. This includes a 10.35 hr period from system activation until Shuttle release (Fig. 9), an 8 hr period for retrieval and docking of the Payload Interface Deployment Module (PIDM) with SIDM attached, and a 5.2 hr period for transferring fuels and cold gas at the fuel depot and for deactivation and storage of systems. By enlarging the motor/generator system (and radiators) it may be possible to reduce the deployment period by 2-3 hrs and also to reduce the retrieval time by a similar amount. Overall, the Shuttle tether operation time period would be expected to remain in the vicinity of 18-24 hrs.

The baseline OTV deployment, as currently envisioned, involves the use of the Orbital Maneuvering Vehicle (OMV) to move the OTV away from the Space Station and place it on a departure path so that the OTV is approximately 37 km (20 nmi) away from the Space Station within 2 hrs of departure. At this point, the OTV would prepare for its mission to high orbit with main engine burn following. The OMV would return to the Space Station within several hours ofmission initiation.

For the tethered OTV launch, the OMV operation would be completely eliminated. The Mobile Remote Manipulating System (MRMS) would move the OTV (with payload) from its hangar and attach it to the PIDM near the deployer. The PIDM in-line cold gas thrusters would provide tether tension to move the OTV to a position about 1 km above the Space Station with normal tether deployment following, similar to the Shuttle deployment. The overall time for tethered OTV operations is approximately 19 hrs, including 16 hrs for deployment and retrieval and the remaining time pre-deployment and post-retrieval operations. OTV tether operation time would be expected to remain in the 16-19 hr time period.

3.0 TETHER DEPLOYER DESIGN CONCEPTS

The deployer designs considered all aspects of a tether system including interfaces with the Space Station and Shuttle. The sequence of events from launch through placement of the deployer on the Space Station, tether operations at the Space Station and return to earth has been examined.

The Space Station configuration shown in Figure 1 is the I.O.C. version of the currently proposed 5-meter modular truss design. This view shows the deployer being transported along the face of the SS using the planned Mobility System. This system will also transport the MRMS, experiments, propulsion units, and solar panels. The deployer design utilizes the Mobility System making the tether deployer system more simple and efficient because a single deployer can be used for both Shuttle and OTV launch operations.

3.1 Tether Deployer Design Approach. Four deployer designs were prepared that cover a range of capabilities from the minimum case which is limited to Shuttle deorbits from altitudes up to 370 km, to the OTV deployer with 150 km of tether. The capabilities of these systems and the major design parameters are shown in Table I. These four configurations are:

Configuration A. This configuration satisfies the maximum downward deployment requirement anticipated. Deorbit of Shuttle, ET and waste disposal from an altitude of 463 km is possible with this design.

Configuration B. This system has the capability to perform ET deorbit and waste disposal from altitudes up to 370 km in addition to the Shuttle deorbit function.

Configuration C. Minimum system only capable of deorbiting the Shuttle from a maximum altitude of 370 km. This configuration is intended to provide the lowest acquisition costs.

Configuration D. This option allows deployment of the OTV with 150 km of tether. This configuration has the capability to perform all the missions considered if employed in the transportable dual mode.

A primary design objective was to provide an integrated system that includes all subsystems in one assembly that will interface with the Shuttle for transport to and from orbit, and will also interface directly with the Space Station structure. The deployer system is designed for return to Earth for repair, checkout and tether replacement. A complete spare deployer system is maintained on the ground to minimize down time. Table I shows that 70% of the total mass of the recommended Configuration D is tether mass. If the tether strength must be increased to assure adequate survivability, the tether mass will become an even larger portion of the total mass. Transporting the total deployer system to orbit is not much more costly than transporting only the tether with its associated support equipment, and represents a much lower risk.

TABLE I CONFIGURATION SUMMARY

CONFIGURATION	REEL SIZE L/D(M)	TOTAL MASS (KG)	TETHER MASS (KG)	MAX TENSION (N)	TETHER SIZE L(KM)/D(MM)	MAX POWER (KW)
C	1.22/1.4	2,389	1,312	10,676	33/7.11	25
B	1.52/1.68	3,878	2,504	10,676	63/7.11	33
A	1.83/1.98	5,796	3,858	15,480	79/8.13	56
D	2.74/2.36	11,113	7,717	20,020	150/8.13	219

NOTE: Tether diameter and mass include 0.25 mm thick teflon jacket on Kevlar tether for atomic oxygen protection.

3.2 Configuration D. Figure 10 shows deployer configuration D which provides the greatest versatility of any system considered. It was designed to accommodate the OTV launch with 150 km of tether. Since this requirement is greater than any other shown in Table I this system can also be used to deorbit the Shuttle, waste modules and the ET.

The deployer support structure interfaces with the Shuttle at two sill trunnion fittings and one keel fitting. The reel, tether and motor/generator are the major contributors to the total mass and are placed slightly above the trunnion fitting centerline to minimize the overturning moment during launch.

The reel assembly includes the level wind and fairlead roller assemblies. The fairlead roller, tensiometer and upper guide roller assemblies direct the tether from the level wind assembly to the docking cylinder.

The power generated during tether deployment is dissipated through high temperature (1100°K) radiators statically mounted to the triangular shaped truss.

Attachment of the deployer to the Space Station uses latches on an interface adapter planned for the Space Station that is required because most equipment will be smaller than the 5-meter truss size. The docking cylinder is positioned on the center of the 5-meter truss so that the tether tension loads react equally at the four node points of the Space Station structure.

The deployable Tether Management Boom (TMB) is used when the Payload Interface Deployment Module (PIDM) is being transported from the deployer to the Shuttle cargo bay in preparation for Shuttle deorbit operations and until the Shuttle has moved far enough that the tether will clear the edge of the 5-meter cube. The deployer is required to maintain a minimum tension on the tether to prevent slack as the Mobility System moves the PIDM to the Shuttle.

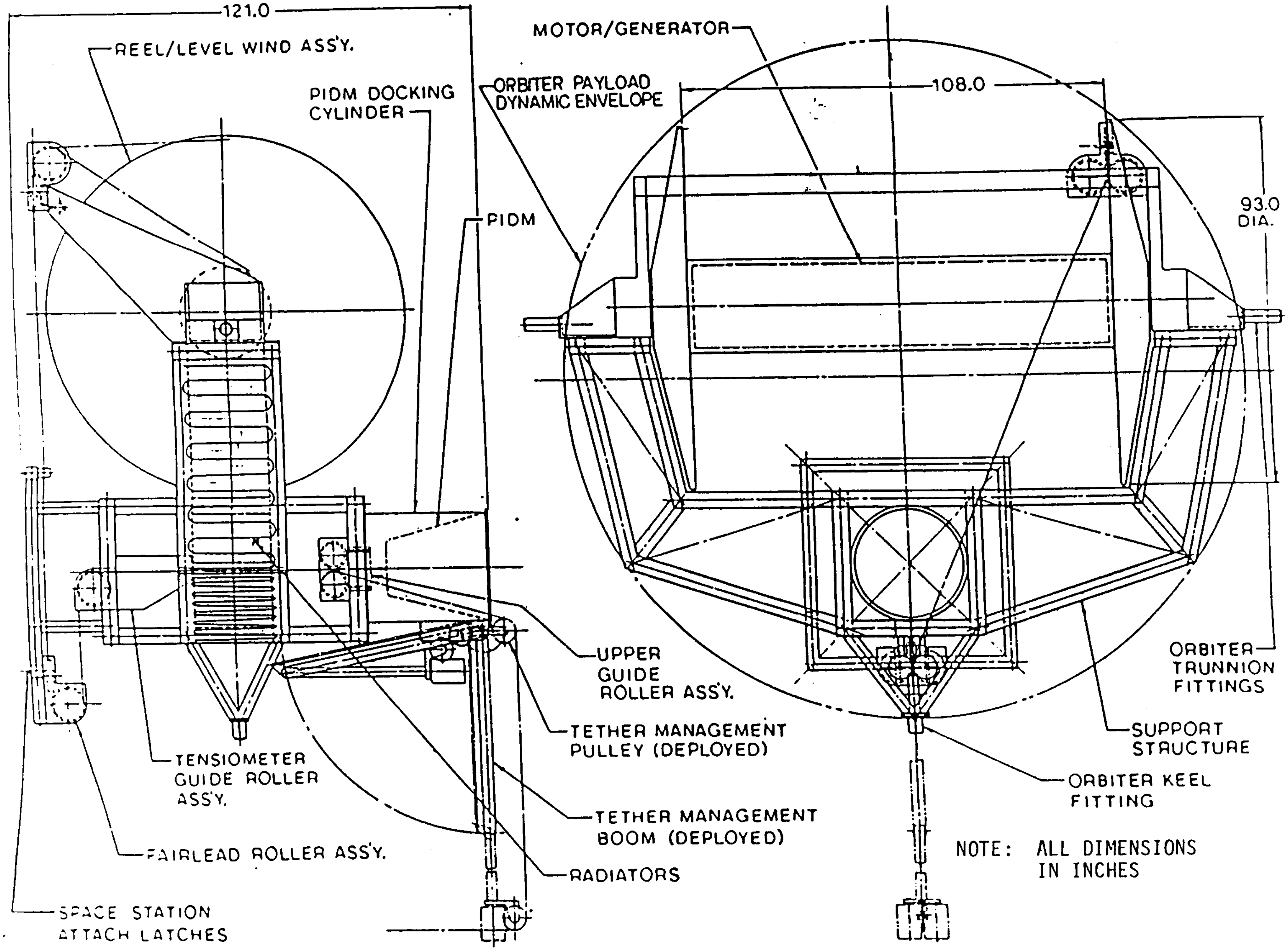

FIG. 10 OTV DEPLOYER D-150 KM OF TETHER

Configuration D has the largest reel size that will fit into the Shuttle cargo bay with the reel positioned laterally, which results in the shortest cargo bay length requirement (3.1 M). If a larger reel is required, to accommodate a stronger tether for example, it will have to be positioned lengthwise in the cargo bay and will require more cargo bay length. A significant increase in tether mass would result in a total deployer mass approaching the cargo carrying capability of the Shuttle making the increased cargo bay length requirement academic.

3.3 Deployer Installation on Space Station. The dual keel Space Station is shown in Figure 11 with the Shuttle docked to one of the modules. The tether leads to the deployer as it will appear prior to Shuttle deployment for deorbit. The deployer is shown attached to the center cube of the lower horizontal boom for downward deployment operations. The deployer would be attached to the center cube of the upper horizontal boom for OTV deployment. These attachment locations result in forces that exceed the buckling strength of the compression members of the truss by a factor of more than two with the current Space Station structural member sizing. If these deployment locations are selected, the size of the compression members must be increase or, as shown in Figure 11, tension members must be added to reduce the bending moment on the horizontal booms. The present truss members are 2.00 in. O.D. x .06 in. wall thickness graphite epoxy tubes. These members must be increased to 5 in. O.D. x .125 in. wall thickness to support these high compression loads. If this change is made to both the upper and lower horizontal booms, the structural weight of the Space Station will increase by 290 kg. The addition of tension reinforcing members would increase the weight by only 34 kg. Another option is to place the deployer at the end of the vertical keel and allow tether tension loads to be reacted directly into one of the twin keel trusses.

Regardless of deployer location, tether forces will cause the Space Station to be gravity stabilized in an attitude dictated by the position of the deployed mass. The Space Station attitude will be changing as the deployed mass librates both in the orbit plane and out of plane. Since these librations are unavoidable, it would appear that the ideal location for the deployer is in line with one of the twin keels, thus avoiding the need to add structure to the Space Station. This location will cuase the Space Station to roll about the velocity vector up to about 18 degrees. This temporary altitude change should not cause any greater problem than the unavoidable in-plane librations of up to about 30 degrees. Locating the deployer at the end of the vertical keel also avoids interference between the Shuttle vertical tail and the tether for all docking locations.

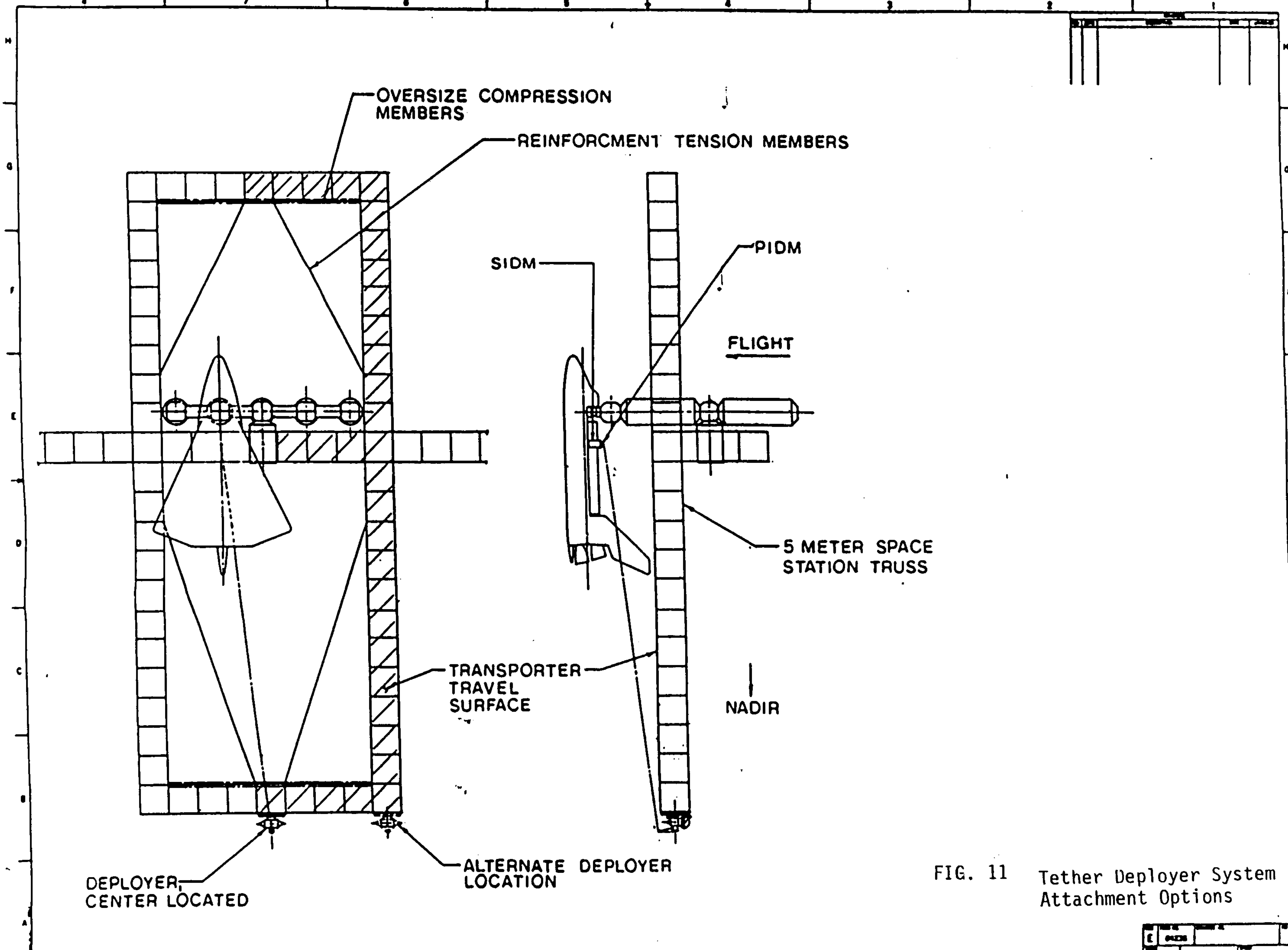

FIG. 11 Tether Deployer System Attachment Options

4.0 COST BENEFITS

4.1 Cost Model and Approach. The cost model developed during this study, Selected Applications Cost Model (STACOM), calculates all phases of the program costs using the technical description of the tether deployer system and the operational requirements. Typical inputs to the model include:

- o Deployer component weights;
- o Complexity factors for components and structures;
- o Operational time lines;
- o Intravehicular activity (IVA) and extravehicular activity (EVA) requirements;
- o Mean Time Between Failure (MTBF) values for hardware components;
- o Supporting program data/cost impacts;
- o Shuttle transportation limitations/capabilities.

The model sums the costs by program phase and hardware element to produce the cost for each Work Breakdown Structure (WBS) element. This model creates cost estimates based upon extensive historical cost data contained in the Martin Marietta Cost Analysis Data Base (CADB). Cost Estimating Relationships (CER) developed from Martin Marietta programs such as Tethered Satellite System (TSS), Viking and Titan as well as from other sources (Space Station and SAMSO Unmanned Spacecrafter) were used to estimate the costs of the STAIS tether deployer system.

4.2 Cost Benefits Summary. The STACOM program was used to develop program costs, calculate the Life Cycle Costs (LCC), determine the net benefits of the tether operations, evaluate competing configurations and operational scenarios, perform sensitivity analyses, and provide funding requirements by WBS and by year. All costs are presented in Constant Fiscal Year (CFY) 1987 dollars.

Costs were assessed for the 4 configurations (both singularly and in combinations) discussed in Section 3.0 and benefits determined for the 5 operational scenarios identified in Section 2.0. The results are summarized in Table II which identifies the number of tethered Shuttle, OTV and Wast Module deployments plus non-tethered Shuttle visits; the deployer system costs through development and fabrication of the flight hardware; Life Cycle Costs (LCC); net benefits relative to non-tethered Space Station operations at both optimum altitude (Case II) and at 463 km (Case I) and; benefit to cost ratio (B/C) also relative to non-tether Cases I and II.

The data on Table II show that the scenario selected has more influence on the net benefits available than the configuration selected. The recommended approach, i.e. Configuration D and scenario Case III/V (Optimum variable altitude for STS and OTV launches) yields the maximum net benefit ($1.89B) with a relatively high B/C of 2.8 (both relative to the optimum non-tether altitude (Case II)). The B/C is an indication of risk. If B/C approaches 1.0, any uncertainty in costs or benefits could completely erode the net benefits. With a B/C of 2.8 risk of not achieving significant net benefits is very low.

Table II Tether System Options Costs, Operations and Benefits Summary

Configuration Options	Space Station Operational Scenario 11 Yrs Operation begin 1994	STS Flights and Number of TDS operations in 11 Yrs STS	ADDL [1] NT STS	WM	OTV	Total [2] Deployer System Cost ($M) [5]	LCC ($M) [5]	Net Benefits [3] ($M) Compared to NT VAR	NT 463km	B/C Ratios [4] NT VAR	NT 463km
A	11 Yrs OPS at Tethered Optimum Variable Altitude	44	99	44		100	310	1274	2031	5.1	7.6
B		44	99	44		91	285	1299	2056	5.6	8.2
C		44	99			85	177	1274	2032	8.2	12.5
D		44	99	44		115	362	1221	1978	4.4	6.5
A → D	5 Yrs OPS at Teth. Var. Opt. Alt. And 6 Yrs OPS at Constant 463 km Alt.	72	71	44	48	143	921	757	1595	1.8	2.7
B → D		72	71	44	48	134	905	772	1611	1.9	2.8
C → D		72	71	24	48	128	863	754	1593	1.9	2.8
D		72	71	44	48	115	843	834	1672	2.0	3.0
A → D	5 Yrs OPS at Teth. Var. Opt. Alt. And 6 Yrs OPS at Combined Var. Alt. (for OTV OPS)	116	27	44	48	143	1122	1813	2645	2.6	3.4
B → D		116	27	44	48	134	1107	1828	2660	2.7	3.4
C → D		116	27	24	48	128	1065	1810	2642	2.7	3.5
D		116	27	44	48	115	1045	1890	2722	2.8	3.6
D	6 Yrs (99 - 04) at Combined Var. Alt	96	7	24	48	115	995	1439	1964	2.4	3.0
D	6 Yrs (99 - 04) at Constant 463 km. Alt	52	51	24	48	115	793	383	914	1.5	2.2

1. Additional non-tethered STS flights.
2. Hardware only - no transportation, installation or operations (equivalent to total phase C/D program cost).
3. Net Benefits = (Gross Benefits - Life Cycle Cost (LCC)). Costs are presented versus non-tethered (NT) variable SS altitude operations and 463km operations.
4. Benefits to Cost Ratio:
   B/C = (Net Benefits / LCC) + 1.
5. All costs in Constant Fiscal Year (CFY) 1987 Dollars.
6. TDS = Tether Deployer System.

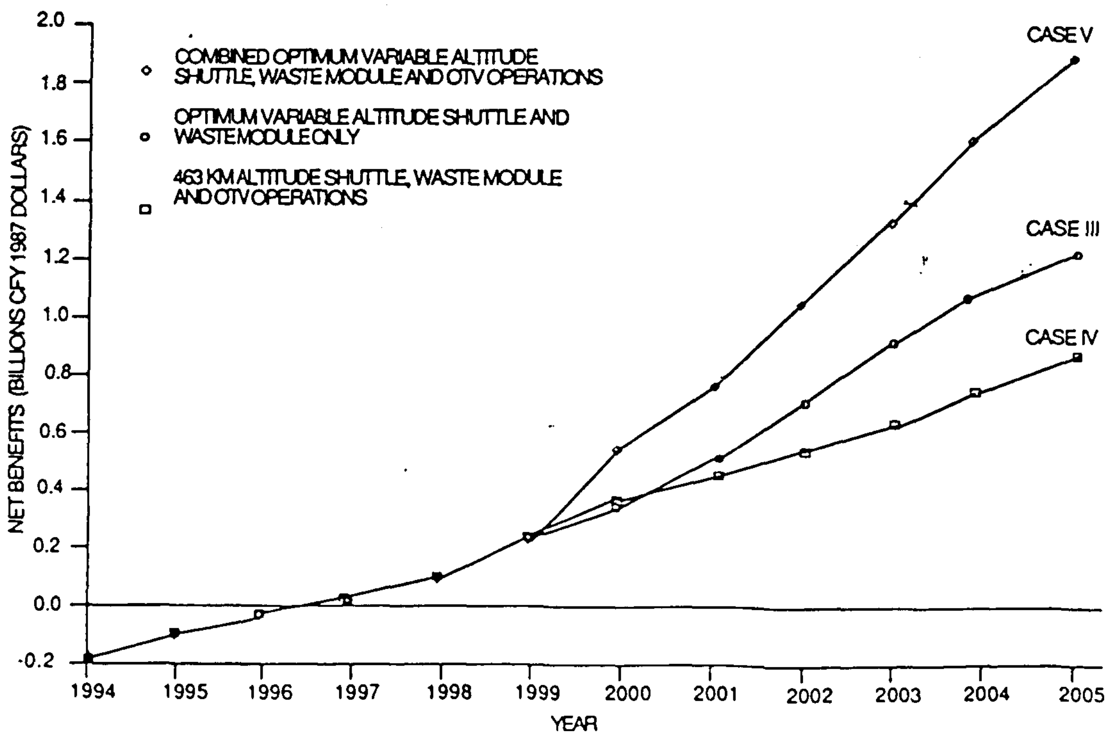

Figure 12 Net Benefits For Tether Deployer Operations

If reducing the Space Station altitude to the levels required for optimum tether operations (305 to 370 km) is not acceptable for other considerations (e.g., more severe atomic oxygen environment, or acceleration from drag) $914M in net benefits can be reaped by deploying Shuttles and OTV's with the Space Station at a nominal altitude of 463 km.

Figure 12 presents the net cost benefits (relative to Case II) accumulated as a function of year for Configuration D. These curves show that the initial investment (including transportation to the Space Station) of $175M is recovered in about 2.5 years. In 1999, when the OTV becomes operational, the choice of three scenarios is available. Continuing with Case III results in a net benefit of $1.22B after 11 years. Incorporating Case V results in $1.89B worth of net benefits while Case IV provides $834M in cost benefits.

5.0 CONCLUSIONS

The following conclusions may be drawn from the results of the STAIS Phase III study:

A. The use of tether assisted launches of Shuttles and OTV's from the Space Station result in net increases in effective cargo weight, compared to the optimum non-tether approach (Case II), varying from 15,000 kg in 1994 (Case III), to 89,100 kg in 2003 (Case V).

B. The maximum benefits (89,100 kg) result from the use of tethers for launching both Shuttles and OTV's from the optimum variable altitude, (Case V). This approach requires the largest number of tether operations (up to 30/year) and results in more frequent disruption of the Space Station altitude, attitude and microgravity environment.

C. Potential net cost benefits over the 11 year period range from $1.3 billion for the Space Station operating at the optimum variable altitude (Case III) for 11 years to $1.9 billion for Case V, launching both Shuttles and OTV's from the optimum variable altitude.

D. Continuing the optimum variable altitude Shuttle deorbits over the 11 year period (Case III) is more cost effective than returning to 463 km when the OTV becomes operational in 1999 and using tether assisted launches of both STS and OTV (Case IV). This approach also allows the use of smaller deployment hardware and fewer tether operations; 4 per year without waste disposal or 8 per year with waste disposal.

E. The cost benefits are much more dependent upon the operational scenario selected than on the hardware configuration used to implement that scenario.

F. If Space Station operations are restricted to altitudes near the 463 km currently planned, net benefits of $914 million are available by using tether assisted OTV and Shuttle launches starting in 1999 (Case IV).

G. Tether replacement frequency is the most sensitive parameter effecting costs, particularly at the lower numbers of tether uses. Increasing tether strength in order to assure at least 20 uses appears to be cost effective.

H. Operational impacts to the Space Station such as acceleration levels, attitude variations and orbit perturbations are inherent to tether applications discussed in this report. Overall strategy for tether usage must consider the compatibility aspects for other Space Station users.

6.0 RECOMMENDATIONS

6.1 Configuration Recommendation. We recommend implementation of Configuration D because it provides maximum versatility at a moderate increase in initial cost. This study has shown that the operational scenario has much more influence on net cost benefits than the implementing hardware and Configuration D supports all scenarios evaluated. The excess capability available with this configuration during the first five years of operation could be used to: (1) increase tether lifetime and reduce recoil by using a large safety factor, (2) gain operational experience with all subsystems operating with large safety margins, and (3) possibly reduce Shuttle deployment time.

6.2 Recommendations for Future Activities. The following studies, test, and development activities are recommended in order to facilitate implementation of the tether deployment system on Space Station:

A. Work closely with the Space Station project to coordinate requirements and operations.

B. Perform test and analyses to develop design and reuse criteria and inspection techniques to assure adequate tether lifetime.

C. Continue analyses and initiate testing to demonstrate slack tether response following payload release and/or a tether break.

D. Perform studies leading to a flight demonstration of angular momentum transfer and tether dynamics.

E. Automate performance benefits analysis and couple it to the cost model (STACOM) developed during this study.

F. Initiate preliminary design studies leading to development of space qualified motor/generator/reel assemblies with up to 300 horsepower.