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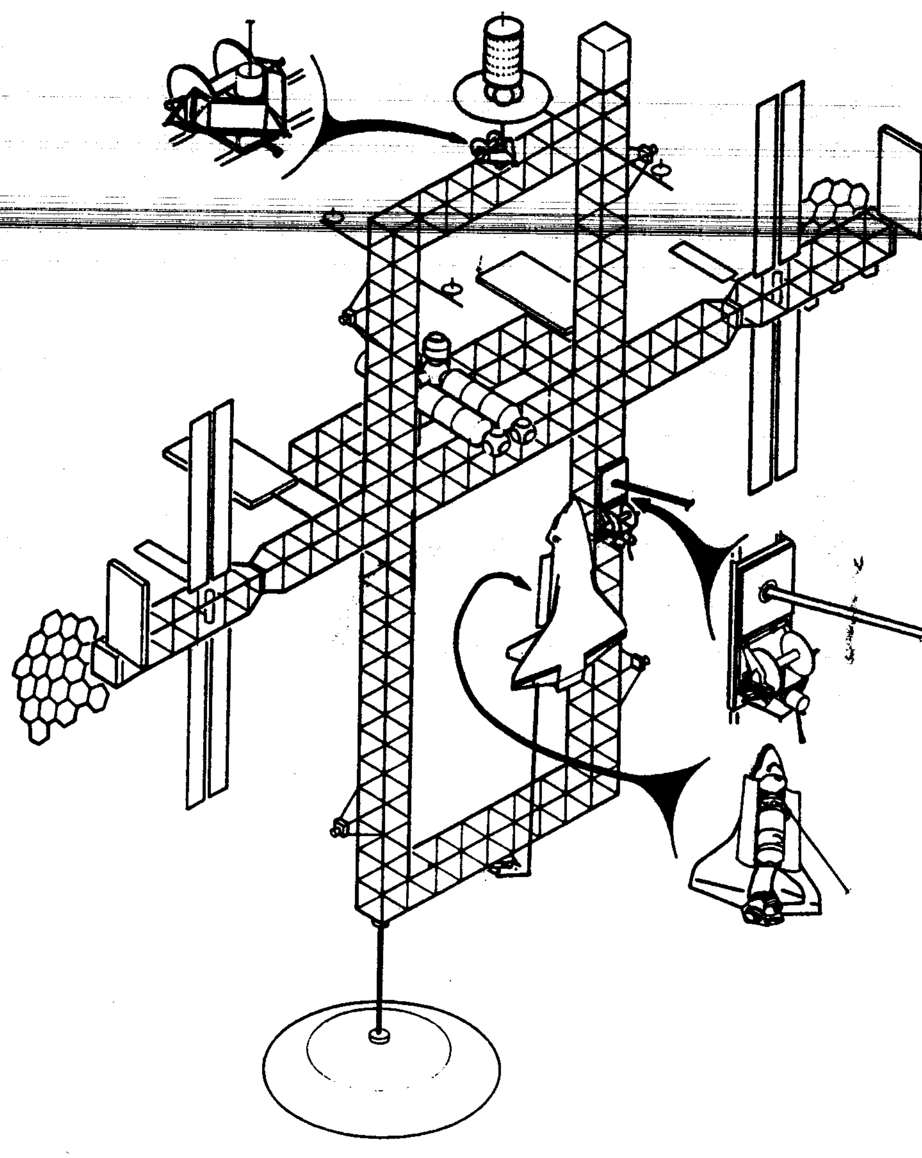

MARTIN MARIETTA

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VOLUME II

FINAL REPORT

STUDY OF SELECTED TETHER APPLICATIONS IN SPACE

PHASE III

CONTRACT NAS8-36616

SEPTEMBER 1986

BY

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FOR

MARSHALL SPACE FLIGHT CENTER

HUNTSVILLE, ALABAMA

FOREWORD

The study was completed 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 deployment dynamics analysis.

This Final Report 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) Items DR-4 and DR-6. The study was accomplished under the technical direction of Mr. James K. Harrison, Marshall Space Flight Center, Huntsville, Alabama.

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ASE	-	Aerospace Support Equipment
B	-	Billion
CADB	-	Cost Analysis Data Base
CCTV	-	Close Circuit Television
C/D	-	Phase C plus Phase D program efforts
CER	-	Cost Estimating Relationship
CFY	-	Constant Fiscal Year
COTS	-	Commercial Off The Shelf hardware
DDT&E	-	Design, Development, Test & Evaluation
DPD	-	Data Procurement Document
DR	-	Data Requirement
DTC	-	Design To Cost
E	-	Energy dissipated or required by SS tether operations (kwh)
ET	-	External Tank
EVA	-	Extra Vehicular Activity
G&A	-	General & Administrative
GEO	-	Geosynchronous Equatorial Orbit
GFE	-	Government Furnished Equipment
GFP	-	Government Furnished Property
GSE	-	Ground Support Equipment
hr	-	Hour
I&A	-	Installation & Assembly
In	-	Inches
IOC	-	Initial Operational Capability
IVA	-	Intra Vehicular Activity
JSC	-	Johnson Spacecraft Center
kg	-	Kilogram
km	-	Kilometer
kw	-	Kilowatt
kwh	-	Kilowatt hours
LCC	-	Life Cycle Cost
LVLH	-	Local Vertical Local Horizontal attitude control mode for the Orbiter.

LIST OF ABBREVIATIONS (Continued)

M	-	Million
MCA	-	Motor Controller Assembly
MISC	-	Mission Integration Support Conrtract
mm	-	Millimeter
MMDA	-	Martin Marietta Denver Aerospace
MMES	-	Martin Marietta Energy Systems
MPS	-	Meters per second
MRMS	-	Mobile Remote Manipulator System
MSFC	-	Marshall Space Flight Center
MTBF	-	Mean Time Between Failure
N	-	Newtons of Force or Number of Shuttle visits to SS
NASA	-	National Aeronautics & Space Administration
nmi	-	Nautical mile (6076 ft.)
N_R	-	Number of Shuttle visits involving reboost of SS
NT	-	Non-tethered
O.D.	-	Outside diameter
OMS	-	Orbital Maneuvering System
OMV	-	Orbital Maneuvering Vehicle
OSCRS	-	Orbital Spacecraft Consumables Resupply System
OTV	-	Space-Based Orbital Transfer Vehicle
PA	-	Product Assurance
PIDM	-	Payload Interface Deployment Module
PM	-	Program Management
RCS	-	Reaction Control System
R&T	-	Research & Technology
RBAR	-	Direction away from the Space Station along the radial direction
SAMSO	-	Space And Missile Systems Organization
sec	-	Second
SE&I	-	Systems Engineering & Integration
SF	-	Safety Factor
SIDM	-	Shuttle Interface Deployment Module
SS	-	Space Station
STACOM	-	Selected Tether Applications Cost Model
SSTDS	-	Space Station Tether Deployer System
STAIS	-	Selected Tether Applications In Space
STS	-	Space Transportation System
TBD	-	To Be Determined
TMB	-	Tether Management Boom
TMP	-	Tether Management Pulley
TSS	-	Tethered Satellite System
UV	-	Ultra violet
Vbar	-	Direction away from the Space Station along the orbital velocity vector.

LIST OF ABBREVIATIONS (Continued)

WBS	-	Work Breakdown Structure
W/C_DA	-	Ballistic coefficient
$\overline{W}$	-	Effective cargo weight delivered to the Space Station (considers cargo delivery weight, OMS propellant scheduled, OTV propellant saved, and SS reboost propellant required/saved, as applicable) associated with Shuttle flights occuring when the SS is reboosted in altitude. (Tether and non-tether cases)
W_{CE}	-	Cargo weight delivered by extra Shuttle flights, associated with Shuttle visits to the SS between reboosts.
$\Delta\overline{W}$	-	Effective cargo weight increase compared to alternate approach.
$\Delta W_{P_{OMS}}$	-	OMS propellant scavenged (storable bipropellant)
ΔW_{PR}	-	Space Station propellant (Hydrazine) required for reboost.
ΔWP_{OTV}	-	OTV propellant saved (cryogens)
yr	-	Year
Δ	-	Incremental change (e.g. velocity, propellant, etc.)
Ω	-	Mean angular rate of orbital motion about earth center.

1.0 INTRODUCTION

This report covers the results of a Phase III study of two Selected Tether Applications in Space (STAIS); deorbit of a Shuttle and launch of an OTV, both from the Space Station using a tether. In an earlier Phase II study the following five concepts were studied:

- A2 Tether Deorbit of Shuttle from Space Station
- B Tethered Orbit Insertion of a Spacecraft from Shuttle
- C Tethered Platform Deployed from Space Station
- E2 Electrodynamic Tether as an Auxiliary Power Source for Space Station
- F Tether assisted launch of an OTV Mission from Space Station

As stated above, Concepts A2 and F were selected for this Phase III activity. 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 has been on the cost model and the cost benefits analyses with the other tasks worked to the depth required to support these two objectives.

Several significant changes in Space Station configuration between Phase II and Phase III had a profound effect on the configuration and operational considerations. Changing from the power tower to the dual keel Space Station configuration rendered the dual deployer concept of Phase II impractical. Fortunately, a Mobility System was created for moving components over one face of the dual keep Space Station making it possible to use a single deployer for both OTV and Shuttle launches.

Key features of the performance analysis were to identify the net increases in effective Shuttle cargo capability if tethers are used to assist in the deorbit of Shuttles and the launching of OTV's from the Space Station and to define deployer system designs required to accomplish these tasks. As was shown in the Phase II study, a balance must be established between the 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 as the mechanism to remove momentum from the Space Station during the first five years. The performance analysis identified optimum variable altitudes to achieve this balance over the range of Space Station mass and drag area and over 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 be used to deorbit the Shuttle from a maximum altitude of 370 km to a full capability deployer system (weighing 11,113 kg) that can deploy the OTV with up to 9,072 kg of payload and using 150 km of tether have been designed and are discussed in Section 4 (Page 56).

Waste disposal is a concern for Space Station operations and tether deorbit of waste is a leading candidate for solving this problem. All tether deployer designs except the smallest (Configuration A) have the capability of deorbiting waste and the associated cost benefits are reflected in the cost analysis (performance benefits are negligible). Once the tether length is increased to accommodate waste disposal, a few additional kilometers of tether will also allow External Tank (ET) deorbit. Benefits were not assessed for ET deorbit because no specific mission was identified; however, the potential for scavenging residual propellants from the ET and the momentum available from deorbiting the ET present significant possibilities of future benefits.

The Shuttle Interface Deployment Module (SIDM) and the Payload Interface Deployment Module (PIDM), defined in Phase II, are not shown in detail in this report. The SIDM has been simplified in that the sensors and cold gas systems have been deleted since it will always be used in combination with the PIDM for Shuttle deorbit. The functions of the SIDM are to provide a structural interface between the PIDM and the Shuttle, to scavenge OMS propellant from the Shuttle during tether deployment and transport scavenged OMS propellant to the Space Station storage tanks. The PIDM provides the sensors and cold gas systems needed for control during tether deployment and retrieval.

Operational scenarios, including timelines, for both tethered and non-tethered Shuttle and OTV operations at the Space Station were evaluated. The proximity operations for deploying the Shuttle with the tether system are compared to the approach currently planned for non-tethered operations.

A summary discussion of the Selected Tether Applications Cost Model (STACOM) and the results of the cost benefits analysis are presented in Section 5 (Page 70). The users guide for the cost model is presented under separate cover. (Ref. 1).

Several critical technologies needed to implement tether assisted deployment of payloads such as the Shuttle and the OTV from the Space Station are discussed in Section 7 (Page 94).

Sections 8 (Page 96) and 9 (Page 97) present the conclusions and recommendations of this study.

2.0 PERFORMANCE ANALYSIS

During the Phase II effort (Aug. 1984 - Feb. 1985) significant performance benefits of tethered Shuttle and OTV operations from the Space Station (SS) were identified (Ref. 2). The benefits were derived from propellant savings (OMS, OTV, and small amounts of SS station keeping propellants) and resulted in a projected savings of about 10 Shuttle flights over a 10 year period.

By the time this Phase III study began in October 1985 the Space Station baseline altitude had been reduced from 500 km (270 nmi) to 463 km (250 nmi) and the OTV flight readiness date had been moved from 1995 to 1999 (Ref. 3). As a result of these two changes a variable Space Station altitude scenario was developed for tether operations before 1999 and the arrival of the OTV to provide a momentum balance using atmospheric drag and tethered Shuttle deployments. This approach significantly increases the Shuttle cargo weight delivered since the Space Station operates at appreciably lower altitudes than the baseline. This direct effect on Shuttle cargo weight has also been added to the Space Station benefits, as will be discussed.

The following subsections refer to 5 cases of interest that cover the 11 year period from 1994 - 2004, dividing it up into the 5 year period (1994-1998) before OTV arrival on the Space Station followed by the 6 year period (1999-2004) with the OTV present. These cases are defined as follows:

Case I — Refers to the Space Station operating near the current baseline altitude of 463 km (250 nmi) without tether operations. (1994-2004).

Case II — Refers to the Space Station operating at lower variable altitudes to maximize the annual performance benefits without tether operations. (1994-2004).

Case III — Refers to the Space Station operating at lower variable altitudes to maximize the annual performance benefits with tethered Shuttle deployment operations. (1994-2004).

Case IV — Refers to the Space Station operating in a balanced momentum mode about the current baseline altitude of 463 km with tethered Shuttle deployments and tethered OTV launch operations. (1999-2004).

Case V — Refers to the Space Station operating in a balanced momentum mode about selected variable altitudes to maximize the annual performance benefits with tethered Shuttle deployments and tethered OTV launch operations. (1999-2004).

In all of the above cases, Space Station aerodynamic drag is considered in the momentum balance and orbit station keeping propellant requirements are determined and included in the analysis.

Three basic Space Station tether operational scenarios are considered for the 1994-2004 time 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 Space Station to 463 km and apply Case IV (tethered OTV launches) and, 3) apply Case V (tethered OTV launches at variable altitude). Effective Shuttle cargo weight gains are presented for all three options.

2.1 General Approach and Assumptions. Using the IOC 1994 Space Station as a starting point for tether operations, an eleven year period (1994-2004) was selected for study. This represents the nominal length of a solar cycle and covers the full variation in atmospheric drag expected at Space Station altitudes. The revision 8 (low) Marshall Space Flight Center Mission Model (Ref. 3) was used to determine Shuttle transportation requirements to the Space Station and also to determine OTV launches from the Space Station during the 1999 through 2004 time period. Space Station mass (varies from 210,000 kg to 455,000 kg over the eleven year period), area, and atmospheric model data were obtained from the Martin Marietta Space Station Study team to determine orbit drag decay rates. A Space Station altitude of 463 km (250 nmi) at 28.5 degree inclination was used as a baseline with a 2-burn (hydrazine system) reboost every 90 days for station keeping (Case I). A variable altitude alternate baseline option (Case II) was also considered in the study.

A direct insertion Shuttle cargo delivery capability of 20,729 kg (45,700 lb) was assumed for the reference altitude of 463 km with a sensitivity of -26.94 kg/km for other altitudes. This information was obtained from the Martin Marietta Space Station Study Team and represents an average projection of Shuttle performance in the 1994-2004 time period. Our analysis is not sensitive to Shuttle performance since the savings in OMS propellant, OTV propellant, Space Station station keeping propellant, and shuttle cargo gains from tethered operations (compared to non-tether) are essentially independent of Shuttle performance (to the first order) due to the fact that all calculations assume the same basic Shuttle capability. In terms of financial benefits, savings from tether operations would likely increase if the cargo carrying capability (moderately optimistic projection) is reduced since anticipated direct cargo gains, OMS propellant scavenged, OTV propellant savings, and station keeping propellant savings would represent more shuttle flights saved than currently estimated.

The mass of the Orbiter at Space Station departure is assumed to be 99,750 kg (220,000 lb) in all cases and tether lengths are selected to prevent the Orbiter from descending below a 185 km (100 nmi) perigee after tether release (the final OMS deorbit burn is executed at the following apogee). Deorbit OMS propellant requirements were obtained from Phase II of the study (Ref. 2) for determination of OMS propellant scavenging benefits.

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

Using the methods and equations provided in Phase II and maximum power factors determined in Phase III (see 2.2.2), tether deployment requirements were obtained for the various scenarios and maximum conditions were determined for use in the deployer system design activity (Section 4.0). Table 2-1 summarizes the design requirements determined.

As seen in Table 2-1, if Case III (variable altitude/no tethered OTV operations) is used for 11 years the maximum Space Station altitude reached at Shuttle deorbit is 370 km. The corresponding maximum tether length required for Shuttle deployment is 33 km with a maximum tension of 10,676 N and maximum power dissipation of 25 kw required. 59 km of tether is required to immediately deorbit the 3,175 kg of waste, while slightly more tether (63 km) is required to deorbit the 31,750 kg external tank. Note that for Case III maximum tether tension is determined by Shuttle deployment and maximum tether length and power (33 kw) are determined by ET deorbit.

If tether operations were switched to the current altitude (Case IV) in 1999 tether length required would increase to 52 km, 73 km, and 79 km for Shuttle deployment, waste disposal, and ET deorbit, respectively. Note that for Case IV the maximum tension (15,480 N) and maximum power (56 kw) is determined by the Shuttle deployment. The maximum design conditions are determined by the OTV launch (150 km tether) with a maximum tension of 20,020 N and a maximum power of 219 kw. Design implications of these requirements are discussed in Sect. 4.0.

TABLE 2-1 TETHER DEPLOYMENT REQUIREMENTS

CASE	MAXIMUM ALTITUDE (km)	TETHER FUNCTION	MAXIMUM TENSION (N)	MAX - TETHER LENGTH (KM)	MAX POWER (KW)
III	370	STS Deployment	10,676	33	25
		Waste Disposal	1,032	59	4.3
		ET Deorbit	7,522	63	33
IV	463	STS Deployment	15,480	52	56
		Waste Disposal	1,223	73	6.3
		ET Deorbit	8,945	79	50
IV	463	OTV Launch	20,020	150	219

NOTE: Case V has conditions (altitude, tension, length, and power) intermediate to Cases III and IV for STS deployment and waste disposal, but design conditions are determined by the OTV launch as in Case IV.

2.2 Variable Space Station Altitude Analysis

2.2.1 Approach. Before OTV operations begin in 1999 atmospheric drag can be used to offset the Space Station momentum received from the tethered Shuttle deployments (Case III). For completeness and comparison in the latter years, a full solar cycle (1994-2004) was analyzed since significant Shuttle cargo delivery gains are realized because the Space Station is operating at lower altitudes. This analysis was also extended to non-tether Space Station operations to provide an equal basis for benefits comparison (Case II). Throughout the analysis the benefits of all scenarios are compared to the current fixed altitude (463 km) approach (Case I) to maintain a common baseline and are compared to each other in the summary of the performance benefits (2.4).

Shuttle deployments using tethers are scheduled for every 90 days when the Space Station is at the low point of its altitude range with the other Shuttle visits (2-15, depending on year) not involving tethers, arriving at higher altitudes. Altitude variation is based on a 90 day drag decay cycle and reboost propellant is used for orbit circularization at apogee. Space Station altitude is varied each year as required to maximize benefits.

The annual performance benefits are determined as follows:

Annual Benefit Factor:

$$\Sigma \overline{W} = 4\overline{W} + (N-4)\,W_{ce} \qquad (1)$$

where:

Effective Shuttle cargo wt.

$$\overline{W} = W_{cargo} + \Delta WP_{oms} - \Delta WP_{r} \text{ for reboost flights} \qquad (2)$$

ΔW_{Poms} = Scavenged Shuttle OMS Propellant (where applicable)
ΔWP_{r} = Space Station Reboost Propellant (hydrazine)
N = Number of annual STS visits
W_{cargo} = Actual Shuttle cargo weight delivered to Space Station
W_{ce} = W_{cargo} for extra flights
$\Sigma \overline{W}_{r}$ = Reference annual benefit factor

Effective cargo wt. increase

$$\Sigma \Delta \overline{W} = \Sigma \overline{W} - \Sigma \overline{W}_{r} \qquad (3)$$

The major influence on the selection of the optimum altitude is the atmospheric density which varies throughout the 11-year solar cycle. As shown in Figure 2-1, the average yearly atmospheric density increases up to a factor of 5 from the low density year (1999) to the highest density year (2003). Altitude loss over a given time period (eg., 90 days) is directly proportional to average density.

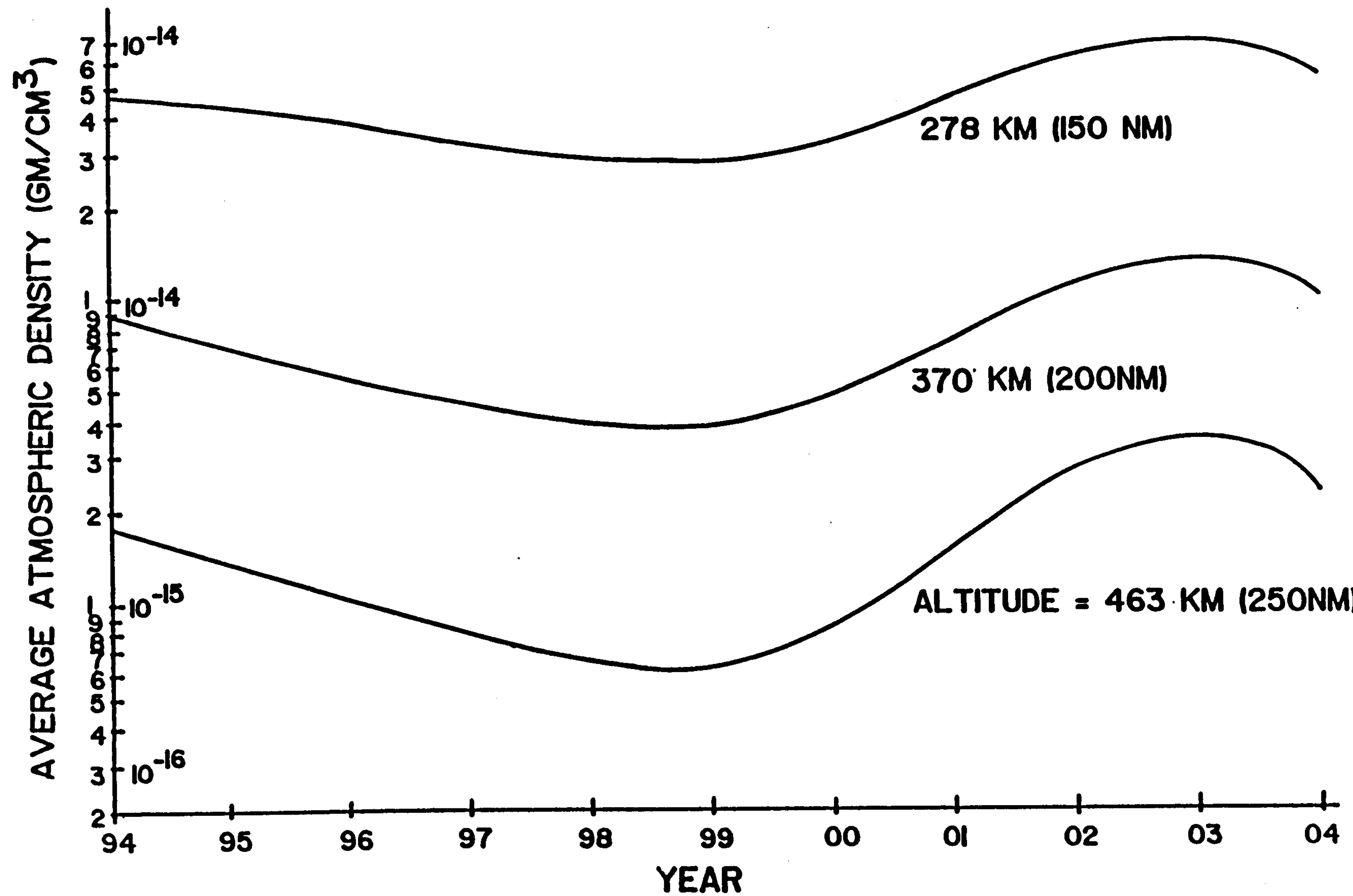


Fig. 2-1 Yearly Atmospheric Density Variations

Figure 2-2 presents the projected Space Station growth in mass (a factor of approximately 2) during the 11-year period studied and also the ballistic coefficient (W/CoA), but this effect is second order when compared to the density effect since the ballistic coefficient only increases by about 50%.

Figure 2-3 shows the resulting Space Station yearly altitude variation for the two optimum variable altitude approaches and the current altitude approach. Minimum and maximum curves for each scenario correspond to the altitude variation from reboost from Space Station propulsion (Cases I and II) or tether Shuttle deployment (Case III) and drag decay for each 90-day period. The current altitude case (463 km) has very little altitude variation and has small reboost requirements, but minimum cargo delivery weight capability (Case I). The minimum Space Station altitude is reduced to as low as 305 km (see Fig. 2-3) for the optimum tether case (minimum over 11 years) with much higher cargo delivery capability, but also higher Space Station reboost propellant requirements (Case III). The optimum non-tether case (Case II) requires intermediate altitudes as indicated. In all cases, the altitude difference between minimum and maximum corresponds to the average altitude loss by the Space Station in 90 days for the particular year, considering both yearly density and yearly Space Station mass to drag area ratio.

For completeness, the altitude variation for Case IV (discussed in 2.3.3) for the years 1999-2004 and for Case V (discussed in 2.3.3) for the years 1999 (low drag year) and 2003 (high drag year) are also shown in Fig. 2-3.

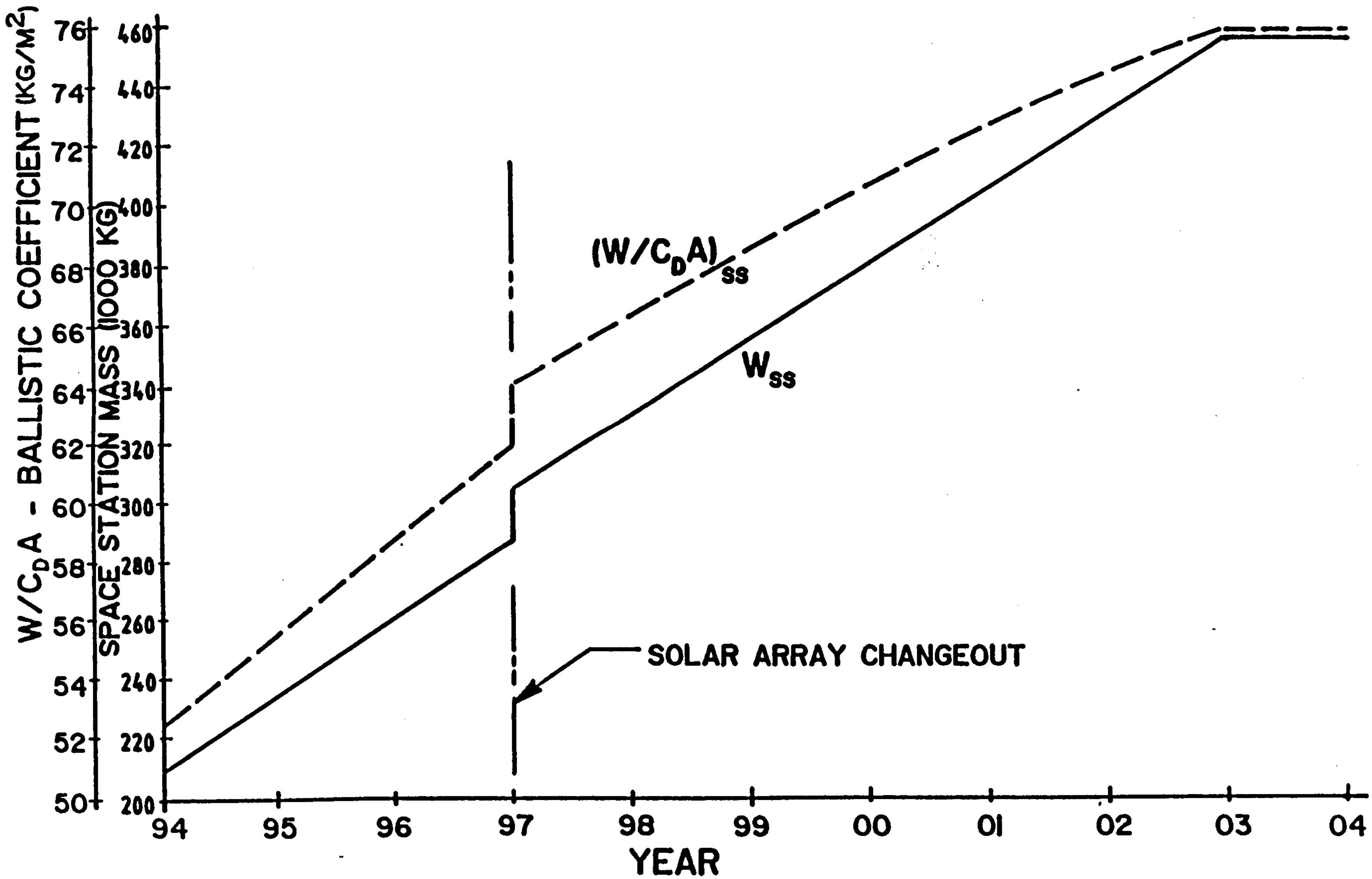


Fig. 2-2 Space Station Yearly Mass and Ballistic Coefficient Variations

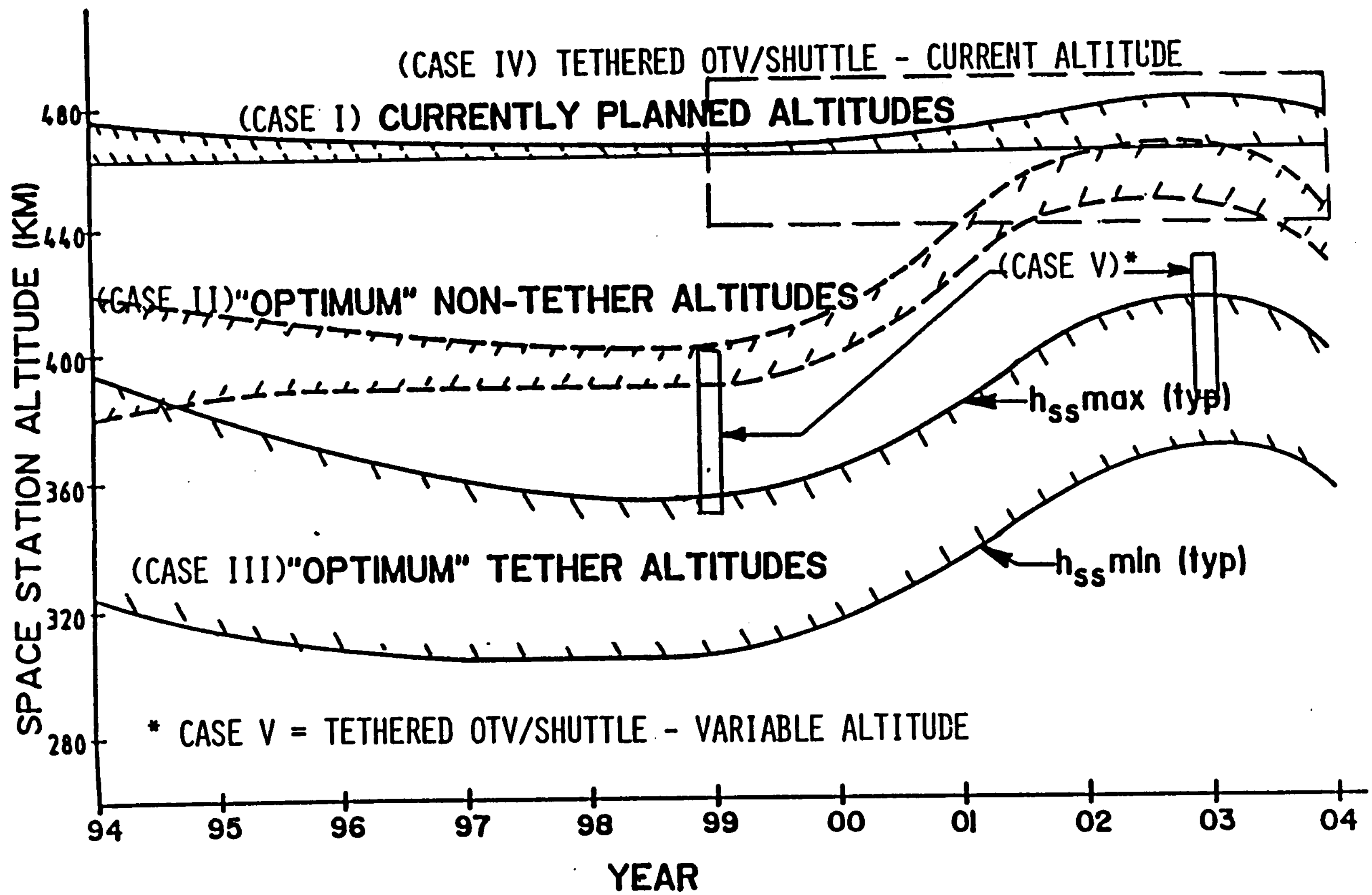


Fig. 2-3 Space Station Yearly Altitude Ranges

2.2.2 Determination Of Tether Requirements - During the Phase II study, basic tether equations were used to obtain the various orbital relationships, the tether tension, and energy requirements as a function of tether length and mass. Those equations follow.

DEFINITIONS

M_1	=	Lower Mass (Including one-half of deployed tether mass)
M_2	=	Upper Mass (Including one-half of deployed tether mass)
M_1'	=	Lower Mass (Excluding deployed tether mass)
M_2'	=	Upper Mass (Excluding deployed tether mass)
σ_M	=	Mass Density of Tether (Mass per unit length)
Ω	=	Orbital Rate of Tethered System (Radians per unit time)
$\bar{M}$	=	Effective Mass Deployed = $(M_1 M_2) / (M_1 + M_2)$
L	=	Deployed Tether Length
R	=	Radius to Point of Interest from Earth Center
λ	=	L/R_0
ν	=	M_2/M_1
P	=	$\lambda[\nu/(1+\nu)]$
Q	=	$\lambda/(1+\nu)$

Subscripts: 0 = Condition Before Tether Deployment
1 = Refers to Lower Mass Condition
2 = Refers to Upper Mass Condition
A,P = Apogee and Perigee, Respectively

EQUATIONS (4)

- $R_{A1} = R_0\,(1-P)$
- $R_{P2} = R_0(1+Q)$
- $R_{P1} = R_0\,(1-4P)/(1+3P)$
- $R_{A2} = R_0\,(1+4Q)/(1-3Q)$
- H(altitude) = R(NMI)-3444
- T (Tether Tension) = $3\,\bar{M}\,\Omega^2\,L$
- E (Energy Developed/Required) = $3\Omega^2(K_1 L^2/2+K_2 L^3/3)$

where $K_1 = M_1'M_2'/(M_1+M_2)$ and $K_2 = \sigma_M\,|M_1'-M_2'|\,/2(M_1+M_2)$

Typically, the mass of the tether is ignored for the first iteration since it is small in comparison to the end mass. After the tether is selected, the tether mass can be incorporated for a second iteration. The preceeding equations provide orbital parameters (apogee and perigee) before and after release of the end mass, maximum tether tension developed, and the energy developed during deployment and the energy required during retrieval.

To check the accuracy of the simplified equations and to obtain the maximum power requirements, computer simulations were run by the Tethered Satellite System (TSS) personnel using the Model 1B Dynamics Program (Ref. 4). Fig. 2-4 shows the computer results for a typical tethered shuttle deployment from the Space Station for an 8-hr. deployment duration. The case shown is for a 64 km tether deployment of the Shuttle from a 500 km (270 nmi) orbit, and is typical of the various tether deployments investigated. The 8 parameters are shown as a function of time (in hours) from start of deployment and are defined as follows:

L	-	Range Separation (km) between M_1, and M_2
LDOT	-	Range Rate (km/hr)
THE	-	In-Plane Libration angle (deg) - from local vertical to tether (in orbit plane)
THEDOT	-	In-Plane Libration Rate (deg/hr)
PHI	-	Out-Of-Plane Libration Angle (deg) - from local vertical to tether (out of orbit plane)
PHIDOT	-	Out-Of-Plane Libration Rate (deg/hr)
TEN	-	Tension in Tether (newtons)
POWER	-	Net Mechanical Power Delivered to Generator (watts)

The data shown in Fig. 2-4 summarizes the simulation of the tethered deployment of the Orbiter below the Space Station, including the effects of libration angle and libration angle rate as well as the dynamics of the tether. These plots reflect the current TSS control strategy for deployment.

Note that in Fig. 2-4 the tether pays out very slowly during the first 2 hrs (less than 3 km of tether) and then begins to build speed (LDOT) until a maximum of about 21 km/hr is reached after 4.6 hr, thereafter decreasing in speed until full deployment is reached. This type of control strategy keeps the in-plane libration angle (THE) well behaved and reaches a maximum of 24 deg in the first half-hour, gradually decreasing to zero in 8 hrs. Out-of-plane librations (PHI, PHIDOT) are also presented and are typically small (1-2 degrees) in the early part of the deployment, decreasing to zero in 8 hrs.

Maximum tension shown in Fig. 2-4 is within a fraction of a percent of that calculated with the use of the simplified equations (4). Maximum power developed (a function of the product of tension and LDOT) occurs at 5.2 hrs and is 3.1 times as large as the average power developed during the 8 hr deployment. To obtain maximum power from the simplified energy equation shown (4), energy is first calculated (in kwh) and average power developed is then calculated by dividing the energy by the 8 hr deployment time. Maximum power developed is calculated by multiplying average power by the factor of 3.1. This procedure gives accuracies of well within 5% compared to the simulation results, and has been used throughout the study for Shuttle deployment calculations. Motor/generator sizing is determined by adding 30% for losses to the previously calculated maximum power developed. Energy and power requirements during retrieval are calculated in a similar manner, but do not size the motor/generator since only the mass of the tether including the PIDM and SIDM (with scavenged OMS propellant) is involved. Tether requirements for the various Shuttle deployment scenarios are summarized in Section 4.0.

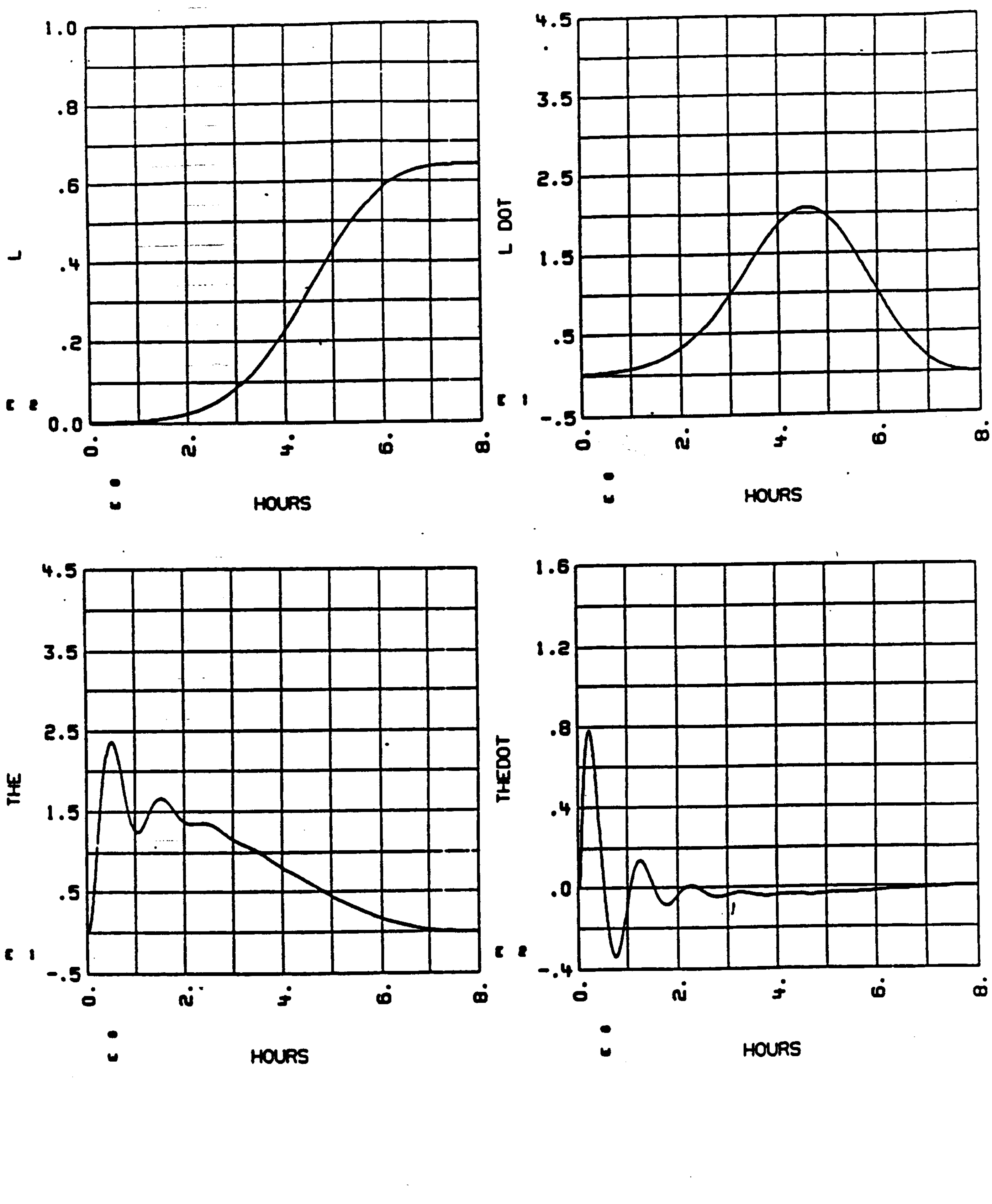


FIG. 2-4 TYPICAL TETHERED SHUTTLE DEPLOYMENT SIMULATION

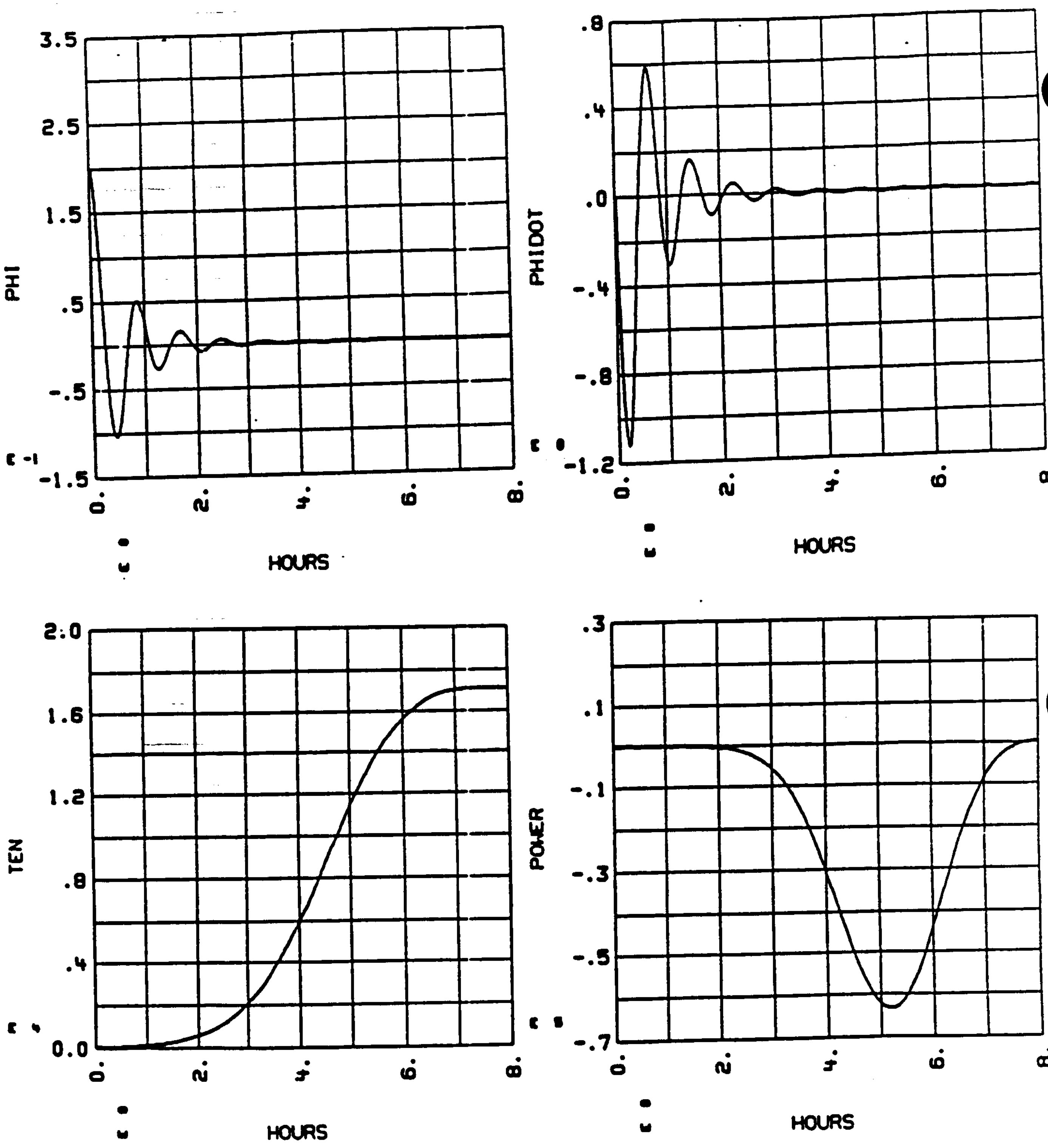


FIG. 2-4 TYPICAL TETHERED SHUTTLE DEPLOYMENT SIMULATION (CONTINUED)

2.2.3 Results of Benefits Analysis. Figure 2-5 presents a typical yearly Space Station altitude profile for the optimum variable altitude tether operation (Case III) based on an average Shuttle revisit frequency of 12 visits per year over the 11 year period. Note that 4 of the Shuttles (beginning of each cycle) are tether deployed from a minimum altitude and cause the Space Station to rise to its highest altitude for each cycle. The other 8 Shuttles arrive when the Space Station is at a higher altitude as indicated. This profile is typical, and only the total number of Shuttle visits and altitude ranges vary yearly. Tether lengths up to 33 km will handle all Shuttle deployments. Both the current fixed altitude (non-tether) and variable altitude (non-tether) approaches will have similar type profiles, but with altitude variations as indicated in Figure 2-3 (Cases I and II, respectively).

Figures 2-6 and 2-7 are presented together to show the relationship to each other as well as the basic improvements over the current approach (Case I). Figure 2-6 shows the benefit of a variable altitude (non-tether) approach (Case II) for the Space Station over the current approach and is the net result of both the cargo savings and reboost propellant increases for the 4 annual flights to reboost altitude (generally the smaller portion of the benefit) and the cargo gain associated with the other (non-tethered) Shuttle flights. Benefits for this approach vary from 5,440 kg/yr (2002) to a maximum of 25,970 kg/yr (1999), with an average yearly benefit of 13,700 kg/year (Case II over Case I) over the 11 year period.

Figure 2-7 presents the benefit of the optimum variable altitude tether approach (Case III) for the Space Station compared to the current approach (Case I). Annual benefits for the reboost flights during the first 4 years represent the larger portion of the savings, with the reverse being true for the latter 7 years as the number of Shuttle visits increase. Benefits for this approach vary from a minimum of 22,100 kg/yr (1994) to a maximum of 58,500 kg/yr (2000), with an average yearly gain of 41,200 kg/yr (Case III over Case I) over the 11 year time period. Benefits (Case III) are approximately 3 times as high as for Case II primarily because of the Shuttle cargo weight gain made possible by the lower altitudes associated with Case III.

- 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

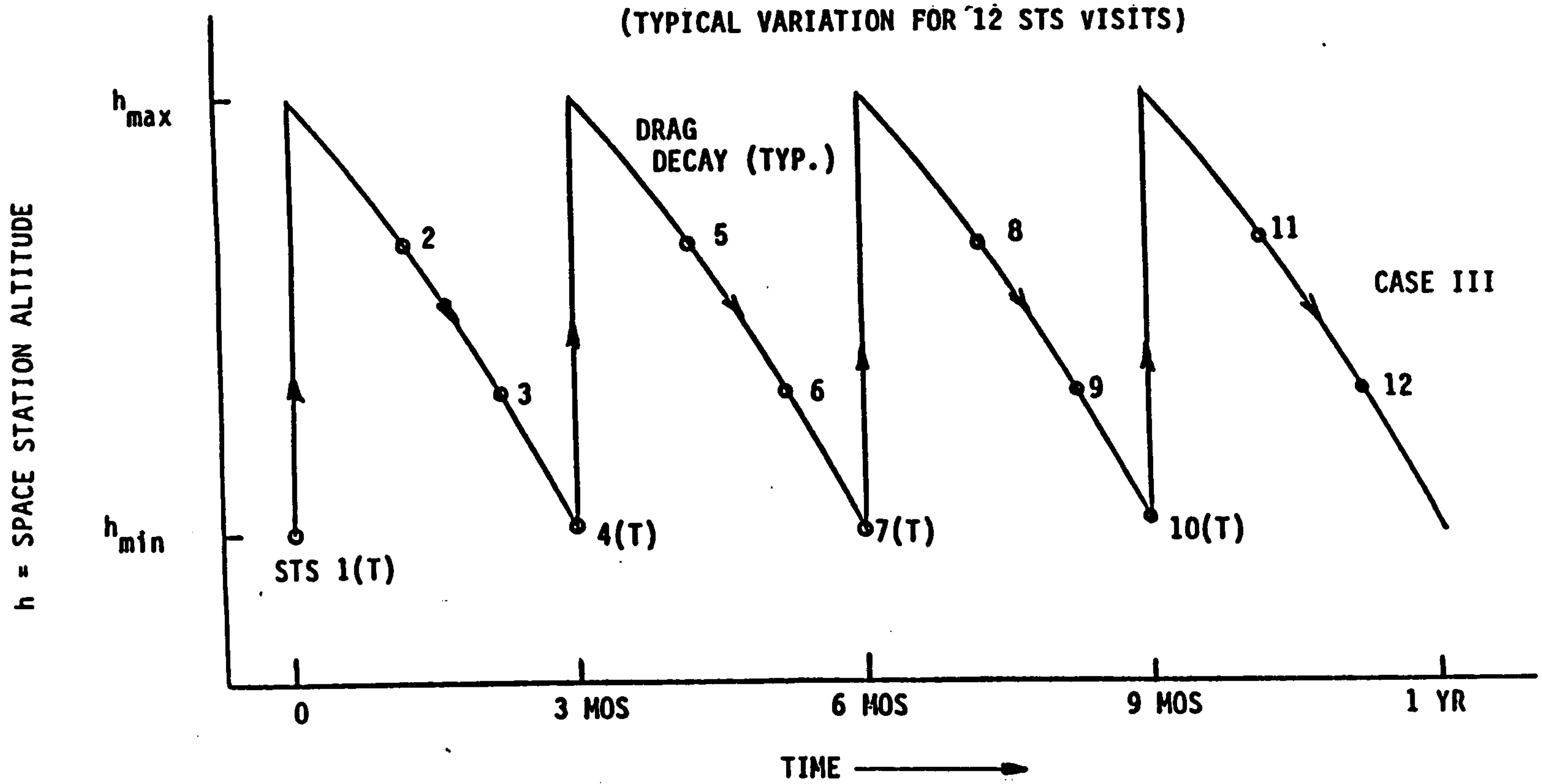


Fig. 2-5 Momentum Balance - Tethered Shuttle Variable Altitude Operations

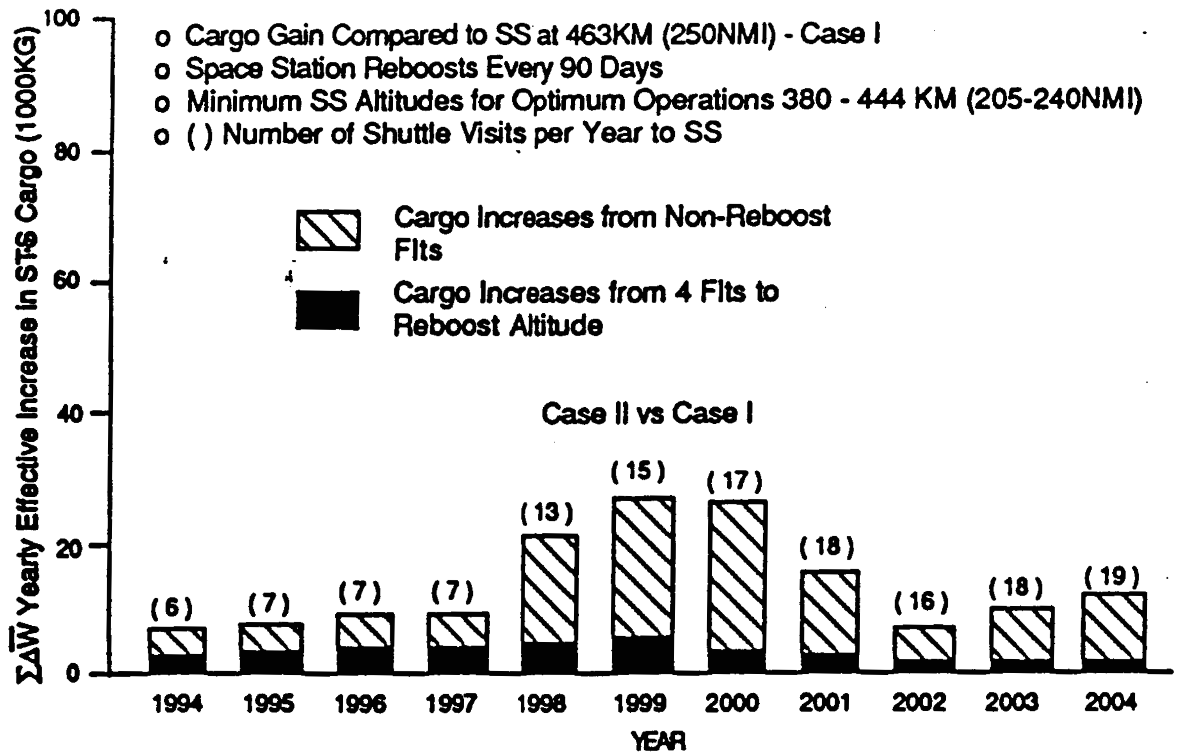


Figure 2 - 6 Benefit of Variable Altitude Operations - Non Tethered Shuttle

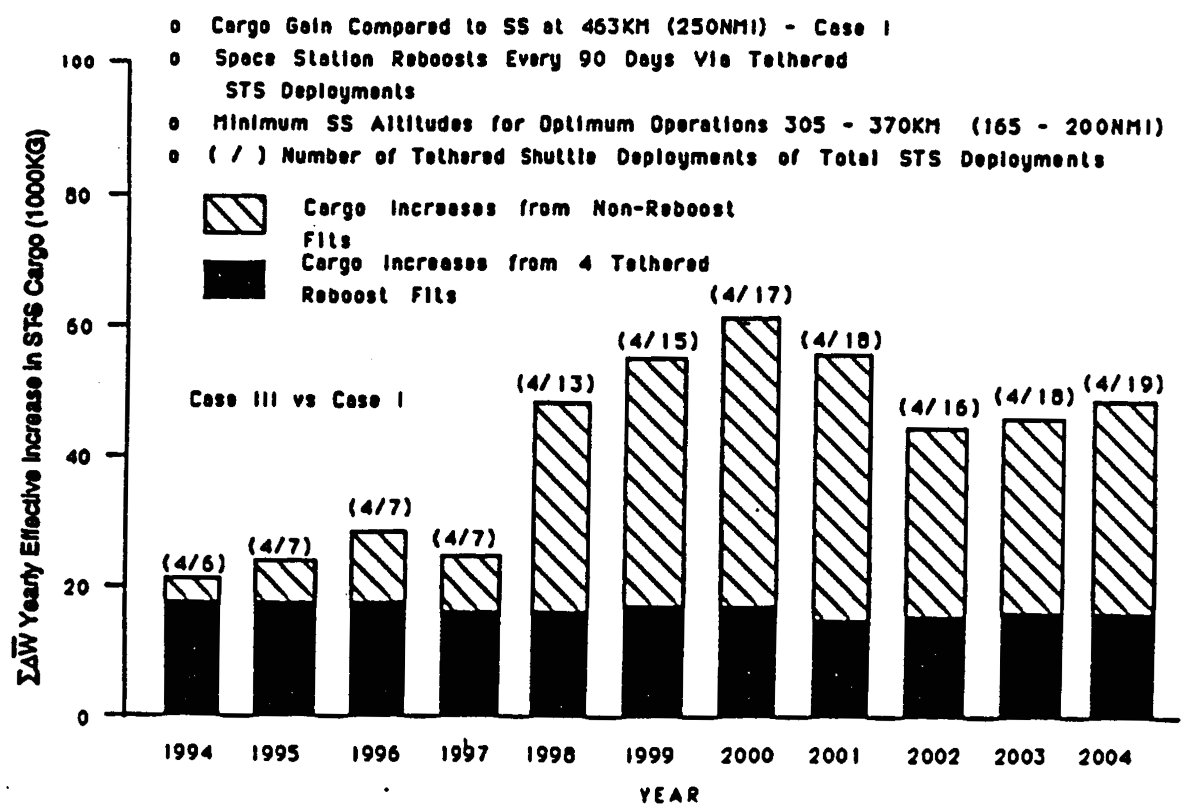


Figure 2 - 7 Benefit of Variable Altitude Operations - Tethered Shuttle

2.3 Tether Assisted Launch of OTV, 1999-2004

2.3.1 Approach. The tethered baseline approach for the overall study period (1994-2004) assumes a variable altitude scenario (Case III) for the first 5 years (1994 through 1998) with the Space Station returning to its nominal altitude of 463 km (250 nmi) for tethered OTV launches (Case IV). The benefit potential of combining a variable altitude/OTV launch scenario has also been investigated as an alternate scenario and results for years 1999 and 2003 are completed (Case V).

The Space Station is generally in an elliptical orbit (no circularization burns) after tethered Shuttle and OTV operations and altitude variations discussed are based on average values. The Martin Marietta OTV Study Team's IOC Space-Based OTV is used (Ref. 5) and is compatible with the MSFC Rev. 8 (low) Mission Model (Ref. 6). This model requires an average OTV launch rate of 8 launches per year (compared to 15-19 Shuttle visits) for the 6-year period studied, Figure 2-8 presents the OTV mission candidates which were selected by the Martin OTV Study Team from the Rev. 8 (low) Mission Model. All 48 missions are to Geosynchronous orbit, with the exception of 2 planetary missions in 1999 and 2003. Payload delivery requirements vary from 2,270 kg (5,000 lb) to 9,075 kg (20,000 lb) with payload return requirements ranging from zero to 2,040 kg (4,500 lb). A total of 103 Shuttle visits to the Space Station are indicated this time period.

The OTV design (Fig. 2-9) is the initial Space-Based Cryogenic OTV design. This design has a 13.41M (44 ft) diameter aerobrake shield and is about 10.0M (33 ft) long. The reusable stage has a burnout weight of 3,721 kg (8,204 lb) and a maximum usable propellant load of 24,573 kg (54,175 lb) with a specific impulse of 475 sec. It has the capability to deliver 9,075 kg (20,000 lb) to geosynchronous orbit and to return the stage to the vicinity of the Space Station via atmospheric aerobraking and OMV assistance. The maximum end mass associated with a tethered OTV launch (with PIDM) is 36,290 kg (80,000 lb).

OTV propellant savings were determined for tethered OTV launches upward from the Space Station for tether lengths up to 150 km. All launches are assumed to require the same energy as that required to achieve geosynchronous orbit (plane change at geosynchronous) and return (including the two planetary missions). The impulsive delta velocities used are 4,307 M/sec (14,131 fps) to achieve geosynchronous orbit and 1,965 M/sec (6,447 fps) for the return leg. Velocity allowances for losses, mid-course corrections, and orbit phasing for rendezvous with the Space Station are also incuded.

Figure 2-10 summarizes the OTV propellant savings for tethered launches up to 150 km in length compared to the baseline (no tether) approach. For the tether length of 150 km, savings of up to 2,130 kg (4,700 lb) or 8.7% can be achieved for a 9,075 kg payload launched to geosynchronous orbit from a Space Station with an average mass of 412,400 kg. Significant savings are also shown for the two missions with a return payload mass.

CANDIDATE SBOTV MISSIONS *	YEAR						ORBIT	ESTIMATED PAYLOAD WEIGHT (KG)
	99	00	01	02	03	04		
GEO. PLATFORM		1(A)				1(B)	GEO.	5445 (A) 9075 (B)
PLANETARY	1				1		PLANETARY	2270
MULTIPLE P/L DELIVERY	2	3	3	2	4	3	GEO.	5445 (UP) 910 (DOWN)
INDIV. GEO. SATS.			1				GEO.	9075
UNMANNED PLATFORM SERV.			1				GEO.	3175 (UP) 2040 (DOWN)
GEO. SERV. STATION ELEMENTS						1	GEO.	5900
DOD	4	4	4	4	4	4	GEO.	5445 - 9075
SBOTV TOTALS	7	8	9	6	9	9	48 TOTAL	
SHUTTLE VISIT TOTALS	15	17	18	16	18	19	103 TOTAL - REV. 8 (LOW)	

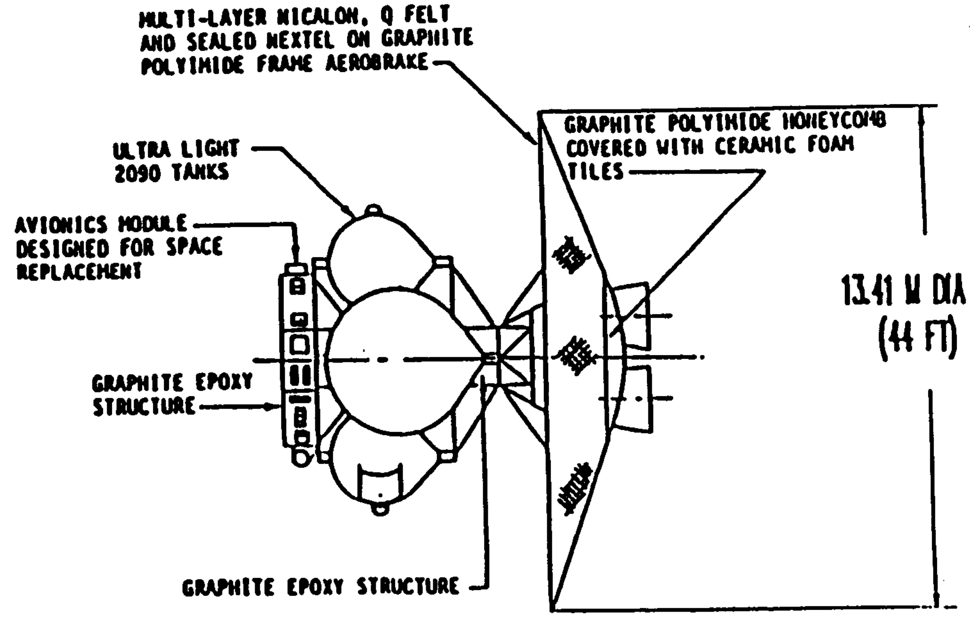
* REF. 6

Fig. 2-8 Tethered OTV Launch Mission Candidates at Space Station

W dry		3340 KG (7364 LB)
W burnout		3721 KG (8204 LB)
Wp usable		24573 KG.(54175 LB)
W initial		28295 KG (62379 LB)
Isp	=	475 SEC

DESIGNED FOR 9075 KG (20,000 LB)
GEO. DELIVERY CAPABILITY

FROM REF. 5



INITIAL SPACE-BASED CRYO OTV

Fig. 2-9 OTV Vehicle Characteristics

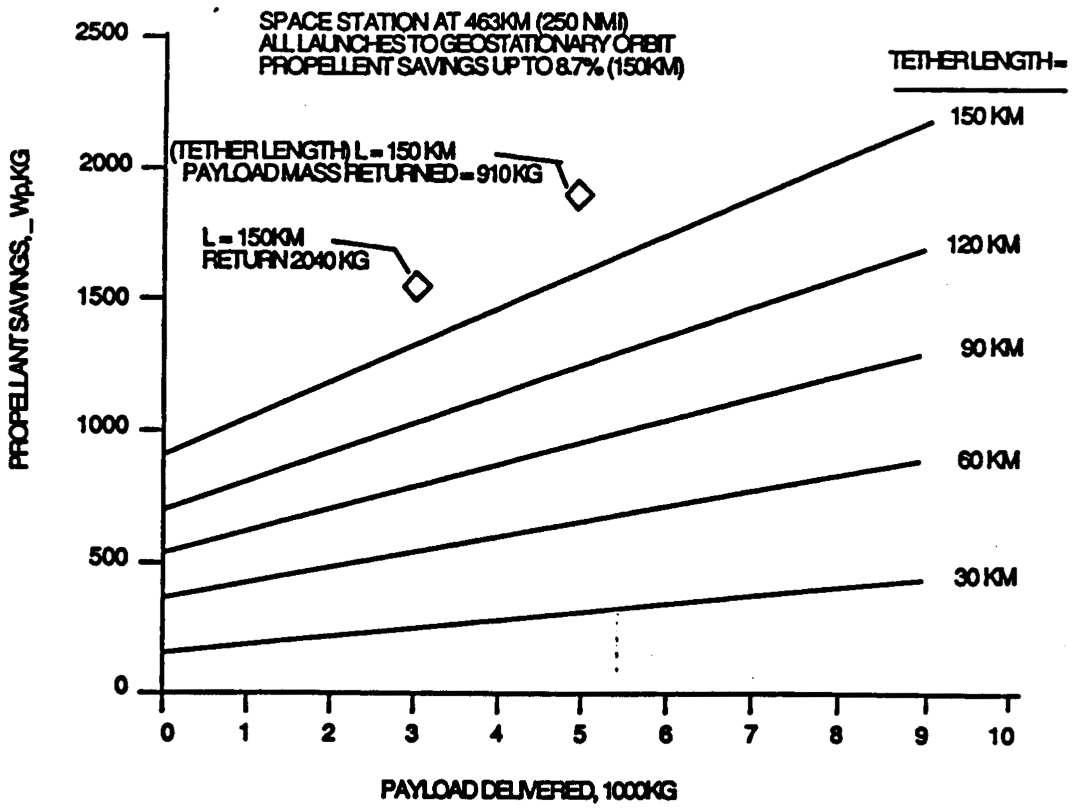


FIGURE 2-10 OTV PROPELLENT SAVINGS FROM TETHER LAUNCHES

For the baseline tethered OTV launch approach (Case IV), the yearly average of 8 OTV launches are balanced by an average of about 9 tethered Shuttle deployments out of a total average of 17 Shuttle deployments each year. For the alternate combined variable altitude/OTV launch scenario (Case V), almost all Shuttle deployments (15-19 per year) are required to be tethered to maximize benefits. Since the Space Station mass is close to its maximum throughout the period, an average mass of 412,400 kg (909,200 lb) was assumed for the baseline tethered OTV approach.

The annual performance benefits (when tethered OTV launches are present) are determined as follows:

Annual Benefit Factor:

$$\Sigma \overline{W} = N_R \overline{W} + (N - N_R)\, W_{CE} \qquad (5)$$

where:

$$\overline{W} = (W\ cargo + \Delta W_{P_{OMS}} + \Delta W_{P_{OTV}} \text{ for reboost flights } (N_R) \qquad (6)$$

W_{CE} = W_{cargo} for extra STS flights

N = Number of STS visits

N_R = Number of Reboost Flights

$\Delta W_{P_{OMS}}$ = Average OMS propellant scavenged

$\Delta W_{P_{OTV}}$ = Average OTV propellant saved/STS reboost flight

2.3.2 <u>Determination of Tether Requirements</u>. Tether requirements and orbital relationships for the deployment and release of the OTV were determined in the same manner as for the Shuttle deployment described in Section 2.2.2.

Since the ratio of the OTV to Space Station mass is small (compared to Shuttle deployments) and the tether length is large (150 km), similar dynamics simulations were run as a check on the accuracy of the simplified equations (4) and also to determine the factor for obtaining maximum power requirements.

Figure 2-11 shows a typical OTV deployment simulation using a 150 km tether for an 8 hr deployment of the OTV from a 500 km (270 nmi) Space Station orbit. Notice that it has similar characteristics to Fig. 2-4, but with slight shifts in the maximum points and higher values of (LDOT), (TENSION), and power, all due to the longer tether length.

Maximum tension is again within a fraction of a percent of that calculated with the simplified equations (4) shown in Section 2.2.2. Maximum power developed occurs at 5.3 hrs and is 3.2 times as large as the average power developed during the 8 hr deployment (compared to 3.1 in the Shuttle deployment). Maximum power calculated from the energy equation is obtained in the same way as described in Section 2.2.2, but using the 3.2 value for the factor (this same value is also used for waste disposal deployment and is also applicable to external tank deployments). Accuracy of this procedure is within 5%, as previously discussed. Motor/generator sizing is then determined by adding 30% for losses as in Section 2.2.2. Retrieval requirements are calculated in a similar manner, but do not size this motor/generator since only the mass in the PIDM is involved, although the motor/generator would have the capability to retrieve the OTV if additional power were supplied on the Space Station.

2.3.3 <u>Results Of The Benefits Analysis</u>. Fig. 2-12 presents a typical annual Space Station altitude profile for fixed nominal altitude (463 km) tethered OTV/STS operations (Case IV) based on an average of 16 Shuttle visits and 8 tethered OTV launches. Average altitude variations about nominal are ± 24 km. Note that 2 tethered Shuttle operations, 2 tethered OTV operations, and 2 non-tethered Shuttle operations are required for each quarter (plus 1 tethered waste disposal, typically). Drag effects shown are small and Tether lengths up to 52 km are required for Shuttle deployments.

Fig. 2-13 illustrates a typical Space Station altitude variation for the alternate OTV case, ie; launches from a variable altitude Space Station (Case V). In this approach, a minimum altitude is selected so that after 2 tethered Shuttle deployments (spaced 20-26 days apart), 2 periods of drag decay, and a tethered OTV launch (40-52 days between launches), the Space Station will return to the same minimum altitude. This analysis was based on the years 1999 (low drag year) and 2003 (highest drag year), and represents the maximum variation in benefits anticipated for the period 1999-2004. The minimum average altitude required varies from 348-383 km (188-207 nmi) and the maximum average altitude varies from 400-428 km (216-231 nmi). Tether lengths up to 38 km are required for the Shuttle deployments (Tethered OTV launches remain at 150 km length).

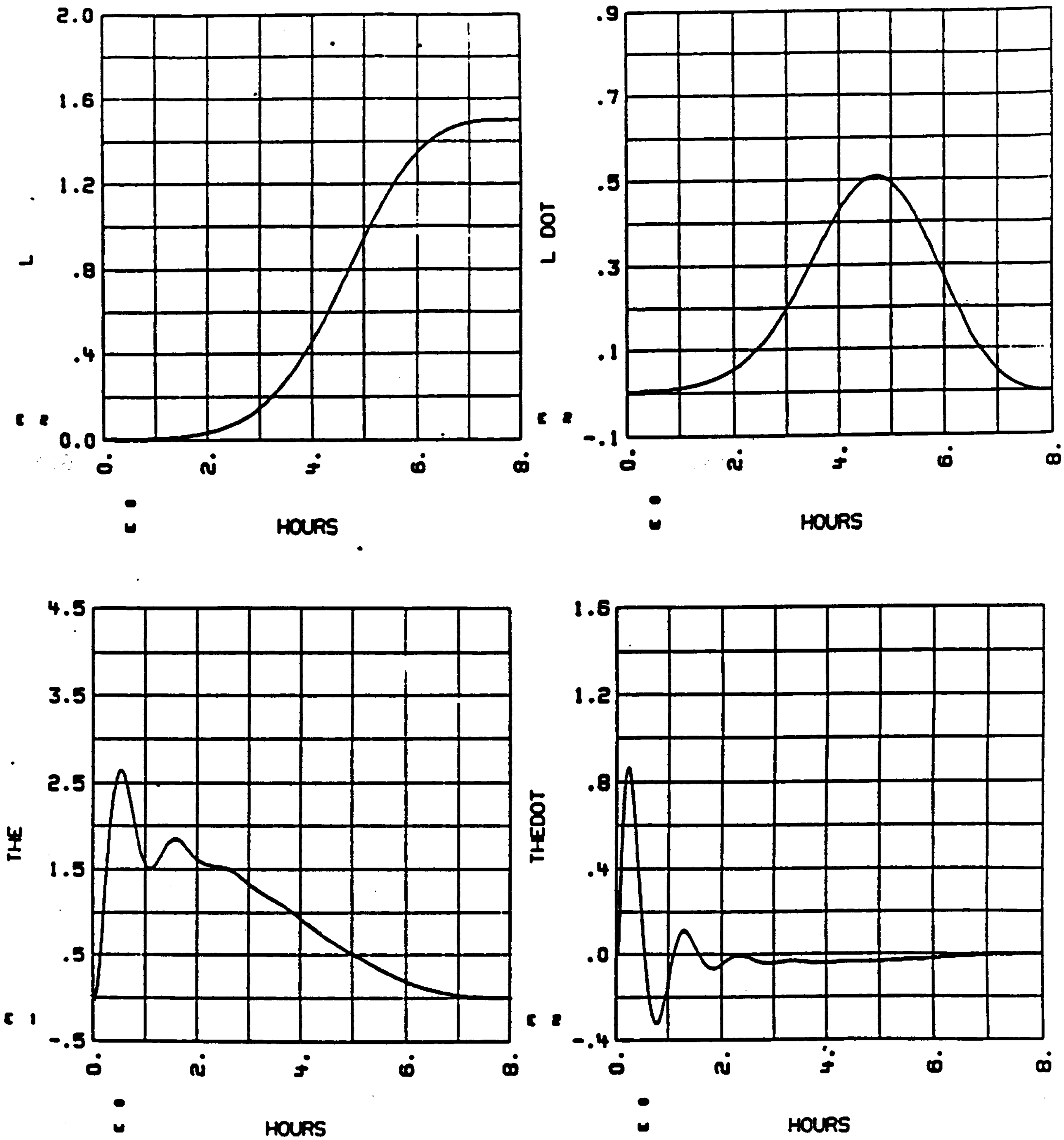


FIG. 2-11 TYPICAL TETHERED OTV LAUNCH SIMULATION

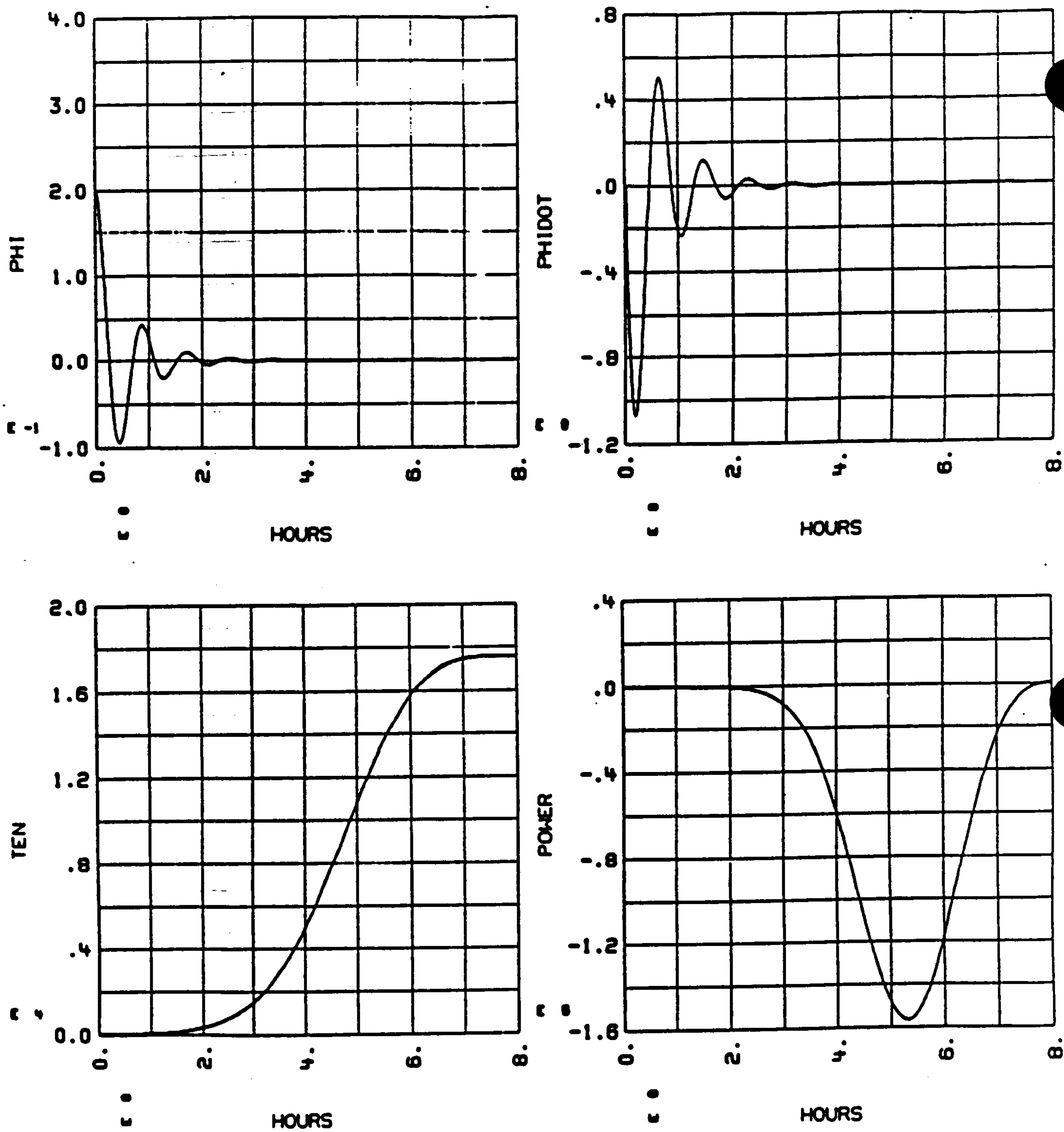


FIG. 2-11 TYPICAL TETHERED OTV LAUNCH SIMULATION (CONTINUED)

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

(TYPICAL VARIATION FOR 16 STS VISITS)

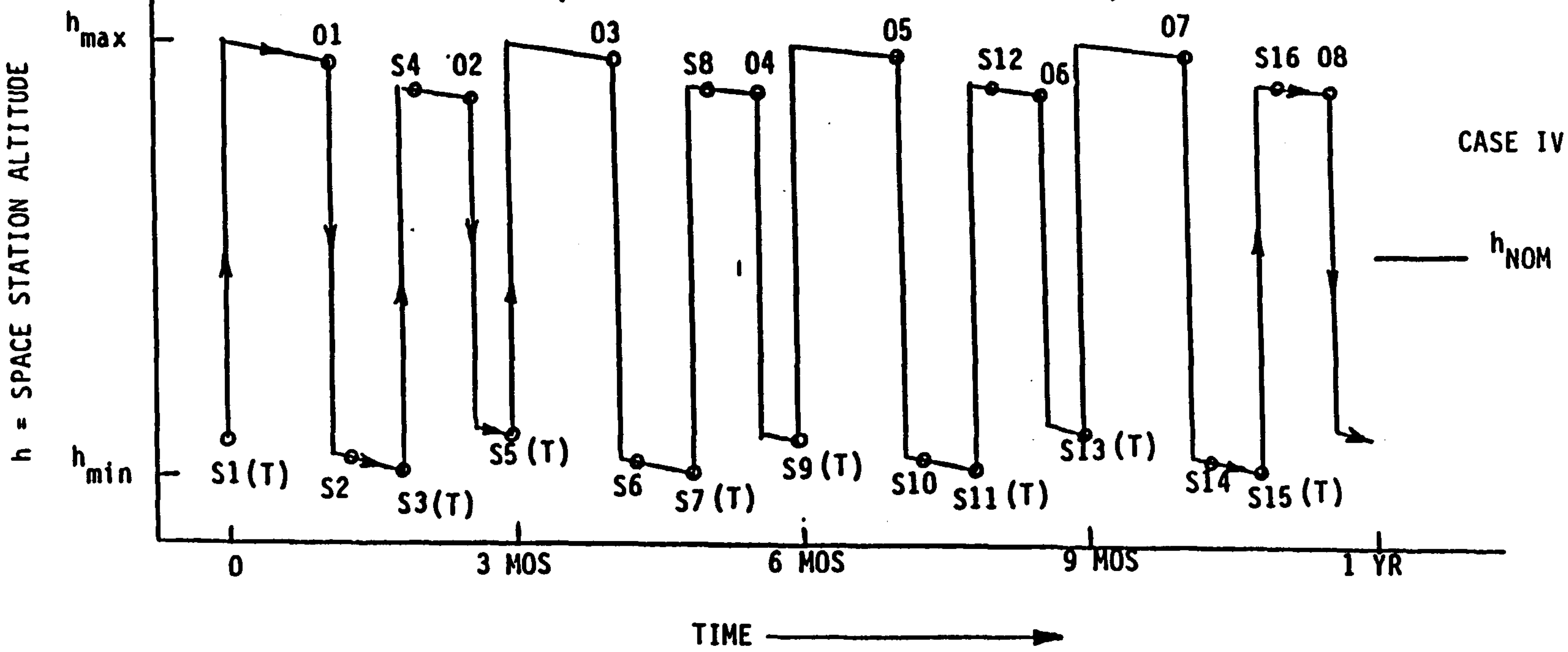


Fig. 2-12 Momentum Balance - Tethered OTV/STS at Current Altitude

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

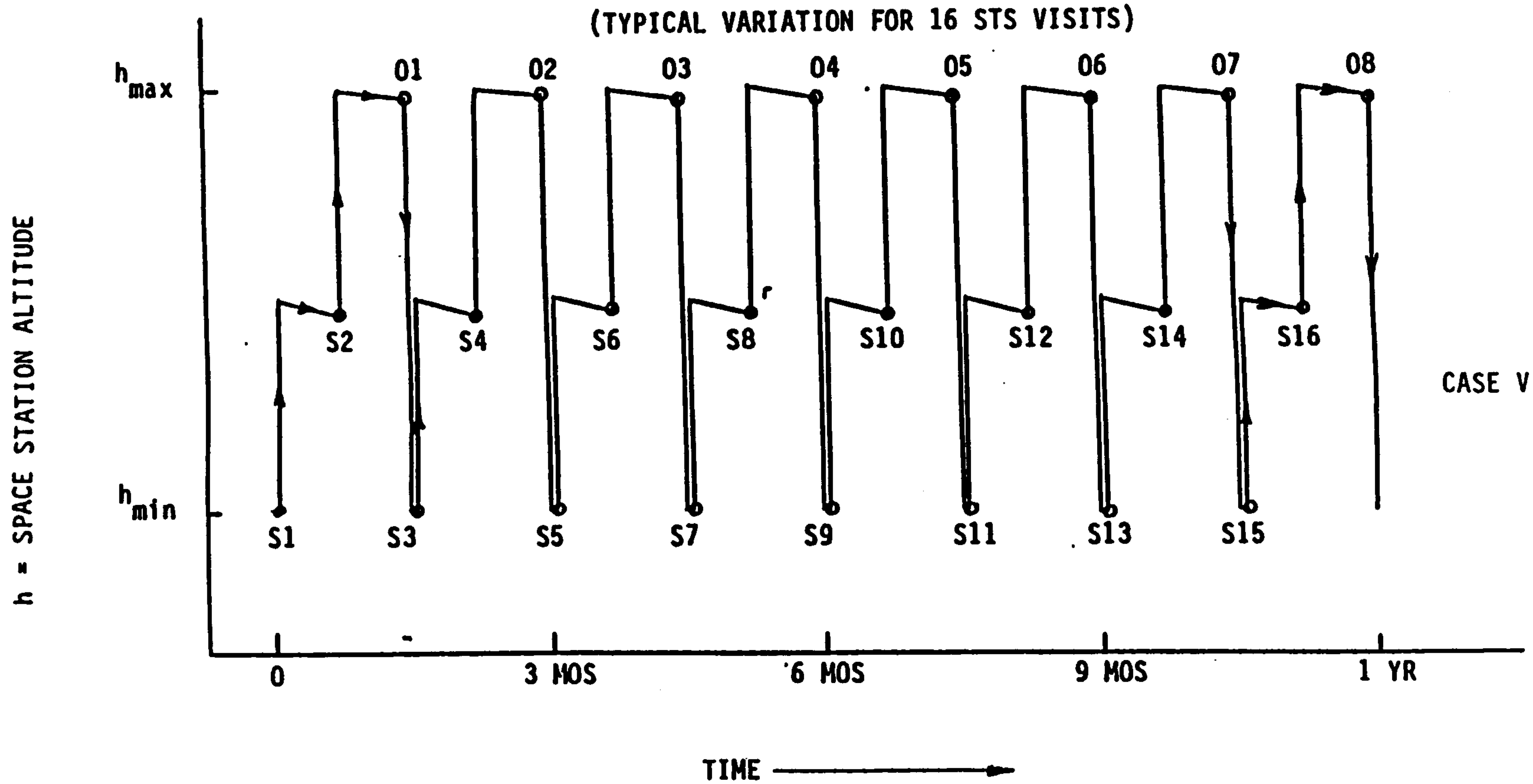


Fig. 2-13 Momentum Balance - Tethered OTV/STS at Variable Altitude

Fig. 2-14 shows the annual effective increase in Shuttle cargo weight (compared to Case I - the current non-tether approach) of combining tethered OTV and STS operations during the 1999 through 2004 time period. Both the fixed nominal altitude/OTV and variable altitude/OTV approaches are presented in this illustration (the variable altitude approach is shown for the two years investigated, 1999 and 2003).

For the fixed altitude (463 km) approach (Case IV), the annual benefits vary from 36,200 kg/yr (1999) to a maximum of 57,300 kg/yr (2003) with an average gain of 47,300 kg/yr over the 1999-2004 time period, with the majority of the benefits derived from propellant savings (OMS propellant, OTV propellant, and Stationkeeping propellant). Although the average yearly benefit (Case IV) is over 3 times as high as for the optimum non-tether approach (Case II), the benefits fall short of (Case III) the variable altitude tether approach (50,900 kg/yr average) over the 6 year period. For this reason and the fact that the tethered variable altitude (no tethered OTV launches) is operationally simpler, the fixed altitude tether approach is not recommended.

The greatest benefits are realized for (Case V) the Space Station variable altitude/tethered OTV launch approach (years 1999 and 2003 shown in Fig. 2-14). The yearly benefit (compared to (Case I) the current non-tether approach) is 78,500 kg for 1999 (about double Case IV - the fixed altitude/OTV approach) and 95,700 kg for the year 2003 (67% higher than Case IV). Note that propellant savings are a larger percentage of the total benefit in 2003 (Space Station at higher altitude) and lower for 1999 when the lower altitude benefits the cargo weight more. Average benefits for the tethered OTV launch approach from a variable altitude Space Station are expected to lie between the above yearly benefits for the 6 year period (ie; 87,100 kg/yr). Note that for each tethered OTV launch, one OMV operation is also eliminated.

2.4 <u>Performance Benefits Summary-Tether Operations, 1994-2004</u>. For convenience, Table 2-2 is supplied to allow a ready comparison between the various cases investigated in this analysis. Average yearly savings in effective cargo weight delivered to the Space Station are shown for the time periods of interest (1994-98; before OTV operations; 1999-2004, after OTV operations; and 1994-2004, the overall period studied)), with reference pages noted where details of the benefits are discussed. Also included in Table 2-2 are the average annual numbers of OTV launches, Shuttle deployments, and tether operations for the cases presented. Part A of the Table shows comparisons with Case I (the current SS altitude non-tether approach). Part B shows comparisons with Case II (the variable SS altitude non-tether approach) and also a comparison of Case V with Case III. Part C presents the preferred approaches for the 1994-2004 time period.

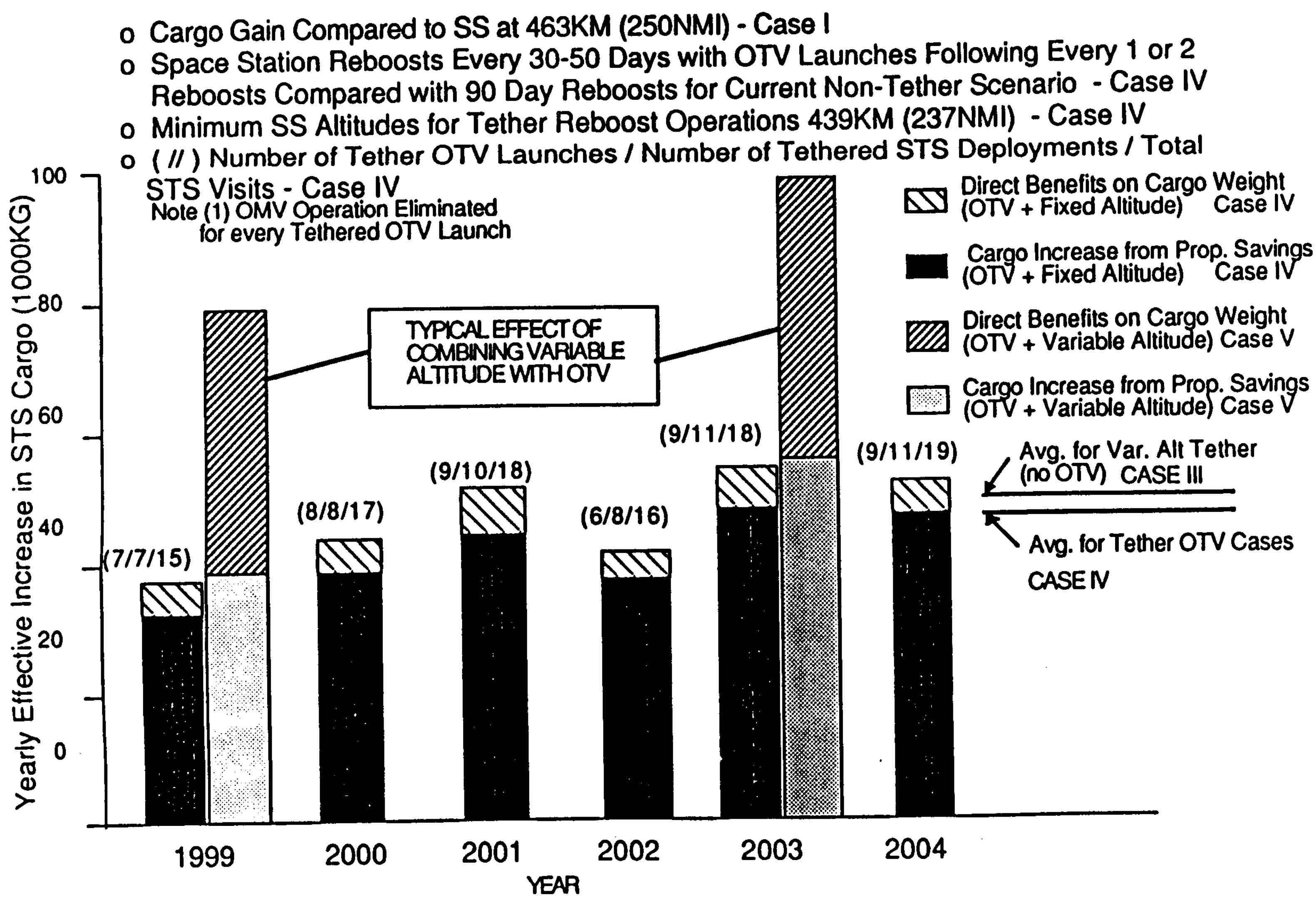


Figure 2 -14 Benefit of Combining Tethered OTV and Shuttle Operations on the Space Station

TABLE 2-2 SUMMARY OF PERFORMANCE BENEFITS

REF. (Page)	AVG. SVGS. (kg/Yr)	TIME FRAME	NO. OF YEARS (Yrs)	BASIS FOR COMPARISON (Case) (1)	YEARLY NUMBER AVERAGES: TETH/TOT. STS/STS (Per Yr)	YEARLY NUMBER AVERAGES: TETH/TOT OTV/OTV (Per Yr)	YEARLY NUMBER AVERAGES: TOT (2) TETH. OPS. (Per Yr)
A. Comparisons with Case I							
15	13,700	94-04	11	II vs I	0/13	0/4	0
15	41,200	94-04	11	III vs I	4/13	0/4	8
27	47,300	99-04	6	IV vs I	9/17	8/8	21
27	50,900	99-04	6	III vs I	4/17	0/8	8
27	87,100	99-04	6	V vs I	16/17	8/8	28
B. Comparisons with Cases II and III							
30	17,800	94-98	5	III vs II	4/8	0/0	8
30	35,500	99-04	6	III vs II	4/17	0/8	8
30	36,200	99-04	6	V vs III	16/17	8/8	28
C. Preferred Approaches (1994-04)							
30	27,500	94-04	11	III vs II	4/13	0/4	8
30	47,200	94-04	11	III/V vs II	10/13	4/4	19

NOTES: (1) Case I - Current SS Altitude (463km) - Non-Tether
Case II - Variable SS Altitude - Non-Tether
Case III - Variable SS Altitude - Tethered STS
Case IV - Current SS Altitude - Tethered STS/OTV
Case V - Variable SS Altitude - Tethered STS/OTV

(2) Includes 4 tethered waste disposals

For this analysis to afford a more reasonable comparison between the tethered and non-tethered scenarios, it is assumed that the Space Station will use an optimum variable altitude non-tether scenario (Case II, Fig. 2-3) to maximize effective cargo delivery weight of the Shuttle. All gains discussed in this summary are therefore compared to the optimum variable altitude non-tether approach (Case II presented in Parts B and C of Table 2-2.

For the 1994 through 1998 time period the optimum tether variable altitude approach (Case III) is recommended. The Space Station would be operating in the 305 km (165 nmi) to 395 km (214 nmi) altitude range, with 6-13 Shuttle visits yearly for a total of 40 visits in 5 years with 20 of the 40 providing reboost capability via a Shuttle tether deployment. Average yearly effective cargo weight savings is 17,800 kg, (Case III vs Case II) or a savings of about 4 Shuttle flights in 5 years. This scenario would require 4 tethered Shuttle deployment operations and up to 4 tethered waste disposal operations annually.

For the 1999 through 2004 time period the optimum tether variable altitude approach (Case III, no tethered OTV launches) is preferred over the fixed Space Station altitude approach with tethered shuttle and OTV launches (Case IV) as indicated in Part A of Table 2-2. The Space Station would be operating in the 305 km (165 nmi) to 417 km (225 nmi) altitude range, with 15-19 Shuttle visits yearly for a total of 103 visits in 6 years with 24 of the 103 providing reboost capability. Average yearly effective cargo weight savings is 35,500 kg (Case III vs Case II), or a savings of 10 Shuttle flights in 6 years. This approach, when combined with the same scenario in the first 5 years would save an average of 27,500 kg per year for 11 years (Part C of Table 2-2) or a potential savings of 14 Shuttle flights out of the total of 143 flights. Four tethered Shuttle operations and up to 4 tethered waste disposal operations would be required yearly for the total period. OTV launches would require the OMV in a proximity operation with this scenario.

If a variable altitude Space Station approach is combined with tether launched OTV's and used for the 1999 through 2004 time period, maximum benefits would be achieved. The Space Station would generally be operating in the 383 km (207 nmi) to 463 km (250 nmi) altitude range over the 6 year period. Based on the results from the 1999 and 2003 analysis (Case V), average annual benefits would provide an additional 36,200 kg/yr benefit over the optimum variable altitude tether approach (Case III) with 96 of the 103 Shuttle visits providing reboost capability. Conservatively, this variable altitude/OTV scenario (Case V) could provide an additional savings of 7-9 Shuttle flights over the variable altitude optimum tether (no tethered OTV) approach (Case III). This approach, when combined with the tethered optimum variable altitude approach (Case III, no OTV) for the first 5 years could result in a potential savings of 21-23 Shuttle flights out of 143 flights (47200 kg/yr, average), compared to (Case II) the optimum variable altitude (non-tether approach) for the 11 year period. Total tether operations (including 4 yearly waste disposal operations) would require 8 operations yearly for 1994 through 1998 and an average of 28 tether operations yearly for the 1999 through 2004 time period (average of 19 tether operations per year for 11 years). Each tethered OTV launch would eliminate the need for an OMV operation (an average of 8 per year in the last 6 years).

3.0 MISSION OPERATIONS

3.1 Introduction. To support the other study tasks operational scenarios have been developed. The elements involved are the Space Station (SS), Shuttle, and the Orbital Transfer Vehicle (OTV) system.

3.1.1 Assumptions and Baselines. The Space Station (SS) design used is the Twin Keel concept utilizing a five meter square box/truss construction. The SS has a Mobile Remote Manipulator System (MRMS) mounted on and transported by it's own mobility system that will be used to transport the tether deployer systems. The MRMS will have access to all points on the SS structure and be able to translate around corners in one plane.

Fuel transfer technologies will be expected to have evolved sufficiently to provide for autonomous fuel transfer operations as required for OMS propellant scavenging by the SIDM and other fuel transfer operations on-board the SS.

At least one Shuttle must be fitted with the necessary modifications to permit SIDM attachment and OMS propellant scavenging.

To develop an operations sequence for tethered deployments, it is necessary to understand the baseline approaches for non-tethered deployments. Operations data were gathered from Martin Marietta projects including OTV, OSCRS, OMV, MISC, Space Station and Tethered Satellite. Some specific Shuttle information was also obtained from Johnson Space Center.

Shuttle deorbits from the SS, using a non-tether departure, will be defined as follows: Upon completion of Orbiter departure preparations,the Shuttle will perform a low Z mode RCS thrust to initiate a V bar separation velocity from the SS (along the direction of flight). Orbital dynamics will require the Shuttle to perform various RCS thrusts to increase the separation velocity and provide attitude and directional control. Once the Shuttle has achieved a separation, along the V bar path, of 18.5 km, (10 nmi) or greater, the OMS burn may be initiated. During the Orbiter/Space Station proximity separation, the Orbiter may alter its attitude to begin the cold soak cycle.

OTV launches from the SS, using a non-tether departure, will be defined as follows: Upon completion of OTV servicing and payload stacking, an OMV unit will be attached. The entire OTV, OMV and payload combination will then be given an initial separation velocity, using a rail system, along the V bar path (along the direction of SS flight). The OMV will utilize its RCS thrusters to increase the separation rate between the OTV and SS, and maneuver the OTV into the desired attitude and position. Once stabilized, the OMV will separate and return to the SS or continue onto another mission. The OTV will then initiate its main mission function.

3.1.2 Operational Events and Timelines. The timeline data is broken into three parts: the Baseline Approach, Tethered Deployment Activities and a Tethered Deployment Timeline. The Baseline Approach will define a non-tether operations timeline as currently available. The Space Station Tethered Deployment System (SSTDS) Activities, will list deployment operation tasks, length of time to perform and personnel required. The Tethered Deployment Timeline will display both parallel and series operations to determine the overall time required to perform the mission. These data are provided for both Shuttle and OTV deployments and launches.

3.2 Shuttle Deployment

3.2.1 Baseline Approach. To define the nominal Space Station and Orbiter separation and subsequent reentry, data were gathered from the Johnson Space Center, Houston, Texas.

The initial Orbiter separation from the SS is of primary concern because plume impingement and contamination from RCS thrusters may cause undesirable effects on Space Station structures and sensors. Because of these concerns, efforts have been made to minimize exposure of SS structures and instruments to these effects.

As illustrated in Fig. 3-1, the Orbiter will initiate a V bar separation rate of .06 mps (.2 fps) from the SS, along the SS flight path using the Low Z mode thrusters. The Orbiter will then coast in LVLH (Local Vertical - Local Horizontal Attitude Control Mode) hold for 10 minutes to a separation distance of approximately 36M (120 ft).

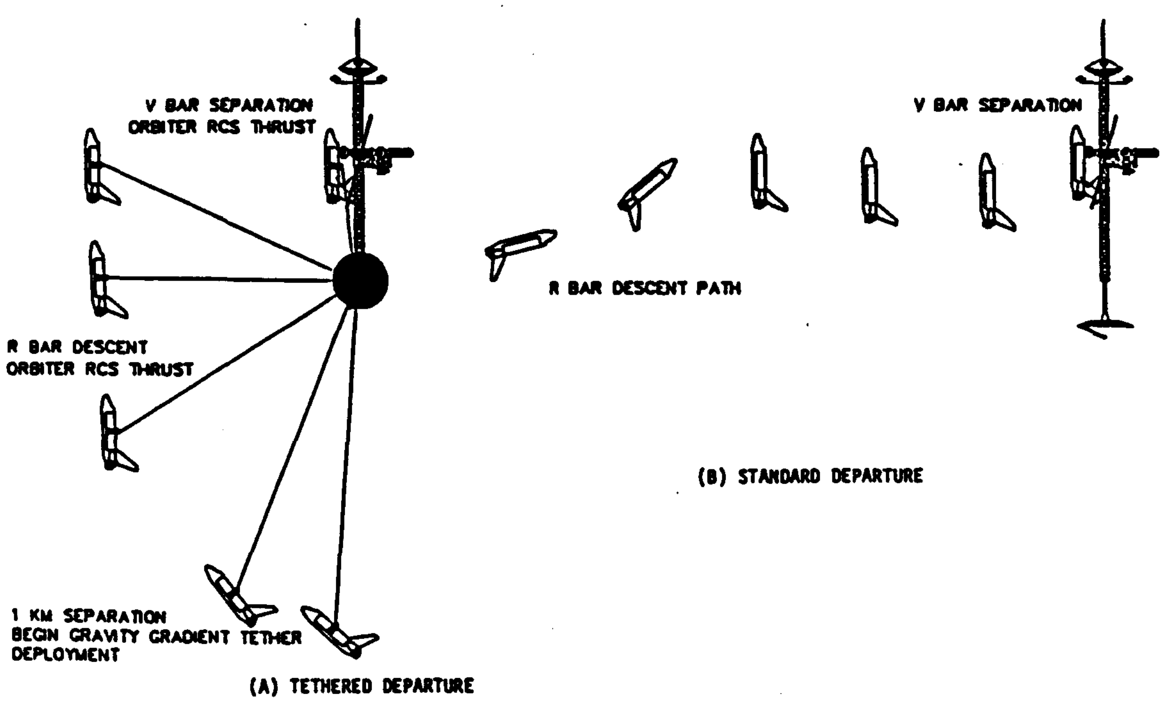


Fig. 3-1 Tethered and Standard Departure of Shuttle from Space Station

At this time, another Low Z mode thrust period will accelerate the separation rate to 0.3 mps (1.0 fps), along the R bar descent path. The Orbiter will then coast in LVLH hold for 15 minutes to a separation distance of approximately 244M (800 ft) along the V bar and 152M (500 ft) below the SS flight path.

The separation distance of the Orbiter and SS is now large enough to permit a 0.9 mps (3 fps) retrograde OMS burn. The Orbiter will then coast for 2 hours to the 18.5 km (10 nmi) range required, to begin a deorbit OMS burn.

This scenario represents a plausible operations plan for Shuttle deorbit from SS and was selected because it represents the currently planned nominal approach although certain details of the operation may be varied on a mission by mission basis. The overall timeline for the baseline Orbiter departure through deorbit and landing is shown in Fig. 3-2.

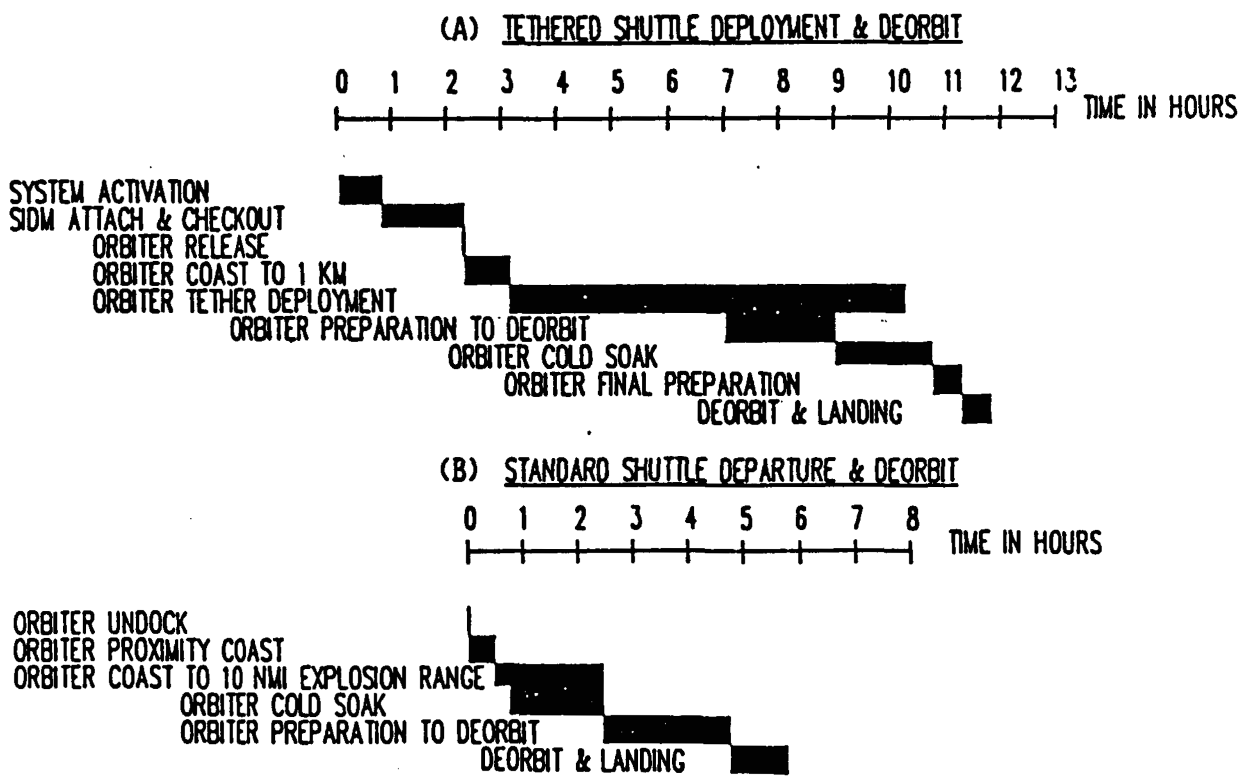


Fig. 3-2 Tethered and Standard Shuttle Deorbit Timelines

3.2.2 Tethered Approach. Initial stages of the tethered deorbit operation will parallel the baseline approach. Differences will be noted in the times between SS separation and the initiation of the R bar descent. During tether deployment, the Orbiter is allowed to continue along the V bar path an additional length of time This allows the Orbiter to perform the R bar descent and reach the desired location, below the SS, with a minimum amount of RCS thrusting. Once the Orbiter has cleared the SS 1 km proximity zone, tether operations utilizing gravity gradient will begin. The Orbiter will not perform nor require any OMS burn until after release of the tether at the prescribed altitude and orbit.

The Orbiter will initiate a V bar separation rate of .06 mps (.2 fps) from the SS, along the SS flight path. The Orbiter Low Z mode thrusters will provide this initial separation rate. The Orbiter will then coast in LVLH hold for 10 minutes and a separation distance of approximately 36M (120 ft). Any attitude or axis alignment responses will be performed if required to maintain proper tether management. The Orbiter will coast in LVLH hold for an additional 10 minutes and a separation distance of approximately 73M (240 ft).

At this time, another Low Z mode thrust will accelerate the separation rate to 0.9 mps (3.0 fps) along the R bar descent path. The Orbiter will then coast in LVLH hold for 18 minutes and a separation distance of approximately 1 km below the SS flight path. This initial sequence is also illustrated in Fig. 3-1 and compared with the baseline approach.

At a separation distance of 1 km, gravity gradient forces are sufficient to begin tether deployment without using the RCS thrusters to provide the R bar descent velocity. Attitude and axis alignment thrusts may be required to maintain proper attitude control.

At this point, OMS propellant scavenging may begin, and continue until the desired tethered orbit altitude is reached. Attitude alignment thrusts may be required to initiate the Orbiter cold soak process while on the tether.

At the desired orbit altitude, the Orbiter will be released from the tether. The release altitude will be such that the perigee of the Orbiter will not be lower than 185 km (100 nmi). The overall tether deployment through deorbit and landing is compared with the baseline approach in Fig. 3-2. The time for the tethered approach is approximately twice that of the baseline approach and includes the scavenging operation to transfer unused OMS propellant to the SIDM.

Tether operations will be concluded when the SIDM has been reeled in and docked to the Space Station. (PIDM cold gas will be utilized for both libration angle control and tether tensioning during retrieval).

The overall timeline for the tethered Shuttle operations is shown in Fig. 3-3 (slightly under 24 hrs) and detailed activities throughout the various phases of the tether operations are presented in Tables 3-1 through 3-5. Microgravity on the Space Station (determined by tether tension) will reach several milli-g's during the 8 hr deployment and will be diminishing from approximately 1 milli-g during SIDM retrieval.

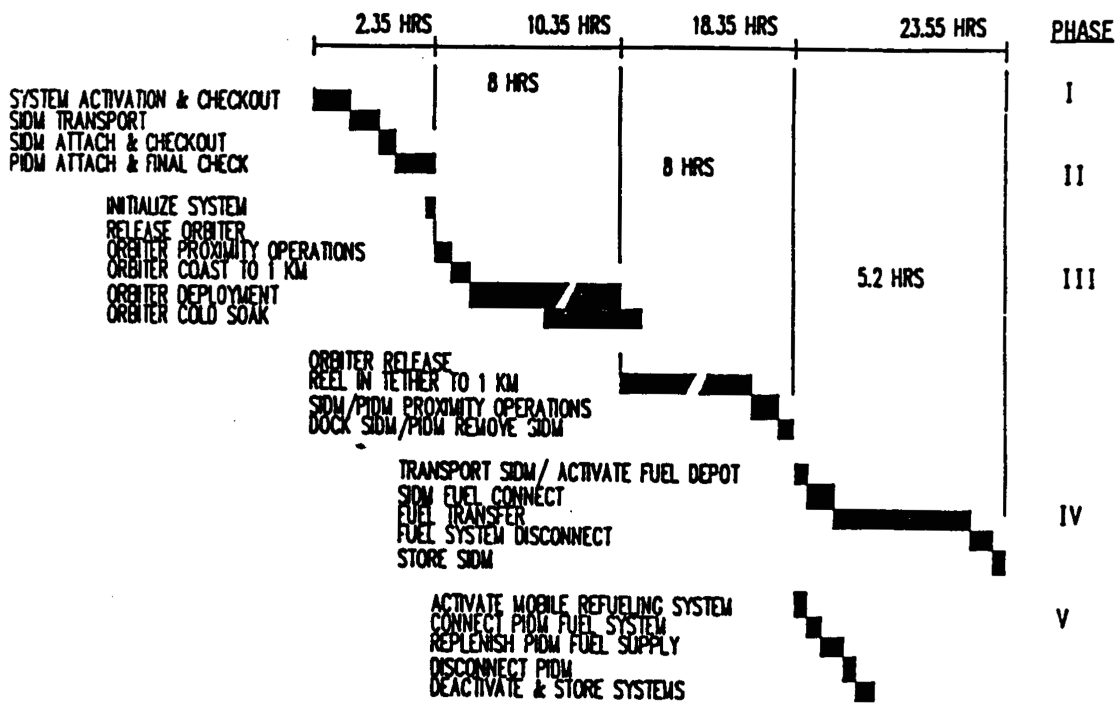


Fig. 3-3 Tether Operations Timeline (Shuttle Deorbit)

Table 3-1 Space Station Tether Deployer System Activities

Phase I Shuttle Tether Deployment Preparation

EVENT	EVENT TIME	PERSONNEL	
		SSTDS	MRMS
Man and activate SSTDS control system/console	15 Min	1	
Checkout SSTDS operability and status	20 Min	1	
Activate & position MRMS for SSTDS transfer ops	15 Min		2
Position deployer for shuttle deploy*	30 Min	1	2
Retrieve SIDM from storage using MRMS**	10 Min	1	2
Transport SIDM to Orbiter using MRMS	15 Min	1	2
Berth SIDM to Orbiter using MRMS	15 Min	1	2
Checkout SIDM/Orbiter interface	1 Min	1	
Checkout SIDM/Orbiter scavenging/comm/power	10 Min	1	
Position MRMS at deployer assembly	15 Min		2
Activate deployer assembly for proximity ops	5 Min	1	
Transport & attach PIDM/tether to SIDM using MRMS	20 Min	1	2
Position MRMS out of operations area	10 Min		2
TOTAL IVA TIME (MAN-HRS)		2.35	4.33

*Only applicable on Dual Mode Deployer concept

**MRMS = Mobile Remote Manipulator System

Table 3-2 Space Station Tether Deployer System Activities

Phase II Tether Deployment

EVENT	EVENT TIME	PERSONNEL SSTDS	PERSONNEL MRMS
Load deployment profile software	1 Min	1	
Verify reel motor/generator brake mechanism initial status	5 Min	1	
Switch control of SIDM from SS to Orbiter	1 Sec	1	
Establish video data link	10 Sec	1	
SS verify communication link with SIDM	10 Sec	1	
Release Orbiter berthing interface/verify	1 Min	2	
Orbiter RCS thrust: V bar separation .2 fps	5 Sec	2	
Orbiter coast to 120' V bar separation	10 Min	2	
Orbiter RCS thrust: Y & Z axis alignment	5 Sec	2	
Orbiter coast to 240' V bar separation	10 Min	2	
Orbiter RCS thrust: R bar descent 3 fps	5 Sec	2	
Orbiter coast to 1 km separation	18 Min	1	
Orbiter deployment	7.3 Hrs	1 @ .5 hrs	
TOTAL IVA TIME (MAN-HRS)		1.61	

Table 3-3 Space Station Tether Deployer System Activities

Phase III Orbiter Release & Tether Retrieval

EVENT	EVENT TIME	PERSONNEL SSTDS	PERSONNEL MRMS
Verify reel motor/generator stopped & secured	1 Min	1	
Shutdown OMS propellant transfer system	1 Min	1	
Verify all propellant line couplings closed	1 Min	1	
Establish SS/SIDM communication link	10 Sec	1	
Verify Orbiter attitude within operational SIDM release envelope	5 Min	1	
Verify SS tracking has SIDM/Orbiter targeted	10 Sec	1	
Release SIDM from Orbiter	1 Sec	1	
Reel in tether to SIDM/SS 1 km separation	7.5 Hrs	1 @ .5 hrs	
SIDM/PIDM cold gas thrust, stabilize motion	1 Min	1	
Establish video data link from SS	10 Sec	2	
Reel in tether to 200' SIDM/SS separation, 3 fps	18 Min	2	
SIDM/PIDM cold gas thrust, stabilize motion	1 Min	2	
Inspect and evaluate SIDM	5 Min	2	
Reel in tether to SS/SIDM separation of 50', 2 fps	13 Min	2	
Dock SIDM/PIDM to lower deployment berthing site	5 Min	2	
Move MRMS to SIDM	15 Min		2
Remove SIDM from PIDM, using MRMS	5 Min	1	2
TOTAL IVA TIME (MAN-HRS)		2.15	.66

Table 3-4 Space Station Tether Deployer System Activities

Phase IV SIDM Fuel Transfer & Storage

EVENT	EVENT TIME	PERSONNEL		
		SSTDS	MRMS	FUEL
Checkout fueling depot control system/console	15 Min			1
Transport SIDM to fuel depot with MRMS truck	15 Min	1	2	
Berth SIDM to fuel depot	10 Min	1	2	1
Connect fueling lines to SIDM using MRMS	30 Min	1	2	1
Activate fueling system	1 Min			1
Transfer OMS propellant	3 Hrs	1 @ .5 hrs		1 @ .5 hrs
Disconnect fueling lines using MRMS/store lines	35 Min	1	2	1
Deenergize fueling system	1 Min			1
Latch onto SIDM using MRMS; grapple and rigidize	3 Min	1	2	
Release SIDM from fuel depot berthing ring	1 Min	1	2	1
Transport and store SIDM at storage site	15 Min	1	2	
TOTAL IVA TIME (MAN-HRS)		2.32	3.63	2.05

Table 3-5 Space Station Tether Deployer System Activities

Phase V PIDM Refueling & Storage

EVENT	EVENT TIME	PERSONNEL		
		SSTDS	MRMS	FUEL
Activate and transport mobile cold gas servicer	15 Min			1
Activate and position MRMS at PIDM location	15 Min		2	
Connect PIDM to cold gas servicer	15 Min	1	2	1
Replenish PIDM cold gas system	30 Min	1		1
Disconnect PIDM refuel lines	15 Min	1	2	1
Deactivate and store PIDM	10 Min	1		
Store mobile cold gas servicer	15 Min			1
TOTAL IVA TIME (MAN-HRS)		1.16	1.5	1.5

3.3 OTV Deployment

3.3.1 Baseline Approach. To define the nominal Space Station and OTV separation and mission operations, data was gathered from the Martin Marietta OTV program.

Proximity operations around the Space Station are of primary concern. As is the case with Shuttle deorbits, plume impingement and contamination are major concerns. To minimize these effects the OTV will not use its RCS system around the SS. Instead the OMV will be used to maneuver the OTV and its payload stack away from the SS. A rail system will be used to initiate the SS and OMV/OTV separation.

Upon completion of OTV servicing and payload stacking, the OMV will be attached to the OTV. The SS will have a rail system in the OTV facility which will initiate a 0.3 mps (1.0 fps) separation velocity along the V bar path (along the flight direction of the SS). The entire system will coast for 30 minutes and approximately 1 km separation from the SS.

At 1 km separation, the OMV will perform a retrograde RCS burn to initiate a 2.1 mps (7 fps) separation velocity. The system will coast another 10 minutes and approximately 2.25 km separation from the SS. The OMV will then separate from the OTV and either return to the SS or continue on, to another mission.

Once separated from the OMV, the OTV Reaction Control System (RCS) is activated. Approximately 95 minutes from SS separation, the OTV will clear zone 2 of the SS, approximately 37 km (20 nmi). The OTV can now initiate steps to perform its main engine burn and complete its mission.

This scenario represents a plausible operations plan for OTV launch from SS and was selected because it represents the currently planned nominal approach although certain details of the operation may be varied on a mission by mission basis.

3.3.2 Tethered Approach. The tethered OTV launch will be completely different from the baseline approach. The rail system will not be used to initiate a separation velocity from the SS, nor will the OMV system be required. Instead the PIDM, using cold gas thrusters, will provide the initial separation and tether tensioning. The OTV system will depart the SS proximity zone vertically away from the zenith end of the SS.

Upon completion of the OTV servicing and payload stacking, the entire system will be transported to the upper deployer assembly. The OTV will be on its own mobility system and able to move about the SS. The OTV system will then be attached to the PIDM, at the deployer reel assembly.

The PIDM will provide for the initial R bar separation and tether tensioning during proximity operations. The initial velocity will be .06 mps (.2 fps) and the OTV system will coast for 10 minutes to a range of 36M (120 ft). Another cold gas thrust from the PIDM will increase the separation velocity to 0.3 mps (1 fps). The system will reach the limit of the 1 km SS proximity zone after 52 minutes.

At approximately 1 km separation, gravity gradient forces are sufficient to begin tether deployment without using the PIDM cold gas system, except for attitude and libration angle control (primarily used during retrieval).

At the desired orbit altitude, the PIDM will release the OTV system to initiate its main engine burn and complete the mission. Tether operations will be concluded when the PIDM has been reeled in and docked to the Space Station.

The timeline for the tethered OTV launch and PIDM retrieval operations is shown in Fig. 3-4 and encompasses a total period of 19 hrs. Detailed activities throughout the various phases of the tether operations are presented in Table 3-6 through 3-9. Microgravity levels on the Space Station (determined by tether tension) will reach several milli-g's during the 8 hr deployment and will be diminishing from about 1 milli-g during the 8 hr retrieval period.

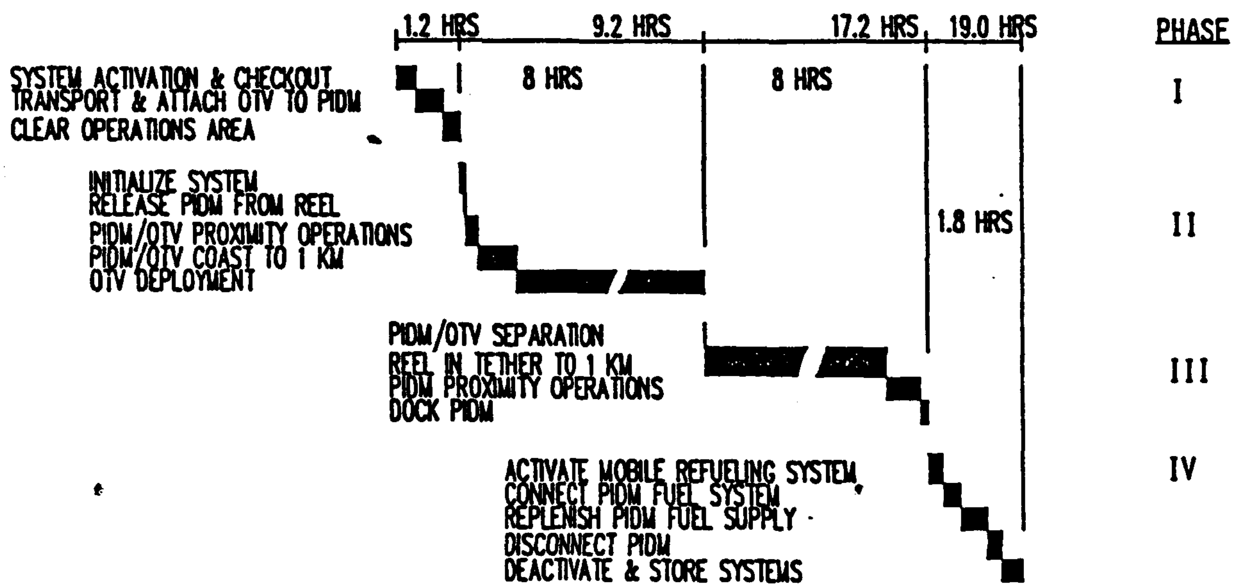


Fig. 3-4 Tether Operations Timeline (OTV Launch)

Table 3-6 Space Station Tether Deployer System Activities

Phase I OTV Tether Deployment Preparation

EVENT	EVENT TIME	PERSONNEL SSTDS	PERSONNEL MRMS
Man and activate SSTDS control system/console	15 Min	1	
Checkout SSTDS operability and status	20 Min	1	
Activate & position MRMS for SSTDS transfer ops	15 Min		2
Position deployer for OTV launch*	30 Min	1	2
Transport OTV to PIDM/upper deployer assembly	15 Min		2
Berth OTV to PIDM	15 Min	1	2
Checkout OTV/PIDM interface	1 Min	1	
Move OTV truck out of tether operations area	10 Min		2
Move MRMS out of tether operations area	5 Min		2
	TOTAL IVA TIME (MAN-HRS)	1.35	3.00

*Only applicable on Dual Mode Deployer concept

Table 3-7 Space Station Tether Deployer System Activities

Phase II OTV Tether Deployment

EVENT	EVENT TIME	PERSONNEL SSTDS	MRMS
Load deployment profile software	1 Min	1	
Verify reel motor/generator brake mechanism initial status	5 Min	1	
Establish video data link	10 Sec	1	
SS verify communication link with PIDM	10 Sec	1	
Release SS/PICM berthing interface/verify	1 Min	2	
PIDM cold gas thrust: R bar separation .2 fps	10 Min	2	
PIDM/OTV coast to 120' R bar separation	10 Min	2	
PIDM cold gas thrust	5 Sec	2	
PIDM cold gas thrust: R bar separation 1 fps	5 Sec	2	
OTV coast to 1 km separation	52 Min	1	
OTV deployment	6.9 Hrs	1 @ .5 Hrs	
TOTAL IVA TIME (MAN-HRS)		1.83	

Table 3-8 Space Station Tether Deployer System Activities

Phase III OTV Release & Tether Retrieval

EVENT	EVENT TIME	PERSONNEL SSTDS	PERSONNEL MRMS
Verify reel motor/generator stopped & secured	1 Min	1	
Verify OTV operability	5 Min	1	
Verify SS tracking has PIDM/OTV targeted	10 Sec	1	
Release OTV from PIDM	1 Sec	1	
Reel in tether to PIDM/SS 1 km separation	7.3 Hrs	1 @ .5 Hrs	
PIDM cold gas thrust to stabilize relative motion	1 Min	1	
Establish video data link from SS	10 Sec	2	
Reel in tether to 200' PIDM/SS separation, 3 fps	18 Min	2	
PIDM cold gas thrust to stabilize relative motion	1 Min	2	
Inspect and evaluate PIDM	5 Min	2	
Reel in tether to SS/PIDM separation of 50', .2 fps	13 Min	2	
Dock PIDM to upper berthing site	5 Min	2	
TOTAL IVA TIME (MAN-HRS)		2.1	

Table 3-9 Space Station Tether Deployer System Activities

Phase IV PIDM Refueling & Storage

EVENT	EVENT TIME	PERSONNEL SSTDS	MRMS	FUEL
Activate and transport mobile cold gas servicer	15 Min			1
Activate and position MRMS at PIDM location	15 Min		2	
Connect PIDM to cold gas servicer	15 Min	1	2	1
Replenish PIDM cold gas system	30 Min	1		1
Disconnect PIDM refuel lines	15 Min	1	2	1
Deactivate and store PIDM	10 Min	1		
Store mobile cold gas servicer	15 Min			1
TOTAL IVA TIME (MAN-HRS)		1.16	1.5	1.5

3.4 Tether Deployer System Requirements

Based upon the analysis of the tethered operations and timelines, a preliminary assessment of tether deployment system interface requirements, key criteria, necessary assumptions, and technical issues has been completed and is summarized in Tables 3-10 through 3-12.

Table 3-10 summarizes the tether deployment system Space Station interface requirements involved with the tethered Shuttle deployment operations. Requirements for SIDM storage and maintenance include communications and data links, power sources, berthing, storage between missions, meteroid protection, contamination/leak sensors, CCTV (Closed Circuit Television) and lighting. Fuel depot interfaces with the SIDM include the storage and maintenance functions (excluding SIDM storage) plus thermal control and umbilicals for fuel transfer and fuel transfer monitoring and leak protection. Communication interfaces with the tether deployment system include communications and data link transmissions (via hard wire or radio link) plus CCTV and lighting.

In addition, Table 3-10 lists the Orbiter interfaces with the SIDM. These requirements include quick disconnect type umbilicals for communications and data links, power source, fuel transfer from the integral OMS system, load transfer interface during deployment, fuel contamination and leak sensors, and CCTV and lighting support.

Table 3-11 summarizes the tether deployment system Space Station interface requirements for the tethered OTV launch operations. Requirements for PIDM storage and maintenance are basically the same as for the SIDM previously discussed. Fuel transfer interfaces for the PIDM require only the transfer of cold gas propellant and include thermal control during transfer, gas umbilicals, and a propellant transfer and monitoring system. OTV interfaces with the PIDM include a load transfer interface, CCTV, and lighting support.

Table 3-12 summarizes key criteria, technical issues, and associated assumptions required for tethered deployment operations on the Space Station and Shuttle. Fuel transfer is a critical technology and tether operations require that standardized quick disconnect refeuling couplings are available in the mid 1990's with acceptable leakage levels both for the Space Station and on the Orbiter. SIDM/PIDM interfaces include umbilicals that are of the Orbiter type. SIDM/PIDM control systems will interface with Orbiter and Space Station common module work station consoles, etc. SIDM Shuttle interfaces and docking mechanisms are required to be capable of immediate shutdown and disconnect. SIDM fuel connects must be compatible with Space Station fuel depot fittings and the Orbiter OMS scavenging system. Other requirements cover PIDM refueling operations and SIDM connect/disconnect considerations. SIDM and PIDM attach/detach operations also assume that no EVA time is required (autonomous operation). The MRMS (Maneuverable Remote Manipulator System) designs are also assumed to provide adequate reach and flexibility and can move to all points on the Space Station.

Table 3-10 Tether Deployer System Requirements
Tethered Shuttle Deployment

1.0 SPACE STATION TETHER DEPLOYMENT SYSTEM INTERFACE REQUIREMENTS

1.1 <u>Storage Site Interfaces Shall Provide For Storage And Maintenance Of The SIDM To Include:</u>

1.1.1 System umbilical providing a communications and data link between Space Station and SIDM systems.

1.1.1.1 Communications and data link transmissions via hard wire or KU band/S band phase modulation link.

1.1.2 Power umbilical for SIDM battery recharge and vital systems power.

1.1.3 Berthing interface providing for rigid storage of the SIDM between missions.

1.1.4 Meteroid shield protecting the SIDM against micro meteroids and debris.

1.1.5 Contamination sensor for fuel and contamination leaks.

1.1.6 CCTV and lighting for SIDM operations.

1.2 <u>Fueling Depot Interfaces Shall Provide For The Replenishment Of SIDM Propellant Tanks To Include:</u>

1.2.1 System umbilical providing a communications and data link between Space Station and SIDM systems.

1.2.1.1 Communications and data link transmissions via hard wire or KU band/S band phase modulation link.

1.2.2 Power umbilical for SIDM battery recharge and vital systems power.

1.2.3 Berthing interface providing a rigid attach of the SIDM for refueling.

1.2.4 Contamination sensor for fuel and contamination leaks.

1.2.5 CCTV and lighting for SIDM refueling operations.

1.2.6 Thermal control of temperature sensitive fuel transfer systems.

1.2.7 Fuel umbilical for the transfer of propellants to and from the SIDM and fuel depot.

1.2.7.1 Leakage during propellant transfer

External: No propellant leakage, engaged or disengaged.

Internal: (TBD).

1.2.8 Fluid transfer monitoring system for all propellants.

1.3 Orbiter Interfaces Shall Provide For the Attachment And Monitoring Of The SIDM For Tether Deployment To Include:

1.3.1 System umbilical providing a communications and data link between Orbiter and SIDM systems, capable of quick disconnect for emergency SIDM jettison.

1.3.1.1 Communications and data link transmissions via hard wire and/or KU band/S band phase modulation link.

1.3.2 Power umbilical for SIDM battery recharge and vital systems power, capable of immediate shutdown and disconnect for emergency SIDM jettison.

1.3.3 Load transfer interface providing for the rigid attachment of the SIDM during deployment.

1.3.3.1 Capable of 2 fault tolerant release under full tension load.

1.3.4 Fuel umbilical for the transfer of OMS propellant during tether deployment.

1.3.4.1 Capable of redundant shut off and disconnect, for emergency SIDM jettison with less than (TBD) leakage for the following:
Disengaged no propellant flow.
Engaged prior to propellant flow.
Engaged during propellant transfer.
Engaged and upon completion of propellant transfer.

1.3.4.2 Leakage tolerances during propellant transfer.
External: No propellant leakage, engaged or disengaged.
Internal: (TBD).

1.3.5 Contamination sensor for fuel and contamination leaks.

1.3.6 CCTV and lighting for SIDM operations.

1.4 Space Station System Interfaces Shall Provide For The Communication And Control Of The Tether Deployment System Components

1.4.1 Communications and data link transmissions via hard wire and/or KU band/S band phase modulation link, for all system components.

1.4.2 CCTV and lighting for SSTDS operations.

Table 3-11 Tether Deployer System Requirements
Tethered OTV Launch

2.0 TETHER DEPLOYMENT SYSTEM INTERFACE REQUIREMENTS

2.1 Upper Deployment Assembly Interfaces Shall Provide For Storage And Maintenance Of The PIDM To Include:

2.1.1 System umbilical providing a communications and data link between Space Station and PIDM systems.

2.1.1.1 Communications and data link transmissions via hard wire or KU band/S band phase modulation link.

2.1.2 Power umbilical for SIDM battery recharge and vital systems power.

2.1.3 Berthing interface providing for rigid storage of the SIDM between missions.

2.1.4 Contamination sensor for fuel and contamination leaks.

2.1.5 CCTV and lighting for PIDM operations.

2.2 Fueling Transfer Interfaces Shall Provide For The Replenishment Of PIDM Propellant Tanks To Include:

2.2.1 Thermal control of temperature sensitive fuel transfer systems.

2.2.2 Fuel umbilical for the transfer of cold gas propellant to and from the PIDM and fuel servicer.

2.2.3 Fluid transfer monitoring system for all propellants.

2.3 OTV Interfaces Shall Provide For the Attachment Of The PIDM For Tether Deployment To Include:

2.3.1 Load transfer interface providing for the rigid attachment of the PIDM during deployment.

2.3.1.1 Capable of 2 fault tolerant release under full tension load.

2.3.2 CCTV and lighting for PIDM operations.

Table 3-12 Tether Deployer System Requirements

3.0 KEY CRITERIA, ASSUMPTIONS AND TECHNICAL ISSUES

3.1 Fuel Transfer Technologies

3.1.1 Standardized refueling couplings are assumed to be available by Space Station IOC completion.

3.1.2 Standardized refueling couplings connect/disconnect are assumed to be autonomous operations.

3.1.3 Standardized refueling couplings will comply with leakage and fault tolerant specifications.

3.1.3.1 Leakage tolerances during propellant transfer.
External: No propellant leakage, engaged or disengaged
Internal: (TBD)

3.1.4 SIDM OMS propellant transfer couplings are required to disconnect immediately with acceptable (TBD) propellant leakage levels.

3.1.4.1 SIDM couplings will be able to disconnect over a range of disconnect angles, to accommodate premature or emergency SIDM release.

3.2 SIDM/PIDM Interfaces, Power And Control Systems

3.2.1 SIDM/PIDM to Space Station umbilicals are assumed to be Orbiter payload bay type.

3.2.1.1 Standard payload harness, Standard AFD harness, T-0 umbilical harness, Standard Mixed Cargo harness. (ICD 2-19001).

3.2.2 SIDM/PIDM Control systems will interface and be compatible with Orbiter and Space Station common module work station system consoles with standard harness, control systems, software and hardware.

3.2.2.1 SIDM control system will provide for continual monitoring of fuel transfer during deployment operations.

3.2.2.2 SIDM/PIDM control system will not require continual monitoring by shuttle/OTV/station crew members during normal operations.

3.2.3 SIDM/Shuttle interfaces and docking mechanisms are required to be capable of immediate shutdown and disconnect.

3.2.4 SIDM fuel connects will be compatible with Space Station fuel depot fittings and Orbiter OMS scavenging system.

3.2.4.1 Separate SIDM fuel system connects may have to be provided for: SS fuel depot standard connect and SIDM/Orbiter scavenging system quick disconnect systems.

3.2.5 PIDM refuel operations will require a mobile fuel servicer, for the replenishment of cold gas supplies.

3.2.6 SIDM power, communication and fuel connects are required to connect/disconnect coincidentally with the SIDM/Shuttle berthing.

3.2.7 SIDM/PIDM attach/detach will require IVA time only (no EVA required).

3.3 <u>Mobile Remote Manipulator System</u>

3.3.1 MRMS designs are assumed to provide adequate reach and flexibility and can move to all points on the Space Station.

4.0 TETHER DEPLOYER DESIGN CONCEPTS

The designs presented show the basic elements required for examining all aspects of a deployer system including the system 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 4-1 is 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 transport the MRMS, experiments, propulsion units and solar panels. The deployer designs depend on the use of this 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.

4.1 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 4-1. 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 sytem 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 necessary 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. This requirement was a significant driver in the final deployer configuration.

The Payload Interface Deployment Module (PIDM) and the Shuttle Interface Deployment Module (SIDM) have not changed significantly from the Phase II STAIS study and are desribed in the Phase II final report (Ref. 2). The outside shape of the PIDM has changed from spherical to a truncated cone shape so that entry of the PIDM into the docking cylinder will be improved and to provide more internal volume for the PIDM subsystems. The SIDM has been simplified by the elimination of the cold gas system and sensors required for control during tether deployment and retrieval. This change was made possible because the PIDM provides this

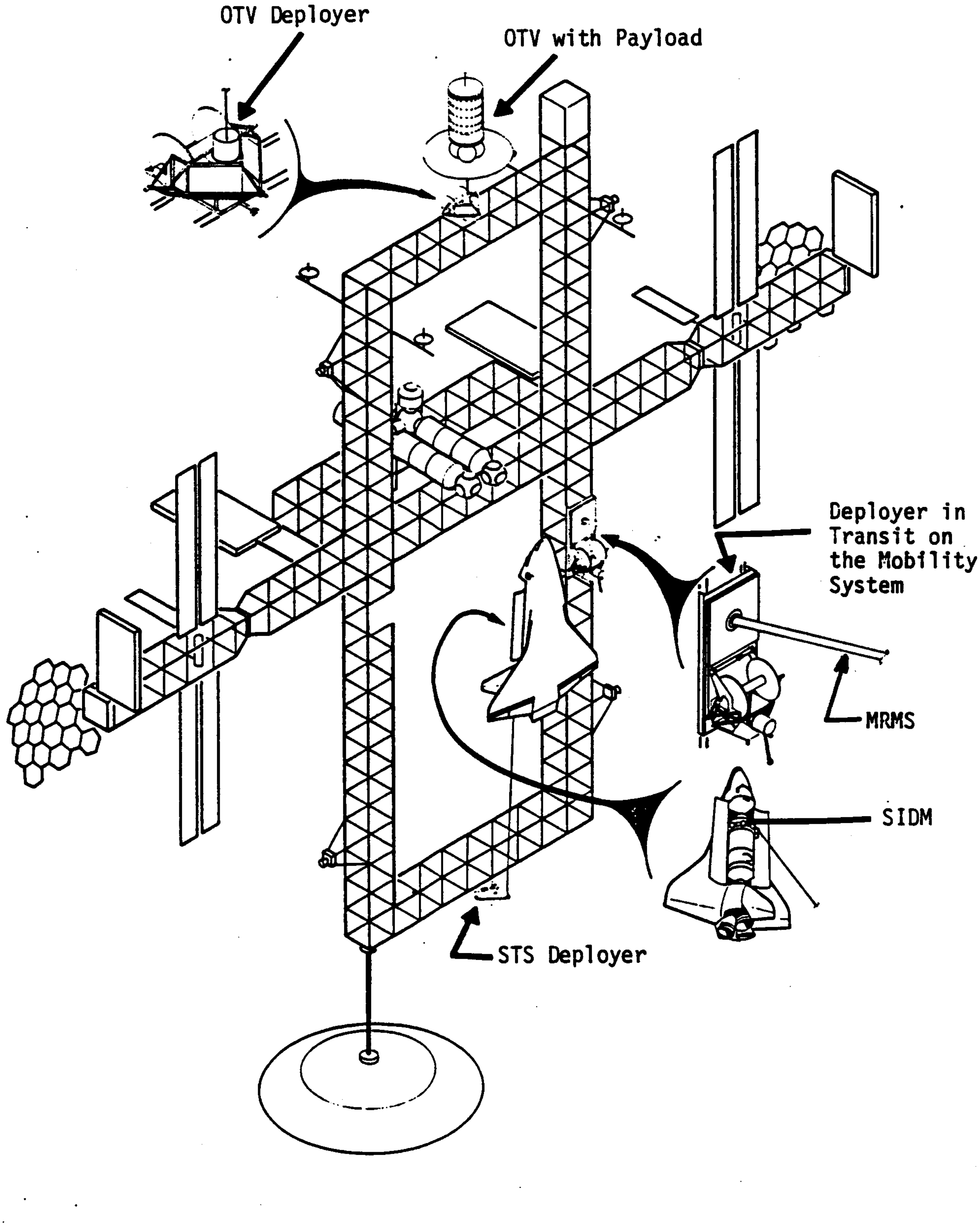


Fig. 4-1 Space Station with Deployer System

function and it will be used in conjunction with the SIDM during Shuttle deployment. The function of the SIDM is to provide a structural interface between the Shuttle and the PIDM and to provide the tanks needed to scavenge OMS propellant from the Shuttle.

The motors for all deployer configurations use the axial gap integral reel/generator/motor permanent magnet design being developed by Martin Marietta Energy System (MMES) at Oak Ridge, Tennessee. It has advantages over the radial gap (an alternative concept) such as lower cost, easier to mount to structure, more experience (at least by MMES), easier heat removal (because the stator is hard-mounted to the structure), more flexibility in reel design (because the motor does not influence the selection of hub diameter) and easier access to the stator/rotor assemblies for repair and maintenance. Both concepts are shown in Figure 4-2.

The power generated during tether deployment will be dissipated through a high temperature radiator that utilizes a 1100°K electrical resistor bank with an emmissivity of 0.8.

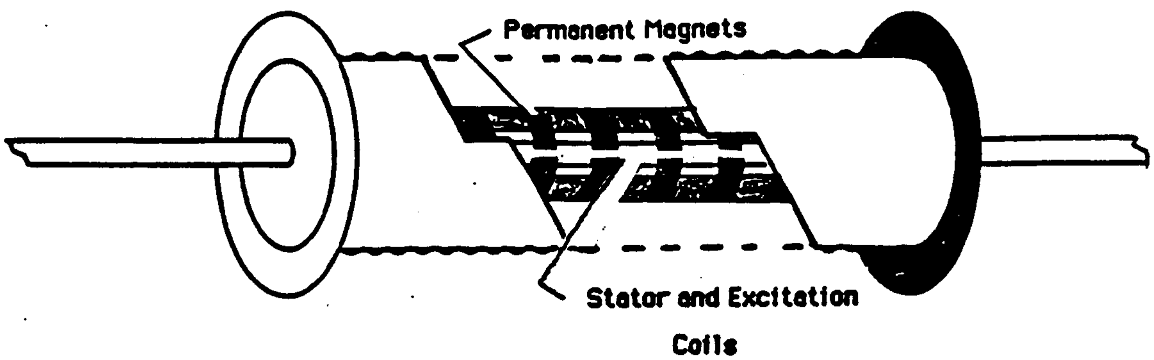
All configurations are designed for return to Earth for repair, tether replacement and checkout. A complete spare deployer is maintained on the ground to minimize system down time. Table 4-1 shows that 55 to 70% of the total system mass is tether so that transporting the total system to orbit is not much more costly than transporting only the tether with its associated support equipment. If larger safety factor tethers are required to assure adequate survivability, tether mass will become a larger percentage of the total mass.

TABLE 4-1 CONFIGURATION SUMMARY

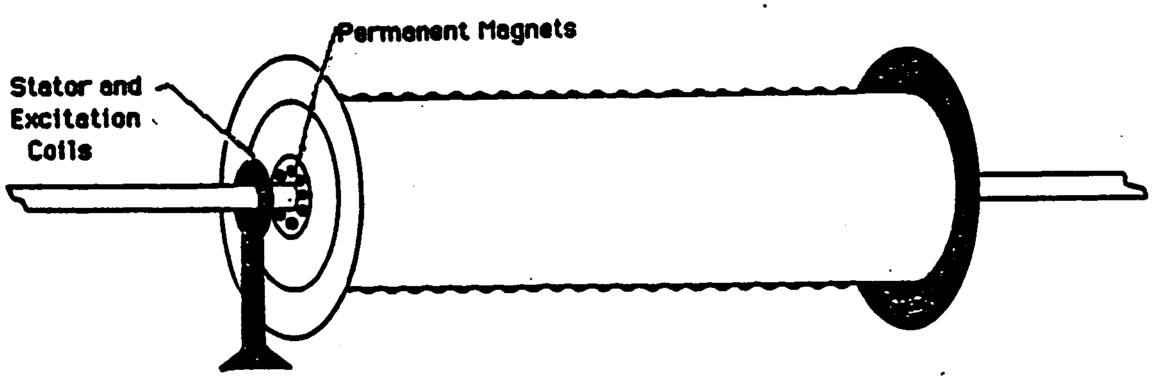
CONFIGURATION	REEL SIZE L/D(M)	TOTAL MASS (KG)	TETHER MASS (KG)	MAX TENSION (N)	TETHER SIZE L(KM)/D(MM)	MAX POWER (KW)
C	1.22/1.4	2,389	1,312	10,676	33/7.11	25
B	1.52/1.68	3,878	2,504	10,676	63/7.11	33
A	1.83/1.98	5,796	3,858	15,480	79/8.13	56
D	2.74/2.36	11,113	7,717	20,020	150/8.13	219

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

4.1.1 Configuration A. Figure 4-3 shows deployer Configuration A which is the maximum capability system for downward deployment. This drawing describes each of the major components which make up the deployer, how they fit together, the total system as it fits into the Shuttle cargo bay for transport to Space Station and how the deployer interfaces with the Space Station.



Radial Gap Motor Integral with Tether Reel



Axial Gap Motor Integral with Tether Reel

Fig. 4-2 Comparison of Radial and Axial Gap Integral Motor/Reel Configurations

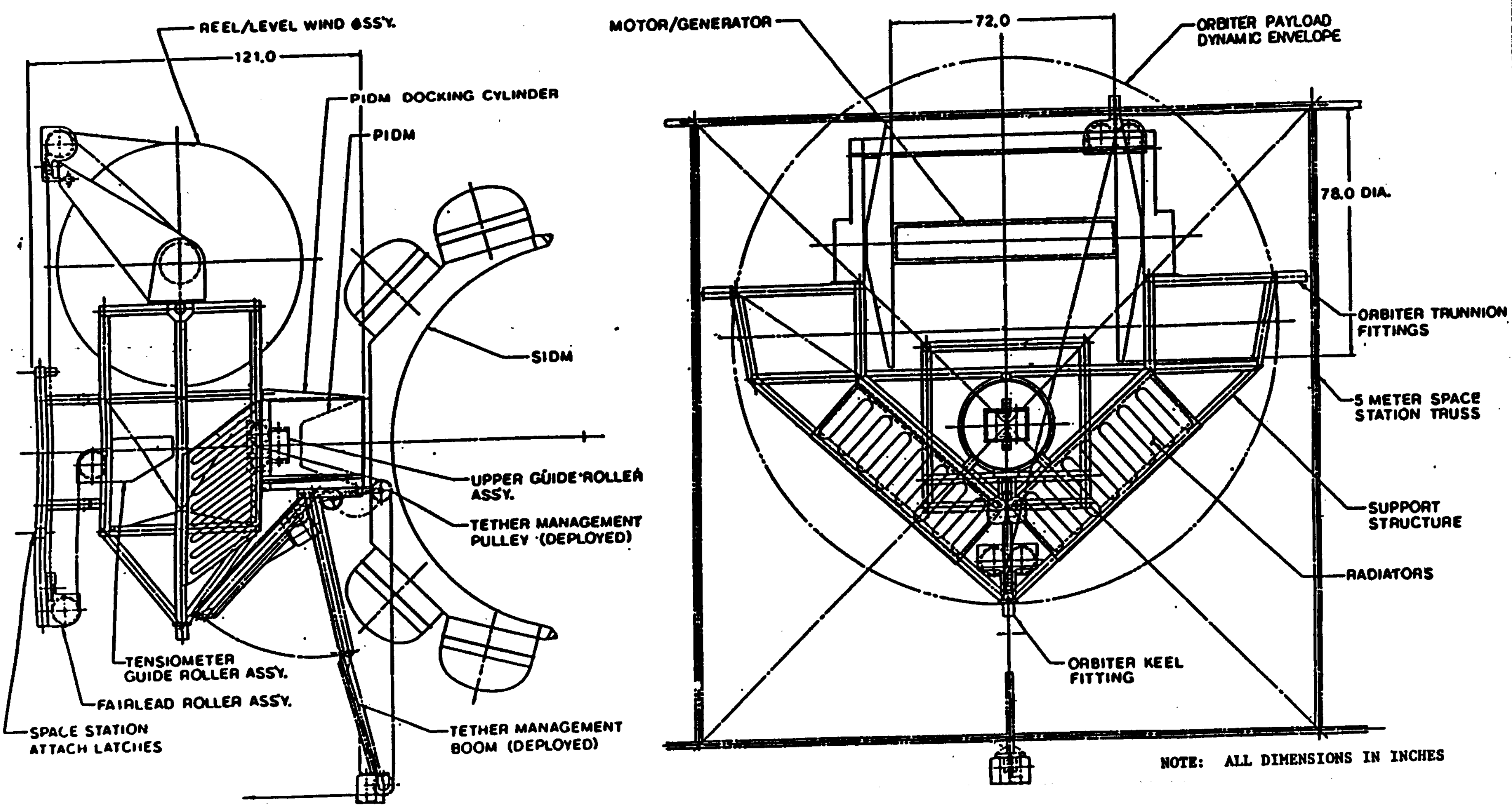


FIG. 4-3 CONFIGURATION A-79 KM OF TETHER

The basic 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, therefore by placing them slightly above the center line of the two trunnion fittings, the combined center of mass should be near the center line of the trunnion fittings. This placement minimizes the overturning moment so that the keel fitting can react the force.

The deployer support structure is triangular shaped forming a truss from one trunnion fitting to the other. The major load through this truss is produced by the reel and tether. The reel assembly includes the level wind and fairlead roller assemblies. The fairlead roller assembly, tensionmeter/guide roller assembly and upper guide roller assembly direct the tether from the level wind assembly to the PIDM docking cylinder. The generator heat rejection radiators are statically mounted to the triangular shaped truss. The SIDM and PIDM are shown in the docked position as they would appear following retrieval after a Shuttle deorbit operation.

Attachment of the deployer to the Space Station is accomplished with the Space Station latches on an interface adapter structure planned for Space Station that is necessary because most equipment will be smaller than the 5 meter truss size.

The PIDM docking cylinder is positioned on the center of the 5 meter truss and the attachment latches are centered on the docking cylinder 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 during the time the 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 Mobility System must move the PIDM around the face of the Space Station structure. Because the deployer is on the outside face of the structure, it is necessary to provide guide rollers which will prevent the tether from dragging and becoming tangled in the structure. The TMB and TMP are deployed with a modular unit with one common drive. The MRMS then removes the PIDM from the docking cylinder and places it on the Mobility System. The tether is positioned in the Tether Management Pulley (TMP) guide rollers and in the pulley on the end of the TMB. The deployer is required to maintain a minimum tension on the tether to prevent tether slack as the Mobility System moves the PIDM to the Shuttle. The TMB and TMP remains deployed until the Shuttle has moved the tether clear of the pulleys.

The TMB is a folding boom that can be stowed and latched during Shuttle launch and deployment operations. The first section of the boom is a four bar linkage device which, during rotation, provides the force to rotate the outer section. Because the outer section must rotate more than the first section, a single stage gear set is provided at the pivot so that the outer section can pivot at a faster rate. The tether management pulley assures the tether will clear the PIDM docking cylinder.

This deployer design makes the most efficient use of the structural members because they serve a dual purpose. They support the systems in the cargo bay as well as at the Space Station.

Figure 4-3 does not show items such as motor controller, support electronic boxes, fluid lines and umbilical connectors. They are connected to Space Station services after the deployer is in place.

4.1.2 <u>Configuration B</u>. Figure 4-4 shows the deployer system designed to satisfy the deorbit requirements for the STS, the ET and waste disposal from a maximum altitude of 370 km. This requirement is consistent with the variable altitude scenario (Case III). The design is similar to Configuration A. The only difference being in the size of the components. As shown in Table 4-1, the reel, tether, motor/generator and radiator requirements are reduced and the total mass is reduced from 5,796 to 3,878 kg and the tether mass is from 3,858 to 2,504 kg. This approach will reduce the acquisition cost and initial transportation cost of the tether deployer system. This option is the logical choice if the variable altitude scenario (Case III) is selected for the 11 year period.

4.1.3 <u>Configuration C</u>. This configuration is also similar to Configuration A. The subsystems are much smaller resulting in a total system mass of 2,389 kg compared to the 5,796 kg of Configuration A. This configuration represents the minimum cost and weight for a system that will perform tether assisted Shuttle departures from the Space Station from a maximum altitude of 370 km.

4.1.4 <u>Configuration D.</u> This option represents the maximum capability system anticipated for tether assisted deployment of items from the SS and is shown in Figure 4-5. This system was designed to accommodate the OTV launch with 150 km of tether. Since the capability of this system is greater than any of the other requirements identified in Table 4-1, it can be used in a dual mode to deploy both the OTV (upward) and STS, ET and waste (downward) by utilizing the Space Station Mobility System.

This configuration results in the largest reel size that will fit into the Shuttle cargo bay envelope with the reel positioned laterally. This orientation results in the minimum cargo bay length requirement (3.1M). If the reel is made larger, to accommodate a stronger tether for example, it will have to be positioned lengthwise in the cargo bay and will require greater cargo bay length. This change may also have a significant impact on the mounting of the deployer on the Space Station. If the tether mass increases significantly, the total deployer system mass will approach the cargo carrying capability of the Shuttle making the increased cargo bay length requirement academic.

Figure 4-6 shows a concept for delivering a replacement reel with 150 km of tether to the Space Station. This approach could be used to change out the tether on the Configuration D, or to upgrade Configuration A or B for OTV deployments by replacing the smaller reel. This latter approach would be valid only if the original system (Configuration A or B) were delivered with increased radiator and electrical power handling capability in anticipation of an eventual upgrade and the motor/generator required for the 150 km tether is delivered with the larger reel.

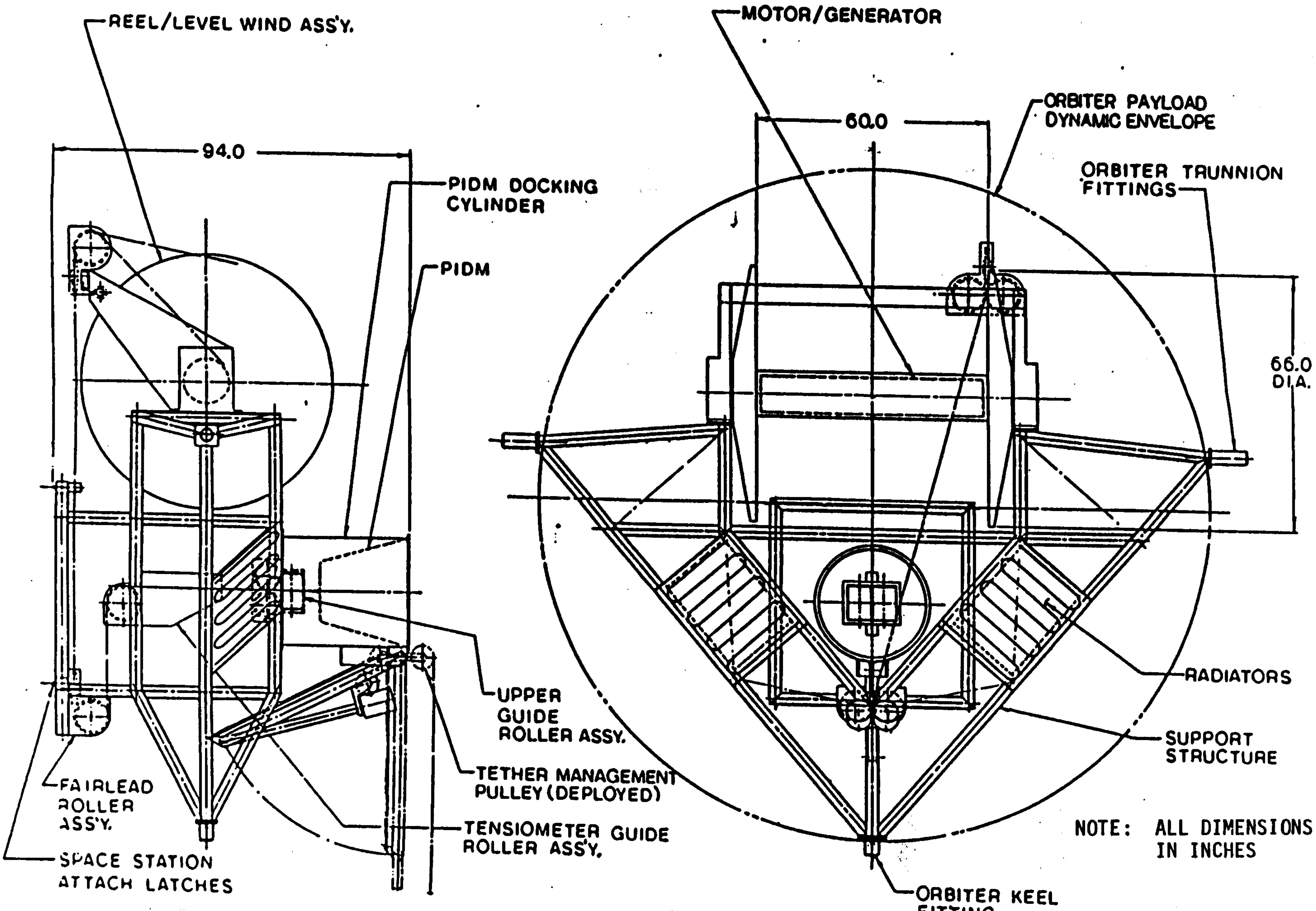


FIG. 4-4 CONFIGURATION B-63 KM OF TETHER

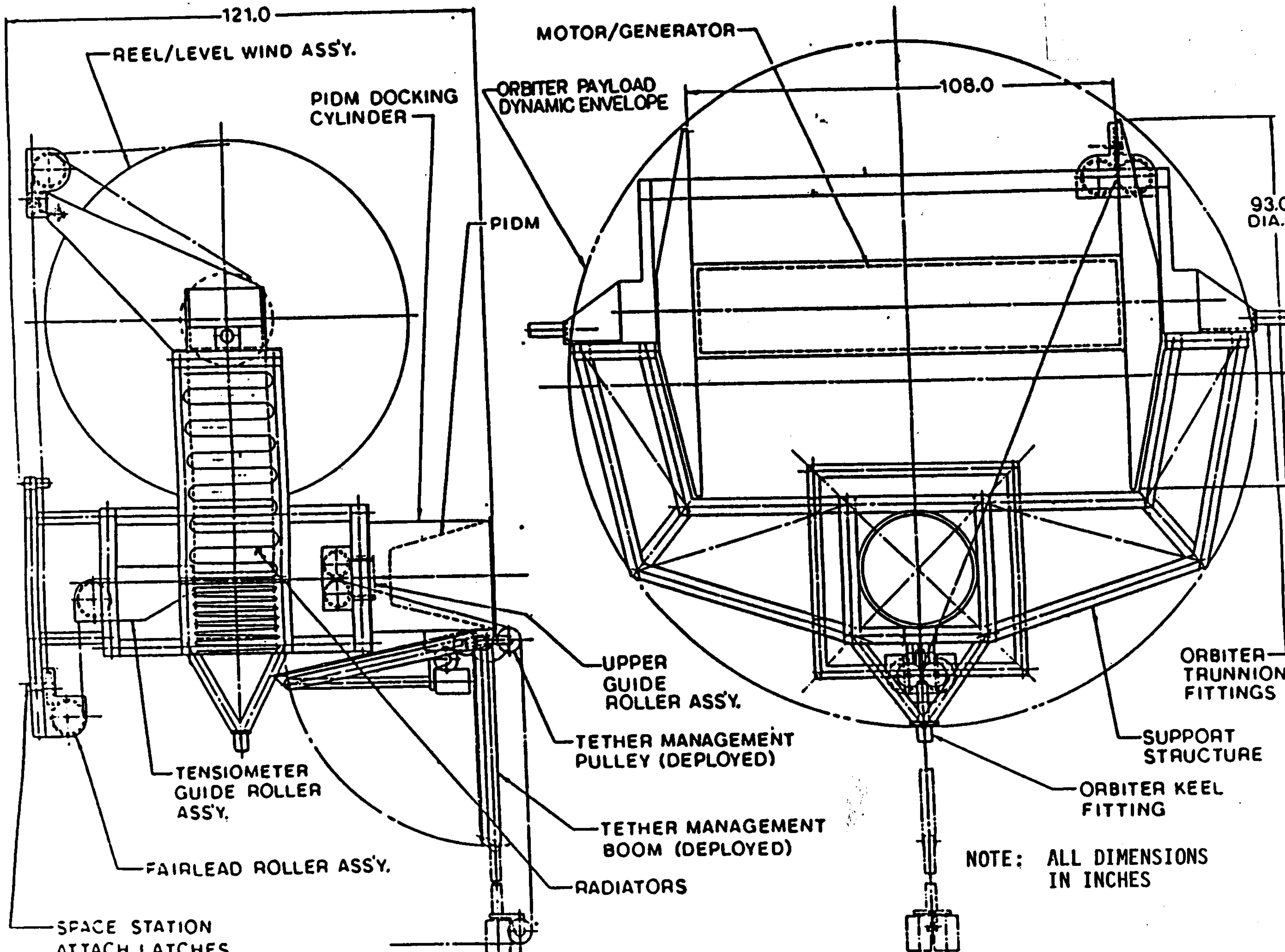
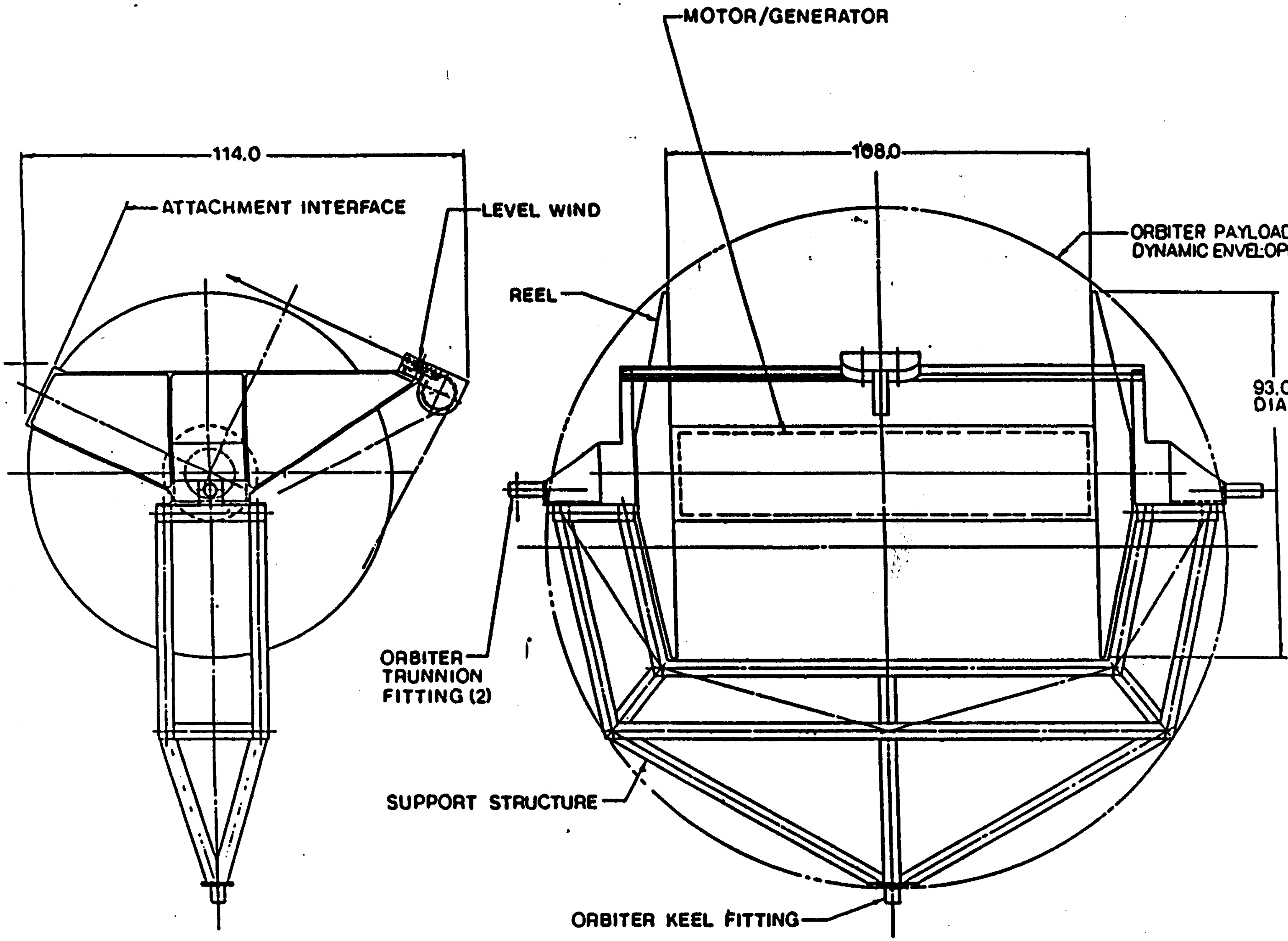


FIG. 4-5 OTV DEPLOYER D-150 KM OF TETHER



NOTE: ALL DIMENSIONS IN INCHES

FIG. 4-6 150 KM REPLACEMENT REEL

The weights of each configuration are summarized in Table 4-2. The weight variations are due mainly to variations in the tether, reel and motor/generator system.

4.2 Configuration Implementation. Several approaches are available to implement the four configurations discussed in paragraph 4.1. Final selection of the optimum apporach is not possible because many of the considerations present intangible benefits or problems and the differences in cost are a small percentage of the total cost benefits. The subsequent paragraphs identify several alternatives and discuss some of the considerations to be used as selection criteria.

4.2.1 Baseline Approach. The baseline implementation approach has been to initially deploy the full capability Shuttle deployer system (Configuration A) with a smaller 63 km x 7.11 mm tether. This approach provides all the deorbit capability required for the variable altitude scenario (Case III) with a moderate initial weight. In 1999 when the OTV becomes operational and if the SS is placed in a constant 463 km orbit, the larger (79 kg x 8.13 mm) tether will be placed on the Option A deployer and the OTV deployer will be delivered. This baseline was selected before we had fully defined the advantages of combining the variable altitude approach with OTV launch, before we had the insight of the Mobility System planned for the Space Station and before we had data showing the benefits of Case III over Case IV. This baseline does not appear to have a lot to offer unless neither the variable altitude approach (Case III or IV) nor the use of a single deployer for both OTV and Shuttle deployments are adopted.

The advantages and disadvantages of this implementation approach are as follows:

Advantages:

1. Moderate acquisition cost and initial delivery weight.
2. Early capability for ET deorbit and waste disposal.
3. Operational Experience is gained before freezing the OTV deployer design.
4. Could use high safety factor tether (at a weight penalty) to gain experience at low risk of tether failure and reduced recoil dynamics.

Disadvantages:

1. Results in the maximum weight final system (Configuration A plus D).
2. Requires tether replacement if SS is raised to higher orbit.
3. Is oversized if variable altitude approach is selected for the eleven year period.

4.2.2 Configuration B Plus D. This implementation approach is nearly the same as the baseline approach except that the smaller Configuration B is initially deployed. The OTV deployer would be added in 1999 when the OTV becomes operational. This approach would be employed if the variable altitude approach is selected for the life of the program and the transportable dual OTV/STS deployer approach is not adopted.

TABLE 4-2

DEPLOYER WEIGHT SUMMARY
(Weights in Kg.)

SUB-SYSTEM	CONFIG. A	CONFIG. B	CONFIG. C	CONFIG. D
SUPPORT STRUCTURE ASS'Y	190	158	136	265
REEL	790	426	295	1,590
MOTOR	318	249	159	681
LEVEL WIND (INCLUDES BEARING - PULLEYS - TRACK SUPPORT STRUCT. TIMING SYSTEM)	113	63	36	160
PIDM SUPPORT CYLINDER & LATCHES	23	23	23	23
TETHER MANAGEMENT BOOM ASS'Y.	68	68	68	68
UPPER, LOWER & FAIRLEAD ROLLER ASS'YS	82	82	82	82
RADIATOR	35	18	14	133
SUPPORT ELECTRONICS	160	160	160	160
COLD PLATE	82	63	45	136
METEOROID COVER (REEL)	23	12	9	37
MISC. HARDWARE	9	7	5	16
TETHER	3,858	2,504	1,312	7,717
WIRING, COOLING LINES, UMBILICALS, INSULATION, ETC.	45	45	45	45
TOTAL DEPLOYER	5,796	3,878	2,389	11,113
PIDM	1,193	1,193	1,193	1,193
SIDM	2,204	2,204	2,204	2,204
TOTAL	9,193	7,275	5,786	14,510

Another situation that would encourage the use of Configuration B is if the variable altitude scenario is adopted and the OTV is launched without tether assist (Case III) because of the possible undesirable frequency of tether operations if all Shuttle and OTV launches are tether assisted or if the upper horizontal boom of the Space Station is occupied with a tethered science platform, a micro gravity tether, an electrodynamic tether or some other system that would preclude tethered OTV deployment operations. In this event the OTV deployer would not be implemented. As seen in Section 2.0, variable altitude deployment of the Shuttle with non-tethered OTV deployment yields significant performance gains.

The advantages and disadvantages of this implementation approach are as follows:

Advantages:

1. Lower acquisition costs and initial weight than Configuration A. Very low weight and cost if Configuration D is never employed.
2. Provides full Shuttle, ET and waste deorbit capability early.
3. Operational experience gained before Configuration D design freeze.
4. Moderate life cycle costs.

Disadvantages:
1. No margin available for higher strength tether.
2. High weight system if used with Configuration D.

4.2.3 Minimum Initial Cost System. This approach is the same as the one discussed in paragraph 4.2.2 except that the minimum capability (Configuration C) deployer system is initially deployed. This approach represents the minimum initial cost and weight system, but also has limited capability since only the Shuttle can be deorbited from altitudes up to 370 km. This approach would be selected if fiscal funding constraints are severe during the development years and there is no interest in ET or waste deorbit and the variable altitude scenario (Case III) is selected for the total 11 year period.

Advantages:

1. Lowest initial cost and weight system.
2. Provides early low cost capability for Shuttle deorbit from altitudes up to 370 km.

Disadvantages:

1. Limited capability.
2. No margin available for higher strength tether during early operations.

4.2.4 Configuration D. This implementation option involves installing the Configuration D deployer initially with a down rated tether (possibly 63 km x 7.11 mm). When the OTV becomes operational a full size (150 km x 8.13 mm) tether will be installed and Configuration D will be transported to the top or bottom of the Space Station to perform both OTV and Shuttle tether assisted launches. This approach results in the lowest LCC for any system offering OTV tether assisted launch capability because only one deployer system must be developed and it provides the maximum capability and versatility.

The advantages and disadvantages are as follows:

Advantages:

1. Provides the lowest LCC of any full capability system.
2. Provides maximum versatility because a very strong tether could be used initially, resulting in a very low risk of failure and reduced recoil. The excess motor/generator capability (for Shuttle, waste or ET deployment) may allow shorter deployment times.
3. All systems have very large margins during early applications and are more forgiving during the learning phase of operations.
4. Maximum cost benefits over total program.

Disadvantages:

1. Highest initial cost and weight
2. No opportunity to gain operational experience before finalizing the Configuration D design.

We would recommend this option (Configuration D and Case III/V operations scenario) if a large number (up to 30 per year) tether operations are permissible because of the potential for maximum cost benefits. We would propose to outfit the reel with a large safety factor tether (perhaps up to 10) for the initial operation. This configuration would remain on the Space Station until something fails or until about 2 to 2 1/2 years before the OTV is scheduled to become operational. At this time the spare deployer would be installed on the Space Station and the initial one returned to the ground for detailed inspection, checkout, repair and to make modifications that may be indicated. It would then be outfitted with a 150 km tether and returned to the SS for OTV and STS deployment operations. The spare deployer system would then be returned to Earth, refurbished and modified as required and stand by to be used as a spare.

4.3 Deployer Installation on Space Station. Figure 4-7 shows the dual keel Space Station configuration with the Shuttle docked to a module with the PIDM and SIDM in place. The tether is attached to the PIDM and leads to the deployer as it will appear prior to Shuttle deployment for deorbit. The deployer is attached to the center cube of the lower horizontal boom for downward deployment operations. For upward deployment operations: i.e. OTV deployment, the deployer would be attached to the center cube of the upper horizontal boom.

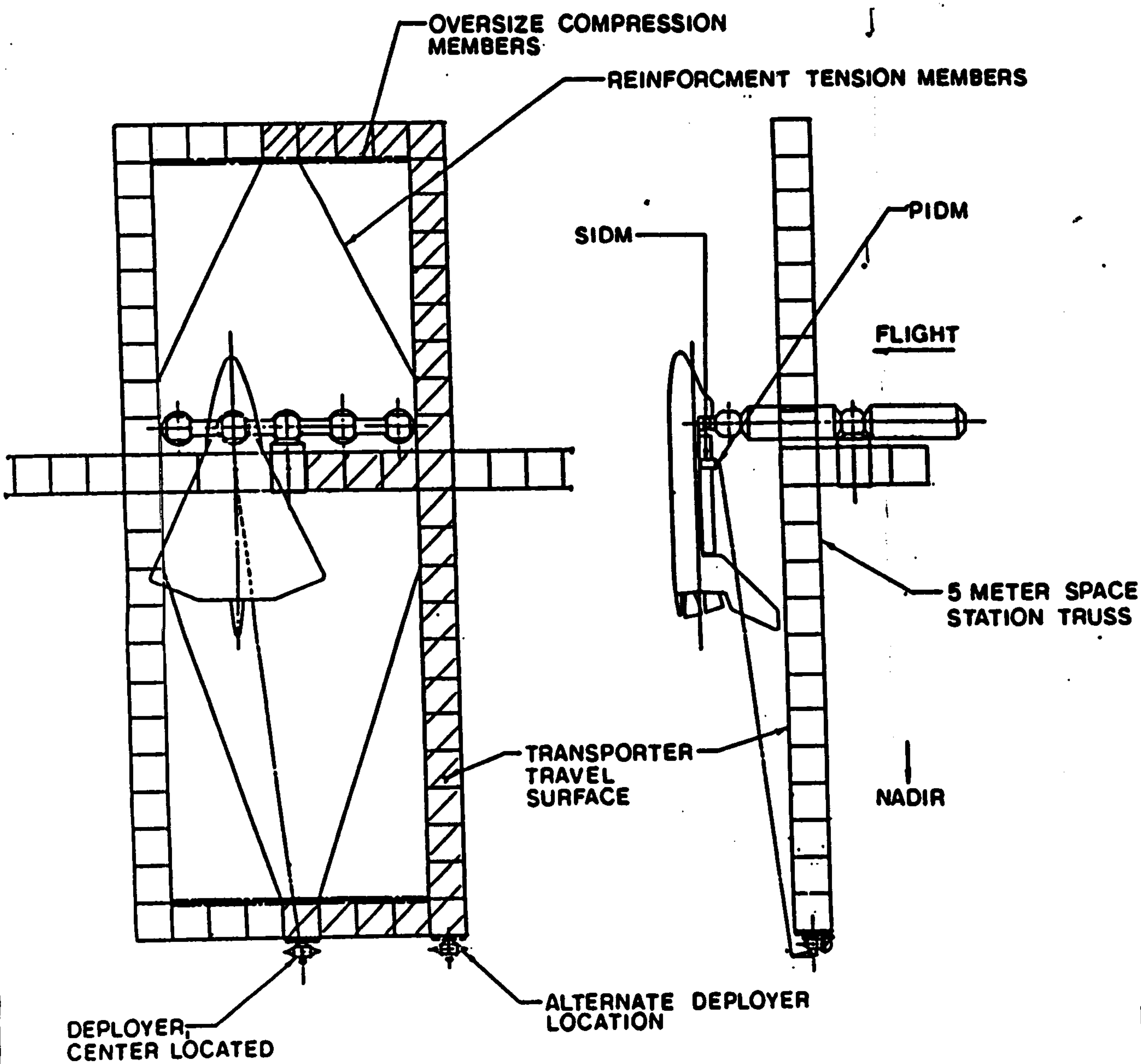


Fig. 4-7 Tether Deployer System Attachment Options

Attachment of the deployer at these locations will not be possible with the present Space Station structural member sizing because the forces applied to the structure at maximum tether tension will exceed the column buckling strength of the compression members by a factor of more than two. If these deployment locations are selected, the compression members must be made larger or as shown in Figure 4-7, additional tension members must be added to remove the load from the lower horizontal booms. Presently the truss members are 2.00 in. O.D. x .06 in. wall thickness graphite epoxy tubes. To support these high compression loads, these members must increase to 5.00 in. O.D. x .125 in. wall thickness. If the members are increased in size at both the upper and lower horizontal boom, the structural weight will increase by 290 kg. If tension reinforcing members are added rather than increasing the truss compression member size, the Space Station structural weight will increase by only 34 kg. Another option is to place the deployer at the end of the vertical keel which would remove beam bending and allow the tension loads to be reacted directly into one of the twin keel trusses.

Tether forces, regardless of deployer location, will exceed the ability of the Space Station attitude control systems to maintain normal Space Station attitude; therefore, during deployment operations, the Space Station will be gravity stabilized in an attitude dictated by the position of the deployed mass. This means the Space Station attitude will be constantly 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 at the end of the boom, in line with one of the twin keels, thus avoiding the requirement to add additional structure to Space Station. This location would cause the Space Station to roll about the velocity vector up to about 18 degrees. This temporary attitude change should not cause any greater problem to SS operations than the unavoidable in-plane librations of up to 30 degrees. Locating the deployer at the end of the vertical keel also avoids interference between the Orbiter vertical tail and the tether for all docking locations. This issue does not have an affect on deployer designs discussed in this report.

Since the Space Station will have a Mobility System for moving equipment to diffferent locations on the truss structure, the tether deployer system will use it to:

1. Transport the deployer from the Shuttle to its operational location on the Space Station.

2. Move the deployer from one end of the Space Station to the other so that only one deployer will be required for both upward and downward deployment operations.

3. Transport the PIDM from the deployer to the docked Shuttle where it is attached to the SIDM (which is already in place on the Shuttle) in preparation for Shuttle deorbit deployment.

4. Transport the SIDM from the docked PIDM to the fuel storage area for transfer of its propellants to the storage tanks and move the SIDM to the storage area until its next use.

5.0 COST MODEL, METHODOLOGY, AND RATIONALE

The objective of the model is to estimate the cost of the Selected Tether Applications in Space program elements so that a cost effective concept can be recommended.

The costing effort represents the current design and includes all costs incurred during the 42 month phase C/D design, development, test, evaluation, flight certification and production efforts. Net program benefits are presented for tethered versus non-tethered Space Station (SS) operations at both variable and constant 463km altitudes for an 11 year period.

5.1 Costing Approach. The WBS and WBS dictionary (Ref. 7) were prepared in cooperation with the MSFC engineering cost group. The WBS was used to provide a format for reporting all STAIS (and related SS, OMV, OTV, and STS) programmatic cost impacts.

The mechanism for estimating and reporting costs to the WBS is a personal computer (PC) predictive cost model called the Selected Tether Applications COst Model (STACOM) which was developed by Martin Marietta using software from Lotus Development Corporation. The model calculates all phases of program costs using the technical description of the STAIS tether deployer systems and the requirements of operations support.

Typical inputs to the STACOM model include:

- o STAIS subsystem component weights;
- o Operational time constraints;
- 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 Specific Shuttle transportation limitations/capabilities.

The model sums the costs by program phase and hardware element to produce a cost for each WBS element. The model is a tool for assessing the impact of design/operational variations on cost estimates.

5.2 Costing Methodology and Rationale. The key to the STACOM cost model is the Martin Marietta Cost Analysis Data Base (CADB). This CADB (Ref. 8) contains historical cost data from previous programs (e.g. Tethered Satellite System (TSS), Viking, Titan, etc) in the form of cost estimating relationships (CERs). These CERs provide the means for estimating the cost of the STAIS program elements. Additional CERs from other sources (e.g. Space Station (Ref. 9), SAMSO Unmanned Spacecraft (Ref. 10)), were also used.

Cost avoidance techniques are used to reduce costs, e.g., the prototype/protoflight design philosophy is used to reduce costs yielding lower phase C/D costs. This results in a lower acquisition cost and reduces the Life Cycle Cost (LCC) by 20%. The prototype design philosophy will be used at the component level which requires testing of the unit as a whole and not testing of each individual component piece. All vibration, thermal, vacuum, acceptance and performance testing is done to flight qualify the hardware at the system level to assure the integrity and flight safety of the protoflight approach.

5.3 Groundrules and Assumptions.

5.3.1 General - The following costing groundrules and assumptions apply:

- o Costs are reported in constant fiscal year (CFY) 1987 dollars.
- o Phase C/D estimates include fee, overhead, and general and administrative (G&A) costs.
- o Normal GFE/GFP (e.g. Space Station launch site facilities and transportation) is assumed.
- o A protoflight testing approach is used at the system level and a prototype testing approach is used at the component level.
- o Hardware design incorporates maximum use of off the shelf mechanical, electrical and structural equipment.
- o A 42 month phase C/D effort was used for design, development, test, evaluation and production estimates for the initial configuration.
- o The flight program begins with the first tethered Space Station Shuttle operation and continues for 11 years.
- o Maximum use is made of Space Station hardware common to the STAIS tether deployer system hardware (e.g. electrical radiators).
- o One tether deployer system shall be operational at all times.
- o One ground based tether deployer system shall be maintained for contingency purposes.
- o No costs for contractor monitoring and test facilities are included.

5.3.2 Design, Development, Test and Evaluation (DDT&E)

- o DDT&E includes all non-recurring costs associated with the STAIS hardware, software, and WBS level 3 integration.
- o SE&I (WBS element 1.3.3) costs include the efforts required to interface the STAIS hardware with the Shuttle and OMV. OTV interfaces are included when the OTV is part of the tethered mission operations.
- o Hardware components produced for test purposes only are included in the estimate.
- o Costs associated with all tests except recurring production acceptance tests are included.
- o When two tether deployer systems are used a cost method of applying similarity factors is used to estimate the second deployer system.

5.3.3 Production.

- o Production costs include all recurring costs.
- o Production acceptance testing is included.
- o No production learning curve was applied to manufacturing due to the small production run.

5.3.4 Operations. Operations are divided into two parts. The first part includes the WBS elements (Mission and Launch Site operations) that occur during the 42 month phase C/D development and production effort. The second part includes the WBS 1.4 (STS) and 1.5 (Space Station Integration) modifications, plus the 11 year space operations costs of tethered Shuttle, waste module and OTV operations.

5.3.4.1 Phase C/D Mission and Launch Site Operations. The phase C/D Mission and Launch Site operations costs include all pre-launch, flight and post-flight planning, procedure development, crew training, flight operations, and post-flight analysis.

5.3.4.2 Space Station Tether Operations.

- o The 11 years of tether operations include all costs associated with pre-launch preparation and testing, flight hardware spares, checkout, deployment, tether operations, and post-flight inspection and storage of the tether deployer system.
- o Spares are assessed using 90% of the the mean time between failure (MTBF) as the maximum life of each part over an 11 year period.
- o Spares include one complete duplicate of each system (i.e. PIDM, SIDM, tether deployer module). They are maintained on the ground and transported to the Space Station when needed.
- o The recurring cost of tethered operations begin with the first flight and continues for 11 years.
- o Payload transportation costs are $100 million per Shuttle flight.
- o Intravehicular activity (IVA) is assessed at $18K per IVA manhour.
- o Extravehicular activity (EVA) is assessed at $150K per EVA manhour (including 2 man EVA plus 1 man IVA monitoring EVA activity).
- o EVA is used only for tether deployer installation and contingency operations.
- o One OMV per tethered OTV mission is eliminated. Each OMV cost is $3.0M (excluding propellant).

5.4 Technology, Test and Operations Philosophy. The philosophy for the technology effort concentrates on early development of critical path technologies (e.g. integral reel motor/generators, tether splicing devices, and 'reduced strength' tether detection mechanisms).

The test philosophy uses the protoflight approach.

The operations philosophy has two parts. The initial Mission and Launch Site operations will make use of the experience gained from the Martin Marietta Tethered Satellite System program. The second part assumes maximum use of automation of the tether deployer interfaces (i.e. OMS propellant transfer quick disconnect valves, total autonomous MRMS mobility about the SS, etc), modular systems for reduced EVA and maintenance, and minimum IVA for tether deployment and retrieval operations.

5.5 Cost Avoidance Techniques. Off the shelf equipment shall be used wherever possible, e.g., electrical radiators and mechanical cold plates. Every effort will be made to share SS hardware, i.e., radiators.

The tether system (including pulleys, level winds and tether boom) shall be designed to accomodate various diameter tethers to satisfy any tether safety factor requirement, or tether deployment operational capability.

Further total program acquisition cost savings could be achieved if a design to cost (DTC) program philosophy is incorporated early in the program and becomes an integral part of tether deployer program requirements.

Space based cost avoidance techniques include transportation of the entire tether deployer module for tether replacement instead of designing and building unique aerospace support equipment (ASE) for each tether deployer system. This technique focuses on eliminating development and production costs for ASE. This may incur increased space based tethered operations costs if the higher weight tether deployer system is used instead of perhaps lower weight ASE to transport replacement tethers to the SS and if the replacement is frequent. This approach offers low operational risks because critical installation and checkout is performed on the ground.

Modular design for decreased EVA of on-orbit repairs reflects a progressive mode of total LCC cost reduction. Modular systems could be designed such that no EVA activity would be required to remove and repair on orbit (i.e. motor controller assembly could be mounted for ease of access, removal and installation, and spare parts conveniently stored on orbit as necessary).

5.6 Cost Model. The Selected Tether Applications Cost Model (STACOM) is an automated PC computer model (Ref. 1) developed by Martin Marietta using Lotus Development Corporation software to calculate all phases of program cost based on the STAIS tether deployer system technical description and tethered operation requirements. Key features of the model include: review of program costs, benefits, or groundrules and assumptions; revise program costs, benefits, tether deployer system hardware lists, or user variables; perform "what-if" sensitivity analyses on one or two variables versus acquisition cost, LCC or net benefits of tethered operations; print groundrules and assumptions, program costs, tether deployer system equipment lists, operations and support costs, or program benefits; and perform funding spread analysis of program costs based on NASA recommended "beta" curves.

5.7 Phase C/D Cost Summary. The STAIS cost analysis provides visibility into the 42 month phase C/D program effort, the 11 year space based recurring operations costs, and the relative net benefits of tethered Shuttle, waste module and OTV operations on Space Station.

The STAIS phase C/D program cost estimates were developed by phases (i.e. DDT&E, production and operations). Figure 5-1 presents the program overview.

A cost profile for each tether deployer system configuration by program phase has been prepared using the cost estimates developed specifically for this study. The STAIS DDT&E cost estimates include the total non-recurring costs to develop, integrate and test the STAIS system with the Shuttle and OMV supporting program interfaces. The OTV integration is included in the cost estimates for the Configuration D tether deployer system. The DDT&E cost estimate is based on a new start, total program philosophy of hardware that requires several unique technology developments and extensive technology survey. GFE/GFP launch and facility costs are not included in DDT&E. The costs for GSE and SSE are included in DDT&E. Spares are included in the production and space based operations sections.

Table 5-1 shows the DDT&E estimates for the STAIS configurations: A, B, C, and D. The total cost ranges from $64M to $88M (CFY 1987 dollars).

The STAIS hardware design and development cost is driven by the large percentage of cost expended on mechanisms (i.e. reel assy, drive mechanisms, latches). These elements account for an average of 20% of the total DDT&E cost.

The recurring production costs for the STAIS system include only the cost estimates for tethered Space Station operations hardware. Excluded are any DDT&E ground test refurbishment costs.

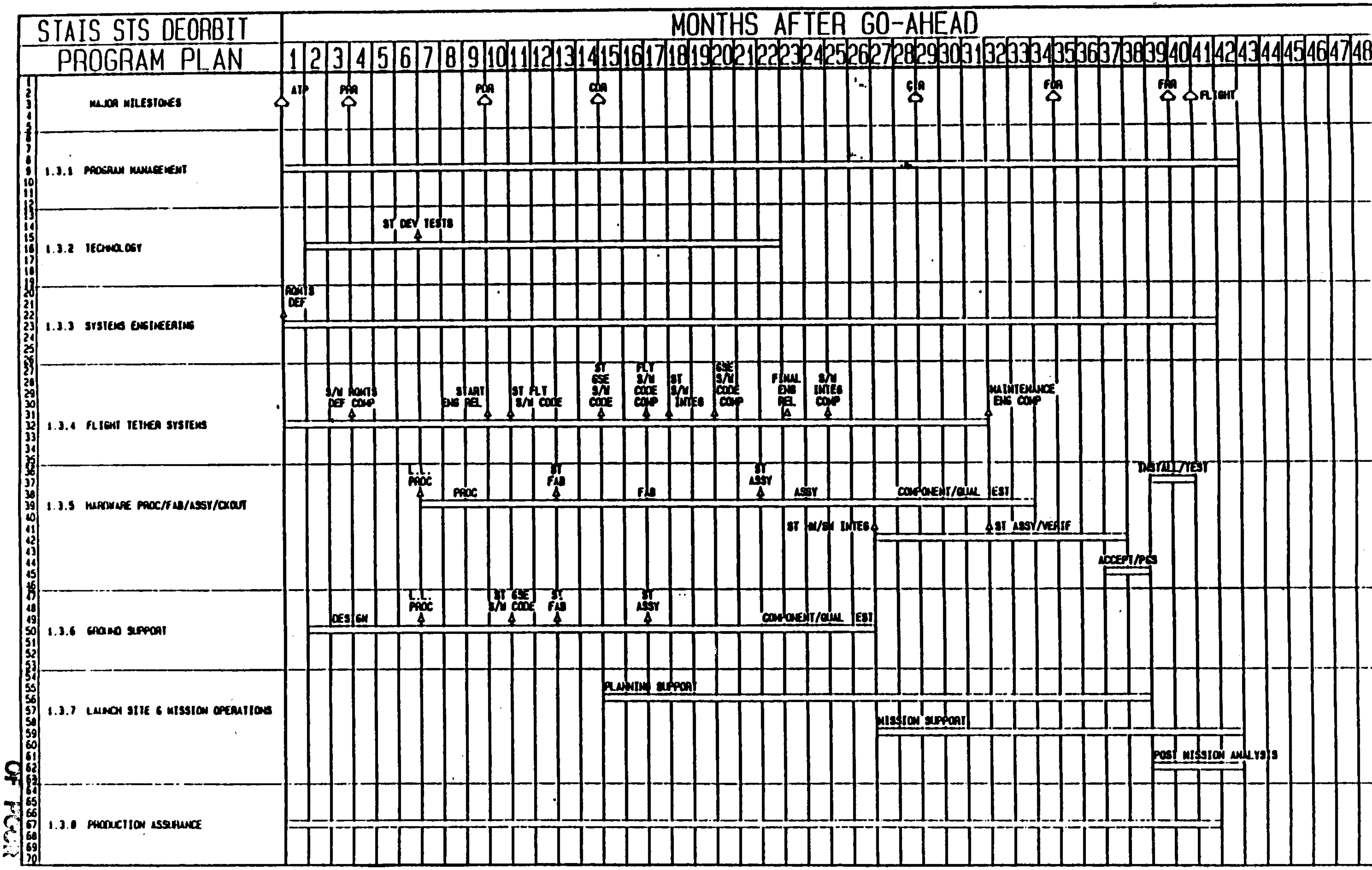


Figure 5-1 Phase C/D Program Schedule

Table 5-1 DDT&E Cost Estimate (Millions of CFY 1987 Dollars)

Description	Configuration A	B	C	D
Support Structure Ass'y	$ 0.15	$ 0.13	$ 0.12	$ 0.18
Reel	8.37	5.78	4.66	12.93
Motor	1.63	1.56	1.45	1.84
Level Wind (Includes bearing, pulleys, track, timing system)	5.52	4.15	3.24	6.60
PIDM Supt Cylinder & Latches	0.05	0.05	0.05	0.05
Tether Management Boom	0.86	0.86	0.86	0.86
Upper, Lower & Fairlead Roller Assy's	2.34	2.34	2.34	2.34
Radiator	0.64	0.50	0.45	1.19
Support Electronics	1.46	1.46	1.46	1.46
Cold Plate	0.47	0.42	0.36	0.61
Meteoroid Cover (Reel)	0.27	0.22	0.20	0.32
Misc. Hardware	0.15	0.14	0.13	0.18
Tether	0.18	0.18	0.10	0.18
Wiring, Cooling Lines, Umbilicals, Insulation, etc.	0.64	0.64	0.64	0.64
PIDM	11.15	11.15	11.15	11.15
SIDM	6.60	6.60	6.60	6.60
Software	3.00	3.00	3.00	3.00
WBS Level 3 Integration and Testing	32.56	28.87	26.85	38.23
Total	$ 76.04M	$ 68.05M	$ 63.66M	$ 88.36M

Table 5-2 presents the production costs for each of the Space Station based tether deployer systems. Estimates for additional ground based hardware to accomodate tethered Shuttle, waste module and OTV operations on Space Station are not included in this estimate. The total recurring cost required to meet initial Shuttle deorbit operations hardware requirements (including one Shuttle tether deployer system, one Shuttle Interface Deployment Module, one Payload Interface Deployment Module) ranges from $22M to $27M.

5.8 Phase C/D Work Breakdown Structure Estimates. The WBS (Ref. 7) used for phase C/D program cost estimates was developed by Martin Marietta. This WBS matrix format provides the flexibility to identify unique STAIS program costs and displays the results in a clear and concise format as can be seen in figure 6-1.

The WBS program estimates were assessed to level 3 (see section 6.0). Table 5-3 presents the total program cost estimate according to the WBS for each deployer system configuration.

The program cost estimate includes DDT&E costs and level 3 Shuttle, Space Station, OTV and OMV integration costs (WBS element 1.3.3). DDT&E WBS program elements comprise an average of 74% of total phase C/D costs.

Production cost estimates include the initial production protoflight unit (with built-in payload carrier hardware). Production WBS program elements comprise an average of 23% of total phase C/D costs.

Phase C/D Mission and Launch Site operations include planning, developing, and implementing pre-launch, flight, and post flight planning, procedure development, crew training, flight operations, and post flight analysis for the tether deployer system. Excluded are space based recurring costs associated with tethered operations: IVA and EVA for tether deployment and retrieval operations, deployer system installation, scheduled maintenance, and modifications for Space Station, OTV, OMV and Shuttle. The phase C/D Mission and Launch Site operations costs account for approximately 3% of the total phase C/D program cost.

Figure 5-2 presents a typical WBS funding spread for Configuration B based on NASA recommended "beta" curves.

Table 5-4 presents the program funding for the initial acquisition of Configuration B over the 42 month phase C/D effort. Annual funding levels were developed and are shown by WBS elements.

5.9 Summary. Table 5-5 presents the summary of the four configurations (operating as single systems or in combination with the more versatile Configuration D tether system) under selected mission scenarios to show relative net benefits of tethered Space Station operations at constant 463km or variable 305km to 395km altitudes.

Table 5-2 Production Cost Estimate (Millions of CFY 1987 Dollars)

Description	Configuration A	Configuration B	Configuration C	Configuration D
Support Structure Ass'y	$ 0.02	$ 0.02	$ 0.02	$ 0.03
Reel	1.51	1.01	0.80	2.39
Motor	0.57	0.53	0.47	0.71
Level Wind (Includes bearing, pulleys, track, timing system)	0.86	0.59	0.41	1.07
PIDM Supt Cylinder & Latches	0.01	0.01	0.01	0.01
Tether Management Boom	0.12	0.12	0.12	0.12
Upper, Lower & Fairlead Roller Assy's	0.35	0.35	0.35	0.35
Radiator	0.08	0.05	0.04	0.19
Support Electronics	0.47	0.47	0.47	0.47
Cold Plate	0.07	0.06	0.05	0.09
Meteoroid Cover (Reel)	0.03	0.02	0.02	0.04
Misc. Hardware	0.01	0.01	0.01	0.02
Tether	0.12	0.12	0.07	0.12
Wiring, Cooling Lines, Umbilicals, Insulation, etc.	0.23	0.23	0.23	0.23
PIDM	3.43	3.43	3.43	3.43
SIDM	1.81	1.81	1.81	1.81
Software	1.00	1.00	1.00	1.00
WBS Level 3 Integration and Testing	13.58	12.83	12.43	14.67
Total	$ 24.27M	$ 22.66M	$ 21.74M	$ 26.75M

Table 5-3
Total Program Cost Estimate by WBS (Millions of CFY 1987 Dollars)

WBS Number	Description	Configuration A	B	C	D
1.3.1	Program Mgmt	$ 4.6M	$ 4.1M	$ 3.9M	$ 5.3M
1.3.2	Technology	0.6	0.6	0.6	0.6
1.3.3	SE&I	13.0	11.8	11.1	14.9
1.3.4	Flight Tether System	34.6	31.1	29.2	39.9
1.3.5	HW Procure, Fab, Assy & Checkout	31.2	28.2	26.5	35.9
1.3.6	Ground Support	7.7	7.1	6.8	8.5
1.3.7	Launch Site/Mission Operations	3.4	3.1	2.9	4.0
1.3.8	Product Assurance	5.2	4.7	4.4	6.0
	Total	$100.3M	$ 90.7M	$ 85.4M	$115.1M

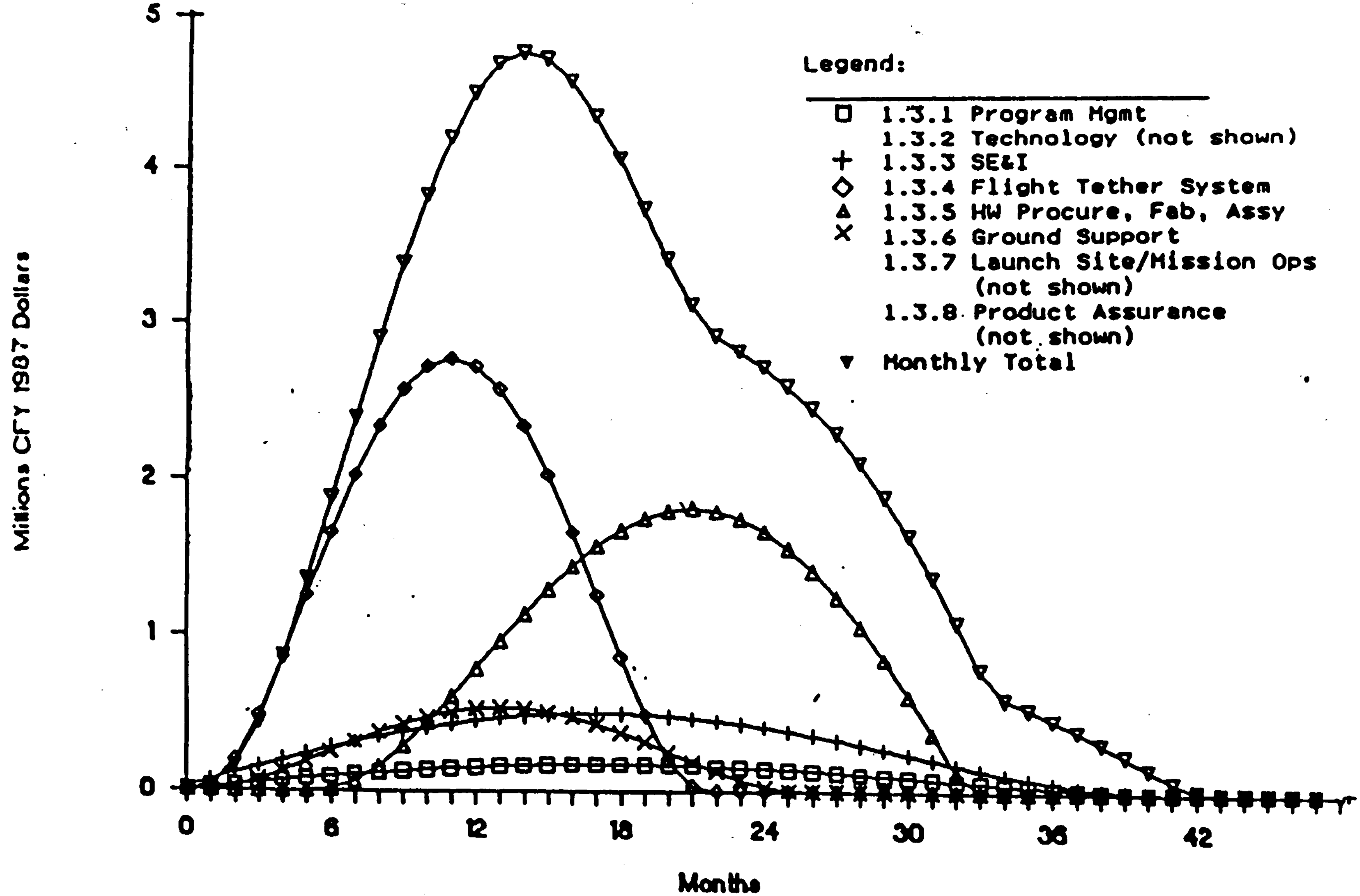


Figure 5-2 WBS Funding Spread for Configuration B.

Table 5-4 Configuration B Funding Spread (Millions of CFY 1987 Dollars)

WBS Number	Description	Fiscal Year 1989	1990	1991	1992
1.3.1	Program Mgmt	$ 0.9M	$ 1.9M	$ 1.1M	$ 0.1M
1.3.2	Technology	0.6	0	0	0
1.3.3	SE&I	2.9	5.7	3.0	0.1
1.3.4	Flight Tether System	16.9	14.1	0	0
1.3.5	HW Procure, Fab, Assy & Checkout	1.6	17.8	8.9	0
1.3.6	Ground Support	2.8	4.3	0.03	0
1.3.7	Launch Site/Mission Operations	0	0.6	2.1	0.4
1.3.8	Product Assurance	0.2	1.4	2.6	0.5
	Subtotal	$ 25.9M	$ 45.8M	$ 17.7M	$ 1.1M

Total $ 90.7M

Table 5-5 Tether System Costs, Operations and Benefits Summary

Configuration Options	Space Station Operational Scenario 11 Yrs Operation begin 1994	STS Flights and Number of TDS[6] operations in 11 Yrs: STS	ADD'L[1] NT STS	WM	OTV	Total Deployer System Cost ($M)5 [2]	LCC ($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.

The fourth mission scenario compares the last six years of tether operations for the Configuration D dual mode deployer operating at either constant 463km (Case IV) or combined optimum variable SS altitudes (Case V) to non-tethered operations at 463km (Case I) and optimum variable (Case II) altitudes.

Total deployer system acquisition costs presented include all phase C/D DDT&E, Production and Mission/Launch Site Operations costs as described in section 5.7.

The Life Cycle Cost (LCC) estimates include total deployer system costs, all system and component replacement transportation costs, on orbit operations IVA and EVA, and costs of using Space Station equipment and resources (i.e. MRMS, computer, electrical power and cooling). WBS elements 1.4 (STS) and 1.5 (Space Station Integration) modifications are included. STS modifications have been assessed at $7.0 M. Space Station modifications have been assessed at $1.0 M.

Net benefits of tethered operations are compared to 11 years of non-tethered Space Station operations at optimum variable or constant 463km altitudes. Benefits to Cost (B/C) (Ref. 11) ratios are included to assess the cost benefits of each deployer system on a mutually exclusive investment alternative basis. A configuration option is deemed worthwhile if the B/C ratio is greater than 1 (Ref. 11). All of the configuration options identified provide superior returns for the amount of investment estimated.

Figure 5-3 presents the net benefits comparison of Configuration B operating at optimum variable SS altitudes (including tethered Shuttle and waste module operations only) for 11 years (Case III), and configuration B for the first five years, plus configuration D for the last 6 years of operations at combined optimum variable (Case V) and constant 463 km SS altitudes (Case IV). The combined optimum variable SS altitude net benefits are based on the results of the Shuttle cargo performance analyses for calendar years 1999 and 2003. Average Shuttle cargo capability factors were derived by using linear regression techniques to provide the time series analysis results shown.

Figure 5-4 presents the net benefits comparison of configuration D operating at optimum variable SS altitudes, combined optimum variable SS altitudes, and constant 463 km SS altitudes for 11 years. The combined optimum variable SS altitude net benefits are based on the results of the Shuttle cargo performance analyses for calendar years 1999 and 2003. Average Shuttle cargo capability factors were derived by using linear regression techniques to provide the time series analysis results shown.

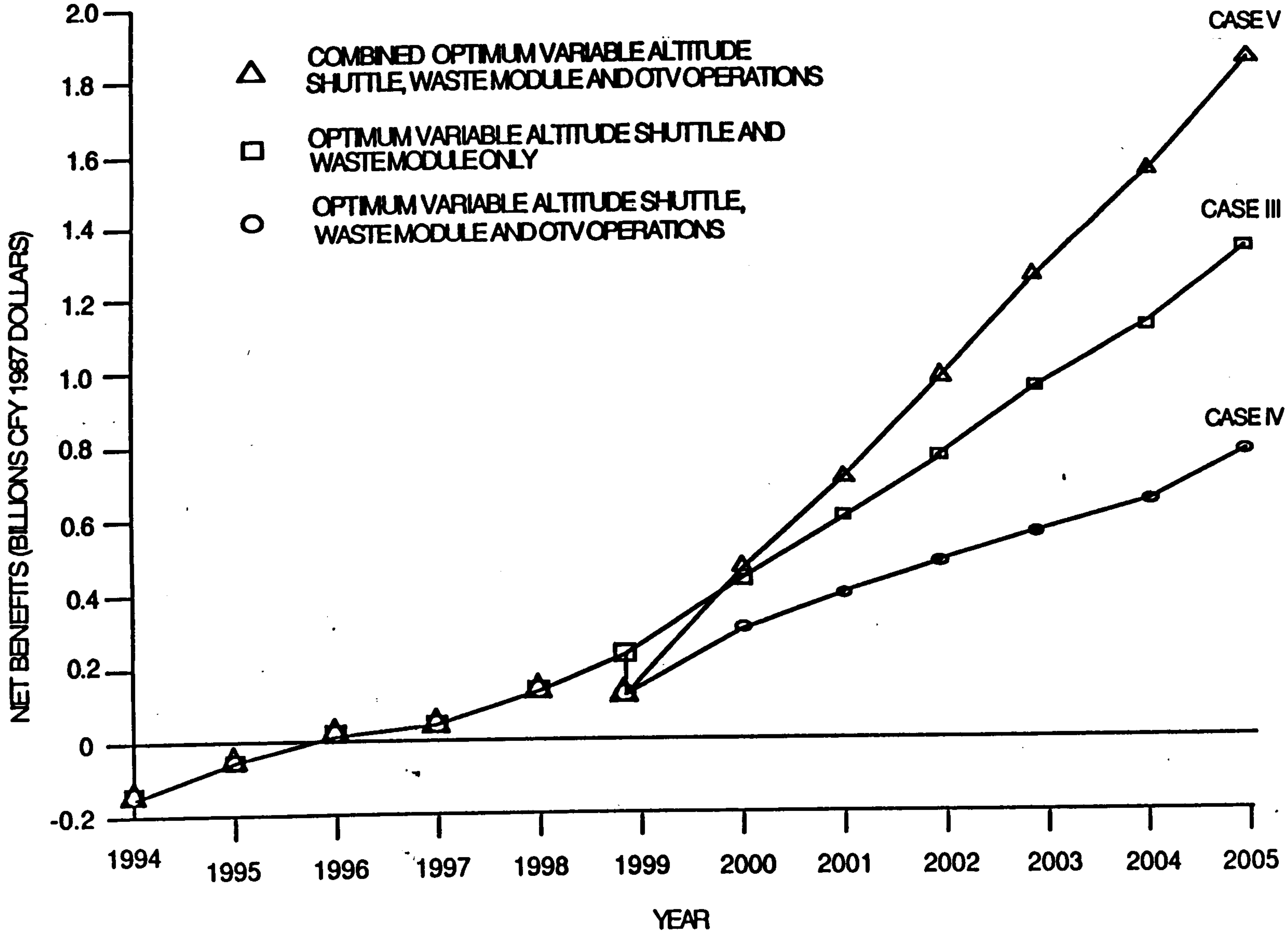


Figure 5 - 3 Net Benefits for OTV Deployer System Operations

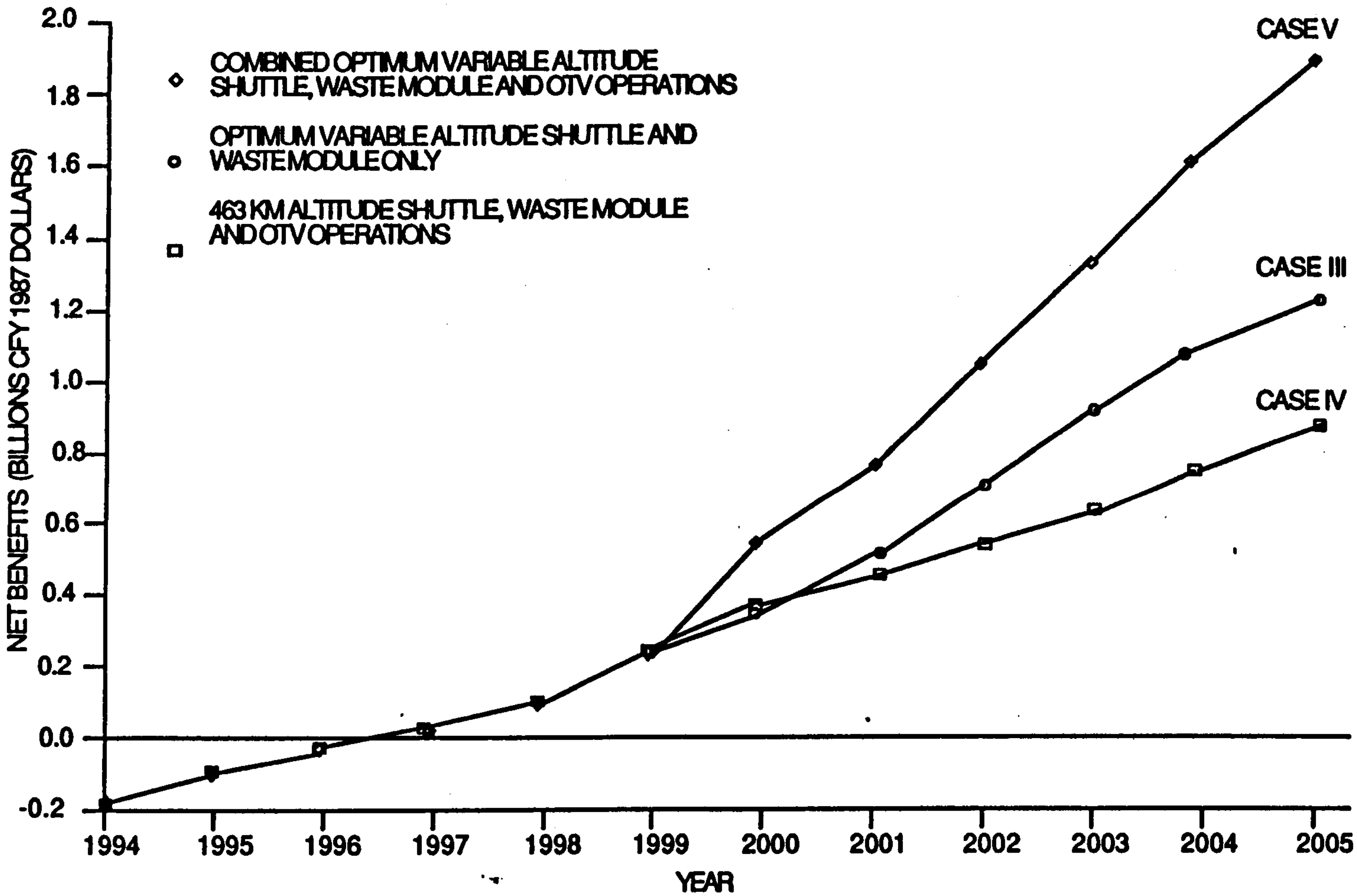


Figure 5-4 Net Benefits For Tether Deployer Operations

Figure 5-5 presents the typical Life Cycle Cost (LCC) breakdown of any of the 4 tether deployer system configuration options. The 6 categories include transportation costs (74%), tether deployer system phase C/D costs (14%), Intravehicular Activity (IVA) costs (8%), Spares (including tethers) costs (3%), Extravehicular Activity (EVA) costs (0.6%) and remaining SS operations costs (0.4%). Because of the large transportation costs identified significant effort must be allocated to tether weight reduction while retaining adequate tether strength.

Figure 5-6 presents the cost sensitivity results of varying Shuttle transportation costs from $50M to $150M per Shuttle launch. Net benefits are presented for Configuration B plus D deployer systems operating at combined variable SS altitudes including a total of 116 tethered Shuttle, 27 non-tethered (extra cargo), 44 tethered waste module and 48 tethered OTV deployments.

Figure 5-7 presents the assumed particle/tether diameter ratio versus safety factor values used to calculate net benefits versus tether replacement frequency. These values cover an arbitrary range of assumptions relating the survivability of tethers following impacts by micrometeoroid or debris. The curves were constructed based on the fact that at a safety factor of 1.0, the tether will break if impacted by any size particle; and curves become asymptotic to some ratio of particle size to crater diameter. Crater diameters to particle size ranging from 3 (typical of steel) to 10 (typical of plastic) are covered in the curves shown. The effects of hypervelocity particle impact on tether under operating tension is the subject of IRAD (Independent Research and Development) task D-67S currently under study at MMDA.

Figure 5-8 presents the results of the cost sensitivity of increasing the safety factor of the OTV tether versus the net benefits of 11 years of combined optimum variable SS altitude tethered Shuttle, waste module and OTV operations. Configuration option B was used during the first five years of variable Space Station (SS) altitude operations including 20 tethered Shuttle deorbits, 20 tethered waste module deployments, and 20 additional increased cargo capability non-tethered Shuttle flights. The last six years included combined optimum variable SS altitude operations including 52 tethered Shuttle deorbits, 24 tethered waste module deorbits, 51 additional increased cargo capability non-tethered Shuttle flights, and 48 tethered OTV deployments. The net benefits are calculated based on changing the tether replacement frequency of the OTV tether for the given safety factors (2, 5, 7.5, 10). The Shuttle tether replacement frequency stayed constant at one replacement for every 20 deployements (Shuttle or waste module) for the analysis. The number of missions between hits for a tether of a given safety factor was determined using the criteria presented in figure 5-8.

C-2

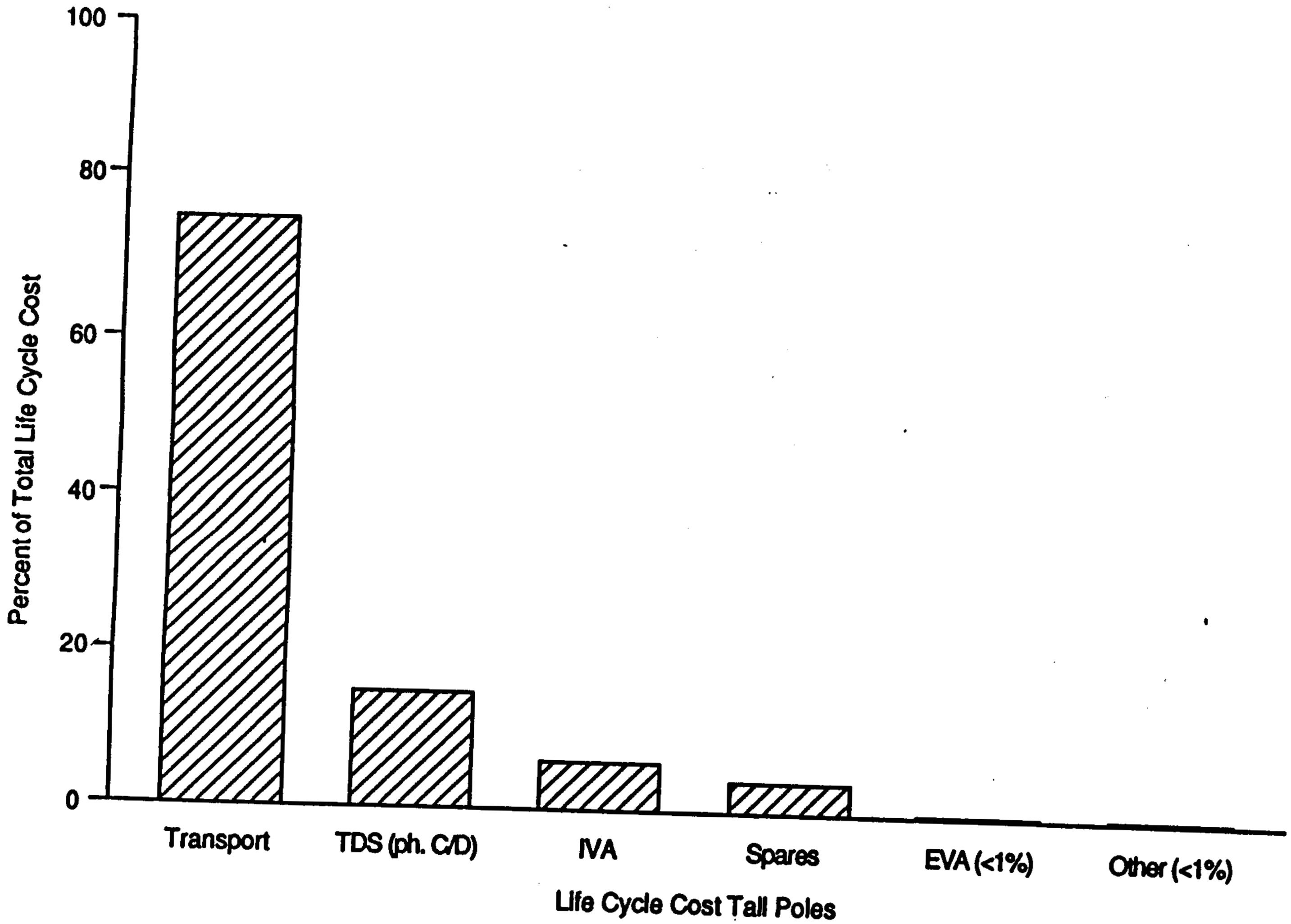


Figure 5 - 5 Typical LCC Breakdown

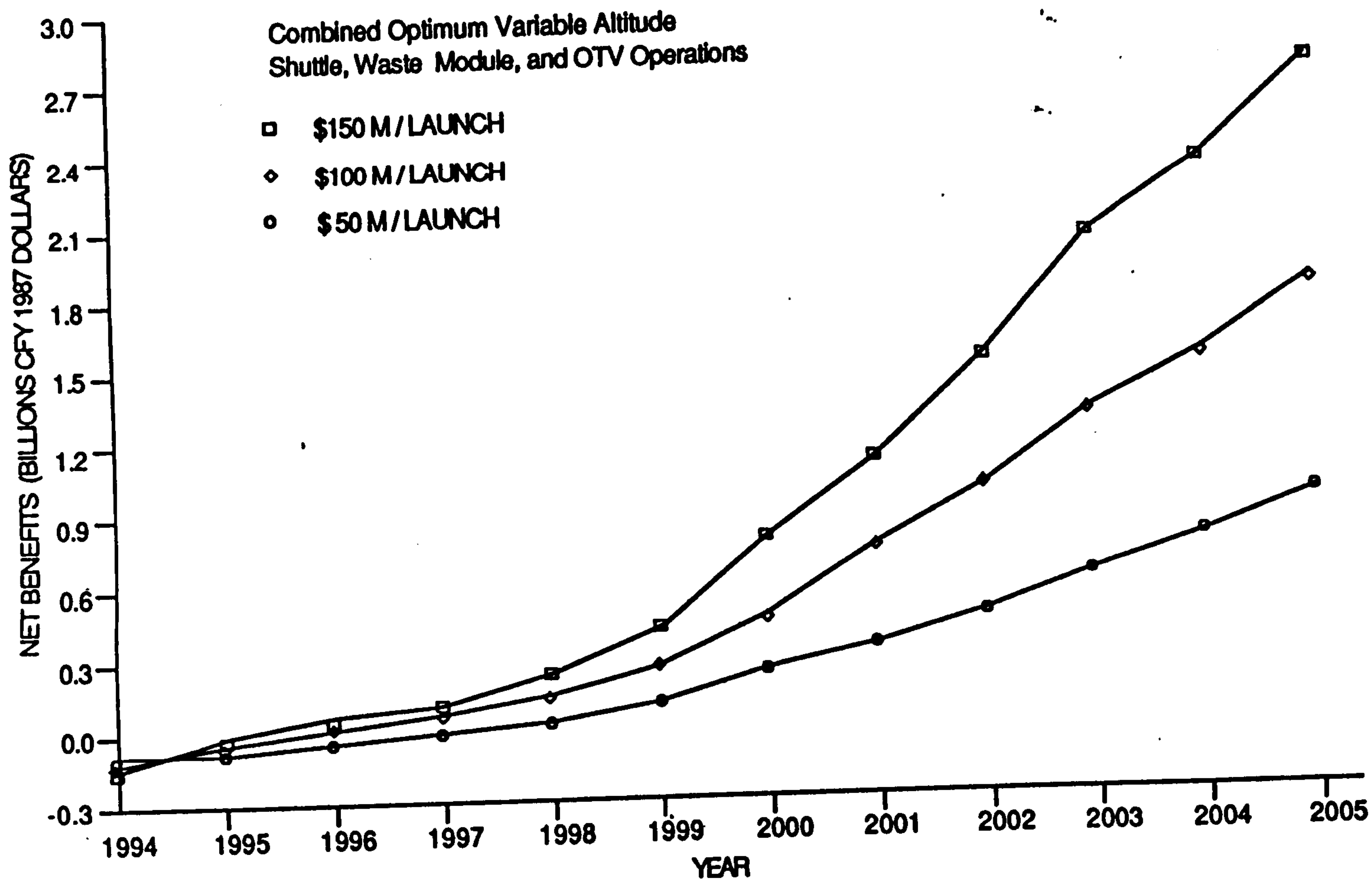


Figure 5 - 6 Net Benefits Versus Shuttle Launch Costs

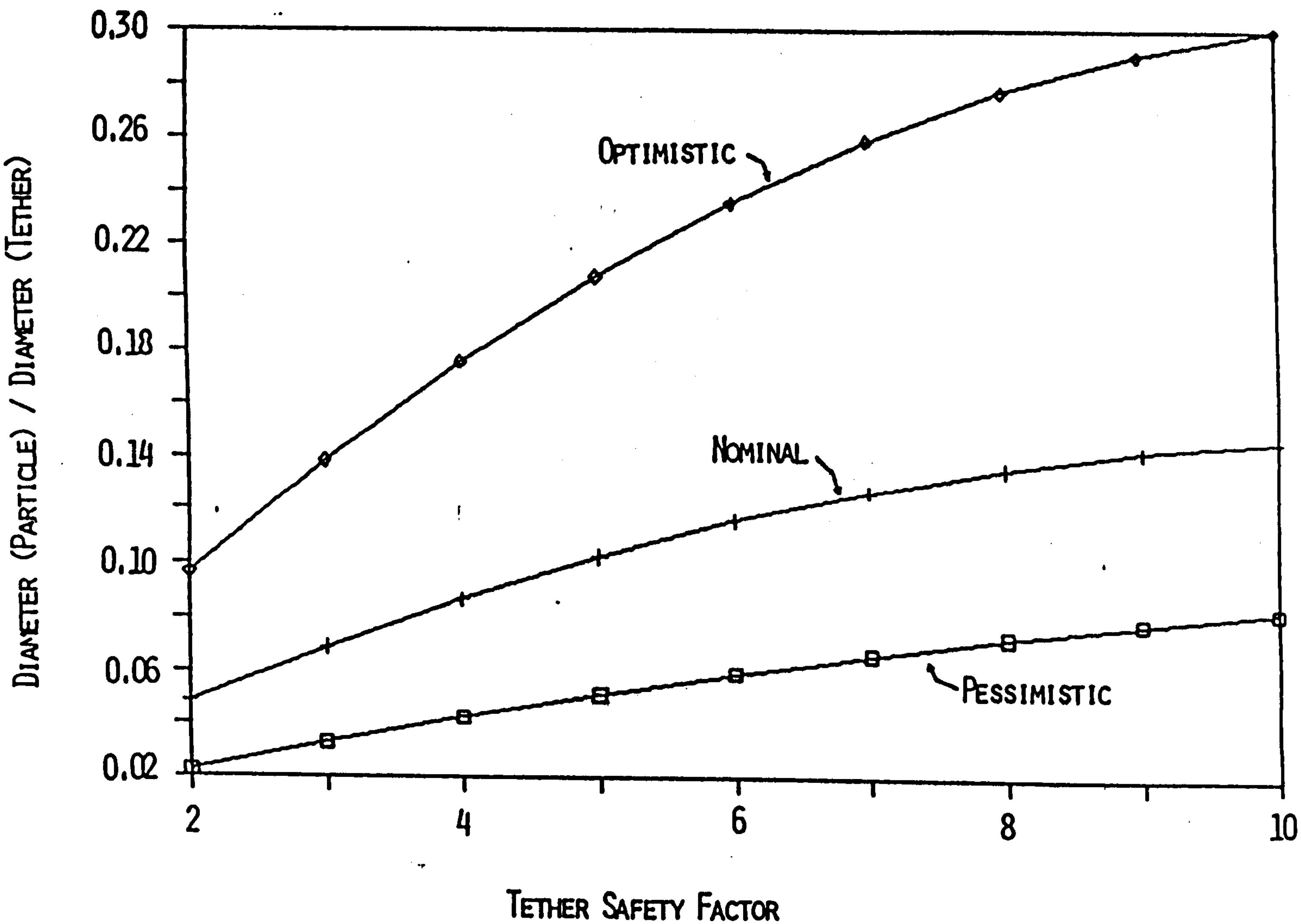
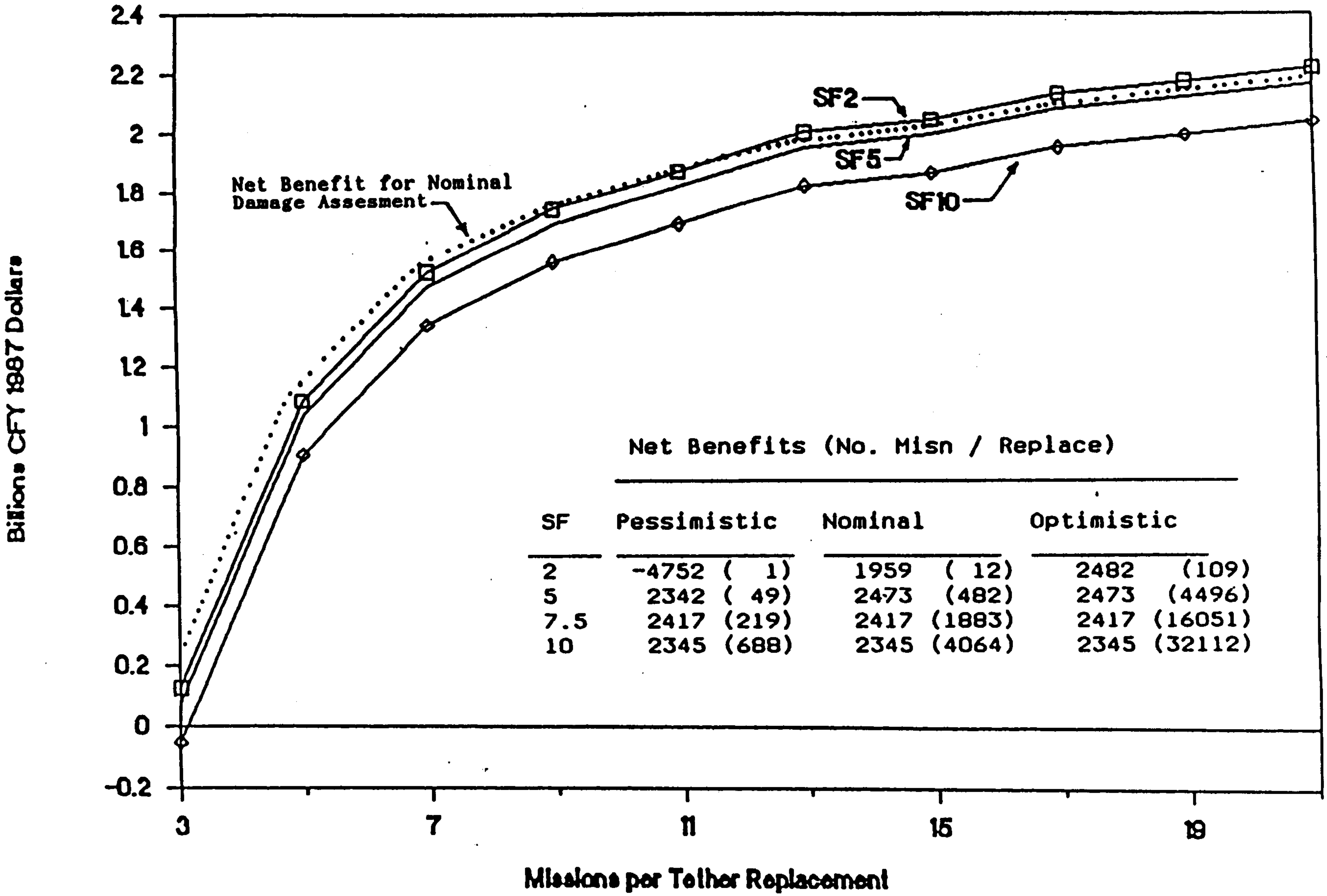


Figure 5-7 Accepted Particle Size / Tether Diameter Ratios



SF	Pessimistic	Nominal	Optimistic
2	-4752 (1)	1959 (12)	2482 (109)
5	2342 (49)	2473 (482)	2473 (4496)
7.5	2417 (219)	2417 (1883)	2417 (16051)
10	2345 (688)	2345 (4064)	2345 (32112)

Figure 5-8 Net Benefits versus OTV Tether Safety Factor

The net benefits table shown in the lower right hand portion of the graph indicates the net benefits versus safety factor for the three (pessimistic, nominal and optimistic) acceptable particle size assumptions, plus the calculated number of missions between hits (numbers are in parentheses on the graph) for the particular tether. Note that for the operational scenario defined the total net benefits peak when the number of missions between unacceptable hits is equal to the total number of missions (168 for this analysis). Increasing the safety factor beyond that required to perform all the missions using one tether is not cost effective, as seen in the table. Using the nominal damage assuption the optimum safety factor would be between 2.0 and 5.0. If the damage assumption curves reflect the range of conditions that actually occurs, the selection of a safety factor of about 5 would be a good risk. At the pessimistic assumption the net benefits are 93% of the maximum available. If the nominal assumption proves valid, the probability is high that only one tether would be required and the net benefits would be 98% of the maximum available. The maximum available net benefit (i.e. $2.5B for the combined optimum variable SS altitude tethered Shuttle and OTV operations) is defined as the benefit achieved if a tether with a safety factor of 2.0 would survive the total eleven year period. Selection of the optimum safety factor must await the outcome of tests to define the performance of the various candidate tether designs in the operating environment.

6.0 WORK BREAKDOWN STRUCTURE (WBS)

A Work Breakdown Structure (WBS) was generated to define the products and services required to design, develop, test, install and operate the tether deployer system for the life of the program. This WBS was used to support the cost analysis. The WBS tree is presented to level 4 in Figure 6-1. The final WBS and the WBS dictionary are published under separate cover (Ref. 7).

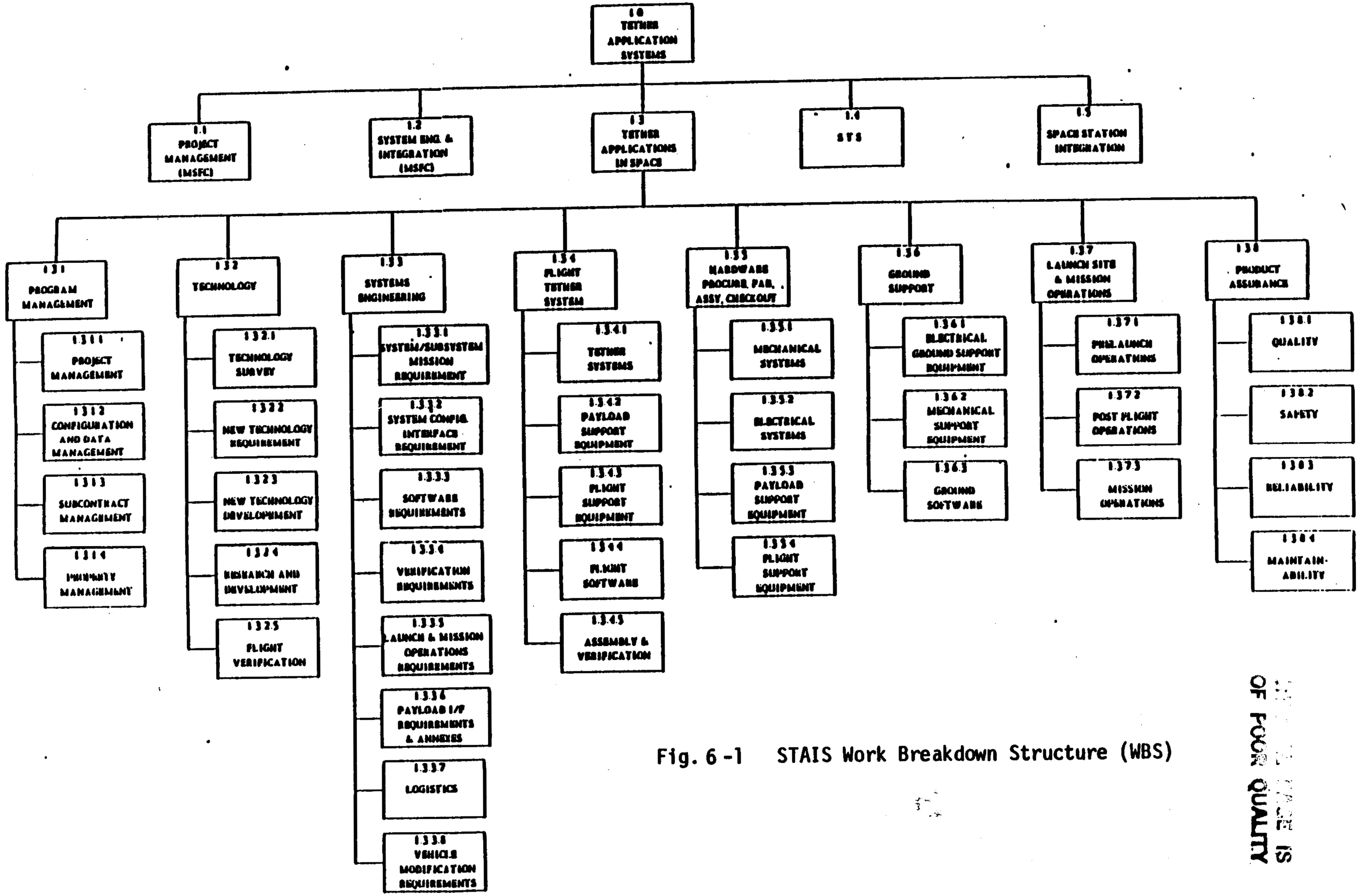


Fig. 6-1 STAIS Work Breakdown Structure (WBS)

7.0 CRITICAL TECHNOLOGY DEVELOPMENT REQUIREMENTS

This study has identified several technology areas that must be solved before the potential benefits associated with tether deployment of Shuttles and/or OTV from the Space Station can be realized. These areas are briefly discussed in the subsequent paragraphs.

7.1 Slack Tether Dynamics. The behavior of the tether following either release of a large payload or a failure of the tether due to debris or micrometeorite impact must be well understood and demonstrated before a safe, reliable tether deployment system can become operational on the Space Station. Several studies and simulations have been performed but the results are not conclusive. The primary concern is the few hundred meters of slack that may form near the Space Station following release of large payloads such as the Shuttle or OTV. This slack tether must be avoided or controlled to prevent it from becoming entangled with SS protrusions such as sensors, antenna, etc.

In case of tether failure, the Shuttle and OTV may also be exposed to slack tethers. An approach that has been proposed is to sever both ends of the tether following an indication of a break. This approach requires a very reliable sensor to avoid severing an unbroken tether following an erroneous signal. Safety considerations may dictate this approach in the near term, however, as a long term operational concept it has the serious shortcoming that two lengths of tether are released into uncontrolled orbits. The orbit lifetime of the upper segment of tether for OTV deployments could be several months, causing the addition of a significant amount of debris.

7.2 Tether Design, Inspection and Repair. A key parameter influencing the cost benefits of the tether system is the frequency of tether replacement. The tether typically accounts for 55 to 70% of the total deployer system mass. This value will be higher if the safety factor of the tether must increase to improve survivability. The tether transportation cost becomes intolerable with frequent replacement making it mandatory that we understand the damage created by particle impact, develop methods of inspecting the tether during retrieval, and establish reuse criteria. Methods of on-orbit repair that vary from patching up surface coating blemishes to cutting and splicing the tether to remove areas showing major damage should be evaluated.

The tether design and construction must be optimized to provide the required lifetime at minimum weight. The materials currently favored for this application are Kevlar and Spectra. Both candidates are susceptible to degradation from exposure to UV and atomic oxygen and will, therefore, require a protective coating. Spectra also has poor creep characteristics but very good fatigue life compared to Kevlar. Optimizing the tension member material, safety factor, coating material etc. is a significant technology development requirement. Methods of reducing recoil by material selections, coating material or impregnation treatment should also be considered.

7.3 Design of the Reel/Motor/Generator System. The motor/generator and reel assembly constitute key components of the tether deployer system. The development of space qualified motor/generators with high power (40 to 300 HP) that may be integral to the reel is expected to be a long lead item. Integration of this system with the Motor Controller Assembly (MCA) cooling system and power dissipation system will represent a significant technology development.

7.4 Propellant Transfer and Management. Significant portions of the benefits available from the tether deployment concepts presented in this report stem from scavenging propellant from the Shuttle. The technologies for managing and transferring propellants from the Shuttle to the SIDM, and from the SIDM to the OMV, SS tank or other uses by remote control must be developed in order to reap the potential benefits offered by the tether deployment concepts.

7.5 Automation and Remote Operations. A significant portion of the operational costs of the tether deployment is the IVA (at $18,000 per hour) and EVA (at $150,000 per hour). These costs may be minimized by using automation and remote operations to the maximum extent possible.

8.0 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 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.

9.0 RECOMMENDATIONS

The recommendations resulting from this study are separated into those involving configuration selection and those involving follow-on studies, design, development and test activities required to enable implementation of tether operations on the Space Station.

9.1 Configuration Recommendations. As seen in previous sections of this report, several operational scenarios and hardware configurations result in very large performance and cost benefits. Since the operational scenario has much more influence on the available net benefits than the hardware configuration selected, we recommend the configuration that provides the greatest versatility; Configuration D. This deployer system provides the maximum capability anticipated for use on the Space Station over the 11 year period, the ability to launch the OTV using 150 km of tether. This configuration provides excess capability during the first 5 years of operation (before the OTV becomes operational). We recommend that deployer Configuration D be initially deployed with a shorter (63 km) tether providing the capability to deorbit the Shuttle, waste and the ET from the optimum variable altitude (Case III). We also recommend that a tether safety factor of approximately 5.0 (final selection after completion of hypervelocity impact tests) be employed for the first implementation. The rationale for this recommendation are as follows:

-Maximum versatility; can support any operational scenario expected.

-Has the potential of reaping the maximum net benefits, $1.89B for Case V.

-Net benefits are only 6% (78M out of $1.3B) lower than the optimum configuration if Case III is used for the 11 year period.

-Excess capability for first five years could be used to (1) reduce Shuttle deployment time, (2) increase tether lifetime and reduce recoil by using a large safety factor, and (3) gain operational experience with all subsystem operating with large safety margins.

We would recommend implementing a lower capability deployer system (i.e. Configuration B) only if it is certain that the OTV will not be tether deployed or if the OTV will be very late, or if the reduced acquisition cost of Configuration B ($91M) versus Configuration D ($115M) is critical to allowing implementation of a tether system on the Space Station.

9.2 Recommendations for Future Activities

Several follow on studies, test and development activities are recommended in order to facilitate implementation of the tether deployment system on the Space Station at the earliest opportunity and to assure maximum benefits of the tether deployment concept.

A. The tether community should work very closely with the Space Station project to identify and coordinate requirements to assure that the Space Station configuration and operational approach are established, from the outset, to enhance implementation of tether deployment capability. This activity should define in detail the physical and operational interfaces that would assure maximum benefits with minimum impact to the Space Station operations. Operational considerations should include integrated time lines, detailed proximity operations, methods of most efficiently utilizing the power generated during deployment, effects of micro-gravity, attitude, and altitude perturbations imposed during tether operations.

B. Activity to establish design criteria for the tether should be continued and intensified. MMDA is performing IRAD Task D67S "Space Tether Materials Study" whose primary activity is to evaluate the effects of particle impacts on candidate tether materials by exposing samples under operational loads to hypervelocity particle impact. The results of this task are expected to provide valuable data but will only begin to provide a database that will be required to establish accurate and complete design criteria. This activity should be extended to a wider range of load carrying materials, coatings, sizes, etc.

   A companion activity should be the development of methods of inspecting, testing or otherwise evaluating the tether after each mission in order to determine its suitability for subsequent missions. Since this study has shown that the transportation costs of tethers is exhorbitant for frequent replacement, methods for on orbit repair of damaged tethers should be investigated.

C. Additional analyses and testing should be performed to define and demonstrate the behavior of the slack tether following release of a large payload or a tether break. Relatively simple ground tests could be performed to characterize candidate tether materials and construction techniques relative to damping and the efficiency of converting strain energy into kinetic energy of recoil. Various treatments and/or combinations of materials could be evaluated with the purpose of reducing recoil. Formulation of ground tests to demonstrate the validity of the analytical simulation models should be pursued.

D. Studies leading to definition of a flight demonstration of the use of tethers for transportation missions should be initiated. The TSS missions will demonstrate deployment and retrieval of tethered satellites and the effectiveness of control laws used to stabilize the system. Another flight demonstration should have as an objective the verification that transfer of angular momentum behaves as predicted. It is particularly important to establish the accuracy with which the resulting trajectory can be predicted or controlled and to determine the post-release behavior of the tether. This flight demonstration could also be used to ckeck out control laws that would amplify and then damp out librations. This activity should result in a detailed test approach and a preliminary design of flight test hardware.

An alternate approach to an early initial demonstration mission may be to utilize the last stage of an expendable launch vehicle (shared payload or dedicated) to deploy a second mass after orbit is achieved and to measure tether response and orbital changes after release of the second mass. This approach requires that the trajectory that places the spent stage into an acceptable orbit is compatible with the primary payload requirements.

E. The performance benefits analysis should be automated and the resulting computer program coupled to the cost model (STACOM) that was developed under the this study. This simulation approach would allow rapid assessment of variations in mission scenarios and ground rules and support sensitivity analyses.

F. Preliminary designs leading to the development of space qualified motor/generator/reel assemblies with the associated control systems over the range of power from 40 to 300 horsepower should be initiated.

10.0 REFERENCES

1 STACOM (Selected Tether Applications Cost Model) User's Guide. MCR-86-1349, Martin Marietta Aerospace - Denver Division, September 1986.

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