# TRANSPORTATION

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C-3

I'd like to summarize where we are today in tether transportation, how we got there, and what we have learned.

I received a notice from my co-speaker, Dr. Gianfranco Bevilacqua, that he has another commitment and will not come. So I guess we can save some time.

We started off after the last workshop with many concepts in tethered transportation. I will show you briefly the sequence of studies through which these concepts had to pass in order to recognize the survivors that are valuable and practical to carry out (Chart 3).

These four steps were used over a time period of three years. Initially, theoretical engineering feasibility and technology requirements were determined. Then the survivors of that effort went into step two in the analysis of promising candidates. Those survivors went into the third phase: engineering design and cost benefit analysis. We are in that phase with several concepts. Finally, those survivors enter into the demonstration mission definition phase.

From some 30 concepts we got down to four, using these phased studies. The technologies that we defined during the studies cover areas listed here on the next chart (Chart 4). In front of all other technologies are tether materials and configurations. Obviously, the tether itself is the heart of the whole system. Then instrumentations, both engineering and science, a very important area that is still in evolution.

## Systems Dynamics Simulation

The numerous simulation programs, which cover the many applications are continuously expanding to include demonstration missions.

Atmospheric aerothermodynamic technology is next. You will hear about that a little bit later.

You have heard about hollow cathodes, and across the board, critical component technology. One critical component, just to mention an example, is the deployment brake which has the size of a large aircraft brake and has to dissipate some five hundred or so kilowatt hours over a deployment period, deploying the orbiter from the Space Station, for example.

Now the demonstrations. We entered the demonstration definition phase with several concepts. First, the demonstration objectives; whatever critical issues exist, the solutions to these must be demonstrated (Chart 5). Second, and very important, we have to be able to afford these demonstrations. They cannot be too expensive, which means they have to be simple and concentrate on the issues.

We like to use as much available hardware at the end of the tether as possible, where we can attach our required instrumentation. We have a number of available instrument carriers. Among others, there is a re-entry vehicle, which has been used before, and which we study to use as a carrier between a Space Station and the ground, eventually. So, when the Space Station has some material or biological specimens and does not want to wait three months for the next orbiter to come, this re-entry vehicle can take it down. So the entry vehicle is a very important potential payload.

Then we want to have a short development time, which goes together with simplicity and affordability. Say two years, or three maybe.

Our transportation studies have covered two kinds of deployments. First, we studied steady state deployment (Chart 6). It´s like the TSS, nearly vertical. It takes a very long time to deploy and involves relatively high tether tension.

A few special studies concentrated on dynamic deployment (Chart 7) where you start your deployment in an almost horizontal direction under a very shallow angle which allows you high deployment rates under very low tension. Momentum transfer here occurs by libration. You release the payload by having a tether swing through the local vertical at which time the payload is disconnected.

We can have payloads that we can retrieve and payloads without retrieval. We have under development a disposable tether deployment system, which weighs much less than one that is capable of retrieving. I have a few words about that later.

In order to study tethered transportation benefits, we use specific payloads. This doesn't necessarily mean that those future payloads will be launched by tether, but they are potential candidates. The advantage was that we know everything about those payloads: their masses, their characteristics, and their conventional deployment methods. Now we have valid comparisons between those and the tether deployment.

The first example was the SSUS spacecraft, which weighed some 6800 kilograms (Chart 9). Our study showed that, in a tethered deployment of this system, we can save almost 2300 kilograms of OMS propellant on the orbiter, because the orbiter doesn't need to go up to that altitude. And the spacecraft itself, the SSUS, saves some 4000 kilograms of propellants.

Another example where all the numbers are known is the AXAF, the Advanced X-Ray Astrophysics Facility (Chart 10). We tried to find out, if you launched that one from the end of a tether, if this facility would be able to go into a 320 nautical mile circular orbit. What we found out was, if you put the orbiter in an elliptical orbit, 290 x 180 nm, and use about a 33 nautical mile long tether, then the payload, the AXAF, goes exactly into its 320 nautical mile circular orbit, while the orbiter itself goes into a 287 to 100 nautical mile orbit with plenty of time to close the cargo doors for reentry. The OMS propellant saved would be some 3300 kilograms.

Another typical example where all the numbers are known is the space telescope. I will just point out the important points on this chart (Chart 12).

The space telescope also needs to go into this 320 nautical mile circular orbit, but with a tether we can put it 50 nautical miles higher.

With a 40 nautical mile tether, the orbiter only needs to go into a 102 x 330 nautical mile eccentric orbit. In doing that, we have propellant savings of 7600 lbs. Sorry about the mixture of units. On the payload side, since the orbiter has to go into a lower orbit than the payload, it has an excess capacity of 8000 lbs of cargo weight.

These are typical examples where we showed the advantages of tethers to transportation.

Now I mentioned at the beginning that, from some thirty concepts we ended up with four transportation concepts, which we have under study now with regard to cost benefits (Chart 13). These are the four: a tethered orbiter de-boost from the Space Station, an OTV boost up from the Space Station, a science platform on a tether with a possible micro-g lab moving in between platform and station, and a tethered boost of payloads from the orbiter, where I just gave you some examples. This is the deployment of the orbiter from the Space Station (Charts 14, 15). We have a dual deployment mechanism in the Space Station that allows deployment of payloads down and up.

What you see on top is an OTV. These two spacecraft can be launched or deployed alternately, within a few days or a week. In that case, you see, the Space Station is the momentum storage facility. It stores angular momentum. Since the Space Station would go up into inaccessible highs by deploying an orbiter, alternate OTV launches will maintain the proper altitude for the station.

The engineering approach was such that the two moments are equal, so the station stays essentially where it was. The benefit of using this on a Space Station is considerable (Chart 16). Through the early 90's we can save eight to ten thousand kilograms of Shuttle, Station and OTV propellant. Later, in the second half of the decade, we can save between 30 and 50 thousand kilograms of propellant annually. The difference between the first and second half of the 90's results from traffic and all sorts of activity differences. The orbital drag will be much higher in the later 90's than the early 90's and would consume more drag make-up propellants.

Another effort that's going on covers automated procedures for tethered rendezvous (Chart 19). I showed you the deployment of an orbiter from a Space Station before. You can envision that an orbiter now docks remotely at the end of a tether below the Station, avoiding any dynamics involved in docking directly to the Station. That's a very tricky maneuver.

We have an effort going on to automate this process because of the short time available to acquire the connection. I have listed next an area that doesn't seem to fit into transportation. It is more a constellation, but I'd like to mention it, anyway.

We studied a three-mass linear constellation. The center mass is a spacecraft containing essentially a big capacitor. You have an electrodynamic tether going up and one going down, with space plasma contactors. This is, hopefully, an efficient communications system for ULF and ELF frequencies.

Then one of our major efforts going on is an expendable tether system payload mission analysis. For our expendable tether system, we want to demonstrate the deployment of certain payloads and verify the disposable tether system.

This is the tethered rendezvous (Chart 20) -- the remote rendezvous — that I mentioned. We have an OTV at the end of a small end effector deployed from the Space Station. This process is being analyzed for an automated approach.

This (Chart 21) is a picture of the ULF-ELF antenna. In the center is the capacitor-spacecraft, then we have the up and down electrodynamic tether. For instance, it may work such that for a millisecond the upper tether generates power which is stored in the capacitor. And during the next millisecond the energy is emitted from the lower conducting tether.

There is a study underway to provide the systems approach here and to assess the possibilities of a system like this.

This (Chart 22) is a flight experiment that has been approved recently. It is the disposable tether system that is deployed out of a so-called GAS can with a payload that can be deployed about 20 or so kilometers and then disconnected.

We have found out that even a disconnected payload can be recovered, under certain conditions, by the Shuttle. Okay. What have we learned of all this? (Chart 26)

One of our concerns are tether issues...what can we do to reduce tether recoil after payload release or breakage? How can we increase durability of the tether so it can be used many times? An what can we do about debris collision hazards?

We have to review statistics and probabilities and come up with tether configurations that are less vulnerable than a round tether. Maybe a ribbon or something.

Now let me say a few words about energy management. During deployment, we generate about 15 to 20 kilowatt hours of energy on the orbiter deployer that have to be dissipated. On the Space Station it is up to 500 kilowatt hours. That's the main issue.

For retrieval, we need about two kilowatt hours of work on the orbiter, and sometimes up to 30. On the Space Station, we require some 70 kilowatts of power.

Of course, we must discuss the impacts. Everything we do on the Space Station induces g levels. What can we do about it? About $10^{-4}$ g may be induced by a number of tether operations.

Structural stress must be discussed because the tether has to be attached somewhere. And the tether tension has to be carried into the structure. Where do we put the deployer system? We have to reduce volume and space. We need energy. And we have to dispose of energy. We have to define that soon. We have made a lot of progress.

There are certain conditions we have to follow in order to have benefits in the first place (Chart 25). The deployment system has to be lightweight. If I saved 3,000 lbs of propellant and have to carry a deployment system that weighs 6,000 lbs, I haven´t saved much. So a disposable tether payload deployment system is under development, weighing only a few hundred pounds.

It is practical to deploy upward payloads toward the end of the orbital mission. You save propellants for the re-entry. Especially if you have one single payload among several that needs to go into a higher orbit, then the tether is of a major benefit. Otherwise, the orbiter has to change its orbit just for one payload.

The maximum payload you can deploy upward from the orbiter is about 12,000 kilograms from a normal orbital altitude. That´s what we have learned.

And I´d like to just say a few words again about the expendable tether system. It´s under development. It´s a candidate for our demonstrations. Because the TSS system is busy for quite a number of years, we have to have our own deployer. And we are fortunate to have a good idea now under development which was originated by Joe Carroll, whom you have listened to before.

It is a low tether tension deployment, almost horizontal which swings in to the vertical. Payload release is at the vertical. We are defining flight experiments, and we have certain payloads for these flights under investigation.

And, finally, assessing the benefits (Chart 23). We can deploy up to 12,000 kilogram payloads from the orbiter. We can save up to 7500 kilograms of propellants on the orbiter. We can launch and deploy from the Space Station up to a hundred tons of payload.

By the way, the Space Station mass, I think it has doubled or is about to double. I don't know exacatly, but the heavier the Space Station, of course, the better are tether operations.

In the early 90's we can save up to nine thousand kilograms of propellants annually. And, in the late 90's, up to 50,000 kilograms. We think this is a remarkable possibility of tethered transportation.

Thank you very much.

| ORGANIZATION: PROGRAM DEVELOPMENT | MARSHALL SPACE FLIGHT CENTER | NAME: GEORG von TIESENHAUSEN |
|---|---|---|
| CHART NO.: 4644–85 | | DATE: OCTOBER 1985 |

# TETHER TRANSPORTATION

PRESENTED AT THE

APPLICATIONS OF TETHERS IN SPACE WORKSHOP

VENICE, ITALY

OCTOBER 15–17, 1985

TETHERED TRANSPORTATION

TETHERED SPACECRAFT CONSTELLATIONS AND PLATFORMS

ELECTRODYNAMIC INTERACTIONS OF TETHER SYSTEM

ELECTRODYNAMIC TETHER COMPONENTS

TETHER TECHNOLOGY AND TEST

SCIENCE AND APPLICATIONS

GRAVITY UTILIZATION THROUGH TETHERS

ADVANCED CONCEPTS DEVELOPMENT

## TETHER APPLICATION IN SPACE CATEGORIES

CHART 2

1) THEORETICAL AND ENGINEERING FEASIBILITY AND TECHNOLOGY REQUIREMENTS

2) IN–DEPTH ANALYSIS OF PROMISING CANDIDATE APPLICATIONS

3) ENGINEERING DESIGN AND COST/BENEFIT ANALYSIS OF SELECTED APPLICATIONS

4) DEMONSTRATION MISSION DEFINITION OF SELECTED APPLICATIONS

## STUDY PLANNING

CHART 3

1) TETHER MATERIALS AND CONFIGURATIONS

2) TETHER APPLICATIONS ENGINEERING INSTRUMENTATION

3) TETHER APPLICATIONS SCIENCE INSTRUMENTATION

4) TETHER SYSTEM DYNAMICS/ORBITAL MECHANICS SIMULATION

5) ATMOSPHERIC/AEROTHERMODYNAMIC TECHNOLOGY

6) HOLLOW CATHODE TECHNOLOGY

7) TETHER APPLICATIONS CRITICAL COMPONENT TECHNOLOGY

# TECHNOLOGY PLANNING

CHART 4

1) CAPABILITY OF FULFILLING FLIGHT OBJECTIVES

2) AFFORDABILITY

3) SIMPLICITY

4) MAXIMUM USE OF AVAILABLE PAYLOAD HARDWARE WITH MINIMUM MODIFICATIONS
    - AVAILABLE INSTRUMENT CARRIERS
    - AVAILABLE REENTRY VEHICLES

5) MINIMUM DEVELOPMENT TIME ( ~ 2 YEARS)

# DEMONSTRATION PLANNING CRITERIA

CHART 5

ORGANIZATION:
PROGRAM DEVELOPMENT

CHART NO.:
~~4645-85~~

MARSHALL SPACE FLIGHT CENTER

# TETHER TRANSPORTATION

NAME:
GEORG von TIESENHAUSEN

DATE:
OCTOBER 1985

## DEPLOYMENT AND RETRIEVAL OPTIONS

- STEADY STATE DEPLOYMENT – BASIS FOR MOST STUDIES SO FAR
  - DEVELOPMENT IS NEARLY VERTICAL
  - LOW DEPLOYMENT RATES
  - HIGH TETHER TENSION (INCREASES WITH TETHER LENGTH)
  - MAY OSCILLATE ABOUT VERTICAL

ORGANIZATION:
PROGRAM DEVELOPMENT

CHART NO.:
4647–85

MARSHALL SPACE FLIGHT CENTER

# TETHER TRANSPORTATION

NAME:
GEORG von TIESENHAUSEN

DATE:
OCTOBER 1985

## DEPLOYMENT AND RETRIEVAL OPTIONS

- DYNAMIC DEPLOYMENT – BASIS FOR SPECIAL STUDIES
  - DEPLOYED PRIMARILY AT CONSIDERABLE ANGLE TO LOCAL VERTICAL
  - HIGH DEPLOYMENT RATES
  - LOW TETHER TENSION

  LIBRATING – DISPOSABLE TETHER PAYLOAD DEPLOYMENT STUDY

  ROTATING – NASA STUDY ON ROTATING DUMBBELL DYNAMICS

  PUMPING – TO BE STUDIED IN THE FUTURE
- WITH RETRIEVAL – TETHERED REMOTE DOCKING STUDY

  CONTROL LAWS + PROPULSION (DEPENDING ON TETHER MEASUREMENT ACCURACY)
- WITHOUT RETRIEVAL – EXPENDABLE TETHER DEPLOYMENT SYSTEM UNDER DEVELOPMENT

  RETRIEVAL PRACTICAL UNDER CERTAIN CONDITIONS

# SSUS ORBITER LAUNCH REQUIREMENTS

- PAYLOAD MASS = 6800kg
- LAUNCH DURING PAYOUT
- SPIN UP AFTER SEPARATION
- 3 KW VARIABLE SPEED RETRIEVAL MOTOR
- HEAT SINK (AIRCRAFT STYLE) BRAKE

**DESIGN SPECIFIC**

TETHER LENGTH – 125KM

MAX TENSION – 1780 N

MAX TETHER VELOCITY – M/S – 366

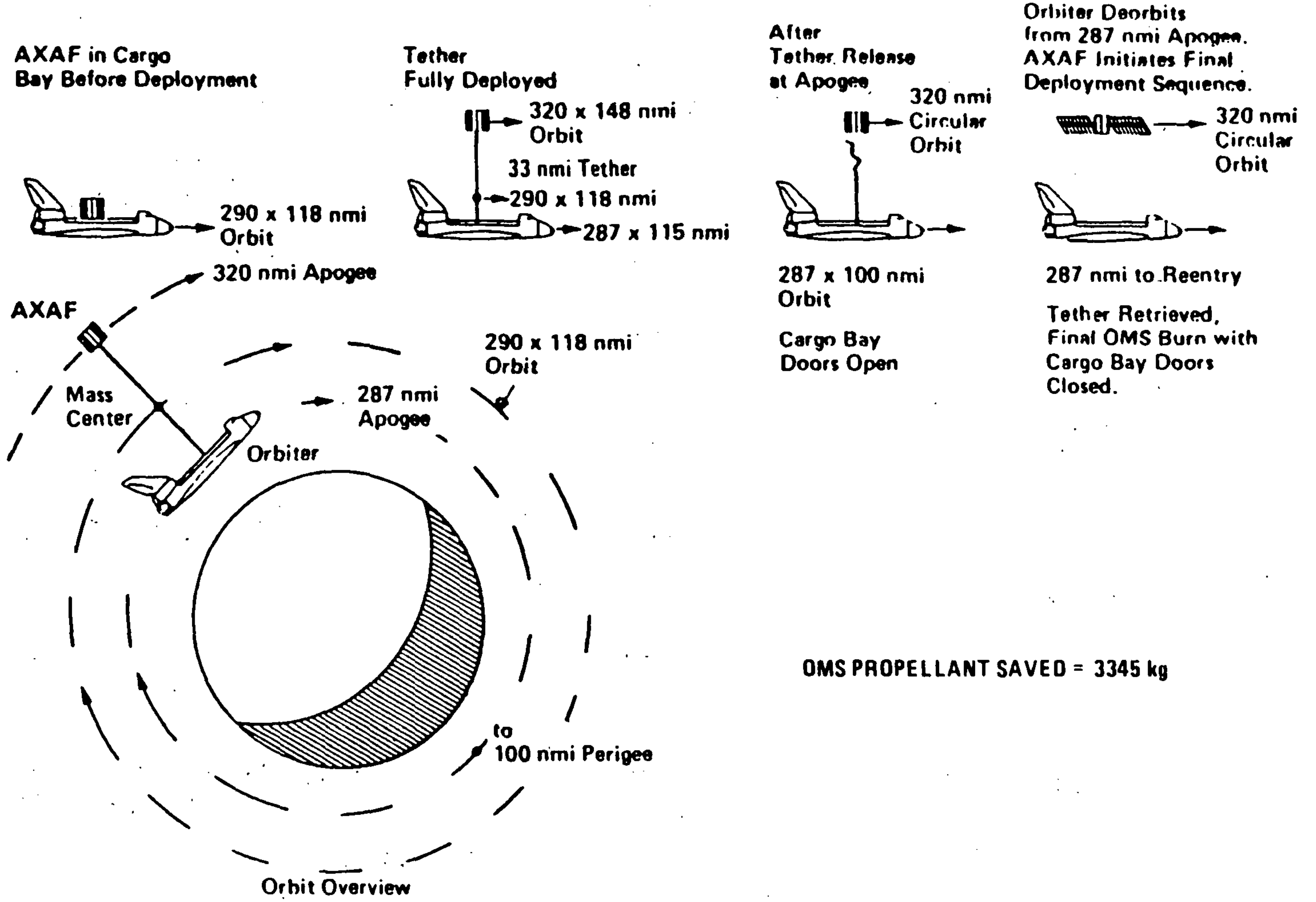
MAX BRAKE POWER – K W – 700

**PROPELLANT SAVINGS:**

OMS – 2270kg

SSUS – 4090kg

CHART 9



OMS PROPELLANT SAVED = 3345 kg

## AXAF DEPLOYMENT SEQUENCE/SHUTTLE RESPONSE

CHART 10

# TETHER ORBIT INSERTION OF SPACE TELESCOPE

| | DIRECT INSERTION METHOD | TETHER INSERTION METHOD |
|---|---|---|
| ST FINAL ORBIT (NMI) | 320 X 320 | 370 X 370 |
| (1) SHUTTLE INITIAL ORBIT (NMI) | 320 X 320 | 130 X 334 |
| TETHER LENGTH (NMI) | – – – – | 40 |
| (2) SHUTTLE FINAL ORBIT (NMI) | 320 X 320 | 102 X 330 |
| OMS PROPELLANT (LB) | | |
| LOADED | 25100 | 25100 |
| REQUIRED, WITH MARGIN | 25100 (EST.) | 12500 (EST.) |
| OFF–APOGEE DEORBIT ALLOWANCE | – – – – | 5000 (MAX) |
| EXCESS OMS PROPELLANT | 0 | (3) 7600 (EST.) |
| SPACE TELESCOPE WT (LB) | 25500 | 25500 |
| ST ASE WT (LB) | 2500 | 2500 |
| TETHER DEPLOYER SYSTEM (LB) | – – – – | 8000 |
| TETHER RETRIEVAL POWER BATTERIES (LB) | – – – – | 4000 |
| CARGO WEIGHT LOADED (LB) | 28000 | 40000 |
| CARGO WEIGHT MARGIN (LB) | 0 | (3) 8000 (EST.) |
| TETHER TENSION (LB) | – – – – | 750 |
| ST RETRIEVAL ENERGY (kWh) | – – – – | 31 |

NOTES:
(1) SHUTTLE DIRECT INSERTION TO APOGEE OF INITIAL ORBIT
(2) SHUTTLE DIRECT DEORBIT FROM APOGEE OF FINAL ORBIT
(3) BASED ON PRELIMINARY ESTIMATE OF SHUTTLE PERFORMANCE WITH ABORT RETURN FROM INITIAL ORBIT.

CHART 12

**MARTIN MARIETTA**

4906-85

# SELECTED TETHER APPLICATIONS IN SPACE STUDY

PHASE I COMPLETED:

SURVEY AND ASSESSMENT OF 26 TRANSPORTATION (AND A FEW CONSTELLATION) CONCEPTS.

PHASE II COMPLETED:

DETAIL ANALYSIS OF FOUR SURVIVING CANDIDATES:

(1) TETHERED ORBITER DEBOOST FROM SPACE STATION

(2) TETHERED OTV BOOST FROM SPACE STATION

(3) TETHERED SPACE STATION SCIENTIFIC PLATFORM

(4) TETHERED PAYLOAD BOOST FROM ORBITER

PHASE III STARTED:

ENGINEERING DESIGN AND COST/BENEFIT ANALYSES OF THE PHASE II CONCEPTS.

CHART 13

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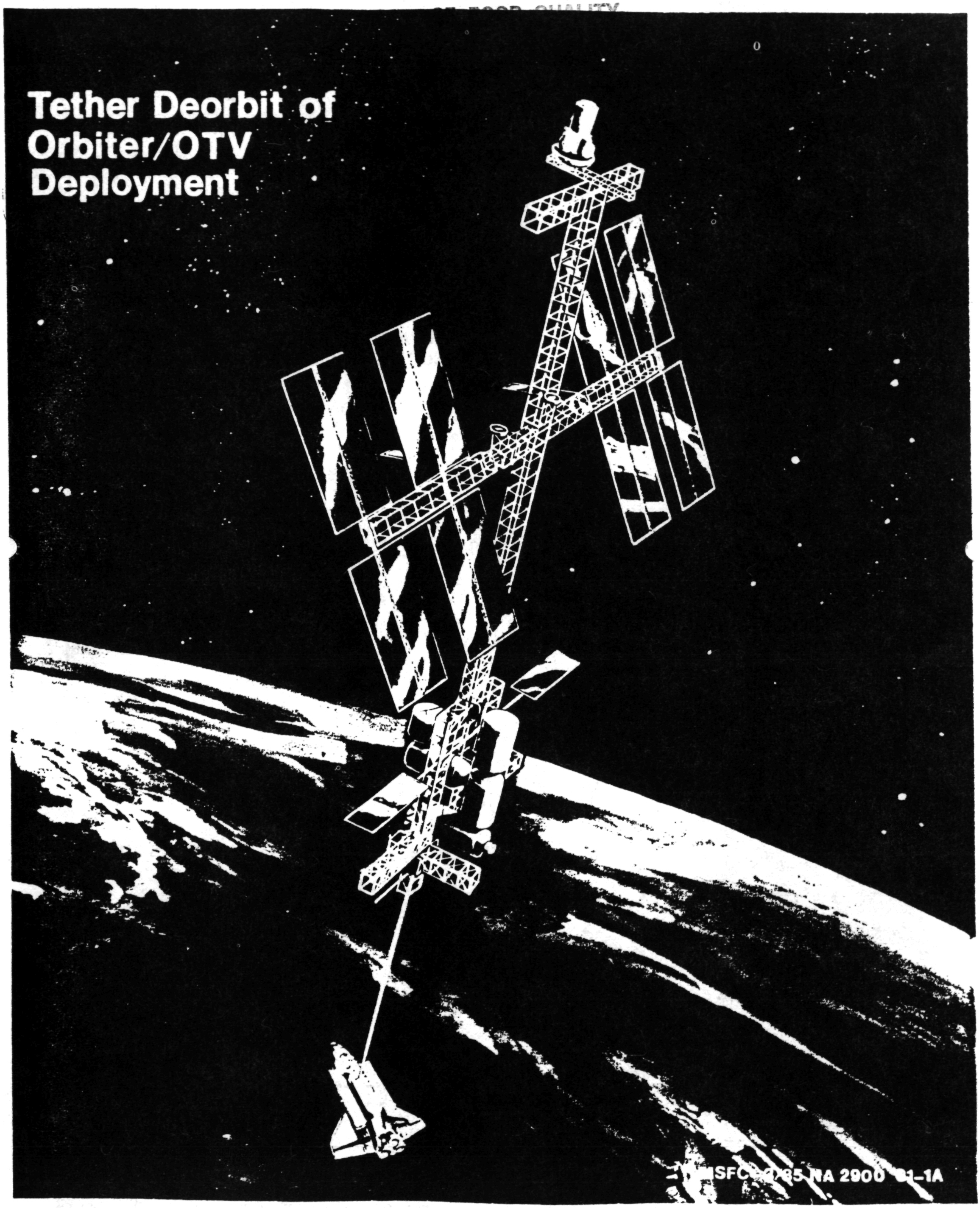
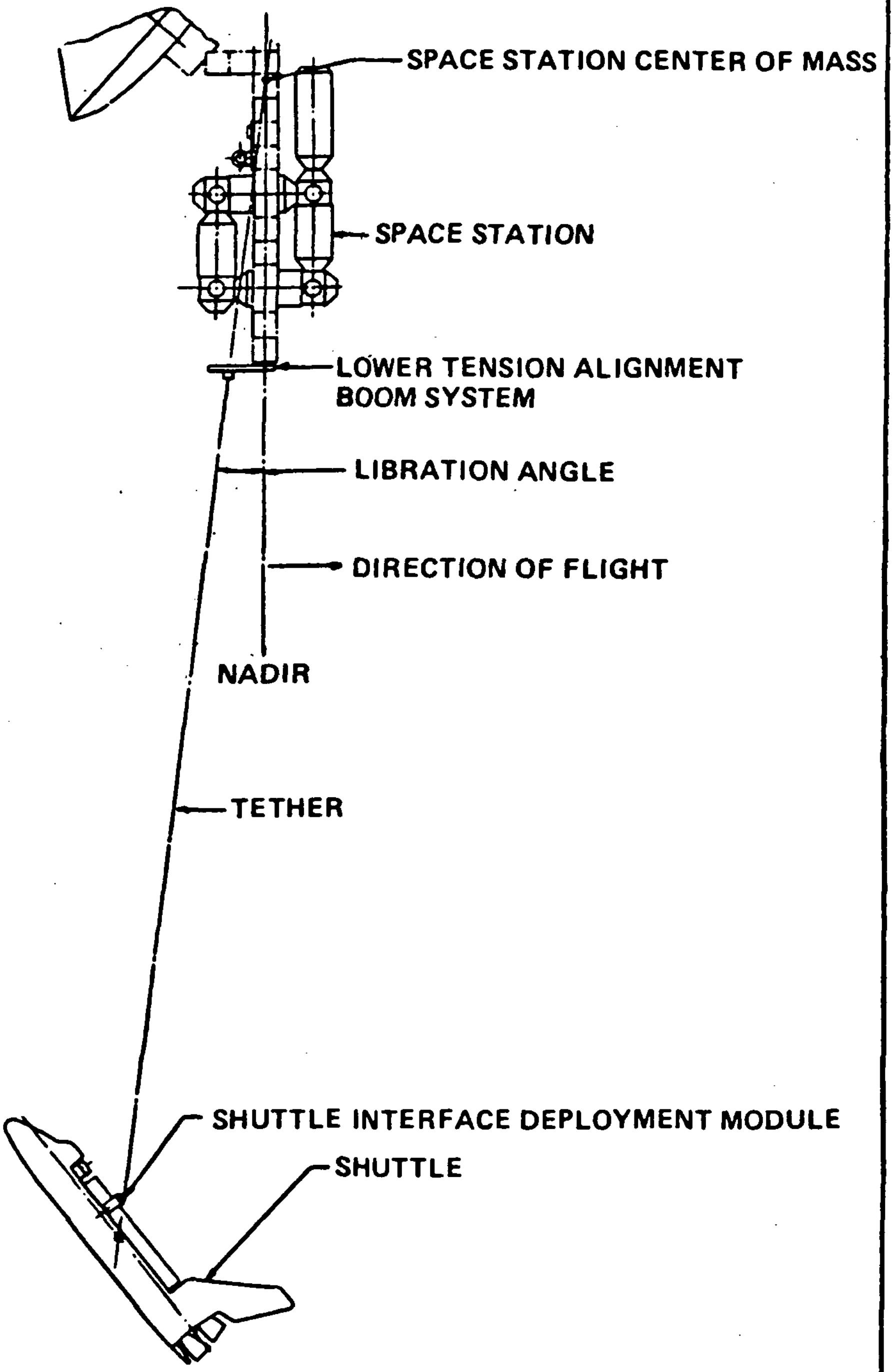


Tether Deorbit of Orbiter/OTV Deployment

MSFC-[illegible]/85 NA 2900 [illegible]1-1A

CHART 14



SPACE STATION/SHUTTLE
ATTITUDE DURING DEPLOYMENT

CHART 15

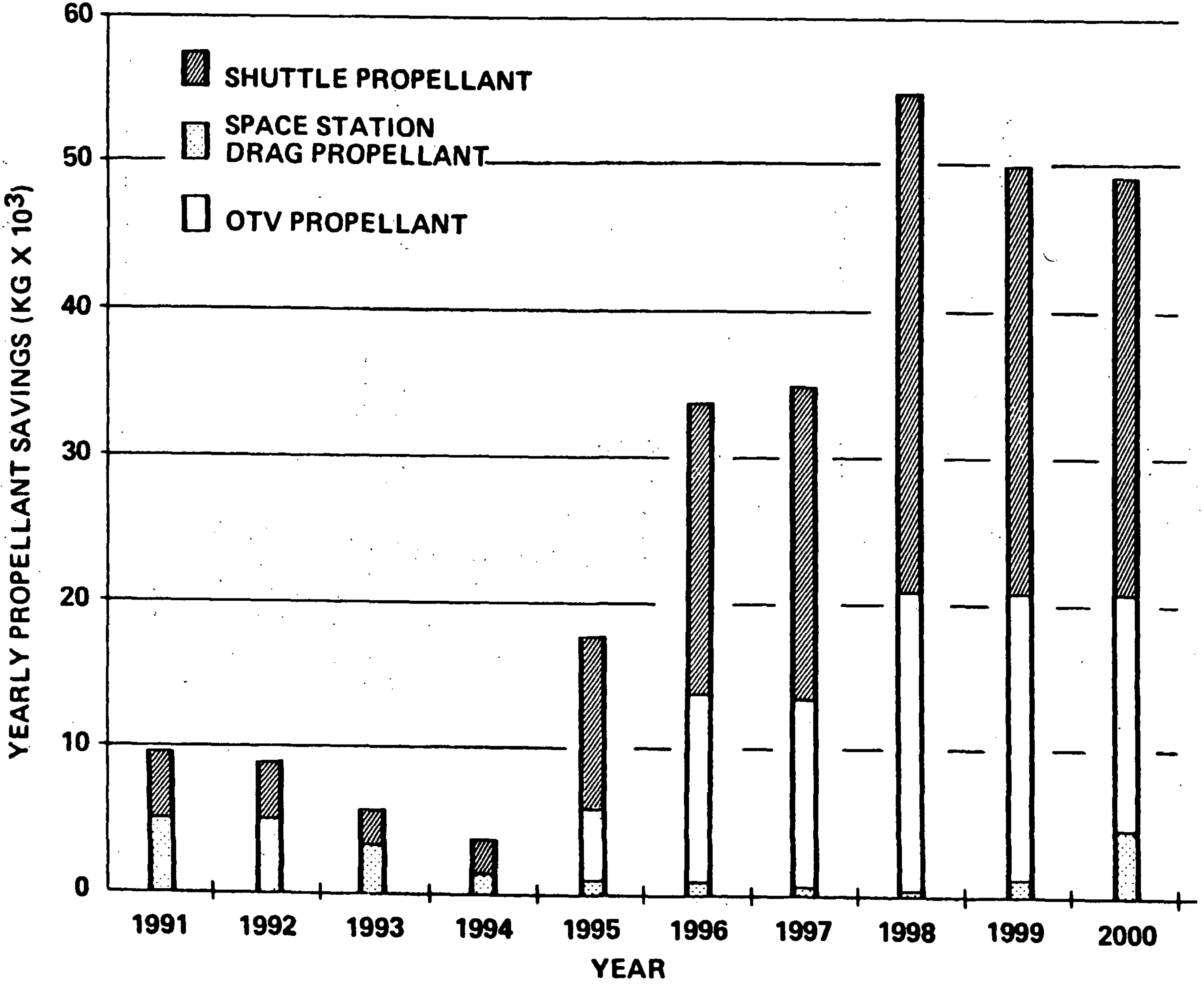
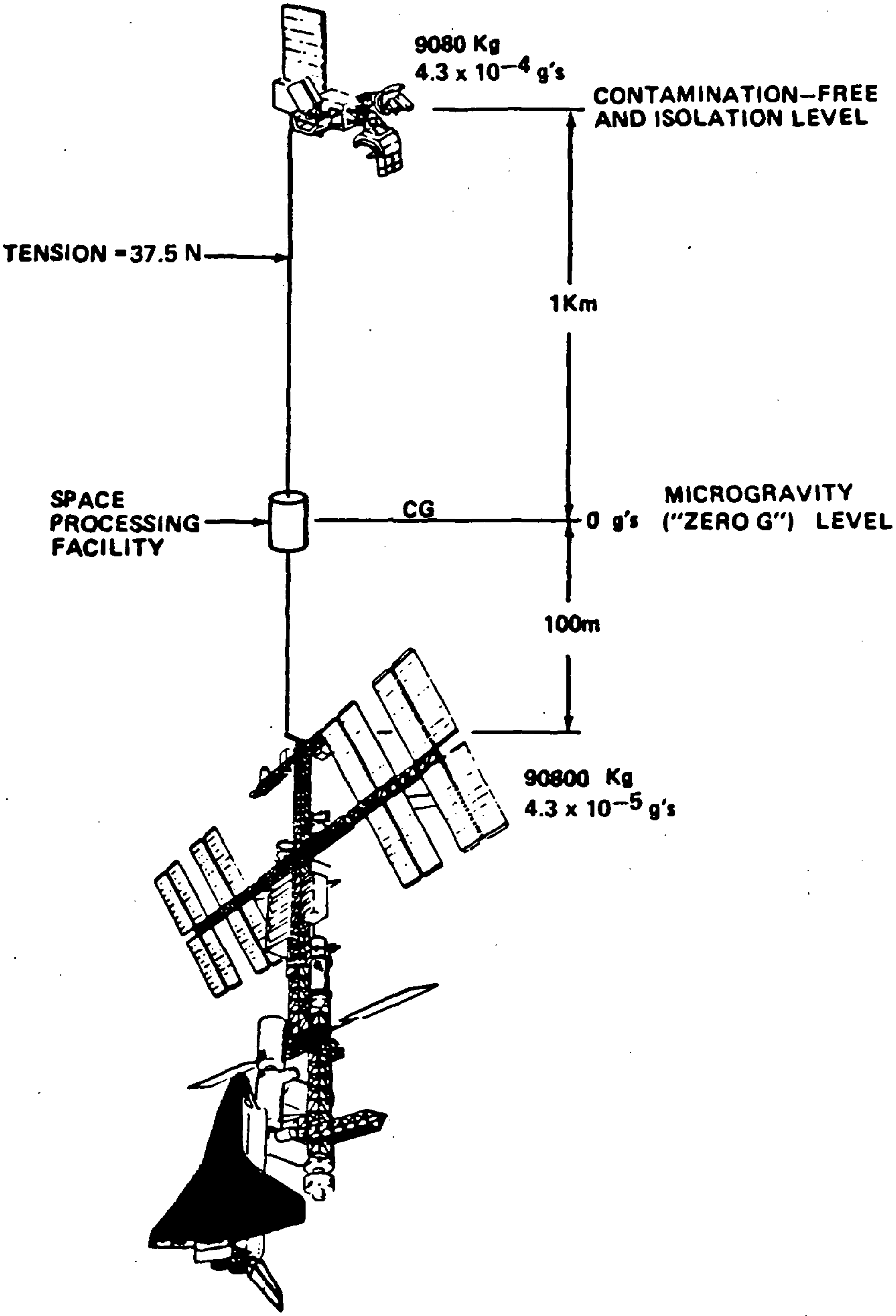


CHART 16

FIGURE . TETHER BENEFITS IN TERMS OF ANNUAL PROPELLANT SAVINGS



TETHERED MICROGRAVITY FACILITY

CHART 17

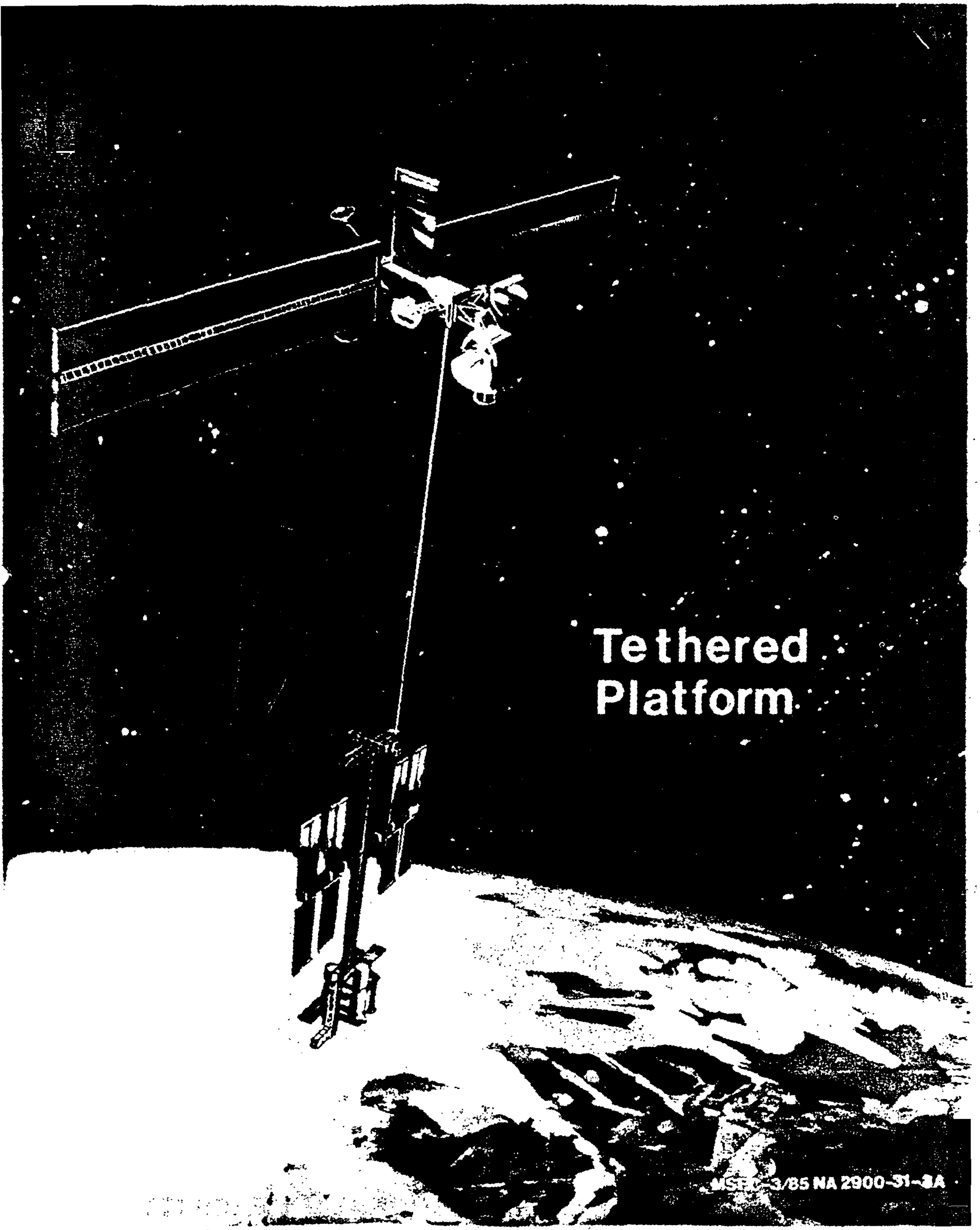


CHART 18

## AUTOMATED GUIDANCE FOR TETHER MEDIATED RENDEZVOUS STUDY

DEVELOPMENT OF AN ALGORYTHM FOR REMOTED DOCKING OF AN ORBITER
TO A TETHERED DOCKING FACILITY OF THE SPACE STATION

## ELECTRODYNAMIC ULF/ELF ANTENNA SYSTEM

DEFINITION OF AN OVERALL ULF/ELF COMMUNICATION SYSTEM AND PRECURSOR FLIGHT EXPERIMENT

## SPACE EXPENDABLE TETHER SYSTEM (SETS) PAYLOAD MISSION ANALYSIS STUDY

ASSESSMENT OF VARIOUS AVAILABLE INSTRUMENT CARRIERS AS PAYLOADS FOR EARLY SETS DEMONSTRATIONS

CHART 19

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OF POOR QUALITY

# OMV-OTV Tethered Rendezvous

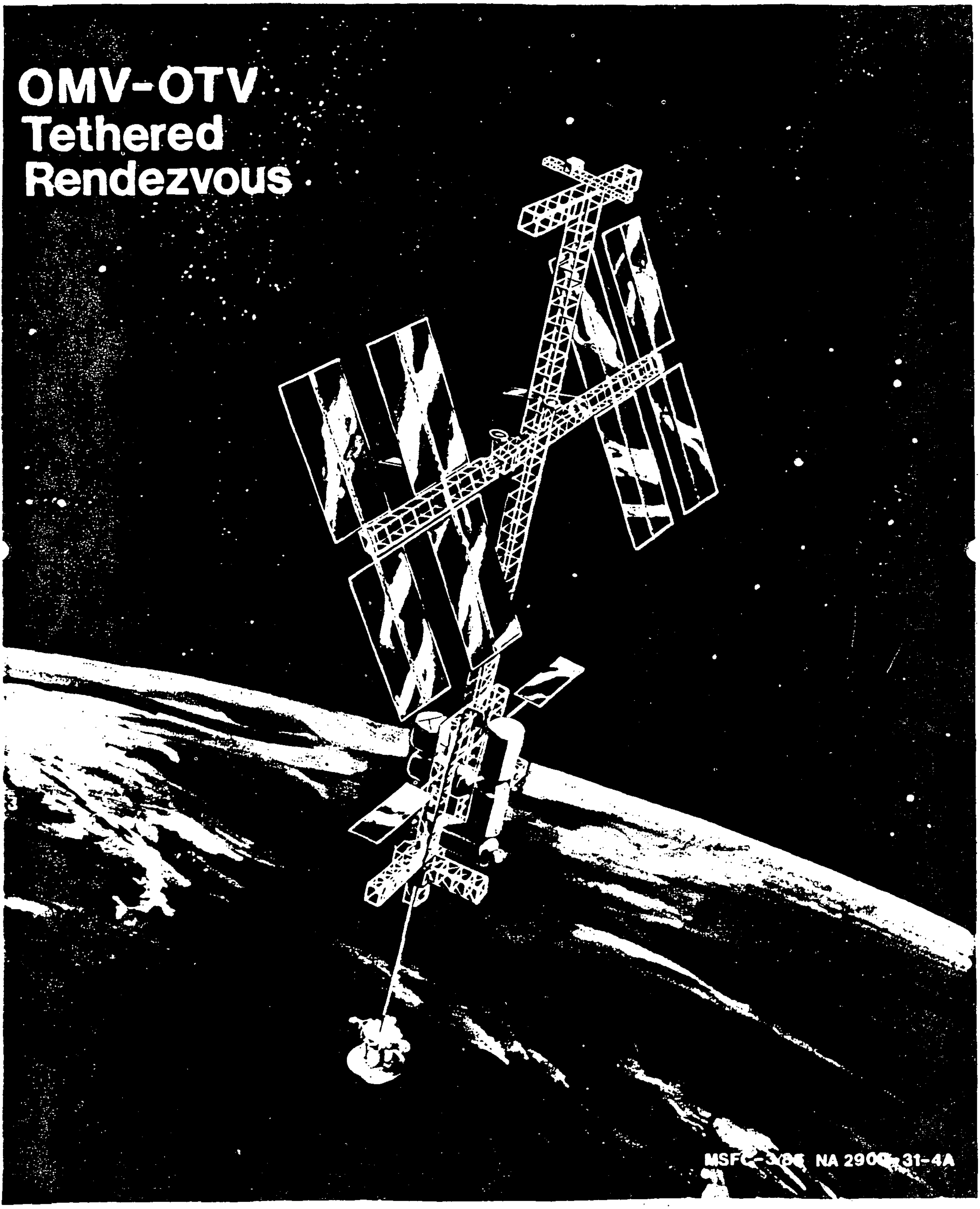

CHART 20

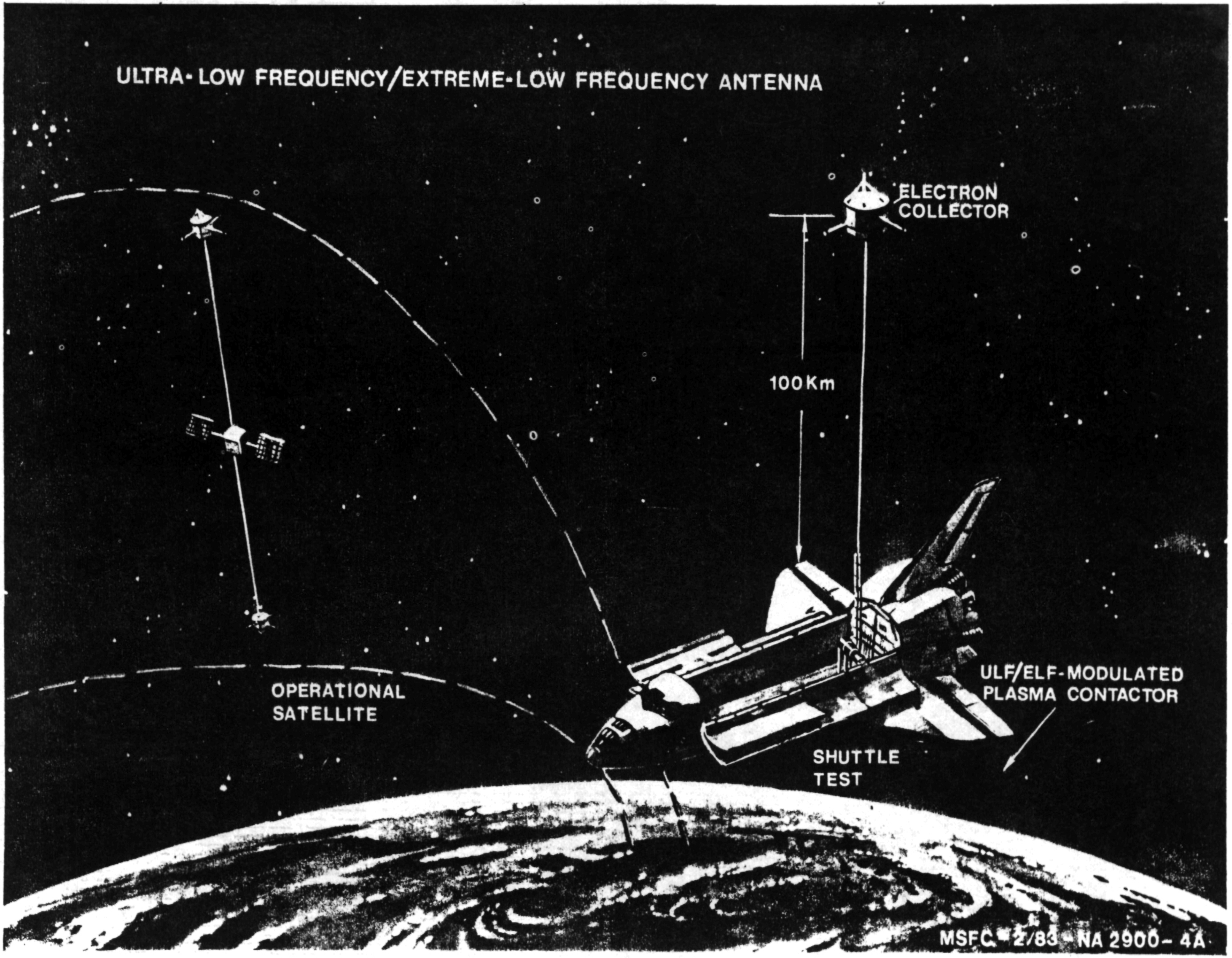
ULTRA-LOW FREQUENCY/EXTREME-LOW FREQUENCY ANTENNA
ELECTRON COLLECTOR
100Km
OPERATIONAL SATELLITE
SHUTTLE TEST
ULF/ELF-MODULATED PLASMA CONTACTOR
MSFC 2/83 NA 2900-4A

CHART 21

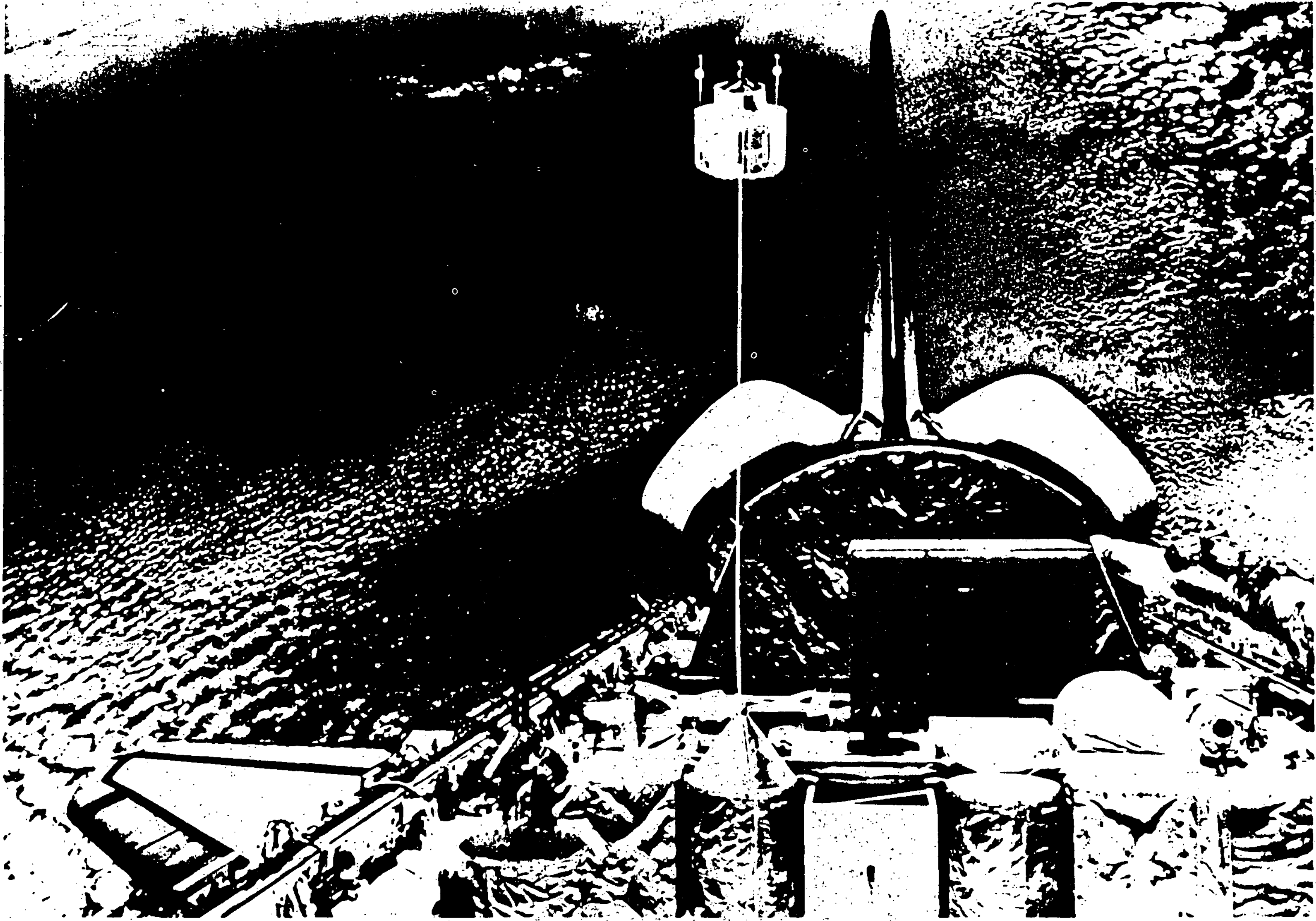

CHART 22

| | | |
|---|---|---|
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| CHART NO.:<br>4651–85 | TETHER TRANSPORTATION | DATE:<br>OCTOBER 1985 |

## BENEFITS ASSESSMENT

- ORBITER BASED PAYLOAD MASS DEPLOYMENT < ~ 12,000kg LIMITED WHEN TETHER DEPLOYER MASS APPROACHES ORBITER OMS PROPELLANT SAVINGS

  NET PROPELLANT SAVINGS < 7500 kg

- SPACE STATION BASED PAYLOAD MASS DEPLOYMENT < 100 TONNES (ORBITER)

  PROPELLANT SAVINGS: OMS, OMV, OTV, STATION DRAG MAKE–UP

  NET PROPELLANT SAVINGS:

| | |
|---|---|
| 1991–1994 | < 9,000kg ANNUALLY |
| 1995–2000 | < 50,000kg ANNUALLY |

| | | |
|---|---|---|
| ORGANIZATION:<br>PROGRAM DEVELOPMENT | MARSHALL SPACE FLIGHT CENTER | NAME:<br>GEORG von TIESENHAUSEN |
| CHART NO.:<br>4650-85 | TETHER TRANSPORTATION | DATE:<br>OCTOBER 1985 |

## SHUTTLE EXPENDABLE TETHER SYSTEM:

- PRESENTLY UNDER DEVELOPMENT
- PRIME CANDIDATE FOR PAYLOAD DEPLOYMENT DEMONSTRATIONS
- LOW TETHER TENSION DEPLOYMENT. SWING THROUGH LOCAL VERTICAL AND RELEASE AT BOTH TETHER ENDS.
- PROPOSED FLIGHT EXPERIMENT FOR FY87
- POTENTIAL PAYLOADS:
  - RECOVERABLE REENTRY CAPSULE
  - UPWARD DEPLOYMENT OF A PDP, SPARTAN, XSAT, AND OTHER AVAILABLE INSTRUMENT CARRIERS

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## NECESSARY CONDITIONS TO ACHIEVE ORBITER MISSION BENEFITS

- LIGHT WEIGHT DEPLOYMENT SYSTEM WITH MINIMUM VOLUME
- DISPOSABLE TETHER PAYLOAD DEPLOYMENT

  UNDER CERTAIN CONDITIONS PAYLOAD RETRIEVAL ADVANTAGEOUS BY ORBITER RENDEZVOUS
- PAYLOAD UPWARD DEPLOYMENT TOWARD END OF ORBITER MISSION
- HAVING ONE PAYLOAD AMONG SEVERAL THAT REQUIRES A HIGHER ALTITUDE
- MAXIMUM PAYLOAD MASS DEPLOYED UPWARD ~ 12,000kg FROM NOMINAL ORBITER ALTITUDE (300km)

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## INSIGHTS GAINED FROM TETHERED TRANSPORTATION STUDIES

### TETHER ISSUES

- DESIGN FOR ACCEPTABLE RECOIL
- MULTIPLE REUSE DURABILITY
- DEBRIS COLLISION HAZARD

### ENERGY MANAGEMENT

- GENERATED BY DEPLOYMENT ~ 15–20kWh (ORBITER); 20–400 kWh (SPACE STATION)
- REQUIRED FOR RETRIEVAL ~ 1–2 kWh NORMALLY; UP TO 30kWh WITH EXTRA BATTERIES (ORBITER); UP TO 70kWh (SPACE STATION).

### ORBITER AND SPACE STATION IMPACTS

- INDUCED ACCELLERATION LEVELS (~ $10^{-4}$g)
- ORBIT PERTURBATIONS
- STRUCTURAL STRESS
- DEPLOYER SYSTEM LOCATION REQUIREMENTS AND MASSES
- ENERGY SUPPLY AND DISPOSAL REQUIREMENTS
- BENEFITS TO STATION, ORBITER, OTV AND OTHERS

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## OUTLOOK FOR 1986 IN TETHERED TRANSPORTATION

- ENGINEERING ANALYSES AND COST/BENEFIT DETERMINATION OF:
  - ORBITER DEPLOYMENT FROM SPACE STATION } COMBINED
  - OTV LAUNCH FROM SPACE STATION } COMBINED
  - PAYLOAD DEPLOYMENT AND RETRIEVAL FROM ORBITER
  - TETHERED SPACE PLATFORMS
- SPACE EXPENDABLE TETHER SYSTEM DEVELOPMENT
  - EXPECTED FLIGHT READINESS – 1988
- DEMONSTRATION MISSION PAYLOADS DEFINITIONS FOR EXPENDABLE TETHER SYSTEM
- SPECIALIZED TETHER SIMULATION PROGRAM DEVELOPMENT
- TETHER REMOTE DOCKING ANALYSIS (SPACE STATION)
- SPACE STATION TETHERED PLATFORM WITH MOVABLE, VARIABLE G MODULE
- KITE FLIGHT EXPERIMENT DEFINITION
- ULF/ELF ANTENNA SYSTEM

CHART 27

THE FOLLOWING INDUSTRIES, INSTITUTIONS, AND NASA FIELD CENTERS HAVE BEEN PARTICIPATING IN RESEARCH AND DEVELOPMENT OF THESE APPLICATIONS.

**INDUSTRIES:**

MARTIN MARIETTA AEROSPACE
BALL AEROSPACE COMPANY
McDONNELL DOUGLAS CORPORATION
BOEING AEROSPACE CORPORATION
CONTROL DYNAMICS COMPANY
ENERGY SCIENCE LABORATORIES
ANALYTICAL MECHANICS ASSOCIATES
S–CUBE CORPORATION
MATERIALS CONCEPTS INCORPORATED

**INSTITUTIONS:**

SMITHSONIAN ASTROPHYSICAL OBSERVATORY
UNIVERSITY OF CALIFORNIA – SAN DIEGO
UNIVERSITY OF UTAH
UNIVERSITY OF ALABAMA – HUNTSVILLE
STANFORD UNIVERSITY

**NASA FIELD CENTERS:**

MARSHALL SPACE FLIGHT CENTER
JOHNSON SPACE CENTER
GODDARD SPACE FLIGHT CENTER
LANGLEY RESEARCH CENTER
LEWIS RESEARCH CENTER
AMES RESEARCH CENTER
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