MCR-86-1329
NAS8-36609
DPD-654
DR-6

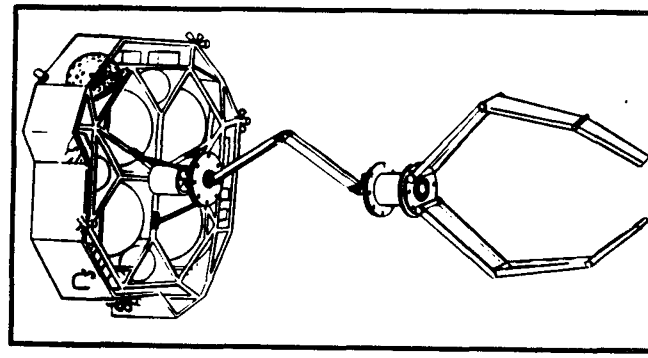
Volume I

Final
Technical
Report

June 1986

Executive Summary,
Study Results

Concept Definition Study for Recovery of Tumbling Satellites



(NASA-CR-179228) CONCEPT DEFINITION STUDY FOR RECOVERY OF TUMBLING SATELLITES. VOLUME 1: EXECUTIVE SUMMARY, STUDY RESULTS Final Technical Report (Martin Marietta Aerospace) 212 p CSCL 22B G3/18

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MCR-86-1329
Contract NAS8-36609
DPD-654
DR-6

Volume I

Final Technical Report

June 1986

Executive Summary/
Study Results

CONCEPT DEFINITION STUDY FOR RECOVERY OF TUMBLING SATELLITES

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FOREWORD

This document was prepared by Martin Marietta Corporation under contract NAS8-36609, Concept Definition Study for Recovery of Tumbling Satellites, to fullfil the requirements of Data Procurement Document 654, Data Requirement DR-6, Final Technical Report, Volume I, Executive Summary and Study Results. This effort was accomplished for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration under the technical direction of Mr. Herbert Lenox and Mr. Stephen B. Hall, as Contract Technical Managers.

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1.0 EXECUTIVE SUMMARY

This Tumbling Satellite Recovery (TSR) study report documents the first assessment of the design requirements and the conceptual definition of a "front end kit" to be transported on the currently defined Orbital Maneuvering Vehicle (OMV) and the Space Transportation System (STS) Shuttle Orbiter, to conduct remote, teleoperated recovery of disabled and noncontrollable, tumbling satellites. Studies related to recovery of disabled satellites or space debris have been conducted by NASA and DOD with academic and industry assistance for over 20 years. None of the literature data quantified the dynamic characteristics of a tumbling satellite, nor did they appear to address the full spectrum of TSR system requirements. This study investigated both aspects with useful results.

The study group conducted a thorough review of the prior recovery-related studies and actual hardware development efforts to identify a concept for the design effort. Five candidate concepts were selected and evaluated as potential recovery concepts, using a set of preliminary evaluation criteria. The assessment revealed that none of the candidates truly had all the elements needed to do the task.

The principal reasons behind this were: (1) typical "complex" satellite motion was not defined; and (2) a remote recovery system as a front-end kit for a well defined Orbital Maneuvering Vehicle was not conceptualized. This study conducted an explicit analysis to determine the most likely tumble mode presented by a non-controllable, disabled tumbling satellite. Satellite "complex" motion was estimated to most likely be flat, single axis spin about the major principal inertial axis. This implies that a recovery system could have to deal with a fifteen-foot diameter, 30-foot long spacecraft, with 33,000 pounds mass that would be spinning end over end about a transverse axis, a quantified challenge that can be answered successfully.

An operations concept was developed and provided a solid frame of reference for the description and operations analysis of a set of six Design Reference Missions (DRMs). In addition, a set of functional and operational requirements were developed and allocated, on a top level basis, to a group of recovery "subsystem" accommodations.

Rather than design a wide range of individual recovery systems to satisfy the six DRMs, the study team selected a modular system readily configured into recovery systems capable of being tailored for specific mission scenarios. As shown in Figure 1.0-1, the selected design concept provides a modular system architecture that is composed of a number of subsystem mechanisms. Thus, a large disabled satellite in a flat spin beyond the range of the Orbiter would require a full-up recovery system, as shown in Figure 1.0-1, that has an extendible boom, a spin table to match rates, and a large envelopment-type grapple mechanism to allow capture and rigidization for transport back to the Orbiter. However, a controllable, non-spinning satellite could be recovered with an extendible boom and a small gripper and thus save launch weight. The recommended conceptual recovery system can serve as a well-founded focal point for future study efforts.

In addition, a Supporting Research and Technology Report recommended four specific areas for studies and hardware development to address recovery system technology issues. Finally, a TSR kit cost analysis established a total program cost estimate of 18 million in constant fiscal year (FY) 84 dollars.

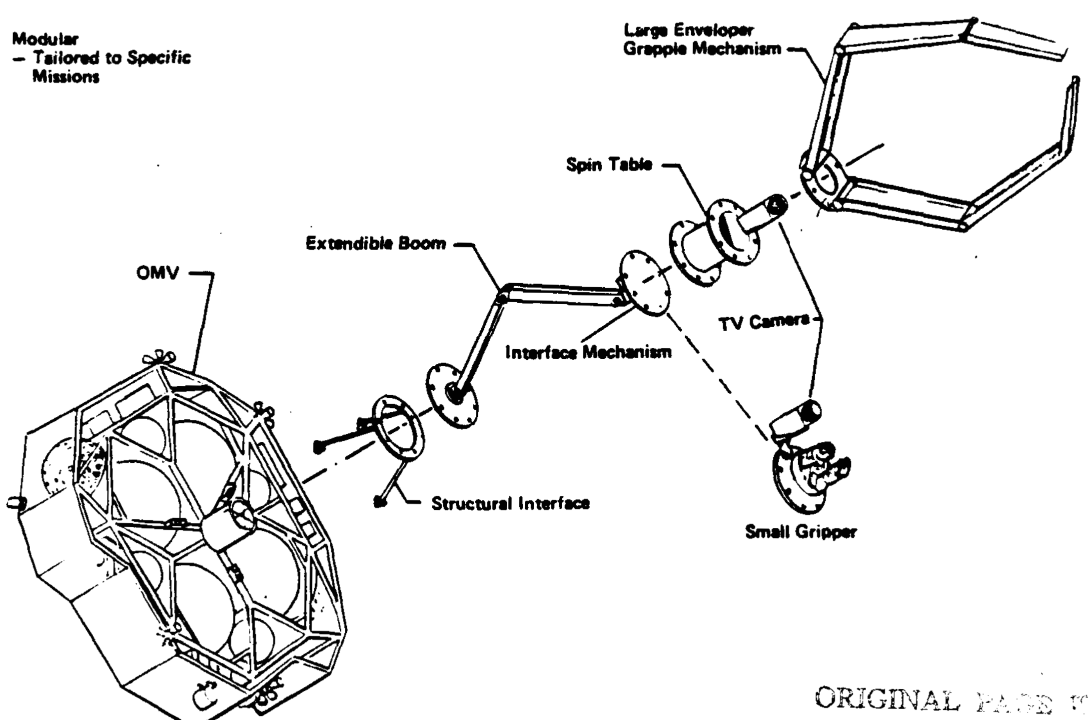

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Figure 1.0-1 Conceptual Modular Recovery System Design

1.1 Study Objectives and Approach

There were two major objectives outlined for the tumbling satellite recovery study. The first of these objectives was to develop realistic candidate recovery systems to support the NASA and MSFC decision making process in preparing to develop an operational capability for remote recovery of disabled satellites, using the OMV as a transport vehicle. A second major objective was to define the full range of remote recovery capability required. The first objective may be restated in this form: to review all known previous, related work in this area, to evaluate new concepts and to focus these efforts into a channeled conceptual framework that would lead to cost effective development of the remote tumbling satellite recovery kit. An alternative form of the second objective is to examine a broad perspective of potential recovery scenarios and to define the full range of required remote, disabled satellite recovery capability.

The MSFC had identified three generally defined levels of capability and requested MMC to establish the rationale for an increasing level of capability and then to provide designs for the requisite systems. These are: (1) System A, the basic OMV, using the NASA baseline configuration. By determining the limits of inherent OMV recovery capability, it was anticipated that the boundary between that level of capability and the next would be more easily determined; (2) System B, the basic OMV with some minimal hardware addition or changeout, such as end effectors, batteries, or special avionics hardware; (3) System C, a "full-up" capacity to recovery satellites with "complex" motion, which was undefined at that time.

The study team proceeded to develop the rationale for differentiating these levels of capability, to define requirements for each level, and to provide conceptual designs for MSFC's recovery Systems B and C.

The approach used for the TSR kit study is outlined in Figure 1.1-1. The approach was centered on conducting the four major tasks outlined in the contract statement of work. The interrelations of these tasks are also shown.

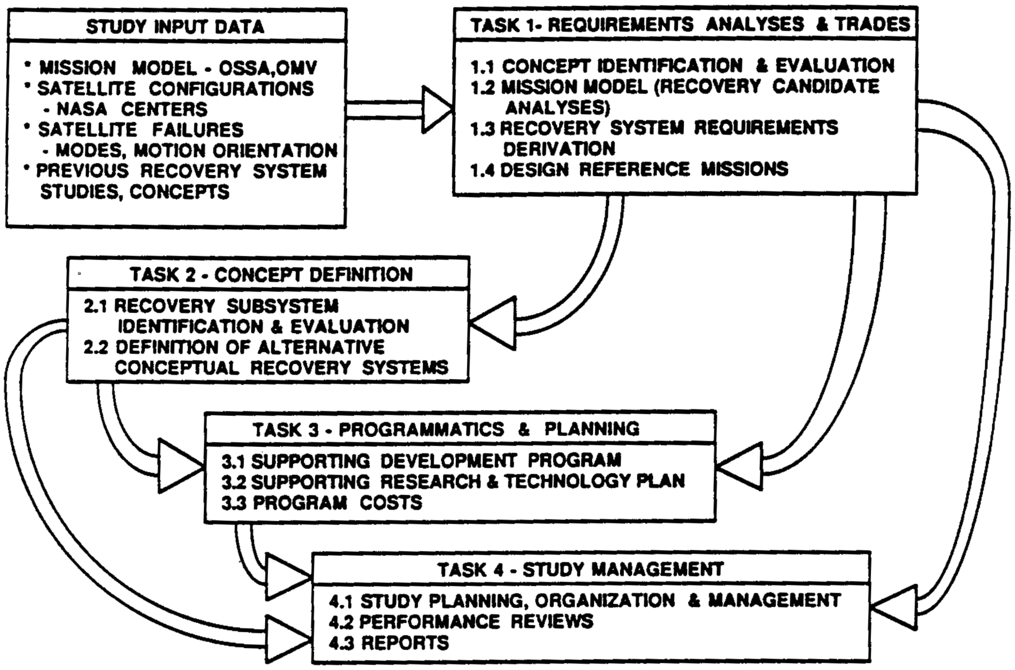

Figure 1.1-1 Study Task Flow

1.2 Requirements Analyses and Trades - Task 1

The overall objective of Task 1 was to perform the type of analyses and trades that would enable identification of recovery system requirements for the broad range of recovery systems. An associated objective was to develop the supporting rationale and the system differentiators that would clearly delineate the level of capability required for each of Systems B and C. The approach used in conducting Task 1 is shown in Figure 1.2-1. The major objectives of each of the four subtasks are shown, together with the interaction between each of them.

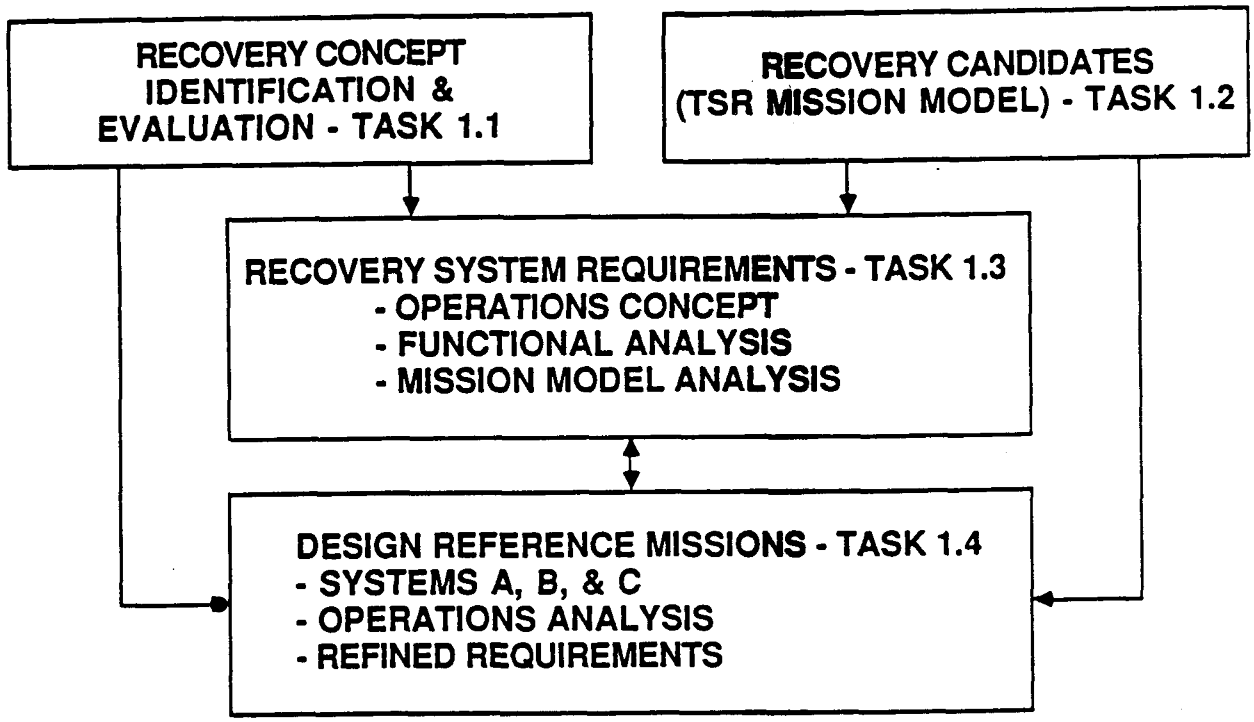

Figure 1.2-1 Task 1 Approach

1.2.1 Concept Identification and Evaluation - The approach used in this task was to conduct a thorough survey of prior related recovery studies and hardware development efforts to obtain an understanding of remote recovery requirements. It was expected that identification of a number of viable concepts would evolve from this process, and evaluation of these concepts would provide a set of concepts for concept definition in Task 2. An example of some concepts identified in the survey effort is shown in Figure 1.2-2.

From the large number of initial concepts, five were selected for further evaluation. Evaluation criteria were selected based on insights and background provided by pre-proposal efforts, and new perspectives gained from the concept identification survey and preliminary assessments. The results of the concept evaluation are presented in Table 1.2-1. The selection criteria, weighting factors and total scores for the concept evaluation are provided in the table. The results were not surprising, as the three top ranked "concepts" all appeared to possess more of what the study team was beginning to understand as requirements for a "full-up" System C recovery device.

However, by simple addition, one could note that the maximum score any concept could receive was 710 points. The highest rated recovery concept received only 80% of that score, and it became clear that more effort should be expended to clearly define the overall recovery problem.

A new and successful approach to addressing these issues was initiated and completed. This approach included an analysis of historical failure mode data, collection of tumble mode data from actual failed satellites, and a dynamics analysis to define and validate expected tumble motion.

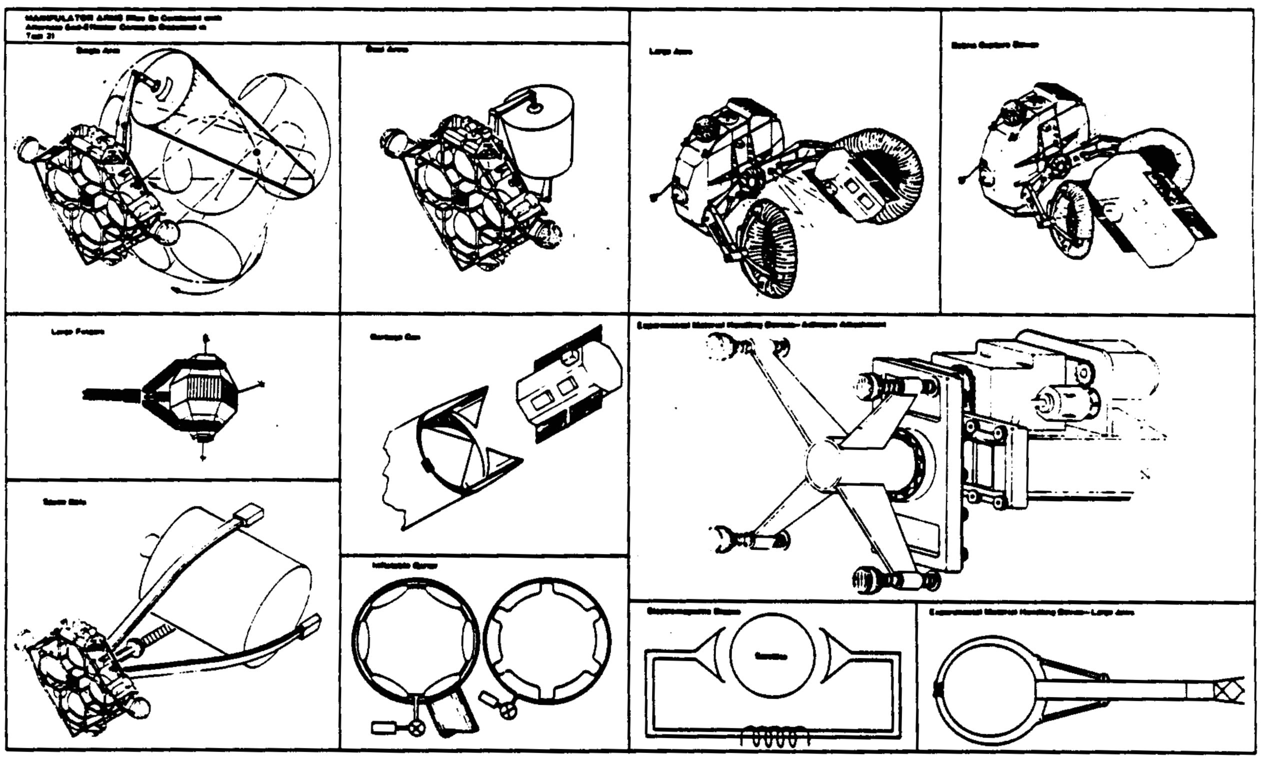

Figure 1.2-2 Concepts Attached to OMV

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Table 1.2-1 Recovery System Evaluation

EVALUATION CRITERIA	Weighting Factor	Teleoperator Grapple Despin Device	Experimental Materials Handling Device	Docking & Retrieval Mechanism	Space Bola	Debris Capture Device
Capability to Recover Broad Spectrum of Satellite Configurations	10	5	8	4	6	8
Minimum Risk to OMV & Recovery System during Recovery	9	8	8	9	5	8
Capability to Accommodate High Single-Axis Satellite Spin Rates	9	6	8	8	5	8
Minimum Risk to Target Vehicle	8	8	8	8	5	8
Compatibility with OMV & Minimum Impact on OMV Design	7	8	8	8	5	8
Dependence on Recovery Vehicle Support Elements	7	5	9	7	9	9
Modularity of Subsystems to Enable TSR System Growth for Flexible Mission Capability	6	6	8	8	5	8
Capability to Deal with Wide Range of Tumble Mode Complexity	5	9	7	7	9	6
Weight to Orbit (Mass & Volume)	5	7	7	7	9	6
Development Risk & Cost	5	8	9	9	8	7
Total Value		487	570	525	448	555

An excellent source of satellite failure data was obtained at Goddard Space Flight Center (GSFC). It examined anomalies of 44 unmanned spacecraft under the cognizance of the GSFC and the Jet Propulsion Laboratory (JPL) during the 1977-1984 time period. An assessment of this data base established three facts. First, that a typical anomaly would result in major mission loss only 1% of the time. (However, major on-orbit failures have occurred recently and are to be expected.) A second major finding was that power and attitude control and stabilization (ACS) subsystem failures accounted for 30% of the satellite subsystem anomalies. This fact implies that approximately 30% of remote, disabled satellites could be non-controllable from the ground and tumbling or spinning in some undefined manner. A third major consideration was that nearly 35% of satellite anomalies were related to the payload or experiment package. Thus, a remote, disabled satellite could be totally controllable from the ground and completely stable.

Thus, a full scale recovery system should be capable of recovering: stable, non-spinning satellites; stable, spin-stabilized satellites; and completely non-controlled, tumbling/spinning satellites.

Next, it became necessary to define typical non-controllable, tumbling or "complex" satellite motion to qualify the upper range of recovery System C capability. A search was made for satellites that had failed in a non-controllable mode, and for which satellite orientation mode and rate data were available. A set of six such cases were identified and the resultant orientation motion was revealed to be similar in all cases. An external torque created angular momentum levels that resulted in a spin-up of the satellite in a general tumble mode, with spin, precession and nutation components. This general tumble motion quickly converged to flat, single axis spin about the major principal inertia axis. The representative nature of this scenario of satellite motion after a major disturbance was confirmed by a dynamics analysis and discussions with dynamics experts outside of Martin Marietta.

The satellite failure environment analysis directly supported a final definition of a set of differentiators (Figure 1.2-3) that led to an enhanced definition of MSFC's Systems A, B, and C. The scenario differentiators are listed and those applicable to each system are check marked. For example, the System A scenario is defined as dealing with a target that is beyond Orbiter range, the target's attitude is stable, and the target has properly situated recovery support elements (RSE), as indicated on the figure. This implies that the target is not spinning, or is spinning so slowly that OMV can match the spin rate. The RSE must be fully accessible to a head-on approach with the OMV RMS end-effector, and not obstructed by arrays or antennas. If these conditions exist, the System A scenario exists and the satellite could be recovered by the basic OMV. Similar scenarios were developed for both System B and System C.

1.2.2 Recovery System Definition - The overall intent of this series of analyses was to develop a rationale for the development of a logical family of satellite recovery systems, with well defined levels of capability. In paragraph 1.2.1, the recovery system differentiators provided a framework for defining the scenarios. Figure 1.2-4 highlights the scenarios and descriptions for Systems A and B.

Recovery Scenario Differentiators

Recovery Scenario Differentiators	TSR System A	TSR System B	TSR System C
Target Is beyond Orbiter Range	X	X	
Target's Attitude Can Be Controlled from Ground	X	X	
Target Has Properly Situated[1] Recovery Support Elements (RSE)[2]	X		
Target Is Controllable, Spin Stabilized at High Rates[3]			X
Target Cannot Be Controlled from Ground and in Minimum-Energy Flat-Spin Mode.			X
Target Is Prevented from Reaching Minimum-Energy State (Due to Internal or External Torques, or Bizarre 3-σ Failures) & Exhibits General Motion at High Rates (Low Probability of Occurrence)			

1. Within Reach of OMV Grapple Devices
2. STS RMS Grapple Fixtures or FSS Berthing Latches
3. Beyond Grapple OMV Rate-Matching Capability

Figure 1.2-3 Recovery Scenario Differentiators

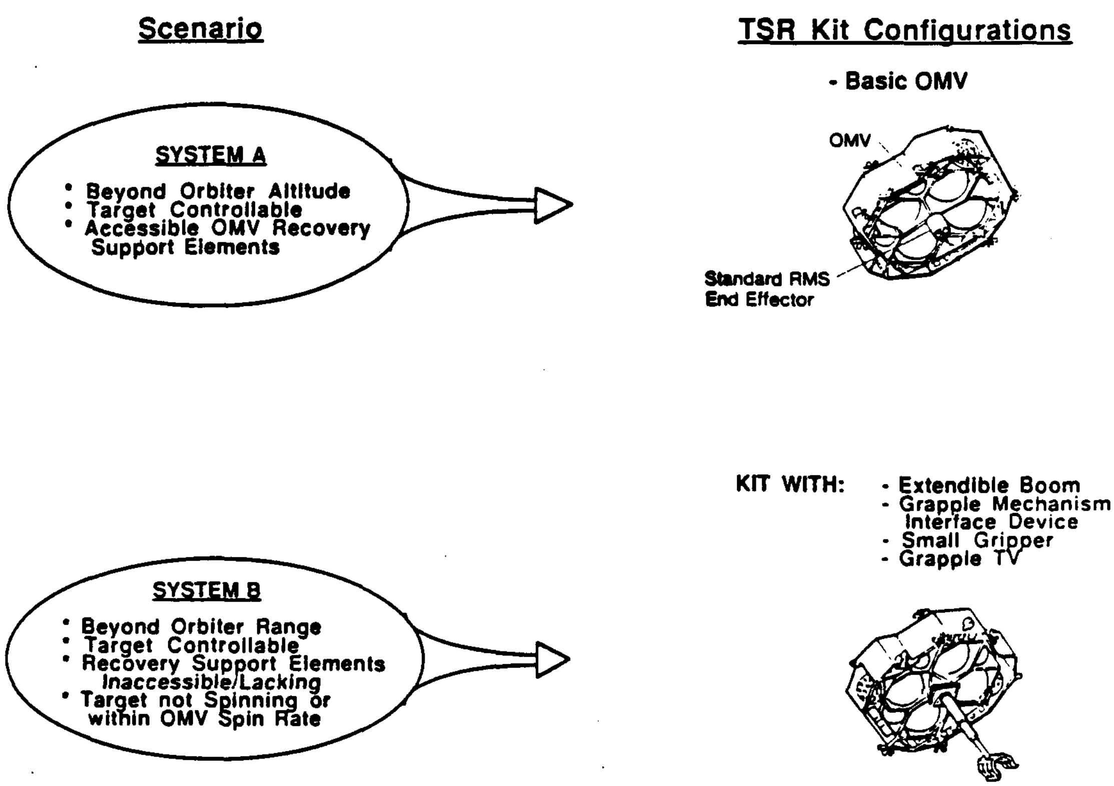

Figure 1.2-4 Recovery Systems A & B Definition

System A is defined as a basic reference configuration OMV, with its capability to dock to unobstructed RMS grapple fixtures and to flight support structure (FSS) latch pins. The capability of the OMV for capture operations is restricted so it is apparent that to accomplish a System A recovery successfully, the target will have to be relatively stable.

For System B, the typical recovery scenario is shown in Figure 1.2-4. A multiple degree-of-freedom manipulator arm is viewed as essential to allow the OMV access to obstructed grapple fixtures and to align the captured target's center of mass with the OMV orbit transfer thrust vector. A second element is a grapple mechanism interface device to allow the ready exchange of various grapple mechanisms. A third element is a small gripper mechanism to enable grapple of small "hard points" on satellites that have no recovery support elements.

The definition of a full-up System C is provided in Figure 1.2-5. For Case 1, the recovery target is beyond Shuttle range and is spin-stabilized between 5 and 50 RPM. In this situation, the recovery system configuration will include an extendible boom, a spin/despin mechanism to match rates with the target, a grapple mechanism interface device, and a "stinger" type grapple mechanism.

The more difficult System C scenario is Case 2, where the satellite is not controllable. The system capability for System C, Case 2, is similar to that of Case 1. A spin/despin mechanism is required to match the spin rate(s) of the target. The tumble or spinning configuration of the satellite, however, will require a large gripper or large envelopment type grapple mechanism to provide a firm, smooth grapple of the target, to rigidize the attachment and then maintain the grip to enable despin and stabilization of the target. A representative system configuration is shown in Figure 1.2-5.

1.2.3 <u>Satellite Recovery System Mission Model</u> - The mission model, developed specifically for this study effort, was composed of specific spacecraft data related to potential recovery missions, for satellites expected to be on-orbit in the mid-1990s. The model provided the basis from which to design a recovery system capable of accommodating the wide diversity of target size, shape, mass and inertia distributions.

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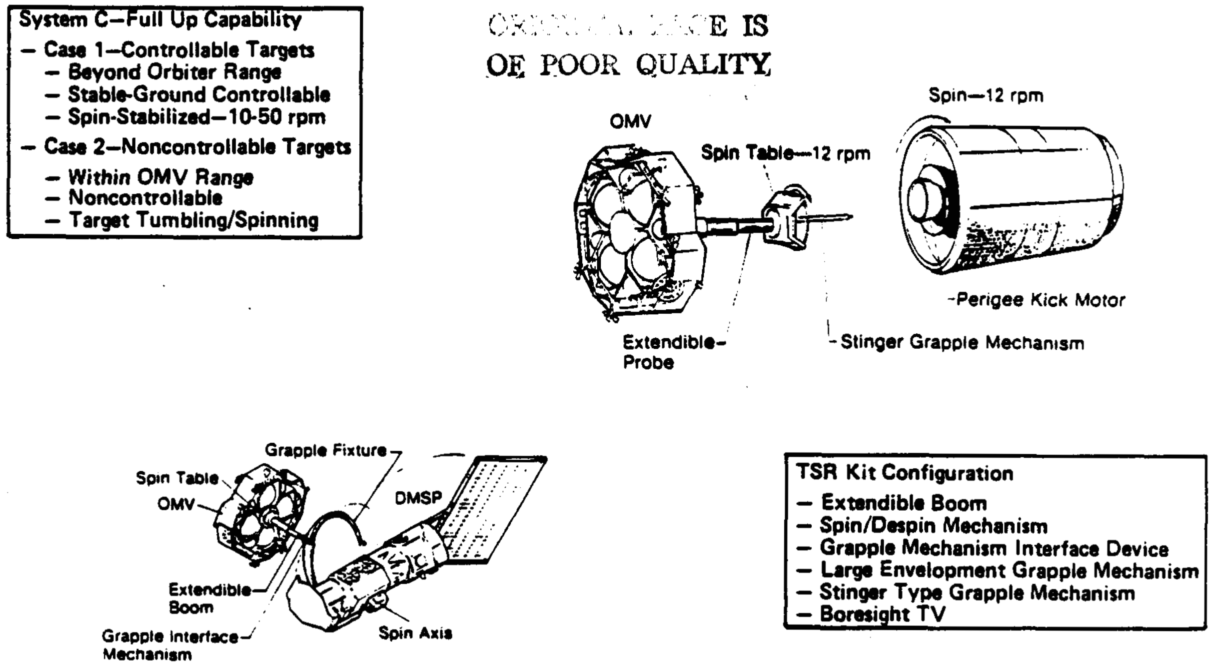

Figure 1.2-5 Recovery System C Definition

The specific satellite data collected in developing the model reflected a wide diversity in target size, mass and configuration. This is illustrated in the mission model data base, shown in Figure 1.2-6. The early stages of development of many of these programs is reflected in the absence of technical information in portions of the matrix. However, the data base was considered to be representative of what is to be expected in the mid-1990s, and provided the basis from which to develop a multi-purpose recovery system.

1.2.4 System Hardware Requirements - Recovery system requirements were generated and refined through a series of independent analyses that included an operations concept, functional analysis, and mission model assessment.

The generation of a preliminary concept of operations supports the development of a broad range of mission operations requirements, including those related to ground and aerospace support equipment. The operations concept is outlined in Figure 1.2-7. In general terms, the TSR kit will be stored in the OMV storage facility and assembled, in modular form, for each specific mission. It will be mated with the OMV in the Orbiter cargo bay during launch processing, deployed into a standby orbit by the Orbiter and transferred to the disabled satellite by the OMV.

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MISSION	WEIGHT (LBS)	LENGTH (INCH)	WIDTH (INCH)	HEIGHT (INCH)	Ixx 2 (SL-FT)	Iyy 2 (SL-FT)	Izz 2 (SL-FT)	Ixy 2 (SL-FT)	Iyz 2 (SL-FT)	Ixz 2 (SL-FT)	ARRAY (INCH)	ANTENNA (INCH)
AXAF	18,900	590	174	174	15,000	125,000	125,000				135	72.5
COBE	10,000	132 91	174 64	174 64	5,022	4,702	5,091	0	0	30		
EXP/ XTP	6,600	59	174 88	39 59							98	
GPB	2,900	60 60	72 9	72 9							54	
GRM	6,174	227 173	41 9	41 9								
GRO	33,000	288	174	174	39,800	57,500	71,750	20	-3,150	-35	330	216
HST	25,027	590	174	174	22,386	56,273	57,384	-58	527	-13		
INTELSAT VI	4,961	304	151	151	6,197	5,103	5,953					
LANDSAT	4,400	158	88	88							165	172
LDEF	21,400	360	168	168								
RADAR-SAT	13,391	256	178	178	10,759	9,784	2,915	-206	-159	325	757	206
SS SPARTAN	5,900	60	174	174	3,900	2,660	4,175				201	
UARS	12,766	348	174	174	9,255	22,849	25,389	-2719	-471	1121		

Figure 1.2-6 Mission Model Data Base

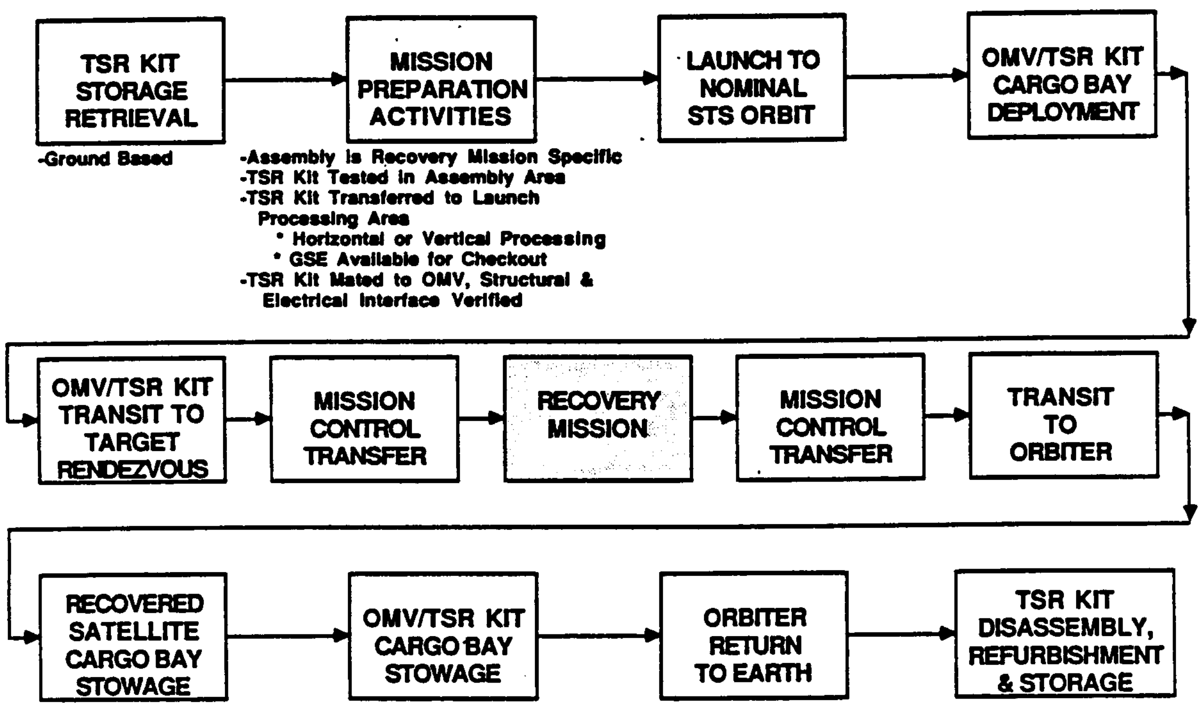

Figure 1.2-7 TSR Operations Concept

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A functional analysis of a full-up System C recovery operation was conducted to support development of mission functional requirements. This analysis is highlighted in Figure 1.2-8. The recovery operation commences with the disabled satellite in visual contact. The OMV/TSR kit operators conduct the sequence of operations shown, under teleoperated control from the ground station. Once the target has been rigidized, or firmly grappled for transport back to the Orbiter, the OMV operator will execute short firings of the lower thrust RCS engines to ensure the new mass is aligned with the OMV thrust vector, and the OMV/TSR kit/disabled satellite will be transported to the Orbiter. These analyses produced a detailed set of functional, operational and mission requirements.

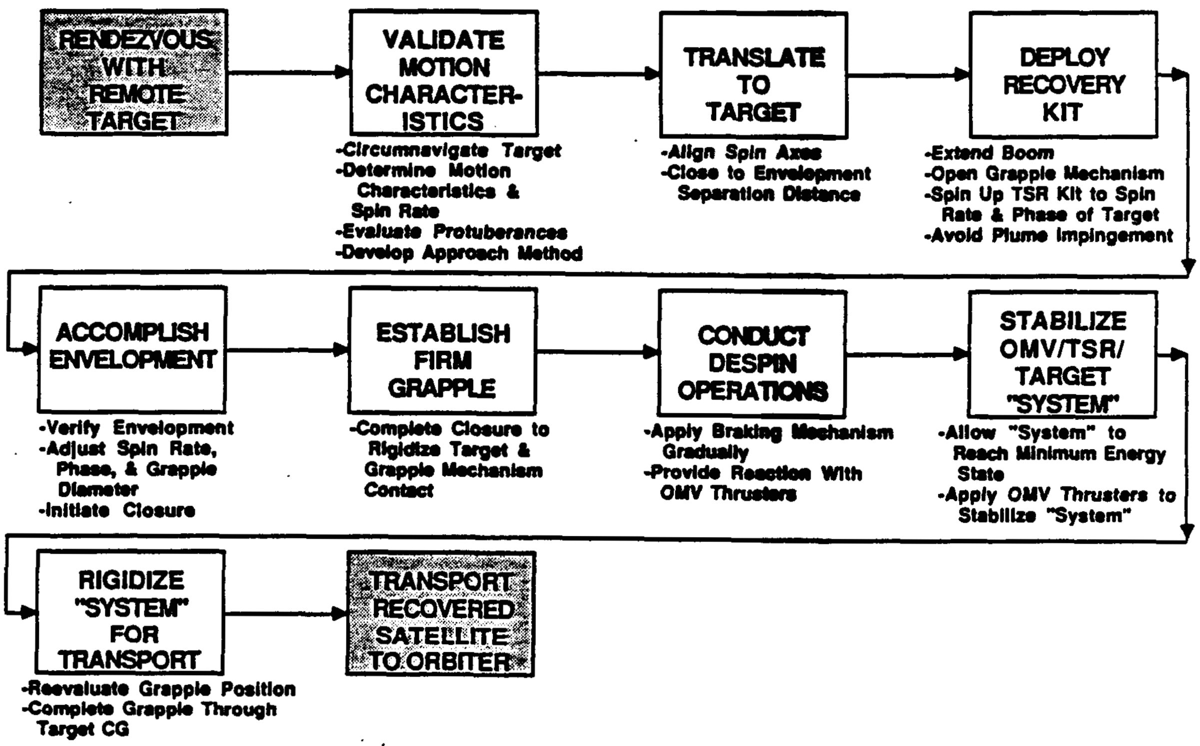

Figure 1.2-8 Functional Analysis of System C Recovery

1.2.5 Design Reference Missions - A set of six Design Reference Missions (DRMs) were selected and approved by MSFC. Two DRMs were chosen for each of the three designated levels of capability, i.e., Systems A, B, and C. An operations analysis was completed for each of the DRMs, to expand and refine the growing requirements data base. The DRM operations analyses included a breakout of: (1) required "pre-mission" activities; (2) specific or direct mission activities; and (3) post mission activities. The last DRM, DRM 6, was defined and developed to describe the most challenging recovery mission. DRM 6 involves recovery of the Upper Atmospheric Research Satellite (UARS), a 10,000 pound disabled satellite in a 324-nautical-mile circular orbit, at an inclination of 57 degrees. The UARS, as shown in Figure 1.2-9, is in an uncontrolled, flat, single axis spin and requires a full-up System C recovery system.

The identification of DRMs that encompass the full range of required recovery system capability, and the subsequent analysis of recovery preparation and execution activities, greatly expanded the evolving set of recovery system requirements.

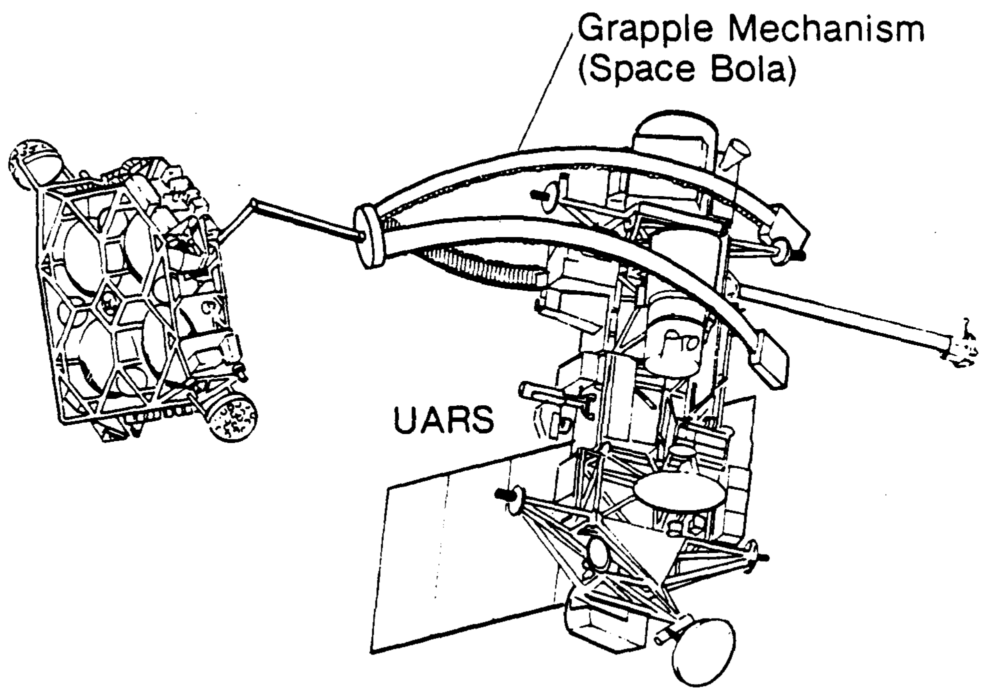

Figure 1.2-9 DRM 6, System C, Case 2

A final step in the requirements analysis phase of this study was the allocation of requirements to recovery system design accommodations. The top level requirements, generated from all the Task 1 analyses and trades, were grouped into categories that related to specific recovery subsystem design accommodations. Representative allocations are shown in Figure 1.2-10. This allocation process clearly suggested the need for a specific set of subsystem mechanisms and elements including an extendible boom (perhaps with multiple degree-of-freedom articulation capability), a spin/despin mechanism, a grapple mechanism interface device, a variety of grapple mechanisms, a boresight or proximity television system and adequate lighting. This allocation supported the development of a system architecture and design concept for the second major study task, Concept Definition.

Requirements	System Accommodation
• Shall Recover Satellites with or without Recovery Support Elements (RSE) - RMS Grapple Fixture, FSS Berthing Pins	Extendible Boom
• Shall Recover Satellites with Recessed/Obstructed RSE's (Due to Deployed Booms, Antennas)	Extendible Boom (Multi-DOF Manipulator Arm)
• Shall Recover Satellites with Protuberances Extending out from Satellite Envelope	Extendible Boom
• Shall Minimize Risk to OMV	Extendible Boom
• Shall Minimize Risk to TSR	Extendible Boom
• Shall Recover Satellites in Non-Stable, Tumble Mode	Extendible Boom
• Shall be Capable of Remote Realignment of Target CG Prior to Transport	Extendible Boom (Multi-DOF Manipulator Arm)
• Shall Match Spin Rate of Controllable Spin	Spin Table
• Shall Accommodate Satellite Spin Rates from 0 to 55 RPM	Spin Table
• Shall Match Spin/Tumble Rates of Non-Controllable Spinning Target	Spin Table
• Shall Match Spin Rates with TBD Accuracy to Accomplish Envelopment, Grapple	Spin Table Accuracy
• Shall be Capable of Despinning Satellites with TBD Level of Angular Momentum without Damage to TSR, OMV, and Target	Spin/Despin Mechanism

Figure 1.2-10 Requirements Allocation Exemplar

1.3 Concept Definition - Task 2.0

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The objective of the second major study task, Task 2, Concept Definition, was to produce a set of conceptual designs for MSFC Systems B and C that would serve as a focal point for continuing design and development efforts aimed at creating a front-end kit for the OMV to remotely recover disabled satellites.

The initial approach for this task was to use the results of the initial concept survey to select the best of the concepts, or any other new concepts, and refine these concepts into meaningful, effective conceptual system designs. During the evaluation of those previously developed concepts, it became clear that none of them could satisfy the widely variant requirements that were evolving out of parallel analysis tasks.

Thus, the study team, with the approval of the MSFC study technical director, restructured Task 2.1 as an identification and evaluation of candidate recovery subsystem elements. These subsystems included an extendible boom, a spin/despin table, a grapple mechanism interface device, and a set of grapple mechanisms for different recovery scenarios.

For Task 2.2, Conceptual Design, the preferred subsystem components were selected and a set of recovery systems were designed for Systems B and C, each with the capability to conduct both of their respective design reference missions. In addition, the MMC study team developed a new design for an envelopment type grapple mechanism, the MMC enveloper.

1.4 Evaluation of Recovery System Mechanisms - Task 2.1

1.4.1 Subsystem Evaluation Approach - A survey of candidates for each of the major subsystems was conducted. Industrial brochures, library inquiries, and discussions with mechanisms experts at MSFC and MMC produced the initial candidates. Though most were viewed quickly as falling short of perceived design requirements, all were evaluated qualitatively. By looking at the apparent advantages and disadvantages of each candidate, more evaluation considerations were derived. The study team did not consider it productive to develop new mechanism concepts, with the major exception of the envelopment type grappler, as many generic mechanisms for each component were available. The evaluations are presented in a format which describes the candidate and highlights the advantages and disadvantages of each.

1.4.2 Evaluation of Extendible Booms

Shown in Figure 1.4-1 are examples of some of the extendible boom concepts identified and evaluated during this phase of the study. The study team considered a wide range of alternatives to avoid unsupportable elimination of questionable candidates. Some of the driving design requirements in this evaluation included: the need to be compact when not deployed (to minimize Shuttle cargo bay delivery space/cost), articulation capability to provide access to obstructed recovery support elements (RSE) and to realign the target center of mass with the OMV orbit transfer thrust vector prior to orbit transfer, and capacity to accommodate grapple/despin force and torque loads.

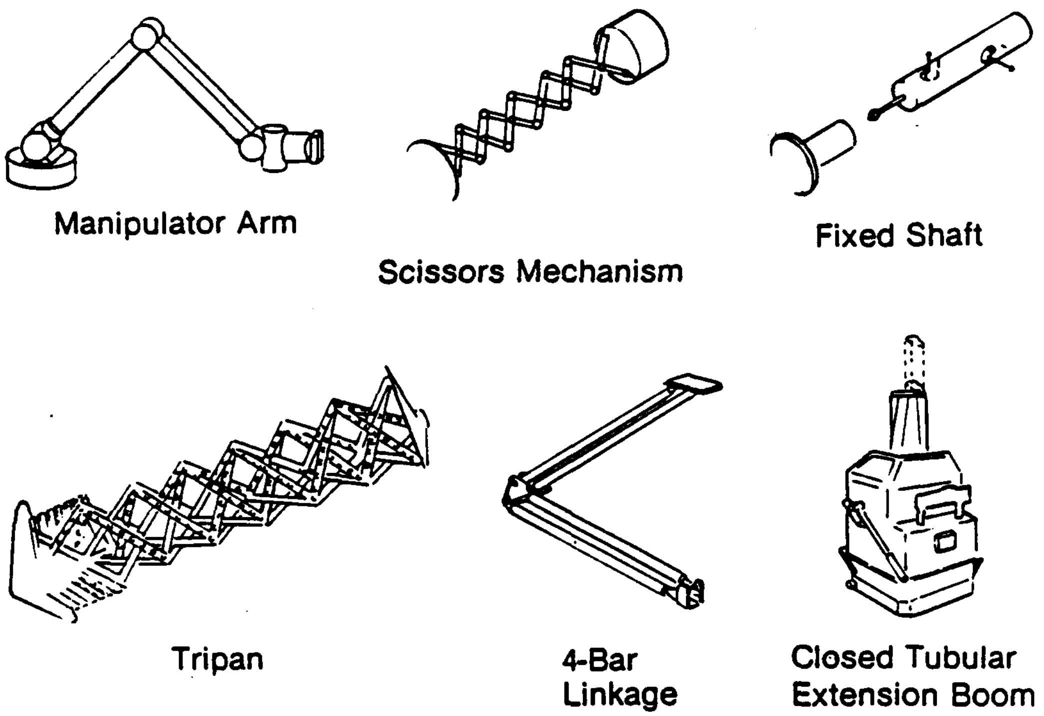
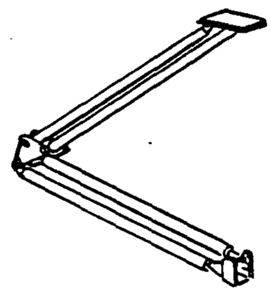


Figure 1.4-1 Extendible Booms

A total of eight extendible boom concepts were identified and evaluated for application to the TSR kit. For this Executive Summary, evaluations of the two best concepts are presented.

The 4-bar linkage illustrated in Figure 1.4-2 was previously developed by MMC for space application. The linkage was designed so that when extended, the end to be attached to a grapple mechanism will travel in a linear path perpendicular to the base plate.

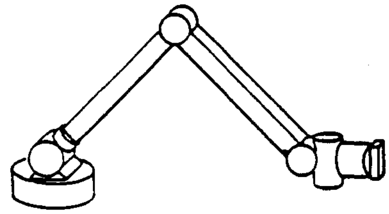
The 4-bar linkage offers a non-complex accommodation to the recovery system extension requirement. As a light weight mechanism, its load carrying capability is limited in bending and torsion. The tradeoff of increased weight for increased load carrying capability will not, however, create a significant increase in compacted volume. The 4-bar linkage, like the Tripan, could be considered for the TSR kit in the absence of the articulation requirement for access to obstructed grapple fixtures and alignment of target center of mass prior to orbit transfer.



ADVANTAGE	DISADVANTAGE
• Compact • Light Weight • Can Support Grapple, Despin Torque Loads • Non-Complex Control	• Insufficient Articulation for Target Realignment • Insufficient Articulation for Access to Obstructed Recovery Support Elements

Figure 1.4-2 4-Bar Linkage Evaluation

The robotic manipulator is the most complex of the extendible boom candidates evaluated, but provides the most capability. The manipulator depicted in Figure 1.4-3 was previously developed by MMC, and it is typical of robotic arm design. A manipulator arm enjoys the advantage of being a multiple degree-of-freedom (DOF) device, capable of providing target realignment and access to obstructed grapple mechanisms. The MMC design includes four DOF, as a result of joints at the base, elbow, and two at the spin/despin mechanism or grapple mechanism interface. A motor, gearbox, and control sensor are part of each joint, and together create control complexity and increased reliability and maintainability requirements. Like the 4-bar mechanism, the manipulator has a very compact stowed configuration. The study team felt that the higher weight and complexity of a robotic arm are offset by its articulation, compacted volume, and load bearing capability. The manipulator was favored as a TSR kit extendible boom concept, for both Systems B and C.



ADVANTAGE	DISADVANTAGE
• Compact • Can Support Grapple, Despin Torque Loads • Existing Designs • Enables Realignment of Target Mass for Transport • Enables Access to Obstructed Recovery Support Elements	• Heavy • Increased Control Complexity

Figure 1.4-3 Manipulator Evaluation

1.4.3 Spin/Despin Mechanism Definition - The concept selected for the Spin/Despin Mechanism subsystem is an existing design, functioning as part of an existing three axis gimbal within the MMC Space Operations Simulation (SOS) Laboratory. An assessment of this design was accomplished in order to provide a conceptual level definition for follow-on efforts. The mechanism consists of a spin platform, DC torque motor, servo control amplifier, tachometer, and electrical brake, as shown in Figure 1.4-4.

1.4.4 Grapple Mechanism Interface Device - The grapple mechanism interface device definition process identified the requirement for unique interface devices for ground assembly of a recovery system to be deployed mated with OMV and delivered into a working orbit by STS. The ground assembled interface flange, conceptually illustrated in Figure 1.4-5, provides an interface connection between recovery subsystems, such as that between the grapple mechanism and the spin/despin mechanism. A bolted assembly is required for each subsystem interface. Initially intended as a grapple mechanism interface device, it will be used as a readily applied interface between several components of a modular, interchangeable recovery system.

- **BIDIRECTIONAL SERVO CONTROL SYSTEM**
  - REVERSIBLE CURRENT DC TORQUE MOTOR
  - TACHOMETER TO SENSE SPEED
  - SERVO CONTROL AMPLIFIER TO ADJUST & DISSIPATE CURRENT
  - ELECTRICAL BRAKE TO SECURE TABLE

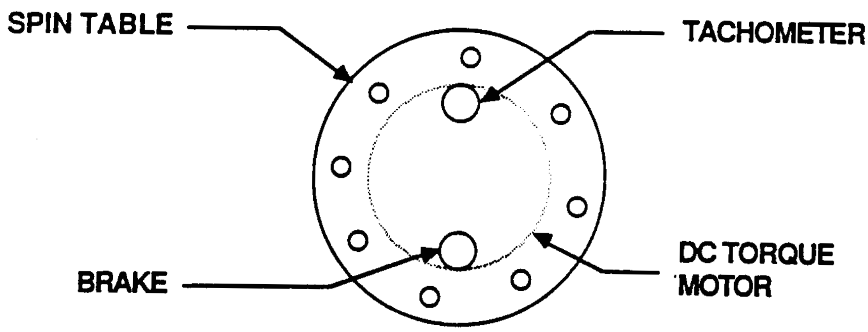


Figure 1.4-4 Spin/Despin Mechanism

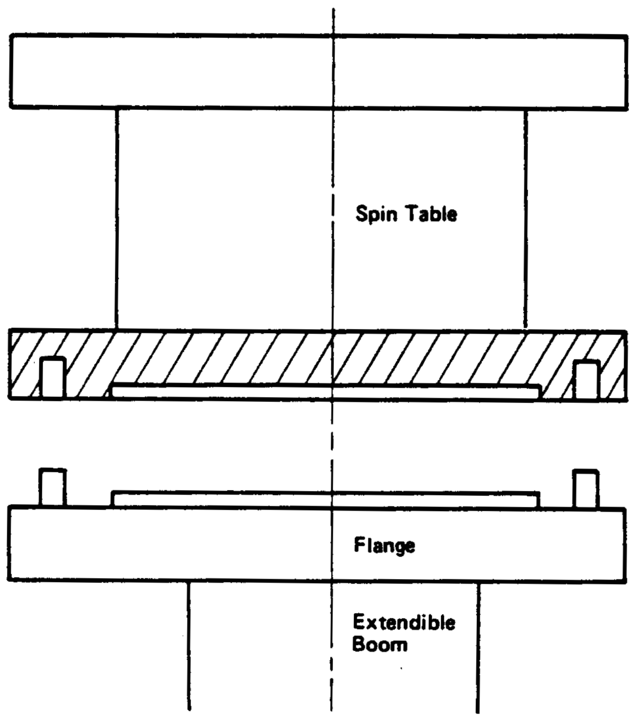
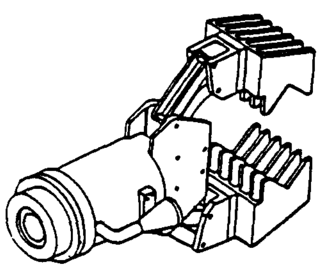
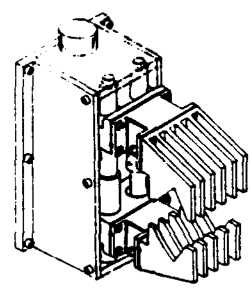


Figure 1.4-5 Ground Assembled Interface Flange

1.4.5 Grapple Mechanism Evaluation - Three categories of grapple mechanisms were identified that addressed the grapple mechanism requirements of Systems B and C. These included: a small gripper type mechanism for System B; a "stinger" type mechanism for recovery of disabled, spin-stabilized satellites, and large grippers or envelopment type grapplers for recovery of non-controllable, tumbling or spinning satellites. Within these categories, alternatives were recognized and evaluated and selections were made. The criteria identified and applied in the evaluations included: compactness, accommodation of a range of satellite size and hardpoint size, strength of grapple, target damage potential, positioning flexibility, and accommodation of grapple, despin, and transport loads.

1.4.5.1 Small Gripper Definition - The MSFC Proto-Flight Manipulator Arm (PFMA) End Effector and the JPL PFMA Smart Hand were selected by the study team as two possible accommodations of the System B, small gripper mechanism requirement, and are illustrated in Figure 1.4-6. Both provide parallel jaw motion, minimizing reaction away from the mechanism during grapple. The intermeshing parallel plate designs and square recessed shapes of the jaws enable grapple of hardpoints of varied size and shape.



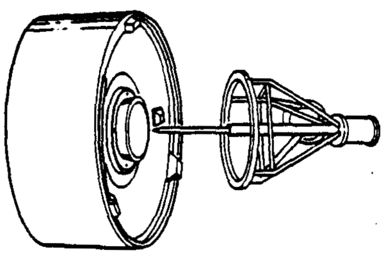


ADVANTAGE	DISADVANTAGE
• Enables Grapple of a Variety of Round, Flat, or Irregularly-Shaped Hardpoints • Intermeshing Jaw Plates Enable Pickup of Smaller Hardpoints • Accomplishes Firm Grip • Adjustable Grip Force and Closure Rate • Grapple Unaffected by Power Loss • Design Available, Proven	• Size of Hardpoints Grappled Limited by Geometry of Mechanism

Figure 1.4-6 Small Gripper Definition - PFMA End Effectors

These existing mechanism designs reflect the state-of-the-art for non-dexterous hands and provide capable accommodation of the small gripper requirement. Follow on efforts involving analyses of transport loads and mission model hardpoint configurations will enable complete assessments of the applicability of these mechanisms to the System B requirements.

1.4.5.2 Stinger-Type Grapple Mechanism - The obvious selection for the grapple mechanism of System C, involving recovery of spin stabilized spacecraft, is the Apogee Kick Motor (AKM) Attachment Device, commonly called the "Stinger". Its capability was proven in the Westar-Palapa B recovery mission, where the recovery of two spin stabilized spacecraft was safely accomplished without damage to either vehicle. The stinger is depicted in Figure 1.4-7.



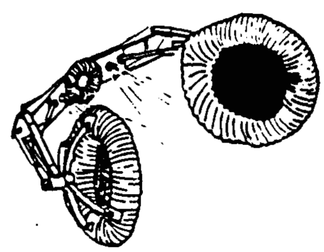
ADVANTAGE	DISADVANTAGE
• Enables Grapple of Spin Stabilized Target • Design Available, Proven	

Figure 1.4-7 Stinger-Type Grappler

1.4.5.3 Evaluation of Large Envelopment-Type Grapple Mechanisms - Accommodation of the System C, large envelopment-type grapple mechanism requirement was provided to the study team by a large number of varied concepts. The six most promising were identified as a possible focus for follow on efforts, and were evaluated in detail. A review of three evaluations of the better concepts is provided in this Executive Summary.

The first of the large envelopers, the Debris Capture Device developed by LTV, is shown in Figure 1.4-8. It consists of a pair of low pressure toroids mounted on adjustable arms, with which it accomplishes a two point grapple. The grapple force is applied through the arm assembly, by a hydraulic system at the base of the mechanism. The toroids minimize damage to recovery candidates by conforming to irregular satellite surfaces and spreading the forces due to contact dynamics.

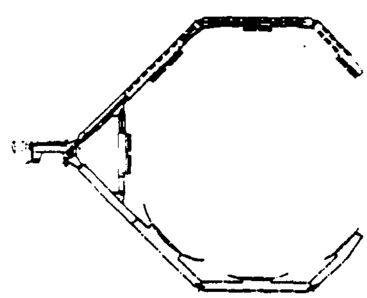
The Debris Capture Device is one of the preferred concepts, yet it has several disadvantages. The mechanism structure is large and heavy. Added control complexity and reliability/maintainability requirements result from the hydraulic systems, toroid control, and the many linkages involved. Following grapple and despin, the mechanism's capability to provide sufficient rigidization during transport is questionable, as contact with the recovery candidate is sustained by a compressible device. Finally, as presently configured, it occupies a significant volume in the Orbiter cargo bay during launch and return.



ADVANTAGE	DISADVANTAGE
• Accommodates a Wide Range of Satellite Sizes • Soft Contact, Minimizes Target Damage	• Not Compact • Heavy • Complex Control • Questionable Transport Rigidization Capability • Bulky, Limited Flexibility in Tight Target Configurations • Increased Reliability/Maintainability Requirements

Figure 1.4-8 Debris Capture Evaluation

The MSFC Enveloper, depicted in Figure 1.4-9, has undergone preliminary design/development by MSFC. Two methods of actuating the grappler's arms have been incorporated in the mechanism. The base links of each arm are connected and operated by an actuation system between the two, which effects an inward/outward rotation of the arms. The remaining two arm links on each side operate in conjunction with one another, and with the similar links of the opposing arm, as a result of a motor within the base and a connecting linkage. The combined effect of the two systems is an increase in flexibility in positioning for envelopment, and an increased capability in recovering smaller satellites as compared to a system without the outboard arm segment articulation.



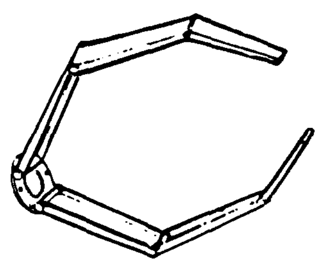
ADVANTAGE	DISADVANTAGE
• Light Weight • Relatively Compact • Accommodates a Range of Satellite Sizes • Flexibility in Positioning for Envelopment	• Increased Reliability/Maintainability Requirements

Figure 1.4-9 MSFC Enveloper Evaluation

The final mechanism evaluation, shown in Figure 1.4-10, involves the MMC Enveloper, which was conceptually designed by the study team to provide a System C grapple mechanism that was designed from the requirements allocated in Task 1 to the envelopment grappler.

The mechanism incorporates a two arm, six member structure. Driven by DC torque motors in the joints, each of the links can be operated independently. To maintain symmetry, control software is employed so that opposing links, e.g., the base links of each arm, operate in conjunction. The geometry of the members allows a folded, and extremely small compacted volume, with sufficient surface area at the end of each arm to enable a two point capture. Like the MSFC enveloper, appropriate structural member design and composition will produce a relatively light weight mechanism.

The substantial increase in flexibility of the grapple operation, as a result of independent actuation of the links, provides a number of advantages. Flexibility in positioning for envelopment and around protuberances is optimized. The design enables envelopment before contact, thereby minimizing target reactions and negating target motion away from the OMV. Target damage is minimized, as contact dynamic forces will be reduced with the grapple elements closer to the recovery target when first contact occurs. The mechanism's increased flexibility though, creates a proportional increase in control complexity and reliability/maintainability demands. These disadvantages are outweighed by the number of advantages shown in Figure 1.4-10, and this enveloper mechanism was selected for inclusion in the System C design configuration.



ADVANTAGE	DISADVANTAGE
• Light Weight • Compact • Optimum Flexibility in Positioning for Envelopment • Accommodates a Wide Range of Satellite Sizes • Control of Multiple Links Equalizes Contact Force/Minimizes Satellite Damage • Accomplishes Envelopment Before Contact • Accomplishes Rigid Grapple	• Added Control Complexity with Multiple Controllable Arm Segments

Figure 1.4.-9 MMC Enveloper Evaluation

1.5 Conceptual Tumbling Satellite Recovery System Design - Task 2.2

The objective of the second concept definition task, Task 2.2, was to develop a set of conceptual designs for TSR Systems B and C. The approach used was to select the preferred set of subsystem mechanisms and to integrate them into a basic OMV TSR kit system that met the study team's objective of system modularity and ready interchange of subsystem components.

1.5.1 TSR Conceptual Design Drivers - The formulation of a design architecture for the recovery systems was influenced heavily by a number of key factors driven out by the requirements analysis. These are shown in Figure 1.5-1. The first of these was the inherently broad range of recovery scenarios identified during Task 1. This fundamental reality caused the study team to select from two apparent options: (1) operate from a design concept that would provide an equally wide range of recovery systems; or (2) develop a design concept with a modular design as a framework that could be configured readily into recovery systems tailored for specific missions. The latter approach was selected.

- Broad Range of Recovery Scenarios Dictates
  - Wide Range of Recovery Systems, or
  - Modular System Easily Configured into Recovery System Tailored for Specific Missions
- Recovery Kit Must Be Compact - Efficient STS Operations
- Minimum Risk to OMV
- Recovery Operations Bounded by OMV Controllability
- Target Rigidized for Return to STS or Space Station

Figure 1.5-1 Key Design Drivers

Another key design criterion was the need for a compact design. The TSR system is being designed as an OMV front end kit and carried into orbit in the STS cargo bay. The OMV has been configured for compactness to minimize cargo bay space necessary for delivery into orbit. Though no other study reflected this requirement, MMC believed the architectural design should be as compact as is possible and selected subsystem options that supported this design factor.

Another prominent design factor was related to minimizing risk to the OMV during all phases of recovery operations. One such element involved the need to maintain a proper distance from the OMV during operations, a design requirement readily accommodated by the selection of an effective extension device. A related secondary design driver was the perceived necessity to retain control of the OMV during recovery operations. The primary concern here was that with contact dynamics forces in excess of OMV control authority, ground controllers could lose the capability of controlling OMV and the TSR kit, with potential resulting damage to both.

Finally, no other study had considered the requirement to have the target satellite firmly grappled for transport back to the Shuttle or to Space Station. This requirement influences the choice of grapple mechanisms for the different recovery systems.

1.5.2 Modular TSR System Design - A representation of a modular design for a family of recovery systems is provided in Figure 1.5-2. This expanded view displays the major components of the system and the inherent capacity to interchange, add, or subtract individual components to tailor the kit for specific missions.

One of the primary features of the design is a structural interface element that is readily attached to the OMV docking latches in manual mating operations in the STS cargo bay during launch processing. The electric power and communications and data management (C&DM) interface will be through the OMV payload umbilical mounted on the front face of the OMV.

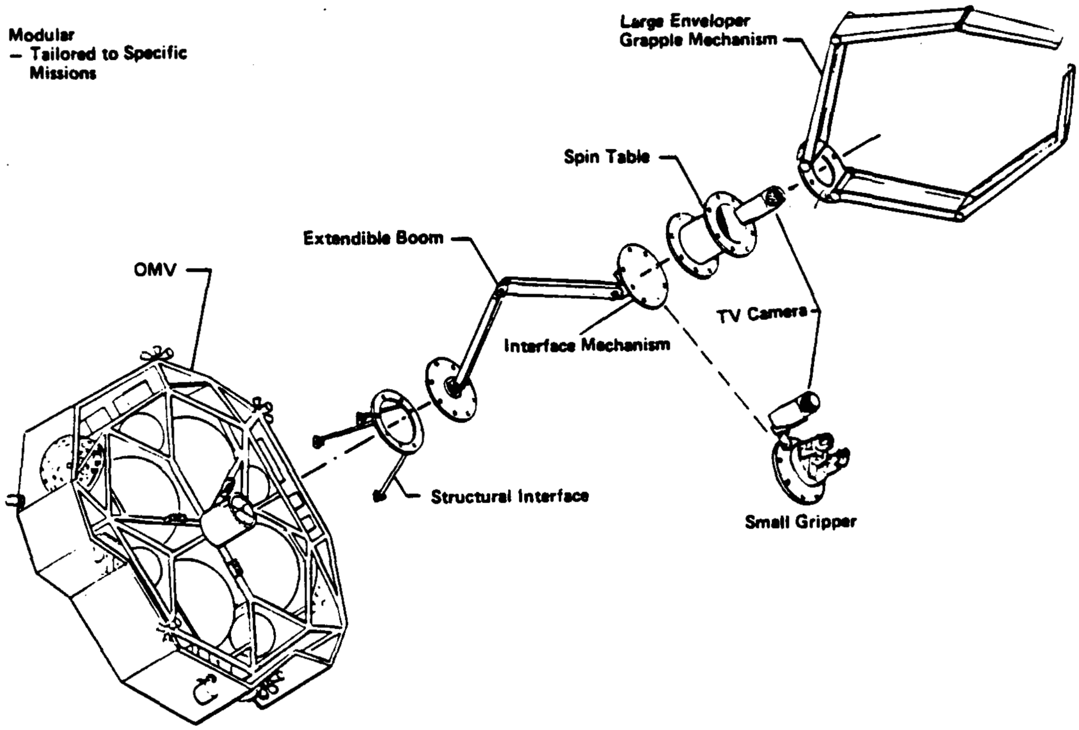


Figure 1.5-2 Tumbling Satellite Recovery Kit

The next component is the extendible boom. A four degree of freedom manipulator arm with pitch and yaw positioning at the grapple mechanism interface was selected. This mechanism is capable of folding into a compact stowed position. Its most important function is to provide safe clearance between the OMV and a spinning target. It also provides the capability to reach recovery support elements that are obstructed to an approach by OMV due to deployed target solar arrays and antennas. Additionally, it enables alignment of a target's center of mass with the OMV orbit transfer thrust vector following capture and prior to orbit transfer.

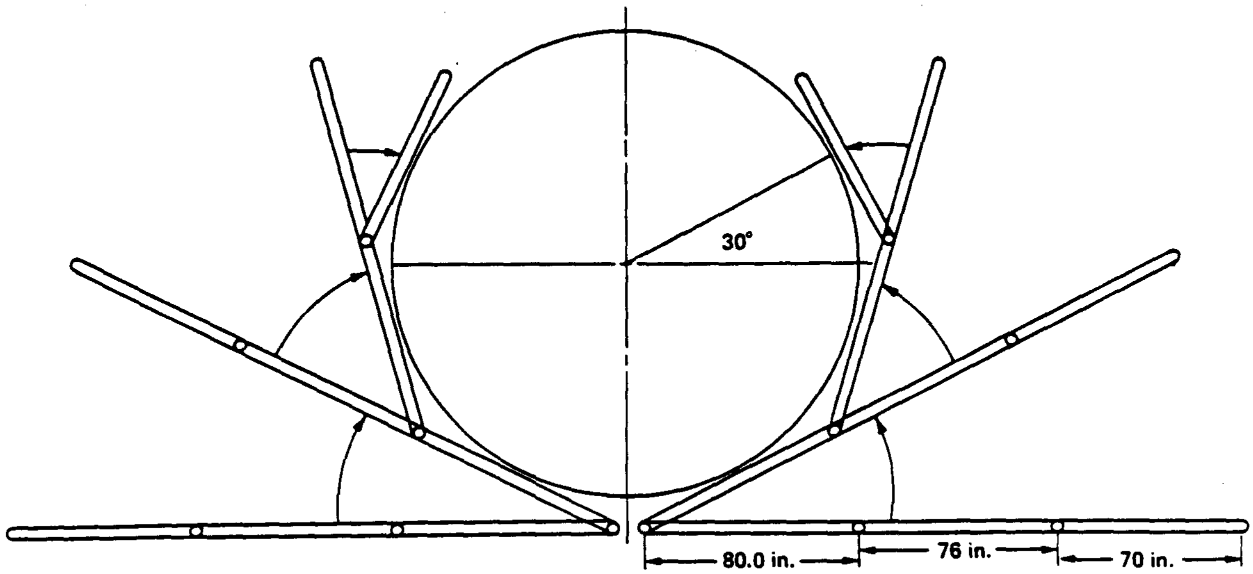
A third major component is the spin table. The spin table can be mounted efficiently to the interface flange on the end of the extendible boom. Also shown configured within the spin table is a boresight, wide angle view television camera. On this base, it can be mounted in a fixed configuration, or configured to spin at the same rate as the spin table.

In this representation of the recovery system, both the System B and System C recovery kits are shown. The full-up System C has the MMC enveloper grapple mechanism attached to the flanged grapple mechanism interface device. This system will be capable of recovering satellites with what was previously defined as the more complex tumble motion. This tumble motion is expected to evolve to single axis spin about the satellite's major principal axis.

The System B configuration is also represented in Figure 1.5-2. This system includes the structural and electrical/C&DM interface with OMV, the extendible boom and a small gripper, connected to the system with the grapple mechanism interface flange. In addition, a close proximity television camera is attached to the smaller gripper to provide localized viewing of the attachment to the hard point of a remote, controllable satellite. This figure portrays how amenable this design is to subsystem interchange and its capacity for accommodating a wide variety of recovery missions.

1.5.3 MMC Enveloper Grapple Mechanism - The conceptual design of the MMC enveloper, which was selected as the grapple mechanism element for one of the conceptual System C recovery configurations, was influenced by an increasing concern on the part of the study team regarding the potential impact of contact dynamics between the TSR kit and the target during grapple operations.

Even with perfect conditions during recovery, with no major target protuberances/appendages and given a reasonably symmetric target for recovery, as the operator begins to grapple and rigidize, the grapple mechanism will begin a series of contacts with the target. These contacts will produce relative position changes between the target and recovery system that are expected to be complex, and have not yet been modeled. When initiating this grapple mechanism closure operation with a two- or even three-point gripping device, such as a C-clamp, in which the target is not enveloped, it is possible that the target position will change in such a manner that a new approach and grapple positioning setup will be required following each contact. If this target reaction was found to be dominant, a "two point" grapple would be untenable. For this reason, grapple of a spinning target appeared to be accomplished more feasibly using an envelopment approach. Thus, the MMC enveloper was designed from the operational concept that envelopment of a spinning target with a spinning grapple mechanism would provide a higher probability of successful grapple and rigidization. The MMC enveloper is shown in a grapple configuration in Figure 1.5-3.



- Three Pairs of Grapple Elements Independently Controlled
  - dc Torque Motors—Harmonic, Planetary
- Grapple Mechanism Deployed to Optimum Envelopment Configuration
  - Then Spun Up—Minimize Deployment Dynamics
- Target Enveloped—Elements Closed Slowly to Minimize Contact Dynamics
- Grapple Mechanism Rigidized for Despin and Transfer to STS or SS

Figure 1.5-3 TSR Grapple Envelope

1.5.4 <u>Conceptual Recovery Systems - Summary</u> - The recommended recovery system architecture and conceptual system designs are presented in a format that illustrates the efficacy of the MMC modular, interchangeable element approach.

Shown in Figure 1.5-4 are the system configurations for System B, for both of the recovery scenarios described in DRM 3 and DRM 4. For Case 1, the scenario is a controllable, stable target, with a recovery support element, an RMS grapple fixture, that is obstructed from a direct OMV approach by a deployed solar panel. For this recovery candidate, the conceptual TSR system consists of the structural/mechanism interface element, a multiple degree-of-freedom manipulator arm (to gain access to the grapple fixture), a grapple mechanism interface flange and an RMS end effector.

For the second System B scenario, a controllable satellite with no grapple fixtures or flight support system latch pins, the recovery system is shown, also, in Figure 1.5-4. The mechanical interface provides the ready attachment to the OMV, and in this configuration, a small gripper, for attachment to target hard points is attached to the interface flange and the extendible boom.

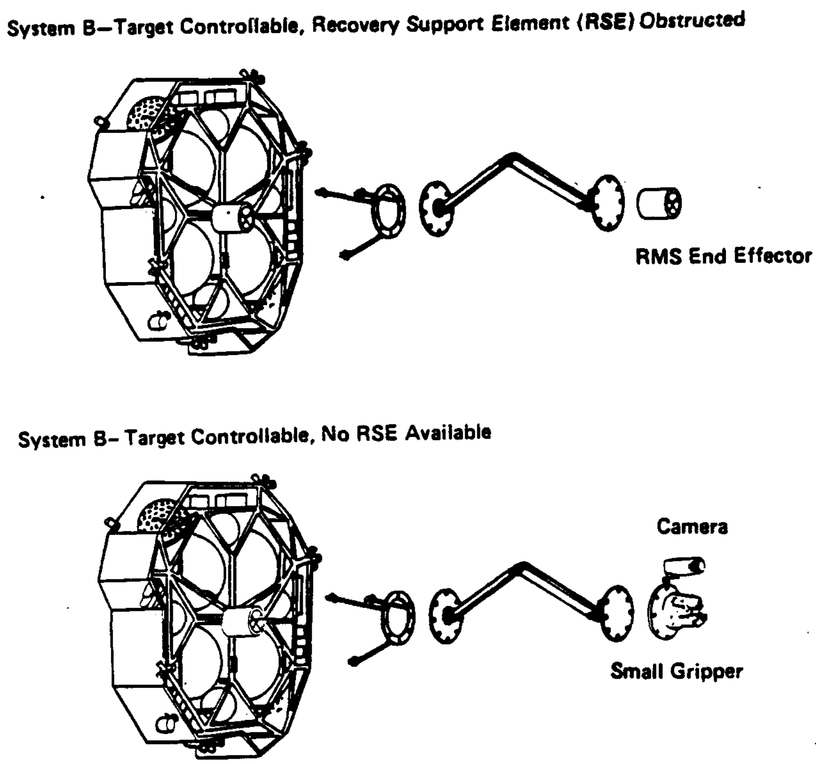


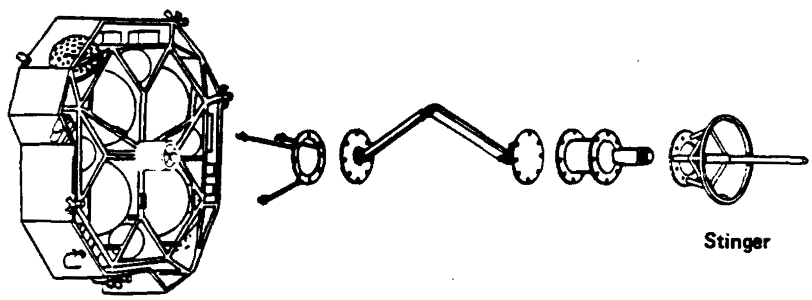
Figure 1.5-4 Conceptual TSR - System B

The recovery system configurations for both System C recovery scenarios are illustrated in Figure 1.5-5. In the first case, with a controllable, spin stabilized target such as INTELSAT-6, the mechanical interfaces (both the structural and umbilical), the extendible boom and the spin table are included. The "stinger" type grapple mechanism, attached to the grapple mechanism interface flange, will be used to secure a solid grip on the spinning INTELSAT kick motor.

The most difficult recovery scenario is the full-up System C scenario, which is most likely a tumbling/spinning satellite. This recovery scenario requires the entire modular system, including an enveloper-type grappler.

Thus, the conceptual modular design contains all of the "fundamental" accommodations to enable recovery of the full range of identified and defined System B and System C mission requirements.

System C—Target Controllable, Spin-Stabilized



System C—Target Noncontrollable, Tumbling/Spinning

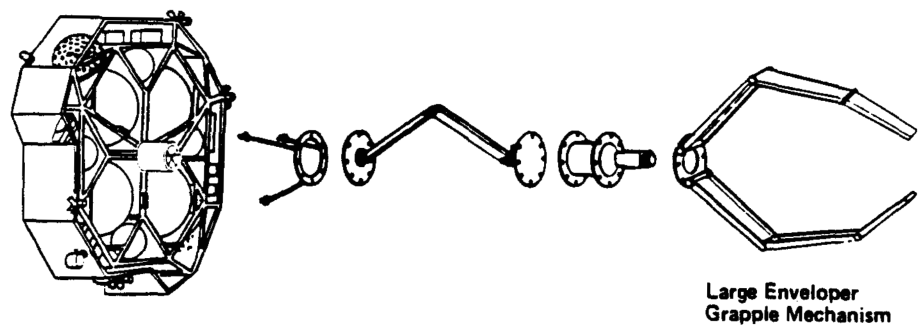


Figure 1.5-5 Conceptual TSR - System C

1.6 Supporting Development Plan

The purpose of the supporting development plan is to: outline research and technology development including ground-based testing and simulation, and Orbiter cargo bay or proximity operations activities; and to structure the flight hardware development program needed to establish the technical readiness of an OMV tumbling satellite recovery front-end kit.

These activities must be integrated into a comprehensive program by recovery kit planners, and must be coordinated with concurrent OMV development activities. The technology development issues identified in the Supporting Research and Technology (SR&T) Report are addressed in either ground or flight-oriented experiments.

1.6.1 Ground Demonstration Activities - The recommended ground-based demonstration approach is highlighted in Table 1.6-1. The principal element of the ground-based program is to design, develop and exploit a set of software and hardware demonstration units to examine the issues identified in the Supporting Research and Technology Report, presented in Volume II of this Final Technical Report. It is clear that the simulation facilities to develop the demonstration units exist at MSFC and at MMC. The approach recommends continued use of ground demonstration devices as laboratory tools to evaluate evolving mechanism and system concepts.

Table 1.6-1

- Design, Develop, & Exploit Recovery Kit Ground Demonstration Unit(s)
  - Evaluate Concepts Feasibility
  - Recovery System Deployment Characteristics
  - Contact Dynamics in Recovery Operations
  - Recovery System Operations/Operator Assessment
- Utilize Existing MSFC/Martin Marietta Simulation Capabilities to Address Identified Technology Issues
  - Contact Dynamics Concerns
  - Force & Moment Measurements, Resulting Position/Motion States
  - Computer Simulations Using Varying Configurations, Evaluate Human Factors Limitations
- Demonstrate Use of Recovery Demonstration Unit as Laboratory Tool
  - Evaluate Alternative Concepts
  - Evaluate Subsystem Mechanisms - Grapple Devices
  - Eventual Use as Astronaut Trainer for Flight Experiment
  - Identify Logical Flight Experiment Candidates

1.6.2 STS Cargo Bay/Proximity Operations - The definition of on-orbit flight experiments to support technology development of the TSR kit will evolve and be refined through experience with the ground demonstration units. It appears that an on-orbit experiment will be required to validate the recovery concept agreed upon for development, and to verify contact dynamics forces and torques and the impact of relative movement between the target and recovery system during the recovery operation. The cargo bay/proximity operations experiments are outlined in Table 1.6-2.

Table 1.6-2 Cargo Bay/Proximity Operations Experiments

- Define an STS Cargo Bay/Proximity Operations Equipment Set
  - Scaled Satellite Recovery System
    - Extendible Boom, Spin Table, Envelopment Grappler
    - Equipped with Interface to STS & RMS
  - Scaled Composite Recovery Target
- Conduct Remote Recovery Experiments in Zero-G
  - Remote Recovery Operations
    - Spin Axis Alignment, Spin Rate Matching/Phasing
    - Operations, Operator Limitations
  - Recovery System Deployment Dynamics
  - Target-Recovery System Contact Dynamics

Cargo Bay Experiments Should Be Phased to Support Flight Hardware Phase C/D CDR.

The on-orbit remote satellite recovery experiments will be conducted with high fidelity equipment to validate the system concept. Thus, definition of the requirements and conceptual design of the scaled down experiment equipment should begin prior to the start of flight hardware Phase C/D for the TSR system.

The experimental recovery equipment would be an extendible boom, a spin table and an envelopment grappler. The system would be designed to interface with the STS RMS end-effector and equipped with an operating interface in the STS. The spacecraft target would be a modification of a current rented bus, designed to be controllable to produce multiple tumble and spin modes and rates. This experiment would enable operators to conduct the first zero-gravity remote recovery operations to enable validations of ground-based experiments. Operators will gain actual experience in conducting remote recovery operations, such as spin axis alignment, spin rate matching and phasing with target, recovery system deployment dynamics and activities conducted in reaction to target/recovery system dynamics.

1.6.3 Flight Hardware Program - The objective of the actual OMV tumbling satellite recovery kit flight hardware program is to be prepared to conduct free flight operations in 1993 with actual or simulated targets. This flight hardware will be developed on a schedule consistent with development plans for OMV and other OMV front-end kits. It will be conducted using the generally accepted NASA/MSFC approach of conceptual, definition and development phases (Phases A, B, and C/D).

The Supporting Development Plan (SDP) schedule is provided in Figure 1.6-1. The schedule outlines an integrated TSR kit development program that includes ground-based and on-orbit STS flight experiments and a flight hardware program that provides for free flight operations in 1993.

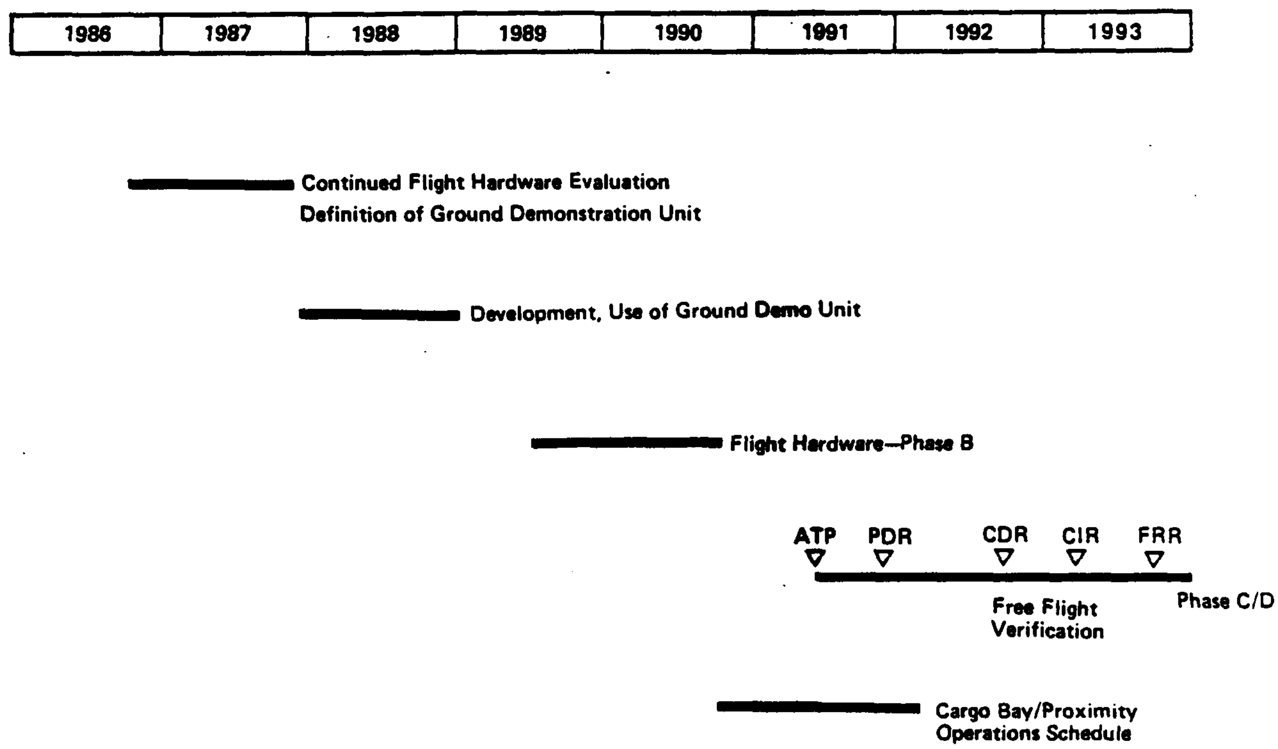


Figure 1.6-1 Supporting Development Plan Schedule

1.7 Supporting Research and Technology Report

The Supporting Research and Technology (SR&T) Report for the Tumbling Satellite Recovery (TSR) conceptual definition study is presented in Volume II of this Final Technical Report.

The MMC study team did not identify any problem areas requiring new state-of-the-art technology development initiatives. They did identify a number of areas where research and laboratory experiments could support resolution of technology issues that could lead to development of a cost efficient remote, disabled satellite recovery system. These technology issues included: provision of terrestrial estimates of disabled satellite motion, deployment dynamics of the capture device, contact dynamics between the target and recovery system and assessments of operator control capabilities for this remote teleoperations mission.

1.8 Cost Estimate and Work Breakdown Structure

A cost estimate of the TSR kit program was prepared, based on a Work Breakdown Structure (WBS) and WBS Dictionary prepared by MMC. These study results are presented in Volume III of this Final Technical report. The initial WBS was presented to MSFC early in the study, and a coordinated effort between MSFC planners and the MMC study team resulted in creation of the final version.

The total program cost for the TRS kit program, leading to a flight ready system was estimated at $18 million, based on the cost elements shown in Figure 1.8-1.

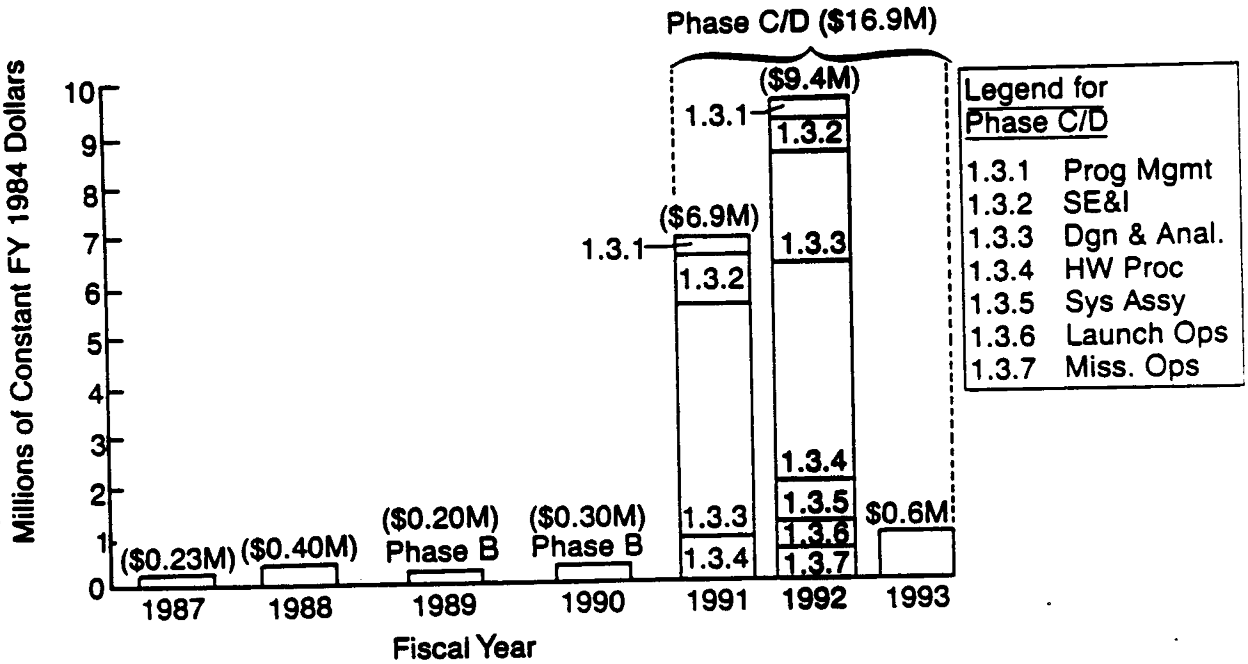


Figure 1.8-1 Total TSR Kit Funding Profile

2.0 STUDY RESULTS - INTRODUCTION AND BACKGROUND

The study results that this Final Technical Report documents are the first assessment of the design requirements and the conceptual definition of a "front end kit" to be transported on the currently defined Orbital Maneuvering Vehicle (OMV) and the Space Transportation System (STS) Shuttle Orbiter, to conduct remote, teleoperated recovery of disabled and possibly non-controllable, tumbling satellites. Studies related to recovery of disabled satellites or space debris have been conducted by the NASA and DOD, academia, and industry for over 20 years. Many different transport vehicles were considered in previous studies, including Gemini, Apollo, and earlier versions of the OMV, including the Teleoperator Retrieval System (TRS), that was under contract for actual design and development for retrieval of Skylab in the mid-1970s.

The unique aspect of this study is the fact that the conceptual tumbling satellite recovery (TSR) system was groundruled as a front-end kit for a well defined OMV transport vehicle, that is, in turn, being delivered into a near earth orbit by the operational Shuttle.

Where many previous studies examined only partial aspects of the remote recovery problem, such as how to grapple tumbling satellites (in various tumble modes), or how to despin satellites, this study encompasses a full range of issues related to the recovery problem. As the study progressed, an operations concept was developed, and this concept provided a solid frame of reference for description and operations analyses of a group of selected Design Reference Missions (DRMs). Using a series of systems requirements analyses, a set of systems requirements and recovery concept requirements were developed and allocated on a top level basis, to a set of recovery subsystem accommodations. From this overall requirements analysis, a recovery system "design concept" was defined and served as a foundation for the total concept definition phase, a major study task. When a significant concern over the nature of "complex" satellite tumble motion surfaced, an explicit analysis was conducted to determine the most likely tumble mode presented by a non-controlled, disabled satellite. This study effort was designed to provide the broadest possible contextual framework in which to determine tumbling satellite recovery system requirements.

2.1 Study Objectives

The NASA Marshall Space Flight Center (MSFC) expressed two major objectives in outlining the expected result of the tumbling satellite recovery study, as shown on Figure 2.1-1. The first of these objectives was to develop realistic candidate recovery systems to support the decision making process in preparing to develop an operational capability for remote recovery of disabled satellites in the mid-1990s timeframe. A second major objective was to define the full range of remote recovery capability required in this same period. A series of supporting objectives were also outlined including: the identification of required new technology initiatives mandated by development of this capability; a supporting development plan to include requisite ground demonstrations and flight experiments; and cost analyses to support estimation of eventual total development costs.

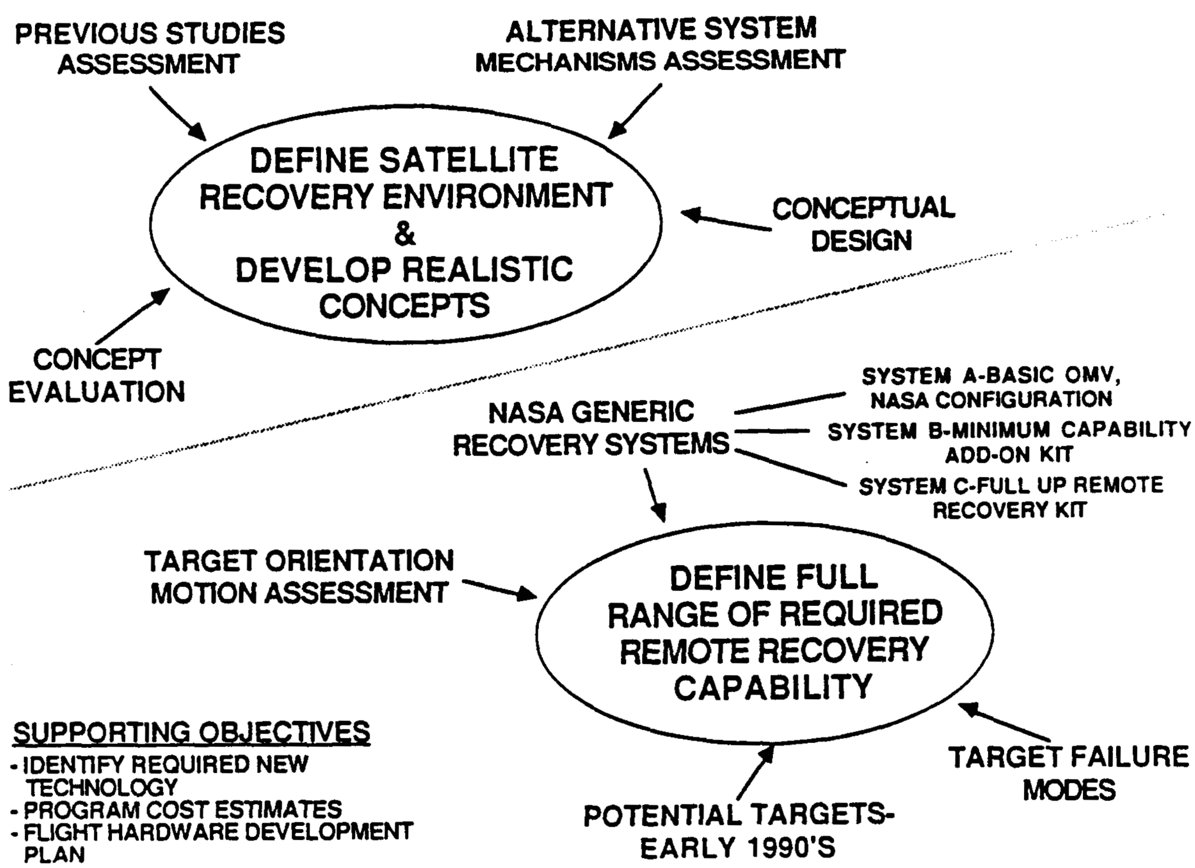


Figure 2.1-1 TSR Study Objectives

The first and principal objective, that of defining viable recovery concepts, came from a MSFC perspective that in over 20 years of general, and in some cases very specific, examinations of concepts related to remote recovery, a large number of widely variant approaches had been considered and suggested to the NASA and to DOD. The specific objectives expressed by one of the MSFC technical managers, Mr. Herbert Lenox, was to review all known previous related work in this area, to evaluate new concepts and to focus these efforts into a more channeled conceptual framework that would lead to cost effective development of the required capability. The study team believed that review of previous concepts and identification of system and concept level requirements would provide the framework on which to develop new alternative candidate concepts, for comparison with the older concepts. This general assessment would lead to selection of viable candidate recovery systems, and provide the desired focus for the continuing development effort.

The second principal objective was to examine a broad perspective of potential recovery scenarios and to define the full range of required remote, disabled satellite recovery capability. The MSFC requested Martin Marietta to study and evaluate three generically defined levels of capability.

The first of these expressed levels of capability was called System A and is the basic OMV, using the NASA baseline configuration at study start time. By determining the limits of inherent OMV recovery capability, it was anticipated that the boundary between that level of capability and the next would be more easily determined.

A second level of capability, termed System B, was described as the basic OMV with some minimal hardware additions or changeouts, such as end effectors, batteries, or special avionics hardware. This level of capability was expressed rather generally to challenge the imagination of the study group to examine intermediate, but realistic, levels of capability with some rationale.

The final desired level of recovery capability, labeled System C, was described as a "full-up" capacity to recover satellites with "complex" motion. This "system" was to be a distinctive OMV front-end kit, capable of recovering some defined maximum level of remote, disabled satellite, in some degree of complex satellite motion.

Thus, it was the responsibility of the MMC study team to provide the rationale for differentiating these levels of capability, defining the requirements for each level, and providing conceptual designs for MSFC's recovery Systems B and C.

2.1.1 Ground Rules - The study ground rules were explicit. The first of these was to make maximum use of completed satellite recovery studies and research efforts on actual hardware generation programs. Also, MMC was directed to review related, ongoing OMV satellite recovery related efforts.

A second study guideline was to use MSFC's OMV baseline reference configuration for all study tasks, including characterization of the OMV's satellite recovery capability and definition of the interfaces, between Systems B and C, and the OMV.

MSFC requested that any simulation work or ground demonstration activities, recommended by the study team as requisite Supporting Research and Technology (SRT) program activities, include consideration of MSFC simulation facilities. A final guideline was to propose early, low cost Shuttle zero-gravity demonstration concepts, where it was considered cost efficient to verify preliminary conceptual mechanisms or techniques.

2.2 Study Approach

The general approach used by Martin Marietta in the conduct of our Concept Definition Study for Recovery of Tumbling Satellites was to view the study as a preliminary Phase A activity. Some of the benefits derived from this differentiation were: (1) the development of a preliminary operations concept, outlining ground and space-based operations (for both Shuttle and Space Station bases); (2) requirements detailed at a lower level of decomposition, including some level of effort in attempting to quantify the requirements; (3) development of a fundamental design concept that supports clarification of varying levels of recovery capability and improved delineation of a family of conceptual recovery systems that were efficiently configured to enable recovery over a broad range of recovery scenarios.

The approach used is outlined in Figure 2.2-1. It was centered on the four major tasks in the contract statement of work. The interrelations of these tasks are also shown.

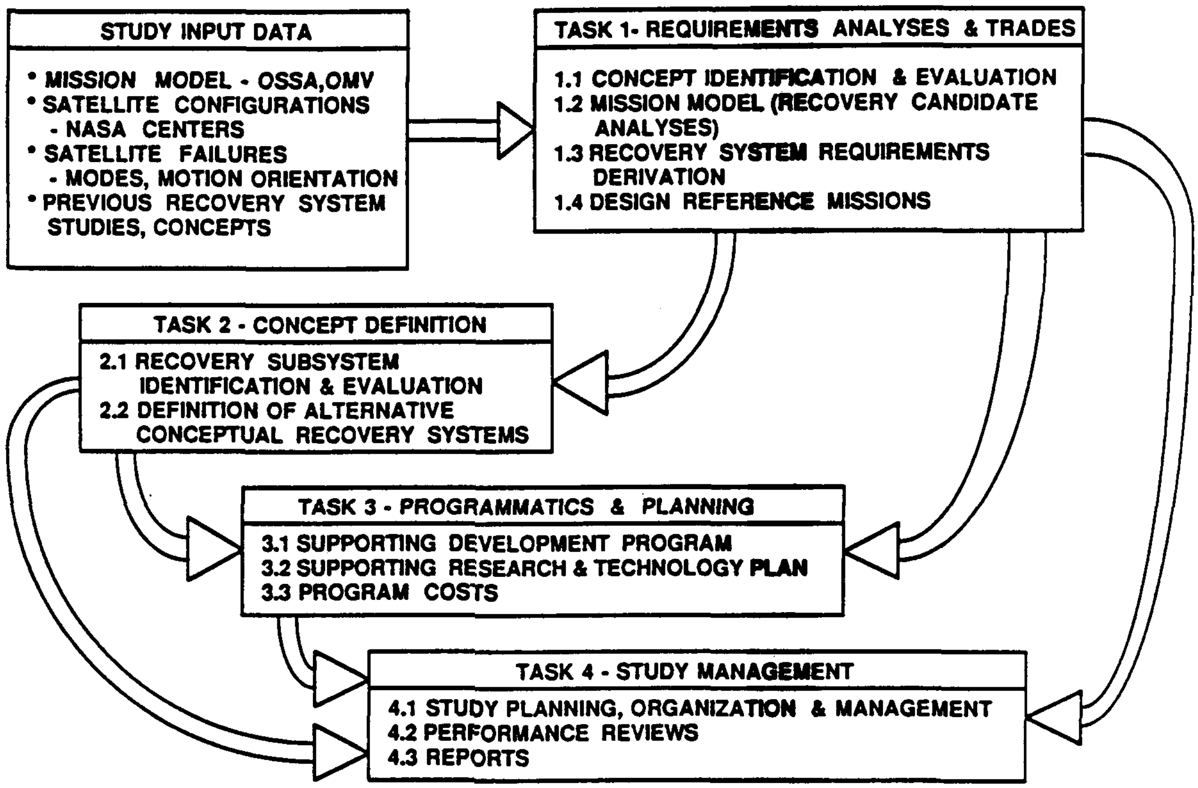


Figure 2.2-1 Study Task Flow

The principal data inputs to the satellite recovery study were: (1) mission model information, provided by the Office of Space Science Applications, OMV and Space Station programs, and specific satellite configuration data provided by NASA, Canada, and commercial satellite program offices; (2) satellite failure mode and tumble mode/motion orientation; and (3) a large number of previously completed and ongoing study efforts related to remote satellite recovery.

Task 1 was one of the two principal study tasks and the general approach was to use a series of systems requirements analysis (SRA) processes that were primarily oriented to deriving system and concept requirements for the family of recovery systems to be defined.

This task had four subtasks, and they were all inter-related and mutually supportive. The first of these was a survey-type effort in which all previously known study and hardware efforts related to satellite recovery were reviewed and a group of potential concepts evaluated against selected system requirements-oriented criteria. Our assessment of this effort was that none of these concepts were worthy of continued detailed design. This was a critical decision as the initial contract guidance was to complete further definition of some of these preferred concepts. This decision resulted in two diversions in the overall study effort.

The first diversion was to comprehend more completely what to expect in regard to probable or "typical" satellite failure modes, and the resulting tumble mode and motion orientation created by these failure modes. It was very interesting to note that none of the previously conducted studies addressed this issue in a definitive manner. The result of this series of analyses, explained in detail in Section 4.4, supported definition of a broad range of recovery scenarios and enhanced definition of MSFC's conceptual Systems B and C.

A second study diversion occurred later when, with the realization that none of the previous concepts could fully meet top level system requirements and design accommodations, it became apparent that the approach to the second major task, Task 2, Concept Definition, would have to be altered. This change is detailed in Sections 9.0 and 1.0.

A second Task 1 subtask was the development of a TSR mission model. It was the study team's view that a clear understanding of the types of missions and actual size, shape and configuration of potential recovery candidates expected to be on-orbit in the mid-1990s would enhance definition of the requirements. This data was obtained and an assessment of the actual satellite configurations enabled development of a set of composite target model characteristics and an improved comprehension of potential, future failure modes and resulting target motion.

In the third Task 1 subtask, Recovery System Requirements Derivation, a series of activities were conducted to blend with results of the initial two subtasks to enable requirements identification and evaluation. First, a concept of operations and a functional analysis of the actual recovery of a disabled satellite in complex tumble motion (see Section 6.0), were both completed. Next, a composite target model was developed as a "worst case" recovery target, and was used to conduct a top level quantification of some of the identified system and concept requirements.

The last of the four Task 1 subtasks was to define design reference missions (DRMs) for satellite recovery. With the broad range of satellite recovery missions identified previously in the prior study task, it was a relatively straightforward effort to define and describe a set of six recovery DRMs. Two DRMs were selected for each of the MSFC defined levels of capability, Systems A, B, and C. A top level operations analysis was conducted on each DRM, using the previously derived preliminary operations concept. This activity provided further identification of recovery system requirements for both System B and System C, particularly in the area of system requirements, such as ground support equipment (GSE) and aerospace support equipment (ASE), for operations based at both the STS and Space Station. Some of the DRMs were defined with the STS as a base for OMV/TSR kit operations, and others designed using the Space Station as an operations base. This was done to highlight the potential for, and to identify the requirements related to a growth option of eventually stationing satellite recovery equipment at the Space Station.

As a final requirements related activity, the study team conducted an allocation of all identified requirements to a group of candidate recovery system components. These components, including a structural interface, an extendible boom, a spin/despin table, a grapple mechanism interface device, a boresight television camera, and a family of grapple mechanisms for varying recovery scenarios, were viewed as the essential subsystems required for conceptual definition of a family of remote, disabled satellite recovery systems. This allocation of requirements and definition of requisite recovery subsystems provided the principal input to the second major study task.

The Concept Definition task, Task 2, was designed to provide alternative conceptual designs for satellite recovery systems and an assessment of no fewer than three grapple mechanisms. At the study Midterm Review in December 1985, the MSFC contract technical managers agreed with the MMC study team that Task 2 should be dedicated to an identification and assessment of alternative conceptual designs for each of the agreed-upon recovery subsystem elements/ components. Conceptual design of recovery systems would then be based on the selection of preferred subsystem components and integration of these into conceptual designs for Systems B and C.

At this point in the study effort, it became apparent to the study team that the overall recovery system could be designed in a modular format and composed of a number of subsystem mechanisms that would be readily interchangeable. Thus, if a particular recovery scenario required only an extendible boom and a small gripper (a System B mission), these elements could be attached to a structural interface unit and mated with the OMV in this form. If a "complex" motion scenario were to surface, this might require a spin table and, perhaps, a large envelope type grapple mechanism. In this case, the design of the modular, expandable recovery system would enable the removal of the small gripper on the end of the extendible boom and with appropriate interface mechanisms, the addition of a spin table and a large envelope grapple mechanism to accomplish the "full up" System C type mission.

In the Subsystem Component Evaluation task, Task 2.1, a number of alternative candidates for each of the subsystems were identified and evaluated. A search of current concepts, including those developed previously by NASA, Martin Marietta and other aerospace contractors was conducted. A set of alternatives providing a wide range of applicability to each subsystem was identified and evaluated.

In the second Task 2 subtask, Definition of Alternative Conceptual Recovery Systems (Task 2.2), the preferred subsystem alternatives were integrated into a set of System B and System C recovery devices. Each of the four specified systems is comprised of a subset of the total recovery system mechanisms that make up a complete recovery system. These recovery system configurations are described in Section 9.0.

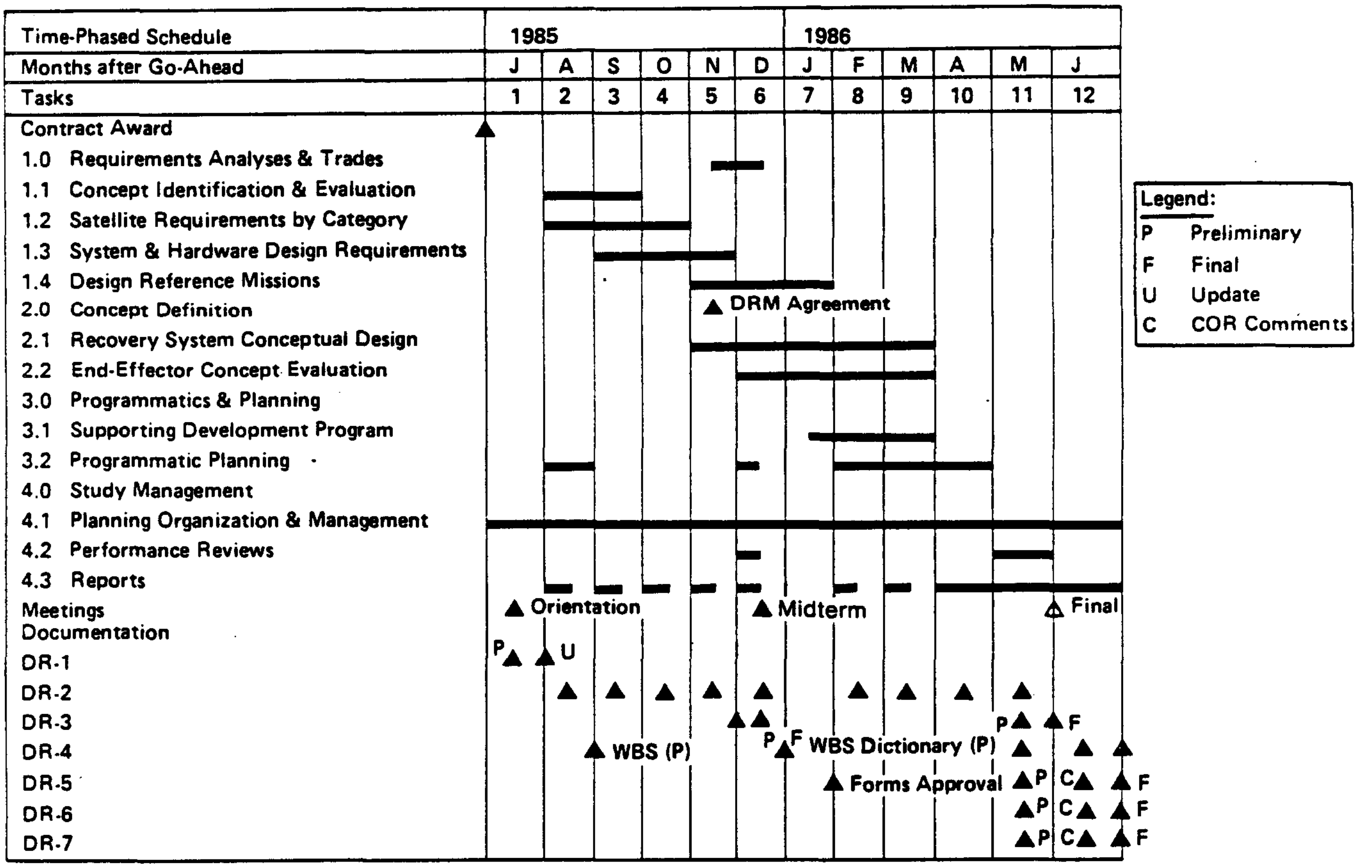
A major portion of the effort expended in the definition of conceptual systems tasks was the conceptual design of a large, envelopment-type grapple mechanism designed for compactibility for transport in the Shuttle cargo bay. This "Martin Marietta enveloper" mechanism was designed to meet all of the grapple requirements identified in the study effort. It is a conceptual design that will enable recovery of the most likely "complex motion" cases expected in a "full-up" System C scenario.

Programmatics and Planning, Task 3, was comprised of three general supporting study efforts. The first of these was the Supporting Research and Technology Report (SR&T). The Supporting Research and Technology Report was prepared from a compilation of those technical issues requiring further study and clarification to enable eventual definition and development of an OMV remote satellite recovery kit. The study team's assessment of the requirement for new technology development initiatives is that there are no critical technology "show stoppers" related to the development effort. A number of ground-based studies and demonstrations were identified, as well as a number of Shuttle cargo bay or proximity operation type on-orbit experiments. Tasks 1 and 2 provided inputs to Task 3, the Supporting Development Plan and TSR Program Cost Estimates.

Task 4, Study Management, as shown in Figure 2.2-1, is supported by the three other tasks and was comprised of study planning and management, the conduct of three directed reviews, i.e., an Orientation Meeting, a Midterm Review, and the Final Review, and preparation of a final report in three volumes. In addition, the study team conducted two additional Technical Interchange Meetings at MSFC to present interim progress reports and to seek advice and recommendations for changes in approach where deemed appropriate by the contract technical manager.

2.2.1 Study Schedule - The schedule used to conduct the tumbling satellite recovery study is shown in Table 2.2.1-1. The requirements oriented activities (Task 1) were scheduled and completed with the exception of the Design Reference Missions, prior to the Midterm Review. A Technical Interchange Meeting was conducted in October 1985. The Task 2 and 3 activities were conducted in early 1986, and a Technical Interchange Meeting was conducted in late March 1986, to secure acceptance of the recovery system modular design concept and the design of the Martin Marietta Enveloper grapple mechanism. The final review and final report material were generated during the final two months of the study period.

Table 2.2.1-1 TSR Study Schedule



3.0 REQUIREMENTS ANALYSES AND TRADES - TASK 1

3.1 Introduction and Approach

The objective of Task 1 was to perform the type of analyses and trades that would identify recovery system requirements for the MSFC designated range of recovery systems, i.e., Systems A, B, and C. The identification of system requirements was designed to support identification of satellite recovery concepts that would show promise of satisfying recovery requirements. The approach used in conducting Task 1 is shown in Figure 3.1-1. The major objectives of each of the four tasks are shown, together with the interaction between each of them. Task 1.1 was designed to secure a thorough survey of prior related satellite recovery studies and hardware development efforts. This was expected to produce a basic conceptual understanding of the problems related to remote recovery and serve as an initialization of the requirements definition process. The Task 1.1 analysis and results are presented in Section 4.0.

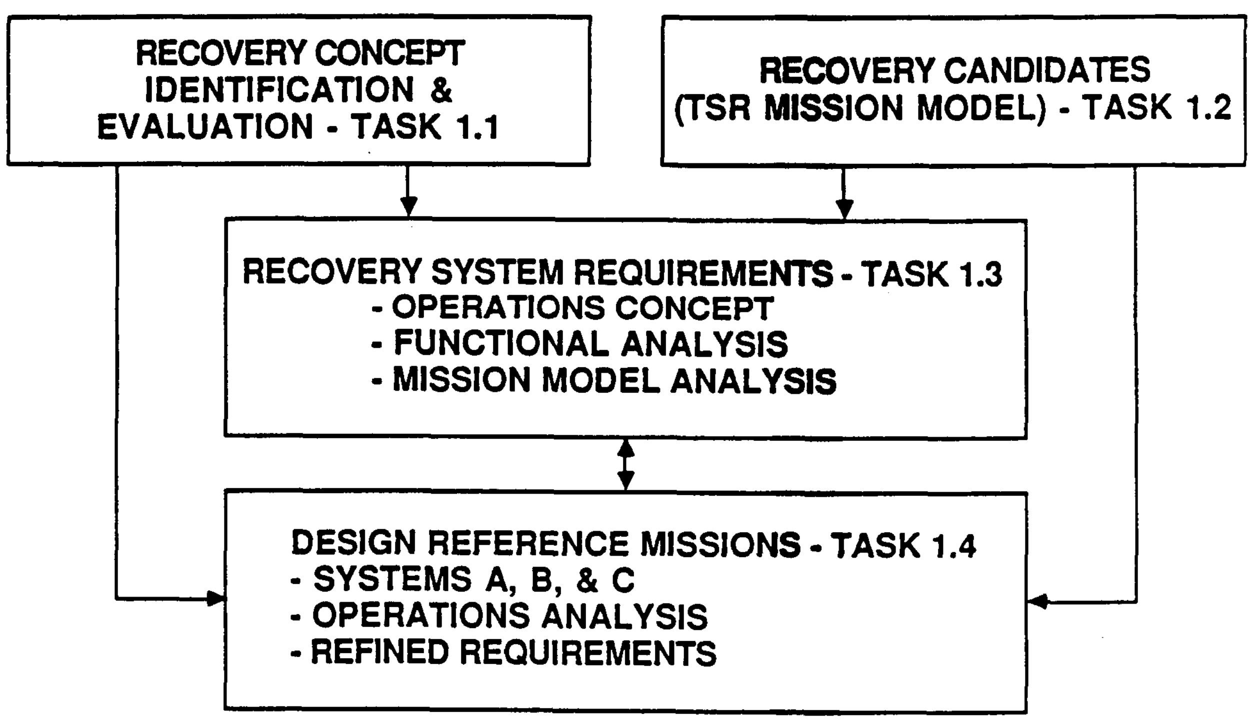


Figure 3.1-1 Task I Approach

The second requirements oriented task, Task 1.2--TSR Mission Model Derivation--was intended to highlight the types of candidates available for recovery and was used by the study team to illustrate how potential recovery targets will drive recovery system requirements. The Task 1.2 information is given in Section 5.0.

In Task 1.3, the results of concept identification and recovery target assessment were used to develop an operations concept for an OMV/TSR kit, and to conduct a functional analysis of a full-up System C recovery operation. Additionally, the study team then conducted a detailed analysis of the mission model to build a "worst case" set of composite targets and to begin to quantify the recovery requirements as they are impacted by recovery target candidates. The approach to and results from these analyses are given in Section 6.0.

The final requirements analysis task was selection and approval of design reference missions (DRMs). A set of six DRMs, two for each of the three MSFC levels of capability (Systems A, B, and C) were defined by Martin Marietta and approved by the MSFC contract technical monitors. A top level operations analysis was conducted for each of the DRMs to gain additional insight on requirements, particularly system requirements, such as GSE and ASE for the TSR kit. The design reference mission information is presented in Section 7.0.

The analyses conducted in Task 1 produced a broad base of system requirements. These were then allocated to recovery system accommodations and provided a sound basis for conceptual definition, the second major study task.

4.0 CONCEPT IDENTIFICATION AND EVALUATION - TASK 1.1

4.1 Introduction and Approach

Concept Identification and Evaluation, Task 1.1, was the first of the requirements analysis tasks. The study team conducted an extensive search for any documentation directly or indirectly related to satellite recovery. The Johnson Space Center (JSC) and MSFC libraries were queried, as well as a large number of knowledgeable individuals at JSC, MSFC, the Jet Propulsion Laboratory (JPL), and Goddard Space Flight Center (GSFC). The NASA centers provided source leads on other aerospace contractors and these produced additional sources. Martin Marietta had completed a number of recovery related studies, experiments, and actual hardware demonstration units and these were all incorporated into the survey data base.

As was to be expected, there was a great deal of variety involved in this collection of data. Some of the studies addressed the overall question of how to remotely recovery "tumbling" satellites. Most of these focused primarily on the mechanics of physically attaching a grapple mechanism to satellites in various states of motion. These were categorized as "concepts attached to OMV" and some of these are shown in Figure 4.1-1. Another group of recovery system analysts apparently presumed that tumble motion would typically be so complex that attachment to the target would be impossible or inappropriate and chose to deploy rocket propelled nets to encircle the target, or to fire harpoons or adhesive grapples at the target to achieve a firm connection. These concepts were categorized by the study team as "deployable from the OMV" and are shown in Figure 4.1-2. As can be seen, some of these concepts addressed only partial aspects of the problem, such as simply despinning the disabled satellite using plume impingement, yo-yo despin packages, self contained thruster stabilization packages, or electromagnetic despin. None of these recovery concepts considered the necessity of providing a firm attachment to the target satellite once despin was completed.

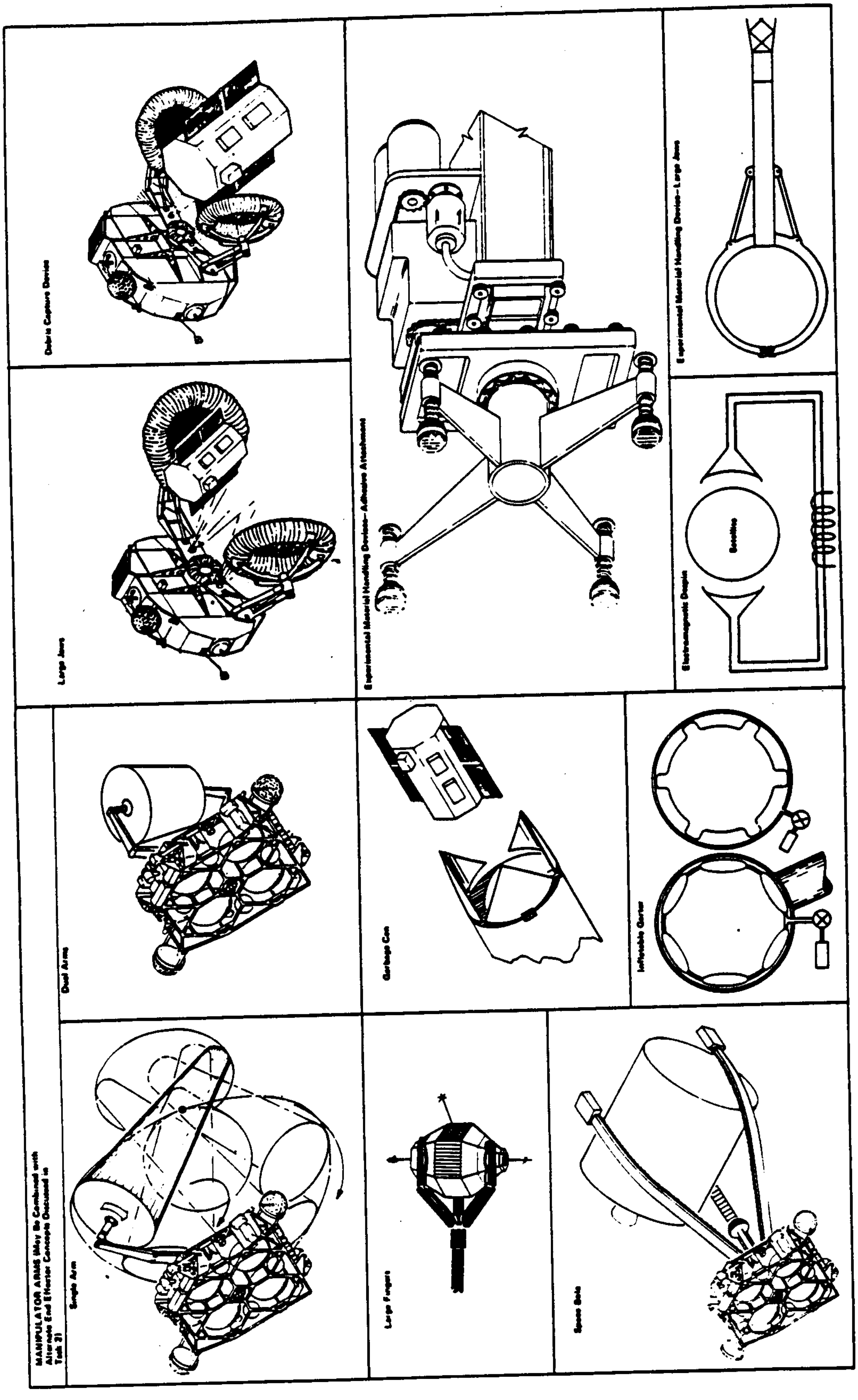


Figure 4.1-1 Concepts Attached to OMV

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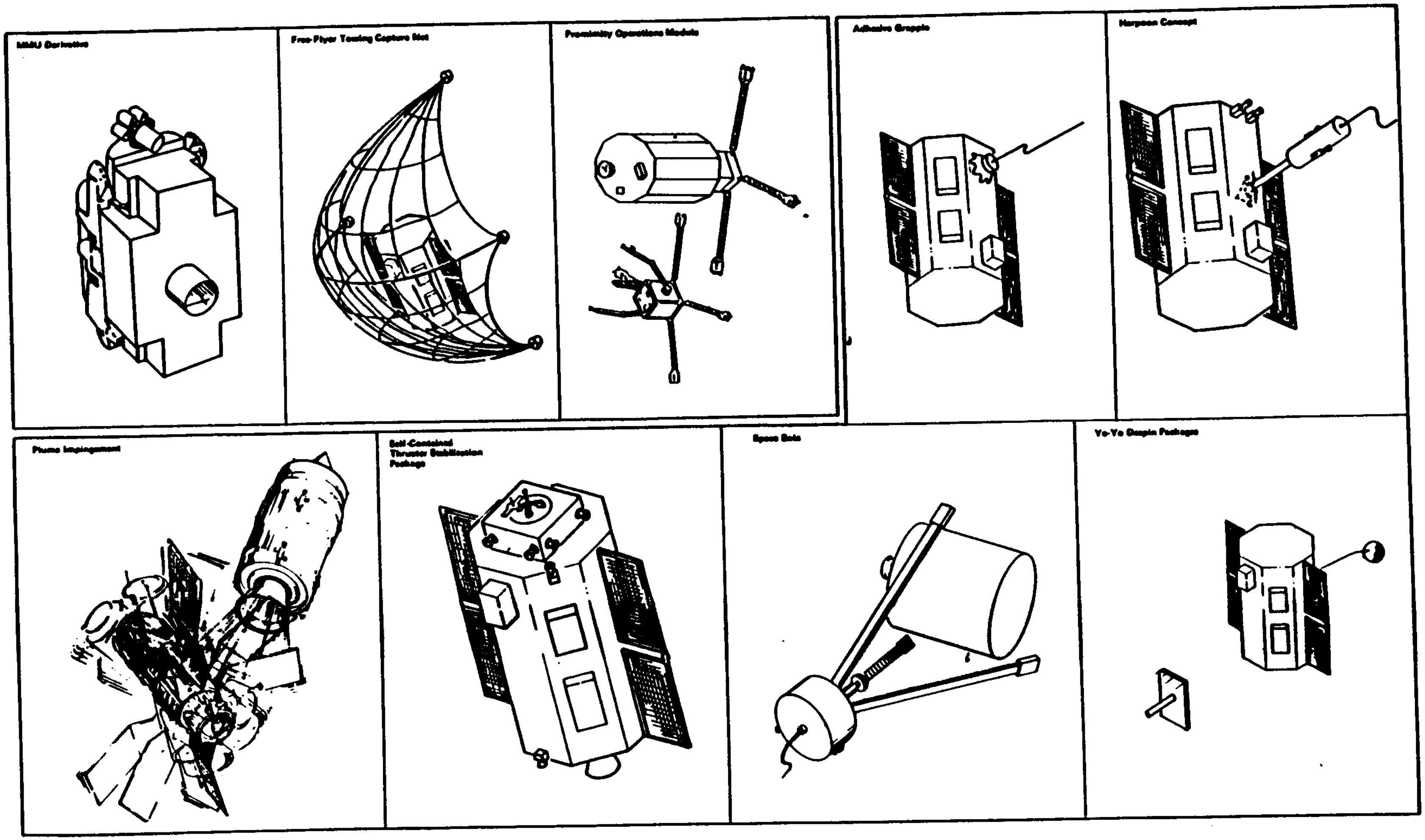

Figure 4.1-2 Concepts Deployable from OMV

Most importantly, none of these conceptual study and hardware development efforts were conducted from the perspective of transporting a recovery system front end kit using a well defined OMV and an operational Shuttle.

These concepts represent a myriad of satellite recovery/retrieval and space debris collection concepts that have evolved over many years. The transport vehicles for the recovery devices have varied from Apollo to Gemini, and to early versions of the OMV, such as Earth Orbital Teleoperator System (EOTS) and Teleoperator Retrieval System (TRS). There were only a few recovery concepts that were sufficiently "systems"-oriented to be considered as "concepts" for overall evaluation under this analysis task. The study team selected five of the best of these concepts for further definition and evaluation against a set of evaluation criteria. The results of this definition and evaluation process are presented herein.

4.2 Concept Identification

4.2.1 Debris Capture Device - The Debris Capture Device (DCD) is a recovery concept developed by Vought, a Ling-Tempco Vought (LTV) company, as a space debris collection, front-end system for the Teleoperator Maneuvering System (TMS) (now OMV) in 1982. The DCD, shown in Figure 4.2.1-1, consists of a pair of inflatable, low pressure toroids, that are mounted on adjustable arms for varying the reach of the system. This portion of the DCD is the grapple mechanism of the system. This grapple mechanism is mounted on a rotatable beam that is capable of spin about an axle. A television camera mounted on the spin axis rotates with the arms, and the capture area is illuminated by lights situated on the beam. This viewing capacity is supported by the TMS pan/tilt/zoom camera.

The DCD, mated to the TMS or OMV, would operate by observing the tumbling debris and approach the target along its spin axis. The grapple mechanism portion is "spun up" until the TV image of the debris is no longer spinning. This will reflect the fact that the spin rates have been matched. The arms would then be closed to allow the soft, compliant toroids to grip the irregularly shaped debris and damp out oscillations. Figure 4.2.1-1 shows the envelopment of a debris element by the DCD.

Vought

- Grapple Mechanism Includes Inflatable, Low-Pressure Toroids
- Adjustable Dual Arms for Varying Reach
- Rotatable Axis for Spin Matching
- Television Cameras on Arms for Proximity Operations

Initial Assessment

- Addressed Most Identified TSR Functional Requirements
- Has Applicability for Capture of Tumbling Active Satellites & Space Debris

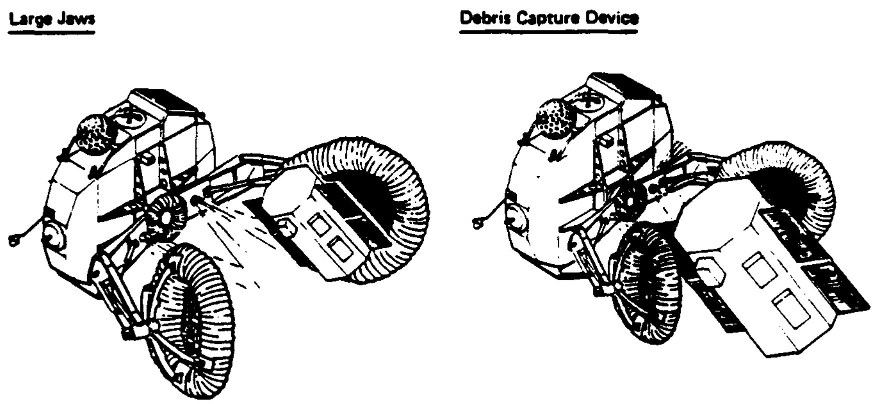

Figure 4.2.1-1 Debris Capture Device

The general assessment of the DCD was that is could satisfy most of the TSR requirements identified at this early point in the study effort. Later, it would be devalued for its lack of compactness for transport as an OMV front end kit in the Shuttle and for lack of an extendible boom to provide safety clearance between OMV and a target satellite.

4.2.2 Teleoperator Retrieval Manipulator - The Teleoperator Retrieval Manipulator was a NASA/MSFC concept modified by Martin Marietta for applications related to recovery of satellites with "complex" motion. It is illustrated in Figure 4.2.2-1. The recovery device consists of a spin table to match target spacecraft spin rates, an extendible manipulator arm to match coning angles created by free precession of the target, and a rotatable grapple wrist with a small RMS snare-type grappler to grasp an RMS end effector on the tumbling satellite. Such a manipulator arm would follow the complex coning motion of the satellite and grasp the grapple fixture, then apply forces to reduce the spinning and coning rates to zero.

NASA Concept Modified by Martin Marietta

Major Features
- Device Designed for Multiaxis Motion
- Spin Table to Match Spacecraft Spin Rates
- Extendible Manipulator Arm to Match Coning/Free Precession Angles
- Rotatable Grapple Arm for Longitudinal, Body-Axis Spin

Initial Assessment
- Enables Grapple of Satellites with multiple Spin Axes
- Possesses Most Subsystem Elements Required for Recovery

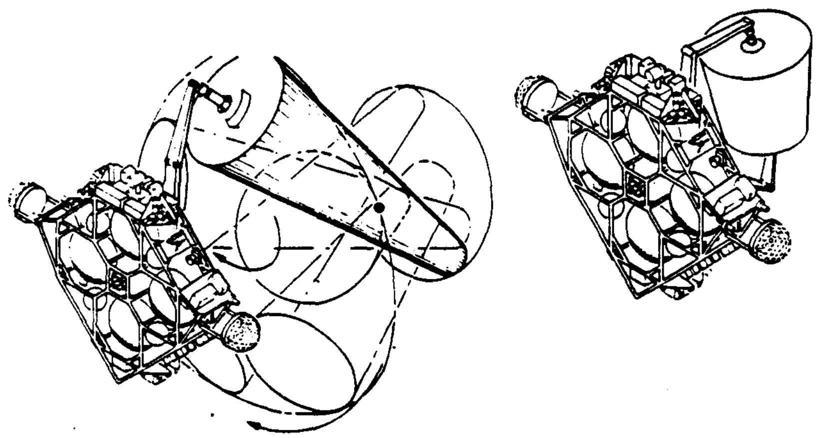

Figure 4.2.2-1 Teleoperator Retrieval Manipulator

The initial assessment of this device was that it would enable grapple and despin of satellites with this type of motion assuming that a grapple fixture was properly located on the tumbling satellite. The system could not deal effectively with targets that had no grapple fixtures or had complex motion that required envelopment. (The envelopment requirement was developed in subsequent analysis efforts.) In general, the recovery device was considered to be effective for this type of recovery scenario; however, the study did not address the likelihood of this or any other type of tumble motion.

4.2.3 Experimental Materials Handling Device - The Experimental Materials Handling Device (EMHD) recovery concept evolved out of a Marshall Space Flight Center/Martin Marietta Aerospace study conducted during 1970. The system, shown in Figure 4.2.3-1, was developed for use as a front end kit for the Apollo command module. The recovery system included a flexible interface between the kit and the command module to enable ready adaptation of a variety of potential grapple mechanisms to the recovery system. The study considered several alternative grapple mechanisms, such as the "C-clamp", shown in Figure 4.2.3-1, clamps with three and four arms and even some adhesive grapples. In fact, physical representations of all these grapple mechanisms were built and tests conducted to validate them.

This device included a spinning interface to enable matching of the spin rate about one potential spin axis of the tumbling satellite.

The assessment of the EMHD concept was that it contained most of the mechanisms assumed as essential elements during this preliminary phase of the TSR study. However, there were no provisions for dealing with multi-axis spin or tumble, and the EMHD study provided no assessment of expected or probable "complex" motion. As subsequent analysis suggested that single axis spin is the most probable state of a non-controllable tumbling satellite, the initial assessment of EMHD meeting most requirements proved to be quite accurate. In addition, it turned out to have potential for applications in recovery scenarios that were later categorized as System B and System C cases. This concept included a grapple mechanism interface device to enable ready application of special purpose grapple fixtures, such as have already been developed for recovery of the Solar Maximum satellite, and WESTAR and Palapa-B.

Martin Marietta Concept

Major Features
- Developed for Use with Apollo Command Module
- Device Includes Spinning Interface with Variable Grapple Fixtures
  - C-Clamps, Two & Four Arms, Adhesive Grapple
- Equipment Built & Tests Conducted

Initial Assessment
- Simple, Can Accommodate Target with Single-Axis Spin
- Grapple Mechanism Interface Concept Supports Use of Simple and Complex Grapple Mechanisms

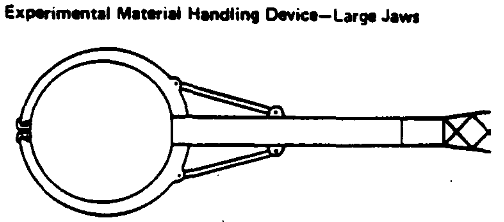

Figure 4.2.3-1 Experimental Materials Handling Device

4.2.4 Docking and Retrieval Mechanism - The Docking and Retrieval Mechanism (DRM) concept evolved from another Marshall Space Flight Center/Martin Marietta study on an earlier version of the OMV that was known as Earth Orbital Teleoperator System (EOTS). At the completion of a definition study, MSFC directed Martin Marietta to design and fabricate an engineering prototype design of the DRM adaptable for installation in the MSFC mobility unit simulator facility, now known as the Teleoperation and Robotics Engineering Facility. The DRM concept is shown at Figure 4.2.4-1.

The principal mechanisms of the DRM included: (1) a spin table capable of spin-up to 100 revolutions per minute (RPM) and despin; (2) an extendible boom to enable the EOTS to station keep with the payload while extending the docking mechanism, in lieu of using the EOTS translational capability to effect the insert, capture, latch and dock sequence; and (3) a section containing a latch mechanism that could be converted readily to a grapple mechanism section. This potential recovery concept contained an extendible docking probe for stationkeeping with the EOTS, but the boom would, in fact, also provide a safe clearance zone between OMV and a tumbling recovery target.

Martin Marietta Design from Earth Orbital Teleoperator Systems (EOTS) Study (1976)

Major Features
- Extendible Docking Probe Mechanism
- Payload Docking Receptacle
- Control Electronics & Displays
- Prototype Hardware Delivered to MSFC

Initial Assessment
- Spin Table Capable of Spin & Despin to 100 rpm
- System Includes Extendible Probe Mechanism
- Grapple Mechanisms Could Replace Latch Mechanism

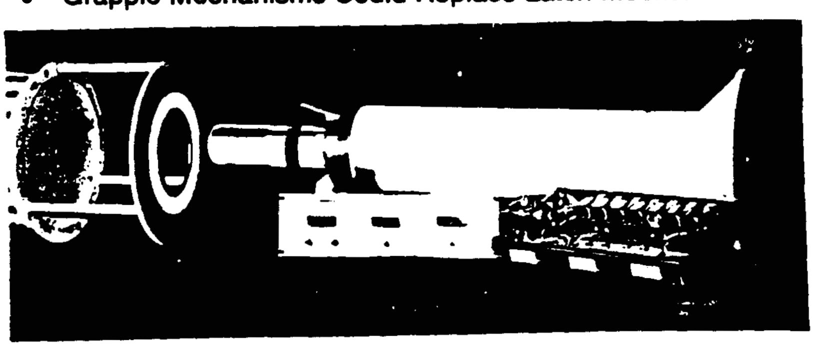

Figure 4.2.4-1 Docking Retrieval Mechanism

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The deliverable DRM hardware included the EOTS extendible docking probe mechanism, a payload docking receptacle, the DRM control electronics and the controls and displays shown in Figure 4.2.4-1.

This concept was chosen for extended evaluation because it did appear to include many of the features seen as requisite to remote recovery of disabled satellites. The primary exception was a grapple mechanism and its related interface device, i.e., that element required to accommodate ready changeout of grapple devices for varying recovery scenarios. The study team believed that a grapple mechanism element could replace the DRM latching mechanism, making this a feasible concept for this evaluation task.

4.2.5 Space Bola - The last of the five recovery concepts selected for the expanded evaluation was the Space Bola, a recovery concept introduced in the early 1960s. The space bola concept is illustrated in Figure 4.2.5-1.

Martin Marietta—Mid-1960s

Major Features

- Inflatable, Extendible Grappling Arms To Envelop Satellite
- Rockets in Arm Tips Fired To Achieve Grapple

Initial Assessment

- Flexible, Extendible Grapple Mechanism, To Accommodate Varying Target Sizes
- Contact Sensor & Envelopment by Arms Provides Rigidization for Transport
- Spin Table, Extendible Boom Readily Added

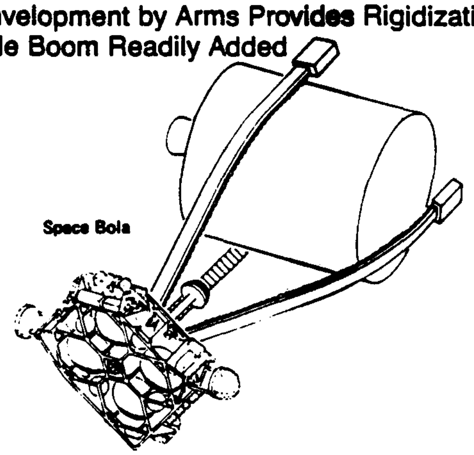


Figure 4.2.5-1 Space Bola

The Space Bola concept was patterned after the bolas used by the gauchos of South America. The gauchos make their bolas by attaching balls of stone or iron to the ends of a cord. A third ball is attached to the main cord at the bisecting point. By hurling the bola at the legs of animals, the animals become entangled and are captured. The Space Bola concept consists of a grappling unit, which is a set of three inflatable arms that are inflated to a fully extended position to provide a capturing volume, and a contact sensor. On approaching the target the grappling phase would commence at contact with the target. The extended arms are partially deflated, and small solid propellant charges in the end of the arms drive the arms around the target. Velcro pads on the ends of the arms lock the arms together as they overlap. The arms are then reeled back into the grappling unit until a firm attachment is achieved. With the spin table, added by the study team, the disabled satellite would be despun and prepared for return to the STS.

The major redeeming value of this concept was the potential provided by the Space Bola's enveloping grapple mechanism, a feature that became increasingly more relevant as the study effort progressed. In addition, the study team believed an extendible boom (for clearance between OMV and the tumbling satellite) and a spin table could be readily added to make this a viable concept. With these additions, the Space Bola was included in the group of recovery concepts for expanded evaluation.

4.3 Initial Concept Evaluation

4.3.1 Introduction - The survey of prior remote recovery related study and hardware activities provided the study requirements analysis task some initial insights on fundamental recovery requirements. As one would expect, as the study progressed and other analysis tasks were completed, the breadth and depth of both recovery system and recovery concept requirements was expanded. Thus, the initial concept evaluation was conducted from a relatively limited view of total requirements and is presented herein from this perspective. In actuality, the resulting evaluation, and its perceived shortcomings, provided the study group with an alternative analysis approach that produced highly rewarding results.

4.3.2 Evaluation Criteria - The evaluation criteria eventually selected for the concept comparisons were derived from: (1) insights and background provided by pre-proposal efforts; (2) new perspectives gained from the concept identification and assessments; and (3) discussions with various MSFC and MMC personnel. The selected evaluation criteria are shown on Table 4.3.2-1. Each of the evaluation criteria was weighted to illustrate its relative importance to the criterion considered to be of highest importance.

The "capability to recovery a broad spectrum of satellite configurations" was selected as the highest value evaluation criterion. The study team was gathering data on the projected satellite mission model for the mid-1990s and it was clear that there was to be a wide diversity in satellite size, shape, mass and potential failure mode for recovery candidates in this period.

Table 4.3.2-1 Concept Selection Criteria

	Weight
• Capability to Recover Broad Spectrum of Satellite Configurations	10
• Minimum Risk to OMV & Recovery System during Recovery	9
• Capability to Accommodate High Single-Axis Satellite Spin Rates	9
• Minimum Risk to Target Vehicle	8
• Compatibility with OMV; Minimum Impact on OMV Design	7
• Dependence on Recovery Vehicle Support Elements	7
• Modularity of Subsystems to Enable TSR System Growth for Flexible Mission Capability	6
• Capability to Deal with Wide Range of Tumble Mode Complexity	5
• Weight to Orbit (Mass & Volume)	5
• Development Risk/Cost	5

Another highly ranked criterion was the necessity for the eventual recovery system to conduct operations with minimum risk to the OMV and the TSR kit during recovery operations. It was not known at that time what the potential complexity of recovery operations might be, but safety of recovery equipment appeared to be high in importance.

This evaluation was actually conducted twice, before and after the satellite failure modes analysis described in Section 4.4.1. The next criterion, capability to accommodate high, single axis spin rates, was derived from that analysis, and added to the evaluation criteria, with the high designated weight shown in Table 4.3.2-1.

The sole purpose of a remote disabled satellite mission is recovery of a valuable satellite for refit and return to functional operation. Thus, minimum risk to the target vehicle was also considered high in potential ranking for concept evaluation. It was clear and became increasingly apparent that certain deployed target elements such as antennas and non-retractable solar panels might have to be sacrificed during recovery; in some cases to enable access to onboard recovery support elements, such as RMS grapple fixtures, and in others to preclude damage to OMV and the TSR kit during orbit transfer maneuvers. Return of a recovered satellite to the ground in the Orbiter could also result in the sacrifice of its on-orbit deployable appendages.

The conceptual design of a recovery vehicle was considered to have to be basically compatible to that of the OMV and to have minimum impact on the design of OMV, and, thus, this criteria was rated relatively high. OMV will be designed and developed well in advance of the TSR kit and the TSR kit should be designed to be cost efficiently integrated into the OMV program. Continuing analyses proved it would be equally important to design the TSR kit for compatibility with STS Shuttle operations.

Dependence on target recovery support elements (RSE) was actually a negative criterion and those concepts requiring this feature were downgraded. It was felt that many potential targets would not have RMS grapple fixtures or flight support structure berthing rings, or given they were present, would not likely be in a position where they would support attachment to a TSR kit. If the target were spinning or tumbling, the recovery system would have to grapple on an axis of spin through the target center of gravity, and the RCE was not likely to be there.

The next criterion was titled "Modularity of Subsystems to Enable TSR System Growth for Flexible Mission Capability." A parallel analysis resulted in the inclusion of this evaluation criterion. The broad range of potential recovery scenarios described in Section 7.0 led the study team to believe that an overall recovery system built with a number of readily interchangeable mechanisms would be a recovery system design concept candidate.

Tumble mode complexity was another evaluation criterion that was downgraded due to other ongoing Task 1 analyses. Many of the "previous" concepts had been designed to accommodate complex satellite motion comprised of spin on multiple axes, while others were designed for recovery of single axis spin cases. None of the studies actually addressed "complex" or worst case tumble motion. Subsequent analysis revealed that complex motion was not likely to be multi-axis spin or tumble, so the weight of this evaluation criterion was lowered.

The last two criteria were mass and volume required for the recovery kit and development risk and cost. Though both are important criteria, they were considered as manageable development criteria and rated accordingly.

4.3.3 Concept Evaluation - Shown in Table 4.3.3-1 is the result of the evaluation of the five pre-selected concepts. The selection criteria, weighting factors and total scores are provided in the table. The scoring was provided by five experienced study team members and their associates. Each of the score values was then normalized for each evaluation criteria and each recovery concept.

As was expected, the Experimental Materials Handling Device, the Debris Capture Device, and the Docking Retrieval Mechanism all received higher scores, as these devices appeared to possess, at that point in the study effort, more of what the study team was beginning to understand as requirements for a "full-up" recovery device.

A quick assessment of the results of this evaluation provided beneficial results to the study effort. By simple addition, one can note that the maximum score any concept could receive was 710 points. The highest rated recovery concept received only 80% of that score, and therefore it became clear that more effort was needed to understand clearly what was required to develop a fully effective, general purpose, remote, disabled satellite recovery system.

4.4 Alternative Concept Identification Approach

The total assessment of the concept identification and evaluation task is shown on Figure 4.4-1. In looking at some of the specified study objectives and tasks, it was clear that Task 1.1, Concept Identification and Evaluation, had not contributed to those important issues shown on the top of Figure 4.4-1. This task had not provided differentiators that would support a refinement of the definition of MSFC's three generic recovery system levels of capability, i.e., Systems A, B, and C. The survey added no clarity to the understanding of what the OMV operator would expect to see, in terms of typical satellite motion at the site of the "tumbling satellite." In fact, the study efforts and hardware activities addressed a broad range of perceived tumble motion. Some concepts were configured for recovery of disabled satellites in multi-axis, general tumble motion, some configured more for specific single axis spin, and others, like net and harpoon concepts, were designed apparently for tumble motion with no discernable steady state motion configuration. MSFC had referenced "complex motion" as that required for the full-up system, but no definition of complex motion was readily available.

The study team developed and conducted a new and ultimately successful approach to the clarification and comprehension of these issues. As shown on the bottom half of Figure 4.4-1, this approach included a search for historical failure mode data, the resulting tumble mode data from actual failed satellites, and a dynamics analysis to enable full comprehension of any real world satellite "complex motion" findings. The results of this series of analyses are highlighted in Figure 4.4-1. The first of these analyses was satellite failure mode analysis.

Table 4.4-1 Recovery System Evaluation

EVALUATION CRITERIA	Weighting Factor	Teleoperator Grapple Despin Device	Experimental Materials Handling Device	Docking & Retrieval Mechanism	Space Bola	Debris Capture Device
Capability to Recover Broad Spectrum of Satellite Configurations	10	5	8	4	6	8
Minimum Risk to OMV & Recovery System during Recovery	9	8	8	9	5	8
Capability to Accommodate High Single-Axis Satellite Spin Rates	9	6	8	8	5	8
Minimum Risk to Target Vehicle	8	8	8	8	5	8
Compatibility with OMV & Minimum Impact on OMV Design	7	8	8	8	5	8
Dependence on Recovery Vehicle Support Elements	7	5	9	7	9	9
Modularity of Subsystems to Enable TSR System Growth for Flexible Mission Capability	6	6	8	8	5	8
Capability to Deal with Wide Range of Tumble Mode Complexity	5	9	7	7	9	6
Weight to Orbit (Mass & Volume)	5	7	7	7	9	6
Development Risk & Cost	5	8	9	9	8	7
Total Value		487	570	525	448	555

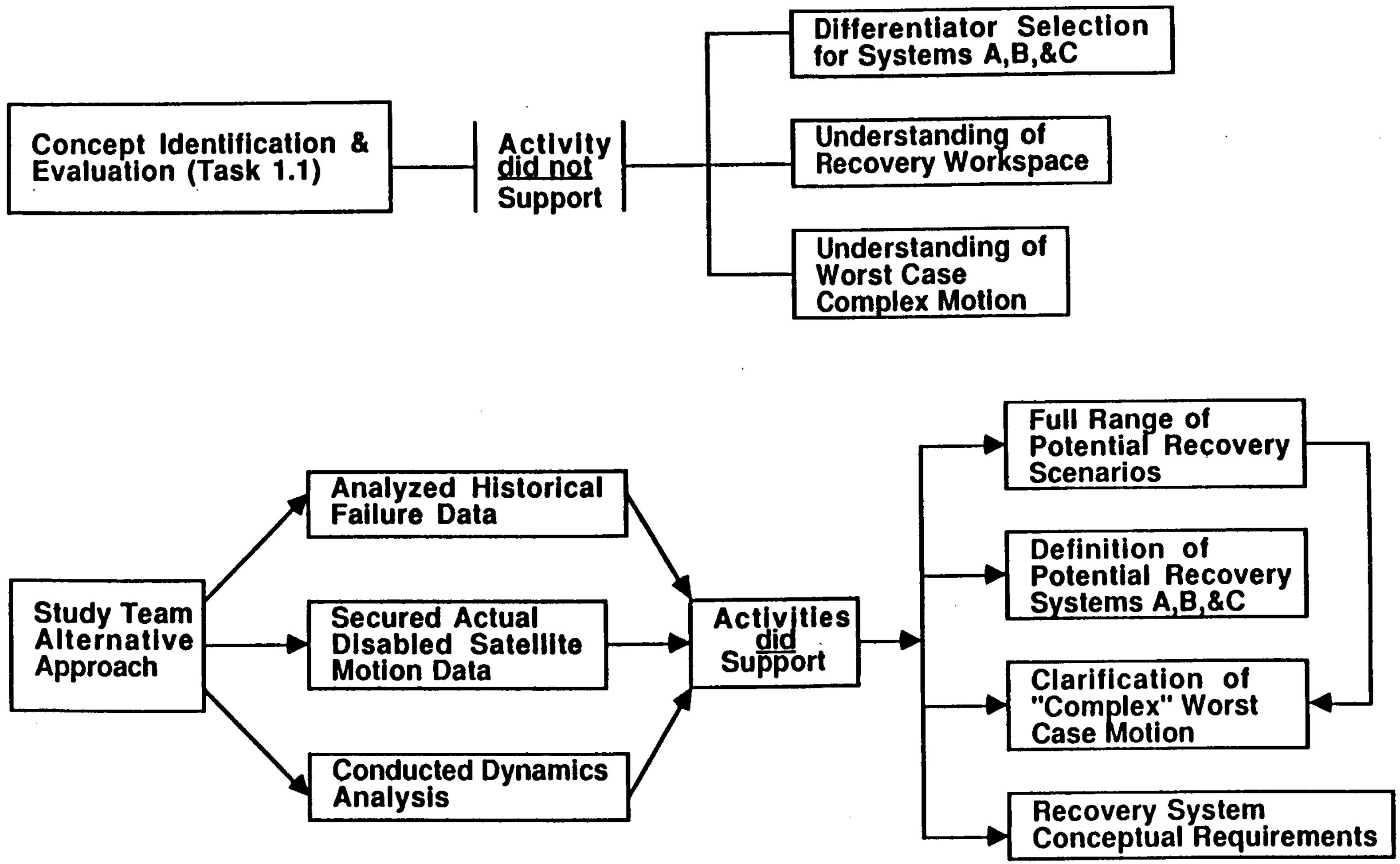


Figure 4.4-1 Concept Identification and Evaluation Assessment

4.4.1 Failure Mode Analysis - It was assumed that a search for satellite failure data would be rewarded quickly and with highly useful data. An extensive series of telecons to offices in NASA headquarters and centers, and to similar Department of Defense focal points produced limited results.

Fortunately, one excellent source of satellite failure data was secured. Mr. Edward Shockey at Goddard Space Flight Center (GSFC) had contracted with Planning Research Corporation (PRC) to conduct a study of spacecraft on-orbit anomalies and lifetimes. The report is titled "Analysis of Spacecraft On-Orbit Anomalies and Lifetimes", PRC R-3579, February 10, 1984. The study examined the orbital performance records of 44 unmanned spacecraft under the cognizance of GSFC and the Jet Propulsion Laboratory (JPL), during the 1977-1984 time period. The PRC study examined each recorded incident of anomalous spacecraft behavior, ranging from momentary malfeasance to complete spacecraft failure. This is an extensive collection of United States satellites and presented a highly representative data base for use in making assumptions regarding satellite failure cause and resulting tumble motion. A synopsis of relevant failure data is presented in Figure 4.4.1-1. The report presented two overall statistical measures of merit. The first of these was an attempt to measure the mission effect of the anomaly. As shown in Figure 4.4.1-1, with a total of 602 reported anomalies, a satellite anomaly will result in greater than 67% mission loss in only 6 out of over 600 cases. That equates to major on-orbit satellite failure, in only 1% of the satellites, or very rarely. But, as will be shown later, major on-orbit failures have occurred recently and are to be expected.

The other measure of merit used in the GSFC report was highly relevant to this study effort. The report included a breakout of anomalies by major spacecraft subsystem. These eight subsystems categories are shown in Figure 4.4.1-1. When assessing this satellite subsystem failure data, two highly relevant observations can be made. First, the power and attitude control and stabilization (ACS) subsystem anomalies account for nearly 30% of satellite subsystem failures. Thus, with power and ACS the major contributors to spacecraft stability, the potential for loss of satellite control from major failure could be projected at nearly one in three. The impact of this is expanded in subsequent portions of this report.

Mission Effect	
Negligible	447
Nonnegligible, but Small	117
1/3 to 2/3 Mission Loss	32
2/3 to Nearly Total Mission Loss	5
Essentially Total Mission Loss	1
	602

Spacecraft Subsystem Anomaly	Number	Percent
Timing, Control, & Command	55	9.1
Telemetry & Data Handling	112	19.1
Power Supply	56	9.2
Attitude Control & Stabilization	123	20.3
Propulsion	26	4.3
Environmental Control	16	2.6
Structure	6	1.0
Payload/Experimental	208	34.3
	602	100%

— Few Major Failures
— 35% Could Fail in Controllable Mode, Not Tumbling
— 30% Could Fail in Noncontrollable, "Tumbling" Mode

Figure 4.4.1-1 Spacecraft Failure Anomaly Analysis

A second major relevant recovery-oriented statistic is presented by an assessment of the payload/experimental subsystems. The GSFC/PRC report noted, as shown again in Figure 4.4.1-1, that nearly 35% of satellite anomalies were related specifically to the payload or instrument package. Thus, one could just as readily project that one-third of major satellite failures could result in a useless mission, a disabled payload package, with a totally controllable satellite.

In summary, a remote, disabled satellite is equally likely to be completely stable and controllable, with power and ACS subsystems intact, or totally out of control, in some form of "complex" tumble motion. The next step taken by the study team was to determine just what that tumble motion would most likely be.

4.4.2 Failed Satellite Motion Analysis - Another search for satellite failure data was conducted. The study team began to query NASA and DOD sources for examples of satellites that had failed in a non-controllable mode and, more importantly had, for some reason, had tumble or satellite motion orientation data collected on them. The search was difficult, again, for obvious reasons. Primarily, it was determined that program/project offices did not care to discuss failures. However, satellite failure and related motion data was collected on six different missions.

The first of these were two failures of the Defense Meteorological Satellite Program (DMSP), Block 5D, flights 1 and 2. Data on these failures was obtained from Roger Hogan, Radio Corporation of America (RCA) in Princeton, New Jersey, and from Ray Skrynska, Aerospace Corporation, Los Angeles, California.

The first reported non-controllable satellite failure, with related tumble motion data, was DMSP Block 5D1, Flight 1. This DoD payload failed in 1976 as a result of a massive failure in nitrogen supply to the reaction control system (RCS) thrusters and some hydrazine leakage. The satellite was spun up to about 3.1 revolutions per minute (RPM) in a general three axis tumble mode, resulting in complete loss of attitude control. Spacecraft attitude control was lost and batteries were soon depleted because of the disorientation to the sun and the satellite eventually lost all power. As DoD was extremely interested in recovering use of this scarce resource, tumble motion data was acquired prior to loss of power through reading attitude control sensors onboard the satellite. The initial motion was general tumble, with spin, precession and nutation components. This general tumble motion quickly converged to flat, single axis spin about the major principal axis. In this case, after several months, the spinning solar panels realigned with the sun, the batteries became recharged and with power again available, the reprogramming of onboard software enabled ground controllers to stabilize and reestablish attitude control of the satellite.

The second non-controllable satellite failure case occurred in the second flight of DMSP Block 5D1 program. DMSP is a DoD weather satellite and a vitally needed military support system. The flight two failure was generally thought to be the result of a ground controller error. During operational checkout of the satellite, the solar boom did not deploy. A ground controller attempting to "shake out" the boom instead loaded the satellite with enough "excess" angular momentum to exceed the spacecraft's attitude control capability. Once again control was lost, placing the spacecraft initially in a general, multi-axis spin, with a spin rate of 7 RPM. Again, the satellite motion, due to system flexibilities including the solar boom, antennas and fuel sloshing in the propellant supply tanks, quickly converged to what the study team would later find is the "classic dynamic solution" - flat, single axis spin about the principal axis of maximum moment of inertia. Fortunately, as with the flight one case, this rotational mode did force deployment of the solar panel, and it realigned with the sun. The batteries recharged and, again the spacecraft was recovered for full operational use. The DMSP flight 1 and 2 configuration is shown at Figure 4.4.2-1. The spin axis, single axis rotation, is illustrated there, and one can see how the solar panel could deploy with forces provided by this spin.

Further examples of satellite non-controllable failure motion were provided by short failures in TIROS-N and NOAA-6. In both cases, hydrazine leaks induced low levels of angular momentum, slightly beyond the capacity of the angular momentum wheels to retain control of the satellites, and tumble motion developed. The final tumble, or single axis spin rate mode, evolved quickly as in the DMSP cases.

The last two cases were both classified military satellites. One was a three axis stabilized spacecraft, the other a dual spinner type satellite. In both cases, subsystem failures produced a tumbling, non-controllable satellite that entered general, multi-axis tumble motion immediately, and very quickly, the motion converged to single axis spin about the major principal axis.

Thus, the process of collecting and assessing motion orientation data on actual non-controllable satellites produced results that appeared to show a somewhat consistent pattern. Different failure causes resulted in non-controllable motion with an apparently predictable pattern. The next step in defining "complex", non-controllable motion was to fully comprehend the characteristics of what practical spacecraft dynamics experience was demonstrating.

Block 5D Configuration—Flights 1 & 2

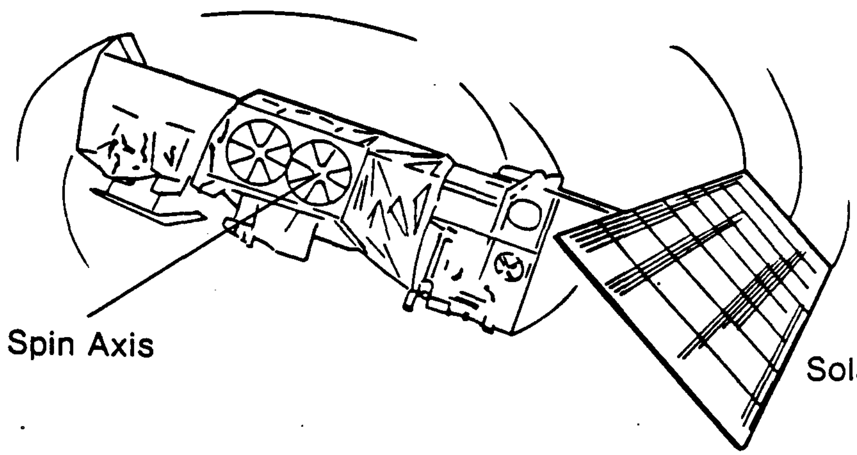


Figure 4.4.2-1 Defense Meteorological Support Program

4.4.3 Spacecraft Dynamics Analysis - An independently conducted analysis provided an analytic solution to the question of why non-controllable satellite general tumble motion rather quickly coalesces into single axis spin. The result of that independent analysis is summarized herein.

Satellite tumble motion is usually initiated by some source of torque on the satellite system, either internally or externally induced. In another recent failure, the NOAA-8 satellite, a sun-synchronous satellite in a 450 nautical mile, polar orbit suffered a battery explosion that disabled the satellite and induced a 1.5 RPM spin on the satellite. The study team intends to study this failure independently to: (1) improve the general understanding of complex tumble motion; and (2) assess the nation's capability to determine tumble motion orientation and rates, using terrestrial sources, for mission planning support.

The induced torque from the failure creates a level of angular momentum beyond the control laws and the control capability of the satellite's attitude control and stabilization (ACS) system. The torque also induces a high level of additional kinetic energy into the spacecraft system, a system that is a quasi-rigid body. This excess energy will create an initial state of general multi-axis tumble, with spin, precession and possibly nutation.

As satellites are truly quasi-rigid bodies, i.e., not solid, inflexible rigid bodies, this kinetic energy will be dissipated quickly by various damping sources, such as flexible appendages, viscous fluid flow in propellant tanks, and even friction in structural fasteners.

When the additional kinetic energy introduced into the satellite system by the external torque source reaches a "steady state" minimum energy level, basic dynamic theory supports the thesis that the angular velocity vector coalesces with the angular momentum vector. This eliminates free precession and "dynamic coning" and the satellite motion becomes flat, single axis spin about the major principal axis, which is the axis of maximum moment of inertia. These results are in agreement with the precept that a spinning system will, in the presence of damping, seek the lowest possible energy level consistent with conservation of angular momentum.

The thesis that satellite "complex motion" is single axis spin, at varying rates, about the spacecraft's major principal inertia axis is supported: (1) analytically; (2) by observed actual satellite failure cases; and (3) by further validation through personal telephone discussions with the dynamics experts listed below.

a. Dr. Farrenkopf, TRW
b. Dr. Cochran, Auburn University
c. Dr. Hubert, RCA
d. Dr. Likins, President, Lehigh University
e. Numerous Martin Marietta spacecraft dynamics experts.

With this assessment of what non-controllable satellite complex motion is likely to be, the study team determined, and was supported by MSFC during study reviews, that the requirements and conceptual design of the tumbling satellite recovery "System C" should proceed from this recognized complex, uncontrollable satellite motion mode.

4.4.4 Recovery System Differentiators - The definition of complex, or worst case, non-controllable motion provided a framework for refining the description of MSFC's hypothetical Systems B and C. The spacecraft failure analysis supported this objective by clarifying what the logical state(s) of motion orientation for disabled satellites could be. These potential states of motion are outlined in Table 4.4.4-1.

A disabled satellite could be, in fact, attitude stabilized and under control from the ground. This would be the case when a payload or instrument package were to fail while the power and ACS subsystems are not affected. The recovery environment in the case of a controllable satellite will be dependent upon whether a disabled satellite has recovery support elements attached to it or not. Recovery support elements (RSE) include: (1) RMS grapple fixtures, which can be grappled by the OMV RMS grapple mechanism/end effector; or (2) STS flight support structure (FSS) berthing "latch pins." Some targets will be equipped with RCE elements, others will not.

Another recovery environmental state, as shown in Table 4.4.4-1, will be the case of a controllable, spin-stabilized satellite, such as a commercial, communications satellite that experienced a kick motor failure after departing the Orbiter cargo bay. The satellite will be spinning at some rate, probably varying from 5 to 50 RPM, though stable, and must be recovered from that motion orientation.

A final motion orientation, or recovery environment, is the case where the disabled satellite is non-controllable, and the failure mode has induced a tumbling or spinning action. Again, from the failure mode analysis, the tumbling case is as likely to occur as the controllable recovery case.

In any event, continuing analysis demonstrated that the recovery requirements and the recovery system capability differs in each of these prospective disabled satellite environments.

Table 4.4.4-1 Failed Satellite Motion Orientation

- **Disabled Satellite Can Be:**
  - **Controllable with Recovery Support Elements Available**
  - **Controllable without Recovery Support Elements Available**
  - **Stable, Spin Stabilized, Spinning**
  - **Non-Controllable, Tumbling/Spinning**
- **Recovery System Requirements/Capabilities Different in Each Case**

The failed satellite environment analysis/summary directly supported a final definition of a set of differentiators that led to an enhanced definition of MSFC's Systems A, B, and C. These differentiating elements are shown in the matrix of Figure 4.4.4-1. The selected recovery scenario differentiators are all listed and those applicable to each system are checkmarked. Thus, the System A scenario is defined as dealing with a target that is beyond Orbiter range, the target's attitude is controllable (either automatically or from the ground), and the target has properly situated recovery support elements (RCE). This implies that the target is not spinning, or is spinning so slowly that OMV could match the recovery target's spin rate. Computer simulation exercises have shown these limitations to be single axis spin at rates no more than two to three degrees per second. The RCE must be fully accessible to a head-on approach with the OMV RMS end-effector, and the RCE cannot be obstructed by antennas or solar arrays. If all these conditions exist in the recovery environment, or recovery workspace, then the System A scenario exists and the satellite could be recovered by the basic OMV.

Recovery Scenario Differentiators

	TSR System A	TSR System B	TSR System C
Target Is beyond Orbiter Range	X	X	
Target's Attitude Can Be Controlled from Ground	X	X	
Target Has Properly Situated[1] Recovery Support Elements (RSE)[2]	X		
Target Is Controllable, Spin Stabilized at High Rates[3]			X
Target Cannot Be Controlled from Ground and in Minimum-Energy Flat-Spin Mode.			X
Target Is Prevented from Reaching Minimum-Energy State (Due to Internal or External Torques, or Bizarre 3-σ Failures) & Exhibits General Motion at High Rates (Low Probability of Occurrence)			

1. Within Reach of OMV Grapple Devices
2. STS RMS Grapple Fixtures or FSS Berthing Latches
3. Beyond Grapple OMV Rate-Matching Capability

Figure 4.4.4-1 Recovery System Differentiators

The System B scenario description varies only slightly from this scenario. Again, the recovery target is beyond the Shuttle's range, and the target is controllable and not spinning beyond the capability for OMV to match the target's spin rate. For System B, however, the target is defined as having no RCE to grapple with OMV retrieval equipment, or the RCE element is obstructed by deployed antennas or solar arrays for normal OMV approaches. As will be shown subsequently, the capability requirements for System B are limited in nature and substance as requested by MSFC.

The System C scenarios are two in number. This implies that there are two fundamental scenarios that will be accommodated with a basic System C, and the recovery system to accommodate these scenarios will vary slightly for each of the two scenarios. In the first System C scenario, the target is beyond Shuttle range, controllable, but spin stabilized at speeds ranging from 5 to 50 RPM, beyond OMV spin rate matching capability.

The second System C scenario, as shown in Figure 4.4.4-1, involves a case where the disabled target is not controllable, through loss of power or ACS subsystem failures, and is in a minimum energy, flat, single axis spin. Note that, in this case, the target does not necessarily have to be out of Shuttle range. The spinning, tumbling satellite would present a large danger to the Shuttle and crew if an extravehicular activity (EVA) recovery were to be attempted in this scenario.

This series of trades and analyses provided the rationale required to define the MSFC family of recovery system capabilities and provide the foundation upon which to define the requirements for the three, actually two, levels of capability required in the OMV satellite recovery kit. This system capability will be discussed subsequently. However, referring back to Figure 4.4.4-1, one should note that none of the systems included the final recovery scenario differentiator shown. When the target is prevented from reaching a minimum energy state, or retains general motion characteristics (spin, precession and nutation) at high rates because of excessive atmospheric drag or other external torques, the recovery requirements can become excessive. The full-up System C does not include these requirements, primarily because of the low probability of occurrence of this scenario.

4.4.5 Recovery System Definition - The overall intent of this series of analyses was to develop a rationale for the development of a logical family of satellite recovery systems, with well defined levels of capability. MSFC, in the contract statement of work, described three levels of capability, Systems A, B, and C, but directed the study team to evaluate the recovery problem areas and to definitively describe the boundaries between the levels of capability. In paragraph 4.4.4, the recovery system differentiators provided a framework for defining the scenarios that could logically apply to an expanding level of recovery system capability. Figure 4.4.5-1 highlights the scenario descriptions and system descriptions for Systems A and B.

The typical System A scenario was described as a situation in which the disabled satellite is beyond Orbiter range, the target is controllable and not spinning beyond OMV's spin rate matching capability, and has OMV recovery support elements that are accessible to the OMV. In this case, the deployed antennas or solar arrays will not interfere with a normal OMV approach. System A is defined as a basic reference configuration OMV, with its capability to dock to unobstructed RMS grapple fixtures and to flight support structure (FSS) latch pins.

The capability of the MSFC reference configuration OMV for capture operations is restricted primarily by pilot workload, based on computer graphic simulations conducted recently at both MSFC and MMC. Simulations conducted at MSFC have indicated that ground controllers can control OMV operations against targets with from two to three degrees per second of target roll, one degree per second of target pitch or yaw, and less than 0.5 degree per second of multi-axis motion. The OMV capture capability is limited by excessive pilot workload impacted by three primary factors. The first of these is the time delay of signals relayed through the Tracking and Data Relay Satellite System (TDRSS). A second factor limiting OMV capture operations is the small envelope of the capture environment, both for an FSS latching pin capture and the capture of an RMS grapple fixture. The third and most limiting factor is the complexity of attempting to dock (and capture), while having to translate and rotate to maintain a position for the eventual capture. It is apparent that to accomplish a successful System A recovery, the target will have to be relatively stable.

For System B, the typical recovery scenario, is shown on Figure 4.4.5-1. The disabled target is: (1) beyond orbiter range; (2) it is controllable and stable; and (3) the target either (a) does not have recovery support elements (RSE), or (b) the RSE(s) are inaccessible to the approach of a basic OMV, and the target is not spinning or is spinning within OMV rate matching capability.

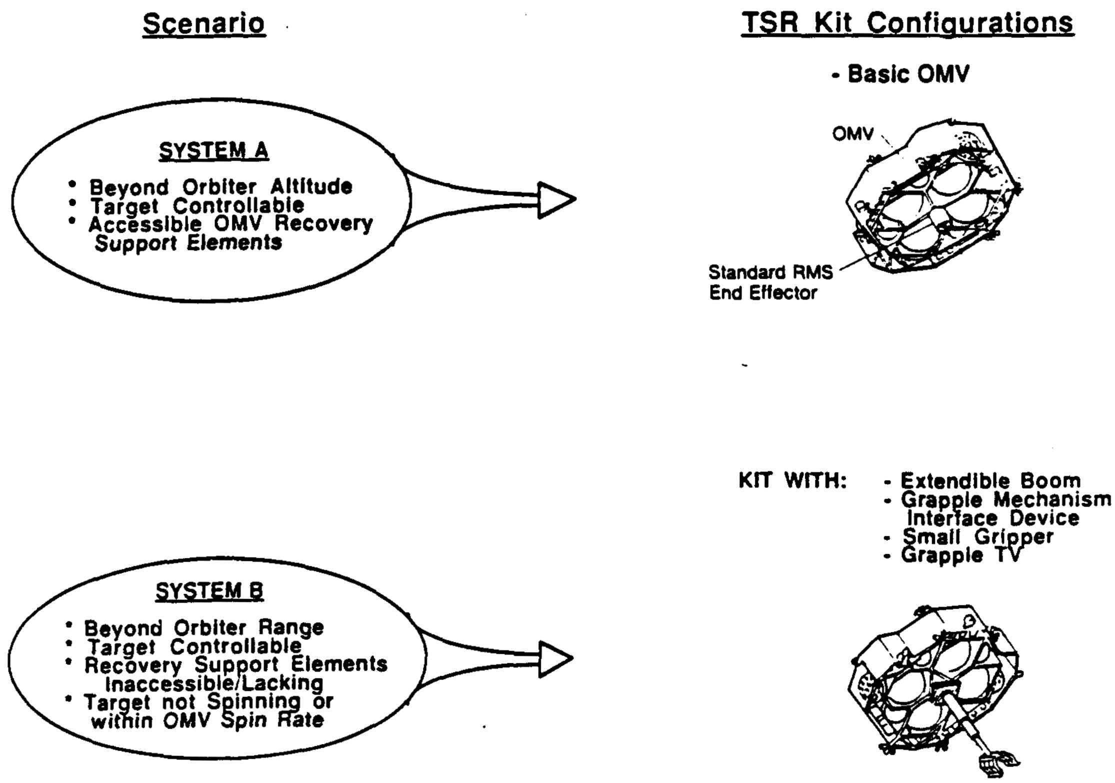


Figure 4.4.5-1 Recovery Systems A & B Definition

The required System B capability is an OMV front-end kit with a configuration including four subsystem elements. Some form of "extendible boom" is required to allow the OMV access to obstructed grapple fixtures or other recovery support elements. A multiple degree-of-freedom manipulator arm is viewed as essential to align the captured target's center of mass with the OMV orbit transfer thrust vector, once a firm grapple is achieved. A second element is a grapple mechanism interface device. This recovery element will allow the ready interchangeability of various grapple mechanisms required for other scenarios. A third element is a small gripper mechanism to enable grapple of small "hard points" on satellites that have no recovery support elements. A television camera located in close proximity to the small gripper (or to an RMS end-effector to be used for grapple of obstructed RCEs in some System B recoveries) is also seen as a required element.

This description of a System B capability appears to meet the MSFC definition of limited capability, minimum impact on OMV. As will be shown later, this kit will be structurally interfaced with the OMV docking latches, and the electrical and command and data management (C&DM) interface will be with the OMV payload accommodations umbilical.

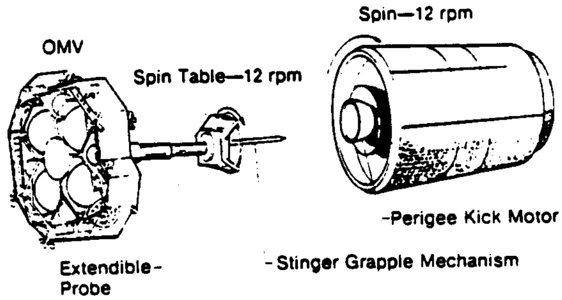
The definition of a full-up System C is provided in Figure 4.4.5-2. The full-up recovery system was designed to deal with two complex motion cases. Case 1, shown in Figure 4.4.5-2, deals with the scenario in which the recovery target is beyond Shuttle range, and is spin-stabilized between 5 and 50 RPM. In this situation, the recovery system configuration will include an extendible boom, a spin/despin mechanism to match rates with the target, a grapple mechanism interface device, and a "stinger" type grapple mechanism, similar to that used on WESTAR and Palapa-B recoveries. This system will also require a boresight camera to support alignment of the spin axis of the OMV/TSR kit and the target's spin axis.

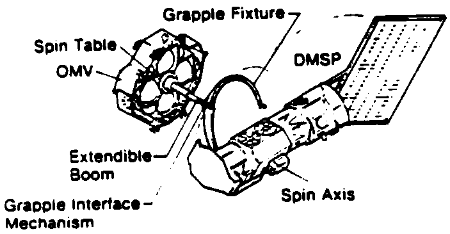
The most difficult System C scenario is Case 2, the situation in which the satellite is not controllable, due to some major malfunction, and has excessive angular momentum. An excessive torque created a tumbling satellite that quickly assumed a state of single axis spin about a single, major principal inertia axis. The satellite could actually be within Shuttle range, but would have a tumble motion considered dangerous to close approach and recovery by EVA, MMU, or other Shuttle dependent techniques. Thus, the recovery would have to be a remote retrieval using OMV and a TSR kit.

The system capability for System C, Case 2, is similar to that of Case 1. A spin/despin mechanism is required to match the spin rate(s) of the target. The tumble or spinning configuration of the satellite, however, will require a large gripper or large envelopment type grapple mechanism to provide a firm, smooth grapple of the target, to rigidize the attachment and then maintain the grip to enable despin and stabilization of the target. A representative system configuration is shown in Figure 4.4.5-2.

In summary, these Task 1.1 analyses provided failure data that supported the identification of a broad range of remote, disabled satellite scenarios. The derived scenario differentiators provided a rationale for a clarification of MSFC's generic levels of recovery system capability, Systems, A, B, and C. With these levels of capability more refined, it was possible to provide a general description of the specific recovery systems.

System C—Full Up Capability
- Case 1—Controllable Targets
  - Beyond Orbiter Range
  - Stable-Ground Controllable
  - Spin-Stabilized—10-50 rpm
- Case 2—Noncontrollable Targets
  - Within OMV Range
  - Noncontrollable
  - Target Tumbling/Spinning





TSR Kit Configuration
- Extendible Boom
- Spin/Despin Mechanism
- Grapple Mechanism Interface Device
- Large Envelopment Grapple Mechanism
- Stinger Type Grapple Mechanism
- Boresight TV

Figure 4.4.5-2 Recovery System C Definition

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5.0 SATELLITE RECOVERY SYSTEM MISSION MODEL - TASK 1.2

5.1 Introduction and Approach

Task 1.2 involved the development of a TSR mission model, a data base of mission and spacecraft specific information regarding satellites expected to be either on-orbit during the mid to late 1990s, were scheduled for launch during that period, or were representative of expected future follow-on systems. The model provides the basis from which to design a recovery system capable of accommodating the diversity of target sizes, shapes, mass distributions, and configurations characteristic of operational satellites in the 1990s. Development of the model included the selection of appropriate missions and the acquisition of detailed information regarding those missions and the spacecraft involved. Figure 5.1-1 illustrates the approach used in developing the model.

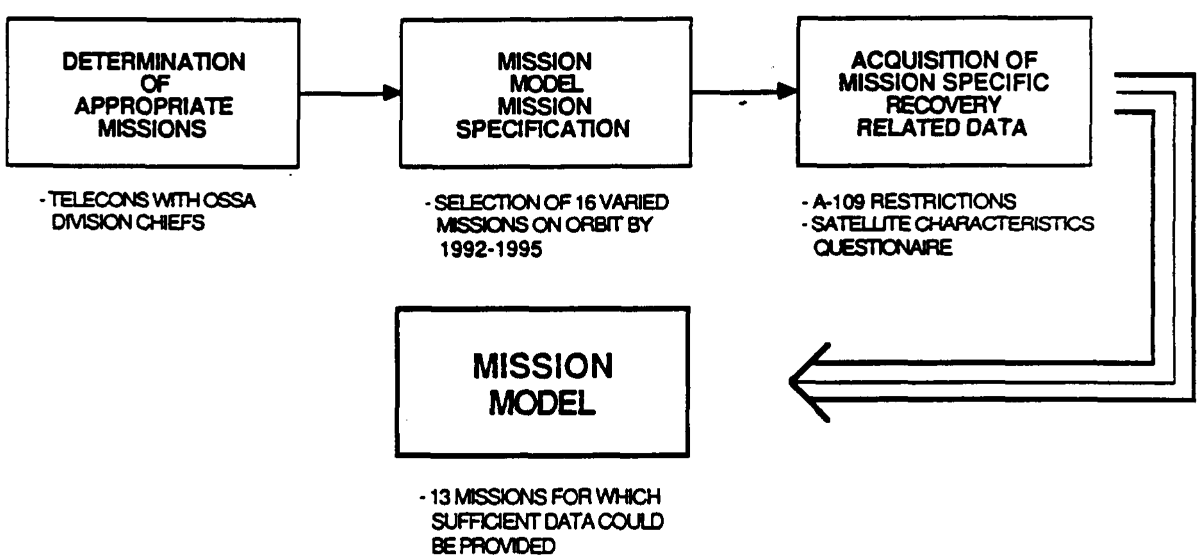


Figure 5.1-1 Mission Model Development

Through telephone conversations with the Office of Space Science Applications (OSSA) Division Chiefs, mission specific information regarding a number of satellite missions of varied maturity was obtained. Based on their operational schedules, the study team selected 16 missions as the most appropriate for inclusion in the initial data base. Although the nature of the study effort precluded consultation with DOD planning offices, the information provided by the OSSA offered a data base of sufficient size and diversity.

To gather specific recovery related data on the selected missions, a survey letter was sent to all NASA program/project managers. In addition to detailed information regarding the satellite's physical configuration, i.e., its size, shape, mass distribution, etc, the questionnaire requested information concerning satellite orbital parameters, attitude control system, hazards, plume sensitivity, safety, safing modes, and the number and cost of the satellites. The inquiry was addressed to the NASA managers, as opposed to contacting contractors directly, in order to avoid limitations imposed by A-109 restrictions. The study team received information from all programs; however, most of the data is of a preliminary nature due to the early stages of some of the programs. As a result, it was felt that the satellite characteristics provided by several of the programs were, as yet, insufficient for analysis, and the mission model was limited to 13 of the 16 initially selected missions.

5.2 Description of Mission Model

The mission model development process provided a collection of diverse mission objectives and spacecraft configurations for 13 missions of varied maturity. As a summary, a brief description of each is outlined below.

The Advanced X-Ray Astrophysics Facility (AXAF), designed for launch and servicing by the Shuttle, will incorporate a 1.2 meter, grazing incidence, X-ray telescope to accommodate instruments collecting high spatial resolution and spectral data on quasars, galaxies, clusters of galaxies, and the intergalactic medium. Evolving from the second High Energy Astronomy Observatory, it will have four times the spatial resolution and at least 100 times the sensitivity. AXAF is one of the largest satellites in the model, having a cylindrical geometry, roughly 15 feet in diameter and 49 feet in length and a weight of 19,000 pounds. Two large solar arrays, measuring 10 by 32 feet, extend from the spacecraft along a transverse axis, while two antennas extend 6 feet along an axis perpendicular to that of the arrays. AXAF is a potential development start for 1987.

The Cosmic Background Explorer (COBE) mission, scheduled for launch by the STS in 1988, is being designed to explore and study diffuse radiation between the one micrometer and 9.6 millimeter wavelengths. An on-board propulsion subsystem will be used to achieve the final circular, sun-synchronous, 900-kilometer orbit from a 300-kilometer STS parking orbit. Twelve solar arrays form the perimeter of the spacecraft, from which an omni antenna and the propulsion subsystem extend. The Explorer length and diameter are approximately 18 feet and 13 feet respectively. Its weight is approximately 10,000 pounds.

From an altitude of 400 kilometers, the X-Ray Timing Explorer (EXP) will conduct intensive studies of the changing luminosity of x-ray sources, over times ranging from milliseconds to years. Instruments sensitive to x-ray energies from 2,000 to 100,000 electron volts will study known sources and transient events. The EXP leased platform and payload form a boxy structure with no more than a fifteen-foot width, an eight-foot height, and a five-foot length. Two rectangular solar arrays, seven by eight feet, extend from the platform. After the scheduled 1992 launch, the payloads are planned to be replaced every 2.5 years. The platform and its initial payload, the X-Ray Timing Experiment, will weigh approximately 6,600 pounds.

The Gravity Probe-B mission involves one of the smaller spacecraft of the mission model. It will weigh only 2900 pounds and has a conical geometry which tapers from a six-foot diameter to less than one foot over a fifteen-foot length. Four solar arrays are symmetrically attached around the perimeter, increasing the six-foot diameter to fifteen feet. The spacecraft will enable the testing of a fundamental concept of general relativity, by measuring the precession of orbiting gyroscopes as they move through a gravitational field twisted by the earth's rotation. The GPB mission is planned to follow a functioning prototype that will be tested on a 1989 Shuttle flight.

A new start in 1985 and scheduled for launch in 1989, the Geopotential Research Mission (GRM) will provide detailed global mapping of the Earth's gravitational and magnetic fields to an accuracy that is an order of magnitude of improvement over all previous global models. The mission will involve two similar spacecraft, launched to a 275-kilometer orbit, self-deboosted to a 160-kilometer altitude, and then separated a distance varied from 150 to 550 kilometers. The gravitational field mapping will be accomplished by measuring changes in the relative velocity of the vehicles. Magnetometers isolated on the fourteen-foot boom of the leading vehicle will provide the geomagnetic measurements. The spacecraft cylindrical geometries, of 21-foot length and 3.5-foot diameter, consist mostly of propellant, required to maintain their peculiar low-earth orbit. Two solar arrays are firmly attached in a wing-like configuration to each vehicle. The spacecraft weights are 6200 and 5700 pounds.

A significantly larger spacecraft, the Gamma Ray Observatory, will collect data on gamma rays, by observing known sources and by making the first full sky gamma ray survey. Three individual instruments will measure specific gamma ray ranges from one-tenth of a million to 30 billion electron volts. The observatory is being designed to be launched, serviced and retrieved by the STS. Four 100-pound thrusters will boost it to the 450-kilometer circular operating orbit and 28.5-degree inclination. The three instruments help to create a very irregular satellite surface. Two solar arrays measure approximately 70 feet from tip to tip and a high gain antenna extends 21 feet from the surface. GRO has a weight of approximately 33,000 pounds. Its dimensions are roughly 15 feet in diameter and 24 feet in length.

The principal mission in the NASA astronomy program is the eight foot diameter Hubble Space Telescope (HST). The telescope's ability to cover a wide range of wavelengths from the infrared to the ultraviolet, providing fine angular resolution, will enable extragalactic astronomy and observational cosmology for tasks such as investigation of stars in other galaxies to determine their rotation, age, mass, and chemical composition. At the 320 nautical mile HST operating orbit, the Shuttle and Space Station will serve as a base from which to service and replace the HST science instruments, as technological advances and scientific priorities evolve. The telescope's size mandates a large spacecraft, measuring 14 feet in diameter and 43 feet in length, and weighing roughly 25,000 pounds.

INTELSAT VI is representative of STS-launched, spin stabilized commercial communication satellites intended for geosynchronous operating orbits. Its inclusion in the model is based on an assumed failure of the apogee kick motor after deployment from the Shuttle. Typical of these spacecraft, INTELSAT VI has several different antennas extending from one end of its cylindrical envelope. Solar drums form the envelope shape, which measures close to 13 feet in diameter and 21 feet in length. For the assumed failure, the satellites will be typically spin stabilized in the nominal Shuttle operating orbit at rates ranging from 30 to 55 revolutions per minute.

The LANDSAT program had its origin in conceptual studies and planning performed in the late 1960s, culminating with the launch of LANDSAT 1 in July of 1972. The program has focused on the development and application of space remote sensing technology to assist man in his understanding and management of the earth's resources. The most sophisticated and most recent in the family of LANDSAT spacecraft is LANDSAT D, launched in March of 1984. Like its predecessor LANDSAT 4, LANDSAT D carries the Thematic Mapper sensor that enables vastly superior measurement capabilities than the sensors of previous spacecraft. An on-board propulsion subsystem was designed to accomplish altitude changes between its 709-kilometer operating orbit and the nominal Shuttle orbit. The spacecraft can be approximated as a cylinder, over seven feet in diameter and 13 feet in length, weighing 4400 pounds. It employs a large antenna extending more than thirteen feet from its surface and a solar array measuring eight by fourteen feet.

The Long Duration Exposure Facility (LDEF) was placed into its 250 nautical mile orbit by the STS during the Solar Maximum repair mission. It is designed to support a diverse set of international experiments in each of a series of planned flights. Close to two-thirds of its initial 21,400-pound weight resulted from the hardware of 57 experiments, ranging from fiber optic data transmission tests to packaged tomato seeds. The spacecraft measures 14 feet in diameter and 30 feet in length, and provided valuable experience in deploying a Shuttle payload nearly as large as the HST. The facility is totally passive and was gravity gradient stabilized during its one-year exposure.

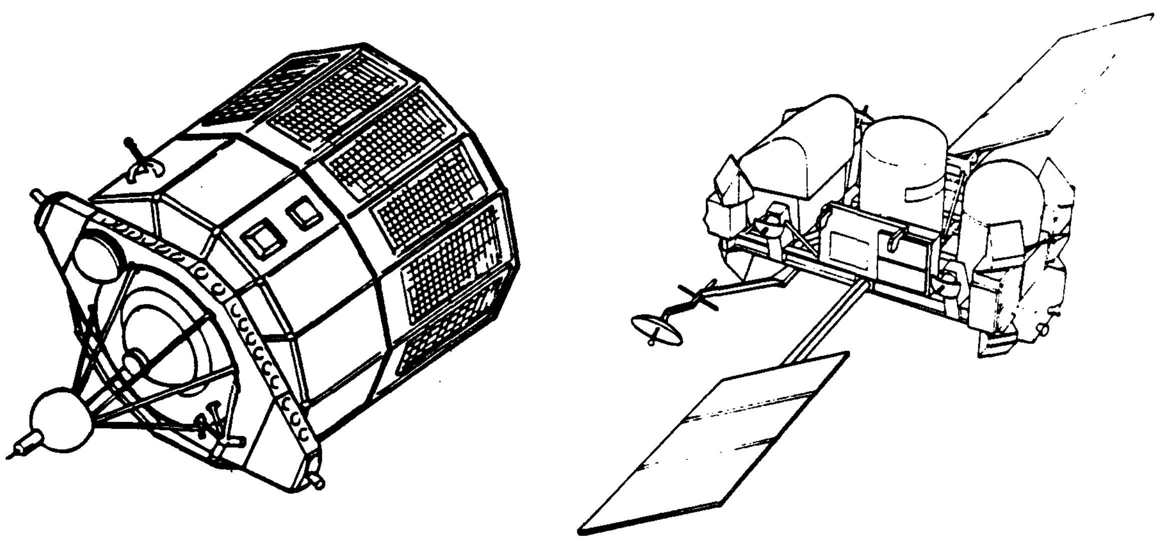
The RADARSAT, a Canadian satellite program, evolved out of Canadian participation and interest in the U.S. SEASAT and LANDSAT programs. Canada produced the ground-based image processor to process data channeled down from SEASAT. The RADARSAT project is an earth resource oriented satellite system. It's synthetic aperture radars are designed for surveillance of North American shipping lanes extending to the arctic region. Three other sensor systems are included in its payload which provide crop and forestry monitoring, ocean/sea state monitoring for ocean meteorology, and ice flow measurement in the far north. The spacecraft body, similar to LANDSAT in shape, measures roughly 15 feet in diameter and 21 feet in length and has a weight of 13,400 pounds. Its protuberances include a large antenna, six feet wide and 49 feet long, and two large solar arrays, both ten feet wide and 49 feet long.

The Space Station Spartan (3S) program is intended to provide the scientific community with a short-duration free-flying carrier for modular single instrument payloads based at the Space Station. It is designed to be reusable and offer quick-turnaround schedules and frequent flights. An on-board propulsion subsystem will place the carrier into its mission position, nominally 250 nautical miles from the Space Station. The spacecraft dimensions do not exceed that of a cylinder, fifteen feet in diameter and five feet in length, from which a large solar array measuring sixteen by fourteen feet extends. The 3S program is an evolutionary step from NASA's fine-pointing sounding rocket program and the STS/Spartan program. A full system flight demonstration is scheduled prior to the Space Station Initial Operational Capability date.

The goal of the Upper Atmosphere Research Satellite (UARS) is to extend scientific understanding of the chemical and physical processes occurring in the Earth's stratosphere, microsphere, and lower thermosphere. Its primary objective is to understand the mechanisms that control the structure and variablility of the upper atmosphere, the response of the upper atmosphere to natural and human-related perturbations, and the role of the upper atmosphere in climate and climate variability. It will use remote sensing instruments, currently in development, to measure trace molecule species, temperature, winds, and radiative energy input from and lost to the upper atmosphere. Presently in a conceptual development stage, the UARS is scheduled for a 1989 STS launch to a 600-kilometer operating orbit. Its weight will be approximately 13,000 pounds, and its dimensions can be roughly estimated as 15 feet in diameter and 30 feet in length. The surface configuration of the spacecraft is very irregular and a number of protuberances extend a significant distance from it.

Figure 5.2-1 depicts the diversity of configuration between COBE and GRO, which is representative of the model.

COBE GRO



WEIGHT: 10,000 LBS WEIGHT: 33,000 LBS

Figure 5.2-1 Recovery Candidate Diversity

Figure 5.2-2 provides a portion of the mission model data base obtained to date. As previously mentioned, the early stages of development of some of the programs are responsible for the lack of technical information within the matrix, such as the moments and products of inertia. The mission model presents a wide range of satellite size, mass distribution, and configuration; and its evolution provides the basis from which to develop and refine a multi-purpose recovery system.

MISSION	WEIGHT (LBS)	LENGTH (INCH)	WIDTH (INCH)	HEIGHT (INCH)	Ixx 2 (SL-FT)	Iyy 2 (SL-FT)	Izz 2 (SL-FT)	Ixy 2 (SL-FT)	Iyz 2 (SL-FT)	Ixz 2 (SL-FT)	ARRAY (INCH)	ANTENNA (INCH)
AXAF	18,900	590	174	174	15,000	125,000	125,000				135	72.5
COBE	10,000	132 91	174 64	174 64	5,022	4,702	5,091	0	0	30		
EXP/ XTP	6,600	59	174 88	39 59							98	
GPB	2,900	60 60	72 9	72 9							54	
GRM	6,174	227 173	41 9	41 9								
GRO	33,000	288	174	174	39,800	57,500	71,750	20	-3,150	-35	330	216
HST	25,027	590	174	174	22,386	56,273	57,384	-58	527	-13		
INTELSAT VI	4,961	304	151	151	6,197	5,103	5,953					
LANDSAT	4,400	158	88	88							165	172
LDEF	21,400	360	168	168								
RADAR-SAT	13,391	256	178	178	10,759	9,784	2,915	-206	-159	325	757	206
SS SPARTAN	5,900	60	174	174	3,900	2,660	4,175				201	
UARS	12,766	348	174	174	9,255	22,849	25,389	-2719	-471	1121		

Figure 5.2-2 Mission Model Data Base

Since the TSR system is being designed to recover satellites in the mid-1990s time frame, it can be affected by changes to the mission model. Figure 5.2-3 depicts a mission model maintenance strategy based on monitoring changes to NASA mission planning and design. Space Station evolution, NASA launching strategy, and the development of individual mission designs were identified as having the potential to indirectly cause significant changes in the model. It is recommended that these areas then be monitored in follow-on efforts, in order to maintain the model and assess impacts on the TSR system design.

The existence of the Space Station would allow missions planned as free-flyers to be collocated on a Space Station platform. Spacecraft subsystems common to free-flyers, i.e., electrical and propulsion, could be combined as part of a platform. Where the number of missions may be unaffected, the number of satellites would decrease. The type of satellite could also change; the mission model may include mostly large spacecraft for very unique missions or the number of Space Station Spartan spacecraft, as they are dedicated to the Space Station, could be increased.

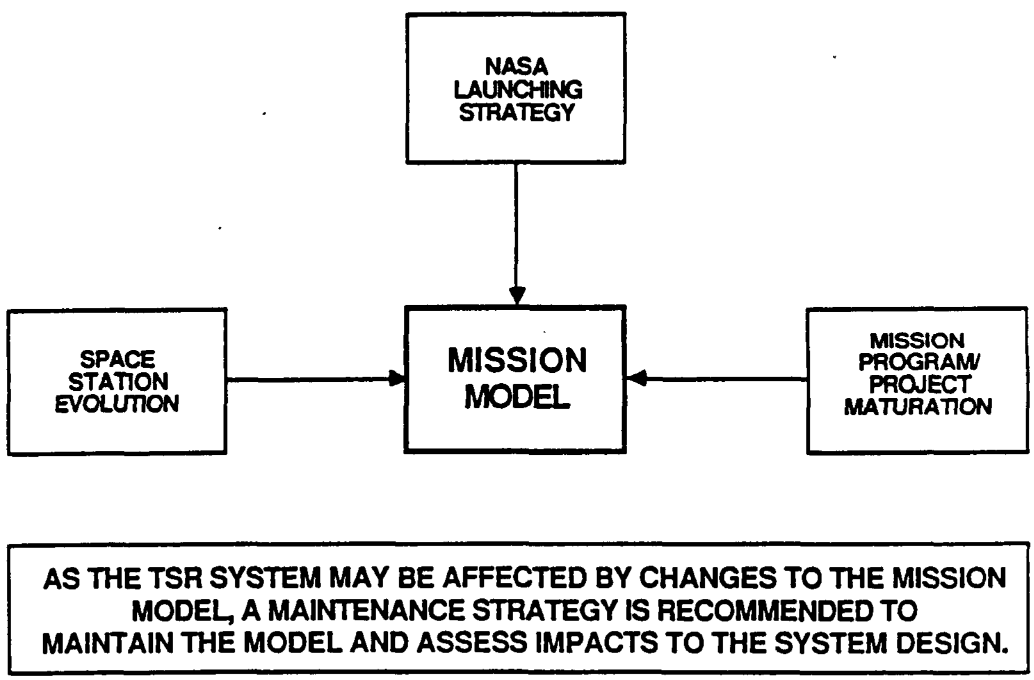


Figure 5.2-3 Maintenance of Mission Model

It is expected that the NASA launching strategy will be impacted as a result of the recent Challenger tragedy. The quantity and types of satellites within the model could be affected as missions are delayed and decisions with regard to mission importance are made. Relative satellite sizes may also be influenced, should expendable launch vehicles be considered to augment launch capacity.

The fact that many of the programs are in an early stage of development can result in revisions of the data collected to date. The moments of inertia provided for the AXAF satellite, for example, have increased 25 percent over the course of the contract. The importance of monitoring individual missions as their designs mature is amplified by a revised launching strategy and/or the evolution of the Space Station. Specifically, the GRO mission, presently being designed for a dedicated STS launch to its operating orbit, could be impacted by a revised launching strategy, under which a dedicated launch may not be appropriate.

6.0 SYSTEM HARDWARE REQUIREMENTS - TASK 1.3

6.1 Introduction and Approach

Several areas were developed and analyzed which contributed to the initial definition of conceptual recovery system requirements. They included a preliminary concept of operations, a functional analysis, and an analysis of the mission model. Together, the analyses resulted in a detailed set of conceptual requirements and form the basis from which to create an operations concept and system specification and initiate follow-on efforts.

The recovery system requirements are presented in the tables on the following pages. The mission operations requirements, provided in Table 6.1-1, were developed as a result of the preliminary operations concept. Many of the requirements are based on OMV, Space Station, Shuttle, and ground operations imposed constraints. The functional analysis was responsible for the mission functional requirements listed in Table 6.1-2. Table 6.1-3 lists a set of mission performance requirements; developed through an analysis of the mission model, they provide a refinement of the functional requirements of Table 6.1-2.

Table 6.1-1 Mission Operations Requirements

- The TSRS shall be OMV compatible with little impact on the OMV reference configuration.
- The TSRS electrical and communication requirements interface will be accomplished through the OMV payload accommodations umbilical.
- The nominal TSRS mission will be accomplished within OMV mission time limitations.
- The nominal TSRS mission will be accomplished within OMV mission range limitations.
- The nominal TSRS mission will be accomplished within OMV mission propellant limitations.
- The nominal TSRS mission will be accomplished within the OMV attitude control deadband.
- The nominal TSRS mission will be accomplished within the teleoperation control limits induced by communication delays and thruster operation.
- The nominal TSRS mission shall be accomplished with minimum risk of damage to the OMV.
- The TSRS stowed diameter shall not exceed the Shuttle cargo bay envelope diameter.
- Stowage of the TSRS in the Shuttle cargo bay shall require a minimum distance parallel to the centerline of the cargo bay.
- TSRS mission operations shall be accomplished without exceeding Shuttle and Space Station proximity operations procedures.
- TSRS mission operations shall be accomplished without exceeding Shuttle workload limitations.
- The TSRS shall accommodate operations testing at a ground assembly area.
- The TSRS shall accommodate a mating to the OMV in either the vertical or horizontal Shuttle payload processing sequence.

Table 6.1-2 Mission Functional Requirements

- The satellite envelopment, rigidization, stabilization, and transport loads shall not exceed OMV ACS limitations.
- Control of the TSRS mission operations shall be accomplished from the OMV mission operations control center.
- The TSRS shall recover ground controllable and noncontrollable disabled satellites.
- The TSRS shall accommodate on-orbit EVA and automated subsystem reconfiguration at Space Station.
- The nominal TSRS mission shall be accomplished with minimum risk of damage to the TSRS.
- The TSRS shall be capable of enveloping the specified configurations of target satellites.
- The TSRS shall be capable of rigidizing contact with the target satellite.
- The TSRS shall be capable of stabilizing the target satellite relative to the TSRS and the OMV.
- The TSRS shall match the satellite spin rate and phase angle with sufficient accuracy to accomplish attachment.
- The TSRS shall align its spin axis to the spin axis of the satellite with sufficient accuracy to accomplish attachment.
- The TSRS shall be capable of remote realignment of the satellite center of mass, with respect to the OMV major thrust axis, after stabilization.

Table 6.1-3 Mission Performance Requirements

- The TSRS shall recover satellites with or without Recovery Support Elements.
- The TSRS shall recover satellites with recessed Recovery Support Elements due to the satellite's deployed configuration.
- The TSRS shall accommodate a range of satellite sizes not to exceed a cylindrical envelope of 180-inch diameter and 590-inch length.
- The TSRS shall accommodate the range of grapple diameters from small hard points to 180 inches.
- The TSRS shall recover satellites in stabilized and nontorqued, nonstabilized configurations.
- The TSRS shall accommodate 11 degrees of geometric coning in a nontorqued, nonstabilized configuration.
- The TSRS shall recover satellites having irregular surfaces ranging from 50% to 100% of the satellite envelope.
- The TSRS shall accommodate the range of spin rates from zero to 55 revolutions per minute.
- The TSRS shall recover satellites with protuberances extending from the satellite envelope with lengths ranging from 51 inches to 757 inches.
- The TSRS shall provide maximum subsystem interchangeability to specifically accommodate the wide range of recovery scenarios.
- The TSRS shall accommodate timely and economic subsystem reconfiguration.
- The TSRS and the TSRS/OMV interface shall accommodate torques associated with attachment, rigidization, stabilization, and transport.
- The nominal TSRS mission shall be accomplished with minimum damage to the recovered vehicle.
- The contact forces between the satellite and the TSRS after envelopment and rigidization shall be sufficient for stabilization and transport.

6.2 Tumbling Satellite Recovery System Operations Concept

6.2.1 Introduction - The generation of a preliminary concept of operations for a modularly designed TSR system at this early stage in the conceptual definition phase was considered essential to the development of a broad range of mission operations requirements, including those related to ground and aerospace support equipment. The operations concept included operations based on deployment from the Shuttle and from the Space Station. This preliminary TSR concept of operations supported both the completion of a functional analysis of on-orbit operations, and the operational analysis conducted on the six selected design reference missions.

The tumbling satellite recovery system will be one of a family of kits to be developed to conduct operations remotely, as front ends for a ground controlled, teleoperated OMV. The kits will be designed to utilize fully the spacecraft services available through the OMV structural and electrical payload accommodations interfaces. The TSR kit equipment and supplies will be collocated with OMV at ground storage facilities. The TSR ground operations console(s) will be situated at the OMV Operations Support Center to enable coordination of training and mission operations. At the Space Station, the elements of the TSR kit will be situated at the OMV storage facility.

As described previously, the TSR kit is conceived to be a modular system, comprised of a number of subsystem mechanisms that can be readily integrated in varying combinations. This will enable the user to quickly configure a specific remote recovery system to meet a broad spectrum of unique mission requirements.

6.2.2 Operations - The TSR operations concept is outlined in Figure 6.2.2-1. The TSR kit elements would be stored at the OMV ground storage facility. For each mission the required subsystem elements would be assembled in the OMV front end kit assembly area and ground tested, using recovery kit ground support equipment. Following assembly and checkout at the ground support facility, the recovery kit would be transported to the STS payload processing facilities at the STS launch site.

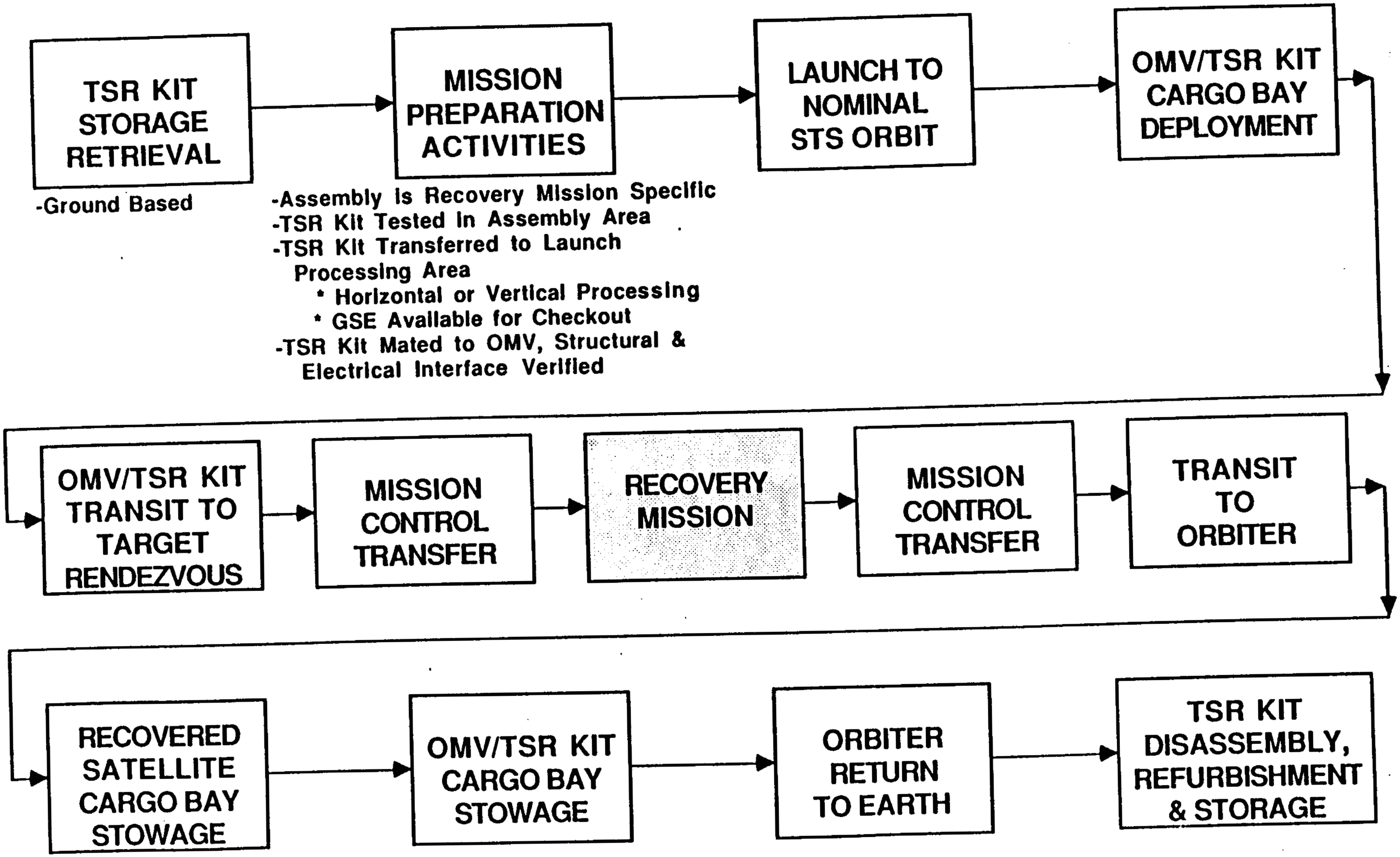


Figure 6.2.2-1 TSR Operations Concept

At the launch facility, like the OMV, the TSR kit would undergo further test and checkout prior to a mating with the OMV in the horizontal or vertical payload processing sequence, as selected by OMV program directors. The assembly and checkout approach recommended for the OMV recovery kit is to emphasize ground testing and verification, with necessary adjustments and replacements done on the ground. If recovery kit subsystems were to fail during on-orbit checkout, it will be difficult to replace them at the Orbiter. Following the launch into an operating/standby orbit, the OMV and mated TSR kit will be deployed from the cargo bay with the Orbiter RMS. The Orbiter will then be maneuvered away from the mated OMV/TSR kit to a safe distance for the OMV orbit transfer. The OMV will then transport the attached recovery kit to a rendezvous with the disabled satellite.

The actual recovery operation will commence with visual sighting of the disabled satellite. The OMV will maneuver to within visual range of the satellite and commence actual recovery operations. These operations are described as part of the functional analyses of paragraph 6.2.3. The on-orbit satellite recovery operations will be controlled from the ground-based OMV Operations Support Center (OSC), so mission control is transferred to the OSC at this time.

Upon completion of a full-up System C envelopment recovery operation, the satellite will be stabilized. It may be necessary to release the enveloped target and regrapple it to align the new center of mass with the OMV orbit transfer thrust vector. The OMV ACS thrusters will be fired in small translation maneuvers to determine the proper positioning of the payload center of mass, prior to orbit transfer to the Orbiter.

The recovered satellite will be positioned in the Orbiter using the RMS end effector, in the Orbiter trunnions or in a pre-configured cradle arrangement. The OMV and TSR kit will be repositioned in the cargo bay, and the Orbiter will return its new cargo to the appropriate STS launch/landing facility.

6.2.3 Maintenance/Refurbishment - When the recovery mission has been completed and the Orbiter has returned to the launch site, the OMV satellite recovery kit will be detached from the OMV and returned to the OMV front end kit assembly and checkout area. Here, the kit will be disassembled, refurbished and/or repaired, and returned to storage for follow-on missions.

6.2.4 Operations Control - The OMV satellite recovery kit will be operated by a ground controller and will require adequate ground consoles and ground support equipment. This equipment will be located witn the OMV ground control console(s) at the OMV Operations Support Center. The OMV satellite recovery kit command and data management formats will be exactly like those used by OMV, as the recovery kit will be linked for C&DM through the OMV payload umbilical(s).

6.2.5 Space Station Operations - When the OMV satellite recovery kit is based at the Space Station, the kit equipment will be transported to and stored in an OMV kit storage area. As is true in recovery operations that are initiated from the ground and conducted from the Orbiter, the mission recovery kit used on any mission will be tailored for that specific mission. The kit will be assembled and attached to the OMV by astronauts on EVA or by robotic or teleoperated manipulators. Once the OMV and recovery kit are mated, they will be deployed from the Space Station by the mobile RMS. The remainder of the mission will be controlled from the ground at the OMV Operations Support Center. Upon return to the Space Station, maintenance, repair, or refurbishment will be conducted at the Space Station, either by EVA, teleoperation or automatically.

6.3 Functional Analysis

A functional analysis of a full-up System C recovery operation was conducted to support the development of mission functional requirements. This analysis is shown in highlighted "flowchart" form in Figure 6.3-1. The actual recovery operation commences with the rendezvous to within visual range of the disabled satellite. The OMV will circumnavigate the satellite to determine target motion orientation and rates. The target is expected to be spinning in a

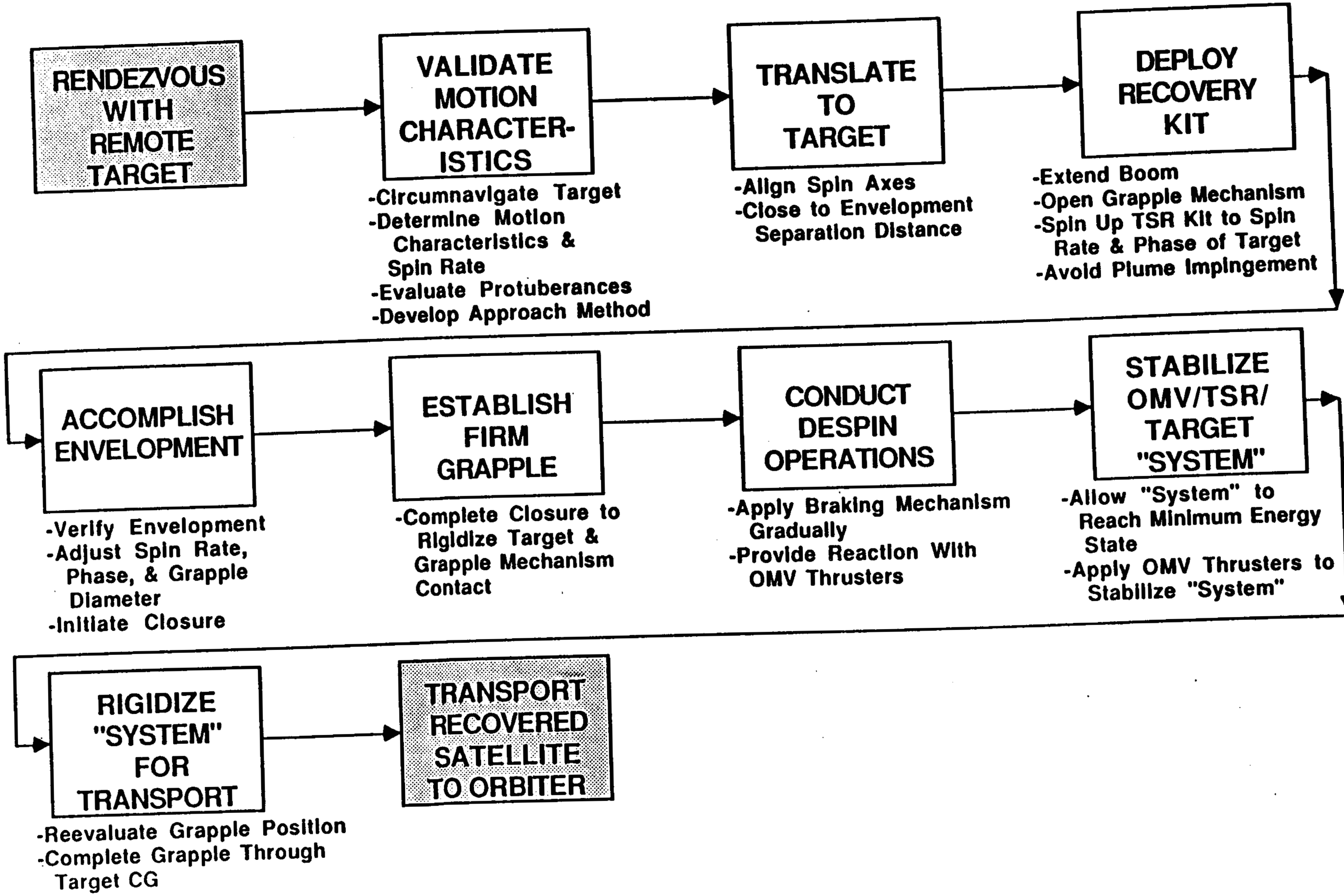


Figure 6.3-1 Functional Analysis System C Recovery

flat, single axis spin about the major principal axis of maximum moment of inertia. The OMV and TSR ground controllers, using OMV and TSR TV cameras will evaluate protuberances, i.e., solar arrays, antennas, instrument packages, and develop an approach strategy.

The TSR operator will determine the spin axis, as the approach to the target will take that path, but the OMV operator will approach from that side of the spinning target that offers the least interference.

The OMV operator will then align the OMV translation axis with the target's spin axis and translate to a distance short of deployment and target envelopment distance.

The next phase of recovery operations involves TSR system equipment deployment. Deployment of the system has the potential of impacting OMV stability and will be conducted in a sequence designed to minimize dynamic interaction between the TSR kit and the OMV. First, the extendible boom will be fully deployed. Next, the large envelopment-type grapple mechanism will be deployed to an envelopment diameter, more than adequate for the target's grapple position configuration. Following this, the spin mechanism will be activated to spin up the recovery system to match the target spin rate and phase relationship of the target. The OMV operator will avoid actions that might result in plume impingement on the target.

The OMV and TSR kit operators now conduct envelopment operations, including adjustment of spin rate and phase during translation to an envelopment grapple range, vis-a-vis the target and the recovery system grapple mechanism. When the recovery kit grapple mechanism is in position, centered as closely as possible to the target's center of mass, the ground controller will slowly close the jaws of the grapple mechanism. Inadvertent contact, and the associated contact dynamics, will be avoided until envelopment is achieved.

The grapple mechanism will then be closed further to provide a rigid grapple of the target so that the ground controller can then "despin" the captured satellite, using a reverse braking action of the direct current (DC) torque motor in the spin table. OMV reaction control thrusters will provide reactive impulse to maintain a stable system during despin operations.

When the OMV/TSR kit and captured satellite "system" is stabilized, the TSR kit controller may need to release the target and regrapple it to refine the alignment of the total system's center of mass with the OMV orbit transfer thrust vector. An iterative series of OMV translational maneuvers and target release and regrapple may be required to realign the new system center of mass, to ensure it is within the OMV center of mass offset capabilities. This will enable OMV to translate and control the system during orbit transfer to the Orbiter.

6.4 Mission Model Analysis

6.4.1 Introduction - Analysis of the mission model was accomplished in order to define the boundaries of expected or possible recovery scenarios, in terms of recovery candidate characteristics. Given the nature of the data within the model, the analysis was maintained at a top level of complexity, producing quantities appropriate for this early phase of TSR development.

A portion of the analysis resulted in the Mission Model Derived Baseline, a composite of worst case recovery candidate characteristics, shown in Table 6.4.1-1. Each of the characteristics, although assembled to form a composite, was derived independently and together do not apply to any single recovery candidate. The baseline enabled the development and quantification of this subset of mission performance requirements.

To further define the recovery scenario an effort was made to bound the diameter necessary to surround a recovery candidate and to verify an extendible boom requirement. The previously defined functions and operations were thereby applied to a recovery candidate with the characteristics of the Mission Model Derived Baseline. Issues were identified and analyzed, clarifying the recovery scenario and providing additional requirement definition and refinement.

Table 6.4.1-1 Mission Model Derived Baseline

<u>ENVELOPE SHAPE:</u> *CYLINDRICAL, IRREGULAR SURFACE (50-100% OF ENVELOPE)*

<u>ENVELOPE DIAMETER:</u> *180 INCHES*

<u>LENGTH:</u> *~50 FEET*

<u>MASS:</u> *34,000 POUNDS*

<u>GEOMETRIC LOCATION OF PRINCIPAL AXIS:</u> *IN Y-Z PLANE, MAXIMUM 11 DEGREES OFF PLANE*

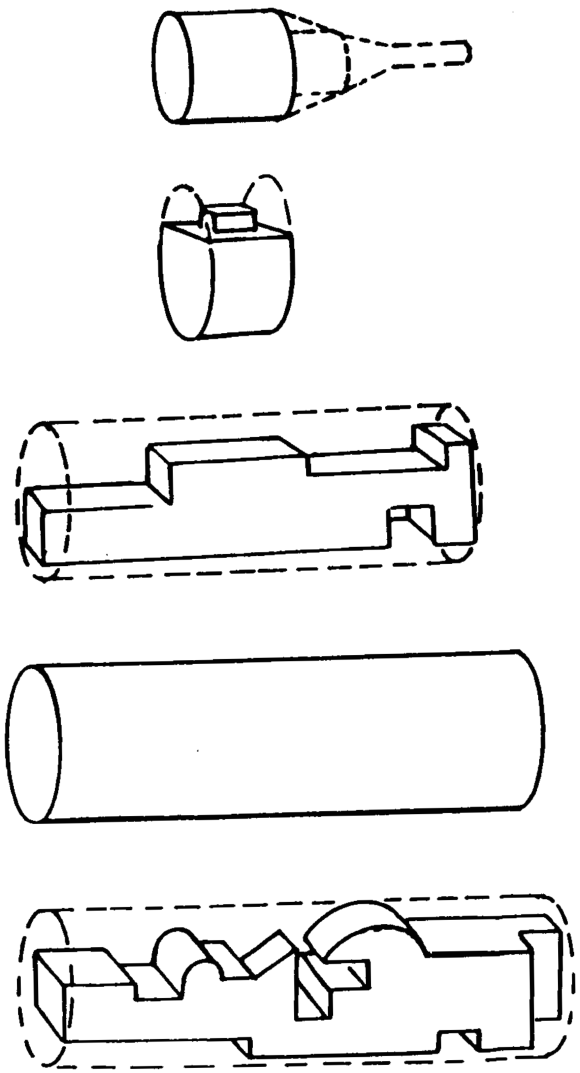
<u>MOMENT OF INERTIA ABOUT PRINCIPAL AXIS:</u> *125,000 SLUG-FOOT* ^{2}

<u>STEADY STATE ANGULAR MOMENTUM:</u> *68,000 FOOT-POUND-SECOND*

<u>SPIN RATE:</u> *55 REVOLUTIONS / MINUTE*

6.4.2 <u>Derived Baseline Definition</u> - The first step in deriving the composite of worst case characteristics involved the definition of satellite configurations, i.e., shape, dimensions and mass, and was accomplished through simplification and categorization of the mission model. Initially, each of the satellites was graphically represented by an envelope shape within which all surfaces of the satellite, excluding protuberances, would lie. Protuberances, strictly solar arrays and antennas, were analyzed separately as their locations and dimensions varied significantly. It was then possible to neatly categorize the envelope shapes, based on size, conformance to the envelope or surface irregularity, and the satellite mass. As a result of the nature of launch vehicle payload accommodations, the envelope shapes were all cylinders or modified cylinders. The resultant categorizations and their discriminators are provided in Figure 6.4.2-1.

The largest and smallest volume or envelope size, largest and smallest mass, and smooth versus irregular surfaces were the obvious extremes within the discriminators. The largest volume and mass were chosen as worst case characteristics in order to satisfy boundary definition, although it was understood that the smallest volume and mass, previously mentioned in the



Relative Volume	Envelope Volume Description	Relative Mass
Small-Medium	2 or More Cylinders of Varying Diameter	Small
Medium	Section of a Cylinder	Small
Medium-Large	Cylindrical Envelope Diameter Varies from 75-100% of Envelope	Small-Medium
Large	Cylinder	Large
Large	Cylindrical Envelope Diameter Varies from 50-100% of Envelope	Large

Figure 6.4.2-1 Mission Model Configuration Derivation

summary for the GPB satellite, produced additional, unique recovery requirements. The HST dimensions of 15 feet in diameter and 50 feet in length were included in the composite along with the GRO weight of 34,000 pounds. An irregular satellite surface was considered to provide a more difficult recovery than a smooth surface and was also selected as a worst case characteristic. The fifth category of Figure 6.4.2-1 included the most irregular surface. Defined as varying between 50 and 100 percent of the envelope diameter, it provided the level of conformance of the actual surface to the envelope diameter for the composite. Both the GRO and the UARS satellite configurations are representative of this level of surface irregularity.

An analysis of the mass distributions within the mission model was accomplished in an effort to define the worst case values for moments of inertia and the location of the principal axes of inertia.

The various satellites in the model were unexceptional in being designed for stability, as evidenced by the relatively small products of inertia. Therefore, for all cases the principal axes were assumed to be not far off the geometric axes. In taking advantage of this, simplified two-dimensional calculations were used to determine the location of the principal axes and the magnitude of the moments of inertia about the principal axes. Those satellites in the mission model with sufficient data to make the calculations provided a range of locations of the principal axes with respect to the geometric axes.

As was described in Section 4.4.3, an initially torqued, disabled satellite having damping provisions will reach a steady state spin about that principal axis with the largest moment of inertia. The calculated magnitudes of the moments of inertia about the three principal axes were compared for each of the individual configurations. In each case the major principal axis was the Z transverse axis, with the Y transverse axis being very close in magnitude.

The accuracy of the analysis was considered sufficient to generally define one of the transverse principal axes as the major principal axis, and to bound the location of the principal axis off the transverse geometric axis. The region locating the principal axis, with respect to the previously defined envelope shape, is shown in Figure 6.4.2-2.

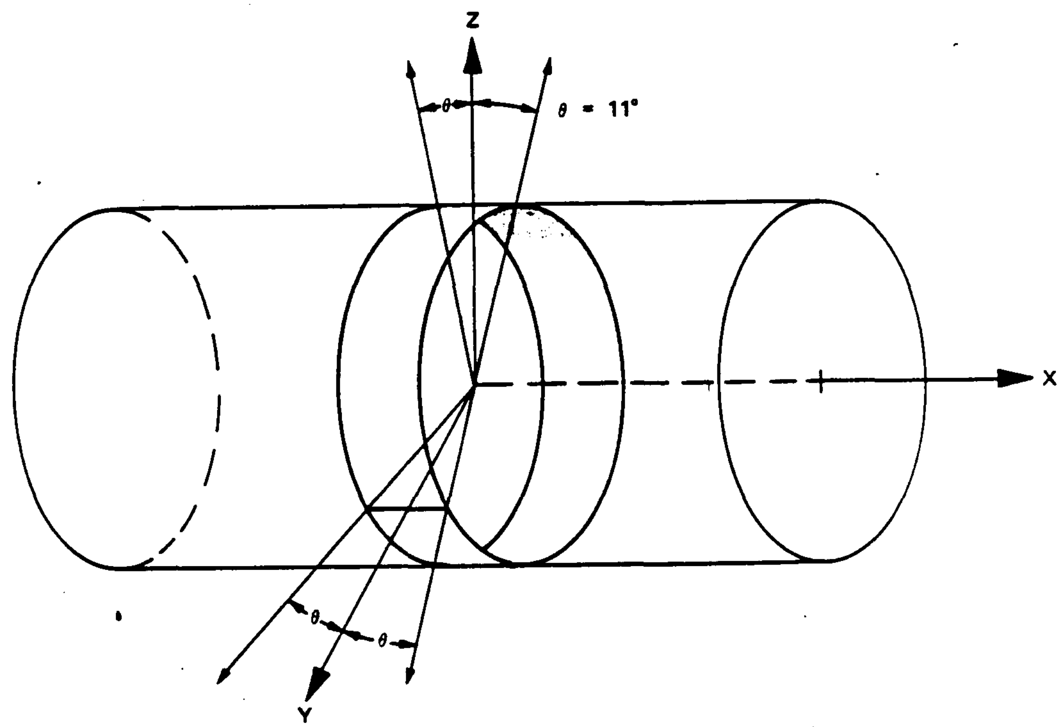


Figure 6.4.2-2 Location of Major Principal Axis

The magnitudes of the calculated moments of inertia about the principal axes approximated the values of the moments of inertia about the geometric axes. For those satellites for which products of inertia were not provided, the value of the moment of inertia about the major principal axis was estimated as the largest moment of inertia about the geometric axes. The largest value of moment of inertia about the principal axis is 125,000 slug-feet squared, for the AXAF satellite, and was included in Figure 6.4.1-1.

The final step in the derivation of the composite baseline involved the determination of worst case satellite motion. Two selected disabled satellite failure modes were assumed in order to determine a maximum angular momentum and spin rate for three axis stabilized spacecraft, as a reference of comparison to the worst case motion characteristics of spin stabilized spacecraft. Failure mode A assumed the failure of the reaction wheels of an attitude control system, effectively transferring their momentum to the spacecraft. Failure mode B involved the failure open of an attitude control system thruster exhausting the available propellant. The location of the thrusters relative to the center of gravity of the spacecraft, and the type and amount of available propellant were required to calculate the angular momentum produced by failure mode B. In the cases where sufficient data was available, it was assumed that the available propellant was restricted to the propellant of one tank, even in the presence of tank cross-strapping, due to cross-strapping isolation valves. For failure mode A the angular momentum was determined simply as the maximum momentum transfer capability of the wheels.

Conversations with Hughes and Ford Aerospace defined the maximum spin rate occurring in low earth orbit for disabled spin stabilized spacecraft as 35 to 55 revolutions per minute, for the Hughes 393 and 376 bus respectively. The angular momentum for the larger and more recent 393 bus was calculated as the product of the moment of inertia about the spin axis and the spin rate.

The maximum angular momentum and spin rate of spin stabilized spacecraft and of three axis stabilized spacecraft, as a result of failure modes A and B, are shown in Figure 6.4.2-3. The angular momentum value and resultant spin rate for failure mode B did not include the Mission Model Derived Baseline value of moment of inertia about the major principal axis, but was calculated uniquely for each satellite of the model. The calculation for GRO produced the maximum value of angular momentum of 68,000 foot-pound-second.

MOTION CHARACTERISTICS	SPIN STABILIZED SPACECRAFT	FAILURE MODE A	FAILURE MODE B
		MOMENTUM TRANSFER FROM REACTION WHEEL	THRUSTER OPEN FAILURE
ANGULAR MOMENTUM (FT-LB-SEC)	16,800	1260	68,000
SPIN RATE (REV/MIN)	55	2.4	9.0

Figure 6.4.2-3 Angular Momentum and Spin Rate

6.4.3 Derived Baseline Application - The diameter necessary to completely surround a recovery candidate, normal to its major principal axis, has been termed "envelopment diameter." The effort to bound envelopment diameter and further define the recovery scenario assumed the envelope dimensions provided by the Mission Model Derived Baseline as an initial reference. Three independent issues were identified which affect the envelopment diameter magnitude: misalignment of the major principal axis and the geometric axis of the recovery candidate (geometric coning), misalignment of the spin axes of the recovery candidate and the tumbling satellite recovery system, and the deadband of the OMV attitude control system. Geometric coning and its affect on envelopment diameter is depicted in Figure 6.4.3-1.

In the presence of geometric coning, the effect on the magnitude of the envelopment diameter is dependent on the location of the major principal axis, or the type of geometric coning. As previously shown, the misalignment of the principal axes and the geometric axes is slight, so that the principal axes can be described as longitudinal and transverse. Geometric coning is produced by misalignment of the longitudinal principal axis with respect to the longitudinal geometric axes, and misalignment of one of the transverse principal axes with respect to its transverse geometric axis. The misalignment of the transverse principal axes will be within the geometric transverse axis plane and/or off the transverse geometric axis plane towards the longitudinal geometric axis. The former produces no geometric coning, and therefore does not affect envelopment diameter. The magnitude of the change in envelopment diameter varies considerably for the remaining two cases of geometric coning.

The two cases, longitudinal and transverse, are respectively depicted in Figure 6.4.3-1. It can be seen that rotation about the principal axis creates an increase in envelopment diameter. For the previously defined maximum angle of misalignment between the principal and geometric axes, the magnitude of the change in envelopment diameter of the longitudinal case is significantly greater than that of the transverse case. Therefore, the tolerance of the angle of misalignment for spin about the longitudinal principal axis is much smaller than that for spin about the transverse principal axis.

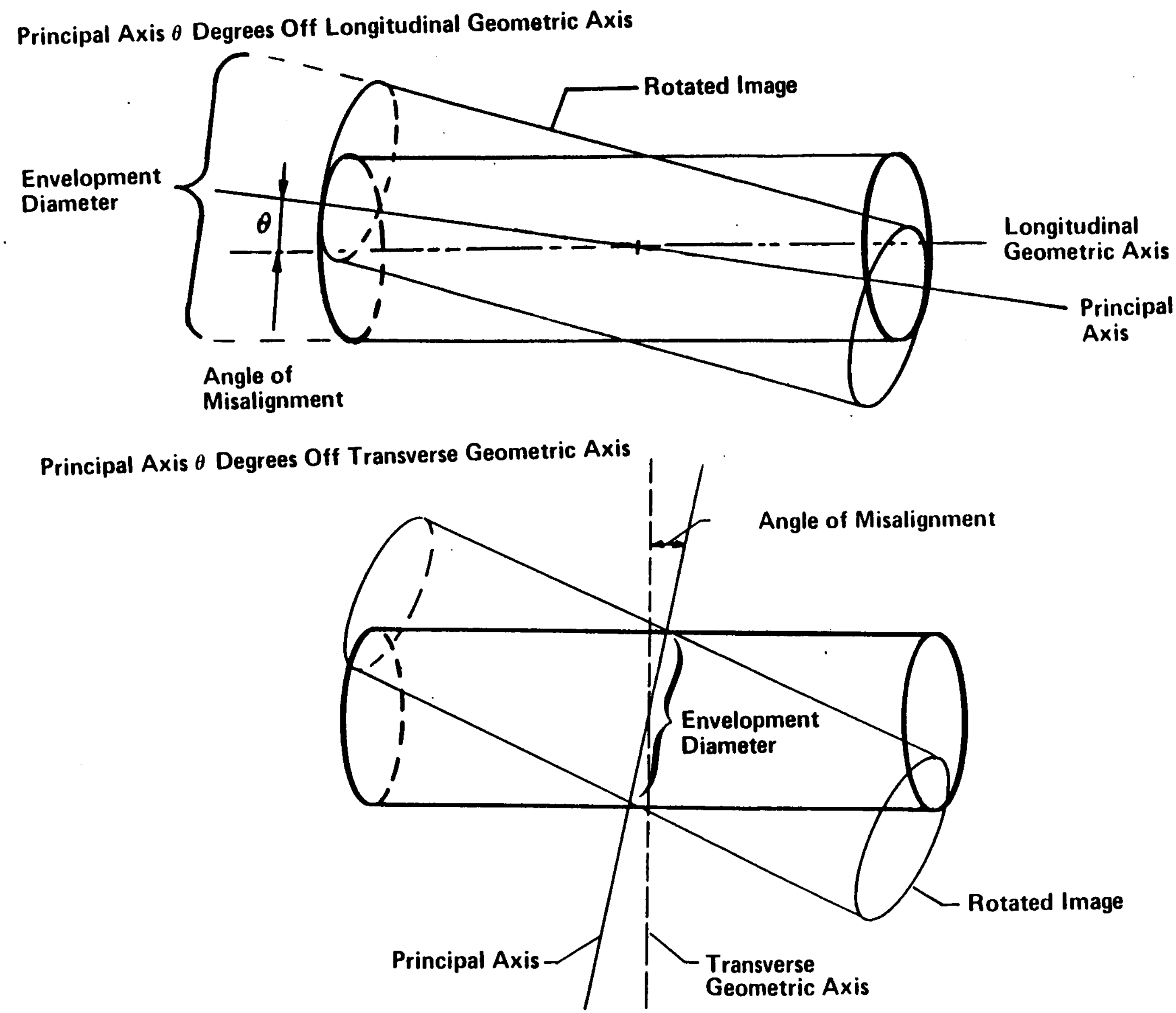


Figure 6.4.3-1 Misalignment of Principal and Geometric Axes

Although geometric coning produced by misalignment of the longitudinal principal axis was examined, it was previously shown that the longitudinal principal axis will generally not be the major principal axis. The occurrence of spin about the longitudinal axis cannot be ruled out, however, due to spin stabilized spacecraft and exceptions within the mission model for which the difference between the moments of inertia about the longitudinal and transverse principal axes becomes difficult to distinguish. For spin stabilized spacecraft, angles of misalignment are normally in the range of fractions of a degree, which represents approximately a one-inch increase in envelopment diameter for Intelsat VI. For the exceptional case, a small spacecraft, the increase in envelopment diameter will be significant relative to its dimensions, but in terms of the more than 180 inches required to envelope the larger spacecraft, it will not effect an overall increase in the TSRS envelopment diameter capability. Misalignment of the transverse principal axis, the driving case, produces an increase in envelopment diameter of approximately four inches, based on the envelopment dimensions of the Mission Model Derived Baseline.

The second issue affecting envelopment diameter, the misalignment of the spin axes of the recovery candidate and the TSR system, is illustrated in Figure 6.4.3-2. The misalignment of the spin axis increases the envelopment diameter in much the same way as geometric coning. The angle of misalignment has not been bounded, although the resultant maximum increase in envelopment diameter is not expected to be severe.

The OMV as used in a TSR mission will have two controllability deadbands. The first is associated with the automatic pilot attitude control and produces rotational deadbands for roll, pitch, and yaw. The second is effected by teleoperator capability, dependent on feedback time delay and the thruster impulse magnitudes.

The effect of the attitude control deadband was addressed and is depicted in Figure 6.4.3-3. The desired initial contact of the TSR system with the recovery candidate was designated as 15 degrees off the diameter normal to the approach direction, to influence a reaction in the direction of the the TSR system and the OMV along the approach diameter. An assumed rotational deadband of one degree results in a six-inch translational deadband at the point of contact, equivalently increasing the envelopment diameter.

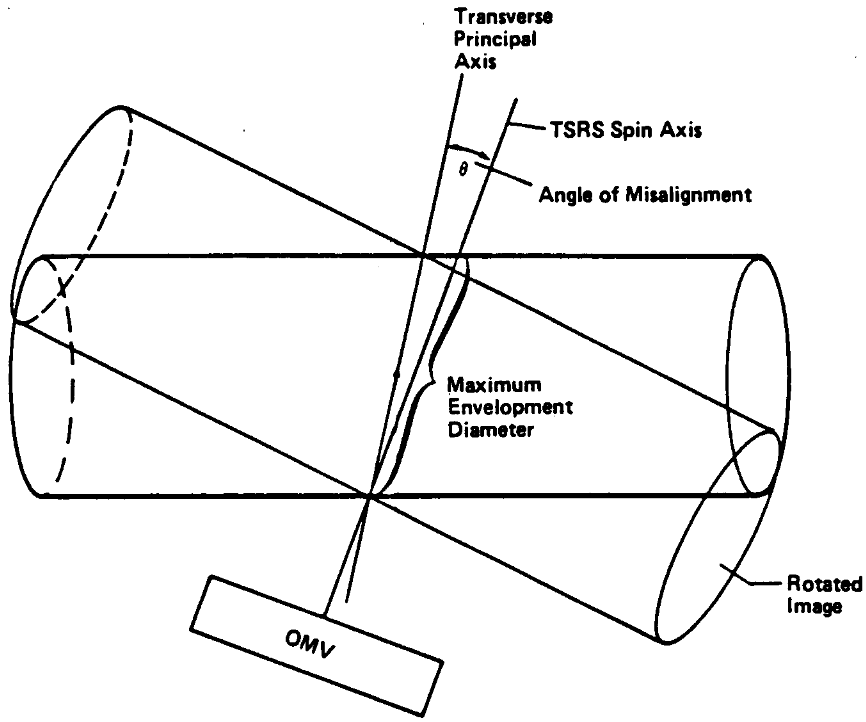


Figure 6.4.3-2 Misalignment of Spin Axes

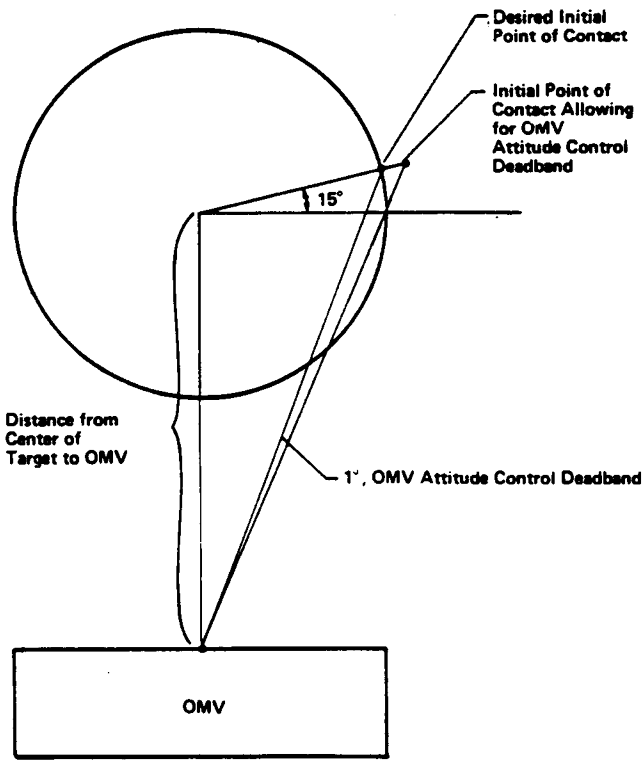


Figure 6.4.3-3 OMV Controllability Deadband

Several issues were identified which provide justification for an extendible boom requirement. Of these, three address the proximity of the OMV to the recovery candidate, where an extendible boom diminishes the possibility of contact between the vehicles; and two are issues of access and alignment, accommodated by a boom having multiple degrees of freedom. Their relationship is shown in Figure 6.4.3-4.

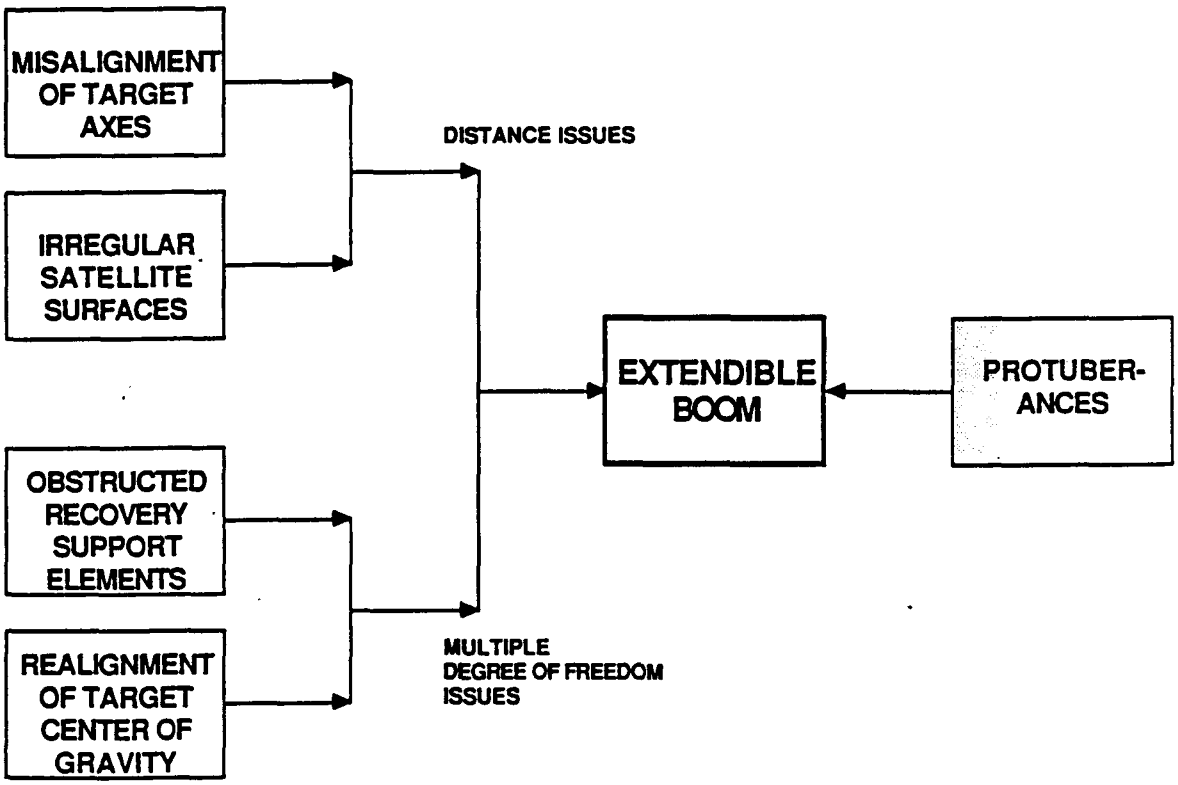


Figure 6.4.3-4 Extendible Boom Issues

The first issue, geometric coning about a transverse axis, is depicted in Figure 6.4.3-5. The condition establishes a distinct barrier between the recovery candidate and the OMV. To avoid vehicle damage, as the recovery candidate is spinning relative to the stable OMV, a distance greater than the "barrier" distance must be preserved. For the angle of misalignment of the Mission Model Derived Baseline, the "barrier" distance is 18 inches.

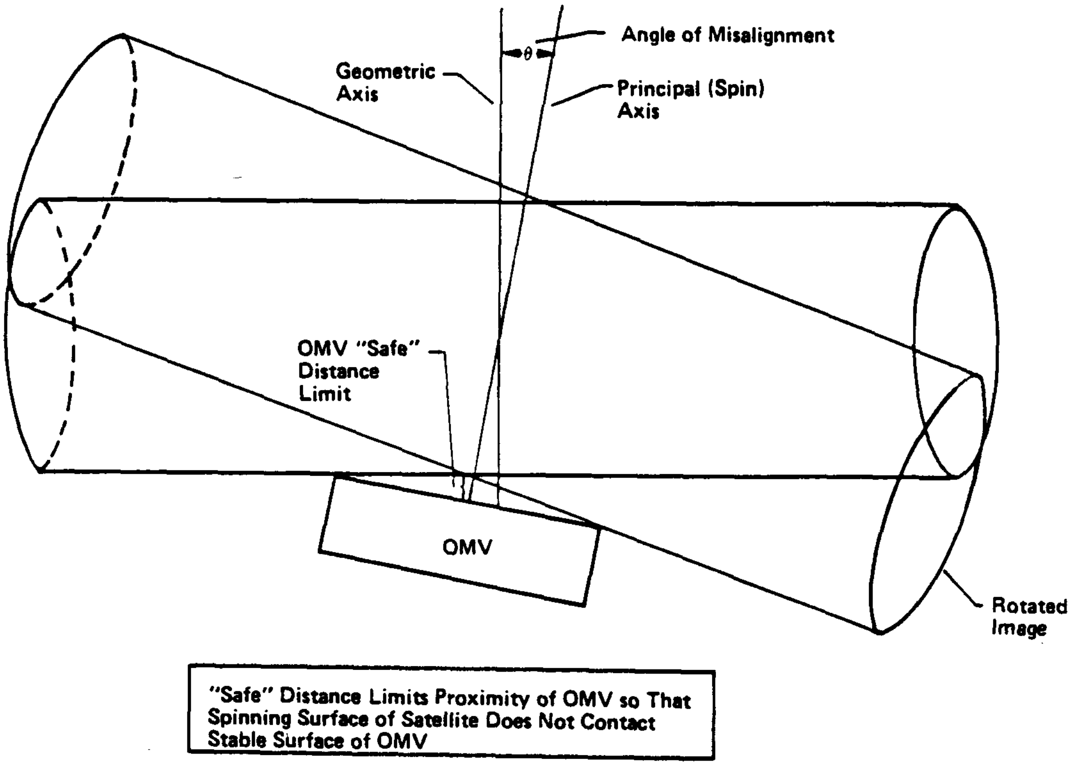


Figure 6.4.3-5 Geometric Coning

Figure 6.4.3-6 shows satellite surface irregularities typical of those of the Mission Model Derived Baseline. As can be seen, a distance is required so that after envelopment, rigidization will not cause the surface of the recovery candidate away from the point of envelopment to contact the OMV. The surface configuration at and near the point of envelopment varies with each recovery candidate. The "safe" distance, however, will not exceed that for a surface with a 50 percent to 100 percent diameter at and near the point of envelopment. The 50 percent to 100 percent ratio results in a 45-inch "safe" distance.

The remaining issues, obstructed RSEs, CG realignment, and protuberances, were identified but not completely analyzed. RSEs accessible to the Shuttle RMS can be obstructed by deployed protuberances, requiring a multiple degree of freedom extendible boom, in order to provide the proper gripper orientation for recovery. Realignment of the recovery candidate CG is required, where the CG location relative to the TSR system and the OMV, exceeds the CG offset limitations of the OMV. As was discussed in the functional analysis, the re-alignment may be accommodated by articulation of a multiple degree of freedom extendible boom.

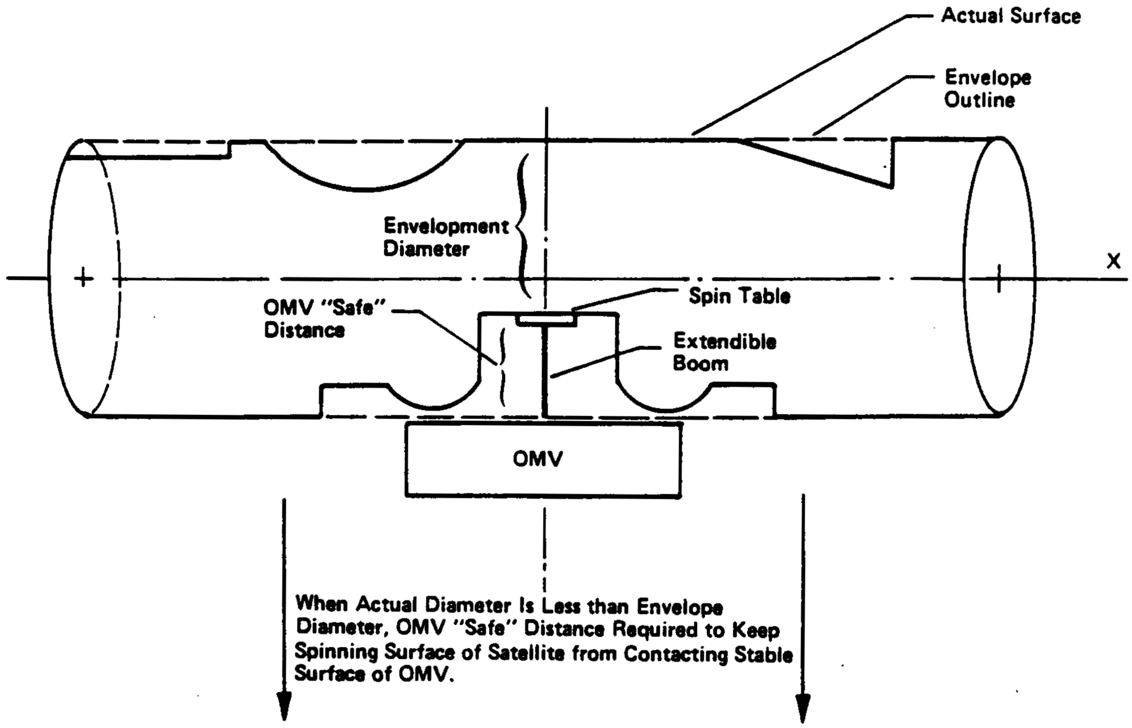


Figure 6.4.3-6 Surface Irregularities

Protuberances, in general, were reviewed for each of the satellites in the mission model. Dimensions were summarized for both solar arrays and antennas, but no effort was made to provide a boundary dimension to include in the Mission Model Derived Baseline. The ranges of extension from the satellite surface are 8 to 63 feet and 4 to 17 feet for solar arrays and antennas respectively. The proximity limitation of the OMV to the recovery candidate, based on protuberances, was considered to be too severe to accommodate with an extendible boom.

7.0 DESIGN REFERENCE MISSIONS (DRM) - TASK 1.4

7.1 Introduction

The Design Reference Mission (DRM) task, contract statement of work Task 1.4, was interpreted by MMC to include: (1) the selection (and MSFC approval) of a group of DRMs covering a broad range of potential remote recovery scenarios; and (2) operations analyses of these DRMs to support refinement of requirements.

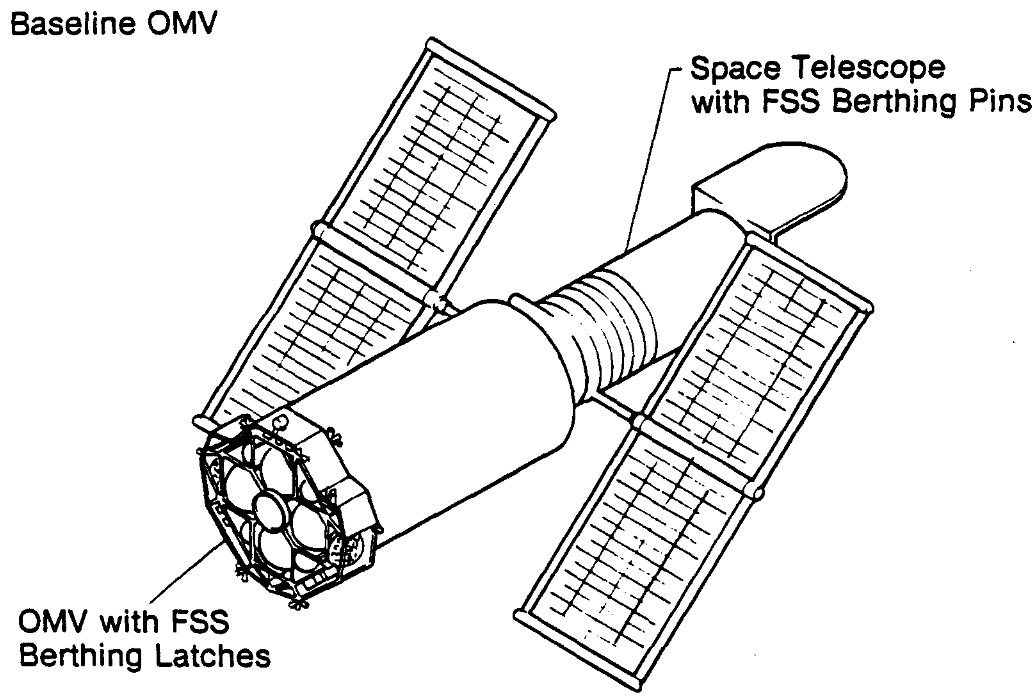
A set of six DRMs was chosen early in the study and included two scenario "cases" for each of the three MSFC defined recovery systems, Systems A, B and C. Each of the DRMs was analyzed in detail and a sequence of events for each was outlined to display the results of functional and operational analyses.

The DRM operations analysis included a breakout of: 1) required "pre-mission" activities; 2) "specific" or direct mission activities and 3) post-mission activities. The "specific" mission events were those activities directly included in the actual conduct of the recovery mission. Post-mission events were those activities, required upon mission completion, that would ensure continued orderly Space Transportation System or Space Station operations, such as cleanup operations, refurbishment and storage of equipment and tools. The DRM event sequencing included a detailed description of recovery activities.

7.2 DRM Operations Analyses

7.2.1 DRM 1 - System A, Case 1 - This DRM and DRM 2 were designed to describe remote recovery missions in which the basic OMV, without any TSR elements, would conduct recovery operations. The MSFC reference configuration OMV is designed with two types of retrieval/recovery support mechanisms. The first is the standard STS RMS end effector, a grapple mechanism designed to enable grapple and rigidization with an RMS grapple fixture situated on the spacecraft, and that is accessible to a large transport vehicle like the OMV. The other OMV recovery support mechanism is a set of STS flight support structure (FSS) docking latch pins to enable retrieval or recovery of spacecraft where these FSS berthing pins are accessible to the OMV.

An onorbit recovery scenario for DRM 1 is illustrated on Figure 7.2.1-1. This System A (basic OMV) recovery DRM describes a realistic mission in which the OMV captures the Hubble Space Telescope (HST), using the OMV FSS berthing latches to mate with HST's FSS latch pins. This "recovery" mission is mandated by a set of instrument failures that occur prior to the first planned HST maintenance mission, and has left HST with an effective capability of only 20%. For this DRM, the HST is significantly disabled; however, the spacecraft's attitude control systems are operable and the satellite is stable.



Case 1: Stable Target—FSS Capture

Figure 7.2.1-1 Design Reference Mission 1, System A, Case 1

This recovery DRM is initiated from the Space Station, as the Space Station and OMV are both assumed fully operational and the reusable OMV has been tested and fully integrated into the Space Station, located at 28.5 degrees in inclination.

7.2.1.1 DRM 1 Pre-Mission Activities - The primary pre-mission activities for DRM 1 are presented in Table 7.2.1.1-1. The OMV will have been integrated fully into Space Station operations prior to this mission. The OMV procedure for retrieval and for recovery in this case should be very similar to a normal OMV recovery mission. However, they must be developed, tested and exercised prior to conduct of the DRM.

Table 7.2.1.1-1 Pre-Mission Tasks

Ground

Develop Operational Procedures

- OMV Rendezvous/Target Close
- OMV Grapple and Rigidization
- OMV Orbit Transfer to Space Station
- OMV/HST Separation

- Conduct recovery operations using OMV Operations Support Center

Space Station

- Conduct local exercises on routine recovery operations, and OMV deployment/recovery

7.2.1.2 DRM 1 Mission Activities - This mission is assumed to commence when the OMV is deployed from the Space Station, probably done with a mobile RMS. This is shown in Table 7.2.1.2-1. The OMV will be controlled to transfer to the immediate vicinity of the HST and achieve rendezvous. The OMV will be operated by OMV ground control operators throughout this mission. There are no TSR elements on the OMV for this DRM and thus no TSR requirements will be derived from this mission. OMV will navigate around the target, HST, and the teleoperator will align the OMV for its translational maneuvers toward the FSS berthing pins. The operator will achieve a firm three-latch hookup with the HST and prepare to return to Space Station. These activities will enable recovery of an HST that is remote from the Space Station.

7.2.1.3 DRM 1 Post-Mission Activities - Following this mission, the OMV will be refurbished and stored in storage depots at Space Station. These activities are strictly OMV-related and will not be detailed here as they do not influence TSR requirements.

7.2.2 DRM 2 - System A, Case 2 - The second System A DRM is designed to outline an OMV remote retrieval/recovery operation using the OMV RMS end effector/grapple mechanism as a recovery support tool. In the second recovery DRM, the Cosmic Background Explorer (COBE) instrument package was considered to be totally failed. However, as in the HST failure, the satellite's attitude control system (ACS) is operable and the satellite is in a semi-controllable mode. The COBE pointing control reaction wheel system has failed, but its magnetic torquers and momentum wheels prevent rotation above

Table 7.2.1.2-1 DRM 1 Mission Event Sequence

Event

Man and Activate OMV Operations Support Center

Checkout OMV Ground Control Console/Equipment

Prepare OMV at Space Station for Recovery Mission

- Remove from Storage
- Fuel
- Conduct Checkout

Deploy from Space Station, Transit to Safe Standoff Distance, with Cold Gas Engines to Main Engine Ignition Position

Orbit Transfer to Rendezvous with HST

Rendezvous and Visually Acquire HST

OMV Ground Controller Conducts Inspection Maneuvers Around HST

HST POCC Operator Closes Contamination Shields, Retracts Solar Arrays and Antenna, Inerts Attitude Control System

OMV Ground Controller Aligns OMV for Transit to HST Berthing Pins

OMV Ground Controller Grapples HST Berthing Pins with OMV FSS Docking Latches, Acquires Firm Grapple for Orbit Transfer

OMV Ground Controller Conducts Transfer of OMV/HST to Space Station Vicinity

Space Station Mission Control Assumes Mission Control and Completes Recovery of OMV/HST one degree per second on the roll axis and close to zero on the other two axes. The OMV reference configuration vehicle is expected to be capable of matching this target roll rate.

This DRM was formatted to be a dedicated STS mission, as the COBE satellite will be in a 99 degree inclination polar orbit. The STS scenario was chosen also to demonstrate the widest possible range of System A remote recovery scenarios. DRM 2 is illustrated in Figure 7.2.2-1. The MSFC reference configuration OMV is shown prepared to match the one degree per second spin rate of the COBE satellite and attach the OMV RMS end effector to the COBE's RMS grapple fixture.

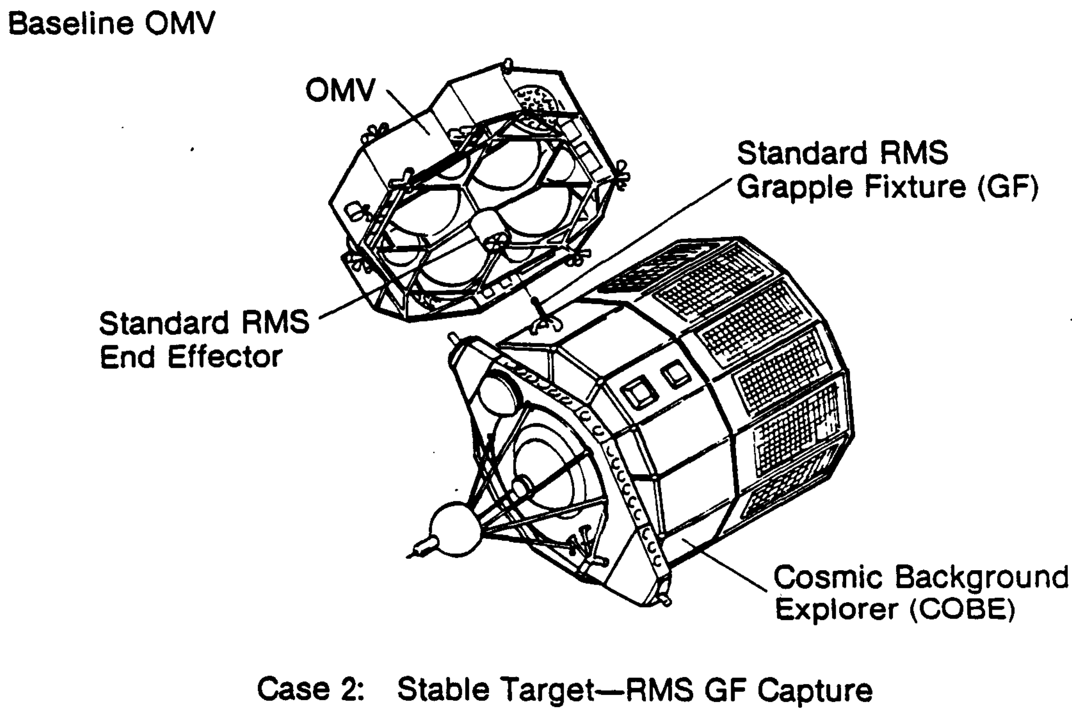


Figure 7.2.2-1 DRM 2, System A, Case 2

7.2.2.1 DRM 2 Pre-Mission Activities - For DRM 2, the pre-mission events are highlighted in Table 7.2.2.1-1. None of these activities impact TSR requirements, so they are presented at a top level. The actual recovery mission is baselined to begin at rendezvous with COBE.

Table 7.2.2.1-1 DRM 2 Pre-Mission Activities

<u>Event</u>

Prepare OMV for Launch in STS

Develop Recovery Operating Procedures

- Rendezvous
- Approach & Survey Target
- Match Target Roll Rate
- Grapple & Despin
- Rigidize for Transport to STS

Perform Simulations, Exercises

Launch OMV to Standard STS Operating Altitude

Deploy OMV from STS with RMS

Maneuver STS to Safe Observation Distance From OMV

Transfer OMV to Rendezvous with COBE

7.2.2.2 <u>DRM 2 Mission Activities</u> - Control of the recovery mission is transferred to the OMV ground control center during OMV transit to the operational orbit of COBE, currently planned for a 486 nautical mile circular orbit. The DRM 2 recovery mission events are outlined on Table 7.2.2.2-1. The OMV ground controller maneuvers OMV to a position to rendezvous with the target including visual acquisition and then proceeds to circle the failed satellite to gather data to develop an approach strategy.

The ground controller will maneuver OMV to align with the target's axis of spin, match the spin rate of the disabled satellite, extend the OMV RMS end effector to snare the grapple fixture on COBE, despin the satellite to a stable condition, and retract the snare wires into the end effector to provide a rigid OMV/COBE mate for transfer back to the Orbiter. As in the case of DRM 1, the events of this DRM do not impact on tumbling satellite recovery requirements, and thus are described in general terms.

Table 7.2.2.2-1 DRM 2 Mission Activities

Event
Ground Controller Maneuvers OMV to Visually Acquire COBE
OMV Maneuvered to Circumnavigate COBE and Select Approach Strategy
OMV Maneuvered to Close Proximity of COBE to Match Spin Rate
With OMV Translating in Circular Manner to Match Rates, OMV RMS is Extended and Grapple of COBE Achieved
OMV Despins COBE to Stabilize Satellite
OMV Ground Controller Uses RMS End Effector to Rigidize COBE to OMV for Transport to STS
OMV Commanded to Return COBE to STS
Mission Control Transferred Back to STS

7.2.2.3 DRM 2 Post-Mission Activities - Following completion of the recovery mission, the OMV and the COBE satellite will be positioned in the Orbiter cargo bay for return to earth. The Orbiter RMS will be used to place the COBE satellite into transfer support cradles and/or STS trunnion mounts, and similarly will be used to position OMV on the STS longeron and keel attach fittings in the cargo bay. The Orbiter will then be returned to earth where OMV will be refurbished and prepared for a future mission and COBE will be returned for repair and/or upgrade and a return launch to its operational orbit.

7.2.3 DRM 3 - System B, Case 1 - DRMs 3 and 4 were developed to describe examples of the type of missions a satellite recovery "System B" would be designed to conduct. System B is the recovery system envisioned to deal with situations where the disabled satellite is:

a. Outside of Orbiter range (either higher or lower than efficient STS operating altitudes);

b. Controllable from the ground and stable, i.e., within OMV retrieval/recovery operating capabilities;

c. Devoid of accessible recovery support devices (RMS grapple fixture or FSS latch pins);

d. Not spin-stabilized or spinning at speeds not in excess of OMV spin matching capabilities, which are projected to be very low.

The recovery target for DRM 3 is the LANDSAT-D satellite that has, without prior warning, suddenly lost the remaining power of a marginally operating solar panel. The LANDSAT-D is in a 380 nautical mile circular polar orbit. The satellite has not as yet developed significant rotation and is generally stable. The LANDSAT-D failure mode did not introduce torque into the satellite system and LANDSAT's altitude of 380 nautical miles will minimize short term atmospheric and gravitational torques. As this is a polar orbit recovery, the mission base of the recovery operation is the Orbiter, and not the Space Station.

7.2.3.1 DRM 3 Pre-Mission Activities - The activities requisite to initiation of DRM 3 are similar to those for DRM 2, shown on Table 7.2.2.1-1. The additional preparation activity relates to the use of the System B recovery kit. This is the "cost effective, minimum OMV impact" recovery kit. The recovery system will consist of an extendible boom, a grapple mechanism interface device, and, for DRM 3, a standard RMS end effector, to serve as a grapple mechanism. These recovery system elements will be collected from the OMV and OMV kit storage area and assembled and checked out, using ground support equipment. The System B kit is then transported to the STS launch processing area and tested again to ensure operability. The System B kit is then mated to the OMV in the STS cargo bay, and continuity checks are conducted to validate a functional OMV/TSR kit interface. All operational testing is done on the ground, where repair or replacement activities can be accomplished readily.

7.2.3.2 DRM 3 Mission Activities - As this DRM is detailed solely for the purpose of refining TSR requirements, the recovery mission is presumed to commence at the point of rendezvous with the target vehicle, the disabled

LANDSAT satellite. The mated OMV/TSR is initially positioned within visible acquisition range of the ground controllable LANDSAT satellite. The recovery mission activity sequence for DRM 3 is presented in Table 7.2.3.2-1, and illustrated in Figure 7.2.3.2-1. The actual recovery mission is initiated at rendezvous with LANDSAT. The OMV and attached TSR kit are maneuvered into close proximity of LANDSAT by the OMV ground controller at the OMV Operations Support Center. OMV is then flown around the disabled satellite to determine its motion characteristics and select an approach and grapple strategy. This motion may be known in advance as a result of analysis of radar returns; however, this data cannot routinely be assumed to be available.

The System B recovery elements will be deployed when the OMV/TSR kit assembly is aligned to track the target's RMS grapple fixture. The extendible boom, possibly a several degree of freedom (DOF) manipulator arm, will be extended to provide clearance between the OMV and the target. It will also provide access to the LANDSAT grapple fixture that is obstructed by the satellite's array of solar panels from a straight-in approach. Once aligned with the LANDSAT's small roll rate by OMV, the TSR RMS end effector/grapple mechanism is prepared for grapple and the snare mechanism grips the fixture, retracts it into the end effector mechanism and rigidizes it for transport. The final recovery mechanism action is to use the multiple DOF extension arm to align the LANDSAT center of gravity with the OMV orbit transfer thrust vector to enable forward translation maneuvers required to return OMV/TSR/LANDSAT to the Orbiter.

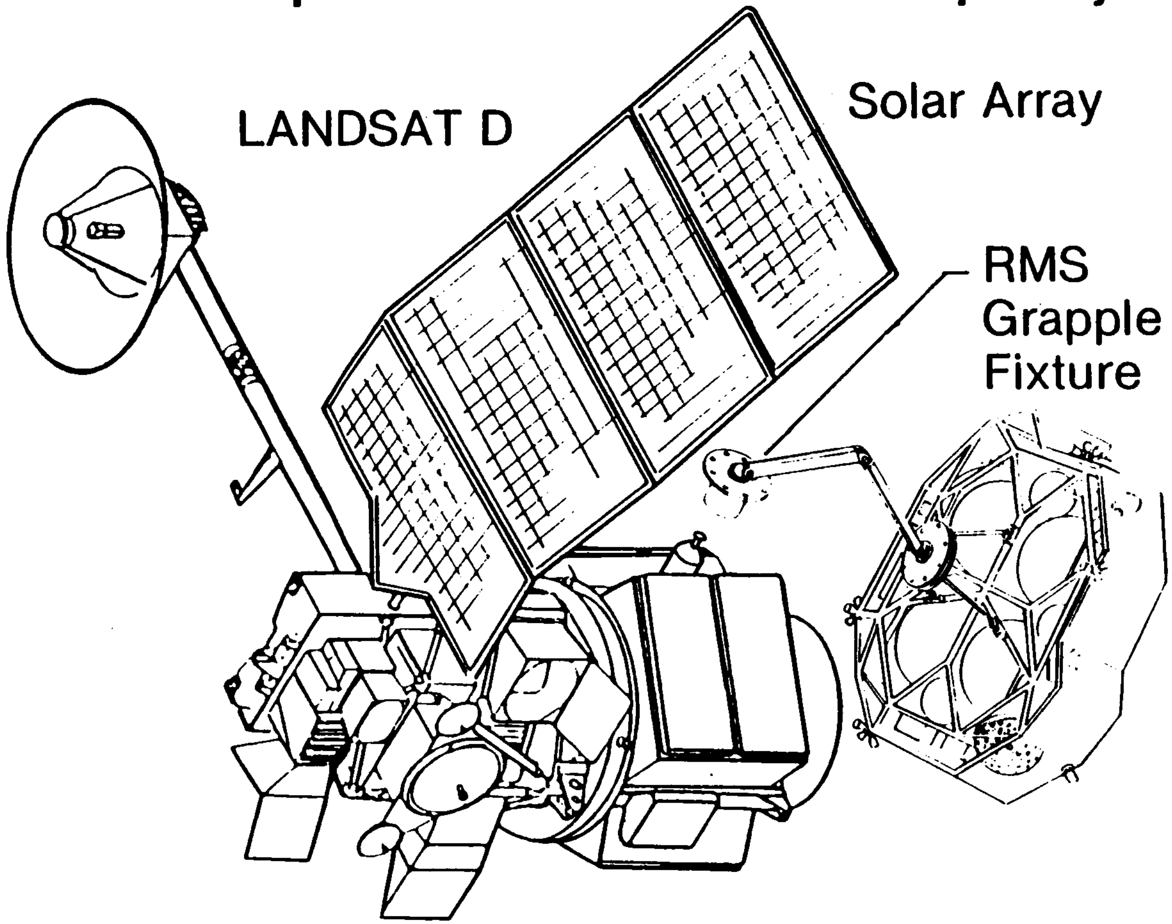
7.2.3.3 <u>DRM 3 Post Mission Activities</u> - When the recovery mission is completed and the LANDSAT satellite has been secured back in the Orbiter, the OMV and attached TSR kit will be positioned in the longeron and sill trunnion latches in the Orbiter and prepared for deorbit, if LANDSAT repairs cannot be completed onorbit.

Back on the ground, the TSR kit will be detached from the OMV and disassembled, refurbished, and stored for future missions.

Table 7.2.3.2-1 DRM 3 Mission Activities

Event
OMV/TSR Kit Delivered to Visual Contact with LANDSAT - Approximately 2000 Feet from LANDSAT
OMV/TSR Control Transferred to OMV Operations Support Center
OMV/TSR Maneuvered by Ground Controller to Close Vicinity of Target - 50-100 ft. - Using OMV TV/Lighting System
OMV/TSR Circumnavigate Target to Determine Spin Rate/Spin Axes, Locate Grapple Fixture, Observe Docking Obstruction(s)
OMV Ground Controller Determines Target Spin Axis, Positions OMV to Match Target Spin Rates
TSR Extendible Boom is Deployed to Full Length, TSR Kit Support Camera Deployed and Activated
TSR RMS Grapple Mechanism Prepared to Grapple.
Ground Controller Maneuvers TSR Kit to Engage LANDSAT Grapple Mechanism - Taking Care to Avoid Contact with Obstructing Solar Panel, & Maintain Position with Slowly Rotating LANDSAT. OMV and TSR Controllers Use Respective TV Monitors to Conduct Mission
Ground Controller Activates OMV RMS End Effector to Snare LANDSAT and Retract Fixture to Achieve Rigid Grapple
OMV/TSR Maneuvered to Despin LANDSAT to Stable Position
Ground Controller Uses Multiple DOF Extendible Boom Arm to Move LANDSAT and Align Its Center of Mass with OMV to Limit C.G. Offset and Permit Transfer of Mated OMV/TSR/LANDSAT Back to Orbiter

Minimum OMV Impact/Low-Cost Increase in Capability



Case 1: Obstructed Grapple Fixture

Figure 7.2.3.2-1 DRM 3, System B, Case 1

7.2.4 DRM 4 - System B, Case 2 - This is the second of the two recovery scenarios designated for recovery System B. This DRM was selected to describe a scenario in which a disabled satellite is:

a. Disabled, all scientific instrumentation has failed;
b. Controllable from ground and stable;
c. Not spin-stabilized or spinning;
d. Beyond Orbiter's nominal operating range; and
e. Does not have standard grapple fixtures, i.e., RMS grapple fixtures or FSS latch pins.

The specific mission involves recovery of one of the Geopotential Research Mission (GRM) satellites that will fly in pairs in a circular, low earth orbit at 100 nautical miles with an orbital inclination of 90 degrees. The mission of this satellite is refined measurement of the earth's gravitational field. The failure mode for this satellite is postulated as a total instrument failure, though the spacecraft power and attitude control subsystems are not affected and the spacecraft remains fully controllable and stable.

7.2.4.1 DRM 4 Pre-Mission Activities - As GRM, the disabled satellite recovery candidate, is in a near-polar orbit, the mission will be conducted from the Orbiter. The pre-mission tasks are described in Table 7.2.4.1-1. The only difference in the recovery system used for this DRM, as opposed to DRM 3, is the type of grapple mechanism used. As the target satellite does not have any standard grapple mechanisms on it, a small, special purpose grapple mechanism must be used to attach to a "hard point" on the GRM satellite. The GRM satellite mission is actually composed of two satellites when deployed, one positioned about 80 miles behind the other. The satellites will be carried into earth orbit in an STS "cradle" mechanism. Each of the GRM satellites has an extension on it to enable structural interface with the cradle, and it is this element that will be grappled by the small gripper device of the System B TSR kit.

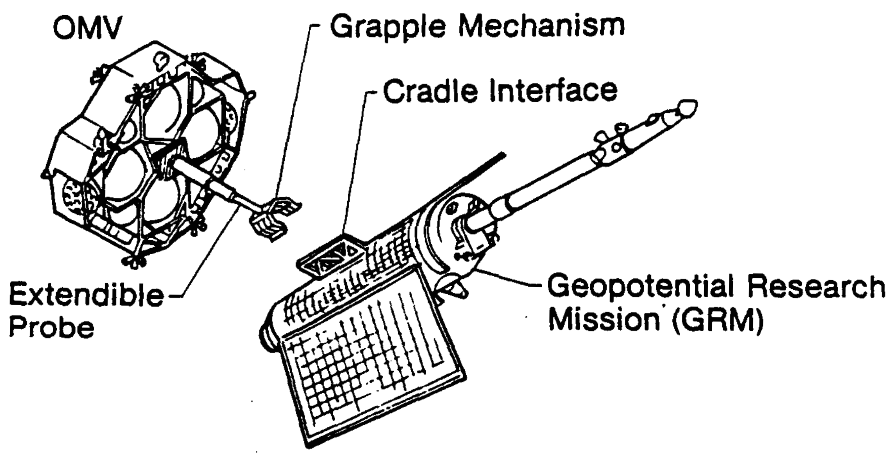
Table 7.2.4.1-1 DRM 4 Pre-Mission Activities

Event
Assemble TSR Kit System Elements for GRM Mission (Extendible boom, Small Gripper)
Conduct Assembly and Checkout Tests Using Ground Support Equipment at OMV Storage Area
Transport TSR Kit to Launch Processing Area
Conduct Final Ground Testing in Vertical or Horizontal Launch Processing Flow
Attach TSR Kit to OMV in Cargo Bay
Conduct Power and C&DM Continuity Checks Between OMV and TSR Kit through OMV Payload Umbilical
OMV/TSR Kit Delivered to Nominal Orbiter Operational Orbit
OMV/TSR Kit Deployed From Cargo Bay with RMS
OMV Transits to Rendezvous with GRM

7.2.4.2 DRM 4 Mission Activities - Again, the DRM 4 mission is similar in most regards to DRM 3. The mission is described in Table 7.2.4.2-1 and illustrated in Figure 7.2.4.2-1.

The recovery mission commences when the OMV/TSR rendezvous with the GRM in its low earth orbit. The OMV will be more strongly affected by the earth's atmosphere and geopotential forces in the lower altitude and necessary recovery actions will be expedited to minimize the effects of these forces during retrieval operations. As GRM will be stable, the tasks of the OMV and TSR ground controllers will be simplified. The OMV ground controller can translate directly to the target satellite and the TSR operator will extend the extendible boom, position the small gripper device on the GRM cradle interface, and effect a rigid grapple on GRM. Finally, the multiple degree of freedom extension arm will be used to reposition the center of mass of GRM, to align it with the OMV thrust vector, to support transfer of the mated OMV/TSR/GRM package back to the Orbiter for repair or return to earth.

Minimum OMV Impact/Low-Cost Increase in Capability



Case 2: No Grapple Fixture

Figure 7.2.4.2-1 DRM 4, System B, Case 1

7.2.4.3 DRM 4 Post-Mission Activities - The GRM satellite will be repaired at the Orbiter if at all possible, and returned to earth if not. The System B recovery kit will be retained on the OMV while positioned in the Orbiter for transport to earth. When back on earth, the TSR kit will be removed from the OMV, either before or after OMV is removed, and the kit will be refurbished and stored for future use.

7.2.5 DRM 5 System C, Case 1 - The final two DRMs, DRM 5 and DRM 6, are missions designed to demonstrate the most difficult of the remote, disabled satellite recovery scenarios. System C, as defined by MSFC, was intended to represent a "full up" recovery system, capable of dealing with the most "complex" type of satellite motion and these two scenarios are representative cases requiring this level of capability.

Table 7.2.4.2-1 DRM 4 Mission Activities

Event
OMV/TSR Kit Delivered to Visual Contact with GRM - Approximately 2000 Feet from GRM
OMV/TSR Control Transferred to OMV Operations Support Center
OMV/TSR Maneuvered by Ground Controller to Close Vicinity of Target - 50-100 ft. - Using OMV TV/Lighting Systems
OMV/TSR Circumnavigates Target to Determine Spin Rate/Spin Axes, (if any), Locate GRM Cradle Interface Device
Ground Controller Determines Approach Strategy, Positions TSR Close to GRM Cradle Interface Device
TSR Extendible Boom is Deployed to Full Length, TSR Kit Support Camera Deployed and Activated
TSR Small Gripper-Type Grapple Mechanism Prepared for Grapple
Ground Controller Maneuvers TSR Kit to Engage GRM Cradle Interface Device
Ground Controller Activates OMV TRS Gripper to Capture GRM, Engage and Achieve Rigid Grapple
Ground Controller Uses Multiple DOF Extendible Boom Arm to Reposition GRM and Align Its Center of Mass with OMV to Limit C.G. Offset and Permit Transfer of Mated OMV/TSR/GRM Back to Orbiter

As has been shown in preceding portions of this report, the more difficult recovery scenarios involve situations where the disabled satellite is spinning, either in an attitude controllable mode or the complex case where the satellite has failed in a mode where attitude control has been lost due to any of a wide variety of potential causes.

Again, as previously shown, when a satellite has failed in a non-controllable mode with angular momentum levels exceeding the attitude control capability of the spacecraft, it will develop an initial multi-axis tumble or spin mode at some tumble rate. The high level of kinetic energy initially imparted to the satellite will dissipate rapidly due to friction in joints, viscous fluid flow in propellant tanks, and flexible appendages on the satellite. When the system reaches a new minimum energy, steady state condition, the initial "tumble mode" coalesces into flat, single axis spin about the satellite's major principal axis of maximum moment of inertia. Thus, the complex motion for which a "full up" remote, disabled satellite recovery system should be designed is, in actuality, flat, single axis spin at some relatively steady rate. The study team discovered cases where the spin rate was as high as seven revolutions per minute (rpm) and spin rates for potential, non-controllable satellites were projected to be in the neighborhood of between 3 rpm and 10 rpm. The spin rate for a controllable, spin stabilized, disabled satellite is expected to range from 10 to 50 rpm and possibly higher, though the trend in spin stabilizing of spacecraft appears to be headed toward the lower ranges of spin rate.

DRM 5 describes the recovery of the INTELSAT-6 satellite. This satellite was delivered into low earth orbit on an Orbiter flight and deployed for transfer into geostationary orbit. The perigee kick motor failed enroute to its higher orbit and the INTELSAT-6 satellite was left in a spin-stabilized, controllable mode in a totally useless orbit within the range of the OMV/Tumbling Satellite Recovery kit.

The recovery kit subsystems required to conduct this mission include the extendible boom, a spin table, a grapple mechanism interface device and a "stinger" type grapple mechanism to support grapple of the spinning perigee kick motor. These subsystems will be assembled into a complete totally integrated recovery kit and prepared for a mate with the OMV. The satellite is in a low inclination orbit, as a result of its 28 degree Orbiter launch injection and this recovery mission can and will be conducted from a Space Station frame of reference.

The development and deployment concept for the recovery systems considered for use in recovering all remote, disabled satellites is to create a versatile set of component subsystems that can be assembled and integrated into specific recovery kits, tailored for the unique recovery scenario presented to the user. In the "full-up" System C scenarios, the disabled satellites are assumed to be spinning, and in DRM 5, the INTELSAT-6 spacecraft is spinning, as it is spin-stabilized. Thus, unlike the System B remote recovery scenarios previously analyzed, this recovery scenario requires a "spin table". This recovery subsystem, the spin table, will enable the total TSR kit to be spun up to match the spin rate of INTELSAT-6. With both the kit and the target spinning at similar rates, the grappling element of the recovery system can be maneuvered to a position wherein the grapple mechanism subsystem can be employed to achieve a firm grapple. The significant point to remember here is that the overall <u>recovery system</u> will be developed in such a manner that the spin table can easily be included as a part of the total system when required by the scenario, or deleted to reduce the total weight to be transferred to the remote, disabled satellite. This design philosophy will produce a resultant savings in operations costs, by minimizing propellant usage in going out to and coming back from the target.

Similarly, the grapple mechanism required for this scenario will be a relatively special purpose mechanism, rather than a general purpose tool and will be attached to the grapple mechanism interface device, another subsystem element of the TSR. This grapple mechanism will be very similar to the mechanism used in the recent Westar and Palapa-B retrieval missions, in which an astronaut/manned maneuvering unit (MMU) served as the basic recovery system. Again, this grapple mechanism can be incorporated easily into the system because of the implied requirement and resultant design accommodation inclusion of the grapple mechanism interface device into the basic recovery system. The concept of a modular design, allowing use of only the subsystem elements specifically needed for the given recovery mission will: 1) increase the breadth and scope of potential remote recovery opportunities that can be conducted with this system and 2) enable efficient and cost effective deployment of the recovery system(s).

7.2.5.1 DRM 5 Pre-Mission Activities - The pre-mission activities for DRM 5 are highlighted in Table 7.2.5.1-1. All of the remote recovery subsystem elements will be stored in the servicing storage area on the Space Station. The recovery system has been tested thoroughly in all possible assembly configurations. In preparation and planning for this mission, a TSR kit configuration for DRM 5 will be selected and assembled. This recovery kit will consist of an extendible boom, a spin/despin table, a grapple mechanism interface device and a stinger-like grapple mechanism. These modular components will be assembled in the servicing area, either manually using astronaut EVA or robotically using a Space Station "smart front-end" kit.

Once assembled, the TSR kit will be mated to the OMV, again using either astronauts on EVA, or robotically. With assembly of the OMV/TSR kit, the OMV will be deployed from Space Station using the Mobile RMS, transit out to a safe launch distance from Space Station (using cold gas jets) and perform an orbit adjust to a rendezvous position close to the disabled INTELSAT-6 satellite.

Table 7.2.5.1-1 DRM 5 Pre-Mission Activities

Event
Assemble TSR Kit System Elements for INTELSAT-6 Recovery Mission in OMV Servicing Area at Space Station - EVA or Robotic Assembly, (Kit includes Extendible Boom, Spin Table, Grapple Mechanism Interface Device, Stinger-type Grapple Mechanism).
Mate TSR Kit to OMV in OMV Service Area (EVA or Robotic Mating)
Deploy OMV/TSR Kit From Space Station with Mobile RMS (MRMS)
Conduct Operational Checkout of OMV/TSR Kit in Proximity Operations Under Space Station Mission Control
Transfer OMV/TSR Kit to Rendezvous with INTELSAT-6

7.2.5.2 DRM 5 Mission Activities - The satellite recovery mission commences when the OMV/TSR kit is maneuvered to a close proximity position with INTELSAT-6, within visual range of the target. The OMV and TSR kit, will be controlled, at this point, by the OMV Operations Support Center, with separate control consoles for the OMV and the TSR. The mission events are illustrated in Figure 7.2.5.2-1 and outlined in Table 7.2.5.2-1.

The OMV controller will maneuver OMV/TSR to align the TSR translation/grapple axis with the spin axis of INTELSAT-6. The TSR capture support mechanisms, i.e., the extendible boom, spin table, and grapple mechanism, will be deployed. The spin table will be activated to generate a TSR spin rate equal to that of the target. These activities will prepare the recovery system for OMV translation maneuvers to position the stinger-type grapple mechanism for a firm grapple of the target. The OMV and TSR controllers will maneuver both systems to achieve a firm grapple of the target, while minimizing torque producing forces caused by incidental contact with the target prior to the completion of a firm grapple.

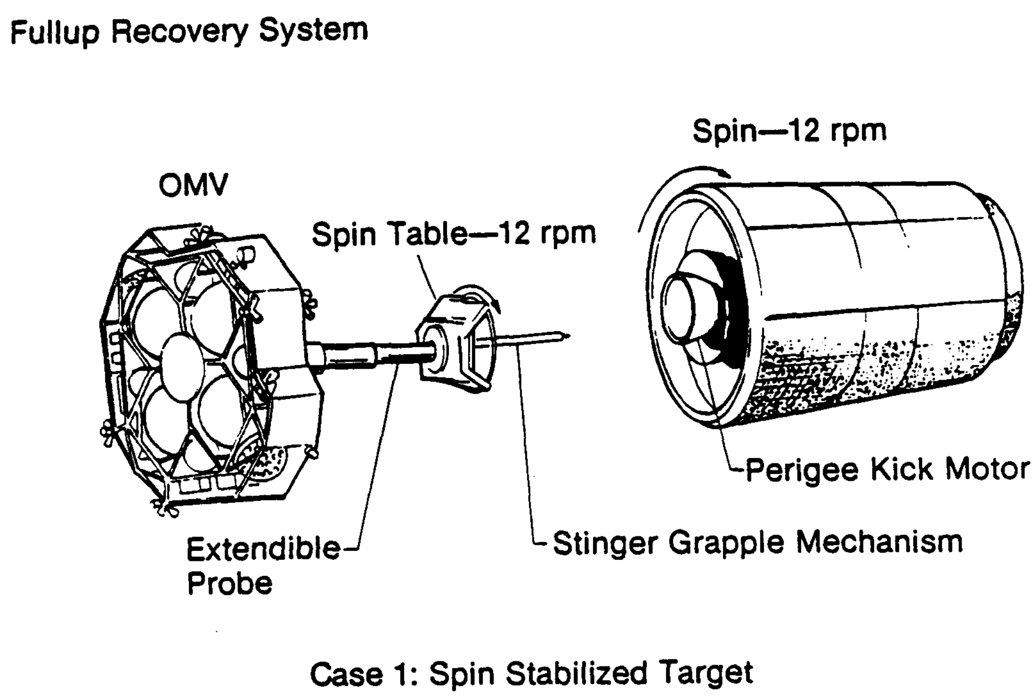


Figure 7.2.5.2-1 DRM 5, System C, Case 1

Table 7.2.5.2-1 DRM 5 Mission Event Sequence

Event
OMV/TSR Maneuvered by OMV Ground Control to Close Visual Contact With Target
OMV Operator Maneuvers OMV/TSR to Align OMV/TSR Axis With Spin Axis of Spin-Stabilized Target
TSR Extendible Boom is Fully Extended by Ground Controller and Stinger-type Mechanism is Deployed. OMV Maintains Stable Attitude during TSR Element Deployment
TSR Ground Controller Spins Up TSR to Match INTELSAT-6 Spin Rate
OMV and TSR Controllers Maneuver OMV and Grapple Mechanism to Proper Grapple Position on Target Spin Axis and Center of Mass
OMV and TSR Controllers Maneuver OMV and TSR Grapple Mechanism to Achieve Firm Grapple of INTELSAT While Minimizing Contact Dynamics Effects
TSR Controller Despins INTELSAT-6 to Perform Satellite Stabilization
OMV/TSR Operators Take Actions to Align INTELSAT-6 For Transit to Space Station
OMV Small Thrusters Ignited to Test Grapple Rigidity and Correct Target Mass Alignment for Transit.
OMV Orbit Adjust Engines Fired to Return OMV/TSR/INTELSAT to Space Station

Following grapple actions, the TSR controller will despin the satellite and OMV and TSR controllers will take necessary follow-on actions to align the mass of INTELSAT-6 with the OMV thrust vector for transfer back to Space Station.

These activities describe the basic mission activities for DRM 5.

7.2.5.3 DRM 5 Post Mission Activities - When OMV is transferred back to the Space Station and delivered back to the servicing area by the Mobile RMS, the TSR kit will be demated from OMV, either by robotic operations or EVA. The subsystem elements will be disassembled and individually refurbished and tested. They will each be positioned in individual storage locations at Space Station, ready for assembly into the next required TSR kit configuration.

7.2.6 DRM 6 - System C, Case 2 - This DRM was defined and developed to describe the most challenging remote, disabled satellite recovery mission envisioned by the study team. A satellite that fails in a mode in which attitude control of the system is lost, and it accumulates significant angular momentum, presents potentially the most difficult recovery scenario.

An orbiting satellite can be subjected to external torque of some form, such as reaction control system (RCS) engine failure, or propellant or pressurant leaks that produce angular momentum levels exceeding the satellite's attitude control system (ACS) capability.

When this occurs, the satellite will assume some initial condition of general tumble motion, more than likely a multi-axis tumble or spin configuration. As shown previously in the condition where additional torque is not added, this motion will very quickly, within minutes or hours, stabilize and become single axis spin about the satellite's major principal axis; i.e., its principal axis of maximum moment of inertia. Thus, it is realistic to assume that a typical, complex motion satellite recovery scenario might involve a 10-15,000 pound satellite, 15 feet in diameter, spinning at 7-10 revolutions per minute about an axis perpendicular to a 20-30 foot long satellite! This is a somewhat accurate description of the DRM 6 scenario chosen by the study team for definition, and, ultimately, for refinement of recovery system requirements.

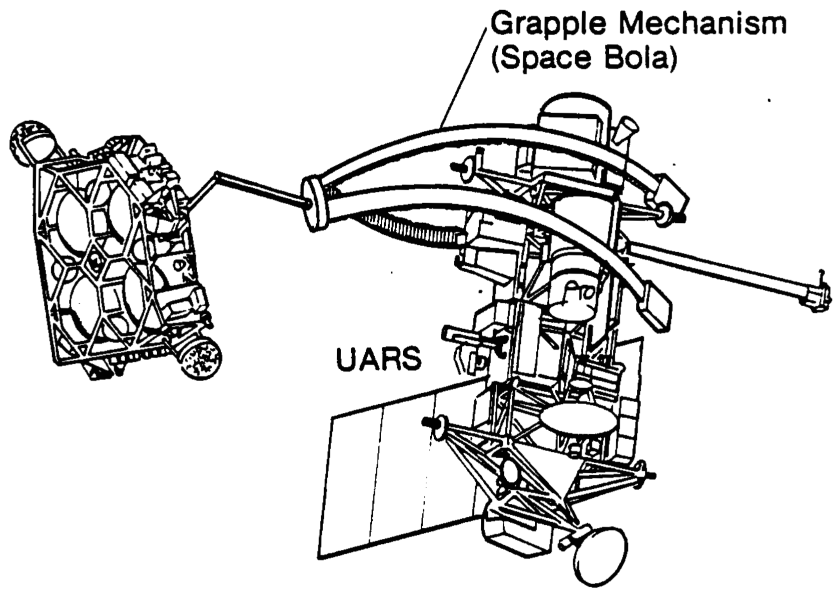
DRM 6 involves recovery of the Upper Atmospheric Research Satellite (UARS), a 10,000 pound satellite, estimated at this time for launch in 1990 into a 324 nautical mile circular orbit at an inclination of 57 degrees. The satellite failure mode is a reaction control motor that fails open, depleting its hydrazine fuel supply. The resultant torque generated by the RCS engine throttle-open failure produces sufficient angular momentum to exceed UARS attitude control authority and produce a multi-axis tumble mode of around 7 rpm. This scenario is illustrated on Figure 7.2.6-1. The recovery operation will be conducted using an OMV launched in the Orbiter, because of the 57 degree inclination of the recovery target.

The DRM 6 recovery mission is the most technically challenging of the DRMs and the TSR kit for this mission contains all of the subsystems being considered for the total system, including the most technically challenging of the family of grapple mechanisms being considered for the total recovery system. This kit will include the extendible boom, the spin/despin table, the grapple mechanism interface device and a large envelopment-type grapple mechanism, similar to that shown in Figure 7.2.6-1. This grapple mechanism must be capable of being deployed and spun up at speeds ranging from 5-100 rpm. It must have grapple arms that can be extended to grapple, circle or envelop a satellite that is 15 feet in diameter. The structural components of the total system must be strong enough to accommodate the forces and torques generated by 1) the contact dynamics of the grapple action, i.e., interactions between the grappler of the recovery system and the target and, 2) similar forces (though smaller) introduced into the recovery system by the despin motor while despinning the grappled satellite. This recovery kit will be assembled on the ground during the pre-mission, or planning, phase.

7.2.6.1 <u>DRM 6 Pre-Mission Activities</u> - As in most Orbiter oriented recovery missions, the planning and preparation activities will be conducted on the ground as shown in Table 7.2.6.1-1.

Those specific recovery system components to be used for DRM 6 will be assembled in an OMV/TSR kit assembly area and thoroughly tested. Following delivery to the launch area, the TSR kit will be tested in the Payload Vertical (or Horizontal) Processing area using special TSR ground support equipment (GSE). It will be relatively inefficient to test it following onorbit deployment from the cargo bay and prior to the OMV flight out to a UARS rendezvous. It is assumed that it would be difficult to repair or replace components at that time (though not impossible), so the launch processing tests will be thorough.

Fullup Recovery Systems



Case 2: Uncontrolled Spin

Figure 7.2.6-1 DRM 6, System C, Case 2

Table 7.2.6.1-1 DRM 6 Pre-Mission Activities

Event

Ground

Assembly and checkout of DRM 6 TSR Kit at OMV/TSR Storage/Assembly Facility - (Kit includes Extendible Boom, Spin Table, Large Enveloper Grapple Mechanism)

Transport of TSR Kit to Launch Processing Payload Assembly Area

Checkout in Payload Processing Area, Mate to OMV, and Installation of OMV/TSR in Vertical or Horizontal Processing Flow

Onorbit

Following Launch to Orbiter Operational Orbit, the Mated OMV/TSR Kit is Deployed from Cargo Bay Using Orbiter RMS

Orbiter is Maneuvered to Provide Separation from OMV Prior to OMV Ignition

OMV is Launched to Rendezvous with the UARS Satellite

The OMV/TSR kit will then be transported into a properly phased 57 degree orbit at nominal Orbiter altitude by the STS. The mated OMV/TSR will be physically deployed from the Orbiter, with the use of the RMS, and the Orbiter will maneuver out to an appropriate separation distance from the OMV. The OMV will receive launch and orbit transfer signals from the OMV Ground Operations Support Center to deliver OMV/TSR to a rendezvous with the disabled UARS satellite.

7.2.6.2 DRM 6 Mission Activities - The recovery mission for DRM 6 commences when the OMV and TSR operators obtain visual contact with the Upper Atmospheric Research Satellite (UARS). The specific mission activities for DRM 6 are outlined in Table 7.2.6.2-1.

The OMV/TSR operators will obtain the first view of a 25 foot long satellite spinning end-over-end in a flat spin about an axis perpendicular to the longitudinal axis of the spacecraft.

The OMV and TSR cameras will be used to estimate the spin rate and determine the spin axis, as the OMV operator circumnavigates the spinning UARS. The OMV operator will use care to assure adequate clearance between OMV and the numerous protuberances on the UARS. The primary objective of this activity is to locate the spin axis (or axes if motion is multi-axis spin; i.e., general motion, including precession and nutation - which should occur only if the satellite is experiencing some form of external torque) on the spinning UARS. This axis should be the colinear major principal axis, angular momentum vector and angular velocity vector. The OMV and TSR operators will identify this axis through visual techniques including determining the spot where the target appears as a single point and everything around that point prescribes apparent perfect circles, rather than elliptic contours.

The study team examined a number of alternatives for providing support to the OMV and TSR operators in finding the central spin axis, including radar and laser ranging, but found no feasible solutions. In most cases, a set of corner reflectors properly positioned on the target were required to enable electronic or visual ranging for motion orientation, and proper prepositioning of the reflectors appears infeasible.

Table 7.2.6.2-1 DRM 6 Mission Activities

Event
OMV/TSR Rendezvous to Within Visual Range of UARS (Under OMV Operations Support Center (OSC) Control)
OMV Circumnavigates Target to Determine Satellite Motion: Spin Axes; Rates
OMV OSC Determines Target Spin Axes and Develops Approach Strategy
TSR Ground Controller (GC) Deploys TSR Kit, Including Boom Extension, Envelopment-Type Grapple Mechanism Deployment
TSR GC Operates TSR Spin Table Mechanism to Match Spin Rate(s) of UARS. OMV Maintains Attitude Control During TSR Deployment
OMV GC, with TSR GC Support, Conducts Translation Maneuvers to Position Spinning Grapple Mechanism at or Near Target Center of Mass
TSR GC Manipulates Enveloper Grapple Mechanism to Surround Target Without Touching It
TSR GC Conducts Grapple Closure Operations to Achieve Firm Grapple and Rigidization with Target
TSR GC Performs Despin Operations to Stabilize Target
TSR Operator Releases UARS, Regrapples Target as Required to Provide Proper Mass Distribution for OMV Transfer
OMV GC Operates Small Attitude Control Thrusters to Test for Rigidity and Correct Orientation of Center of Mass
OMV GC Fires Orbit Adjust Thrusters to Return OMV/TSR/UARS to Orbiter

Once the spin axis is identified, an approach strategy is selected and the OMV/TSR kit is aligned with the target spin axis. The TSR ground controller will deploy the recovery system elements. The extendible boom will be actuated first to provide target/OMV clearance. Next, the large, envelopment-type grapple mechanism will be unfolded and extended to a open configuration adequate to envelop the target. Finally, the TSR system will be "spun up" by the TSR ground controller to match the spin rate and phase angle of the target. The TSR ground controller should be able to refine spin rate matching errors with occasional small adjustments during the recovery operation.

Following deployment of the recovery subsystems, the OMV operator, in coordination with the TSR operator, will translate the mated systems into a position wherein grapple can be effected. The extensive rotating mass of the TSR system may introduce complications preventing a nominal OMV transition to the target grapple, but simulations will be required to validate this assumption and to develop an appropriate safe and efficient approach technique.

When the OMV/TSR systems are positioned such that the spinning, enveloper grapple mechanism has spin rate matched with the target and is surrounding the target at or near the target's center of mass, the grapple mechanism closure can be initiated. This is a phase of operations difficult to define with precision in this phase of conceptual study. The principal uncertainty, of course, relates to the potential for unpredictable contact with the target and resultant contact dynamics, which can possibly affect the target, the TSR kit and the OMV itself. It will be difficult to develop a highly reliable contact dynamics model for recovery operations, certainly until a specific recovery system is selected. It is highly likely that the "contact dynamics" issue can be addressed only in space, and will mandate a cargo bay (or Orbiter proximity operations) experiment eventually. The study team used the assumption that "envelopment" of the target represents its capture and that once enveloped the grapple mechanism can slowly accomplish a firm grapple and rigidization with the target, minimizing damage to the target, the TSR mechanisms and the OMV. The grapple mechanism concept selected and designed for this mission is intended to minimize these potential disturbing factors.

One of the more apparent sources of inappropriate contact is the fact that all of the grapple mechanism arms or fingers must close at the same rate to minimize dynamic stability problems for the TSR itself. Thus, as the mechanism is closing and one arm makes contact with one target surface first, without all arms contacting the target at the same time, a force is imposed on the target. This could disturb its motion, causing target dynamic instability, that could result in unexpected motion creating damage to recovery elements. Another area of uncertainty relates to the natural limitations in the control of OMV. There will be positioning "deadzones" in controlling OMV pitch and yaw motions, and also in OMV translation, that will cause inherent inaccuracies in correctly positioning a grapple mechanism, extended from between 10-15 feet from the OMV, with respect to the UARS target. These positioning uncertainties, coupled with 2-3 second time delays in controlling both OMV and TSR mechanisms will create possibilities for undesired levels of contact with the target prior to achieving a firm grapple.

The TSR operator will achieve a firm grapple with all fingers and/or arms of the grapple mechanism and apply additional gripping pressure to rigidize the contact between TSR and UARS.

The TSR operator will then activate the TSR spin motor to slowly despin the firmly grappled UARS recovery target. This despin will be conducted at very low rates to minimize the torques on the TSR subsystems and on OMV. The OMV attitude control system will automatically retain attitude control of the mated OMV/TSR/UARS package during despin. This same approach was used successfully using EVA in the Manned Maneuvering Unit (MMU) retrieval operations involving both Westar and Palapa-B in 1985.

When the angular momentum of the UARS has been eliminated by TSR despin, the TSR ground controller will release UARS and regrip the satellite appropriately to properly distribute the target's mass distribution for OMV transit back to the Orbiter.

Finally, the OMV operator will fire the small thrusters to test the rigidity of the OMV/TSR/UARS attachments and then fire the OMV main thrusters to return the recovery elements to the Orbiter.

These activities describe the basic mission activities for DRM 6.

7.2.6.3 DRM 6 Post Mission Activities - Following rendezvous of the returned OMV/TSR/UARS at the Orbiter, the UARS will be grappled using the Orbiter RMS and positioned in a flight support system (FSS) cradle for repair or in appropriate trunnion fittings for return to Earth. If the UARS is repaired on orbit, the TSR kit will be removed from the OMV by astronaut EVA and temporarily stored in the cargo bay. The UARS and OMV will be mated, either by remote RMS operations or by astronaut EVA, and UARS returned to its operational orbit by OMV. When OMV returns to the Orbiter the TSR kit will be remated to OMV and returned to earth for refurbishment and storage.

7.3 Requirements Allocation

The overall objective of Task 1, Requirements Analyses and Trades, was to conduct a series of systems requirements analyses to identify the requirements related to development of a system capable of remote recovery of disabled satellites. The six recovery kit DRMs were developed and analyzed to: (1) illustrate the recovery scenarios and capability inherent in each of the recovery systems A, B, and C; (2) further decompose the level of system-oriented and concept-oriented requirements; and (3) support the selection of candidate hardware concepts. These six DRMs described operations related to the six recovery scenarios considered most likely to occur in the mid-1990s. The recovery capability required for each of the DRMs was described in general. The operational analysis did generate additional system level requirements, complementing the other requirements analyses in Task 1. Shown in Figures 7.3-1 and -2 is the study team's approach to using the DRMs to support selection of hardware concepts. The top level requirements, generated from the DRM definition and analyses and from other Task 1 analyses, were grouped into categories that related to specific recovery subsystem accommodations. For example, a number of requirements identified in the DRMs strongly implied the need for an extendible boom. One of these, the requirement to recover satellites with obstructed recovery support elements (DRM 3) suggested an extension device capable of articulation to enable an OMV to close and attach an RMS end-effector to a grapple fixture. The requirement to minimize risk to the OMV, especially in the presence of jutting appendages on a spinning target, also appeared allocatable to an extendible boom.

Requirements	System Accommodation
• Shall Recover Satellites with or without Recovery Support Elements (RSE) - RMS Grapple Fixture, FSS Berthing Pins	Extendible Boom
• Shall Recover Satellites with Recessed/Obstructed RSE's (Due to Deployed Booms, Antennas)	Extendible Boom (Multi-DOF Manipulator Arm)
• Shall Recover Satellites with Protuberances Extending out from Satellite Envelope	Extendible Boom
• Shall Minimize Risk to OMV	Extendible Boom
• Shall Minimize Risk to TSR	Extendible Boom
• Shall Recover Satellites in Non-Stable, Tumble Mode	Extendible Boom
• Shall be Capable of Remote Realignment of Target CG Prior to Transport	Extendible Boom (Multi-DOF Manipulator Arm)
• Shall Match Spin Rate of Controllable Spin	Spin Table
• Shall Accommodate Satellite Spin Rates from 0 to 55 RPM	Spin Table
• Shall Match Spin/Tumble Rates of Non-Controllable Spinning Target	Spin Table
• Shall Match Spin Rates with TBD Accuracy to Accomplish Envelopment, Grapple	Spin Table Accuracy
• Shall be Capable of Despinning Satellites with TBD Level of Angular Momentum without Damage to TSR, OMV, and Target	Spin/Despin Mechanism

Figure 7.3-1 Requirements Allocation

Requirements	System Accommodation
• Shall Accommodate Timely and Efficient Adaptation of Grapple Mechanism	Grapple Mechanism Interface Device
• Shall Accommodate a Range of Grapple Diameters from Small Hard Points to 180 Inches	Large Grapple Mechanism, Small Gripper
• Shall Recover Satellites in Non-Torqued, Non-Stable Configurations	Large Grapple Mechanism
• Shall Recover Satellites in Stable, Controllable Configurations with Recovery Support Elements	RMS End Effector, FSS Docking Pins
• Shall Accommodate 11 Degrees of Geometric Coning in Non-Stabilized Position	Large Grapple Mechanism
• Shall Recover Satellites having Irregular Surfaces	Large Grapple Mechanism
• Shall Observe Satellite Motion Characteristics and Match Satellite Spin Rates	Boresight TV, Lighting
• Shall Observe Grapple Operations, Secure Grapple with Minimum Impact on Target Satellite	TV Near Grapple Contact Point(s), Proximity Sensors

Figure 7.3-2 Requirements Allocation (Concluded)

Also shown on Figure 7.3-1 are the spin-related requirements that would appear to be accommodated by the addition of a spin table or mechanism that will enable the recovery device to match target spin rates with the accuracy required to accomplish envelopment and firm grapple, while minimizing damage to the satellite. Similarly, the spin mechanism must be capable of reverse, or braking operation, to despin recovery targets safely. Spin and despin must be possible in either direction so the grapple can be effected on the most optimum side of the satellite.

Figure 7.3-2 illustrates the remainder of this top level allocation of recovery requirements to potential subsystem components of a TSR kit. The DRM analysis demonstrated the need for a variety of grapple mechanisms. These grapple mechanisms could be readily accommodated on the recovery system with a grapple mechanism interface device, configured with electrical and communications and data management (C&DM) interface hardware. Also shown on Figure 7.3-2 is the broad range of grapple mechanisms needed to accomplish the DRMs. Finally, the requirement to observe target motion characteristics, to match spin rates, and to secure a firm grapple with minimum impact on the target appears to dictate a boresight TV camera, perhaps on the spin table, possibly a TV camera near grapple contact points and perhaps contact sensors on grapple mechanism contact points.

Each of the DRMs was evaluated to determine how many of the candidate "recovery system accommodations" would apply to each scenario. The result of this summary correlation effort is presented on Figure 7.3-3. For DRMs 1 and 2, there are no recovery subsystem accommodations, as these DRMs were designed for System A, the baseline OMV. Several of the candidate TSR subsystem components were required, in some form, in all four of the remaining DRMs. These were an extendible boom, a grapple mechanism interface device, an OMV structural interface device, and an OMV umbilical connect for power and C&DM. In addition, the wide variety of grapple mechanisms outlined in this summary appear to (1) support the need for an efficient method of configuring the overall recovery system for changeover of grapple mechanisms, and (2) reinforces the contractual requirement to evaluate no fewer than three grapple mechanisms in the Concept Definition phase, Task 2.

Recovery System Accommodation	DRM					
	1	2	3	4	5	6
Extendible Boom	(OMV-no TSRS)	(OMV-no TSRS)	X	X	X	X
Spin Table					X	X
Grapple Mechanism Interface Device			X	X	X	X
Grapple Mechanisms						
- Large Enveloper						X
- Stinger					X	
- Small Gripper				X		
- RMS Grapple Mechanism			X			
- FSS Docking Latch			X			
Boresight TV					X	X
Grapple Contact Point TV			X	X	X	X
Umbilical Connect			X	X	X	X
OMV Structural Interface			X	X	X	X

Figure 7.3-3 DRM Requirements Allocation Summary

8.0 CONCEPT DEFINITION - TASK 2

8.1 Concept Definition Approach

The objective of the second major study task, Task 2, Concept Definition, was to conduct design trades that would enable development of conceptual system designs for a set of satellite recovery systems. The primary goal was to produce a set of conceptual designs for MSFC Systems B and C that would serve as a focal point for continuing design and development efforts aimed at creating a front-end kit for the OMV to remotely recovery disabled satellites.

The initial approach for this task was to use the results of the concept survey to select the best of the concepts and any other new, original concepts and refine these concepts into meaningful, effective conceptual system designs. As previously noted, during the evaluation of those prior concepts, it became clear that none of them could satisfy the widely variant requirements that were evolving out of parallel analysis tasks. The study team developed an alternative approach to the conduct of Task 2 and it is illustrated in Figure 8.1-1.

The primary inputs to the development of this approach are shown on the left side of Figure 8.1-1. The analysis of the actual recovery environment suggested that the satellites could fail in either a stable and controllable mode, or be non-stable and tumbling/spinning about a single principal axis, in the non-torqued case. This fact introduced several implications for the conceptual design phase.

First, and most importantly, it validated the requirement for a family of varying capability recovery systems. This, of course, led to the recovery scenario analysis that produced the enhanced definition of the capabilities required for MSFC's Systems B and C. Second, it highlighted some of the recovery system requirements and provided a foundation upon which to conduct analyses that led to identification of a number of the key requirements. For example, a spinning target with whirling appendages, such as solar arrays and antennas, signified the need to protect the OMV and the recovery system from damage during recovery operations. This insight, in turn, suggested the need for an extension device to provide clearance during recovery operations. This

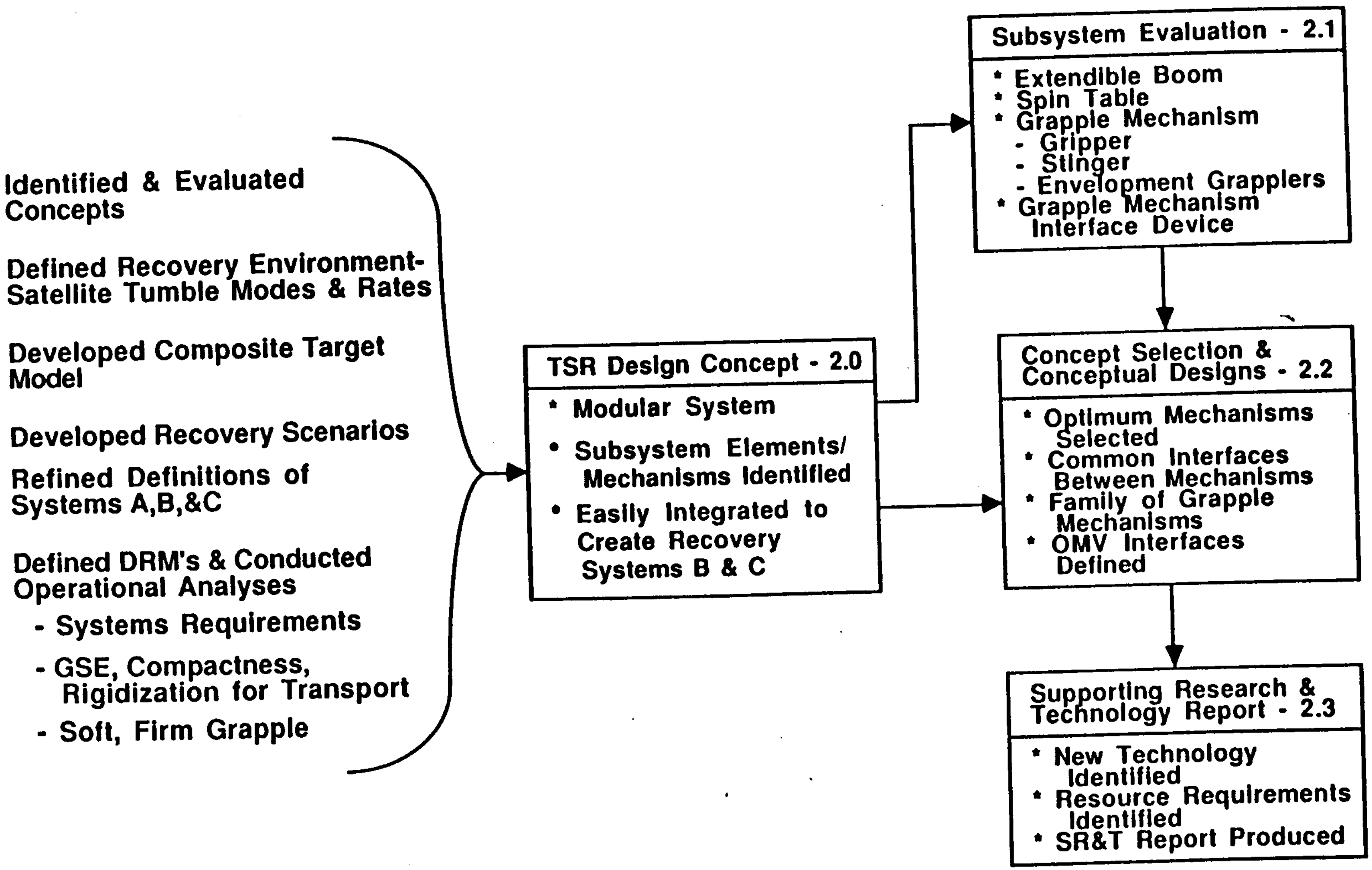


Figure 8.1-1 Concept Definition - Task 2

is a requirement that was not included in any of the previous recovery system studies. As another example, the realization that the targets could very likely be spinning, some at high rates, led to the establishment of a spin table as a potential system accommodation.

Finally, the satellite failure environment assessment supported clarification of the scope of conceivable satellite recovery activities, and enabled definition and approval of the set of six DRMs for the OMV TSR system. The operations analyses of these DRMs outlined a wide range of different grapple mechanisms required for potential recovery operations. To enable ready application of these grapple mechanisms to a "recovery system", the requirement for a grapple mechanism interface device also became apparent. Thus, a full-up recovery system was seen to contain the major subsystem components graphically represented in Figure 8.1-2.

In addition, the operations analyses of the DRMs led to further expected decomposition of requirements, including the need for light weight subsystems, and compact systems for cost efficient STS operations while mated with OMV during transport into nominal satellite orbits.

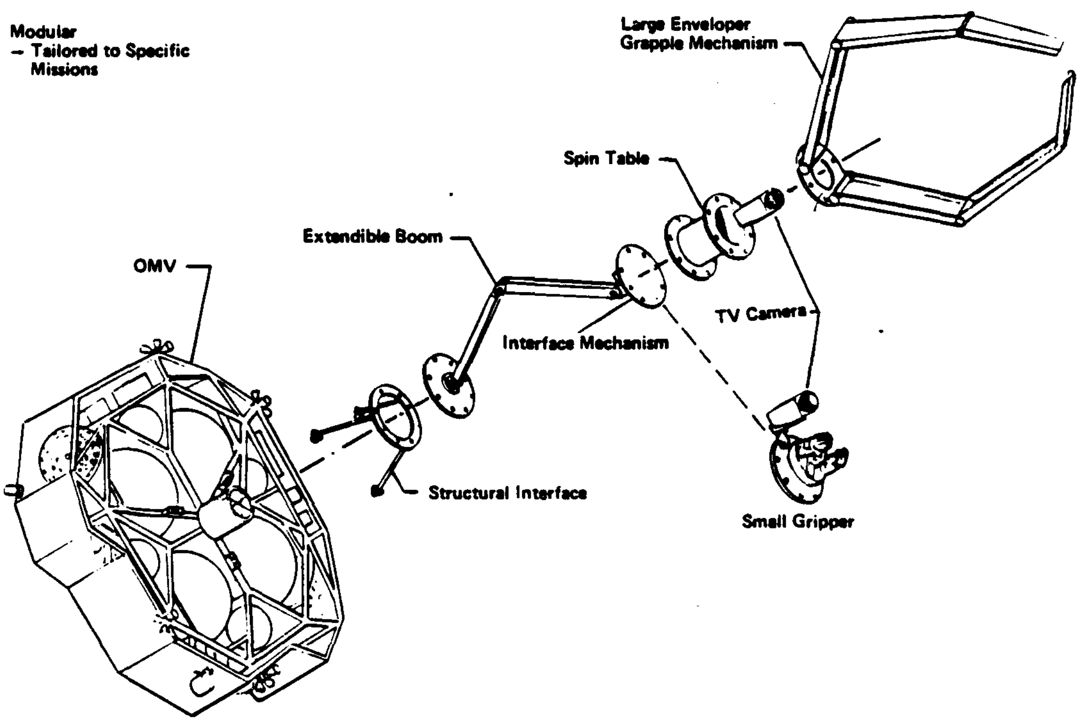


Figure 8.1-2 Full-Up Recovery System

The general assessment of the Task 1 requirements analyses was that the overall architecture of the recovery system should be a modular design, including several major subsystem components. These elements could be readily interchanged to allow tailoring of the "overall system" for the unique requirements of each specific recovery mission. The wide range of potential recovery missions was a major factor in the selection of this architecture. In addition, as shown in Figure 8.1-3, the study team believed that, using this design architecture, the full system could be developed incrementally and cost efficiently, starting with a System B capability and growing to a full-up System C. In addition, the capability to use only a portion of a full-up recovery system to conduct missions requiring only an extendible boom and a small gripper will save in fuel usage and operating costs.

Thus, referring back to Figure 8.1-1, the study team, with the approval of the MSFC Contract Technical Manager, dedicated Task 2.1 to an extended evaluation of candidate recovery subsystem elements. These subsystems include an extendible boom, a spin/despin table, a grapple mechanism interface device, and a set of grapple mechanisms for different recovery scenarios.

For Task 2.2, Conceptual Design, the preferred subsystem components were selected and a set of recovery systems were designed for Systems B and C, each with the capability to conduct both of the related design reference missions. In addition, the MMC study team developed a new design for an envelopment type grapple mechanism, which we termed the "MMC Enveloper."

System A

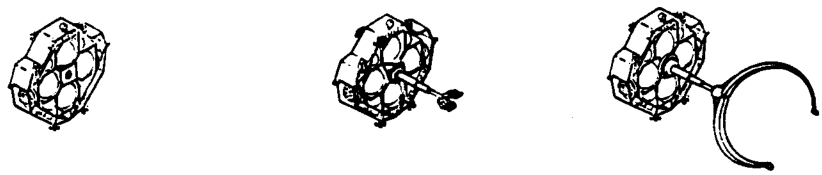
- Extends Recovery Range
- Limited Capability for Controllable Targets

System B

- Expands Capture Geometry of OMV
- Increased Grappling Capability for Controllable Satellites

System C

- Full-Up Capability
- Recovers Controllable Spinners
- Noncontrollable Tumble/Spinners



Capability Increases through Modular, Incremental Growth

Development Implications

- Can Be Developed & Tested Incrementally
- System Elements Are Modular
  - Elements Added as Needed
  - Common Interfaces Support Element Addition & Deletion
- Cost Efficient
  - System Elements Common
  - Use Only Those Needed—Weight to Orbit

Figure 8.1-3 Family of Recovery Systems

9.0 EVALUATION OF RECOVERY SYSTEM MECHANISMS - TASK 2.1

9.1 Subsystem Evaluation Approach

A survey of candidates for each of the major subsystems listed in Figure 9.1-1 was conducted. Industrial brochures, library inquiries, and discussions with mechanisms experts at MSFC and MMC produced the initial candidates. Though most were viewed quickly as falling short of previously perceived design requirements, all were evaluated qualitatively. By looking at the apparent advantages and disadvantages of each candidate, more evaluation considerations were derived. The study team did not consider it productive to develop new mechanism concepts, with the major exception of the envelopment type grappler, as many generic mechanisms for each component were available. The evaluations are presented in a format which describes the candidate and highlights the advantages and disadvantages of each.

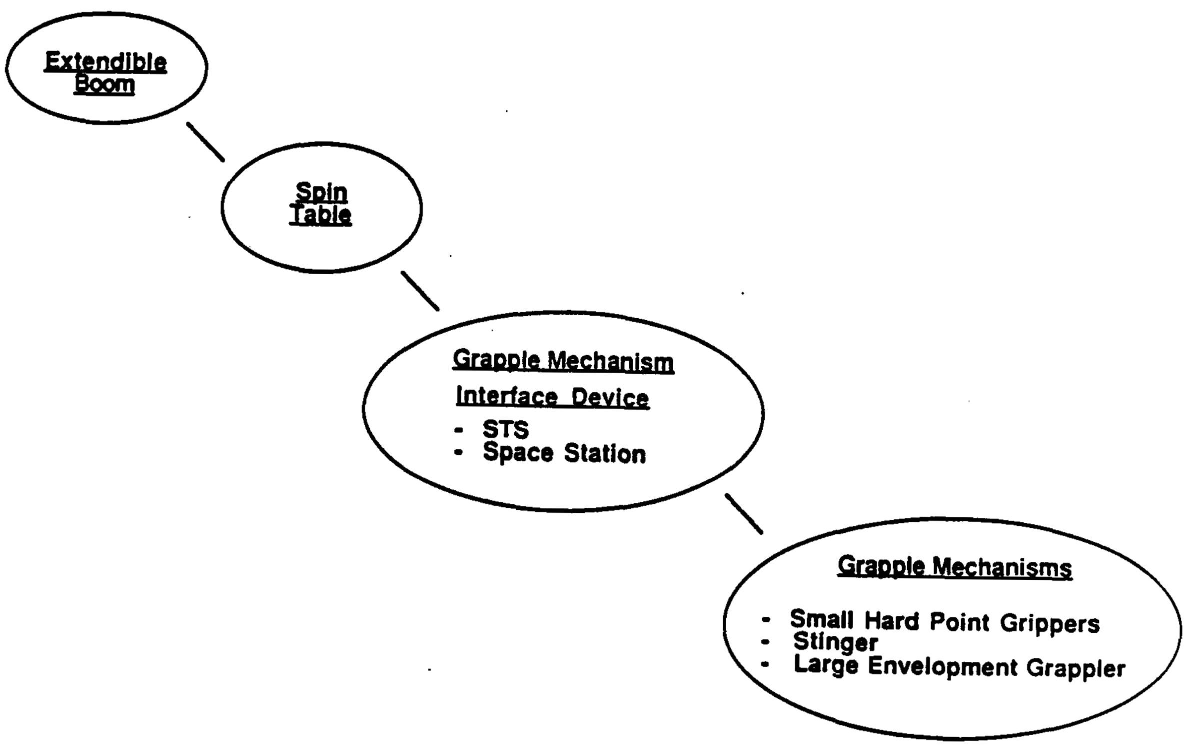


Figure 9.1-1 Recovery Subsystems Evaluation

9.2 Evaluation of Extendible Booms

9.2.1 Introduction - Shown in Figure 9.2-1 are examples of some of the extendible boom concepts identified and evaluated during this phase of the study. The study team considered a wide range of alternatives to avoid unsupportable elimination of questionable candidates. A total of eight extendible boom concepts were identified and evaluated for applications in the TSR Kit. Some of the driving design requirements in this evaluation included: the need to be compact when not deployed (to minimize Shuttle cargo bay delivery space/cost), articulation capability to provide access to obstructed recovery support elements (RSE) and to align target center of mass with the OMV orbit transfer thrust vector prior to orbit transfer, relative weight, and capacity to accommodate grapple/despin force and torque loads.

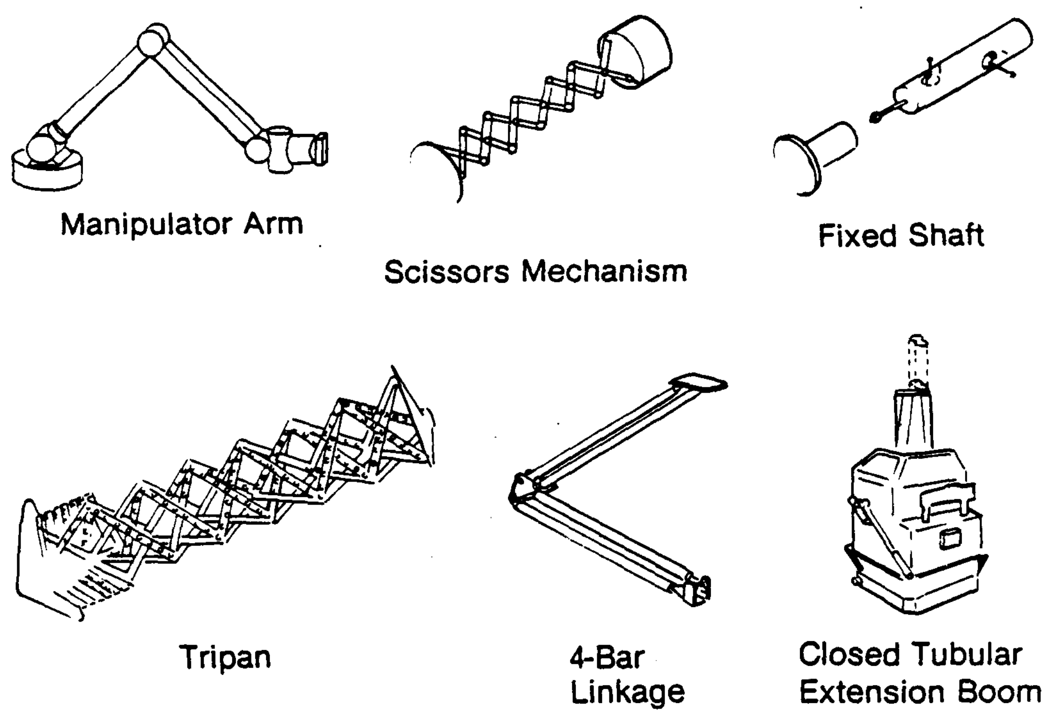
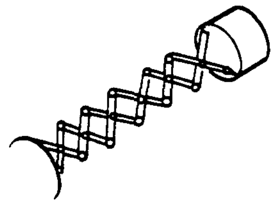


Figure 9.2-1 Extendible Booms

9.2.2 Evaluations - The first of the extendible boom concepts selected for evaluation is the scissors mechanism depicted in Figure 9.2.2-1. The scissors structure, a collection of links, each rotatively pinned at the center and ends, will most likely be actuated by a motor driven screw at the base of the mechanism. The ends of the two links attached at the base will be forced



ADVANTAGE	DISADVANTAGE
• Light Weight • Non-Complex Control	• Limited Capacity for Grapple, Despin Torque Loads • No Articulation for Target Realignment • No Articulation for Access to Obstructed Recovery Support Elements • Not Compact

Figure 9.2.2-1 Scissors Evaluation

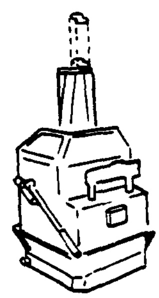
together by travel on the screw. Each of the links will thereby be caused to move from a horizontal position, where the mechanism is in a stowed configuration, to a vertical position, or the fully deployed mechanism configuration.

Of the disadvantages listed in the figure, the most significant is the inability of the mechanism to support grapple and despin torque loads, specifically those in bending and torsion. Load support in tension and compression could be accommodated by a nonbackdrivable actuation system. Any increase in the strength of the links in order to increase the load bearing capability, would only add to an already relatively large stowed volume; as the width of each of the links contributes to the perpendicular distance from the mechanism base, the significant stowed volume dimension.

Although articulation of the extendible boom, listed among the scissors mechanism disadvantages, is a mission specific requirment, it is recommended that the TSRS extendible boom selection be capable of satisfying all mission requirements. Chosen for evaluation because of its simplicity, the scissors mechanism provides a light weight, variable method of satisfying the grapple mechanism extension requirement, but its disadvantages make it unwarranted as an extendible boom choice for the TSRS.

The tubular extension mechanism, illustrated in Figure 9.2.2-2, provides an extremely compact and light weight method of extension. The mechanism employs two long, tape-like plates, joined at the edges by a connection which allows a limited amount of sliding to occur between the plates. The plates are bowed, so that when constricted, their surfaces are flush, but when freed, the plates will curve, and together form an oval. Similar to a tape measure in operation, the plates may be constricted then spooled. When freed they extend from the base. Actuation can be accomplished by a nonbackdriveable motor system within the base. Existing designs employ the device as an extendible antenna, and it has been used in this capacity for space application.

Load bearing capability is not inherent in the design of the tubular extension mechanism and its capacity for grapple and despin torque loads is very limited. Also listed below as a disadvantage is the mechanism's lack of capability to provide target realignment and access to obstructed RSEs. Early in the conceptual design process the mechanism was considered as a method of extension, however, the lack of articulation and load bearing capability make it an unsuitable choice for the TSR kit extendible boom.

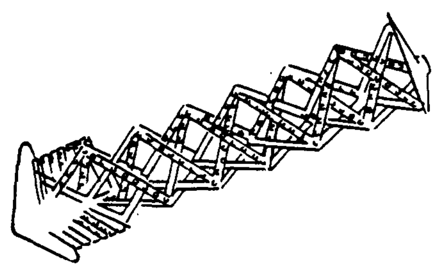


ADVANTAGE	DISADVANTAGE
• Compact • Light Weight • Existing Design • Non-Complex Control	• Limited Capacity for Grapple, Despin Torque Loads • No Articulation for Target Realignment • No Articulation for Access to Obstructed Recovery Support Elements

Figure 9.2.2-2 Tubular Extension Evaluation

Depicted in Figure 9.2.2-3, the Tripan mechanism structure, like that of the scissors mechanism, is a collection of links rotatively hinged at the center and ends. Where the scissors mechanism structure emanates from two links and two base attachment points, the Tripan structure extends from six links and three base attachment points which collectively form a triangle. Each of the two links extending from a base attachment point is pinned at the center and at the far end to another of the links extending from a separate base attachment point. The pinning of the other ends of these base links to additional links then begins the Tripan's triangular structure progression. Again, like the scissors mechanism, the Tripan could incorporate motor drive screws as the methoa of actuation, where the base attachment points are forced to the center of the triangular base. Not recently designed, the Tripan structure is used today in varied industrial applications.

The Tripan mechanism differs significantly from the scissors mechanism in that its structure provides the added load bearing capability in both bending and torsion; yet while heavier than the scissors mechanism, it still offers a light weight method of extension. Should the articulation requirement, to provide access to obstructed grapple fixtures, decrease in significance, the Tripan could be considered as an extendible boom selection.

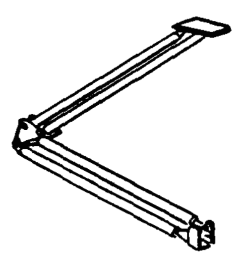


ADVANTAGE	DISADVANTAGE
• Light Weight • Can Support Grapple, Despin Torque Loads • Non-Complex Control	• Not Compact • Higher Reliability, Maintainability Demands • No Articulation for Target Realignment • No Articulation for Access to Obstructed Recovery Support Elements

Figure 9.2.2-3 Tripan Evaluation

The 4-bar linkage illustrated in Figure 9.2.2-4 was previously developed by MMC for space application. The linkage was designed so that when extended, the end to be attached to a grapple mechanism will travel in a linear path perpendicular to the base plate. One of the two links of each of the linkage arms is hinged at the elbow plate; the remaining two links have attached gears which mesh at the elbow. A rotation of the geared link secured at the base is effected by a nonbackdriveable torque motor. This rotational actuation and a two to one gear ratio at the elbow are responsible for the linear extension. The linkage is very compact in terms of the critical volume dimension; although the length of the links, constrained by the radius of the Orbiter cargo bay, limits the extension to roughly 15 feet.

Like the previous concepts, the 4-bar offers a non-complex accommodation to the recovery system extension requirement. As a light weight mechanism, its load carrying capability is limited in bending and torsion. The tradeoff of increased weight for increased load carrying capability will not, however, create a significant increase in compacted volume. The 4-bar linkage, like the Tripan, could be considered for the TSRS in the absence of the articulation requirement for access to obstructed grapple fixtures and alignment of target center of mass prior to orbit transfer.

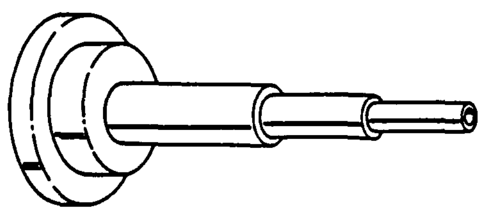


ADVANTAGE	DISADVANTAGE
• Compact • Light Weight • Can Support Grapple, Despin Torque Loads • Non-Complex Control	• Insufficient Articulation for Target Realignment • Insufficient Articulation for Access to Obstructed Recovery Support Elements

Figure 9.2.2-4 4-Bar Linkage Evaluation

One possible design for the telescoping extendible boom concept, previously developed by MMC and shown in Figure 9.2.2-5, involves a series of tubes, threaded to allow extension of one with respect to another. Actuation of the mechanism is accomplished by reversible torque motors surrounding each tubular section. Rotation of any of the sections, effected by its corresponding motor, will extend that section and those sections of smaller diameter. The telescoping mechanism will provide a variable method of extension, capable of supporting the grapple and despin torque loads of a recovery mission.

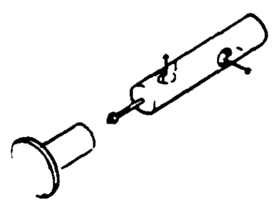
Although the telescoping mechanism is incapable of articulation, the other disadvantages identified in the figure, make it unwarranted as a TSRS boom selection for even limited recovery missions. The fact that the material of which the tubular sections are made must be capable of maintaining a threaded interface, precludes the boom from being a light weight structure. Additionally, the structure is difficult to design to be compact in terms of the volume dimension perpendicular to the base. The grounded or initial tubular section, into which the other sections are compacted is proportional to the overall extension of the mechanism. A decrease in the length of this section, in an effort to decrease the compacted volume, will produce a decrease in the overall extension. Reliability and maintainability requirements higher than the previous concepts are also introduced, as a result of torque motors associated with each tubular section.



ADVANTAGE	DISADVANTAGE
• Can Support Grapple, Despin Torque Loads	• Heavy • Not Compact/Difficult to Design to be Compact • No Articulation for Target Realignment • No Articulation for Access to Obstructed Recovery Support Elements • Higher Reliability/Maintainability Requirements

Figure 9.2.2-5 Telescoping Boom Evaluation

The simplest of the extendible boom concepts is a fixed shaft. Although relatively heavy, there are no constraints regarding its composition, and a number of materials could be used to reduce its weight. But by providing the greatest capability to support grapple and despin torque loads, it also includes the most significant disadvantage: inflexibility in requiring valuable Orbiter cargo bay volume. A fixed shaft, though obviously not recommended as a TSRS selection, can be used for comparative evaluation, and was included for completeness. A summary of its advantages and disadvantages is provided in Figure 9.2.2-6.

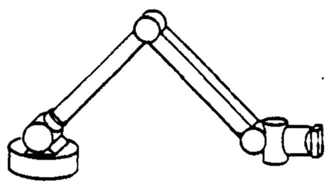


ADVANTAGE	DISADVANTAGE
• Can Support Grapple, Despin Torque Loads • Non-Complex Control	• Heavy • Not Compact • No Articulation for Target Realignment • No Articulation for Access to Obstructed Recovery Support Elements

Figure 9.2.2-6 Fixed Shaft Evaluation

Contrary to the fixed shaft, of the extendible boom concepts selected for evaluation, the robotic manipulator is the most complex. The manipulator depicted in Figure 9.2.2-7 was previously developed by MMC, and it is typical of robotic arm design. A manipulator arm enjoys the advantage of being a multiple degree-of-freedom (DOF) device, capable of providing target realignment and access to obstructed RSEs. The MMC design includes four DOF, as a result of joints at the base, elbow, and two at the spin/despin mechanism or grapple mechanism interface. A motor, gearbox, and control sensor are part of each joint, and together create significant control complexity and increased reliability and maintainability requirements. Tubular arms composed of aluminum alloy are incorporated, in an effort to minimize weight, yet the mechanism weight remains relatively high. Like the 4-bar mechanism, the manipulator has a very compact stowed configuration.

The study team felt that the higher weight and complexity of a robotic arm are offset by its articulation, compacted volume, and load bearing characteristics. The manipulator was favored as the preferred TSR kit extendible boom concept.

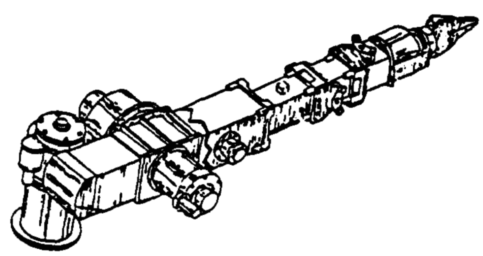


ADVANTAGE	DISADVANTAGE
• Compact • Can Support Grapple, Despin Torque Loads • Existing Designs • Enables Realignment of Target Mass for Transport • Enables Access to Obstructed Recovery Support Elements	• Heavy • Increased Control Complexity

Figure 9.2.2-7 Manipulator Evaluation

The Extendible Stiff Arm Manipulator (ESAM), a more specific design of robotic manipulator developed at MSFC, was included in the extendible boom subsystem evaluation. Shown in Figure 9.2.2-8, the ESAM structure consists of an extendible structural section deployed from within a grounded section, both of square cross section. Roll, pitch, and yaw end effector positioning are incorporated in the wrist assembly of the extendible section. This positioning, coupled with the azimuth, elevation, and extend/retract capability of the grounded section, make ESAM a six DOF mechanism. Each of the ESAM joints includes a reversible DC motor, for which a control system effects position and rate control. The ESAM extension range is approximately 27 inches.

Most of the advantages and disadvantages of the manipulator can also be attributed to ESAM, as both are robotic manipulators. A significant difference though, exists between the methoas of articulation of the mechanisms. ESAM, while a six DOF mechanism, does not enable access to obstructed RSEs nor target realignment, as its articulation is accomplished at either the base or the end effector. Modification of the ESAM design could provide a more appropriate extension range and adequate load bearing capability, but a complete redesign would be necessary to meet the articulation requirement.



ADVANTAGE	DISADVANTAGE
• Compact • Can Support Grapple, Despin Torque Loads • Modification to Existing Design	• Heavy • Increased Control Complexity

Figure 9.2.2-8 ESAM Evaluation

9.3 Spin/Despin Mechanism Definition

The concept selected for the Spin/Despin Mechanism subsystem is an existing design, functioning as part of a three axis gimbal within the MMC Space Operations Simulation Laboratory. An assessment of this design was accomplished in order to provide conceptual level definition for follow-on efforts. The mechanism consists of a spin platform, DC torque motor, servo control amplifier, tachometer, and electrical brake.

Rotation of the spin platform in either direction is effected by the reversible backdrivable DC torque motor, through a direct interface between the two. The backdrivable system necessitates an electrical brake to hold the grapple mechanism stationary during stowage, before spin up, and after despin. Speed control is accomplished by coupling the tachometer signal with current adjustment of the amplifier. In the spin up mode, the amplifier increases the current to effect a proportional torque increase of the motor, until the tachometer senses the correct speed. In the despin mode, the DC torque motor functions as a generator. The current generated is dissipated across the amplifier, producing a proportional decrease in torque.

9.4 Definition of Grapple Mechanism Interface Devices

The grapple mechanism interface device definition process identified the requirement for unique interface devices for both ground assembly, for Orbiter based operations, and on-orbit recovery kit assembly, for potential Space Station operations. An interface device was defined for each case and they are discussed below.

The ground assembled interface flange, conceptually illustrated in Figure 9.4-1, provides an interface connection between subsystems, such as that between the grapple mechanism and the spin/despin mechanism. The flange was identified as part of ground assembled recovery kits which require no on-orbit changeout of subsystems. A bolted assembly is required for each subsystem interface.

Initially intended as a grapple mechanism interface device, it can be used as a readily applied interface between several components of a modular, interchangeable recovery system.

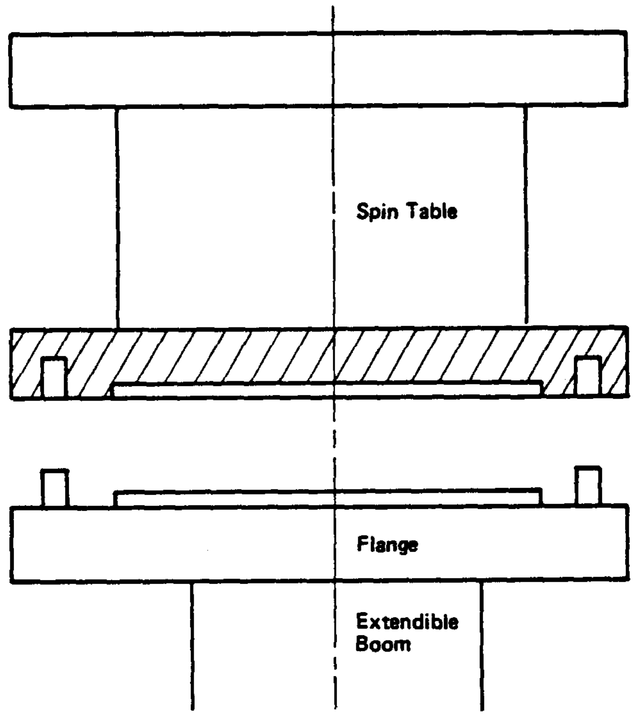
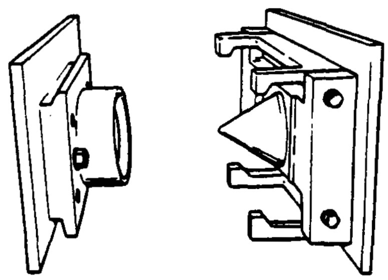


Figure 9.4-1 Ground Assembled Interface Flange

For recovery kits based at the Space Station, it was assumed that assembly of recovery kit elements would be accomplished robotically. This, in turn, requires an interface mechanism capable of providing a simply accomplished, firm connection during assembly. The Robotically Operated Interface Device, illustrated in Figure 9.4-2, was identified and assessed as a possible on-orbit interface accommodation.

The device includes both a passive and an active element. The latter consists of an alignment cone and electrically operated latches. The passive element includes a plate with lips on opposite edges, on which the latches secure, and a cavity hollowed to the shape of the cone. The elements will be attached to opposing subsystems at the interface. As the mechanisms are brought together, the mating of the cone and cavity provides an accurate alignment. Actuation of the latches is accomplished by a small motor, effecting a simultaneous rotation of the latches through an open/lock sequence. The travel of the latches, in degrees, is small and the rotation is accomplished quickly. A secure connection is maintained as a result of incorporating a nonbackdriveable system. Like the ground assembled interface flange, the device is required at each subsystem interface.

The device has been previously developed, which provides the additional advantage of being an existing design. As with other robotic devices, it has higher reliability and maintainability requirements and additional control complexity.



ADVANTAGE	DISADVANTAGE
• Simple and Very Rigid Connection • Enables Accurate Alignment • Compact, Allows Access to Volume-Limited Regions • Standardized Interface, Common to TSRS Subsystems, and to Other OMV Kits • Existing Design	• Additional Control Complexity • Higher Reliability, Maintainability Requirements

Figure 9.4-2 Robotically Operated Interface Device

9.5 Grapple Mechanism Evaluation

9.5.1 Introduction - Three categories of grapple mechanisms were identified which address the grapple mechanism requirements of Systems B and C. The mechanism types and their corresponding systems are shown in Figure 9.5.1-1. Within the categories, alternatives were recognized and evaluated, from which the selections for the more detailed evaluation of follow-on efforts may be

• Small Gripper - System B

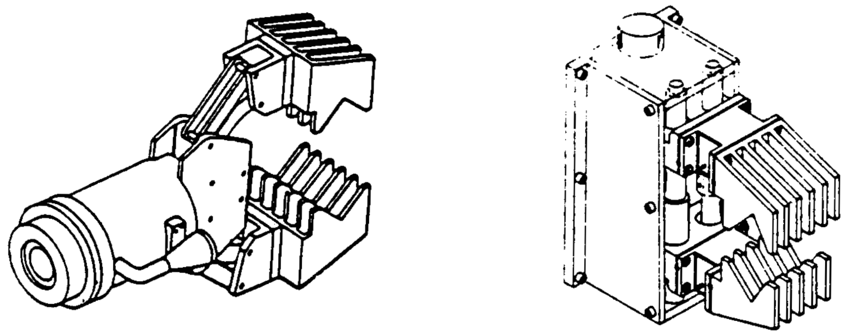
• Stinger - Spin Stabilized, Controllable - System C

• Large Enveloper - System C

Figure 9.5.1-1 Grapple Mechanism Evaluation

accomplished. The criteria identified and applied in the evaluations included: weight, compactness, accommodation of a range of satellite and hardpoint sizes, strength of grapple, target damage potential, positioning flexibility, accommodation of grapple, despin, and transport loads, and complexity.

9.5.2 <u>Small Gripper Definition</u> - The MSFC Proto-Flight Manipulator Arm (PFMA) End Effector and the JPL PFMA Smart Hand were selected by the study team as two possible accommodations of the System B small gripper mechanism requirement and are illustrated in Figure 9.5.2-1. Both provide parallel jaw motion, minimizing reaction away from the mechanism during grapple. The intermeshing parallel plate designs and square recessed shapes of the jaws enable grapple of hardpoints of varied size and shape; although in both cases, the maximum jaw opening is limited to 3.5 inches. Variable closure rates and grapple forces are incorporated, with maximum grapple forces of 90 and 120 pounds. Each of the mechanisms includes a provision which maintains the grapple force in the event of power loss.

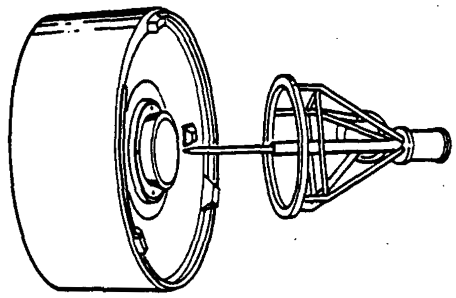


ADVANTAGE	DISADVANTAGE
• Enables Grapple of a Variety of Round, Flat, or Irregularly-Shaped Hardpoints • Intermeshing Jaw Plates Enable Pickup of Smaller Hardpoints • Accomplishes Firm Grip • Adjustable Grip Force and Closure Rate • Grapple Unaffected by Power Loss • Design Available, Proven	• Size of Hardpoints Grappled Limited by Geometry of Mechanism

Figure 9.5.2-1 Small Gripper Definition - PFMA End Effectors

These existing mechanism designs reflect the state-of-the-art for non-dexterous hands and provide capable accommodations of the small gripper requirement. Follow on efforts involving analyses of transport loads and mission model hardpoint configurations will enable complete assessments of the applicability of these mechanisms to the System B requirements.

9.5.3 Stinger-Type Grapple Mechanism - The obvious and unique selection for the grapple mechanism of System C, involving recovery of spin stabilized spacecraft, is the Apogee Kick Motor (AKM) Attachment Device (Stinger). Its capability has been proven in the Westar-Palapa recovery mission, where the recovery of two spin stabilized spacecraft was safely accomplished without damage to either vehicle. The stinger is depicted in Figure 9.5.3-1.



ADVANTAGE	DISADVANTAGE
• Enables Grapple of Spin Stabilized Target • Design Available, Proven	

Figure 9.5.3-1 Stinger-Type Grappler

9.5.4 Evaluation of Large Envelopment-Type Grapple Mechanisms - Accommodation of the System C, large envelopment-type grapple mechanism requirement was offered to the study team by a large number of varied concepts. The five most promising were identified as a possible focus for follow on efforts, and are illustrated in Figure 9.5.4-1. An additional MSFC concept was later identified and evaluated. A summary of each of the concept evaluations is provided below.

Shown in Figure 9.5.4-2, the Multisegmented Arm proposes envelopment-type capture of recovery candidates. Composed of a hinged series of small links, its two arms are actuated by a combination of spring force and cable tension. Cables are attached to the links at the tips of each arm and wound through the remaining links in such a way, that when tightened by a motor and reel at the base, cause an inward curling motion of the arms. Springs located in each segment, oppose the cable tension and with the cables released, effect the fully deployed, straightened configuration of the arms. A high cable tension is required to overcome the force of the springs and produce sufficient contact force at the satellite surface. Inherent in the linkage structure are mechanical stops, which limit the minimum grapple diameter and compacted volume.

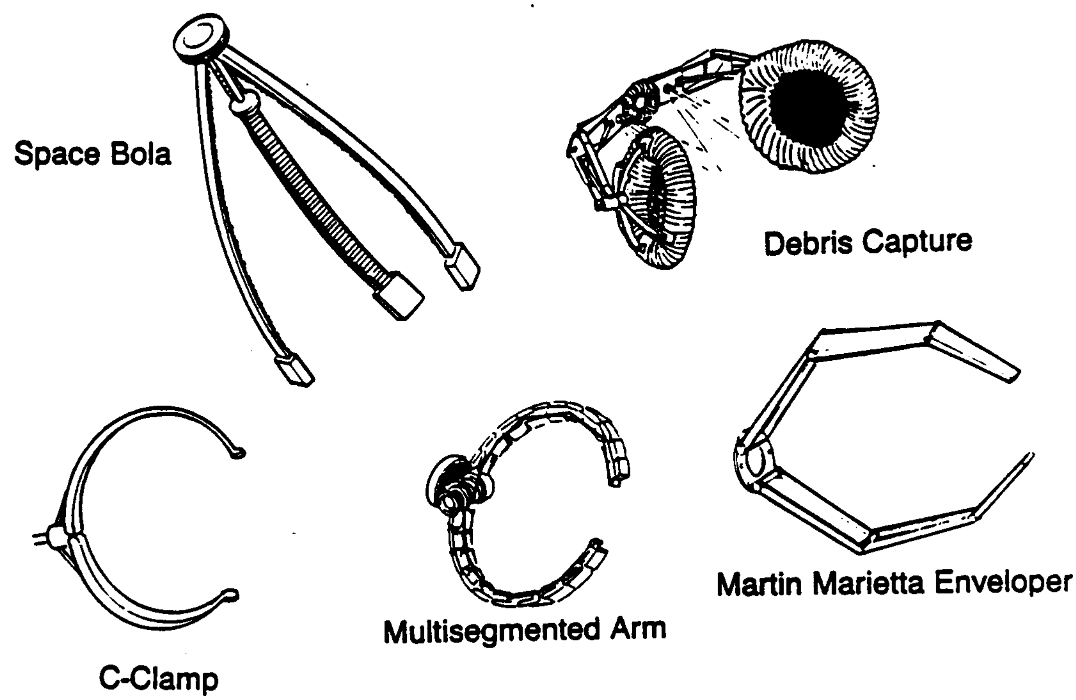
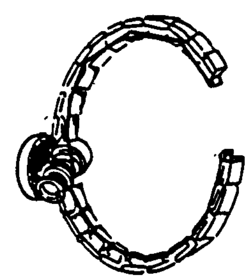


Figure 9.5.4-1 Enveloper Mechanisms



ADVANTAGE	DISADVANTAGE
• Accomplishes Rigid Grapple	• Not Compact • Limited Capacity for Target with Spin on Longitudinal Axis • Relatively Heavy • Limited Flexibility in Positioning of Grapple Mechanism • System Not Applicable to Wide Range of Satellite Sizes

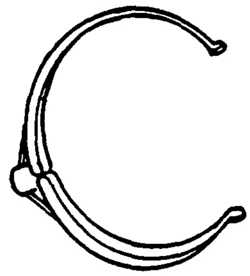
Figure 9.5.4-2 Multisegmented Arm Evaluation

The mechanism provides a consistent but unalterable envelopment motion, and its recovery capability is limited in tight target configurations. The number of hinges within the arms prevents the Multisegmented Arm from being a light weight device. Additionally, the negligible surface area at the tips of the arms, contributes to an already limited capability of the mechanism to recover satellites with spin on the longitudinal axis. These, and the more significant disadvantages of not having a compact stowed volume and a limited envelopment diameter range, withhold the Multisegmented Arm from consideration for follow on efforts.

The C-Clamp mechanism and its evaluation summary are shown in Figure 9.5.4-3. Although designed for recovery of satellites with spin on the longitudinal axis, it also accommodates transverse axis spin for satellites within a small range of diameters. The mechanisms two solid arms are hinged at the base, and through a variety of possible actuation methods, are caused to rotate. Satellite capture is then accomplished between the large surface areas of the arm tips. For satellites with large diameters and transverse axis spin, actuation of the mechanism is accomplished in the same way, but the arms envelop the satellites, with satellite surface contact possible over the length of the arms. The solid composition of the arms prevents a small compacted volume and severely restricts the mechanism's capability in dealing with tight satellite configurations.

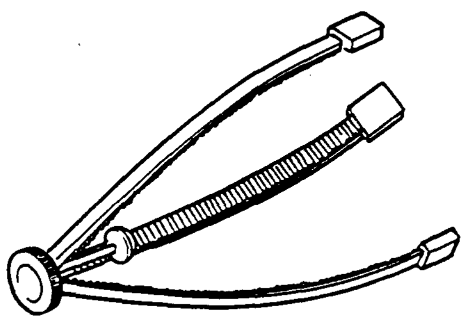
Although limited as an overall System C grapple mechanism, the C-Clamp provides a viable method of capturing a specialized case of disabled satellites.

The Space Bola, depicted in Figure 9.5.4-4, provides the most unique recovery method of the concepts selected for evaluation. The mechanism consists of three inflatable arms of light weight, flexible material, with a velcro covering on the arm tip surfaces and small rockets attached near the ends. Initially, the arms are inflated to deploy them from a stowed configuration. They are then deflated, simultaneous to the firing of the rockets. Together, the arms are forced to wrap around a recovery candidate, their ends make contact, and a velcro connection is secured. To rigidize the grapple, tension is applied to the arms by motor driven spools.



ADVANTAGE	DISADVANTAGE
• Light Weight • Applicable to a Wide Range of Satellite Sizes (Longitudinal Axis Spin Only)	• Not Compact • Limited Capacity for Target with Spin on Transverse Axis • Limited Flexibility, to Grapple in Tight Target Configurations, in Positioning of Mechanism

Figure 9.5.4-3 C-Clamp Evaluation



ADVANTAGE	DISADVANTAGE
• Light Weight • Compact	• Limited Flexibility in Positioning for Envelopment • Grapple Operation not Repeatable - Velcro Fastener Closed - Rocket Reload Required • Strength of Arms Questionable for Despin, Target Transport to STS & Space Station • Rigid Grapple is Questionable

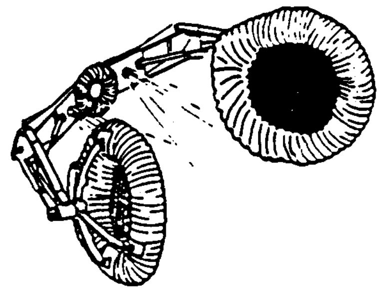
Figure 9.5.4-4 Space Bola Evaluation

In concept, the Space Bola provides an extremely compact and light weight accommodation to the System C grapple mechanism requirement, but many aspects of the envelopment operation are questionable or impractical. Of these, the most significant are the strength of the velcro connection and the possibility of an inaccurate envelopment by the arms, requiring a reload of the rockets. Additionally, the inflexibility of the envelopment method makes recovery of satellite configurations involving protuberances impractical.

Seemingly a simple concept, yet a significant development effort would be required to produce an operational mechanism in which confidence was high.

The Debris Capture Device developed by LTV, is shown in Figure 9.5.4-5. It consists of a pair of low pressure toroids mounted on adjustable arms, with which it accomplishes a two point grapple similar to that of the C-Clamp. The grapple force is applied through the arm assembly, by a hydraulic system at the base of the mechanism. The toroids minimize damage to recovery candidates by conforming to irregular satellite surfaces and dissipating the forces of contact dynamics. Although providing only a two point capture, the large surface area of the toroids securely accommodates a wide range of satellite sizes.

The Debris Capture Device is one of the preferred concepts of those selected for evaluation, yet it has several disadvantages. The mechanism structure is large, mandating a voluminous mechanism of relatively high weight. Added control complexity and reliability/maintainability requirements result from the hydraulics, toroids, and the many linkages involved. Following grapple and despin, the mechanism's capability in providing sufficient rigidization during transport is questionable, as contact with the recovery candidate is sustained by a compressible device. Finally, as presently configured it offers limited compactness.

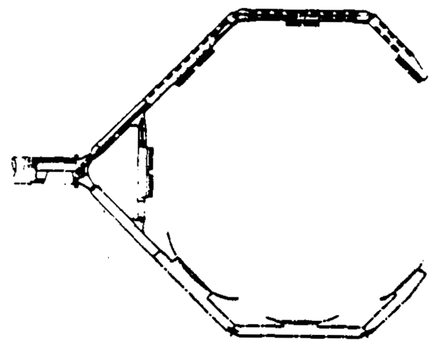


ADVANTAGE	DISADVANTAGE
• Accommodates a Wide Range of Satellite Sizes • Soft Contact, Minimizes Target Damage	• Not Compact • Heavy • Complex Control • Questionable Transport Rigidization Capability • Bulky, Limited Flexibility in Tight Target Configurations • Increased Reliability/Maintainability Requirements

Figure 9.5.4-5 Debris Capture Evaluation

The MSFC Enveloper, depicted in Figure 9.5.4-6, has undergone preliminary design/development by MSFC. The mechanism is similar in operation to a combination of the Multisegmented Arm, in which all of the arm links operate in conjunction, and the MMC Enveloper, evaluated below.

Two methods of actuating the grappler's arms have been incorporated in the mechanism. The base links of each arm are connected and operated by an actuation system between the two, which effects an inward/outward rotation of the arms. The remaining two arm links operate in conjunction with one another, and the similar links of the opposing arm, as a result of a motor within the base and a corresponding linkage. The linkage causes an equal rotation of all four arms, producing a curling motion like that of the Multisegmented Arm. The combined effect of the two systems is an increase in flexibility in positioning for envelopment, and an increased capability in recovering smaller satellites.



ADVANTAGE	DISADVANTAGE
• Light Weight • Relatively Compact • Accommodates a Range of Satellite Sizes • Flexibility in Positioning for Envelopment	• Increased Reliability/Maintainability Requirements

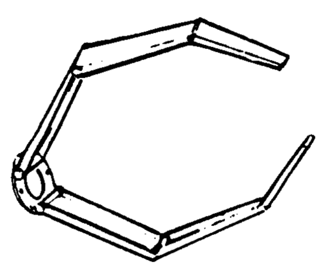
Figure 9.5.4-6 MSFC Enveloper Evaluation

The device is designed for envelopment-type capture, yet the width of the end links also enables a two point capture, thereby accommodating longitudinal axis spin. Hard rubber pads are provided on the links and the cross member actuation system, in an effort to minimize target damage. It is a relatively light weight mechanism but its compacted volume remains large. A slight increase in control complexity and reliability/maintainability requirements, relative to some of the other concepts, results from its increased flexibility.

The final mechanism evaluation, shown in Figure 9.5.4-7, involves the MMC Enveloper, which was conceptually designed by the study team to provide a System C grapple mechanism which was designed from the requirements allocated to the envelopment grappler, done in Task 1. A detailed description of the mechanism is presented in the Task 2.2 accomplishments (see Section 10.0); therefore only a brief overview and evaluation are provided here.

The mechanism incorporates a two arm, six member structure. Driven by DC torque motors in the joints, each of the links can be operated independently. To maintain symmetry, control software is employed so that opposing links, i.e., the base links of each arm, operate in conjunction. The geometry of the members allows a folded, and extremely small compacted volume, with sufficient surface area at the end of each arm to enable a two point capture. Like the MSFC enveloper, appropriate structural member design and composition will produce a relatively light weight mechanism.

The substantial increase in flexibility of the grapple operation as a result of the independent activation of the links, provides a number of advantages. The flexibility in positioning for envelopment, around varied protuberance configurations is optimized. The design enables envelopment before contact, thereby dissipating target reactions and negating target reaction away from the mechanism. Target damage is minimized, as contact dynamic forces will be reduced with the grapple elements closer to the recovery target when first contact occurs. The mechanism's increased flexibility though, creates a proportional increase in control complexity and reliability/maintainability demands. These disadvantages are outweighed by the number of advantages shown in Figure 9.5.4-7, and this enveloper mechanism was selected for inclusion in the System C design configuration.



ADVANTAGE	DISADVANTAGE
• Light Weight • Compact • Optimum Flexibility in Positioning for Envelopment • Accommodates a Wide Range of Satellite Sizes • Control of Multiple Links Equalizes Contact Force/Minimizes Satellite Damage • Accomplishes Envelopment Before Contact • Accomplishes Rigid Grapple	• Added Control Complexity with Multiple Controllable Arm Segments

Figure 9.5.4-7 MMC Enveloper Evaluation

The matrix of Figure 9.5.4-8 provides a summary of the System C envelopment-type grapple mechanism evaluation. The advantages identified in the evaluations are shown appropriately applied to each of the mechanism concepts.

ADVANTAGES	LIGHT WEIGHT	APPLICABLE TO A WIDE RANGE OF SIZES	MINIMIZES TARGET DAMAGE	COMPACT WHEN STOWED	MINIMIZES CONTACT DYNAMICS	FLEXIBILITY IN POSITIONING FOR ENVELOPMENT	ACCOMPLISHES A RIGID GRAPPLE	ACCOMPLISHES ENVELOPMENT BEFORE CONTACT	MINIMIZES DYNAMICS OF MECHANISM DEPLOYMENT	LOW RELIABILTY/ MAINTAINABILITY REQUIREMENTS
MULTISEGMENTED ARM							X		X	X
C-CLAMP	X								X	X
SPACE BOLA	X	X	X	X	X					
DEBRIS CAPTURE		X	X		X			X	X	
MSFC ENVELOPER	X	X			X	X	X		X	
MMC ENVELOPER	X	X	X	X	X	X	X	X	X	

Figure 9.5.4-8 Envelopment-Type Grappler Evaluations - Summary

10.0 TUMBLING SATELLITE RECOVERY SYSTEM CONCEPTUAL DESIGN - TASK 2.2

The objective of the second concept definition task, Task 2.2, was to develop a set of conceptual designs for TSR systems. The approach used was to select the preferred set of subsystem mechanisms and to integrate them into a basic OMV TSR kit that met the study team's objective of system modularity and ready interchange of subsystem components. This, of course, enables the system to be assembled readily into a variety of different recovery systems tailored to the unique recovery scenario presented to the user.

10.1 TSR Conceptual Design Drivers

The formulation of a design architecture for the recovery systems was influenced heavily by a number of key factors driven out by the requirements analysis. These are shown in Table 10.1-1. The first of these was the inherently broad range of recovery scenarios identified during Task 1. This fundamental reality caused the study team to select from two apparent options: (1) operate from a design concept that would provide an equally wide range of recovery systems; or (2) develop a design concept with a modular design as a framework that could be configured readily into recovery systems tailored for specific missions. The latter approach was selected.

Table 10.1-1 Key Design Drivers

- Broad Range of Recovery Scenarios Dictates
  - Wide Range of Recovery Systems, or
  - Modular System Easily Configured into Recovery System Tailored for Specific Missions
- Recovery Kit Must Be Compact - Efficient STS Operations
- Minimum Risk to OMV
- Recovery Operations Bounded by OMV Controllability
- Target Rigidized for Return to STS or Space Station

Another key design criterion turned out to be the need for a compact design. The TSR system is being designed as an OMV front end kit and carried into orbit in the Orbiter cargo bay. The OMV has been configured for compactness to minimize cargo bay space necessary for delivery into orbit. Though no other study reflected this requirement, MMC believed the structural design should be as compact as possible and selected subsystem options that supported this design driver.

Another prominent design factor was related to minimizing risk to the OMV during all phases of recovery operations. One risk element involved the need to maintain a proper distance from the OMV during operations, a design requirement readily accommodated by the selection of an effective extension device. A related secondary design driver was the perceived necessity to retain control of the OMV during recovery operations. The primary concern here was the concern that with contact dynamics forces in excess of OMV control authority, ground controllers could lose the capability of controlling OMV and the TSR kit, with potential resulting damage to both.

Finally, no other study had considered the requirement to have the target satellite firmly grappled for transport back to the Shuttle or to Space Station. This requirement influences the choice of grapple mechanisms for the different recovery systems.

10.2 Modular TSR System Design

The representation of a modular design for a family of recovery systems is provided in Figure 10.2-1. This expanded view displays the major components of the system and the inherent capacity to interchange, add, or subtract individual components to tailor the kit for specific missions.

As shown on Figure 10.2-1, one of the primary features of the design is a structural interface element that is readily attached to the OMV docking latches in manual mating operations in the STS cargo bay during launch processing. The electrical power and communications and data management (C&DM) interfaces will be through the OMV payload umbilical mounted on the front face of the OMV.

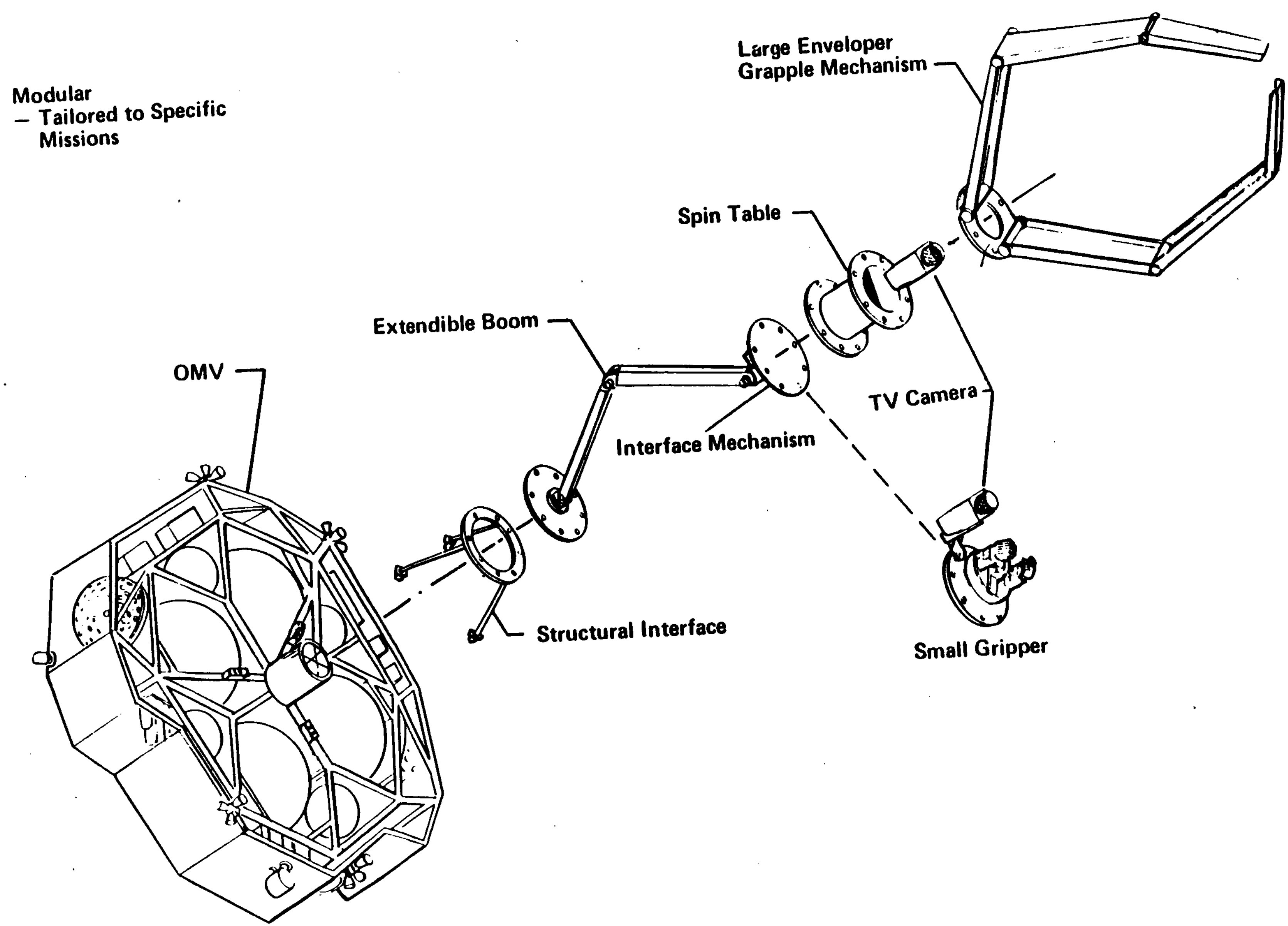


Figure 10.2-1 Tumbling Satellite Recovery Kit

The next component, referring to Figure 10.2-1, is the extendible boom. A four degree of freedom manipulator arm with pitch and yaw positioning at the grapple mechanism interface was selected as the extendible boom for the system. This mechanism is capable of folding into a compact stowed position. Its most important function is to provide safe clearance between the OMV and a spinning target. The manipulator arm provides the capability to reach recovery support elements that are obstructed to an approach by OMV due to deployed target elements, such as solar arrays, antennas and experiment packages. It also enables alignment of a target's center of mass with the OMV orbit transfer thrust vector following capture and prior to orbit transfer.

A third major component is the spin table. The spin table will house a direct current reversible torque motor and a tachometer unit to enable precise control of the spin-up of the recovery system and maintenance, within close tolerance, of the spin rate and phasing of the system during recovery operations. The spin table can be mounted efficiently to the interface flange on the end of the extendible boom. Also shown configured within the spin table is a boresight, wide angle view television camera. On this base, it can be mounted in a fixed configuration, or configured to spin at the same rate as the spin table. During initial independent research in satellite recovery simulations, it was unclear whether the operator was supported best by a fixed or spin rate matching boresight camera. This optional camera configuration was included to support development of a flexible system design architecture.

In this representation of the recovery system, both the System B and System C recovery kits are shown. The full-up System C has the MMC enveloper grapple mechanism attached to the flanged grapple mechanism interface device. This system will be capable of recovering satellites with what was previously defined as the more complex tumble motion to be expected. This motion will be created by a satellite failure producing some level of angular momentum that exceeds satellite attitude control capability. The resulting tumble motion will be general motion initially, with multi-axis spin; however, it is expected to evolve to single axis spin about the satellite's major principal axis.

The System B configuration is also represented on Figure 10.2-1. This system includes the structural and electrical/C&DM interface with OMV, the extendible boom and a small gripper, connected to the system with the grapple mechanism interface flange. In addition, a close proximity television camera is attached to the smaller gripper to provide localized viewing of the attachment to the hard point of a remote, controllable satellite. This portrays how amenable this design is to subsystem interchange and its capacity for accommodating a wide variety of recovery missions.

10.3 TSR System - Compact Design

As expressed earlier, one of the key design drivers was the requirement to make all the TSR kit elements as compact as possible for efficient transport with OMV in the Orbiter cargo bay. In Figure 10.3-1, this presentation of the full-up recovery System C shows all of the subsystem mechanisms in folded or non- deployed configurations. All of the subsystem alternatives shown here and evaluated in Section 9.0 were the most compact of the alternatives considered. The single exception is the case of the extendible boom, where the 4-bar mechanism is considered equally compact when compared with the foldable manipulator arm. The scale of this set of mechanisms is accurate as shown, however, these designs are conceptual and have not been optimized for compactness.

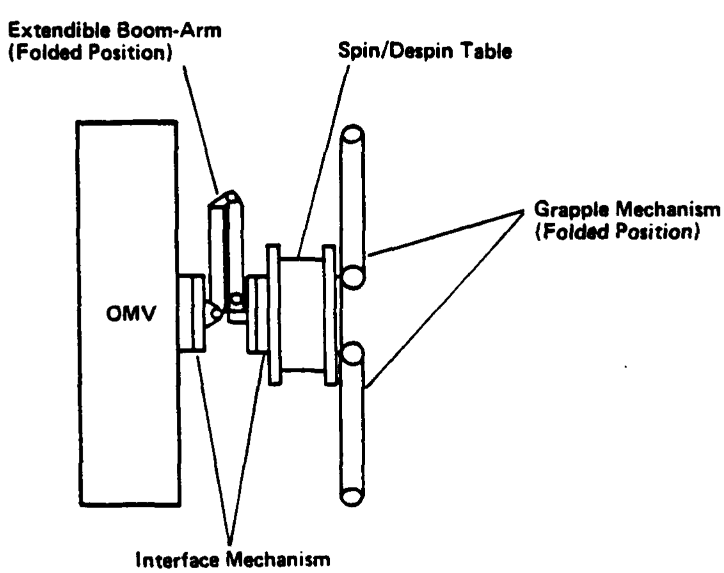


Figure 10.3-1 TSR - A Compact Design

Another example of how this conceptual TSR system was designed for compactness is shown in Figure 10.3-2. One of the key features of this grapple mechanism was the designed-in capacity to fold each of the outer two grappler segments, in each of the two arms of the grapple mechanism, into the adjacent segment of the arm. This design feature provides a highly compact grapple mechanism. None of the other grapple mechanism candidates were considered as having even a reasonable degree of compactness and that was one of the reasons the study team concentrated on the conceptual design of the MMC enveloper grapple mechanism.

The size of the grapple mechanism envelope is illustrated in Figure 10.3-2. The length of one of the pair of grapple arms, which is sized to envelope a fifteen-foot diameter target is nearly 19 feet. The inner segments of the grapple elements are sufficiently larger than the adjacent outer elements to allow each of the two outer segments to fold inside the other. This design approach was used to provide maximum compactness for the folded grappler.

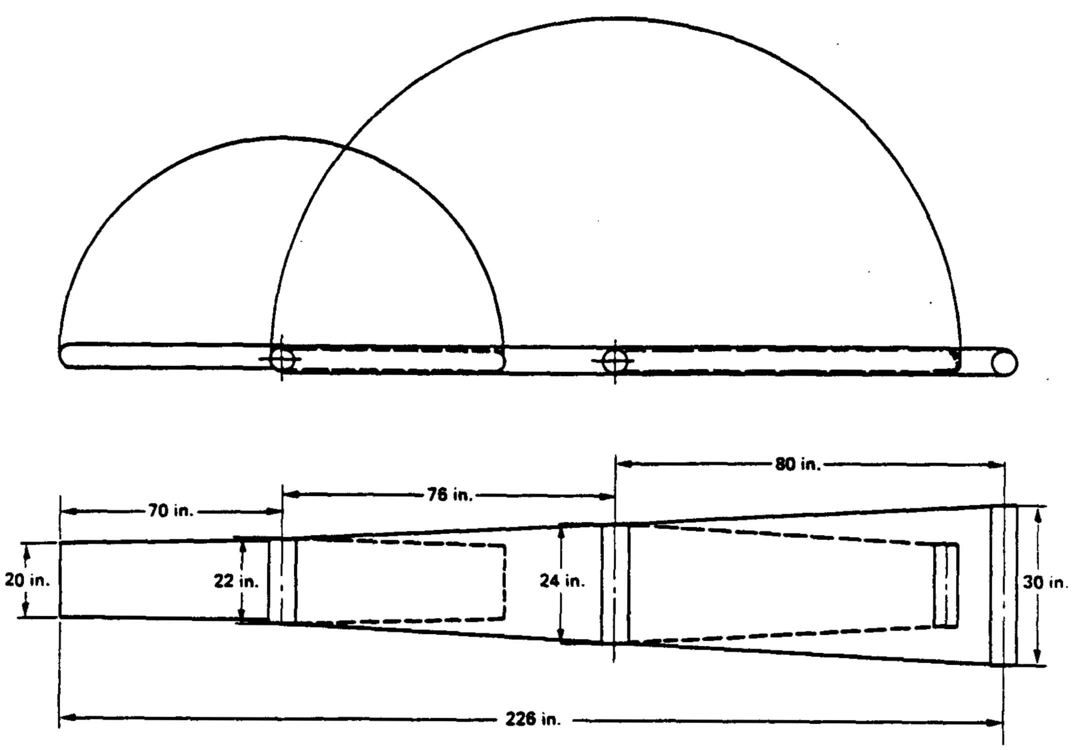


Figure 10.3-2 MMC Enveloper Grapple Mechanism

Another of the principal design drivers for the recovery system was minimizing risk to the OMV and TSR kit during recovery. In addition to providing compactness, as shown in Figure 10.3-3, the half-deployed extendible boom was incorporated into the system to reduce risk to OMV. The extendible boom, shown in Figure 10.3-3 as a four-degree-of-freedom manipulator arm, is extended to provide clearance between the OMV and a rotating satellite with spinning appendages.

10.4 MMC Enveloper Grapple Mechanism

The conceptual design of the MMC enveloper, which was selected as the grapple mechanism element for one of the conceptual System C recovery configurations, was influenced by an increasing concern on the part of the study team regarding the potential impact of contact dynamics between the TSR kit and the target during the grapple phase.

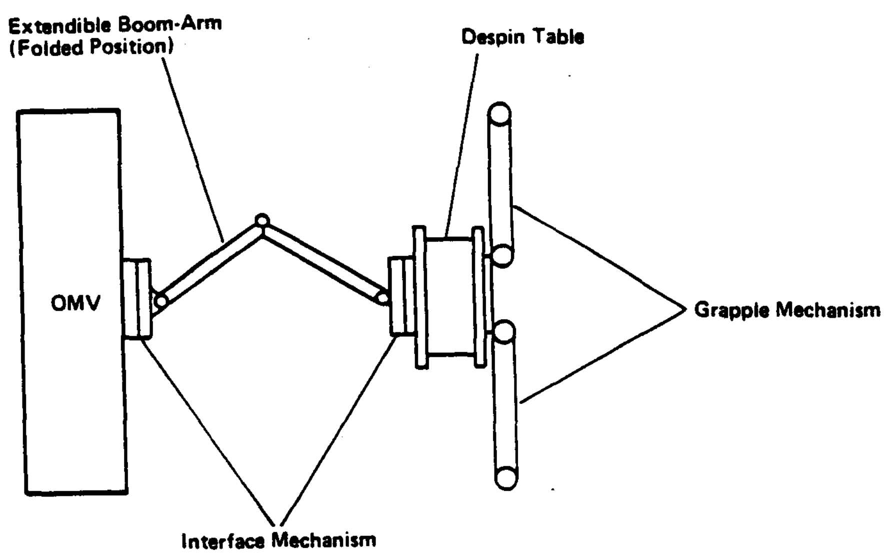
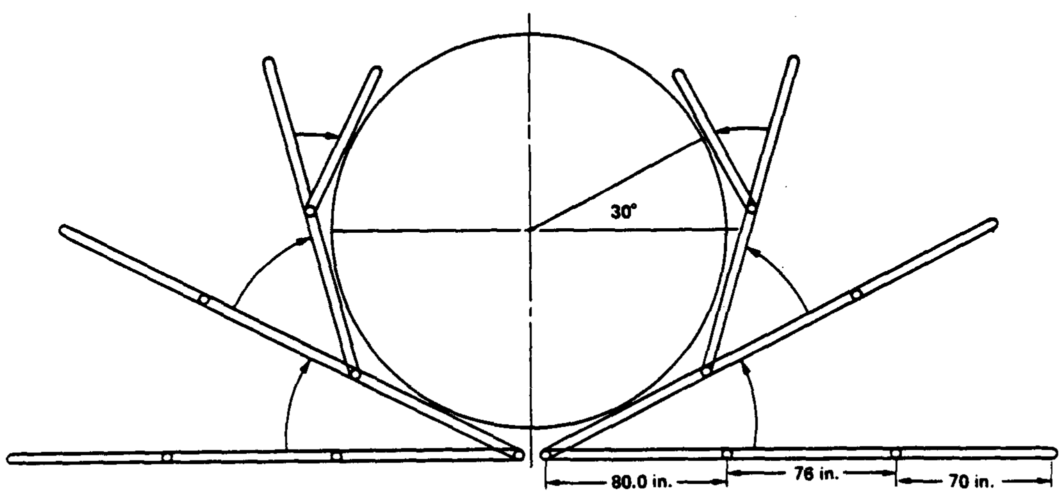


Figure 10.3-3 TSR - OMV Risk Reduction

Even with perfect conditions during recovery, with no major target protuberances/appendages and given a reasonably symmetric target for recovery, as the operator begins to grapple and rigidize, the grapple mechanism will begin a series of contacts with the target. These contacts will produce relative position changes between the target and recovery system that are expected to be complex, and have not yet been modeled. When initiating this grapple mechanism closure operation with a two- or even three-point gripping device, such as the C-clamp, in which the target is not enveloped, it is possible that the target position will change in such a manner that a new approach and grapple positioning setup will be required following each contact. If this situation were to become prominent, this type of grapple would be untenable. For this reason, grapple of a spinning target appeared to be accomplished more feasibly using an envelopment approach. Thus, the MMC enveloper was designed from the operational concept that envelopment of a spinning target with a spinning grapple mechanism would provide a higher probability of successful grapple and rigidization. The MMC enveloper is shown in a grapple configuration in Figure 10.4-1.



- Three Pairs of Grapple Elements Independently Controlled
  - dc Torque Motors—Harmonic, Planetary
- Grapple Mechanism Deployed to Optimum Envelopment Configuration
  - Then Spun Up—Minimize Deployment Dynamics
- Target Enveloped—Elements Closed Slowly to Minimize Contact Dynamics
- Grapple Mechanism Rigidized for Despin and Transfer to STS or SS

Figure 10.4-1 TSR Grapple Envelope

This grapple mechanism is configured with three pairs of independently controlled grapple segments. Each of the segment pairs will be controlled with direct current (DC) torque motors with backdrivable gearboxes. The extension and retraction operations of each pair of segments will be synchronized, within close tolerances. This is essential to maintain a stable system configuration when opening and closing each of the segment pairs, while the TSR system is spinning to match rates with a spinning target.

During recovery operations. the enveloper will be unfolded gradually and deployed to an optimum envelopment configuration, prior to the spin-up of the system. This procedure will minimize the dynamics of the deployment of the TSR kit, a non-trivial matter. Deployment dynamics of the TSR system could impact OMV attitude control requirements and deployment dynamics is considered a subject for early research and study. The three segment arms will provide the operator with extended flexibility in aligning the grappler to envelop a target with complex shape. Following spin-up of the system and target spin rate and phase matching, the OMV ground controller and the TSR operator will position the grapple mechanism to envelop the target, at the target's center of mass. This will be accomplished by translating the cantilevered TSR kit to the target with the OMV, and maneuvering the TSR kit to a position of envelopment of the target. The TSR ground controller will then operate each pair of enveloper segments independently to grapple the satellite, while using care to minimize pre-engagement contact and the resulting irregular relative motion. As shown in Figure 10.4-1, the target will be enveloped, avoiding target contact, and the ground controller will commence closure for grapple and rigidization of the target. The grapple mechanism will be capable of softly grasping the target, accommodating the resulting forces and torques generated by target contact, and rigidizing the target grapple. The grapple points on the MMC enveloper will be rubber coated to absorb forces, minimize relative motion induced by contact, and reduce damage to the target.

Following accomplishment of a firm grapple, the TSR kit operator will reverse the current of the TSR spin/despin motor (generator) and despin the satellite. The OMV will provide adequate reaction control forces to dissipate the target's excess angular momentum and to stabilize the target. The TSR system will then reposition the extendible boom, the OMV operator will initiate a short series of translation maneuvers to test the new "system" center of mass offset, and fire main thrusters for return to the operating on-orbit base, Shuttle or Space Station.

10.5 TSR Capture Envelope Flexibility

Many of the grapple mechanisms evaluated in the concept definition task were not capable of grappling a wide range of target satellite sizes. The assessment of the TSR mission model revealed a substantial range of target capture envelopes, with satellites ranging from four to fifteen feet in diameter. As shown in Figure 10.5-1, the MMC enveloper grappler mechanism is capable of capturing a broad spectrum of target satellite sizes, and would be limited solely by the ultimate decision on length of grapple elements.

The conceptual System C, non-controllable, tumbling satellite recovery system with the MMC enveloper is shown in Figure 10.5-2, capturing the recently disabled and abandoned NOAA-8 satellite, and demonstrating a recovery that could be accomplished today if the OMV and TSR kit were available. NOAA-8 was lost recently, in January 1986 and its replacement, NOAA-10, was destroyed in a launch failure in May 1986.

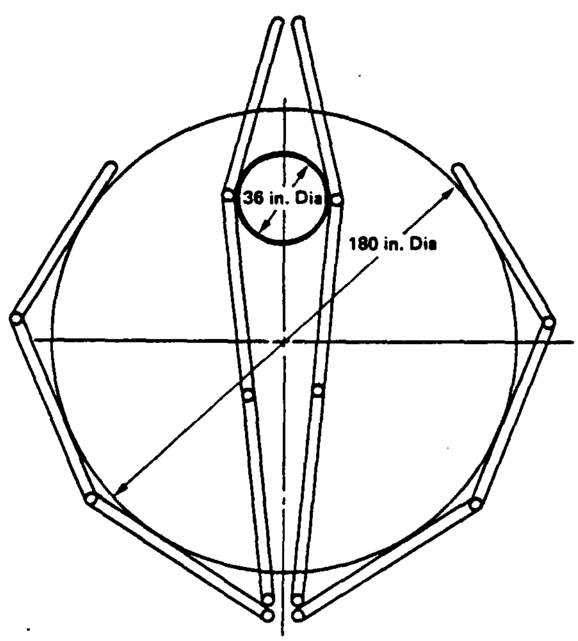


Figure 10.5-1 MMC Enveloper
Target Capture Envelope Flexibility

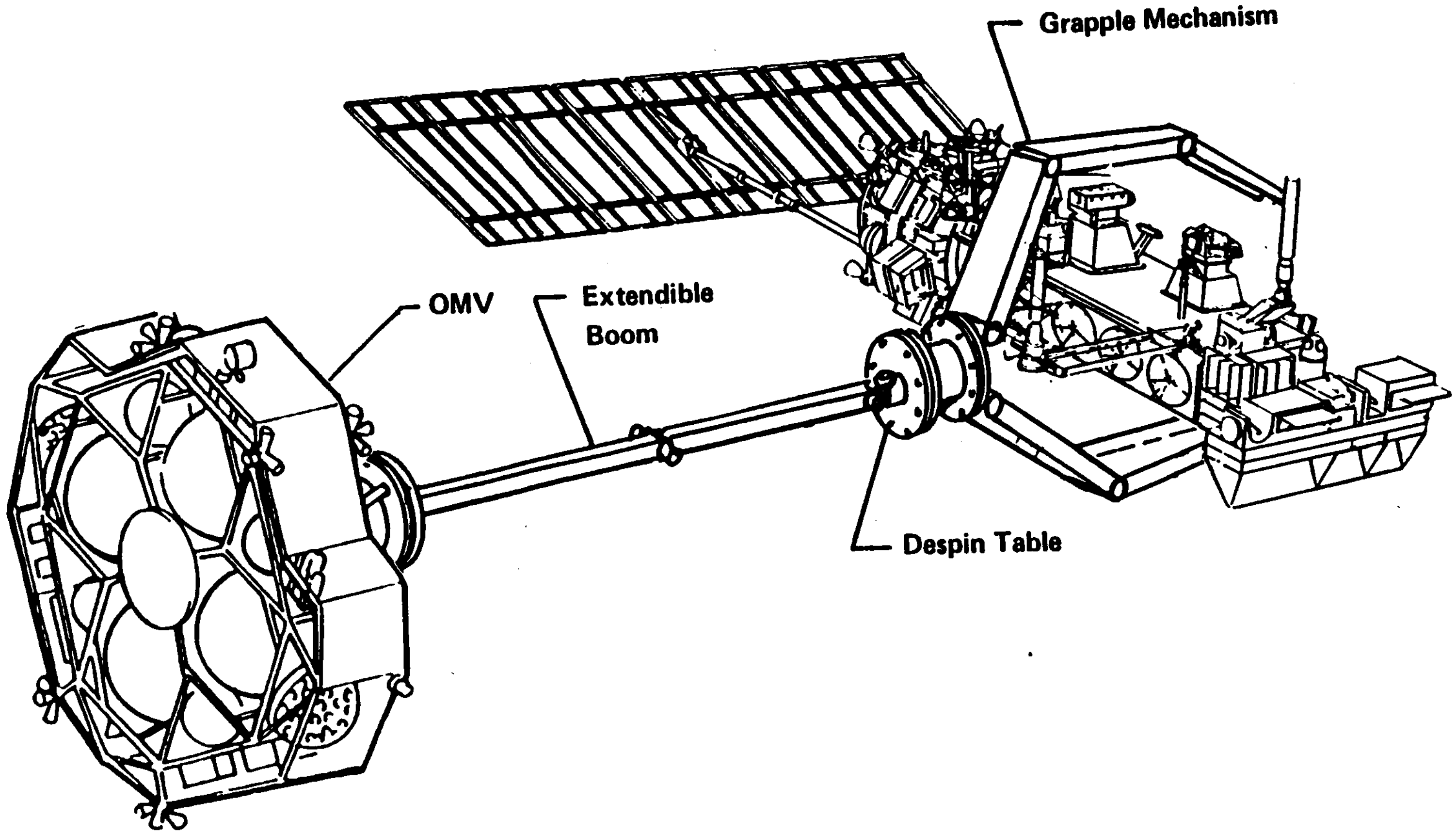


Figure 10.5-2 Conceptual TSR with MMC Enveloper

10.6 OMV/TSR Kit Interfaces

The design of the TSR system takes into account a number of interfaces with the OMV to ensure that the recovery kit can perform a variety of missions while connected to the OMV. The basic TSR kit consists of a set of interchangeable mechanisms, a data processor (microprocessor) to collect sensor data and format it for transmission via OMV communication links, a TV camera and lighting. All system support functions such as electrical power, telemetry and control communications, structure/mechanisms, attitude control and stabilization are interface requirements that must be met by the carrier vehicle, the OMV. An outline of the general interface requirements/accommodations for the TSR kit is shown on Table 10.6-1.

Table 10.6-1 OMV/TSR Kit Interfaces/Accommodations

- o Mechanical
  - Standard docking latches
  - Payload accommodation umbilical
- o Electrical Power
  - 28 vdc only
  - 250 watts operational
  - 50 watts standby
- o Telemetry
  - Sensor control data, system status - 64 kbps
- o Commands
  - 1 kbps
- o Attitude Stabilization and Control
  - Adequate for maintaining control during:
    - -- deployment, envelopment, contact dynamics, despin, orbit transfer

The mechanical/physical interface for the conceptual TSR kit will be the standard OMV docking latches. These latches will grapple standard FSS latch pins on the TSR kit in mating operations in the Orbiter cargo bay during payload processing. The other physical interface/accommodation is the electrical/ communication interconnection between the OMV and TSR kit and that will be the payload accommodations umbilical.

The electrical power requirement will be 28 volts direct current (DC). The torque motor for all mechanisms is baselined at 28 volts DC power. The maximum operational power level is anticipated to be required during despin. Power required during the despin operation, using a despin period of 500 seconds, is approximately 175 watts. With an allowance of 75 watts for other electrical functions underway at that time, the maximum operational power requirement is approximately 250 watts. The standby power requirement of 50 watts is required for heating motors, gearboxes and the microprocessor.

Telemetry data requirements include sensor and system status data sent to the ground and is estimated at 64 kilobits per second (kbps). Video communications will require a telemetry capability of 256 kbps.

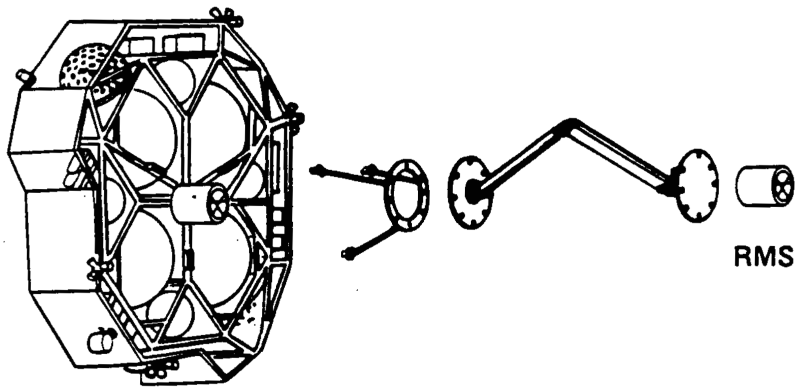
The attitude control and stabilization requirement is varied and extensive in scope. The OMV ACS system and control laws must be adequate to maintain control of the OMV, TSR kit and disabled satellite during all recovery operations including deployment of mechanisms. The completion of recommended studies and experiments related to deployment and spin-up of the recovery kit elements, and experiments designed to examine contact dynamics forces and torques during grapple operations, will support the determination of ACS requirements for kit operations.

10.7 Conceptual Recovery Systems - Summary

The recommended recovery system architecture and conceptual system designs are presented in this section in a format that will illustrate the efficacy of the MMC modular, interchangeable element approach.

Shown in Figure 10.7-1 are the system configurations for System B, for both of the recovery scenarios described in DRM 3 and DRM 4. For Case 1, the scenario is a controllable, stable target, with a recovery support element (RCE), an RMS grapple fixture that is obstructed from a direct OMV approach by a deployed solar panel. For this recovery candidate, the conceptual TSR system consists of the structural/mechanism interface element, a multiple degree-of-freedom manipulator arm (to gain access to the grapple fixture), a grapple mechanism interface flange and an RMS end effector. This System B configuration has the requisite capability to recovery disabled satellites in this category of recovery scenario.

System B—Target Controllable, Recovery Support Element (RSE) Obstructed



System B- Target Controllable, No RSE Available

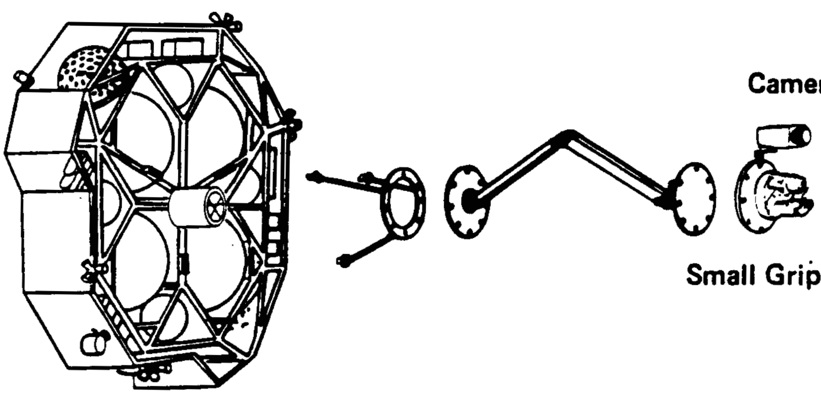


Figure 10.7-1 Conceptual TSR System B

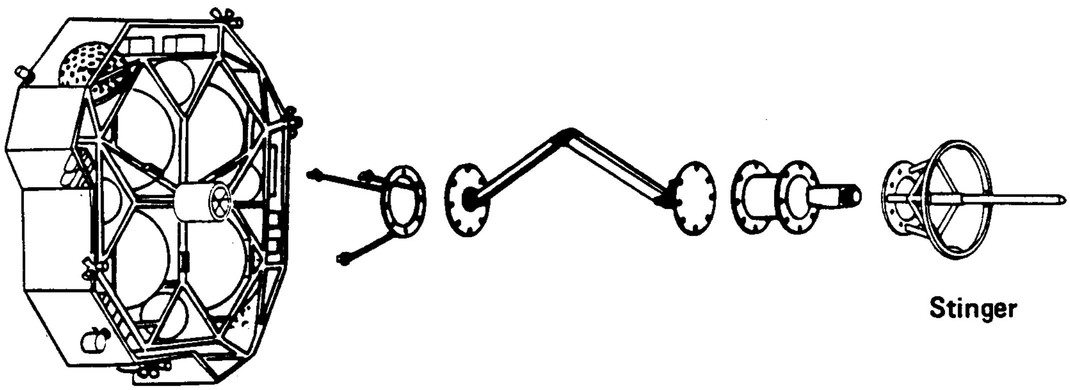
For the second System B scenario, the case of a controllable satellite with no grapple fixture or flight support system latch pins, the recovery system is also shown in Figure 10.7-1. The mechanical interface provides for ready attachment to the OMV, and in this configuration a small gripper, for attachment to target hard points, is attached to the interface flange and the extendible boom. Again, the basic system is tailored to the specific recovery scenario. In the System B cases, cost benefits will be derived from the lower weight required for these recovery missions, when compared with the full-up system shown next.

The recovery system configurations for both System C recovery scenarios are illustrated in Figure 10.7-2. In the first case, with a controllable, spin stabilized target such as INTELSAT-6, the mechanical interfaces (both the structural and umbilical), the extendible boom and the spin table are included. The "stinger" type grapple mechanism, attached to the grapple mechanism interface flange, will be used to secure a solid grip on the INTELSAT kick motor, when the OMV and TSR operators have matched the spin rate and positioned the grappler for attachment. Again, the basic modular system is configured or tailored for this mission through assembly and checkout operations at the OMV kit storage area.

Finally, the most difficult recovery scenario is the full-up System C scenario, which the previously described analysis indicates is most likely a tumbling/spinning satellite. This is the actual "complex" motion case in which the satellite is non-controllable, due to excessive angular momentum being introduced into the system through some torque inducing failure, and as a result is tumbling or spinning about a major axis. This recovery scenario requires the largest complement of modular system elements, including an enveloper-type grappler. Once this TSR kit configuration has matched rates with the spinning satellite and the grappler is positioned in phase with the geometric mass of the target, the OMV and TSR operators maneuver the system to envelop the target and manipulate each of the independently operated grappler element pairs to effect a smooth, firm grapple.

Thus, the conceptual modular design does contain all of the "fundamental" accommodations to enable recovery of the full range of the identified and defined System B and System C mission requirements.

System C—Target Controllable, Spin-Stabilized



System C—Target Noncontrollable, Tumbling/Spinning

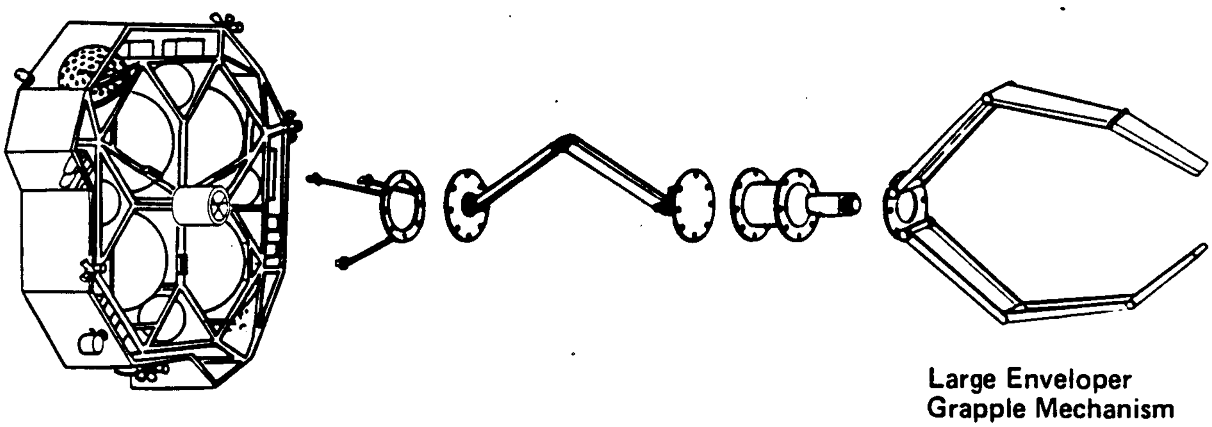


Figure 10.7-2 Conceptual TSR - System C

As a final summary note, the conceptual modular TSR kit just described was compared to the initial recovery concepts, as shown in Figure 10.7-3. This evaluation, which does include critical design factors, such as the requirement for compactness, demonstrates the substantial increase in effectiveness of the alternate approach selected by MSFC and MMC in completing the concept definition phase, Task 2. While the best of the initial recovery concepts was evaluated at 80% of the maximum possible score, the selected concept was evaluated at 96% of that maximum possible score.

EVALUATION CRITERIA	Weighting Factor	Teleoperator Grapple Despin Device	Experimental Materials Handling Device	Docking & Retrieval Mechanism	Space Bola	Debris Capture Device	TSR Recovery System
Capability to Recover Broad Spectrum of Satellite Configurations	10	5	8	4	6	8	10
Minimum Risk to OMV & Recovery System during Recovery	9	8	8	9	5	8	10
Capability to Accommodate High Single-Axis Satellite Spin Rates	9	6	8	8	5	8	10
Minimum Risk to Target Vehicle	8	8	8	8	5	8	10
Compatibility with OMV & Minimum Impact on OMV Design	7	8	8	8	5	8	9
Dependence on Recovery Vehicle Support Elements	7	5	9	7	9	9	10
Modularity of Subsystems to Enable TSR System Growth for Flexible Mission Capability	6	6	8	8	5	8	10
Capability to Deal with Wide Range of Tumble Mode Complexity	5	9	7	7	9	6	8
Weight to Orbit (Mass & Volume)	5	7	7	7	9	6	9
Development Risk & Cost	5	8	9	9	8	7	9
Total Value		487	570	525	448	555	683

Figure 10.7-3 Final Recovery System Evaluation

11.0 SUPPORTING DEVELOPMENT PLAN

11.1 Objectives and Summary

The purpose of the supporting development plan is to outline the research and technology development, including ground-based testing and simulation and on-orbit demonstration activities, and the flight hardware development needed to establish the technical readiness of an OMV tumbling satellite recovery front-end kit.

The elements of the tumbling satellite recovery development program include ground based research and study efforts, Orbiter cargo bay or proximity operations experiments and the flight hardware development activities required to provide a validated, operational recovery system for future users. These activities must be integrated into a valid program for recovery kit planners, and must be coordinated with concurrent OMV and Space Station development activities. The technology development issues identified in the Supporting Research and Technology (SR&T) report are addressed in either ground or flight-oriented experiments.

11.2 Ground Demonstration Activities

The recommended ground-based demonstration approach is outlined in Table 11.2-1. The first recommended initiative is to design, develop and use a set of recovery kit ground demonstration units, including software simulation and hardware systems, capable of addressing the SR&T issues described in Volume II of this final study report. As shown in Table 11.2-1, these programs and hardware demonstration unit(s) will be used (1) to evaluate alternative recovery concepts; (2) to examine system deployment characteristics; (3) to assess contact dynamics and resultant target and recovery system reactions to recovery operations; and (4) to expand tests directed at determining operator capabilities (or limitations) in conducting recovery operations.

The plan would include the examination and possible use of existing MSFC/MMC laboratory configurations to conduct these types of ground-based technology efforts.

Table 11.2-1 Ground Demonstration Activities

- Design, Develop, & Exploit Recovery Kit Ground Demonstration Unit(s)
  - Evaluate Concepts Feasibility
  - Recovery System Deployment Characteristics
  - Contact Dynamics in Recovery Operations
  - Recovery System Operations/Operator Assessment
- Utilize Existing MSFC/Martin Marietta Simulation Capabilities to Address Identified Technology Issues
  - Contact Dynamics Concerns
  - Force & Moment Measurements, Resulting Position/Motion States
  - Computer Simulations Using Varying Configurations, Evaluate Human Factors Limitations
- Demonstrate Use of Recovery Demonstration Unit as Laboratory Tool
  - Evaluate Alternative Concepts
  - Evaluate Subsystem Mechanisms - Grapple Devices
  - Eventual Use as Astronaut Trainer for Flight Experiment
  - Identify Logical Flight Experiment Candidates

A third element of a ground demonstration program will be to use the new ground demonstration units or modifications or extensions of existing facilities as development tools, as the program proceeds through the development process. Developers will need to continue to evaluate new or revised concepts or subsystem mechanisms, including the extensive family of large and small potential grapple mechanisms. This equipment would be used eventually as training devices for astronauts conducting Orbiter cargo bay or proximity operations flight experiments.

As a final note, the conduct of ground-based experiments related to remote satellite recovery will support clarification of what technology issues can be more efficiently addressed on the ground and which of these must be addressed by flight experiments.

The recommended schedule for development of ground demonstration software and hardware elements to support the evolution of design and development of a tumbling satellite recovery system is provided in Figure 11.2-2. It is recommended that a series of requirements trades and analyses be conducted

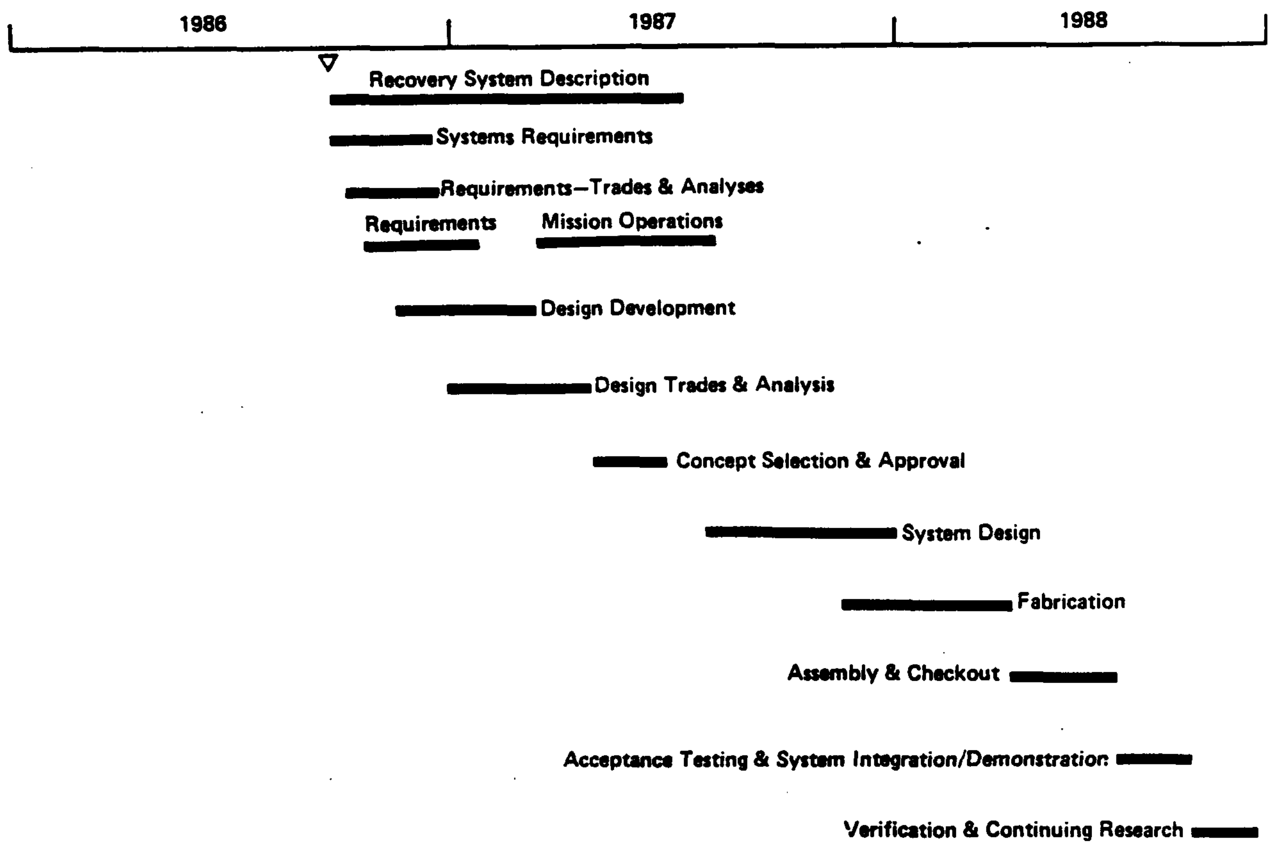


Figure 11.2-1 Ground Demonstration Schedule

initially to support determination of the number and type of software and hardware units that will cost effectively address those issues identified in Volume II. This task would include evaluations of existing laboratory configurations in NASA and in industry.

With ground demonstration objectives and requirements identified, concept design and design trades and analyses are recommended to enable concept selection of the ground demonstration unit(s) in mid-1987 and approval by MSFC. With MSFC direction to proceed, the system design, fabrication, checkout and demonstration of selected software and hardware elements for ground-based TSR technology support will be conducted and completed in FY 1988.

Following production of these software and hardware units, they will be used throughout the TSR kit flight hardware definition and development periods to support resolution of evolving technology issues.

11.3 STS Cargo Bay/Proximity Operations

The definition of on-orbit flight experiments to support technology development of the TSR kit will evolve and be refined through experience with the ground demonstration units. It appears that an on-orbit experiment will be required to validate the recovery concept agreed upon for development, and to verify contact dynamics forces and torques and the impact of relative movement between the target and recovery system on the recovery operation. Candidate cargo bay/proximity operations experiments are outlined on Table 11.3-1.

Table 11.3-1 Cargo Bay/Proximity Operations Experiments

- **Define an STS Cargo Bay/Proximity Operations Equipment Set**
  - **Scaled Satellite Recovery System**
    - **Extendible Boom, Spin Table, Envelopment Grappler**
    - **Equipped with Interface to STS & RMS**
  - **Scaled Composite Recovery Target**
- **Conduct Remote Recovery Experiments in Zero-G**
  - **Remote Recovery Operations**
    - **Spin Axis Alignment, Spin Rate Matching/Phasing**
    - **Operations, Operator Limitations**
  - **Recovery System Deployment Dynamics**
  - **Target-Recovery System Contact Dynamics**

Cargo Bay Experiments Should Be Phased to Support Flight Hardware Phase C/D CDR.

The on-orbit remote satellite recovery experiments should be conducted with high fidelity equipment to validate the system concept. Thus, definition of the requirements and conceptual design of the scaled down experiment equipment should begin prior to the start of flight hardware Phase C/D for the TSR system.

The experimental recovery equipment would be an extendible boom, a spin table and an envelopment grappler. The system would be designed to interface with the Orbiter RMS end-effector and equipped with an operating interface in the Orbiter. The spacecraft target would be a modification of a current rented spacecraft bus, designed to be controllable for multiple tumble and spin modes and rates. This experiment would enable operators to conduct the first zero-gravity remote recovery operations that validate ground-based experiments. Actual experience to be gained includes remote recovery operations, such as spin axis alignment, spin rate matching and phasing with target, recovery system deployment dynamics and activities conducted in reaction to target/ recovery system dynamics.

The schedule for the cargo bay/proximity operations experiment is presented in Figure 11.3-1. The program phases are similar to those shown for the ground demonstration unit(s) program. Again, the schedule is designed to provide a proof-of-concept experiment prior to flight hardware Critical Design Review.

11.4 Flight Hardware Program

The objective of the actual OMV tumbling satellite recovery kit flight hardware program is to be prepared to conduct free flight operations in 1993 with actual or simulated targets. This flight hardware will be developed on a schedule consistent with development plans for OMV and other OMV front-end kits. It will be conducted using the generally accepted NASA/MSFC approach of conceptual, definition and development phases (A, B, and C/D).

During the flight hardware program, the plan is to continue to examine and define requirements for accommodating the Space Station and TSR kit for deployment to, and operations from, the Space Station.

The Supporting Development Plan (SDP) schedule is provided in Figure 11.4-1. The schedule outlines an integrated TSR kit development program that includes ground-based and on-orbit STS flight experiments and a flight hardware program that provides for free flight operations in 1993.

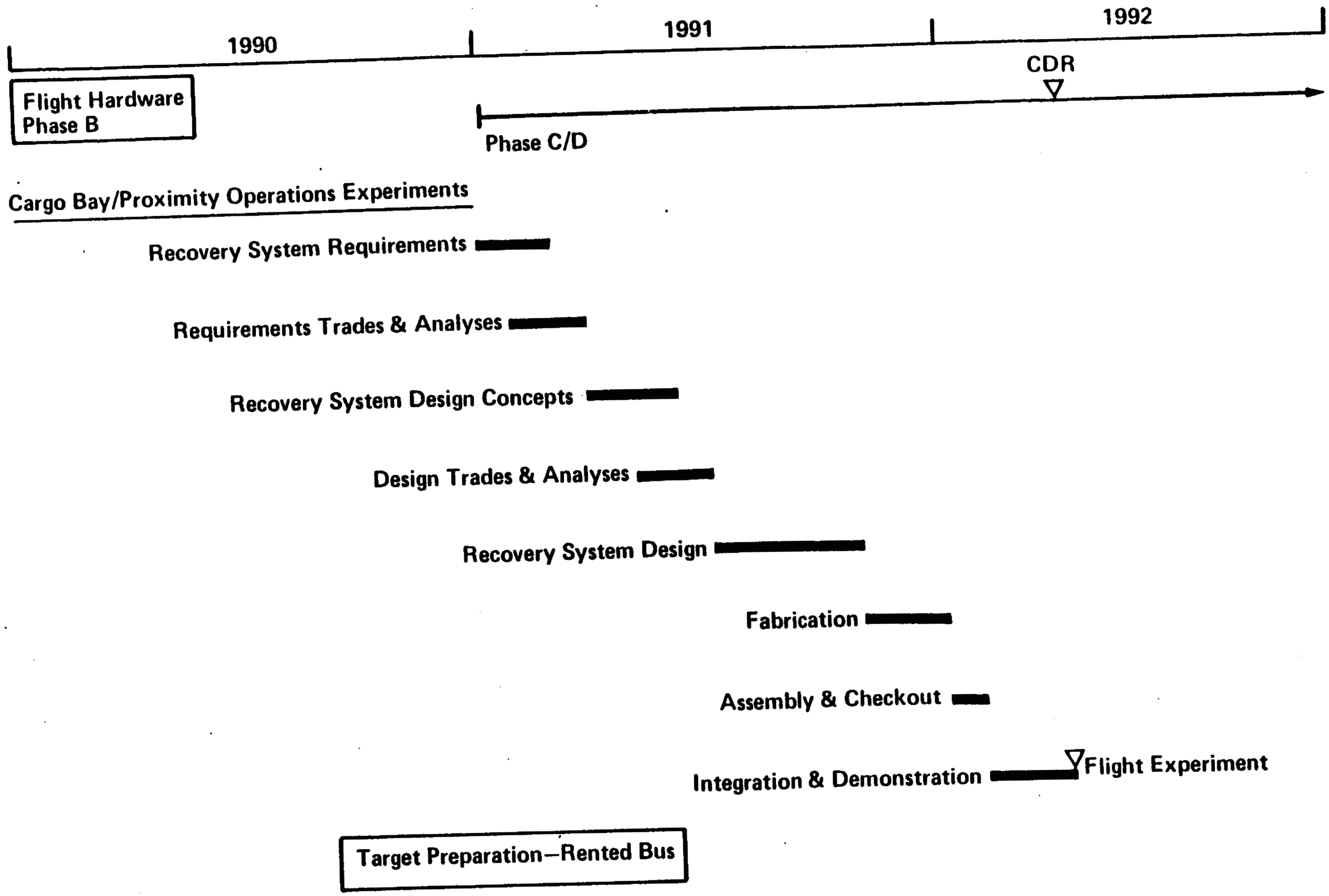


Figure 11.3-1 Cargo Bay/Proximity Operations Experiment Schedule

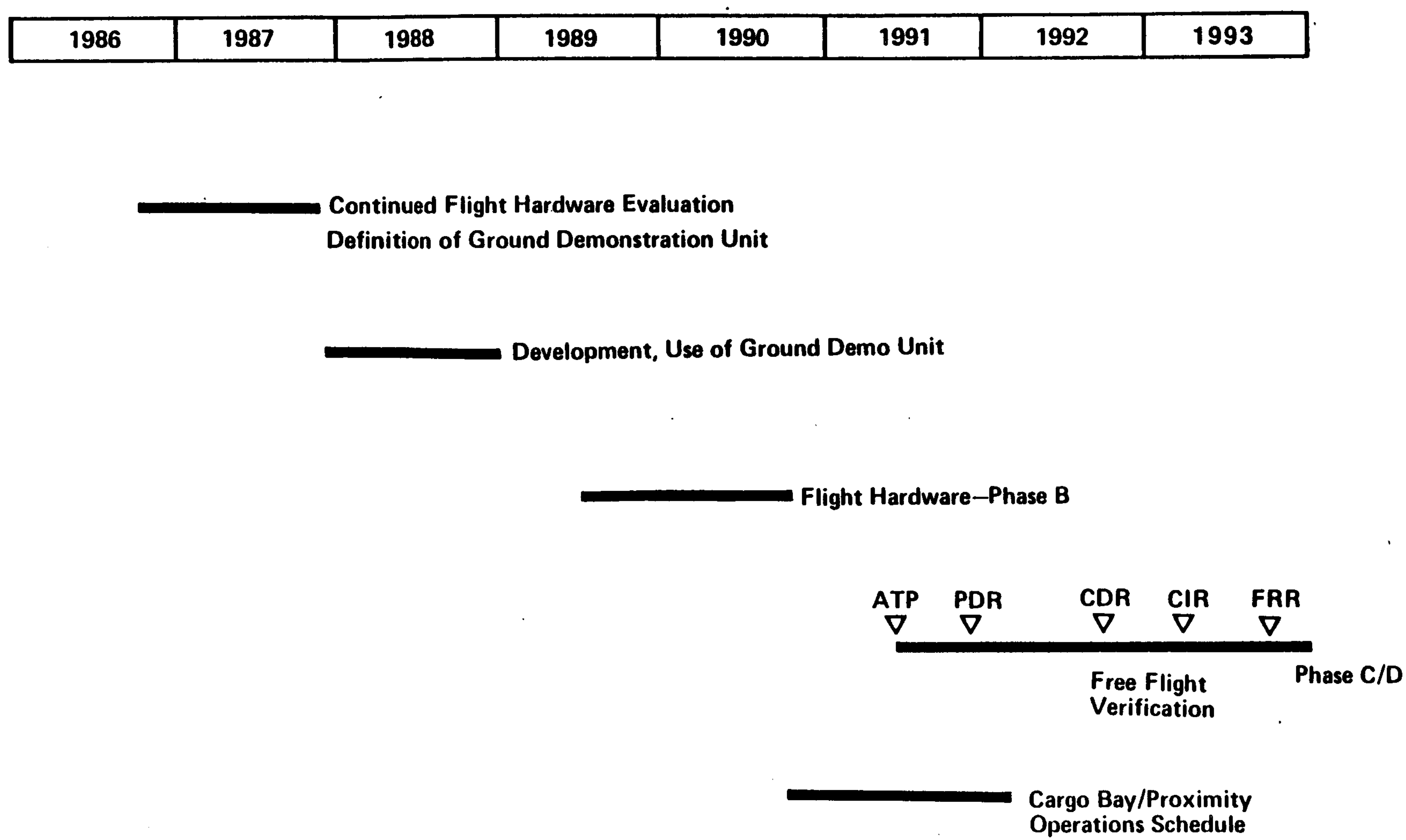


Figure 11.4-1 Development Program Schedule