NASA-TM-108704

TETHERED SATELLITE SYSTEM CONTINGENCY INVESTIGATION BOARD

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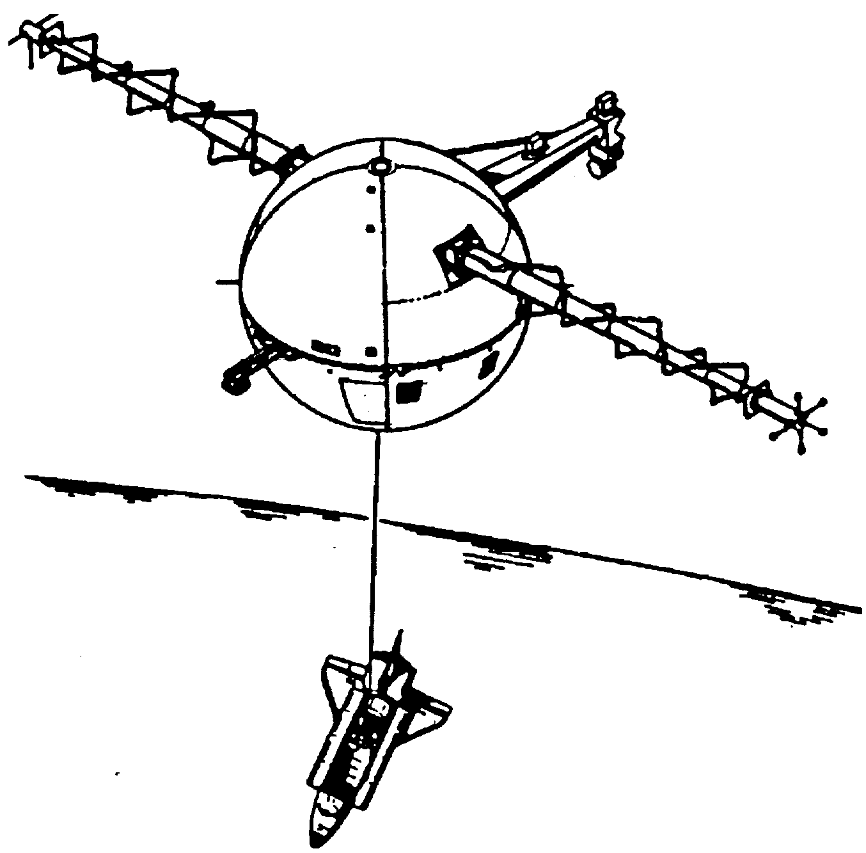
FINAL REPORT



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ENCLOSURE A

TETHERED SATELLITE SYSTEM (TSS-I)
CONTINGENCY INVESTIGATION BOARD
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EXECUTIVE SUMMARY

The Tethered Satellite System (TSS-1) was launched aboard the Space Shuttle Atlantis (STS-46) on July 31, 1992. During the attempted on-orbit operations, the Tethered Satellite System failed to deploy successfully beyond 256 meters. The satellite was retrieved successfully and was returned on August 6, 1992.

The National Aeronautics and Space Administration (NASA) Associate Administrator for Space Flight formed the Tethered Satellite System (TSS-1) Contingency Investigation Board on August 12, 1992. The TSS-1 Contingency Investigation Board was asked to review the anomalies which occurred, to determine the probable cause, and to recommend corrective measures to prevent recurrence. The Board was supported by the TSS Systems Working Group as identified in MSFC-TSS-11-90, "Tethered Satellite System (TSS) Contingency Plan".

The Board conducted its investigation through examination of flight data and mission logs; briefings and discussions with the TSS Systems Working Group, the government project team, and the contractor project team; interviews with the STS-46 astronaut crew and flight directors; and post-flight hardware inspections, tests, and analyses. The information in this report is based on the analyses and tests requested by the Board and Working Group, presentations given to the Board, and the documentation found during the investigation.

The Board identified five anomalies for investigation: initial failure to retract the U2 umbilical; initial failure to flyaway; unplanned tether deployment stop at 179 meters; unplanned tether deployment stop at 256 meters; and failure to move tether in either direction at 224 meters. Initial observations of the returned flight hardware revealed evidence of mechanical interference by a bolt with the level wind mechanism travel as well as a helical shaped wrap of tether which indicated that the tether had been unwound from the reel beyond the travel by the level wind mechanism. Examination of the detailed mission events from flight data and mission logs related to the initial failure to flyaway and the failure to move in either direction at 224 meters, together with known preflight concerns regarding slack tether, focused the assessment of these anomalies on the upper tether control mechanism. After the second meeting, the Board requested the working group to complete and validate a detailed integrated mission sequence; to focus the fault tree analysis on a stuck U2 umbilical, level wind mechanical interference, and slack tether in the upper tether control mechanism; and to prepare a detailed plan for hardware inspection, test, and analysis including any appropriate hardware disassembly.

Post flight deployer operation confirmed that the level wind travel was blocked by a protruding bolt. The bolt had been installed as part of a reel foot mod-kit late in the TSS-1 processing flow after hardware delivery from the factory and after completion of deployer systems level testing. The reel foot mod-kit was required to overcome negative margins of safety that were discovered in the STS-46 verification loads analysis cycle.

Post flight tests using a mock-up Upper Tether Control Mechanism (UTCM) and post flight tests on the flight UTCM confirmed that slack tether in the deployer operation can result in tether binding in the UTCM. These demonstration tests confirmed the most likely cause of the initial failure to flyaway and the failure to move tether in either direction at 224 meters as binding tether which resulted from excessive tether acceleration by the vernier motor during vernier motor activation.

The post flight fault tree analysis identified three likely causes for a stuck U2 umbilical:

- Excessive force at detent resulting from vlier pin adjustments
- Lanyard mechanism latch plate jam in the hoop spring
- U2 motor operates at less then nominal performance.

Post flight inspection, analysis, and testing to date did not provide any conclusive information as to the most probable cause.

The Board identified three lessons learned:

- The Spacelab carrier-to-TSS-1 structural loads analyses should have discovered the structural problem much earlier;
- Flight hardware changes late in the project cycle are high risk; and
- Ground testing should fully explore the dimensions of the expected flight environment.

The Board also made the following recommendations focused on readying the Tethered Satellite System for a future reflight opportunity:

- Use larger fasteners in lieu of the reel-foot mod-kit to resolve the reel-foot structural design issue;
- Assess the reel, level-wind, drive chain assembly and replace any damaged hardware;
- Increase the deployer operating margins, particularly in the Upper Tether Control Mechanism, to avoid binding;
- Redesign the umbilical subsystem to satisfy mission environment conditions; and
- Validate system/hardware operations in simulated mission environmental to the degree practical.

CHAPTER I - INTRODUCTION

The Tethered Satellite System-1 (TSS-1) -- a joint project of NASA and ASI under an agreement signed in 1984 -- consists of a satellite, a 2.54 mm (0.1 inch) diameter tether, and a deployer in the Shuttle's cargo bay.

The 515 kg (1,139 pound) satellite was developed by the Italian Space Agency (ASI), and the tether and deployer system were developed by the NASA. The 12 main experiments were selected jointly by NASA and ASI.

The Tethered Satellite System for STS-46 Mission was mounted on 2 Spacelab carriers: the Enhanced Multiplexer-Demultiplexer Pallet (EMP) and a Mission Peculiar Equipment Support Structure. The deployer and the tether control hardware were mounted on the EMP pallet (Figure 1.1).

The deployer hardware fabrication and certification testing was completed at the prime contractor, Martin Marietta Corporation, in September 1990. Integration of the flight hardware on the Spacelab pallet, verification tests, and installation of the flight tether was completed in October 1991 at the Kennedy Space Center.

STS-46 was launched on July 31, 1992. During the mission, a number of flight anomalies occurred. Full deployment of the tethered satellite was not achieved. The Associate Administrator of the NASA Office of Space Flight established the Tethered Satellite System Contingency Investigation Board on August 12, 1992. In accordance with the letter of appointment, the Board has been supported by the Tethered Satellite Systems Working Group which had been activated by the MSFC Center Director in accordance with the procedures of the TSS-1 Contingency Plan MSFC-TSS-11-90.

The Board conducted a telecon on August 12 1992, and the first meeting of the Board was held in Huntsville, Alabama, at Marshall Space Flight Center on August 17-19,1992. Two subsequent meetings were held at Kennedy Space Center on August 25-27 and September 16-17, 1992. A fourth meeting was held at Marshall Space Flight Center on September 22-24, 1992 and a final meeting was held at Marshall Space Flight Center on October 7-8, 1992 . A summary of the Board meetings and attendees can be found in Appendix C.

The investigation was focused on five anomalies:

- U2 Umbilical Retraction Failure
- Initial Failure to Flyaway
- Unplanned Tether Deployment Stop at 179 Meters
- Unplanned Tether Deployment Stop at 256 Meters
- Failure to Move Tether in Either Direction at 224 Meters

Development of a fault tree and integrated mission sequence of events using mission logs and engineering flight data were initiated. Observation of the flight hardware on

August 26, 1992 led to the discovery of mechanical interference of the level wind translation travel as the cause of the unplanned stops at 179 meters and 256 meters. Detailed assessment of the mission sequence and flight data pointed the initial failure to flyaway and the failure to move in either direction at 224 meters to binding tether in the Upper Tether Control Mechanism (UTCM).

This report of the Board's investigation describes the flight anomalies and the cause or probable cause of the anomalies along with related data from the fault tree; mission logs and flight instrumentation; and hardware inspections, tests and analyses. The Board's judgments clearly benefit from hindsight with the knowledge that the engineering analysis associated with the Reel Foot Mod Kit should have, but failed to identify the mechanical interference with the level wind translation path. The report also addresses lessons learned and related recommendations as well as recommendations for achieving a successful reflight of the Tethered Satellite System.

Tethered Satellite System

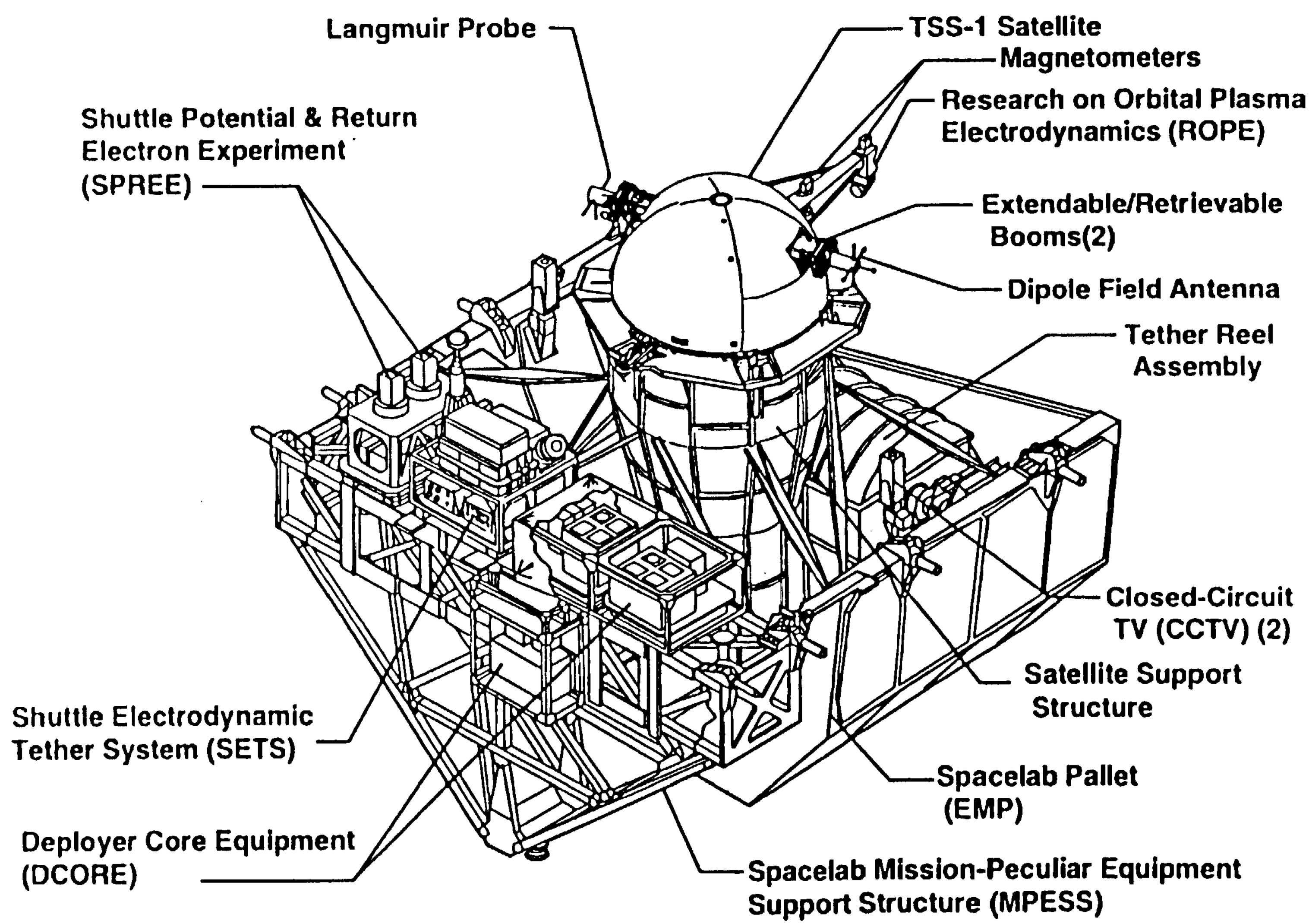


Figure 1.1

CHAPTER II - THE TSS-1 MISSION

TETHERED SATELLITE SYSTEM (TSS-1)

The NASA/Italian Space Agency Tethered Satellite System (TSS-1) was to demonstrate for the first time exciting new capabilities for probing the space environment and conducting experiments by a tethered satellite deployed during the STS-46 Shuttle Flight.

The Tethered Satellite System is made up of a satellite attached by a tether to a deployer system mounted on a Spacelab Pallet. The deployer remained in the Shuttle's payload bay and the satellite was deployed into space. Although the satellite was deployed only 256 meters of the planned 20 km, TSS-1 was the longest structure ever flown in space.

For the TSS-1 mission, the 20 km long tether was constructed with electrically-conducting copper strands in its core. The conducting tether was to generate high voltage electrical currents by the same basic principle as a standard electrical generator -- by converting mechanical energy (the Shuttle's more than 17,000-mile-an-hour orbital motion) into electrical energy by passing a conductor (the tether) through a magnetic field (the Earth's magnetic field lines).

TSS-1 scientific instruments, mounted in the Shuttle payload bay, the middeck and on the satellite, were designed to examine the electrodynamics of the conducting tether system, and clarify the understanding of physical processes in the ionized plasma of the near-Earth space environment.

The TSS-1 mission was the first step toward several potential future uses for tethers in space now being evaluated by scientists and engineers. One possible application is using long conducting tethers to generate electrical power for Space Station Freedom or other orbiting bodies.

Conversely, by expending electrical power to reverse the current flow into a tether, the system could be placed in an "electric motor" mode to generate thrust for orbit maintenance. Tethers also may be used to raise or lower spacecraft orbits. This could be achieved by releasing a tethered body from a primary spacecraft, thereby transferring momentum (and imparting motion) to the spacecraft. Another potential application is the creation of artificial gravity by rotating two or more masses on a tether, much like a set of bolas.

Downward deployment (toward Earth) could place a satellite in regions of the atmosphere that have been difficult to study because they lie above the range of high-altitude balloons and below the minimum altitude of free-flying satellites. Deploying a tethered satellite downward from the Shuttle also could make possible aerodynamic and wind tunnel type testing in the region 50 to 75 nautical miles above the Earth.

Mission Objectives

Space-based tethers have been studied theoretically since early in this century. The first practical application of a shuttle-based tether was proposed by Dr. Mario Grossi, Smithsonian Institution, in the early 1970s. Professor Guiseppe Colombo, University of Padova, Italy, subsequently proved the dynamic feasibility of the tether concept and suggested various uses. More recently, the projected performance of such systems has been modeled extensively on computers.

In 1984, the growing interest in tethered system experiments resulted in the signing of an agreement between NASA and the Italian Space Agency (Agenzia Spaziale Italiana - ASI) to jointly pursue the definition and development of a Tethered Satellite System to fly aboard the Space Shuttle. Scientific investigations (including hardware experiments) were selected in 1985 in response to a joint NASA/ASI announcement of opportunity.

The mission objectives were to evaluate the capability for deploying, controlling and retrieving a tethered satellite; to validate predictions of the dynamic forces at work in a tethered satellite system; to conduct exploratory electrodynamic science investigations; and to demonstrate the capability of the system to serve as a facility for research in geophysical and space physics.

Since the dynamics of the Tethered Satellite System are complex and only can be tested fully in orbit, it was impossible to predict before the mission exactly how the system would perform in the space environment. In particular, retrieval and recapture presented the greatest uncertainties. Even with its limited deployment, TSS-1 provided significant dynamic and control information during the retrieval/capture phase.

CHAPTER III - TETHERED SATELLITE SYSTEM HARDWARE

Tethered Satellite System Hardware

The Tethered Satellite System has five major components: the deployer system, the tether, the satellite, the carriers on which the system is mounted and the science instruments. Under the 1984 memorandum of understanding, the Italian Space Agency agreed to provide the satellite and NASA agreed to furnish the deployer system and tether. The carriers are specially adapted Spacelab equipment; and the science instruments were developed by various universities, government agencies and companies in the United States and Italy.

Carriers

TSS-1 hardware rides on two carriers in the Shuttle cargo bay. The deployer is mounted on a Spacelab Enhanced Multiplexer-Demultiplexer pallet, a general-purpose unpressurized platform equipped to provide structural support to the deployer, as well as temperature control, power distribution and command and data transmission capabilities. The second carrier is a Spacelab Mission Peculiar Equipment Support Structure which holds science support equipment and three of the TSS-1 science experiments.

Deployer

The deployer system includes the structure supporting the satellite, the deployment boom, which initially lifts the satellite away from the orbiter, the tether reel, a system that distributes power to the satellite before deployment and a data acquisition and control assembly.

Cables woven through the structure provide power and data links to the satellite until it is readied for release. When the cables are disconnected after checkout, the satellite operates on its internal battery power.

The boom, with the satellite resting atop it, is housed in a canister in the lower section of the satellite support structure. As deployment begins, the boom will unfold and extend slowly out of the turning canister, like a bolt being forced upward by a rotating nut. As the upward part of the canister rotates, horizontal cross members (fiberglass battens similar to those that give strength to sails) are unfolded from their bent-in-half positions to hold the vertical members (longerons) erect. Additional strength is provided by diagonal tension cables. The process is reversed for retrieval. When it is fully extended, the 12 meter (40 foot) boom resembles a short broadcasting tower.

The tether reel mechanism regulates the tether's length, tension and rate of deployment -- critical factors for tether control. Designed to hold up to 110 km (68 miles) of tether, the reel is 0.11 meter (4.44 inch) in diameter and 1.2 meters (48 inches) long. The reel is equipped with a "level-wind" mechanism to assure uniform winding on the reel, a brake assembly for control of the tether and a drive motor. The mechanism is capable of letting out the tether at up to about 4.5 meters per second (10 miles per hour). However, for the TSS-1 mission, the tether was released at a much slower rate.

Tether

For the TSS-1 mission, the satellite was planned to be deployed on the tether out to an altitude about 20 km above the Shuttle, which would have made the TSS-1/orbiter combination 100 times longer than any previous spacecraft. The 2.54 mm thick tether is a conducting cord designed to anchor a satellite kilometers above the orbiter. The TSS-1 tether was 22 km long. When deployed, it was expected to develop a 5,000-volt electrical potential and carry a maximum current of 1 ampere. At its center is the conductor, a 10-strand copper bundle wrapped around a Nomex (nylon fiber) core. The wire is insulated with a layer of Teflon, then strength is provided with a layer of braided Kevlar -- a tough, light synthetic fiber also used for making bulletproof vests. An outer braid of Nomex protects the tether from atomic oxygen (see figure 3.1).

Satellite

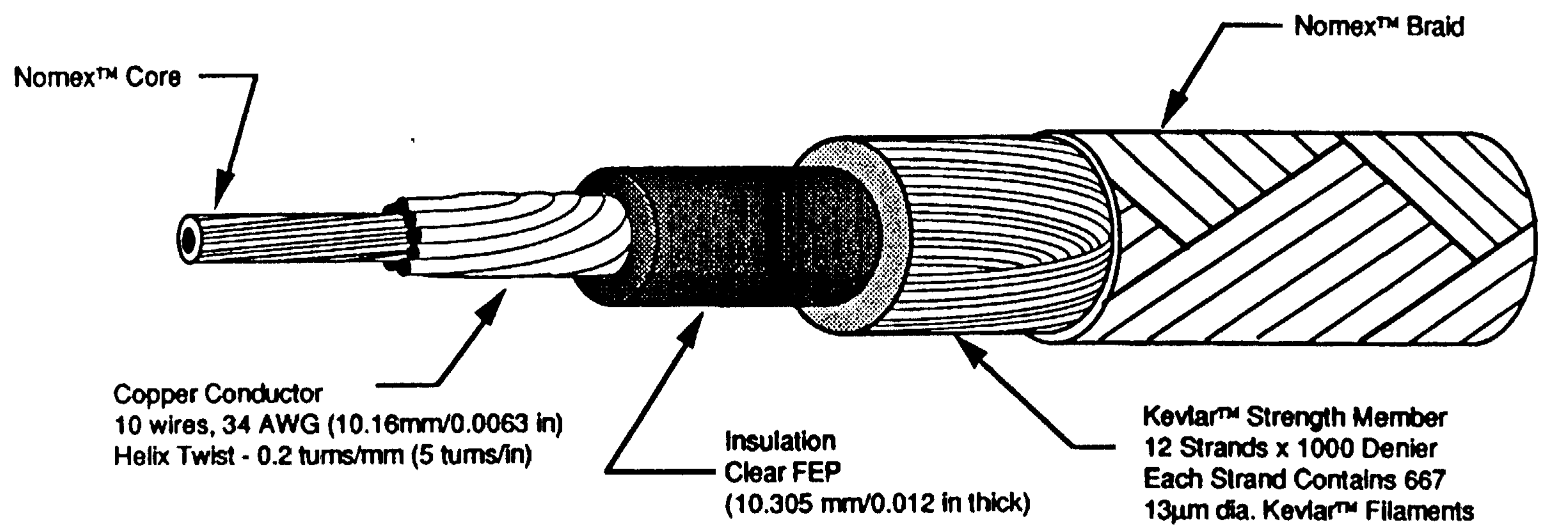
Developed by the Italian Space Agency, the spherical satellite is a little more than 1.5 meters (5 feet) in diameter and is latched atop the deployer's satellite support structure. The six latches are released when boom extension is initiated. After the satellite is extended some 12 meters above the orbiter atop the boom, tether unreeling begins.

The satellite is divided into two hemispheres and a centered propulsion module. The payload module (the upper half of the sphere opposite the tether) houses satellite-based science instruments. Support systems for power distribution, data handling, telemetry and navigational equipment are housed in the service module or lower half. Eight aluminum-alloy panels, covered with electrically conductive paint, developed at the Marshall Space Flight Center, form the outer skin of the satellite. Doors in the panels provide access for installing/servicing batteries; windows for Sun, Earth, and charged-particle sensors; and connectors for cables from the deployer.

A fixed boom for mounting science instruments extends 1 meter (39 inches) from the equator of the satellite sphere. A short mast opposite the boom carries an S-band antenna for sending data and receiving commands. For the TSS-1 mission, the satellite is outfitted with two additional instrument-mounting booms on opposite sides of the upper sphere. The booms may be extended up to 2.4 meters (8 feet) from the body of the satellite, allowing instruments to sample the surrounding environment, then be retrieved inside the payload module before the satellite is reeled back to the Shuttle.

Attitude of the tethered satellite is controlled by its auxiliary propulsion module, while the satellite motion is controlled by the deployer's tether reel and motor. The module also initiates, maintains and controls satellite spin at up to 0.7 revolution per minute on command from the Shuttle. Two sets of thrusters (primary and backup) near the tether attachment provide extra tension on the tether, canted in-plane and out-of-plane thrusters can be used to reduce or eliminate pendulum-type motions in the satellite, and yaw thrusters can be used to spin and despin the satellite. A pressurized tank containing gaseous nitrogen for the thrusters is located in the center of the sphere.

TSS-1 Electrically Conductive Tether



Diameter	2.54 mm (0.1 in)
Max Mass	8.2 kg/km (.0055 lb/ft or 29.0 lb/mile)
Breakstrength	1780 N (400 lb)
Temp Range	-100°C to +125°C (-148°F to +257°F)
Max Elongation	5% @ 1780 N
Elec Breakdown Voltage	10 kV (specified), 15 kV (qual)
Elec Resistance	0.12 Ω/m (specified) 0.015 Ω/m (actual @ room temp)
Leakage Current Limit	5 mA (max) @ 10 kVdc

Figure 3.1

CHAPTER IV - DEPLOYER SYSTEM

TETHER CONTROL MECHANISMS

The tether control mechanisms include the reel drive mechanisms, the reel brake mechanisms, the upper tether control mechanism, and the lower tether control mechanism (Figure 4.1).

REEL DRIVE MECHANISM

The reel drive mechanism provides controlled spooling of the tether during the deployment and retrieval phases of TSS operations. The reel drive mechanism consists of the storage reel, the tether level wind assembly, and a 5-horsepower drive motor.

The tether storage reel is a 0.11 meter (4.44 inch) diameter by 1.2 meter (48 inch) wide shaft with 1 meter (38 inch) diameter flanges on each end. It can accommodate a variety of tether dimensions and lengths. The starboard end is joined to the reel drive motor by a coupling and to the brake by a brake rotor.

The primary function of the level wind subassembly is to uniformly lay tether across the width of the reel in a compact, reversible manner. It contains a ball reverser that moves back and forth along a ball reverser shaft that rotates in a constant direction driven by a chain from the timing gearbox. The ball reverser is bolted to a cap end which has a slot for a ball key connected to the actual level wind mechanism. The level wind mechanism slides along a track. The level wind subassembly is shown in Figure 4.2.

The reel motor is a three-phase, torque-type, brushless permanent magnet motor. No gear reduction is used because the motor is connected directly to the reel by a mechanical coupling. The motor is capable of supplying up to 73.25 joules (54 ft-lb) of torque with a nominal power of 3.73 kW (5 horsepower).

LOWER TETHER CONTROL MECHANISM (LTCM)

The LTCM (see figure 4.3) is mounted on the Satellite Support Structure (SSS) base on the aft end. The LTCM performs the following functions:

- Routes the tether between the reel and UTCM
- Provides inboard tether tension measurement
- Provides measurement data for the length and length-rate of tether passing through the unit
- Provides a tether cutting capability

Tethered Control Mechanisms

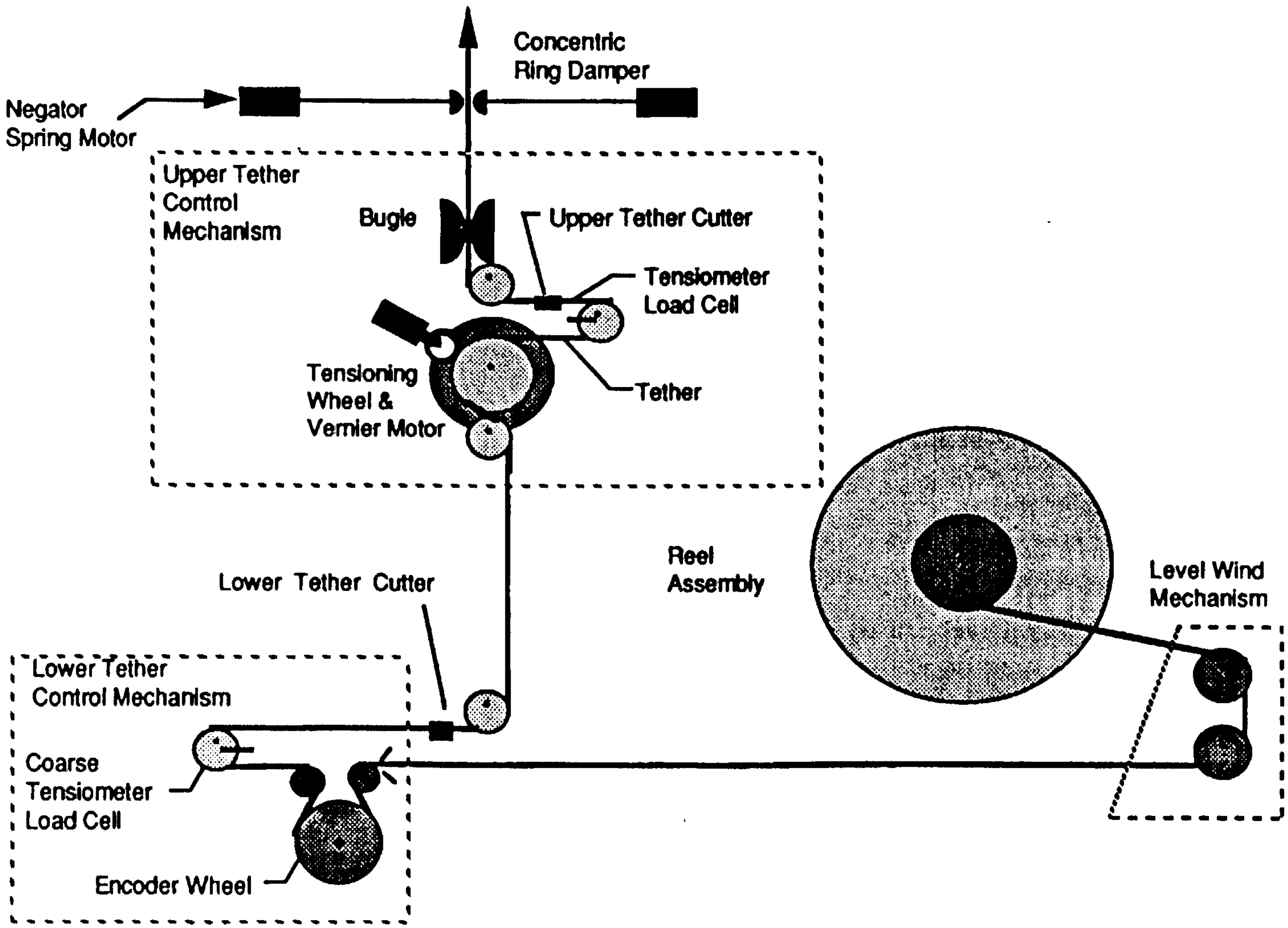


Figure 4.1

Level Wind Mechanism

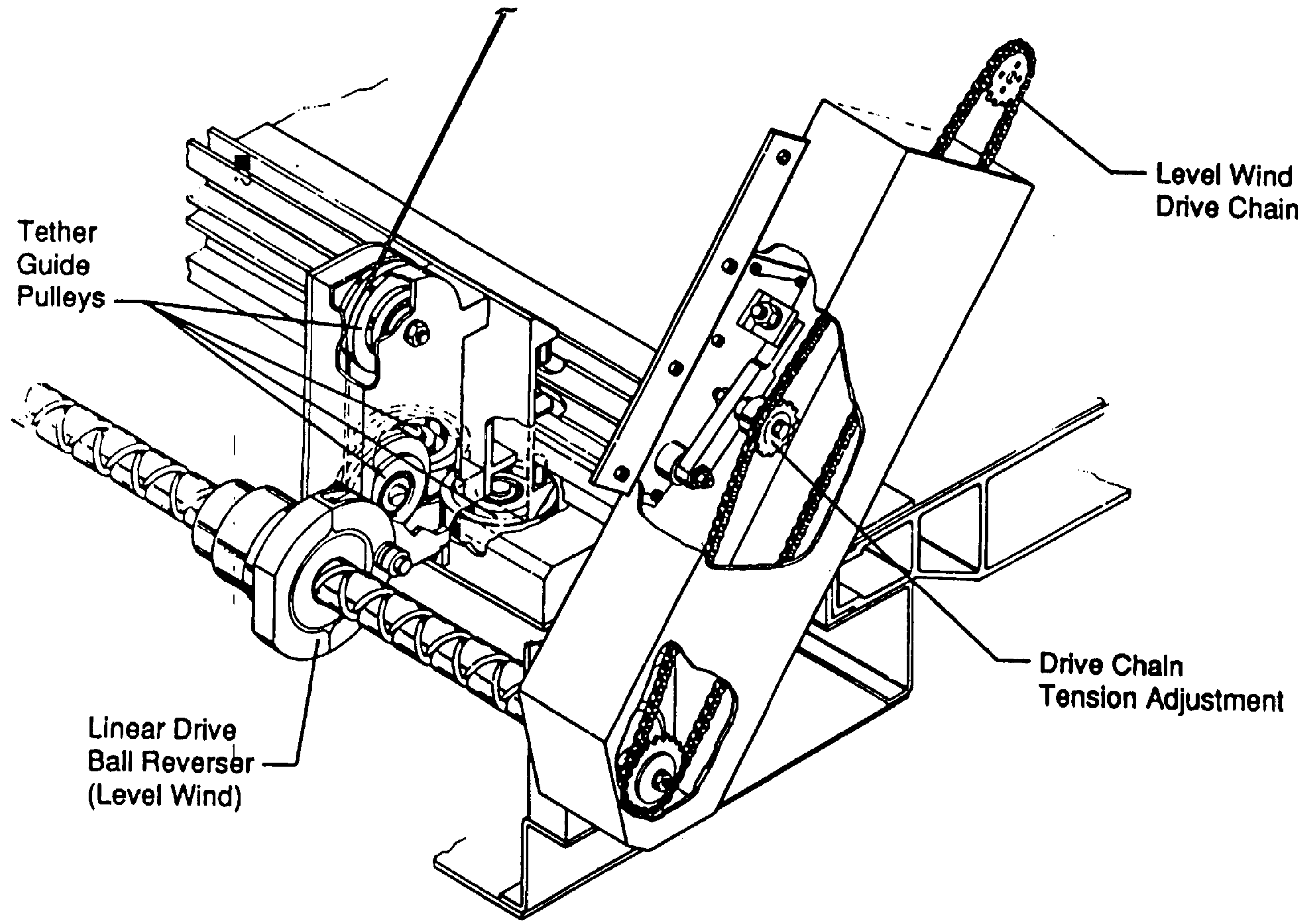


Figure 4.2

Lower Tether Control Mechanism (LTCM)

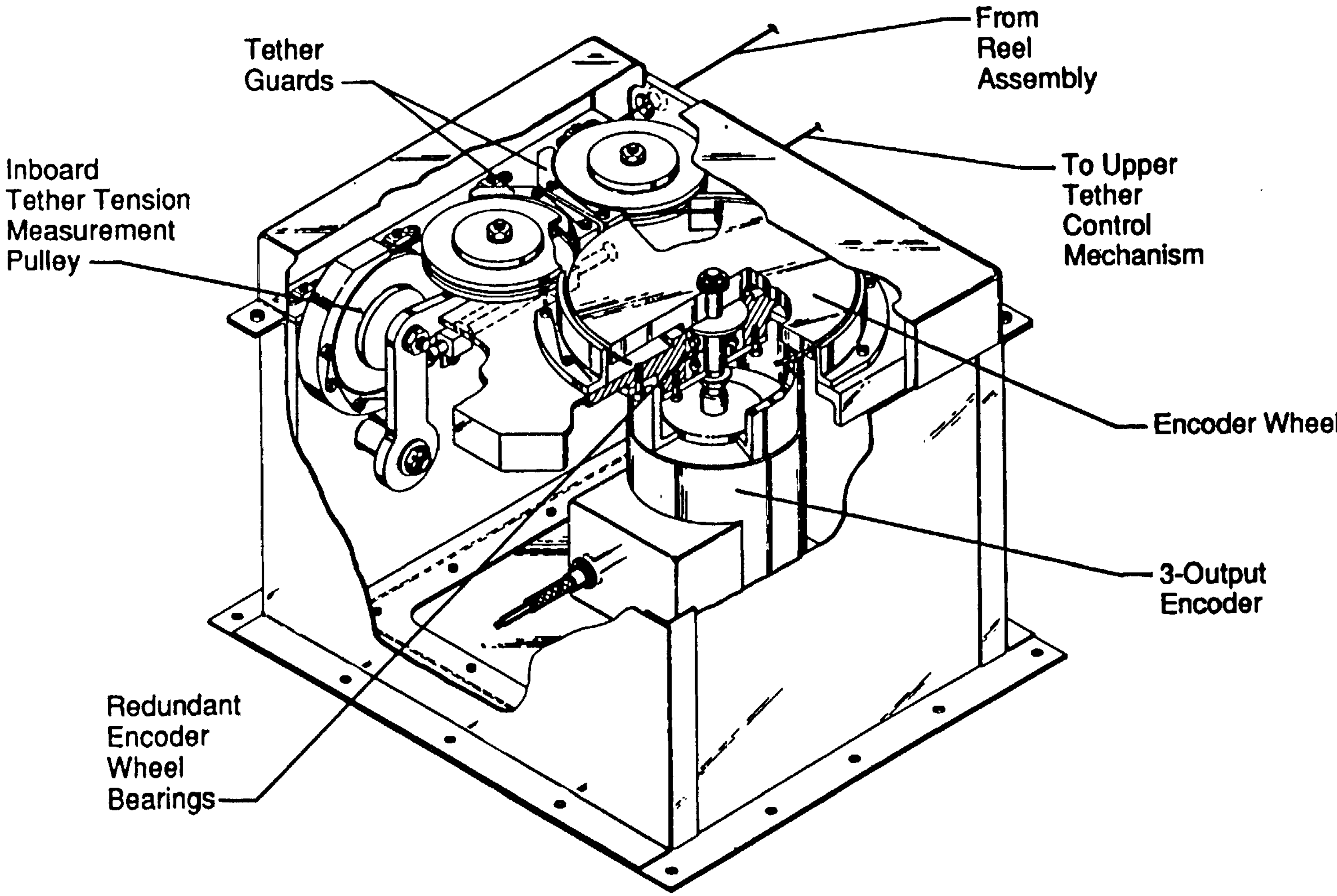


Figure 4.3

The tether path from the reel follows a specified path through the LTCM. The tether first encounters the encoder wheel, around a load cell pulley, and out through the tether cutter.

The inboard tension is necessary to ensure the health of the inboard tether routing. When in the basic control mode, the control system utilizes the inboard tension measurement as an open loop compensation to regulate the reel motor output with respect to the vernier motor during deployment. By knowing the system friction and resistance and the tension characteristics of the vernier motor, the tensiometer dictates the reel motor torque resistance required to offset the system resistance. The inboard tension measurement also provides an indication of the inboard tether tension at the reel to preclude slack and the possibility of the tether coming off a pulley and jamming.

UPPER TETHER CONTROL MECHANISM (UTCM)

The UTCM (figure 4.4) is located on the top of the satellite deployment boom in the upper canister just below the docking ring. The UTCM performs the following functions:

- Guides the tether from the boom to the satellite
- Gives outboard tension measurements
- Provides constant boom-to-reel tension for reeling operations
- Provides a tether cutting capability

The tether path (from satellite down through boom) follows a specified route. First, the tether encounters the tether bugle, which straightens the tether angle vertically for a pulley below that directs the tether 90°. The tether then travels through a tether cutter, around a load cell pulley and around a vernier motor grip pulley before embarking down the centerline of the boom.

The vernier motor and clutch provide tether tension between the UTCM and the reel mechanism when the natural gravity gradient tensions induced by the deployed satellite fall below the tension necessary to overcome the resistance of the system. The vernier motor drives the system during initial deployment; the reel motor is used to control deployment against the constant tension produced by the vernier motor and against the outboard tension. The vernier motor was designed and qualified for operation in a stall condition for a maximum of 30 seconds.

Upper Tether Control Mechanism (UTCM)

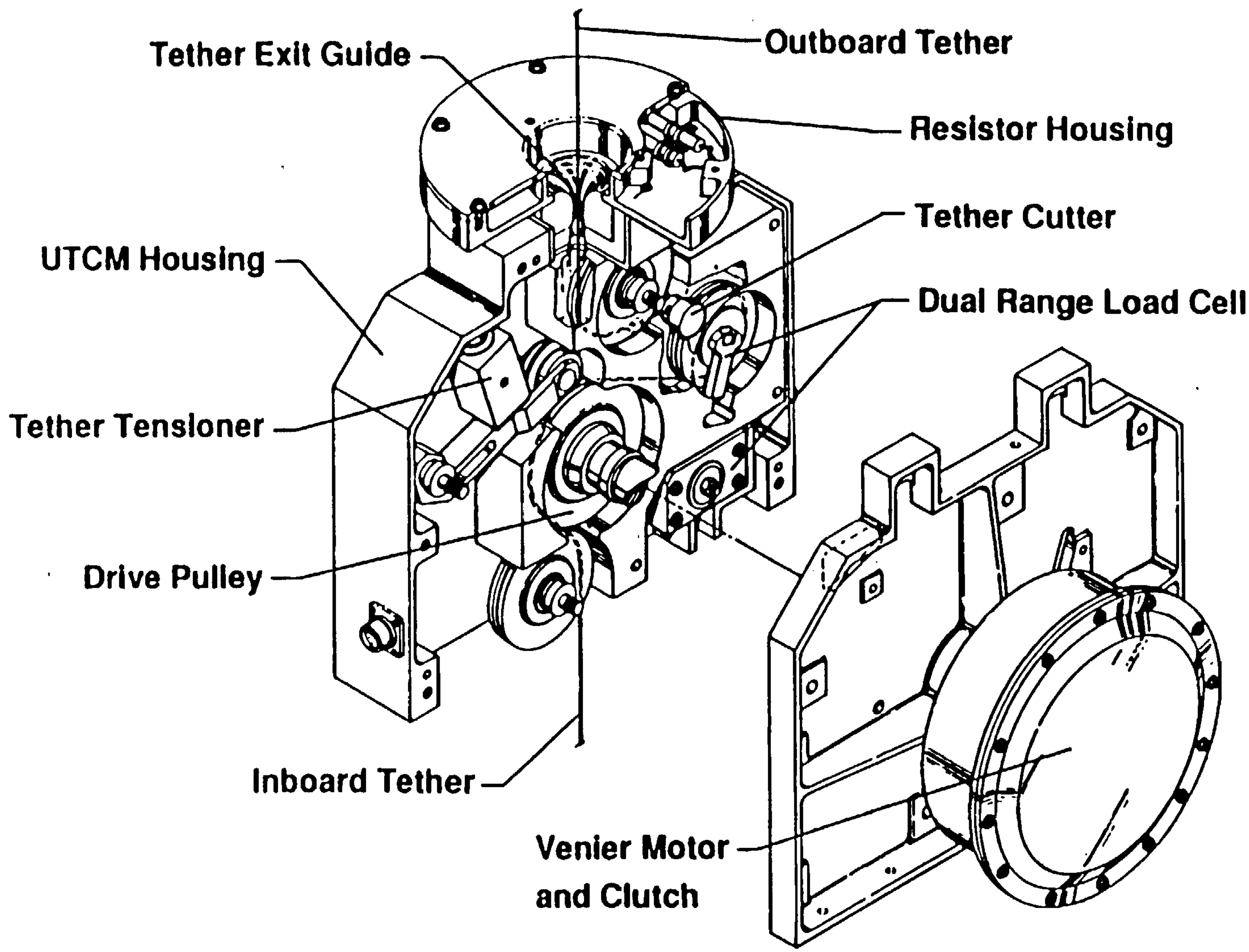


Figure 4.4

UMBILICAL PULLERS

The U1 and U2 umbilical mechanisms consist of umbilicals to interface between the deployer and the satellite and retraction mechanisms to demate, retract, and restrain the umbilicals.

The U1 umbilical is separated from the satellite after the satellite is powered and prior to Satellite Deployment Boom extension. The U2 umbilical is separated from the satellite after full Satellite Deployment Boom extension and after rotation of the satellite and docking ring to establish communications between the orbiter and satellite.

The umbilicals demate with detent force of 30 lb for the U1 connector and 48 lb for the U2 connector, with the lanyard force applied within a cone at 30° from the axis of the connector. The U2 mechanism (Figure 4.5) utilizes a cable and yoke attached to the male connector. A motor, installed on the lower docking ring, winds the cable in and the tension in the cable pulls the connector lanyard, releasing the connector from the satellite. When the motor winds the cable in, the connector disengages from the satellite, and guide pins on the yoke settle the connector/yoke into slots on the retention bracket. The U2 umbilical mechanism can accommodate a minimum of 19 cm (7.5 inches) of Satellite Deployment Boom travel and +0.5° satellite docking ring rotation prior to docking ring contact with the satellite.

TETHER CONTROL SYSTEM OVERVIEW

The deployer control system provides active control of the tether and satellite during the dynamic mission phases. The control system is a closed-loop system that utilizes tether tension, tether length, length rate, and motor supply voltage as feedback to follow a preselected mission profile. Control is attained through the active resistance and positive torque applied by the reel motor during deployment and retrieval, respectively.

U2 Umbilical

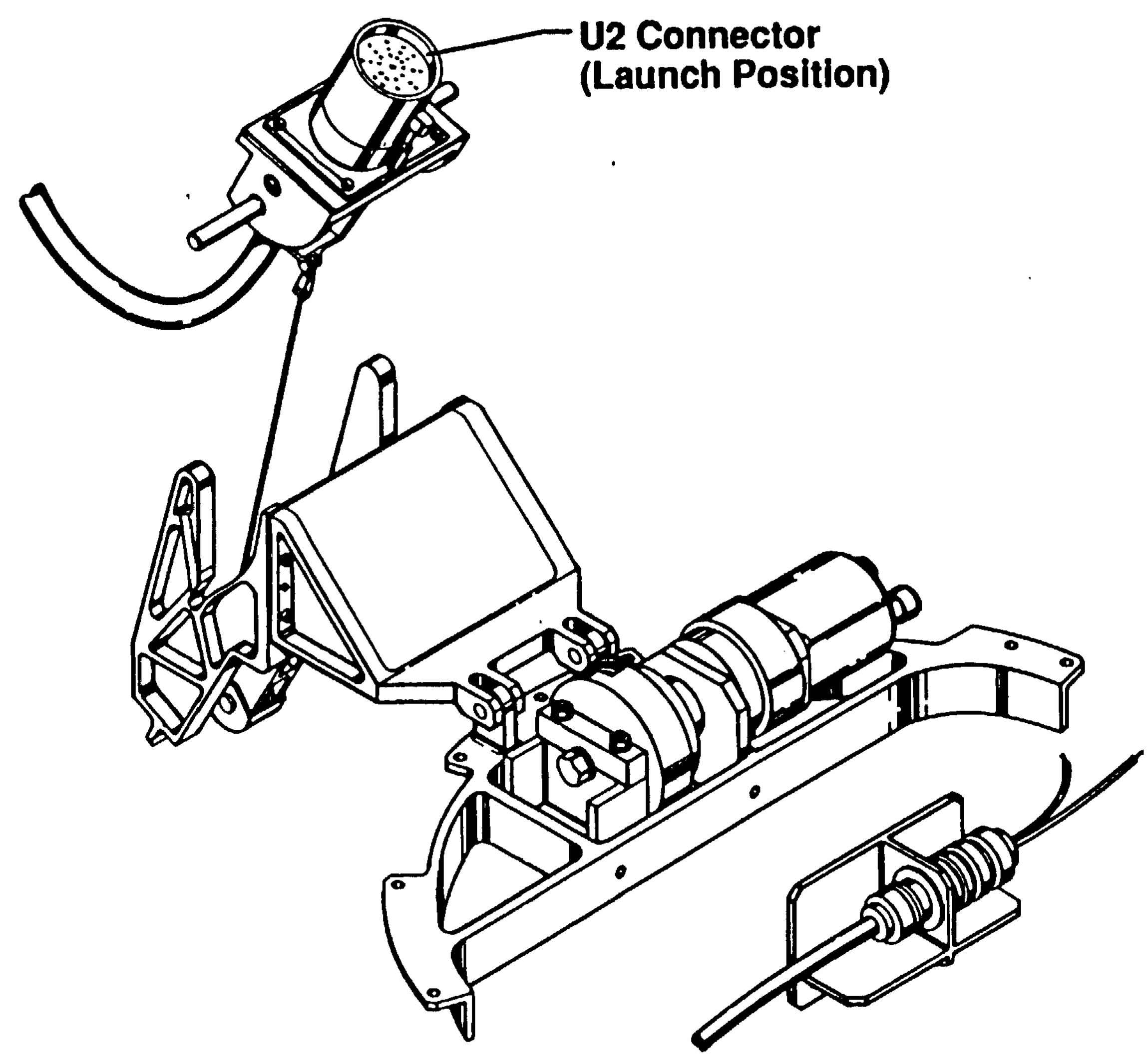


Figure 4.5

CHAPTER V - FLIGHT ANOMALIES

The Investigation Board identified five In-Flight Anomalies (IFA) that occurred during the TSS-1 Mission:

- U2 Umbilical Retraction Failure
- Initial Failure to Flyaway
- Unplanned Tether Deployment Stop at 179 Meters
- Unplanned Tether Deployment Stop at 256 Meters
- Failure to Move Tether in Either Direction at 224 Meters

U2 Umbilical Retraction Failure

Initial attempts to retract the U2 umbilical connector were unsuccessful. The umbilical was retracted successfully after both warming the connector in the sun and performing an orbiter +Z burn while commanding U2 retraction.

Initial Failure to Flyaway

Upon initial deployment, the tether deployed approximately 0.13m and then stopped. The Satellite was reeled back to the docking ring and a successful second attempt made using a modified procedure sequence.

Unplanned Tether Deployment Stop at 179 Meters

The Satellite deployment unexpectantly stopped at 179m. The satellite was reeled back 10m in two 5m increments. In an effort to deploy beyond 179m, manual control was used to maximize the satellite momentum and the satellite successfully continued to deploy.

Unplanned Tether Deployment Stop at 256 Meters

The Satellite deployment unexpectantly stopped again at 256m. The satellite was reeled back to 224m.

Failure to Move Tether in Either Direction at 224 Meters

After performing a vernier motor check out, the tether and satellite would not deploy nor retrieve. Performing a partial retraction of the Boom (0.5 meters) with the reel motor on and subsequent Boom deployment with the reel motor brake on cleared the apparent jam and the satellite was retrieved by reeling in the tether.

The Investigation Board determined that the five separate anomalies were not all unique and were due to three separate failure modes. Listed below, in relative importance with respect to mission impact, are the three failure modes with their associated In-Flight Anomalies.

1. UNPLANNED TETHER DEPLOYMENT STOPS AT 179 AND 256 METERS ANOMALIES
   - Unplanned Tether Deployment Stop at 179 Meters
   - Unplanned Tether Deployment Stop at 256 Meters

2. INITIAL FAILURE TO DEPLOY AND A SUBSEQUENT FAILURE TO MOVE IN EITHER DIRECTION AT 224 METERS
   - Initial Failure to Flyaway
   - Failure to Move Tether in Either Direction at 224 Meters

3. U2 UMBILICAL RETRACTION FAILURE
   - U2 Umbilical Retraction Failure

CHAPTER VI - ANOMALY RESOLUTION AND VALIDATION

UNPLANNED TETHER DEPLOYMENT STOPS AT 179 AND 256 METERS ANOMALIES

CAUSE: Level wind mechanical interference (protruding bolt).

MISSION SEQUENCE

During the TSS mission anomalies occurred which resulted in stopping the deployment of the tether at 179 and 256 meters.

The following flight parameters were used during this analysis:

1) Tether length and rate were obtained from the Lower Tether Control Mechanism (LTCM) encoder
2) Inboard tether tension obtained from the tensiometer load cell in the LTCM
3) Outboard tether tension obtained from the tensiometer in the Upper Tether Control Mechanism (UTCM)
4) Reel motor current, used to measure the active resistance being applied
5) The vernier motor status (on/off) in the UTCM.

Friction forces were calculated using the above flight data parameters.

When the system is operating normally in the deployment mode, the vernier motor is pulling tether from the reel with a constant force of 25-30 newtons. The deployment rate is controlled by varying the resisting force applied by the reel motor. The reel motor resisting force can be controlled two ways, via control laws or manual control. When the system is operating under the control laws, the resisting force of the reel motor is controlled by the Data Acquisition Control Assembly (DACA) which compares the tether length from the LTCM Encoder to a previously calculated length for the given time of deployment. The resisting force is changed depending on whether the read length is greater or less than the previously calculated length for that time of deployment. When the system is under manual control, a given resisting force is keyed into the DACA and the system will obtain a steady state deployment rate.

After the two initial anomalies (U2 Umbilical Retraction Failure, Initial Failure to Flyaway) were overcome, tether deployment was normal (0.16 meters per second tether deployment rate). When tether deployment reached 170 meters, flight data (a decrease in tether deployment rate and a decrease in reel motor current) indicated there was an anomaly in the system. The inboard tether tension remained constant at 25 newtons, indicating the vernier motor was operating properly. The outboard tether tension remained at approximately 2.5 newtons indicating the UTCM was operating properly. The tether rate continued to decrease until the deployment stopped at 179 meters. Since UTCM and LTCM parameters were nominal and the reel motor current dropped to zero, this indicated an anomaly inboard of the LTCM.

After the deployment stopped at 179 meters, a decision was made to retrieve 5 meters of tether to assess system operation. After successful retrieval of 5 meters, an additional 5 meters of tether was retrieved. The additional tether length would allow a redeployment to gain momentum in an attempt to "break through" whatever had stopped the deployment. Flight data indicates that both 5 meter retrievals were nominal. The redeployment was resumed under manual pulse width control to achieve higher momentum with a commanded deployment rate of 0.2 meters per second. After the 10 meters were redeployed, the flight data indicated: (1) large tension spikes at both inboard and outboard tension measurements at 179 meters; and (2) tether deployment rate gradually decreased from the initial 0.2 meters per second until the system stopped at 256 meters. Since these measurements were taken by the UTCM and LTCM, they were operating properly and the anomaly was probably inboard of the LTCM.

During the deployment from 179 meters to 256 meters, flight data indicated the system had more than anticipated friction indicating an anomaly within the system. In addition, inboard and outboard tether tensions as well as reel motor current were very erratic; length and tether rate were not smooth. During this period vernier motor operation was nominal as indicated by inboard tether tension of 25 newtons.

Since the stop at 256 meters was under manual control, an attempt was made to place the system under control laws and continue deployment. This attempt was unsuccessful.

Next, a decision was made to retrieve the satellite to again determine if the system could obtain enough momentum to "break through" the anomaly. Retrieval to 224 meters was nominal. (A subsequent deploy attempt at 224 meters resulted in a jam and will be discussed in the "Initial Failure to Deploy and a Subsequent Failure to Move in Either Direction at 224 meters" section.)

FAULT TREE

The fault tree has been base lined. Items that could be closed by the analysis of flight data and the initial inspection have been closed. The remaining items have been assessed and are expected to be closed by the testing and inspection that has been performed.

HARDWARE INSPECTION TEST AND ANALYSIS

A two step observation/inspection plan was developed for the flight hardware. The initial observation was intended to look for obvious anomalies and failed hardware without disturbing the functioning hardware. Significant findings were:

1) A bolt protruded into the path of the ball nut collar. Indentations were found on the collar that matched the threads on the bolt and metallurgical analysis

confirmed that the ball screw collar had contacted the threads on the bolt (Figure 6.1a and 6.1b)

2) A large helix angle in the tether lay was found in the second layer of tether (Figure 6.2)
3) The level wind was 57.2 cm (22.5 inches) from the bolt. This dimension correlates to the 256 meters retrieved during the mission and indicates the level wind apparently operated correctly in the retrieve direction (Figure 6.3).

Based on these observations and the flight data, a failure hypothesis for the stops at 179 meters and 256 meters was developed. The following is a sequence of events believed to have occurred:

1) Tether deployment was nominal up to 170 meters at which time the protruding bolt was impacted by the ball nut collar on the level wind system.

2) Compliance in the system was sufficient to permit tether to deploy to the 179 meter full stop. Flight data indicated increasing system deployment resistance from 170 to 179 meters.

3) Slippage in the system allowed the deployment to continue from 179 to 256 meters. Tether was retrieved 10 meters from the 179 meter stop and deployment reinitiated at a higher deployment rate. Flight data from 179 to 256 meters was erratic and different from nominal operations. This supported the failure hypothesis that the ball nut collar recontacted the bolt between 170 and 179 meters. Deployment continued to 256 meters due to some unknown system condition.

The hardware post-flight test and inspection plan involved accomplishing an inspection of the chain drive, level wind, and reel subsystems. This revealed that the chain in the chain drive subsystem had lost some of its pre-flight tension. Completion of this inspection permitted manual and power up tests to begin with known hardware condition and status.

The large helix angle of the tether that was found in the initial observations corroborated that the ball nut collar contacted the bolt at 170 meters and stopped traversing the ball screw while tether was still being pulled from the reel (the tether lay moved down the reel). As the angle of the tether entering the level wind pulleys increased, system friction increased and finally stopped deployment at 256 meters. When retrieval was initiated, the helix was generated as the level wind was reversed and tether was rewound on to the reel.

Post-flight tests clearly validated that during the mission, the ball nut collar had contacted the bolt at 170 meters and remained in contact with the bolt up to 256 meters. Additional post-flight tether deployment tests, using flight data as limits, resulted in an override of the chain drive system, i.e. the chain jumped the sprocket

(Figure 6.4). This "jumping the sprocket" demonstrated a "system condition" whereby the system could have continued to deploy tether after full contact with the bolt during the mission.

RECOMMENDATION

To complete validation of the anomaly cause, additional tear down inspections of the level wind chain drive system should be performed to verify the chain drive "jumped the sprocket" as the system condition which allowed deployment past 179 meters.

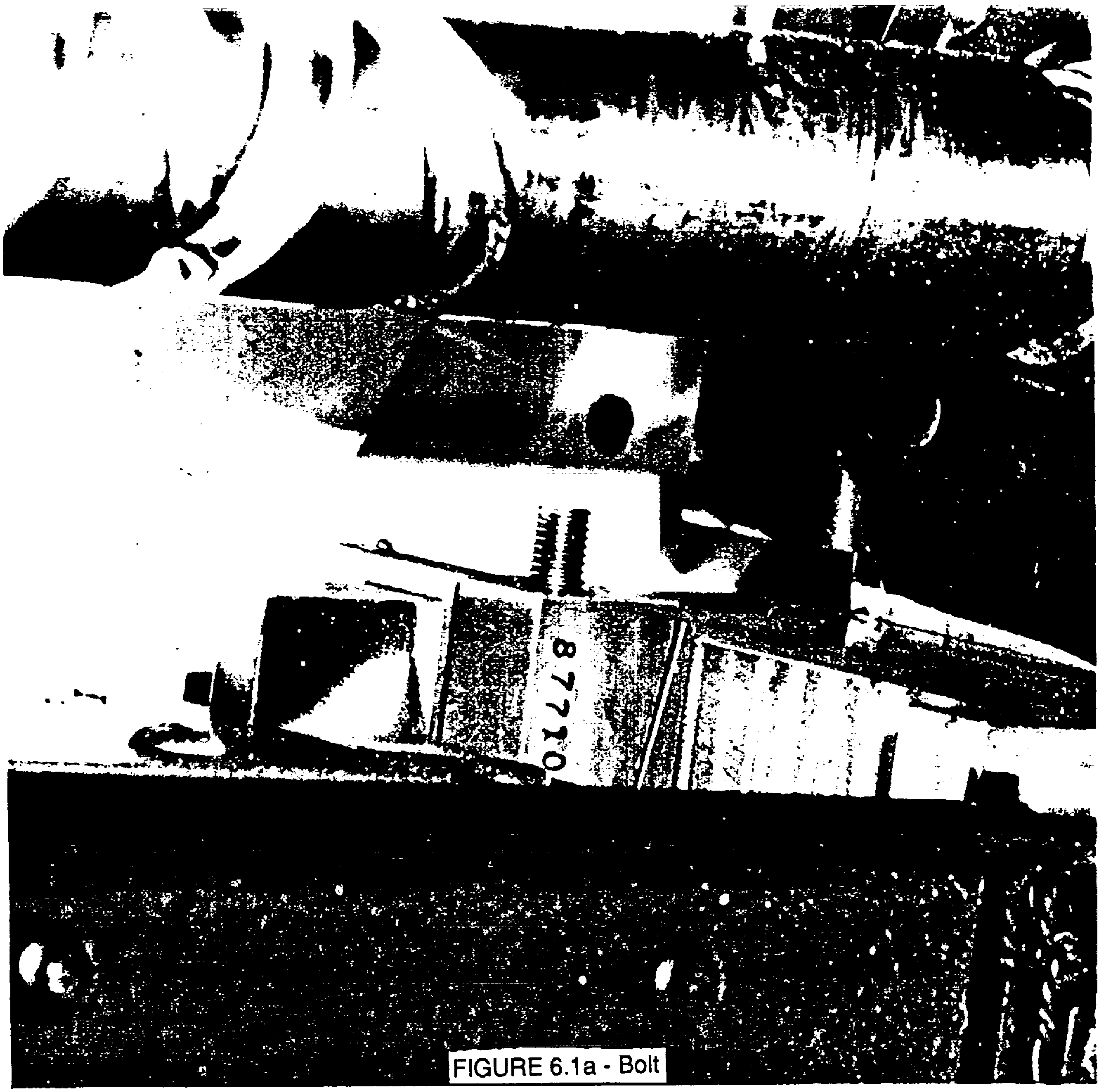


FIGURE 6.1a - Bolt

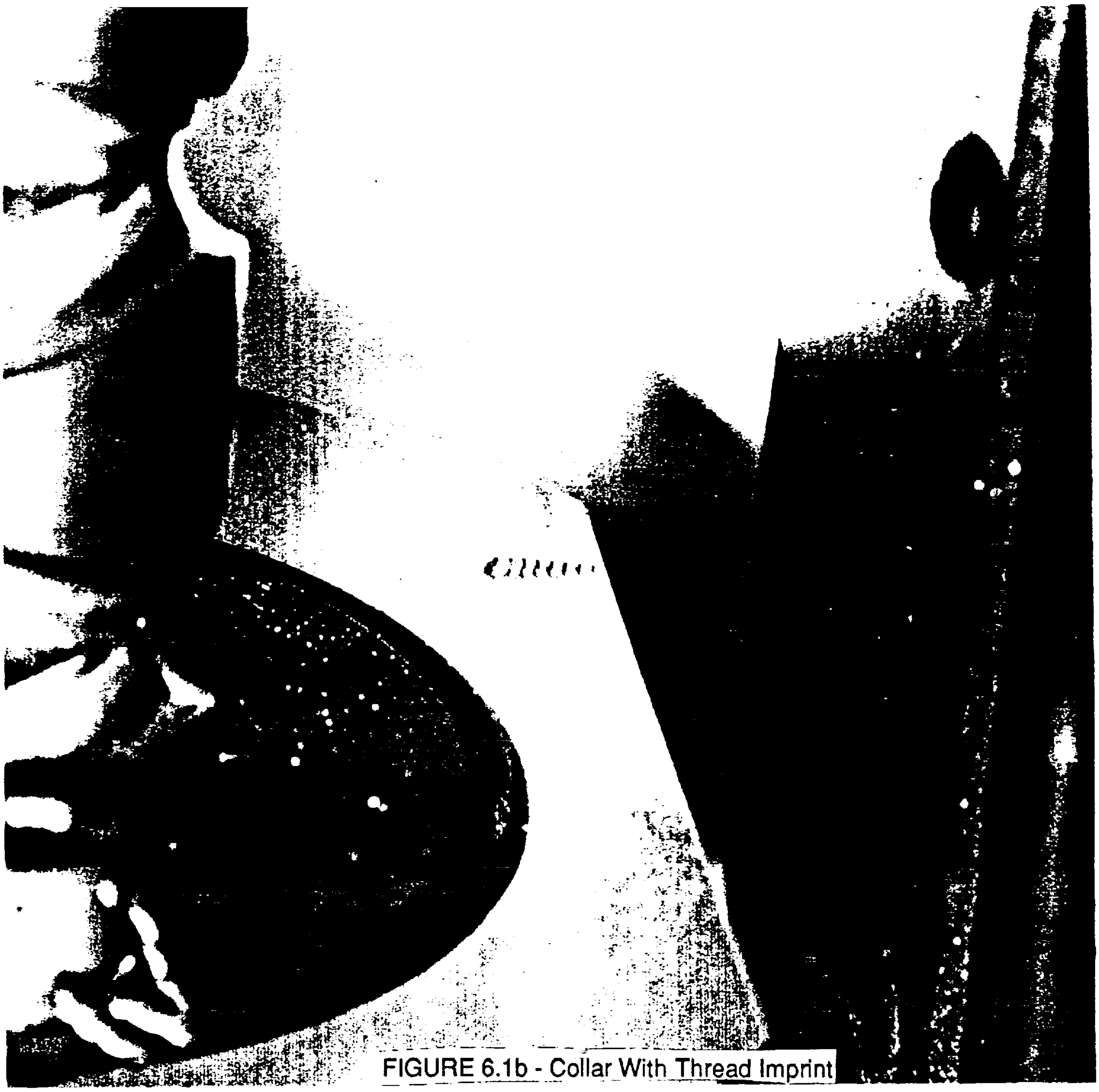


FIGURE 6.1b - Collar With Thread Imprint

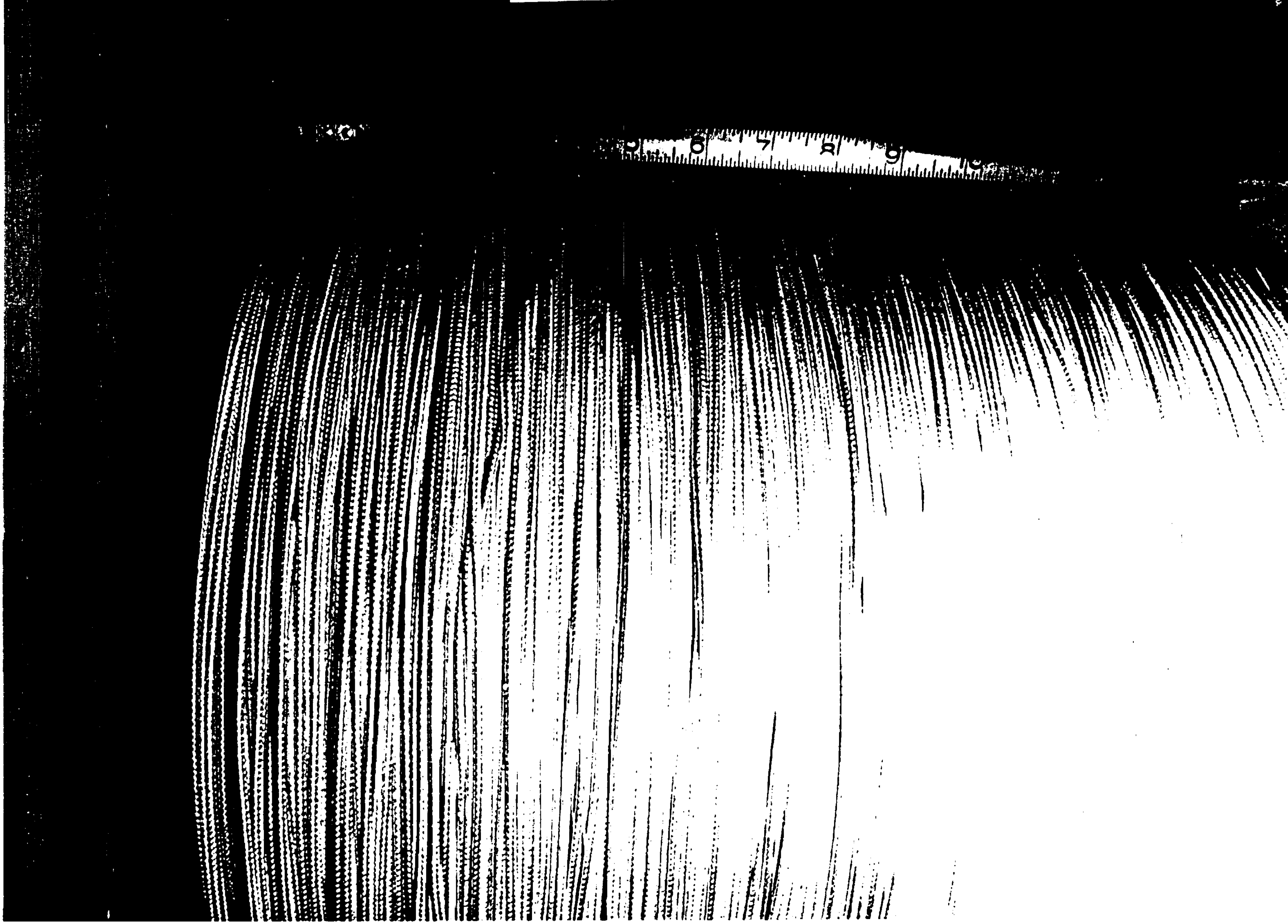


FIGURE 6.2 - Tether Helix Angle

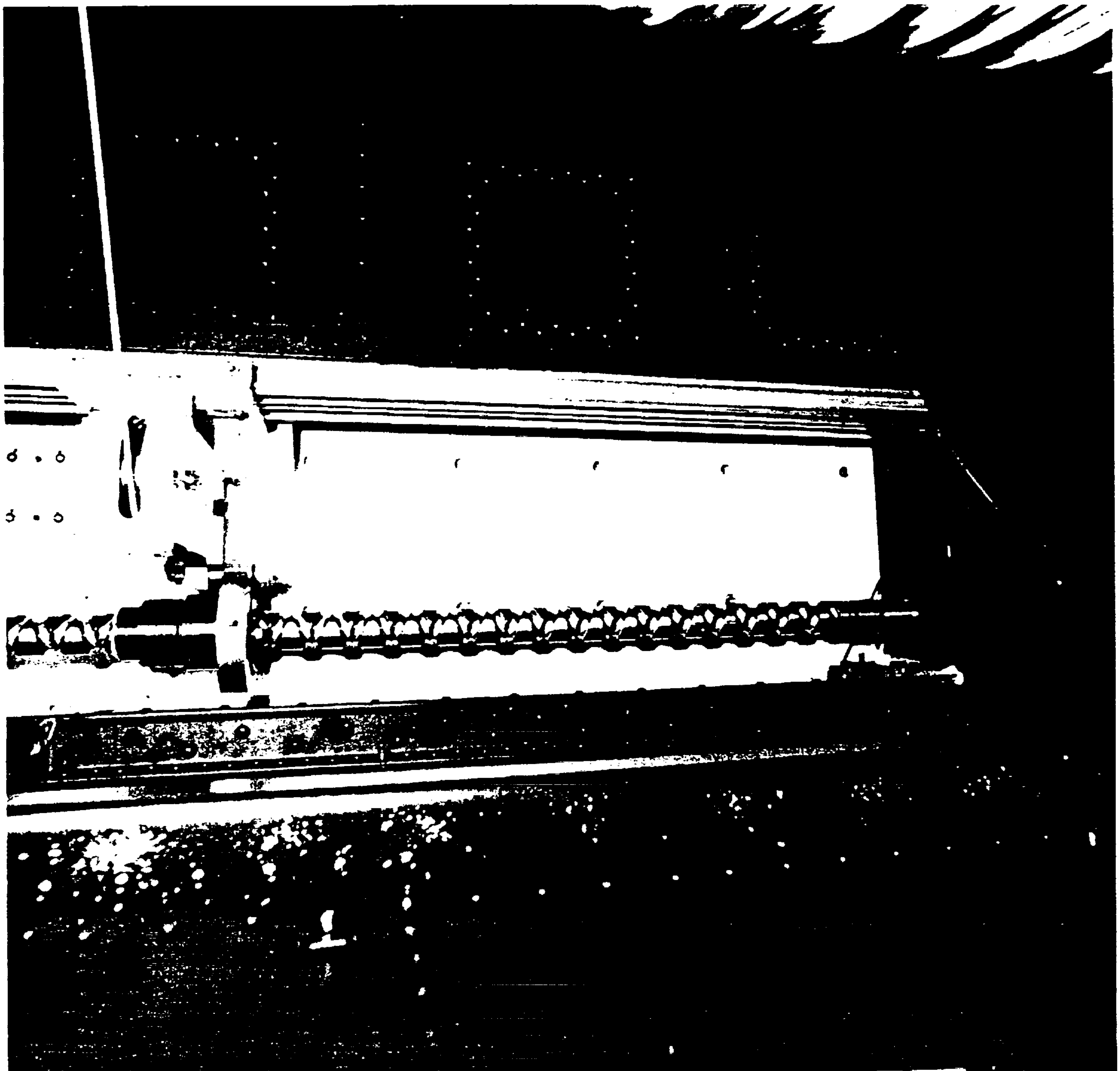


FIGURE 6.3 - Post Flight Level Wind 22.5 Inches (256 M) From Bolt

FIGURE 6.4

NINE SEQUENTIAL STILL PHOTOGRAPHS OFF OF THE VIDEO TAPE SHOW THE CHAIN SLIPPAGE ON THE UPPER SPROCKET. PHOTOGRAPHS 1 THROUGH 8 DEPICT THE CHAIN IN THE PROCESS OF SLIPPING. SPECIFICALLY, PHOTO 1 SHOWS THE MARKED CHAIN LINK (ARROW), PHOTO 7 SHOWS A MARK (DATUM POINT, ARROW "A") ON THE SPROCKET THAT IS IN EVERY PHOTO. ARROW "B" IN PHOTO 7 SHOWS THE ADJACENT SPROCKET TOOTH WITH RESPECT TO THE DATUM POINT (THIS IS THE NEXT TOOTH THAT THE MARKED LINK ON THE CHAIN JUMPS TOO). PHOTO 9 SHOWS THAT THE MARKED CHAIN LINK (TOP ARROW) HAS JUMPED ONE TOOTH AS REFERENCED BY THE DATUM POINT (ARROW "C" AND IT'S ADJACENT TOOTH (ARROW "D").

INITIAL FAILURE TO DEPLOY AND A SUBSEQUENT FAILURE TO MOVE IN EITHER DIRECTION AT 224 METERS

MOST PROBABLE CAUSE: Binding tether/vernier motor stalling resulting from excessive tether acceleration during vernier motor activation with condition of slack tether.

MISSION SEQUENCE

The initial deployment was attempted with one set of thrusters on (in-line 2, which provides about 2 newtons of thrust); control laws activated (which allows adjustment of tether tension); and vernier motor on. The tether deployed approximately 0.13 meters and then stopped. After reseating the satellite, a second attempt was made using a different procedure which included "both" in line thrusters on (4 newtons of thrust) and the vernier motor on "before" activating the control laws. This procedure resulted in a successful deployment.

The second failure to deploy occurred during the final attempt to deploy while at 224 meters. A vernier motor checkout was performed which produced an increase of only 16 newtons inboard tension (22 newtons would be normal), but there was practically no motion of the tether. An attempt to reel in with the maximum torque available (60 newtons) was unsuccessful. Unable to deploy or retrieve, the boom was retracted 0.5 meter (one bay) with the reel active. As the boom retracted the tether was reeled in until the boom was stopped indicating that the anomaly was in the Upper Tether Control Mechanism (UTCM). The reel brake was applied and the boom was extended which applied a force adequate to free the tether and allow retrieval of the satellite.

FAULT TREE

Fault Tree (Appendix E) Block F3A --Tether fails to move nominally through the UTCM-- has three branches for possible failures: 1) tether binding inside the UTCM due to satellite rotation, 2) a tether anomaly, or 3) a UTCM anomaly. There was no satellite rotation prior to fly-away; therefore, this is not the failure condition. Post flight inspection of the tether at KSC did not identify any of the following anomalies which would account for the deployment failures: contamination, tether damage, splice location, tether diameter out-of-specification, pliability or tether twist. However contamination due to an ice accumulation on the tether can not be proved or disproved with the evidence available. The most probable cause for the failure to deploy at fly-away and at 224 meters is due to binding tether (jam) between the UTCM vernier drive and the outboard tether guide. As discussed in the next paragraph, this jam is due to vernier motor accelerating tether in the UTCM faster than the tether can be pushed out the bugle head.

HARDWARE INSPECTION, TEST AND ANALYSIS

Analysis of anomaly flight tether tension data and post flight testing indicated that both anomalies were caused by tether binding which resulted in stalling of the vernier motor. Both anomalies occurred immediately after engaging the vernier motor while there was inadequate tension (slack) in the tether system which resulted in hang-up (binding) of the tether in the UTCM. Post flight testing of the system with slack tension was conducted by the manufacturer using a mock-up UTCM (Figure 6.5a), and by the investigation team using the actual flight hardware at KSC. Both tests resulted in tether hang-ups in the UTCM as encountered in flight. Tests indicate that the inertia of the accelerating tether from activation of the vernier motor with slack in the system results in a hang-up of the tether within 3-150 cm. The hang-up occurs as the tether overlaps and binds the vernier pulley between the vernier motor grip pulley and the upper tensiometer (Figure 6.5b). The tests show that after binding, the tether retained physical evidence of the bind. Examination of the flight tether revealed similar evidence. Tests of the mock-up UTCM revealed a force of 60-120 newtons was required to unbind the tether. Post-flight tests of the flight UTCM required about 60 newtons to unbind the tether.

ANOMALY TWO (INITIAL FAILURE TO FLY AWAY)

Prior to the deploy attempt normal tension existed in the system (inboard 77 newtons, outboard 57 newtons). Analysis indicated that slack in the system during the initial deployment was the result of the control laws rapidly reducing the inboard tension as it sensed there was no change in deployed tether length. Activation of the vernier motor "after" the control laws (tension decreasing, inboard 3.9 newtons - outboard 9.2 newtons) resulted in increased tether acceleration and binding. Indications are that binding was aggravated by reduced outboard tension due to acceleration of the satellite being slower than the tether deployment/acceleration.

Analysis indicates that after the initial anomaly, the second deployment was successful because: (1) the bind was pulled from the UTCM when the satellite was reseated onto the docking ring resulting in a tension spike of approximately 90 newtons (flight hardware tests required 60 newtons to unbind the jam); (2) the vernier motor was turned on (while tension was still in the system) "prior" to activating the control laws; and (3) both sets of the satellite in-line thrusters were activated which helped maintained tension in the system during vernier motor activation and satellite deployment. A comparison of the system condition for the unsuccessful and successful fly away is provided in Figure 6.6.

ANOMALY FIVE (FAILURE TO MOVE IN EITHER DIRECTION AT 224 METERS)

Prior to the final attempt to deploy, a vernier motor checkout was performed with low inboard (5 newtons) and outboard (1.5 newtons) tension which resulted in the binding and vernier motor stalling after only 0.03 meters of tether deploy . The vernier motor

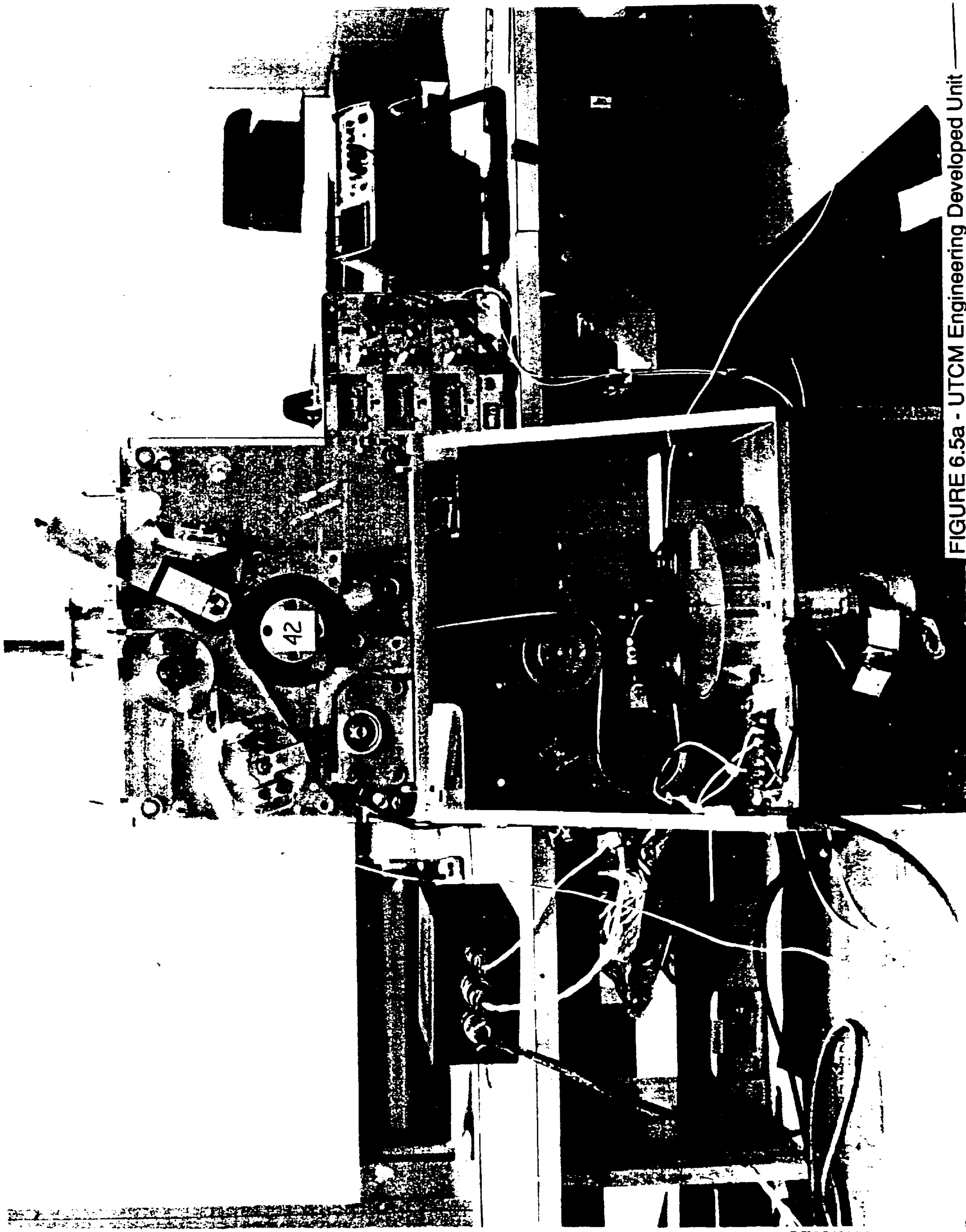


FIGURE 6.5a - UTCM Engineering Developed Unit

FIGURE 6.5b - Tether Jam - UTCM

Next Altitude Command Operations

	Unsuccessful Fly Away	Successful Fly Away
1st Command	Control Laws ON	Vernier Motor ON
2nd Command	Vernier Motor ON	Control Laws ON
Pulse Width	511 Gen	511 Motor
Tension (LTCM)	Low	High
Tether (Inboard)	Slack	Tight
Thrusters On	2	4

Figure 6.6

checkout provided a peak inboard tension of 16 newtons which then dropped to 1.5 newtons (22-25 newtons of tension was expected). The data indicates that the final attempt to deploy was conducted while the bind, which occurred during the vernier motor checkout, was present in the UTCM. This condition prevented deployment and retrieval until the tether was released by movement of the boom (85 newtons tension spike).

PRE-MISSION TESTING

Pre-flight tests were performed using pulleys and weights to provide continuous outboard tension. However, in one test the outboard tension was reduced by holding the tether one to two meters above the bugle while the tether was being deployed (binding of the tether was not encountered). Tests were not conducted activating the vernier motor with slack tether tension, which was the condition encountered during the two in-flight anomalies. Tests were not performed that simulated the satellite at 0.11 meters from the bugle head and moving away slower than the tether was being deployed which was the flight condition for the first anomaly.

U2 UMBILICAL RETRACTION FAILURE

PROBABLE CAUSE: No most probable cause has been determined within the time frame of this investigation; three likely causes have been postulated.

MISSION SEQUENCE

One of the anomalies that occurred during the TSS-1 mission resulted in failure to separate the U2 umbilical on several attempts. At the first command execution the U2 connector was in a dark condition and the telemetry indicated that the separation relay was actuated and the separation motor operated for the programmed 15 seconds. The U2 separation command was issued ten more times with the following combination of different operational conditions:

- manual control of the separation relay
- docking ring was rotated for a continuous warm-up of the U2 connector (satellite skin temperature reported to increase from -16 to +68 °C)
- separation motor activated for 31, 102, 21, and 5 seconds, respectively
- tether tension reduced in subsequent steps (71, 20 and 5 newtons respectively)
- contingency separation relay was used

The last or twelfth separation command was executed in conjunction with a +Z orbiter thruster burn, which added approximately 130 newtons (30 pounds) to the nominal separation motor force; the satellite skin temperature was approximately +68° C. This attempt resulted in a successful U2 umbilical separation. Processing of the satellite accelerometer data, strongly suggests that successful separation occurred after the +Z orbiter thruster burn.

FAULT TREE

The fault tree analysis for the U2 umbilical failure to release (reference Appendix E - Fault Tree) was divided into five major categories:

- U2 satellite interface anomaly (jammed connector)
- U2 lanyard mechanism fails to release spring
- U2 connector spring fails to provide adequate force for separation
- Improper alignment of U2/satellite interface
- Mechanical interference between connector yoke guide pins and retention bracket

Review of all available post flight hardware and mission data suggests that the "U2 lanyard mechanism fails to release spring" branch includes the most likely potential causes for failure of the U2 to separate during the mission. All these potential causes are being further worked in more detail to identify additional hardware inspection and testing.

REVIEW OF PRE-MISSION TESTING

Pre-mission ground testing of the U2 umbilical consisted of unit (connector) qualification tests and system level tests (joint qualification acceptance and final functional verification tests). In the unit qualification tests, the connector was subjected to random vibration, thermal cycling from -197° C to +200° C, separation impulse, and durability testing. In these tests separation forces at cold temperature increased to 102 newtons from the nominal range of 31 newtons to 53 newtons. After thermal cycling, the connector was successfully demated 250 times at ambient temperature with separation forces within the nominal range of 31 newtons to 53 newtons. The flight units were tested for electrical and mechanical performance only; the connectors were not subjected to any environmental exposures.

The flight connector plug, without satellite receptacle; separation mechanism; and separation motor combined subsystem were subjected to joint qualification acceptance tests (JQAT). Random vibration and thermal vacuum tests (-65° C to +65° C and $1x10^{-5}$ Torr) were conducted separately with successful demating under thermal vacuum at the two temperature extremes. The test were performed using a rigid mounting plate that did not fully simulate the U2 flight hardware configuration. Final separation subsystem verification tests were performed at ambient atmospheric pressure and temperature; two successful demates of U1 and U2 umbilicals were accomplished.

HARDWARE INSPECTION, TEST AND ANALYSIS

An investigation plan was prepared for hardware inspection, test, and analysis. The major points of the plan includes:

- Inspect/photograph U2 umbilical mechanism
- Inspect/photograph/X-ray U2 connector
- Inspect/photograph satellite receptacle half of connector
- Remove plug half from deployer and perform detailed visual examination (no disassembly)
- Add strain gauges to cable, connector lanyard, and clevis
- Mate U2 by KSC Level IV procedure and perform three pull tests with separation motor, recording detent force (on two of those tests) required to separate the connector
- Perform two additional pull tests manually measuring force required to separate with hand held spring scale

Post-flight visual inspection of flight hardware prior to pull test showed no obvious damaged parts or obstructions. After pull tests, inspection of the two vlier pin assemblies and their interface with the actuator assembly showed that the protrusion of vlier pin assembly shoulders from the housing assembly did not meet drawing specifications (Figure 6.7). The hardware drawings called out a 0.030 inch maximum protrusion from the housing assembly; however, the two shoulders extended 0.051 and 0.072 inches in the post flight hardware, resulting in clearances between the actuator assembly and the shoulder of the vlier pin assembly of zero on one side and 0.005 inch on the other side . This out of specification condition likely occurred preflight, when adjustments to the vlier pins were made to meet a 214 newtons separation force to prevent premature umbilical release during the mission. In addition, personnel performing the adjustment indicated that to meet this separation force requirement, one of the vlier pins had bottomed out and was then backed off slightly. However, this adjustment was performed after all thermal vacuum tests were completed; the effects of this adjustment were never tested prior to flight at mission temperature extremes.

Post-flight pull tests of the flight U2 umbilical showed successful separation occurred in every case and detent forces required for separation in ambient conditions were nominal. The performance of the separation motor during these tests was nominal at approximately 507 newtons. To date, post-flight tests of an engineering mock-up of the U2 umbilical in both ambient and thermal vacuum conditions have resulted in nominal separations.

LIKELY CAUSES FOR THE MISSION ANOMALY (U2 Umbilical Retraction Failure)

Three likely causes, or combinations thereof, have been identified within limits of the current knowledge of post flight hardware inspection and testing, mission data evaluation results, and the fault tree analysis. The three likely causes are:

- Excessive force at detent resulting from vlier pin adjustments

- Lanyard mechanism latch plate jam in the hoop spring

- U2 motor operates at less then nominal performance

The "excessive force at ball detent", can prevent pivot arm movement and will not allow proper lanyard activation of the connector separation spring. This situation is believed to have been caused by the improper adjustment of the vlier pin (Figure 6.7) in the pivot arm actuator assembly and by the low temperature in flight environment. Post flight visual inspection and measurement of protrusion of the vlier pins (housings shoulder) confirm that an interference between the vlier housings and actuator assembly can exist. At low temperatures, such as experienced during the mission, this clearance problem could have resulted in an interference between the shoulder of the vlier pin housing and the actuator assembly; this situation would not allow proper movement of the actuator assembly. The detent separation force was increased (adjustment of the vlier pin) from the specification value of 111 newtons to 205 newtons after completion of the thermal vacuum tests. This critical configuration change was not tested in a thermal vacuum simulation of the flight environment prior to the mission.

U2 Umbilical Mechanism

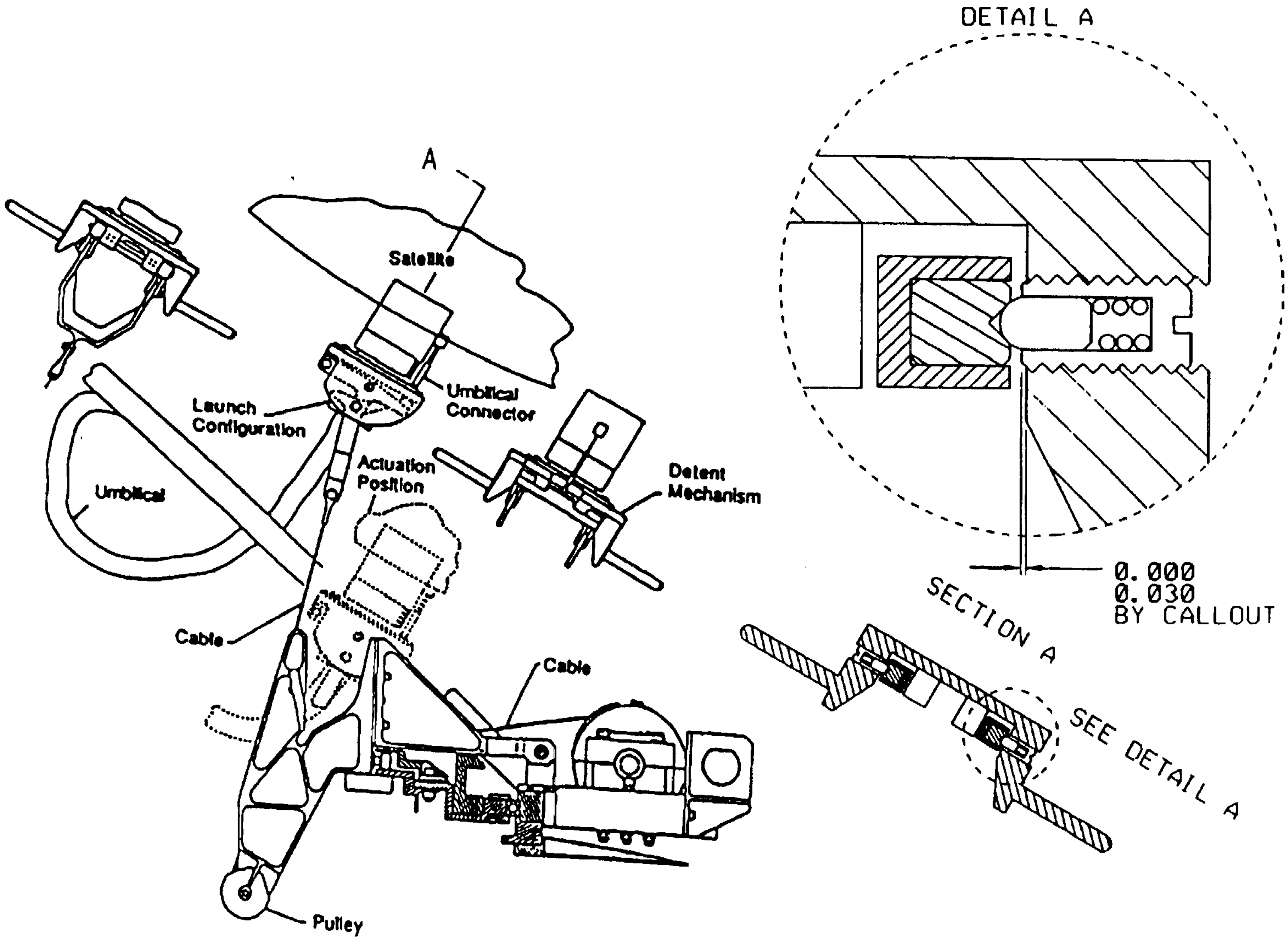


Figure 6.7

The "lanyard mechanism latch plate jam in hoop spring", can prevent U2 separation. The jamming of the hoop spring can be caused by the docking ring cushion compliance associated with the flight hardware configuration. Jamming of the hoop spring can prevent the proper release of the lanyard mechanical latch plate. U2 umbilical qualification separation tests were performed using a rigid support structure which did not fully simulate the flight hardware configuration. Since this condition was not ground tested, it is uncertain if the flight configuration can cause jamming of the hoop spring. In addition, ground testing showed that at low temperatures higher lanyard activation forces (increase from approximately 32 newtons to 125 newtons) were required when 423 newtons was applied to the hoop spring prior to lanyard activation; this effect was not observed with tests conducted at ambient temperature.

The "U2 separation motor operation less then nominal", can cause insufficient force to be applied to the pivot arm cable and prevent proper pivot arm operation. This problem would have had to be related to the separation motor performance at low temperature conditions; no data were available to resolve the likelihood of this case.

RECOMMENDATION

To complete anomaly cause validation, the project and/or working group should perform thermal tests on the U2 assembly at simulated mission environmental conditions with flight hardware at KSC (perform thermal vacuum test on U2 assembly if required). Additionally, the project and/or working group should review test specifications and determine if system design was adequately verified to meet mission environments.

CHAPTER VII
WHY THE ANOMALIES WERE NOT DETECTED PRIOR TO FLIGHT

LEVEL WIND MECHANICAL INTERFERENCE

A major structural problem was identified during the Verification Loads Analysis Cycle (VLAC) when negative margins of safety in the front reel foot to reel Support Structure fasteners were discovered. The deployer contractor considered altemate solutions to attain a positive margin of safety in these fasteners including the preferred solution of installing larger fasteners. This would have required deintegration of several pallet subsystems and the deployer from the carrier and repeating of carrier/deployer integration verification testing after reintegration. The result was an unacceptable schedule impact and therefore rejected. The deployer contractor recommended a modification which used shear wedges to provide a shear path at the front reel foot. The Reel Foot Mod Kit provided a positive margin of safety and geometric models installed in the field indicated that the Mod could be installed without deintegration of deployer. The change to implement the Reel Foot Mod Kit was approved by the contractor's Change Board Process and NASA's Change Board Process.

The potential for interference between the Reel Foot Mod bolt and the Level Wind Mechanism was not identified and/or recognized. Existing assembly drawings, which may have revealed the interference, were not completely up to date pictorially (project requirements and contractor policy did not require updating top assembly drawings until after three modifications) and did not contain a view which directly showed the interference.

The review process appears to have had a narrow structural mod perspective without adequate systems level assessment (e.g. potential for modification to intrude into the dynamic envelop of the level-wind mechanism translation travel). Opportunity existed to visualize this interference during the modification designs, during the contractor change board review progress, during the government change board review, and during the installation of the modification hardware at the launch site. These opportunities were inhibited by changes occurring after contractor shipment of hardware from the factory to the launch site and the attendant situation where by the modification hardware was being designed by individuals in Denver and the actual hardware was being viewed by different individuals at the launch site over 2,000 miles away. Certainly in the February-March 1992 time frame when this modification was taking place, there were launch schedule pressures associated with resolving a major structural problem which had been discovered very late as well as great satisfaction from identifying an innovative mod that could be implemented within launch schedule constraints.

The delayed identification of the structural negative margin of safety until after hardware delivery from the factory to the launch site is certainly a <u>contributing factor</u>.

Indeed, if the structural problem had been identified much earlier, the preferred solution would have been larger fasteners and the mod-kit with the bolt would not have become part of the flight hardware. Even if the mod-kit solution had been used and installed earlier, the interference would have been revealed during systems testing or as late as September 11, 1991 when the engineering model tether was reeled off and the flight tether reeled on at the launch site.

The Board believes that the root cause of the lateness in the identification of the structural problem is within the structural models and loads analyses process involving the Enhanced Multiplexer-Demultiplexer Pallet development and the Tethered Satellite System development. Indeed the structural problem was identified by a launch vehicle to payload element process (the Shuttle Verification Loads Analysis Cycle) rather than within the payload (carrier to Tethered Satellite System) loads analysis process. One potential contributing factor in the reduced structural margin of safety was a change to the carrier whereby the attachment of a thermal subsystem component (the coldplate) to the carrier structure was changed. The structural model which was used by the Tethered Satellite System development reflected an early design whereby the coldplate in effect was acting as a load carrying element of the carrier/satellite structure. Changes were also made in the tethered satellite system including increases in mass and mass redistribution. The significance of the design change of the coldplate (a thermal subsystem component) attachment and mass changes within the Tethered Satellite System and their relative contribution to the carrier/satellite structural design were not recognized by either the carrier organization, the satellite organization, or supporting engineering organizations. The Board believes this problem should have been identified much earlier through carrier to Tethered Satellite System loads processes as opposed to the launch system to payload load verification process.

BINDING TETHER IN THE UTCM

Vulnerability of the UTCM to jams under conditions of slack tether (zero tension) was obviously recognized, given the design of the deploy system. However, not fully recognized were the dynamic operating conditions within the system which would lead to zero or minimum tensions, such as:

- Acceleration/displacement of the satellite relative to the acceleration/displacement of the tether being pushed through the vernier motor during initial deploy.

- Relationship of the control law activation sequence to the vernier motor engagement.

Pre-flight tests concentrated on testing to flight expected conditions. Little off nominal testing was performed. All pre-flight tests of tether deployment were done under conditions which provided positive inboard and outboard tensions. Tests to "simulate" zero tension involved grabbing and holding the tether above the bugle as the vernier motor pushed tether from the system. This was not done under conditions where the tether was held before the vernier motor was engaged which would have more closely matched in flight conditions.

Minimal test hardware was available on which to conduct off nominal testing. There was a reluctance to use the actual flight hardware to perform off nominal testing.

U2 UMBILICAL

To date post-flight inspection, analysis and testing has not identified a probable cause; and thus, "Why This Anomaly was not Detected Prior to Flight" was not determined.

CHAPTER VIII - LESSONS LEARNED

1. Every effort should be made to fully analyze Spacelab Carrier to satellite system (e.g. TSS-1) integrated/coupled loads prior to the Shuttle Verification Loads Analysis Cycle. The failure of the Spacelab Carrier to Tethered Satellite System structural and loads analysis processes in discovering the structural negative margins of safety resulted in a much later discovery during the Shuttle Verification Loads Analysis Cycle. The parallel developments of the EMP and TSS by separate organizations and contractors likely contributed to the failure to identify the structural negative margin of safety much earlier.

2. Ground testing should fully explore the dimensions of the expected flight environment. When hardware operation is anticipated to be sensitive to a parameter (slack tether for the TSS-1 mission), ground testing should include the inducement of off-nominal conditions related to the parameter (the inducement of slack tether in the case of the TSS-1 mission).

3. Flight hardware changes incurred late in the project cycle (in particular after completion of systems test) are at best a high risk undertaking: When "necessary" changes are made the engineering assessment and change board process must place increased emphasis on the systems implications of the change and avoid being drawn into a narrow discipline oriented process. This is particularly true when changes are being made at a location geographically adjacent to an operational envelop such as that required by a translational level-wind mechanism. An aggressive and adequate systems engineering assessment capability must be maintained at late stages in a project cycle when typically the systems engineering resources available through project design are significantly reduced and the focus has changed to hardware checkout and operations. The importance of "doing it right the first time" is again reflected.

CHAPTER IX - RECOMMENDATIONS

LESSONS LEARNED

1. A critical process improvement team should be formed to review the structural and loads analyses processes and structural interface documentation currently used between the Spacelab carriers and user organizations. A specific focus should be a detailed assessment of the process used in the conduct of the TSS-1 project, the failure to earlier identify a major structural problem within this process, and the parallel development aspects of the process.

2. Independent assessments should be required for flight hardware changes which are made after the hardware has completed systems level testing and shipped from the factory. Such assessments should emphasize the overall systems implications of the changes. CAD/CAM technology and software have matured to a significant degree (particularly software associated with configuration control and the geographical relationship of components and component operational envelopes) and are commercially available. Projects should adopt this technology to facilitate systems level assessment of project design as well as systems level assessment of changes.

3. NASA as an agency, Marshall Space Flight Center, nor the contractor have specific failure policies requiring that projects pursue ground testing to off-nominal conditions. NASA as an Agency should adopt specific policies outlining criteria for projects to pursue off-nominal testing.

REFLIGHT

1. LEVEL WIND MECHANICAL INTERFERENCE: Assuming that the deployer is deintegrated from the carrier for other reasons, the Board recommends deletion of the Reel Foot Mod Kit and replacing the existing fasteners (bolts) with larger fasteners. If the Reel Foot Mod Kit is retained, then adequate clearance with the Mod Kit and Level Wind Mechanism should be assured. Replace damaged Reel/Level Wind/Chain Drive assembly hardware (e.g. level wind collar).

2. BINDING TETHER IN THE UTCM: Increase deployer system operational margins. Considerations should include, but not limited to the following:
    - Vernier motor design that permits slower/adjustable start up and deployment rates (including qualification for running in an extended stall condition)
    - Increase Satellite thruster size to increase ability to accelerate tether outboard of vernier motor pulley
    - Modify operational procedures, including control law changes if necessary, that assure inboard and outboard tether tension is maintained