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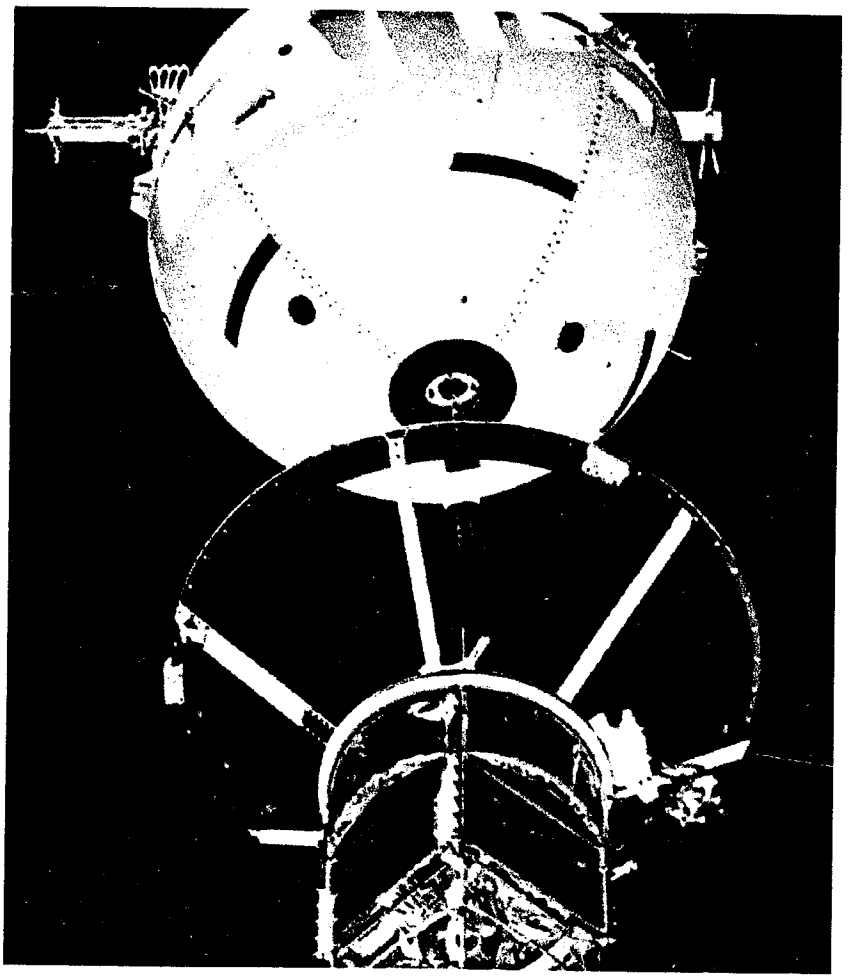
TSS-1R Mission Failure Investigation Board

Final Report



National Aeronautics and Space Administration

TSS-1R Mission Failure Board

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Acknowledgments

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- The Marshall Space Flight Center "Tiger Team" who worked intensely to conduct numerous tests and analyses in support of the investigation. The Tiger Team met approximately 50 times during the course of this investigation, and was ahead of the Board in the early stages of the investigation, anticipating tests and the need for specific data.

- The Kennedy Space Center team who deintegrated the TSS-1R payload and conducted initial inspection and photographic assessments of the TSS systems. The KSC staff ensured no data was lost or destroyed in the process.

- The Johnson Space Center team for providing an expert assessment of orbiter systems and mission operations for TSS-1R, and for conducting extensive photographic and video analyses.

- Lockheed Martin and Cortland Cable, who provided valuable expertise, technical data, and information about the design and development of the TSS systems.

- The Langley Research Center for conducting independent analyses of the flight tether.

- The TSS-1R Program Manager, Mr. Tom Stuart (NASA HQ), and Project Manager, Mr. Robert McBrayer (NASA MSFC), who provided the Board with significant technical, logistical, and management support.

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Notes:

1. Kevlar, Nomex and Vespel are rgistered trademark materials of the E.I. DuPont de Nemours & Col (Inc.).

2. Test data/charts received by the Board in English units have been used directly in the report. Conversions to Metric units were not made on some charts.

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Definition of Terms, Acronyms, and Abbreviations

Acronym	Definition
A	Amperes
AC	Alternating Current
ACBP	AC Boom Package
AMAG	Aspect Magnetometer
AMCS	Attitude Measurement & Control System
AOS	Acquision of Signal
ASI	Angenzia Spaziale Itallana (Itallian Space Agency)
AWG	American Wire Gauge
B	Magnetic Field
BMSP	Boom Mounted Sensor Package
C	Celsius
CCP	Charge & Current Probe
CCTV	Closed Circuit TV
CDR	Critical Design Review
CEG	Core Electron Generator
CEGHS	Core Electron Genrator Head Switch
cm	centimeters
CMM	Current Mode Monitor
CMS	Current Mode Switch
DACA	Data Acquisition & Control Assembly
DC	Direct Current
DCBP	DC Boom Package
DCORE	Deployer Core Equipment
DFRC	Dryden Flight Research Center
DIFP	Differential Ion Flux Probe
DMS	Deployer Master Switch
DPP	Deployment Pointing Panel
DPU	Digital Processing Unit
DRB	Deployable Retrievable Boom
DV	DECORE Voltmeter
e'	Engine Bell Discharge
EDO	Extented Duration Orbiter
EDS	Energy Dispersive Spectroscopy
EDX	Energy Dispersive X-Ray
EGA	Electron Generator Assembly
EMP	Enhanced Multiplexer/Demultiplexer Pallet
ERIM	Environmental Research Institute of Michigan
FEP	Flourinated Ethylene Propylene
FO	Flight Objective
FPEG	Fast Pulse Electron Generator
FT	Fault Tree
FTIR	Fourier Transform Infrared Spectroscopy
GMT	Greenwich Mean Time
Hr	Hour

HV	High Voltage
I/F	Interface
I/O	Input/Output
in	inches
JSC	Johnson Space Center
kg	kilogram
km	kilometer
KSC	Kennedy Space Center
kV	kiloVolt
kVDC	Kilovolt Direct Current
L	Length
LaRC	Langley Research Center
lb	pound
Ldot	Length Rate
LOS	Loss of Signal
LP	Langmuir Probe
LTC	Lower Tether Cutter
LTCM	Lower Tether Control Mechanism
MCA	Motor Control Assembly
MCC	Mission Control Center
MET	Mission Elapsed Time
MMOD	MicroMeteoroid Debris
MMS	Mechanical Mode Switch
MPE	Mission Peculiar Equipment
MPESS	Mission Peculiar Equipment Support Structure
MS	Mission Specialist
MSFC	Marshall Space Flight Center
N	Newton
NASA	National Aeronautic and Space Administration
NSI	NASA Standard Initiator
OARE	Orbiter Acceleration Research Experiment
P/L	Payload
PI	Principal Investigatior, Payload Interrogatory
POCC	Payload Operations Control Center
PROT	Protection
PS	Payload Specialist
Psi	Pounds Per Square Inch
Psia	Pounds Per Square Inch Atmospheric
RETE	Research On Electrodynamic Tether Effects
RF	Radio Frequency
ROPE	Research on Orbital Plasma Electrodynamics
SA	Satellite Ammeter
SCORE	Satellite Core Equipment
SEM	Scanning Electron Microscope
SETS	Shuttle Electrodynamic Tether System
SPES	Soft Particle Energy Spectrometer
SPREE	Shuttle Potential & Return Electron Experiment
SRPA	Spherical Retarding Potential Analyzer
SSA	Satellite Support Assembly

STS	Space Transportation System
TCM	Tether Current Monitor
TCVM	Tether Current Voltage Monitor
TDRS	Tracking & Data Relay System
TEMAG	Tether Magnetic Field Experimentt
TSS-1	Tethered Satellite System First Flight
TSS-1R	Tethered Satellite System Reflight
TVM	Tether Voltage Monitor
U1	Umbilical One
U2	Umbilical Two
USMP	United States Microgravity Payload
UTCM	Upper Tether Control Mechanism
V	Velocity Vector
VDC	Volts Direct Current
WBS	Work Breakdown Structure

TSS-1R Mission Failure Board
Members and Advisors

Chair:	Kenneth J. Szalai	(DFRC)
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	John W. Young	(JSC)

Executive Summary

On February 22, 1996, the STS-75 Space Shuttle Columbia launched at 53/20:18 GMT. The orbiter was inserted into a 296 km (160 nautical miles) orbit at an inclination of 28.5 degrees. The crew consisted of 7 members, including commander, pilot, 3 mission specialist, 1 payload commander, and 1 payload specialist. The TSS-1R payload was a reflight of TSS-1 in 1994, where deployer mechanism problems limited the tether deployment to slightly less than 300 m. The planned duration of the flight was 14 days. The payload bay configuration consisted of the Tethered Satellite System (TSS) experiments, two U.S. Microgravity Lab pallets (USMP-3), Orbiter Acceleration Research Experiment (OARE) pallet, and Extended Duration Orbiter (EDO) pallet.

Deployment of the satellite began at 56/20:46 GMT. On 57/01:29:26 GMT, at a tether length of 19.7 km, the satellite tether broke within the 12 m deployer boom, and the satellite separated from the orbiter. The rate of tether deployment was under control of the science computer. At the time of the tether separation, the deployment rate was being ramped down, per timeline, in preparation for halting at 20.7 km tether length. The tether deployment rate was approximately 1 m/s when it separated. There were no injuries and no damage to the orbiter or its subsystems due to the tether break.

The orbiter was located at 2 degrees N Latitude and 100.4 degrees W Longitude, and was at an altitude of 296 km (160 nautical miles) at the time of tether break. The TSS-1R experiments were in the passive mode, with no current flowing in the tether. The tether had an electric potential of -3500 VDC with respect to the orbiter ground, as planned, during this mode.

Telemetry from the orbiter and the satellite was operating prior to, during, and after the tether separation. Video imagery of the tether was available after the separation, but no video coverage exists showing the break itself. Video and still photography were taken during the mission of the failed end of the tether within the boom. The tether remaining in the boom was rewound on the reel during the mission.

Post flight inspection of the tether end showed it to be charred, with an apparent final tension failure of a few strands of Kevlar. The Board established that the tether failed as a result of arcing and burning of the tether, leading to a tensile failure after a significant portion of the tether had burned away.

The arc started in the Lower Tether Control Mechanism (LTCM), resulting in a 1 A current discharge to orbiter ground in the LTCM. This event occurred during a passive mode of science operations, with -3500 VDC on the tether conductor. The arc continued intermittently for 9 s, as the breached part of the tether traversed at 1 m/s through the remaining deployer mechanisms and into the 12 m deployer boom, where the space plasma provided the current return path. This arcing produced significant burning of most of the tether material in the area of the arc. The nominal load on the tether, 65 N (15 lb.), finally separated

the tether at the burn location, while it was within the deployer boom. The upper tether section was pulled through the Upper Tether Control Mechanism (UTCM), away from the orbiter at a speed of 3 m/s, due to tether dynamics and the satellite movement away from the orbiter. The lower section of the tether remained within the boom, and was recovered after the flight.

The arc initiated at a breach in the FEP insulation layer of the tether. Pressure within the LTCM, the proximity to a ground plane at the LTCM entry pulley, and the high voltage on the conductor, provided the favorable environment for the conductor to arc through the breach in the tether insulation.

Although the damaged area of the insulation was destroyed due to burning, the Board found sufficient evidence from test and analysis to establish foreign object penetration, or damage to the FEP insultation layer in manufacturing or handling, as the probable cause of the breach of the insulation layer.

Manufacturing and inspection records show that the tether fabrication task was very difficult, and that numerous problems were encountered in the extrusion and braiding processes of this very long tether. The fabrication of the tether was carried out in a normal manufacturing shop environment.

Metallic and non-metallic contamination was found within the FEP insulation layer of flight tether, including the 9 m that had gone through the lower deployer mechanisms prior to the failure. Non-metallic and metallic contamination was also found between the Nomex and insulator layers of several samples of flight tether. EDS analysis revealed foreign material near the failed end.

In addition to the contamination found within the tether, debris was found in several locations within the deployer mechanism. Metallic debris, large enough to breach the FEP, was found in the LTCM, the deployer boom assembly, and the reel housing. In the LTCM, a small piece of very fine silver plated wire, aluminum shavings, and unidentified non-metallic debris was found. Small metallic shavings were found attached to the back of small screw holes in the boom assembly.

Damage to the copper conductor was found in both the returned flight tether, and in a section of qualification tether examined after a special spark test. This damage appeared to have taken place during fabrication of the tether.

The final wind of the tether onto the flight reel was at a tether tension of 50 N. This results in high compression forces on the tether layers deep within the reel. The Board calculated that compressive forces at the layer where the tether breach was located, were as high as 35 N/mm for several days after the winding process. This compressive force is more than sufficient to force small debris through the insulation layer of the tether.

The Board found one contributing cause was that the degree of vulnerability of the tether insulation to damage was not fully appreciated. A seond contributing cause was high voltage effects on the insulator itself.

The Board was able to conclusively eliminate several major areas as causal. They included:

- Satellite Hardware and Operations
- Core Science Equipment and Operations
- Hardware and Operations of the Experiments
- Mission Operations (Ground and Flight)
- Induced Loads (static or dynamic)
- Pyrotechnic Tether Cutters
- Heating of the Tether During Commanded and Controlled Current Flow
- Design Changes Made to TSS-1
- Aging of the Components (shelf life)
- Micrometeoroid or Orbital Debris Collision
- Electrical Storm Activity

The Board made recommendations to use rigid standards for fabrication and handling of the high voltage cable; to ensure that the deployer path is free of debris; to reduce, through design and operations, the possibility of arcing; to conduct electrical integrity tests as close to the flight date as possible; to conduct high fidelity tests on critical subsystems; and to strengthen the integrated systems development approach.

The Board made several observations in the course of the investigation. Among these are that: the tether failure is not indicative of any fundamental problem in using electrodynamic tethers; there was a significant amount of scientific data secured from the flight, before the tether separated; the science, engineering and support teams were highly competent, motivated, and committed to the experiment; electrostatic charge build-up could be an issue in the future; the documentation provided by the project to the Board was appropriate; the tether configuration was affected by the winding loads on the reel; and the load paths of the composite tether are complex. The Board finally observed that the long time span between the fabrication of the hardware and the flight missions increased the exposure of the hardware to contamination and damage.

Lessons Learned

1. High voltage systems must be thoroughly understood for electrodynamic tether applications. It is also crucial to assure that the actual operating environment matches the expected operating environment assumed by designers and developers.

2. Excellent designs can be defeated through quite common cleanliness and handling violations. There is certainly a requirement for project teams to concentrate on the most complex and challenging aspects of a systems development. There must be an overt effort to assure that routine processes or actions which can violate the design intent are not overlooked.

3. Some tests are so critical to assuring the readiness of a system for flight, that consideration should be given to repeating them as close to the mission date as practical.

4. Failure mode identification for failure modes analysis should include participation by outside specialists in the various disciplines represented by the system to assure inclusion of all critical failure scenarios.

1.0 Description of Key Mission Elements

1.1 Science Mission

The main goals of the Tethered Satellite System (TSS) program were to demonstrate the feasibility of deploying and controlling long tethers in space, and to demonstrate some of the unique applications of the TSS as a tool for research by conducting exploratory experiments in space plasma physics.

The primary goal of TSS-1R was to accomplish the science objectives that were not achieved in the first mission (TSS-1). These involve the characterization of the electrodynamics and dynamics of long tethered systems deployed in space.

The main objectives required to meet this goal included:

1. Characterization of the system current-voltage response and demonstration of electrical power generation

2. Characterization of the satellite's high voltage plasma sheath, current collection and current closure

3. Verification of control law and basic dynamics

4. Demonstration of the effect of neutral gas on the plasma sheath and current collection process

During the TSS-1R mission, the satellite was deployed, according to the nominal timeline shown in Fig 1.1-1, out to 19.7 km when the tether separated.

The investigation titles and Principal Investigators (PI) listed in figure 1.1-2 were the same as the first mission with the exception of the SETS PI who was Dr. Peter Banks. Figure 1.1-3 shows the location of the experiments on the satellite, while the experiments on the MPESS are shown in Figure 1.1-4.

The investigations provided an integrated laboratory, shown in Figure 1.1-4, and were to conduct a coordinated and timed sequence of experiments according to a pre-stored timeline in the science computer on the orbiter. In its motion through the Earth's magnetic field the conducting tether was creating a motional EMF voltage across the TSS, whose value is varying during one orbit by about a factor of two, and whose maximum value was estimated to be 6 kVDC. The two active experiments, DCORE and SETS, allowed controlled current flow in the tether according to the science operations described in section 3.5.

NOMINAL TSS-1R SCIENCE MISSION PROFILE

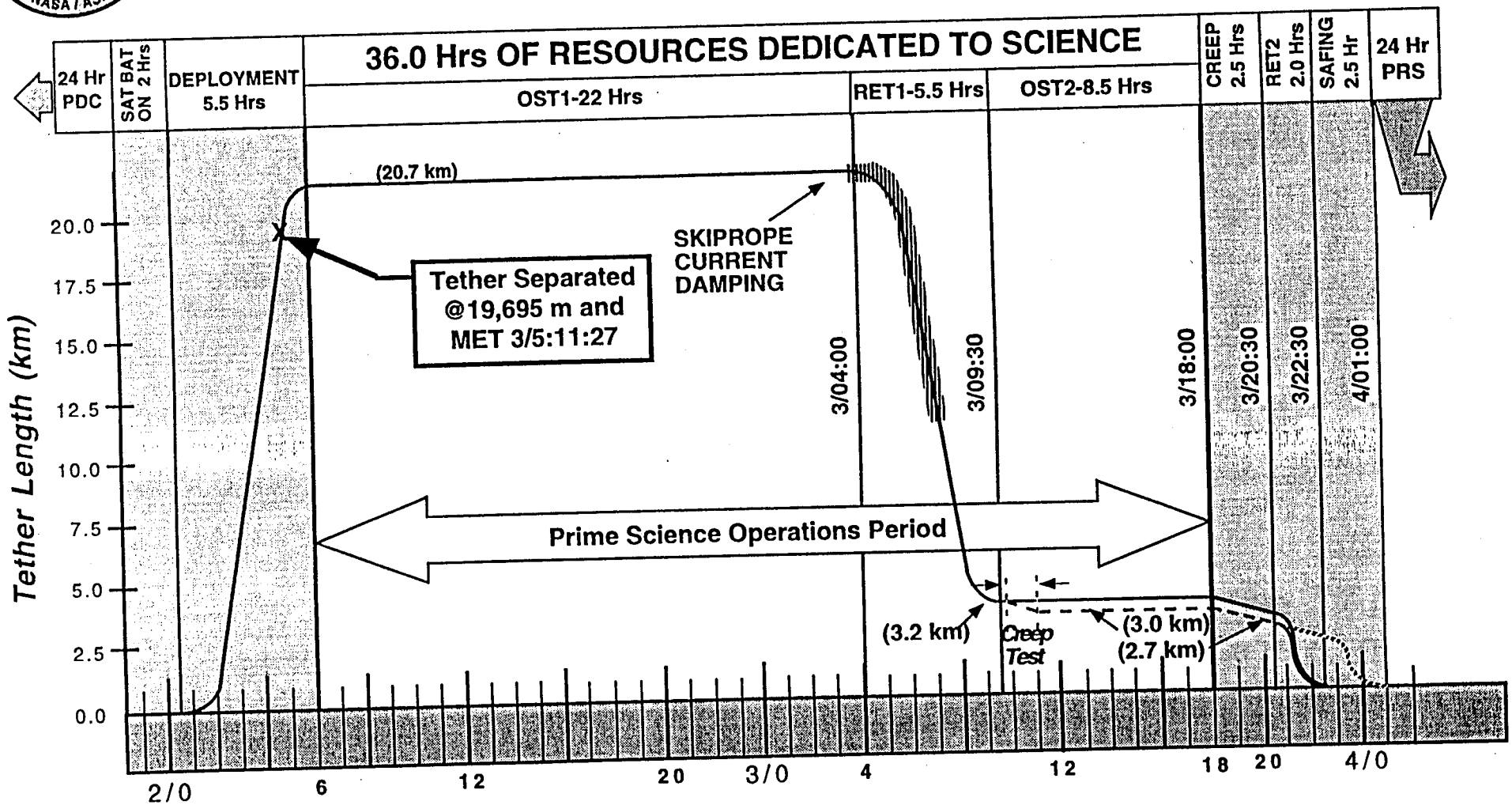

Figure 1.1-1 — TSS-1R Mission Timeline

TSS-1R SCIENCE INVESTIGATORS

PI/INSTITUTION	INVESTIGATION	INSTRUMENTATION
GILCHRIST, U. OF MICHIGAN	SHUTTLE ELECTRODYNANIC TETHER SYSTEM	FPEG, SRPA, SLP, CCP, TETHER CURRENT-VOLTAGE MONITOR
BERGAMASCHI, PADUA UNIVERSITY	A THEORETICAL & EXPERIMENTAL INVESTIGATION OF TSS DYNAMICS	THEORETICAL
DROBOT, SAIC	THEORY & MODELING IN SUPPORT OF TETHER (ELECTRODYNAMICS)	THEORETICAL
DOBROWOLNY, CNR/IFIS	RESEARCH ON ELECTRODYNAMIC TETHER EFFECTS	E-FIELD ANTENNA, SEARCH-COIL MAGNETOMETER, LANGMUIR PROBE (SAT. DRB-MOUNTED)
ESTES, SAO	INVESTIGATION OF EM EMISSIONS BY THE ELECTRODYNAMIC TETHER	GROUND-BASED
GULLAHORN, SAO	INVESTIGATION OF DYNAMIC NOISE IN THE TSS	THEORETICAL
MARIANI, U. OF ROME	MAGNETIC FIELD EXPERIMENT FOR TSS MISSIONS	3-AXIS MAGNETOMETERS (SAT. BOOM MOUNTED)
STONE, NASA/MSFC	RESEARCH ON ORBITAL PLASMA-ELECTRODYNAMICS	DIFP & 2 SPES's (SAT.BOOM-MTD.) 3 SPES's (SAT. SURFACE-MTD.)
TACCONI, U OF GENOVA	OBSERVATION AT EARTH'S SURFACE OF ELECTROMAG. EMISSIONS BY TSS	GROUND-BASED
BONIFAZI, ASI	DEPLOYER/SATELLITE CORE EQUIPMENT	ELECTRON-GUNS, TETHER I-V MONITOR., SAT. ACCELEROMETER
HARDY, USAF PHILLIPS LAB	SHUTTLE POTENTIAL & RETURN ELECTRON EXPERIMENT	ELECTRON/ION ELECTROSTA ANALYZERS
MENDE, LOCKHEED	TETHER OPTICAL PHENOMENA	LOW-LIGHT LEVEL TV CAMERA

Figure 1.1-2 — Principal Investigators and Investigations

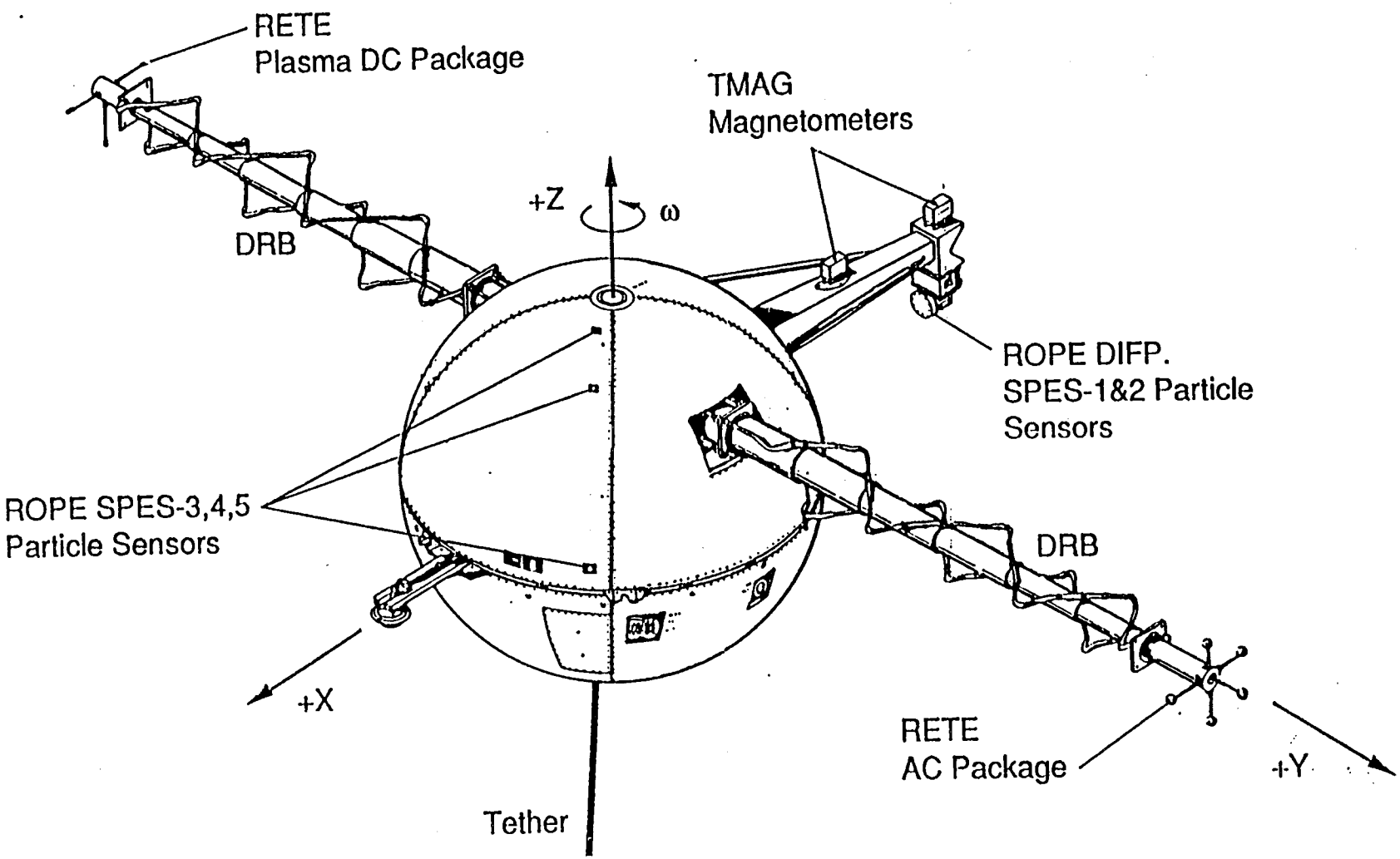

Figure 1.1-3 — TSS-1R Satellite

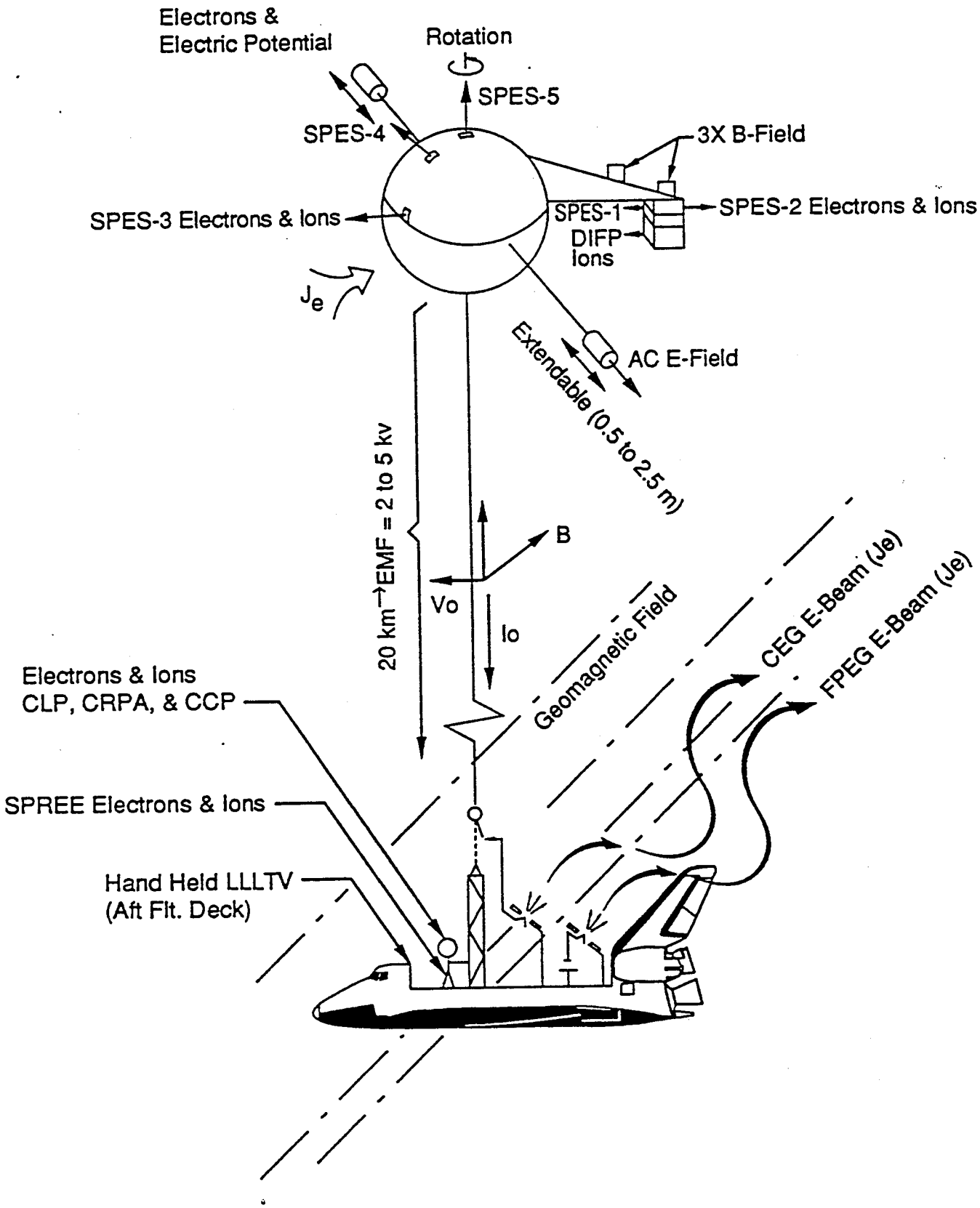

Figure 1.1-4 — TSS-1R Electrodynamic Experiment Configuration

The control of the science mission was primarily at the Science Operation Center at MFSC.

The PI's operated jointly in the Principal Investigator Team (PIT), chaired by the mission scientist. The PIT was responsible for all decisions regarding science replanning and the evaluation in real time of science data.

The science hardware operations were the responsibility of each PI's Science Support Team (SST). Each SST had an Experiment Manager who reported to the PI. Each Investigation's SST had an operation area similar to those for Space Lab missions.

1.2 Deployer/Tether Overview

The Tethered Satellite System has four major components (figure 1.2-1); the deployer, the tether, the satellite, and the science instruments which are mounted on the MPESS specially adapted space lab carriers. Under the 1984 memorandum of understanding, which was amended to include the TSS-1R flight, the Italian Space Agency (Angenzia Spaziale Italiana — ASI) agreed to provide the satellite and the CORE equipment, and NASA agreed to furnished the deployer system and tether. The science instruments were developed by various universities, government agencies and companies in the United States and Italy.

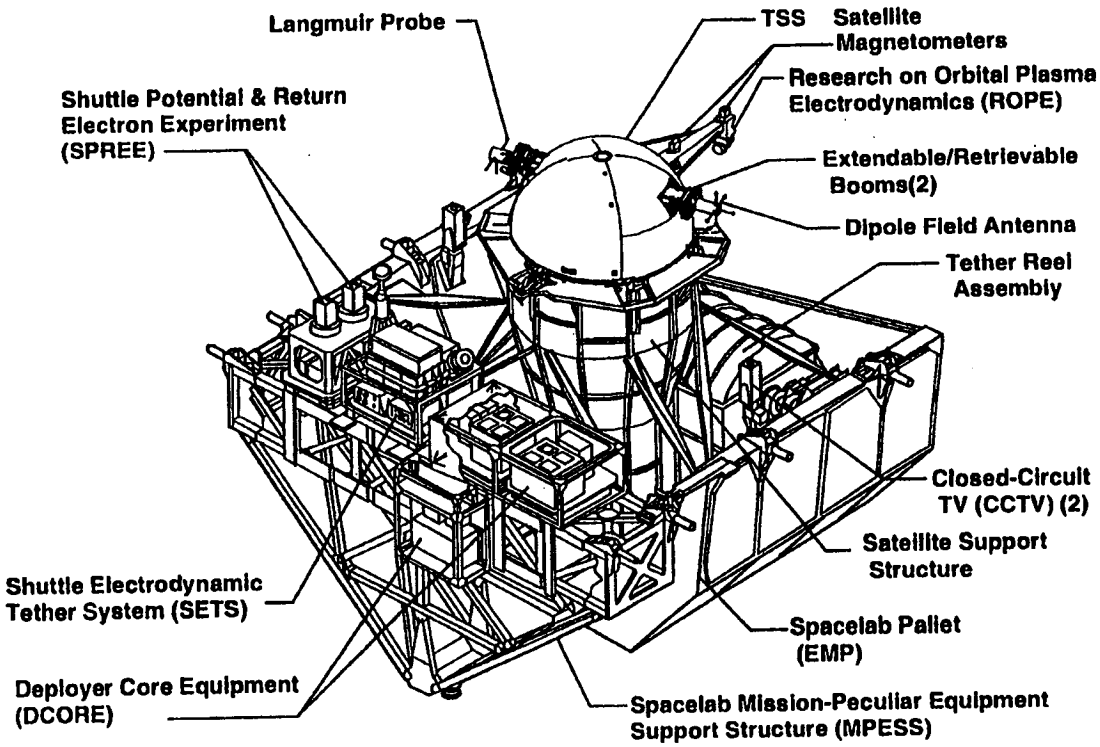

Figure 1.2-1— Tethered Satellite System (TSS-1R)

The deployer system includes the structure supporting the satellite, the 12 m deployer boom, which initially lifts the satellite away from the orbiter, the tether reel, the Lower Tether Control Mechanism (LTCM), the Upper Tether Control Mechanism (UTCM), a system that distributes power to the satellite before deployment, and a data acquisition and control assembly. A schematic of the deployer tether path is shown in figure 1.2-2.

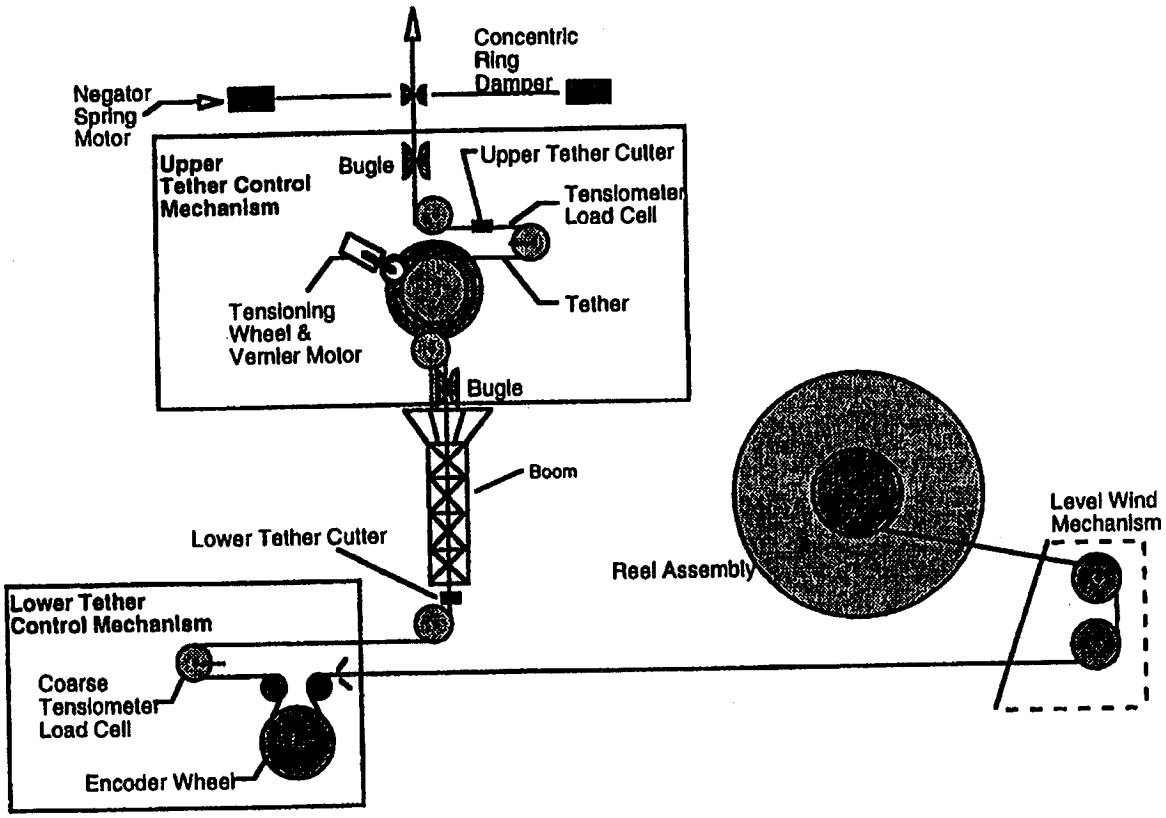

Figure 1.2-2 — Deployer Tether Path Schematic

1.2.1 Tether Reel Assembly

The tether reel drive mechanism (Figure 1.2-3) provides controlled spooling of the tether during the deployment and retrieval phases of the TSS operations. The reel is 0.11 m (4.44 in.) in diameter and 1.2 m (48 in.) long. The reel is equipped with a level-wind mechanism to assure uniform winding on the reel, a brake assembly and a reel motor. The mechanism is capable of releasing the tether at a rate of up to approximately 4.5 m/s.

The reel motor is a three-phase, torque-type, brushless permanent magnet motor. The motor is capable of supplying up to 43 N-m (32 ft-lb.) of continuous torque.

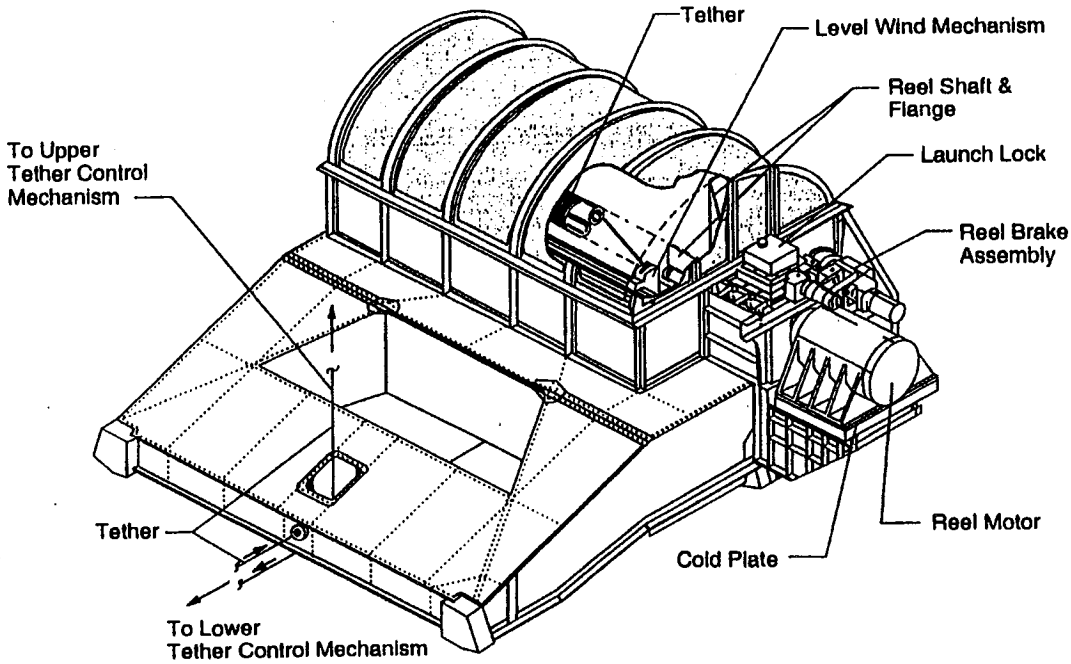

Figure 1.2-3 — Reel Mechanism

1.2.2 Lower Tether Control Mechanism (LTCM)

The LTCM (figure 1.2-4), mounted on the aft end of the Satellite Support Assembly (SSA) base, consists of an encoder, inboard tensiometer, and various tether guards and pulleys. Its primary function was to measure the tether length, speed and tension. The tether enters the LTCM from the reel assembly level wind mechanism, passes around the encoder pulley via two idler pulleys, passes around the tensiometer pulley and exits the LTCM through a guide tube.

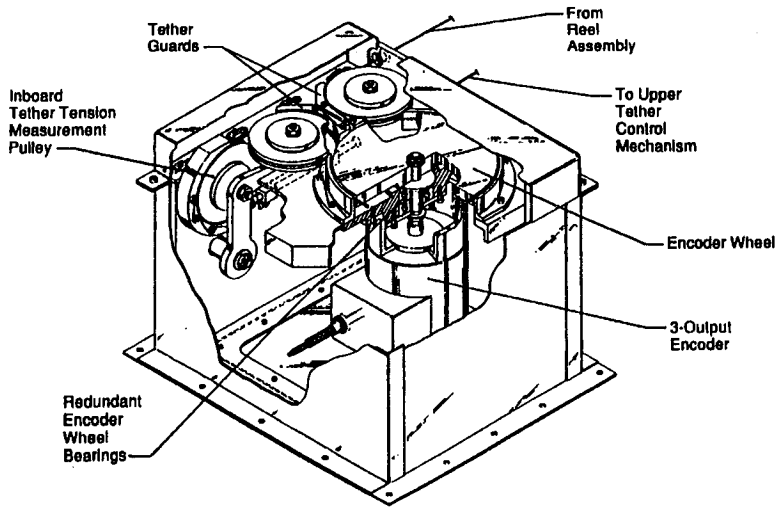

Figure 1.2-4 - Lower Tether Control Mechanism (LTCM)

1.2.3 Deployer Boom

The satellite 12 m deployer boom is an extendible/retractable space lattice structure designed to position the satellite clear of the Orbiter's vertical stabilizer for deployment and retrieval.

The canister has a rotating nut with internal threads that engage rollers on the corners of each bay to raise or lower the boom. The boom has a square cross section and consists of 24 individual bays. Each bay is 0.46 m X 0.46 m X 0.46 m (18 in. on a side). The boom is deployed or retracted by the rotating nut engaging these rollers and moving them in the desired direction.

The boom has two redundant drive motors and associated motor drive electronics. The motors drive the deployment nut through a gear assembly and differential.

1.2.4 Upper Tether Control Mechanism (UTCM)

The UTCM (figure 1.2-5), located in the tip canister at the top of the 12 m deployer boom, contains a vernier motor drive to overcome inboard system friction, a tensiometer for measuring outboard tension, a pyrotechnic tether cutter, and high voltage static discharge resistors to discharge tether electrostatic buildup during retrieval. The tether enters the UTCM from the boom through a bugle-shaped ceramic guide, wraps around the tether drive pulley, around the outboard tensiometer, passes through the emergency tether cutter and exits through a bugle-shaped ceramic guide.

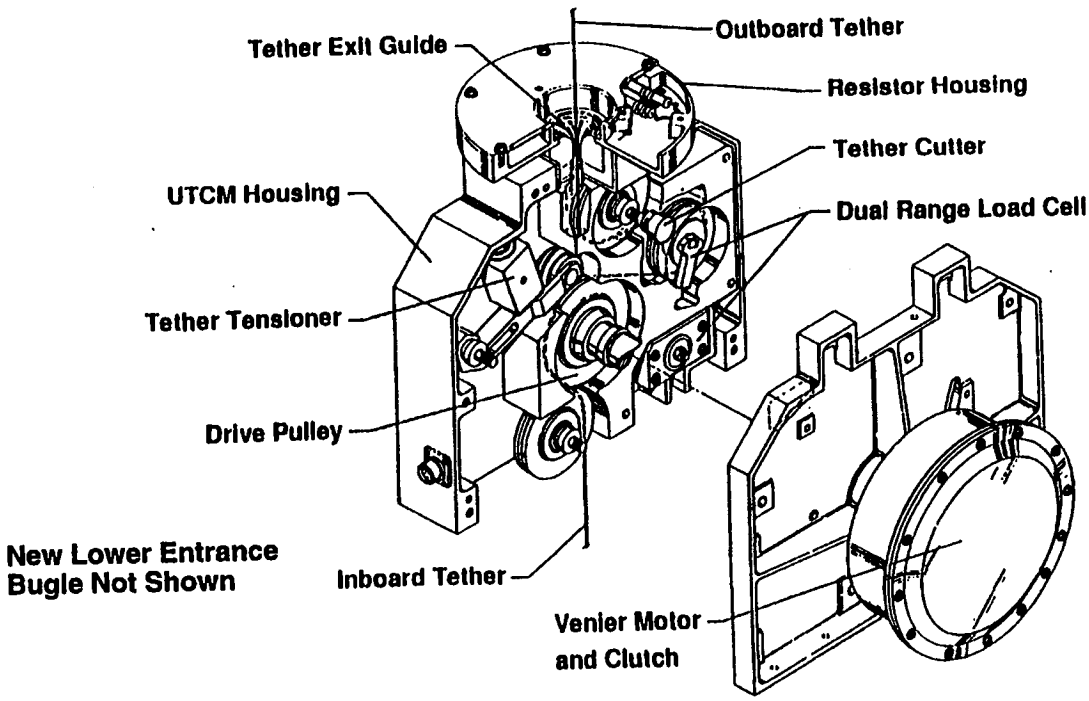

Figure 1.2-5 — Upper Tether Control Mechanism (UTCM)

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 the outboard tension.

1.2.5 Tether

The 2.54 mm (0.1 in.) thick tether is a composite structure with an inner Nomex core. Wrapped around the Nomex in a helix arrangement are ten 34 gauge copper wires. The copper wire Nomex combination was insulated with a layer of extruded FEP. The tether strength is provided by a braided Kevlar layer located just external to the FEP layer. An outer braid of Nomex protects the tether from atomic oxygen and abrasion (Figure 5.2.6). The tether was designed for a 15 kVDC potential and qualified to 10 kVDC. In the TSS-1R experiment the tether was qualified to carry, 2.5 A amps for 20 minutes. The tether was designed to carry tensile loads up to 1780 N (400 lb.).

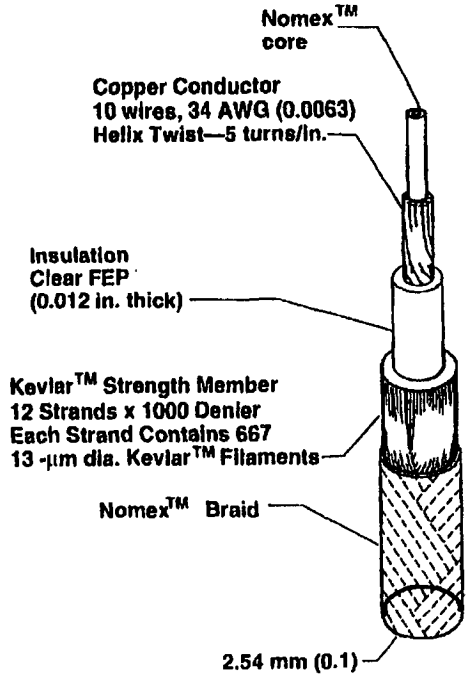

Figure 1.2-6 — Electrically Conductive Tether

A single 22 km flight tether was required for the TSS mission. Since the maximum length of the individual copper strands was approximately 3600 m, it was necessary to join strands end-to-end to make up the total required length for each tether conductor. A special butt welding procedure was developed to join the wire strands without increasing the overall conductor diameter. Six butt weld sets were required for the flight tether conductor. Similarly during the Kevlar braiding process, ten sections were spliced together to form a single Kevlar braid.

This is the same tether that was used on TSS-1. After TSS-1, 300 m of the 21 km (13 mi.) long tether was removed (reference Section 1.3) leaving 20.7 km of tether remaining on the spool for TSS-1R.

1.2.6 Deployment Control

The deployer uses a closed loop control scheme where reel motor voltage is pulse width modulated to control tether length and velocity. The Data

Acquisition and Control Assembly (DACA) reads the LTCM encoder and calculates the actual tether length and velocity parameters. The actual values are compared to pre-stored profile values. Corrections are made, as needed, to the pulse width commands sent back to the Motor Control Assembly and ultimately to the reel motor. The reel motor generally acts as a generator when the satellite is being deployed, and provides resistance to control tether velocity. During satellite retrieval, the motor acts in a true motor mode and pulls the tether inward at a rate directed by the DACA software control laws.

1.3 Changes Since TSS-1

Numerous modifications and refurbishments were made to the TSS hardware between the TSS-1 and TSS-1R flights. After several comprehensive reflight studies and management reviews, recommended modifications went beyond those required to resolve the TSS-1 flight anomalies, and included changes and/or refurbishment to nearly every major sub-system. This section covers the applicable modifications to the deployer sub-system. A detailed summary of all the modifications and refurbishments can be found in "Tethered Satellite System (TSS-1R) Major Management Review" available from the MSFC project office.

The most notable modifications to the deployer were those to resolve the TSS-1 flight anomalies:

- U2 umbilical failure to disconnect
- UTCM tether jams
- Early termination of tether deployment

The U2 umbilical failure was never reproduced during post TSS-1 flight ground testing, and thus, an ultimate cause could not be determined. The U2 umbilical critical functions were moved to the U1 umbilical and the U2 umbilical was eliminated for the TSS-1R flight.

TSS-1 experienced several tether jams in the UTCM during initial deployment. To resolve this anomaly, several modifications were implemented: the tether eye splice at the satellite was shortened from 22.9 to 7.6 cm (9 to 3 in.) to prevent the stiff splice section from jamming in the UTCM; the vernier motor speed controller was modified to provide a 180 s ramp up (as opposed to the on/off voltage used in TSS-1) to provide a gradual force application to the tether; a ceramic entrance bugle was added to the bottom of the UTCM; operational procedures and deployment control laws were modified to prevent any slack tether during initial deployment.

The failure to fully deploy the tether in the TSS-1 mission was due to a mechanical interference between a shear wedge block bolt, added just prior to flight, and the level wind mechanism. The necessary modifications included shortening the wedge block bolt, modifying the level wind ball nut retainer to allow for greater clearance and replacing of level wind components which were damaged and/or stressed during the flight.

Comprehensive TSS-1R reflight studies, management reviews and lessons learned during TSS-1 integration/deintegration provided further modification/ refurbishments as listed below:

- Addition of a motor power conditioner partial redundant power path to eliminate the possibility of a power control box relay single point failure leading to loss of mission.
- Relocation of the Lower Tether Cutter (LTC) to reduce the possibility of tether entanglement during contingency boom ejection of the 12 m deployer boom.
- Refurbishment of the deployer boom which included adding anti-galling coating to guide rails, narrowed strong batten lugs to prevent sliding contact with rails and hard anodizing detent housings to improve sliding friction uniformity.
- Removal of the first 300 m of tether (256 m had been deployed during TSS-1).
- Performance of continuity, high voltage tests, and coarse visual inspection.
- Performance of two tether unspool/spool operations.
- Modification of the hot nest connector bracket to eliminate a possible interference with the docking ring.
- Refurbishment of pyrotechnic circuits and fixed one broken wire.
- Modification of the tether side connector to correct a loss of electrical continuity between the tether-to-satellite connection.

All of the systems changed operated normally during TSS-1R. In the course of this investigation, there were no indications that any of the design changes made to the TSS-1 system contributed in any way to the TSS-1R tether failure.

Design changes to TSS-1 did not contribute to the tether failure.

2.0 Narrative Description of Failure/Anomaly

On February 22, 1996, the STS 75 Space Shuttle Columbia launched at 53/20:18 GMT. The orbiter was inserted into a 296 km (160 nautical miles) orbit at an inclination of 28.5 degrees. The crew consisted of 7 members including commander, pilot , 3 mission specialist , 1 payload commander, and 1 payload specialist. The TSS-1R payload was a reflight of TSS-1 in 1994, where deployer mechanism problems limited the tether deployment to slightly less than 300 m. The planned duration of the flight was 14 days. The payload bay configuration consisted of the Tethered Satellite System (TSS) experiments, two U.S. Microgravity Lab pallets (USMP-3), Orbiter Acceleration Research Experiment (OARE) pallet, and Extended Duration Orbiter (EDO) pallet. The payload bay configuration is shown in figure 2.0-1.

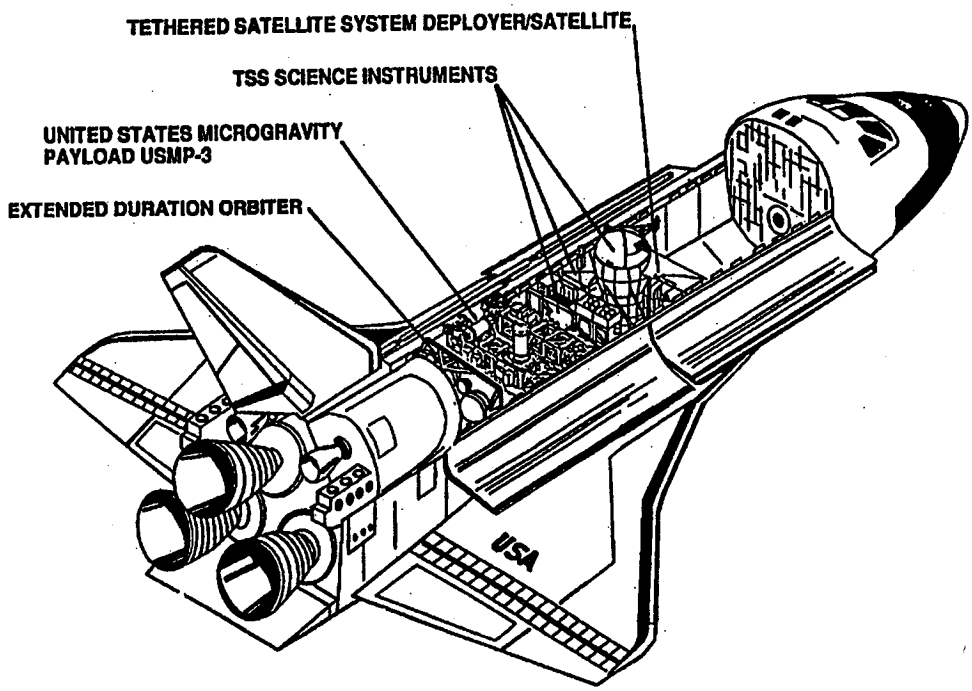

Figure 2.0-1 — Primary Shuttle Payloads

On day 3 of the flight, after a one day delay, TSS operations were begun. Checkout and initiation of the deployment sequence went according to the timeline and without difficulty.

Deployment of the satellite began at 56/20:46 hours GMT. The deployment of the satellite required that the satellite's cold gas thrusters be fired to provide a separation velocity, and tension on the tether until orbital dynamics could provide forces on the satellite sufficient to maintain separation of the two craft. The rate of deployment followed a preplanned scenario which at some points in

the timeline slightly exceeded 2 m/s tether deployment rate. The rate of tether deployment was under control of the experiment computer (DACA).

On 57/ 01:29:26 GMT, at a tether length of 19.7 km, the satellite tether broke within the 12 m deployer boom, and the satellite separated from the orbiter. There were no injuries and no damage to the orbiter or its subsystems.

The orbiter was located at latitude 2 degrees N and longitude 100.4 degrees W and was at an altitude of 160 NM at the time of tether break. The TSS-1R experiments were in the passive mode, therefore, no current was flowing in the tether, which had a potential of -3500 VDC with respect to orbiter ground.

At the time of the tether separation, the deployment rate was being ramped down, per timeline, in preparation for halting at 20.7 km tether length. The tether deployment rate was approximately 1 m/s when it separated. Although the deployer pallet did have a brake on the tether reel mechanism, it was not being used to slow the deployment rate. The rate of satellite deployment and the slowing process was controlled by the reel motor. Distance to the satellite was measured via an optical encoder located in the LTCM which measured the length of the tether pulled through the LTCM and via a range measurement from the orbiter Ku Band radar.

Satellite telemetry was transmitted to the orbiter payload interrogator (PI) where it was combined with the orbiter downlink and transmitted to the ground . In a similar manner, ground commands to the satellite were relayed through the orbiter communications system to the PI and then to the satellite.

A number of science experiments were operated during the deployment phase. At the time of the tether break the science operation was passive. The first indication of a tether break was from the crew. The crew observed ripples or apparent slack in the tether. Shortly there after, the end of the tether could be seen separating from the orbiter. Subsequent review of the telemetry indicated that unexpected current and voltage signatures were experienced on the tether for 9 s, just prior to tether separation.

Timeline:	**Time (GMT)**	**Event**
	57/1:21:30	EGA firing ended as planned
	57/1:25:55	FPEG firing ended as planned
	57/1:26:02	Tether was taken to an open circuit configuration
	57/1:29:17	Tether EMF changed sharply from, –3500 VDC to less than -200 VDC and tether current started to flow at 1A.
	57/1:29:26	Telemetry indicated that the tether had broken
	57/1:29:36	Crew reported the tether had separated

Time histories of key parameters are shown in figure 2.0-2. The SETS Voltage, the SETS current, and the satellite current are presented from approximately 15 s prior to the tether failure to 15 s after the failure. The failure at 57/01:29:26 is indicated on the figure.

At approximately 01:29:17, the satellite current jumps to slightly more than 0.9 A, indicating a current discharge from the tether. The SETS current is zero, however, indicating the experiments are in the passive mode, with no current path through the experiments. This indicates that the tether conductor is arcing directly to orbiter ground, and not through the experiment current path. When the current is flowing, the tether voltage drops to approximately -50 to -200 VDC.

This spurious discharge continues intermittently for approximately 9 s before the tether fails. The tether current continued to flow at approximately 1A for another 60 s, indicating a current path directly to the space plasma from the lower end of the tether attached to the satellite.

These measurements provided the data that the Board used to establish that arcing was the primary cause of the ultimate failure of the tether. Based on the measured deployment rate of the tether at this time (1.04 m/s), and the length of the tether retrieved on orbit, it was possible to determine that the arcing started in the LTCM.

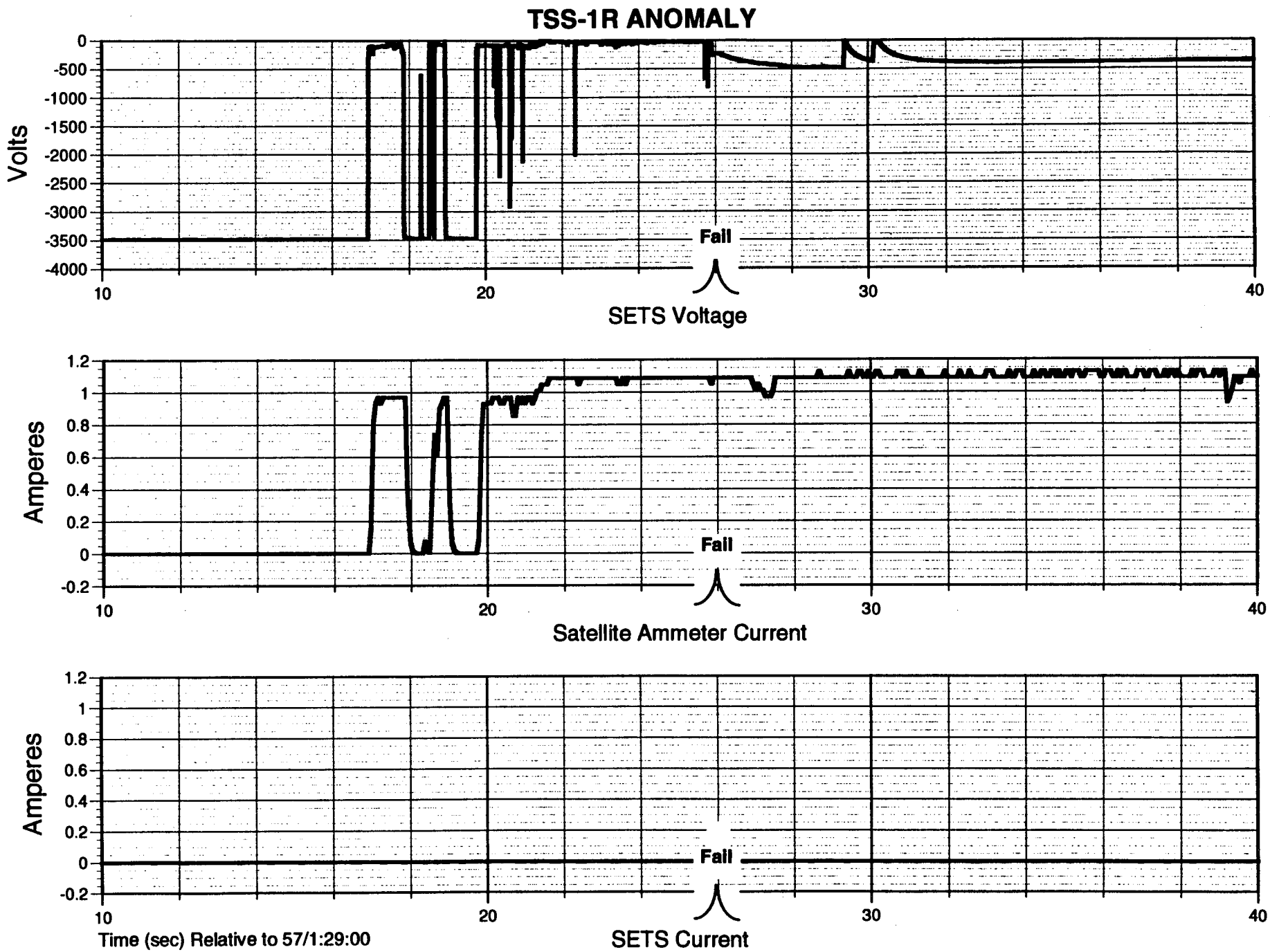

Figure 2.0-2 – History of Key Parameters

3.0 Data Analysis

3.1 Approach

Soon after the Tethered Satellite System (TSS-1R) failure, a Tiger Team was assembled at MSFC and charged with the responsibility to develop a TSS-1R failure fault tree. Fault trees (Appendix G-1) are especially beneficial when failed systems have significant technical complexity and have multiple possibilities for synergistic affects to contribute to the ultimate failure. Dealing with a complex system demands a methodical, orderly approach that accommodates all the rational possibilities that can contribute to the ultimate failure. The Tethered Satellite System had this level of complexity.

The fault tree team consisted of 71 experts, primarily MSFC personnel, but included members from other NASA Centers and private industry as well. (See Appendix G-2). The composition of the group spanned all the necessary technical disciplines to construct a comprehensive fault tree for the TSS-1R failure.

The fault tree team convened daily for updates on the validity of the tree, status of action items, discussion of results of on-going tests and analyses, plans for new blocks on the fault tree and new tests and analyses. "Owners" of blocks on the fault tree had to attend the daily meetings, and status their activities. The entire process was tracked using a work breakdown structure (WBS) approach.

3.1.1 Fault Tree

In considering possible causes for the failure, it was deemed prudent to consider two main avenues of investigation: 1. The likelihood that the failure was precipitated by a tether anomaly per se, and 2. the possibility of a failure precipitated by a factor or factors unrelated to tether characteristics. These relevant blocks are listed as block 1 and block 2 as seen on figure 3.1-1. The fault tree is shown in Appendix G-3.

Items related to the latter category and exonerated early-on were: micrometeoroid severing block 2.1 (figure 3.1-2) and tether cutter system being inadvertently activated, block 2.2 (figure 3.1-2). Items pursued relative to the tether which were closed out expeditiously were those related to excessive loading of the tether such as "nominal loads - design inadequate", block 1.1.1 (figure 3.1-1), and "induced loads above nominal", block 1.1.2 (figure 3.1-1).

Post flight inspection of the tether and LTCM indicated that the failure was caused by arcing in the LTCM. The primary investigation thrust then shifted to the fault tree path starting with block 1.2 (figure 3.1-1) "tether anomaly, degradation, or damage, weakens tether load-bearing capacity. "Eventually five of the six major possibilities were eliminated, leaving only degradation of the Kevlar due to electrical discharge/arcing as the mainline investigation, block 1.2.1 (figure 3.1-3).

By test, analysis, and examination of flight evidence returned, it was proven that proximity of the tether to structure (specifically, the LTCM) was essential to induce failure, as seen on block 1.2.1.1.1 (figure 3.1-4). In addition, dielectric breakdown of

TSS Tether Anomaly Fault Tree Action Item / Closure

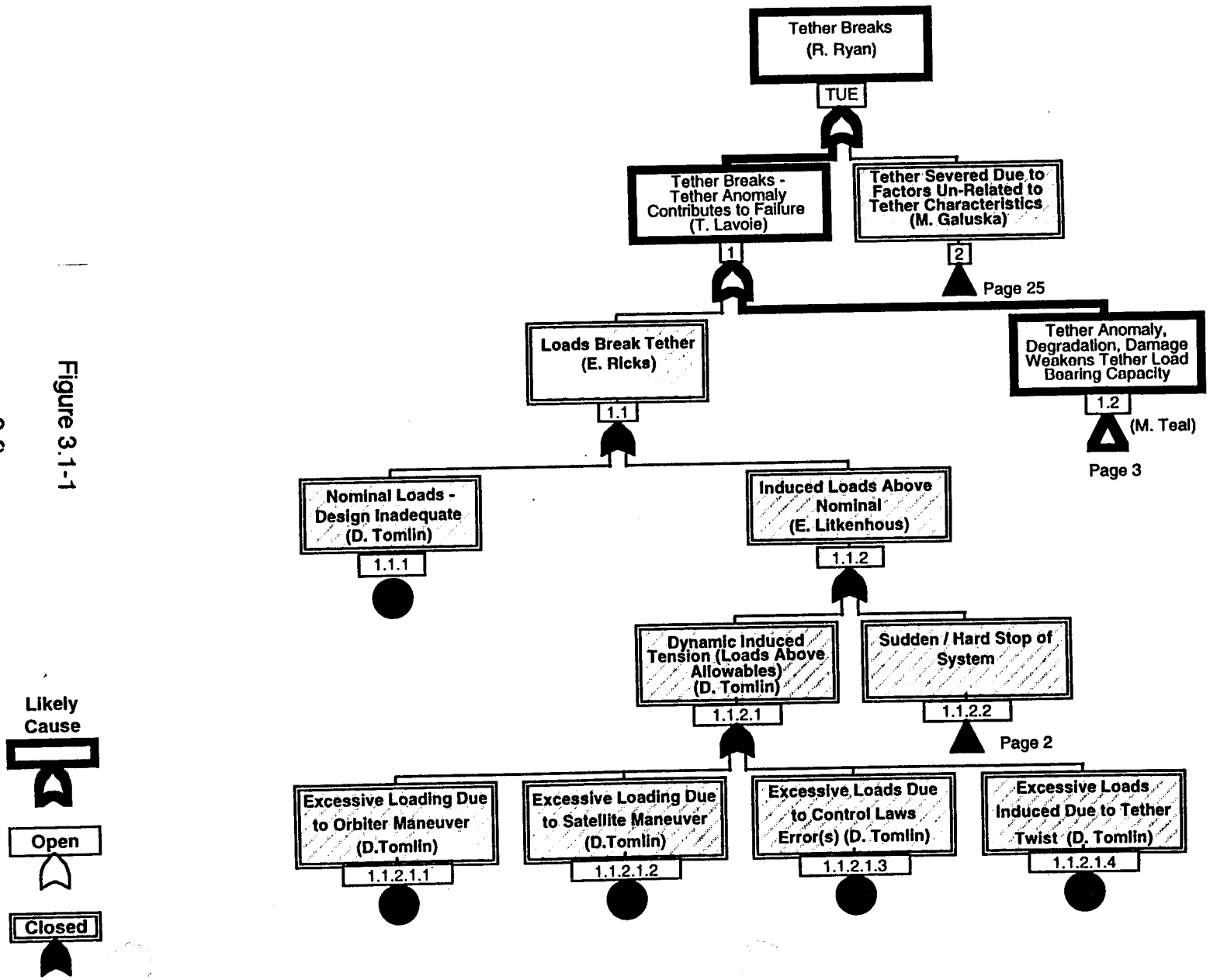

Figure 3.1-1

TSS Tether Anomaly Fault Tree Action Item / Closure

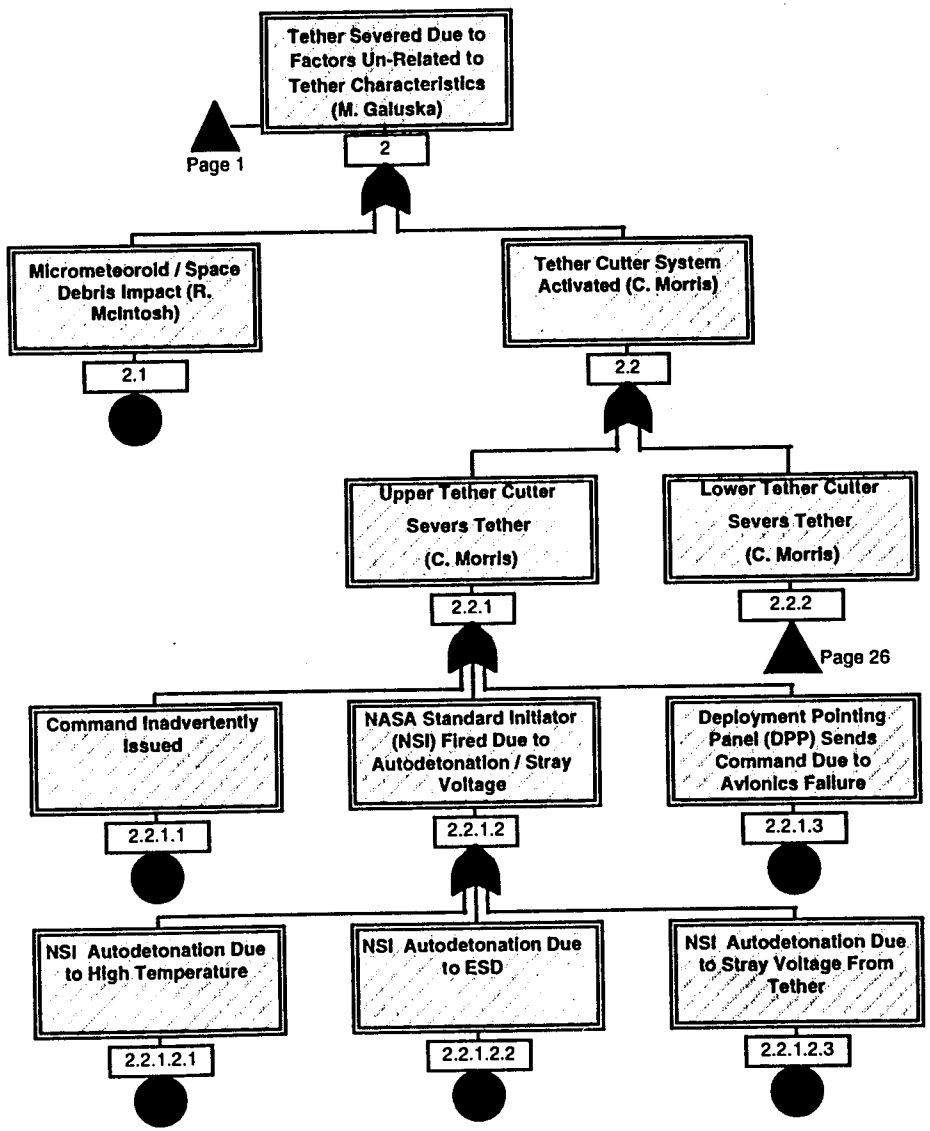

Figure 3.1-2

TSS Tether Anomaly Fault Tree Action Item / Closure

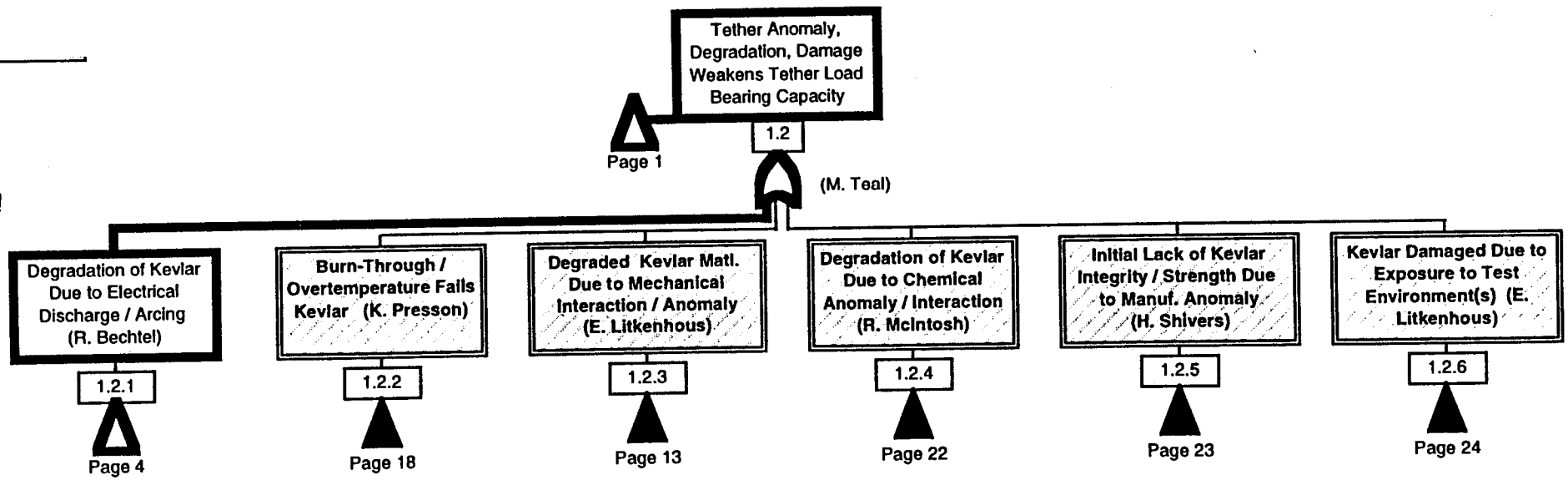

Figure 3.1-3

TSS Tether Anomaly Fault Tree Action Item / Closure

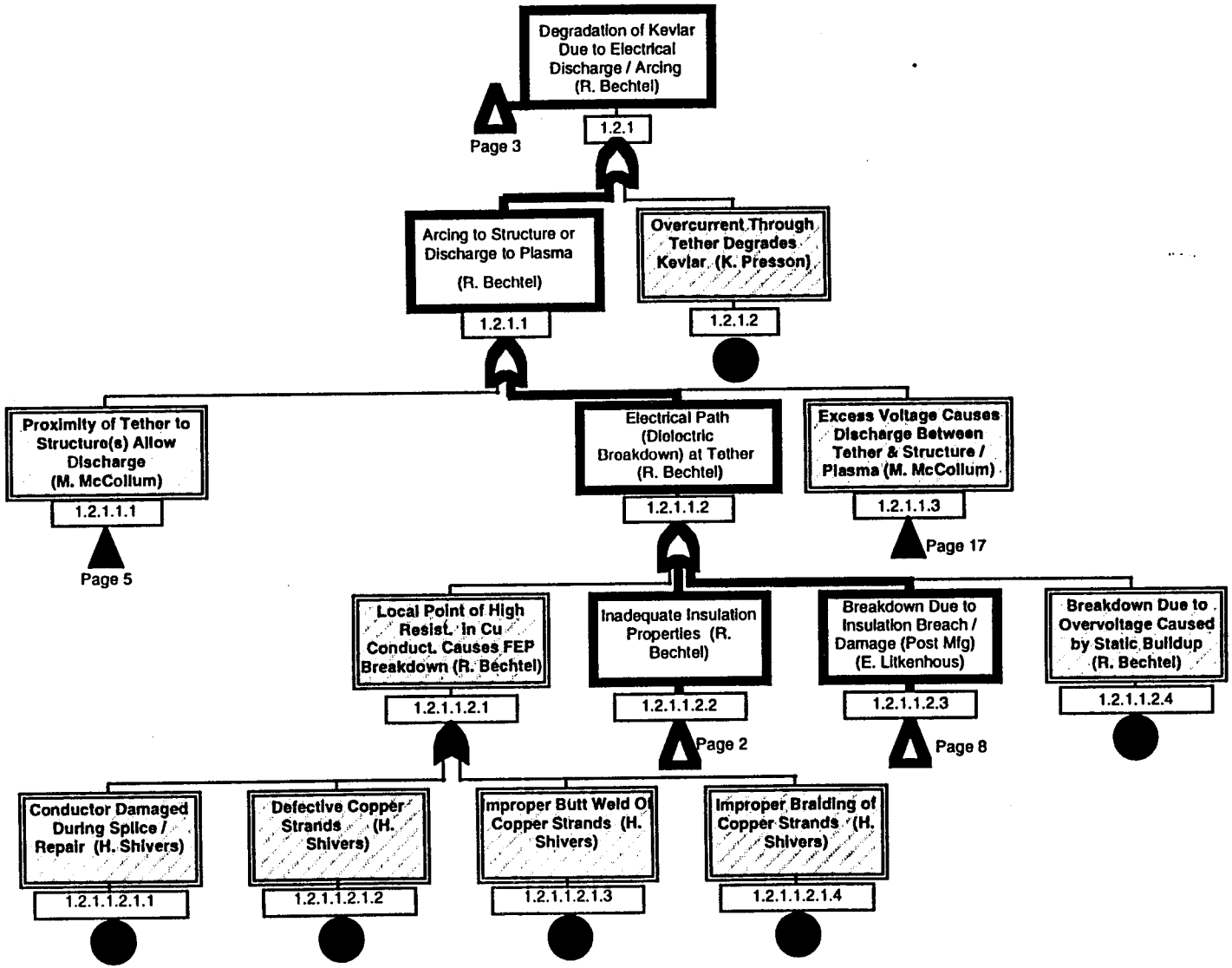

Figure 3.1-4

the tether by discharge or arcing was evident, which implied inadequate insulation, block 1.2.1.1.2.2 (figure 3.1-4); breach of insulation, block 1.2.1.1.2.3 (figure 3.1-4); or breakdown due to overvoltage caused by static charge build up, block 1.2.1.1.2.4 (figure 3.1-4). The evidence then warranted shifting strong effort to the possible causes as noted above.

Fault Tree Statistics

By the end of the investigation, the vital statistics of the fault tree were as follows:

- Total blocks on Fault Tree - 264
- Legitimate exoneration blocks and a few tandem redundant block listings closed out all but three major, and seven contributing minor possibilities. Figure 3.1-5 and figure 3.1-6 show a mini-fault tree version of the final conclusions.

Most Probable Causes

Fault Tree Block Title	Master Fault Tree Page	WBS
1. Mechanical damage to FEP during mfg (defect)	2	1.2.1.1.2.2.1.4
2. Tether physically damaged due to improper handling	14	1.2.1.1.2.3.1.6
3. Debris damages tether due to forces in reel or deployer part	16	1.2.1.1.2.3.1.9

Sub-headings to "mechanical damage to FEP during manufacturing (defect)" can also be seen in figure 3.1-6 of the mini-fault tree, and are designated as:

1. Copper strand damage during manufacture resulting in reduced effective FEP thickness (1.2.1.1.2.2.1.4.1).

2. Kinking during manufacture, due to tether twist/loads (1.2.1.1.2.2.1.4.2).

Sub-headings to "Tether physically damaged due to improper handling (post mfg)" can be seen in figure 3.1-6 of the mini-fault tree, and are designated as:

1. Mishandling damage to FEP during post-manufacturing, (1.2.1.1.2.3.1.6.8)

2. . Kinking during handling due to tether twist/load (1.2.1.1.2.3.1.6.10)

3. Copper strand damage during handling resulting in reduced effective FEP thickness (1.2.1.1.2.3.1.6.9)

Sub-headings to "debris damages tether due to forces in reel or other deployer part" can also be seen in figure 3.1-2, and are designated as:

1. Debris within the tether (1.2.1.1.2.3.1.9.1)

2. Debris external to the tether (1.2.1.1.2.3.1.9.2)

The genesis of the process of elimination leading to the final three major potential causes can be readily inferred from figure 3.1-5 and figure 3.1-6.

TSS Tether Anomaly Fault Tree Action Item (Open Faults)

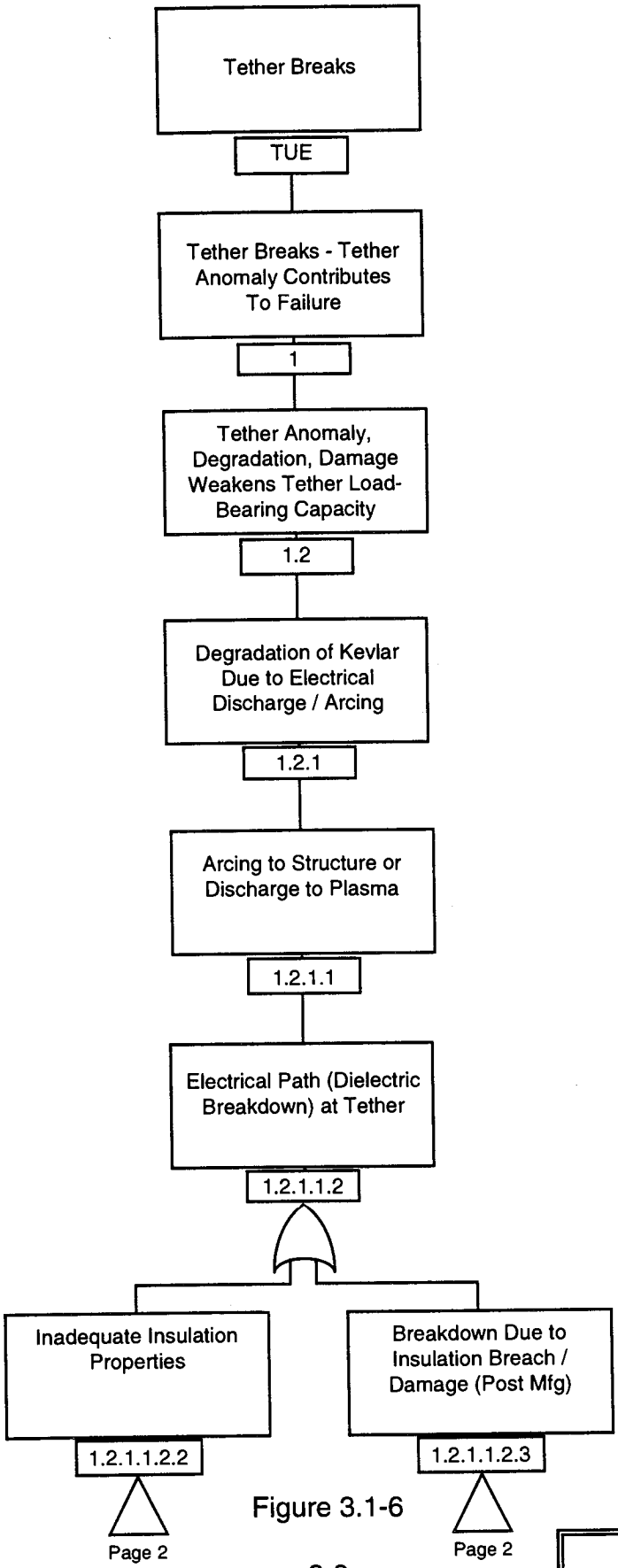

Figure 3.1-6

5-10-96 Rev. R

TSS Tether Anomaly Fault Tree Action Item (Open Faults)

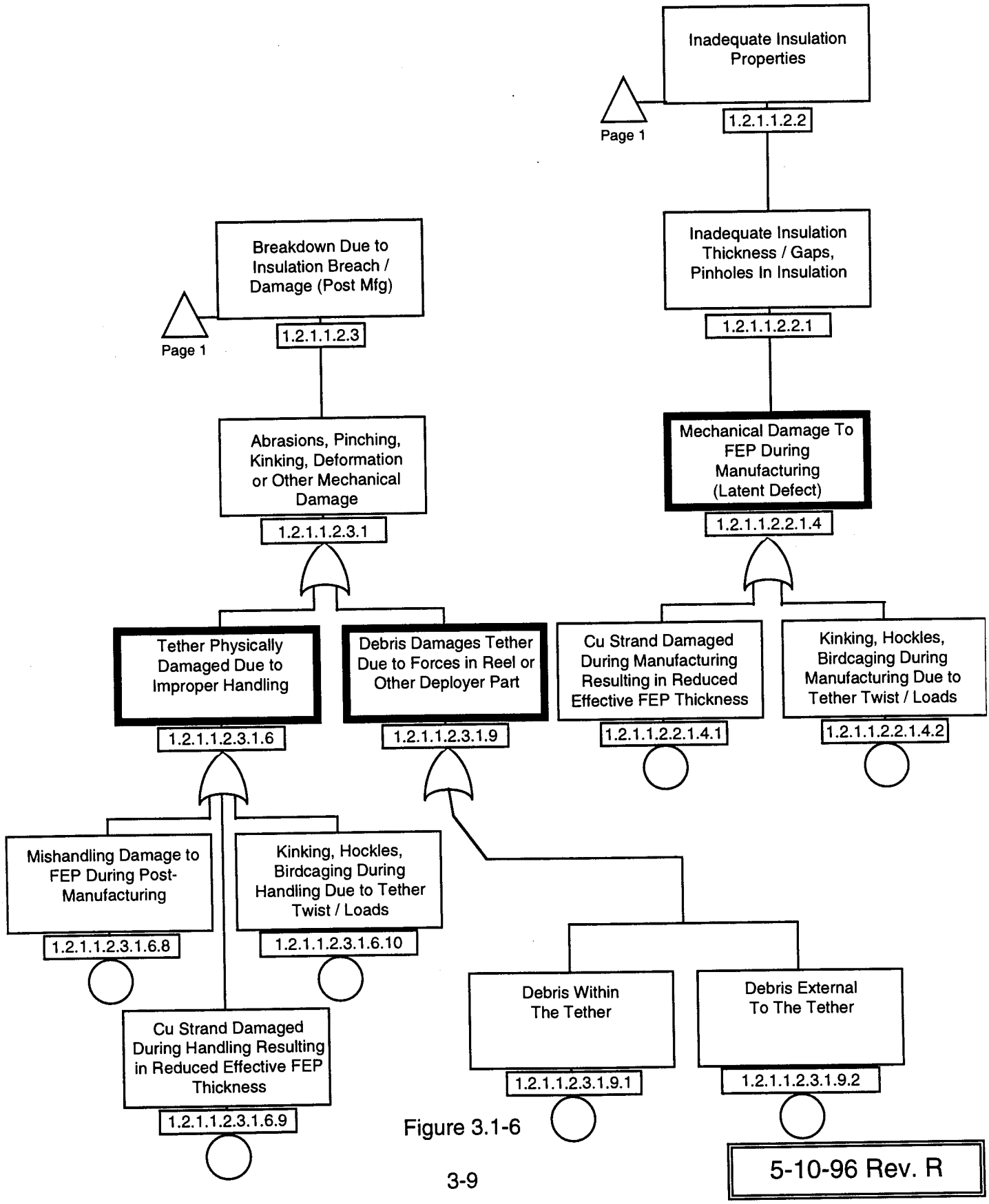

Figure 3.1-6

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3.1.2 Photos, Lab Tests, KSC, MSFC, LaRC

A very large number of photos and lab tests were generated during the conduct of the investigation. Compete files of the photographic and laboratory test results are on file at the MSFC TSS-1R Project Office. Included in these data files are photos taken at the Kennedy Space Center, and tests done by the Langley Research Center.

3.1.3 Analysis

During the course of the investigation, over a hundred analyses were done, addressing various aspects of the tether failure.

The question of tensile strength of the tether was addressed early on, and numerous analyses were done to exonerate inadequate strength as the cause of failure. Concern over the environment inside the LTCM led to analyses involving Paschen's Law relating voltage breakdown propensity as a function of the pressure-distance parameter. Overtemperature was addressed in several analyses, as was the venting of the LTCM, and the outgassing of the tether.

Appendix G- 4 contains the analyses documented in the TSS-1R Fault Tree.

3.1.4 Historical Records

Immediately after the TSS-1R tether failure, all records, data, and relevant TSS-1R information were impounded. Subsequently, when the actual nature of the failure became more evident, data needed to conduct an effective investigation were released on an as-needed basis. Approval for data release was acquired on a case-by-case basis from the Chairman of the Failure Investigation Board. What follows is a summary of information which was impounded since the TSS-1R failed on February 25, 1996.

a) Working documents in the MSFC Spacelab Mission Operations Control Center were retained in the facility; engineering and science console logs were secured by the TSS-1R Chief Engineer and Mission Scientist, respectively.

b) Original Payload Operations Control Center (POCC) data on various computer media and written POCC Console logs were secured in a locked room. Written statements were secured from POCC staff who were at consoles at the time of the failure.

c) Original mission raw data was secured on computer systems in place.

d) All pertinent mission video tapes were impounded at all Centers.

e) TSS Project files were secured in place.

f) The Defense Contract Management Command (DCMC) assisted MSFC by verifying that information being held at Lockheed Martin in Denver, Cortland Cable in New York, and Abel Engineering, in California, was secured and identified. In addition a MSFC quality assurance specialist traveled to Denver to segregate Martin Denver TSS data to minimize interference with other work in progress there.

g) Mission Control logs and downlinked data at the Johnson Space Center and the Kennedy Space Center were impounded, and statements were secured from mission controllers who were monitoring TSS-1R operations.

h) All payload integration and preflight test data were impounded at KSC. Deintegration plans were developed by KSC, in collaboration with the Board, to protect the flight hardware after return, and to document the payload configuration in the payload bay and in the Operations and Checkout Building at KSC.

i) TSS information held in the MSFC Documentation Repository was impounded and could be accessed only by authorized persons.

The complete inventory of impounded files is held by the MSFC TSS-1R Project Office.

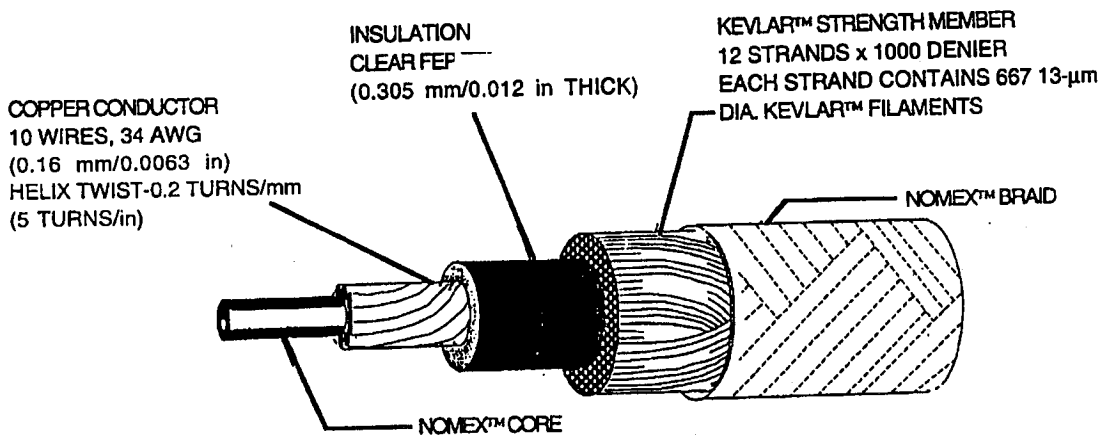
3.2 Tether Tests and Analyses

In the beginning of this investigation many possible failure scenarios were considered. Numerous tests, analytical studies, and failed component analyses were performed in an attempt to arrive at the most probable cause of the tether failure.

3.2.1 Background

3.2.1.1 Tether Description

The tether is a very complex system of interacting structural and electrical elements uniquely designed and manufactured to function together so as to properly share the tensile loads produced by the satellite and conduct current to the orbiter.



DIAMETER	2.54 mm (0.1 inch)
MAX MASS	8.2 kg/km (0.0055 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% AT 1780 N
ELEC BREAKDOWN VOLTAGE	10 kV (SPECIFIED), 15 kV (QUAL)
ELEC RESISTANCE	0.12 Ω/m (SPECIFIED), 0.15 Ω/m (ACTUAL AT ROOM TEMP)
LEAKAGE CURRENT	5 mAmp (Max) AT 10 kV-dc

Figure 3.2-1 — Tether Configuration

The conducting element of the tether is composed of an inner Nomex core around which is wrapped ten strands of #34 uninsulated copper wire to form a helix. A 0.3 mm thick layer of clear FEP insulation is extruded over this core. (see Figure 3.2-2)

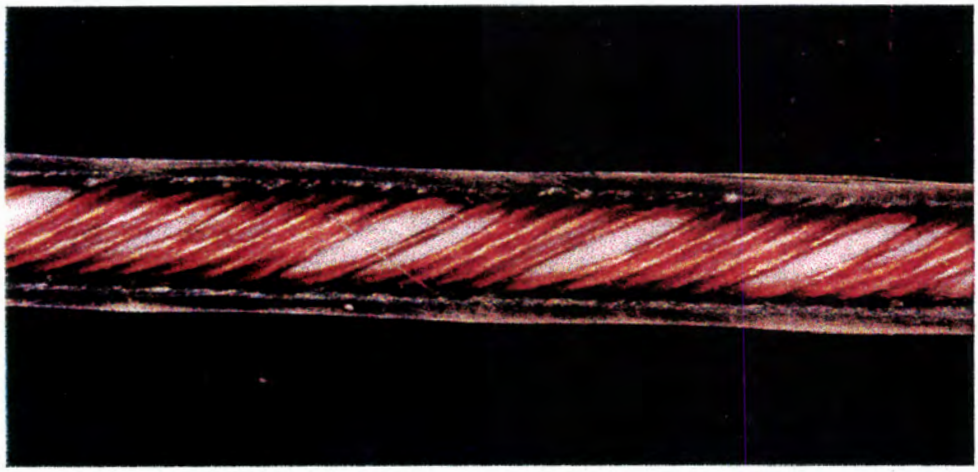


Figure 3.2-2 — FEP Insulation on Copper Helix

Outside of, but not physically attached to the FEP coating is the major structural element made of a Kevlar braid. Outside of, but not attached to the Kevlar structural weave is a protective layer of Nomex braid.

After the copper wire is wrapped onto the Nomex core, the entire length is wound onto a reel. This reel is then shipped to another facility to have the FEP insulation extruded over the wire. As the insulation is applied it is fed through a spark tester (to check for pin-holes) after which it is continuously wound onto a reel. This reel of insulated wire is moved to another facility to have the Kevlar woven over the FEP . Again the full length is continually wound onto a reel. The last step involves braiding the protective Nomex over the Kevlar and then winding the completed tether onto a storage reel. At the time of the TSS-1R flight the tether had been stored on various reels over a nine year period. The Board collected an extensive amount of documentation concerning the design, fabrication, testing, and handling of the tether. Excerpts from this material are contained in Appendix C.

The total length of the tether is stowed on the tether reel assembly with a pre-tension that varies from 20N (4.5 LB) to 80N (18 LB).

The completed tether had a diameter of 2.54 mm (0.1 in.) and a length of 22 km (13 mi). The ultimate tensile strength of this tether is 1780 N (400 LB) and the induced tensile load measured at the time of failure was 65N (15 LB).

At the satellite end, only the Kevlar element of the tether is attached as a load-carrying member to the satellite. The Nomex is not attached to the satellite, and the copper conductor is electrically connected in a configuration to assure no tension loads are transmitted. The insulation and copper layers have strain relief sections to avoid placing tension loads on them from the satellite. The Kevlar (structural member) was designed to take the total load of the satellite "pull".

3.2.1.2. TSS -1R Qualification & Certification Tests and Analysis Pre-TSS-1

There were many qualification and certification tests performed prior to TSS-1. The following list the most significant tests and corresponding results :

Breaking Strength (1780 N Requirement)
- 16 Specimens Flight Tether 1885 N (424 LB) avg.
- 16 Specimens Qual Tether 1906 N (428 LB) avg.

Insulation Dielectric Strength (15 kVDC, 38 hr. Requirement)
- 16 Specimens Qual & Flight Tether (32 Total)
  No breakdown in Salt Water Bath at 15 kV for 76 hr.

Thermal Vacuum (-100° C to + 125° C, 10^{-6} Torr.)
- 2 Specimens Qual & Flight Tether (4 Total)
  Specimens installed in chamber and loaded to 110N
  Conductor continuity measured continuously
  4 cycles with 12 hr. dwells at each temp extreme

Post Thermal Vacuum Break strength 1780 N (400 LB Req.)
- 2 Specimens Flight Tether 1869 N (420 LB) & 1914 N (430 LB) Avg.
- 2 Specimens Qual Tether 2047 N (460 LB) & 2114 N (475 LB) Avg.

Post Thermal Vacuum Insulation Dielectric Strength (15 kVDC, 38 hr.)
- 2 Specimens Qual & Flight Tether (4 Total)
  No breakdown in Salt Water Bath at 15 kVDC for 38 hr

The tests performed for development and certification of the tether demonstrated that the tether met or exceeded the requirements.

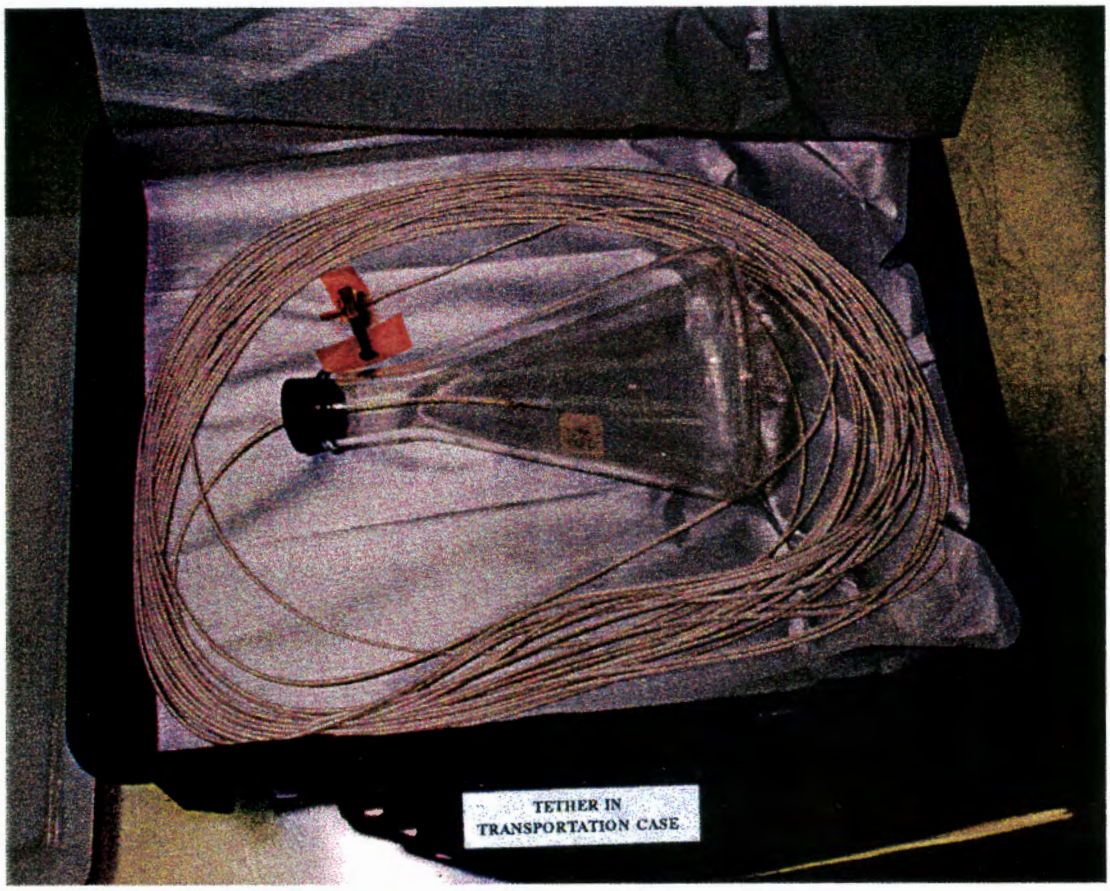
3.2.2 Post-Flight Findings on the Tether

After the tether failure, that part of the tether which remained within the boom and deployer mechanism was rewound onto the reel by the flight crew for postflight investigation. Approximately 9 m of tether behind the failure point had been deployed from the tether reel at the time of the separation.

The Board and two STS-75 flight crew members visually inspected the tether in the KSC Operations and Checkout Building. The burning and charring of the tether was immediately apparent.

During the deintegration of the TSS-1R after landing at KSC, approximately 27 m of tether containing the separated end was cut from the reel for detailed examination. This particular length was selected to capture the maximum length of tether that could have gone through the deployer mechanisms, and to have an equal reference length immediately adjacent to this section which had not gone through the deployer. The failed end of the tether was placed in a flask for

protection and the 27 m section with flask was packaged as shown in figure 3.2-3 for shipment to the laboratory. Approximately 1,989 m of tether remained on the reel. It was later removed for examination.



Transporting Failed End of Tether
Figure 3.2-3

In the laboratory, detailed inspections and analyses were made on the failed end and on the 27 m tether section with emphasis placed on the 9 m immediately behind the failure point that had passed through the deployer mechanism at the time of the break. Equipment or processes used to aid in the analyses were microphotography, x-ray, Energy Dispersive Spectroscopy (EDS), Fourier Transform Infrared spectroscopy (FTIR), Scanning Electron Microscope (SEM), and Computed Tomography (CT). The remaining 1,989 m of flight tether was also inspected and tested in the laboratory to determine its condition. The following sections give the results of these tests, inspections, and analyses.

3.2.2.1 Failed End of Tether

The end of the recovered tether where the failure occurred first had extensive noninvasive inspection and testing performed on it. Initial inspection revealed that the end had significant charring and melting of the tether components as

shown in figure 3.2-4. Images using x-ray, microphotography, and SEM were taken. These revealed that 2 to 4 of the 10 copper conductors failed in tension and the others melted through. The FEP insulator was completely burned or melted away in the break area. Most of the Kevlar, and inner and outer Nomex were also burned or melted away. Some remaining Kevlar and Nomex fibers, which did not burn, were failed in tension (see figure 3.2-4).

Figure 3.2-4 — Failed End of Flight Tether

SEM images were taken and 3 montages were compiled from these images showing views at 90 degrees rotation. One of these montages is presented in figure 3.2-5. An EDS examination was done around the separated end and several foreign elements were identified in the break area. Figure 3.2-6 is an example of the elemental composition found. The identified foreign elements are: iron, titanium, sodium, calcium, silica, and aluminum. EDS analysis of other areas of the failed end also showed traces of nickel.

TSS-1R FAILED END

Figure 3.2-5 — SEM Montage of Failed End

EH22.96058.P0059

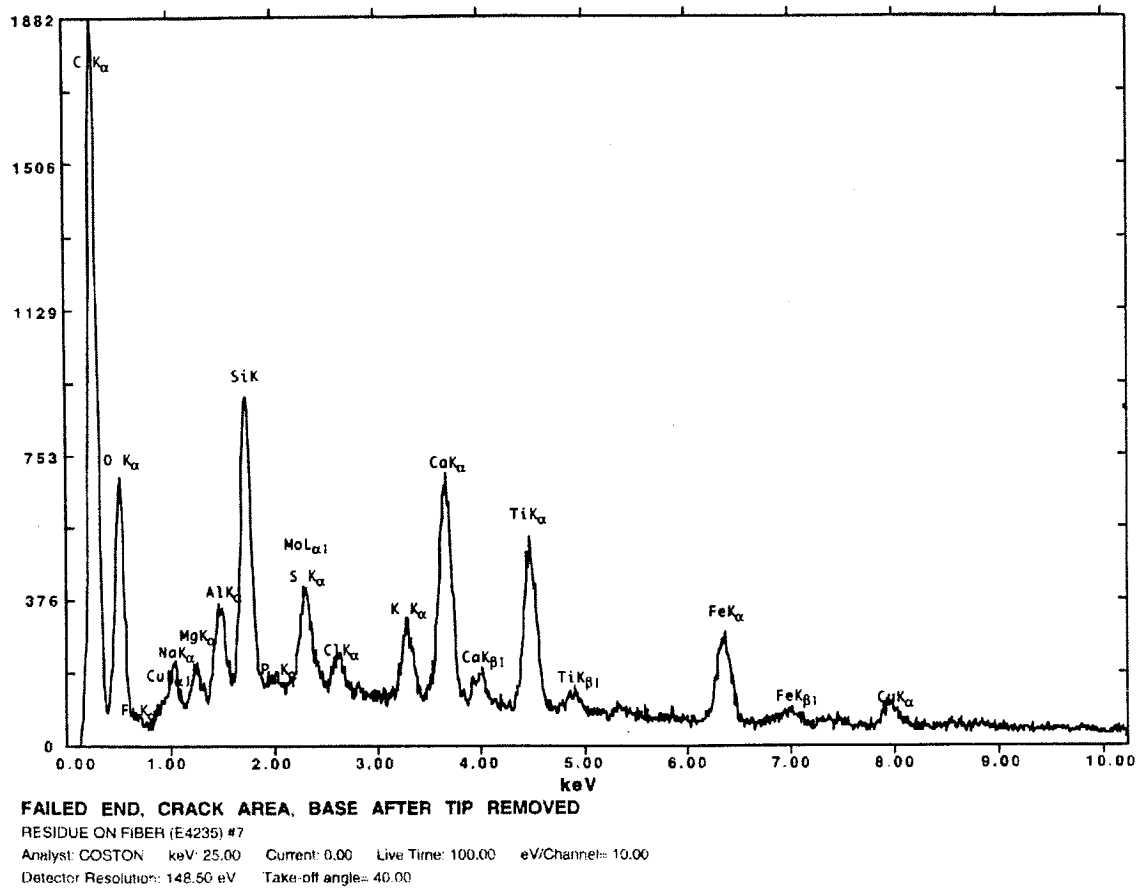


Figure 3.2-6 — Elemental Analysis at Failed End of Tether

Intrusive examination of the failed end consisted of removal of the Nomex and Kevlar jackets such that the FEP insulation and copper wire could be examined just aft of the burned area. As each jacket was removed, that interface was subjected to SEM and EDS analyses.

Visual observations made during this intrusive examination are as follows:

a) Three millimeters from the estimated arc discharge start point in the tether, one of the Kevlar tow wraps had a linear break across all of its fibers (see figure 3.2-5). Later tests demonstrating tether discharge arcing in a vacuum replicated similar breaks in Kevlar tows. The board concluded that this linear break phenomena is characteristic of Kevlar charring action and did not contribute to the tether separation.

b) Two small holes (approximately 0.03 mm diameter) were found in the FEP located under the Kevlar tow-break discussed in paragraph a) above (see figure 3.2-7). It can not be determined whether these holes might have

contributed to the arcing, or merely a result of the discharge/burning or heating which occurred in the immediate area.

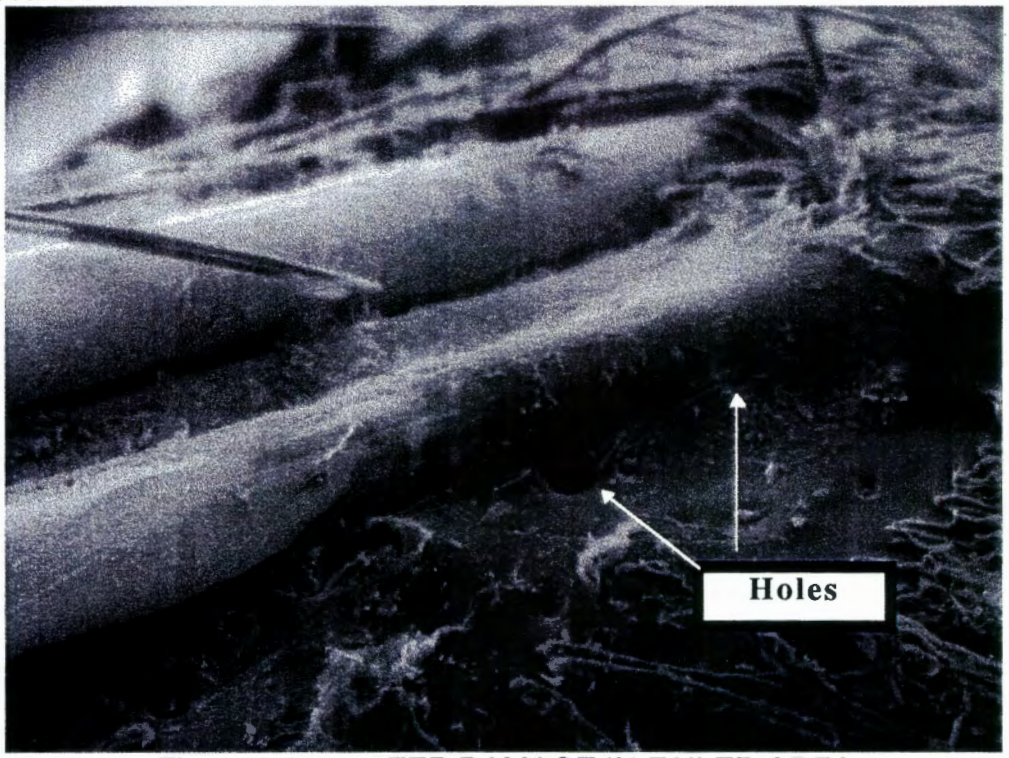


Figure 3.2-7 — FEP DAMAGE IN FAILED AREA

c) Immediately adjacent to the copper wire melt-area, 8 of the 10 wires had multiple "nicks" across them and the wire with the deepest nick was cut half way through its diameter (approximately 0.075 mm deep). The FEP at these nicks had burned away. A second location of nicked wires was found approximately 2 m away from the failed end. At this location, 7 of the 10 wires were nicked and the deepest penetration on one wire was about 1/3 of the wire diameter. These indentations appear to have been made by a sharp object. The FEP insulator immediately over the nicks show no signs of any damage, indicating that the wires were damaged prior to the FEP application.

d) Three areas on the 27 m section of tether had bumps. One area was at the failed end; two areas were some distance away from the failed end and will be discussed in section 3.2.2.2.

A bump consists of a raised portion of FEP typically 0.05 mm or greater above the surrounding FEP surface. These bumps always appeared in pairs and were adjacent to each other in a helical path around the FEP. This path is similar to the crisscross similar to the helical pattern of the Kevlar tows that wrap around the insulation. Lacerations within the FEP were always found in the vicinity of a bump-pair. Some of these lacerations appear to emanate from impressions left in the FEP by Kevlar tows or fibers. These bumps, lacerations,

were duplicated in the laboratory by twisting the tether to cause a kink and then pulling on the tether.

The bump-pair located at the failed end of the tether had a maximum height of approximately 0.25 mm. There was a crevice that ran between the bumps and extended deep into the FEP to the point of reaching the copper wires. It is not known if this exposed copper existed before the initial arc discharge. Lacerations in the FEP were also noted in the vicinity approximately 12 mm from the peak of the bumps. FEP indentations of Kevlar tows/fibers were very apparent in this region.

- The failed end was burned significantly. The remaining tether material failed in tension under the nominal load of 65 N (15 lb.).
- Foreign material was found in the immediate vicinity of the failed end.
- A pair of bumps and lacerations on the FEP was observed near the failed end

3.2.2.2 Twenty-Seven Meter Section of the Flight Tether

Non-invasive inspection and analyses were performed on the 27 m of tether cut from the reel at KSC before any intrusive analyses were done. The intrusive inspection consisted of cutting the tether at 11 selected locations, removing the Nomex and Kevlar wraps, and dissecting the FEP at points of interest. For purposes of recording the findings along the 27 m section, each anomaly was assigned a number starting at the cut end where the 27 m section was removed from the reel (i.e., the highest anomaly number is at the failed end). Also each anomaly site is measured and identified in meters from the cut end (the benchmark). X-ray radiology was done on the total length of this section and any abnormal images were also assigned an anomaly number preceded by an "R". A summary of all the anomalous findings is presented in figure 3.2.-8a. A distribution of anomalies without the spots placed on the tether by the hot pulley section is shown in figure 3.2-8b

A discussion of the examination findings on the 27m section are as follows:

a) Approximately 61 black spots were found along the tether section from the failed end out to 9 m, which is the tether length that passed through the LTCM before breaking. These spots varied somewhat in the intensity of blackness and were generally round and typically of similar size. The largest spot was approximately 0.2 mm in diameter. Each spot was examined and determined to be deposits of carbon soot embedded in the surface fibers of the Nomex jacket. The Nomex itself was determined to be unharmed.

Figure 3.2-8a

SUMMARY OF TETHER ANOMALIES

CUT/ANOMALY No.	DISTANCE FROM BENCHMARK (m)	COMMENTS I	COMMENTS II
Anomaly 62a	26.996	break region; end of Kevlar fibers	
Bump 1	**est. 26.8-26.9**	**Large bump in FEP; helical groove attributable to Kevlar**	**Helical groove cuts completely through FEP to copper wires beneath; debris in FEP**
Anomaly R19	*est. 26.91*	*Heavy particulate suspended in Kevlar fibers*	*Beyond designated break point; visible in Kevlar fibers*
Anomaly R18	*est. 26.83*	*Large HDI (high density indications) in damaged material*	*Does not have same appearance as heavy particulates or other HDIs*
Anomaly R17	*est. 26.83*	*Heavy particulate in Kevlar*	*near break; position may be slightly inaccurate*
Anomaly R16	*est. 26.82*	*Very light HDI streaks*	*near break; position may be slightly inaccurate*
Anomaly 61	26.737	normal dark spot	
Cut 1	**26.667**		
Anomaly 60	26.597	normal dark spot	
Anomaly 59	26.498	Normal dark spot	
Anomaly 58	26.478	Very, very dark spot	
Anomaly 57	26.358	normal dark spot	
Anomaly 56	26.317	surface contamination	
Cut 4	**26.310**		
Anomaly 55	26.260	normal dark spot	
Anomaly R14	*26.200*	*Heavy particulate in Kevlar*	
Anomaly 54	26.116	normal dark spot	
Anomaly 53	26.020	Normal dark spot	
Anomaly 52	25.978	light but wide dark spot	
Anomaly 51	25.873	small normal dark spot	
Cut 5	**25.825**		
Anomaly 50A	25.779	normal dark spot	
Anomaly 50	25.757	small normal dark spot	
Anomaly 49	25.661	dark material attached to Nomex fibers	
Anomaly 48	25.651	dark material attached to Nomex or Kevlar fibers	
Anomaly 47	25.632	normal dark spot	
Anomaly 46	25.622	Kevlar protruding	
Bump 2	**25.622**	**Moderate bump in FEP; helical groove attributable to Kevlar**	**Debris in FEP**
Anomaly 45	25.540	normal dark spot	
Anomaly 44	25.517	Very, very light dark spot	
Anomaly 43	25.478	Very light dark spot	
Cut 6	**25.436**		
Anomaly 42	25.392	normal dark spot	
Anomaly R13	*25.320*	*Possible inclusions*	*High density material, possible inclusion in Kevlar braid*
Anomaly 41	25.278	Small, light dark spot	
Anomaly 40	25.152	normal dark spot	
Cut 8	**25.121**		
Anomaly 39	24.981	Very, very light dark spot	
Anomaly 38	24.912	normal dark spot	
Anomaly 37	24.673	normal dark spot	
Anomaly R12	*24.600*	*Multiple heavy particulates + HDI streaks*	*Most prominent streak feature observed*
Anomaly 36	24.432	normal dark spot	
Anomaly R11	*24.42-24.48*	*3 large heavy particulates in Kevlar*	*Radiographic exam confirms in Kevlar only (4/12/96)*

CUT/ANOMALY No.	DISTANCE FROM BENCHMARK (m)	COMMENTS I	COMMENTS II
Anomaly 35	24.192	normal dark spot	
Anomaly R10	*23.980*	*Cloudy HDI in Kevlar*	
Anomaly 34	23.953	normal dark spot	
Anomaly R9	*23.870*	*Possible inclusions*	*High density material, possible inclusion in Kevlar braid*
Anomaly 33	23.714	normal dark spot	
Anomaly R8	*23.570*	*Large heavy particulate*	
Anomaly 32	23.544	light dark spot	
Anomaly 31	23.475	normal dark spot	
Anomaly 30	23.234	light dark spot	
Bump 3	**23.226**	**Small bump in FEP; helical groove attributable to Kevlar**	
Anomaly 29	23.044	Very, very light dark spot	
Anomaly 28	22.994	normal dark spot	
Anomaly R7	*22.860*	*Multiple heavy particulates + HDI streaks*	
Anomaly 27	22.753	normal dark spot	
Anomaly 26	22.512	normal dark spot	
Anomaly R6	*22.440*	*Heavy particulate in Kevlar*	
Anomaly 25	22.272	normal dark spot	
Cut 2	**22.168**		
Anomaly 24	22.043	Very, very light dark spot	
Anomaly 23C	22.034	Kevlar protruding + dark material	
Anomaly 23B	22.031	normal dark spot	
Anomaly 23A	22.024	Kevlar protruding + dark material	
Cut 3	**21.873**		
Anomaly 22	21.791	normal dark spot	
Anomaly 21	21.550	normal dark spot	
Anomaly 20	21.309	normal dark spot	
Anomaly 19	21.069	normal dark spot	
Anomaly 18	21.000	Very, very light dark spot	
Anomaly 17	20.829	normal dark spot	
Anomaly 16	20.588	normal dark spot	
Anomaly 15	20.347	normal dark spot	
Anomaly 14	20.107	normal dark spot	
Anomaly 13	19.864	normal dark spot	
Anomaly 12	19.624	normal dark spot	
Anomaly 11	19.384	normal dark spot	
Anomaly 10	19.144	normal dark spot	
Anomaly 9	18.905	normal dark spot	
Anomaly 8	18.860	normal dark spot; #6 to #8 is 0.240 M	
Anomaly 7	18.667	normal dark spot	
Anomaly 6	18.620	light dark spot; #6 to #8 is 0.240 M	
Anomaly 5	18.539	normal dark spot + one red/brown spot on rt.	
Anomaly 4	18.505	normal dark spot + two red specs on each side	
Anomaly 3	18.037	Very light dark spot	
Anomaly 2	18.007	Very light dark spot	
Cut 9	**15.398**		
Anomaly R5	*15.270*	*Large heavy particulate in Kevlar*	*Dissected: debris present at site of anomaly*
Cut 10	**15.111**		

Figure 3.2-8a — Summary of Anomalies (2)

CUT/ANOMALY No.	DISTANCE FROM BENCHMARK (m)	COMMENTS I	COMMENTS II
Anomaly R4	*14.370*	*Linear HDI streak + small heavy particulates*	
Anomaly R3	*13.320*	*Cloudy HDI + heavy particulates*	
Anomaly R2	*6.140*	*Cloudy HDI in Kevlar*	
Anomaly R1	*3.200*	*Linear HDI streak in Kevlar*	
Cut 11	**1.296**		
Cut 7	**0.298**		
Anomaly 1	0.140	Bend in tether	
BENCHMARK	**0.000**		

Figure 3.2-8a — Summary of Anomalies (3)

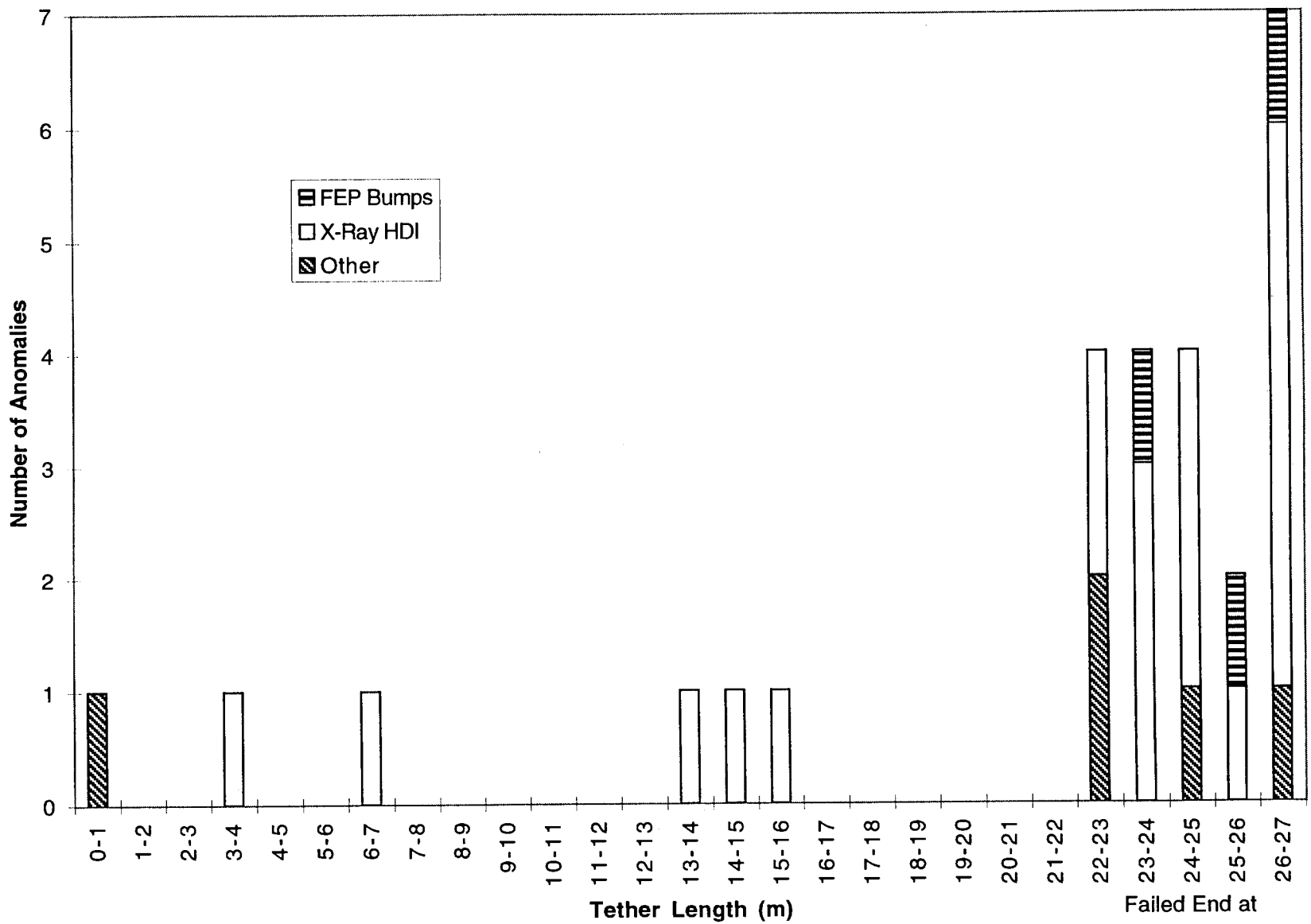


Figure 3.2-8b — Histogram of Anomalies

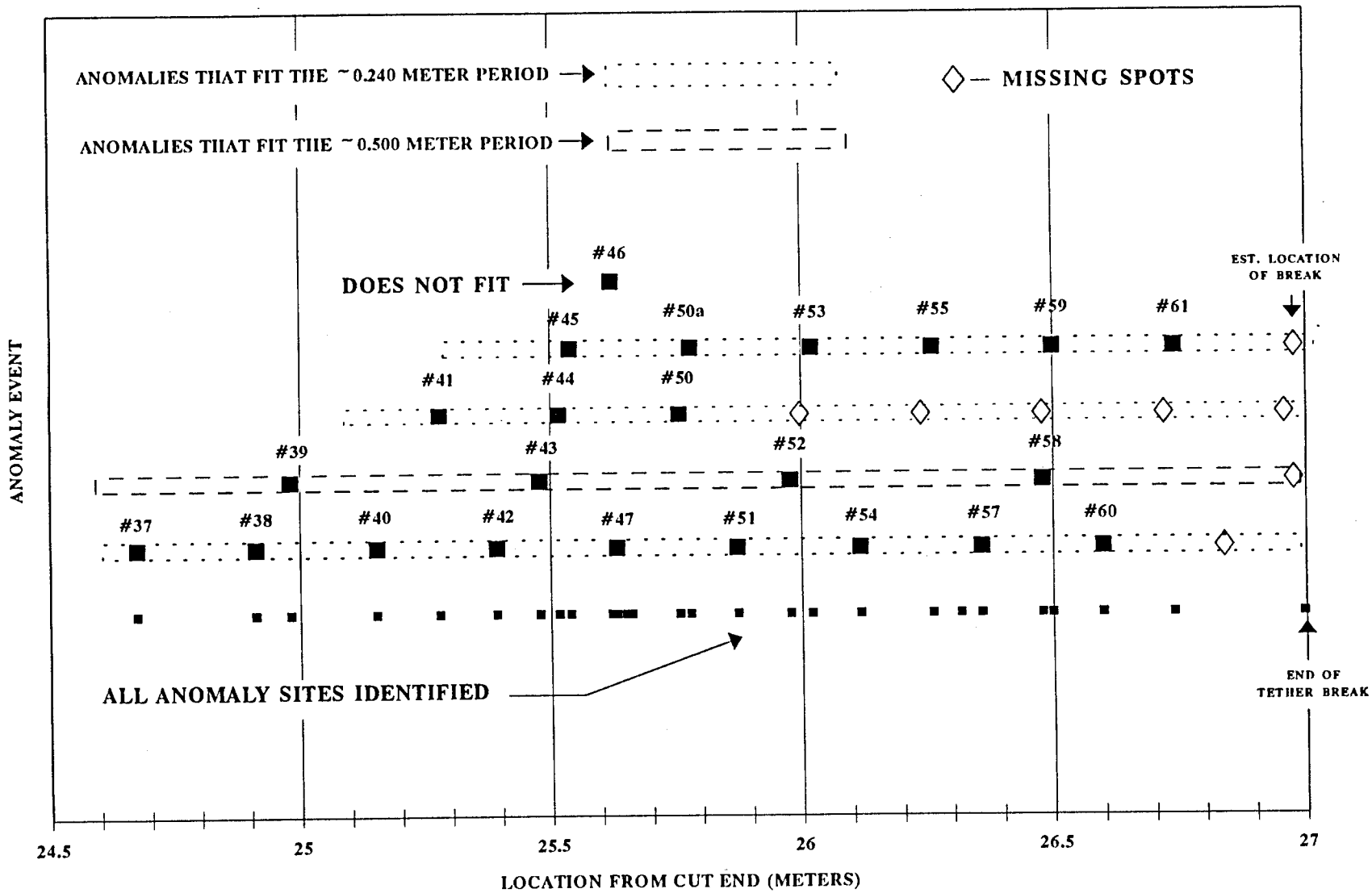


Figure 3.2-9 — Black Spot Anomalies

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An analysis of the spot locations revealed that all but one of the spots were within a definite linear pattern of finite spacings. Sets of these spots matched up perfectly with the linear distance (circumference) around the 4 pulleys located in the LTCM. The 2 idler pulleys and the tensiometer pulley all have the same circumference of 0.24 m and the encoder pulley has a circumference of 0.50 m. As discussed in section 3.3 each of these pulleys have one pyrolized spot on its circumference; therefore the conclusion is that as the tether traveled through the pulleys, each pulley repeatedly deposited some of the carbon on the tether as it rotated. This process continued for approximately 9 m (or 9 s) from the failed/burned tether end. Figure 3.2-9 summarizes the analysis showing the set of spots for each of the 4 pulleys. Figure 3.2-10 is a picture of a typical spot.

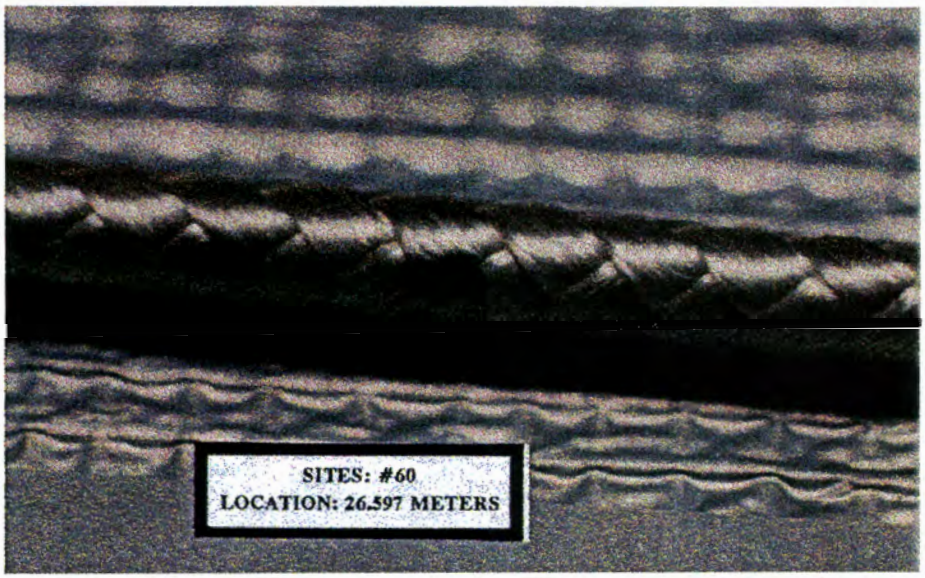


Figure 3.2-10 — Typical Spot

b) At three locations on this section of tether, Kevlar fiber was found to be protruding out from under the Nomex tows. The cause of these tufts are unknown and remain unexplained. Figure 3.2-11 shows a typical tuft of Kevlar. The Board did not attribute any part of the failure to these tufts.

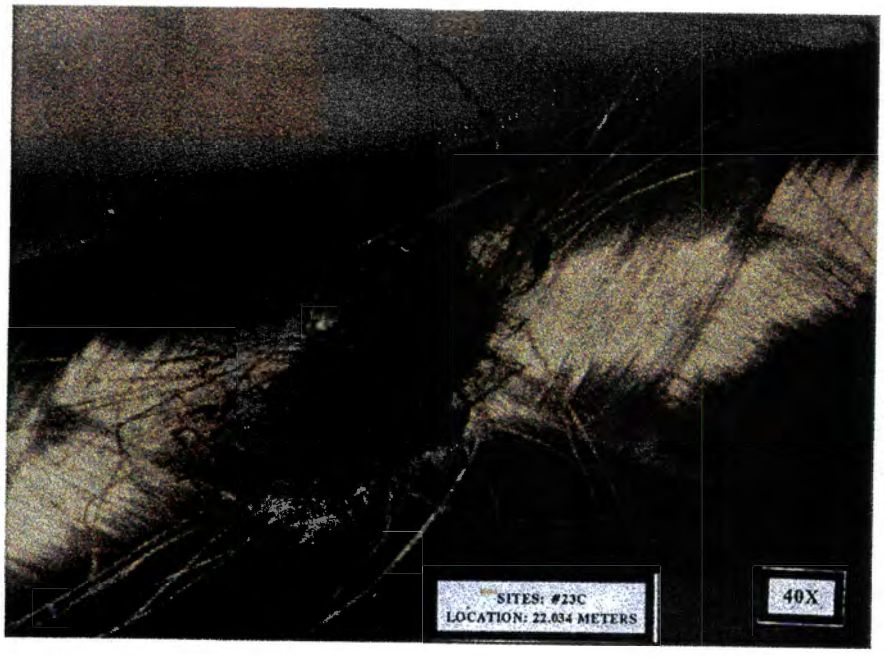


Figure 3.2-11 — Kevlar Fiber Protrusion

c) X-ray data and visual inspection found significant contamination contained within the Kevlar and Nomex weaves, between the FEP and the Kevlar, and within the FEP itself.

The x-ray data is summarized as follows

1. High concentrations of debris over the first 4 m from the burned end.

2. Moderate concentrations of debris from 4 m from the burned end to 9 m from the burnt end.

3. Low concentrations of debris in the remaining 27 m.

4. Very small particulates contained within the FEP insulator shell all along the length of the tether section.

The largest particle found within the fiber weaves by inspection was a piece of polypropylene (see figures 3.2-12 and 3.2-13) which was 4.97 m from the failed end (anomaly #23A). The particle was approximately 0.8 mm in length and 0.4 mm in width.

Figure 3.2-12 — Contaminant Particle in Tether

Figure 3.2-13 Polyropylene Particle

Other contaminants were found in the weave at several locations. As an example, at 11.73 m from the failed end (anomaly R5) a contaminated area was found (see figure 3.2-14). The contaminants included a particle approximately 0.4 mm in size (in upper right view of figure3.2-14), as well as, a microscopic metal particle (in lower left view of figure 3.2-14). The EDS analysis on the first particle indicates that it is an accumulation of dirt (figure 3.2-15a), and the metal piece, (figure 3.2-15b) was identified as aluminum. The elemental constituency of contaminants found in different layers of the tether at other locations included: silicon, zinc, iron, calcium, chlorine, aluminum, and potassium. These were generally in low concentrations.

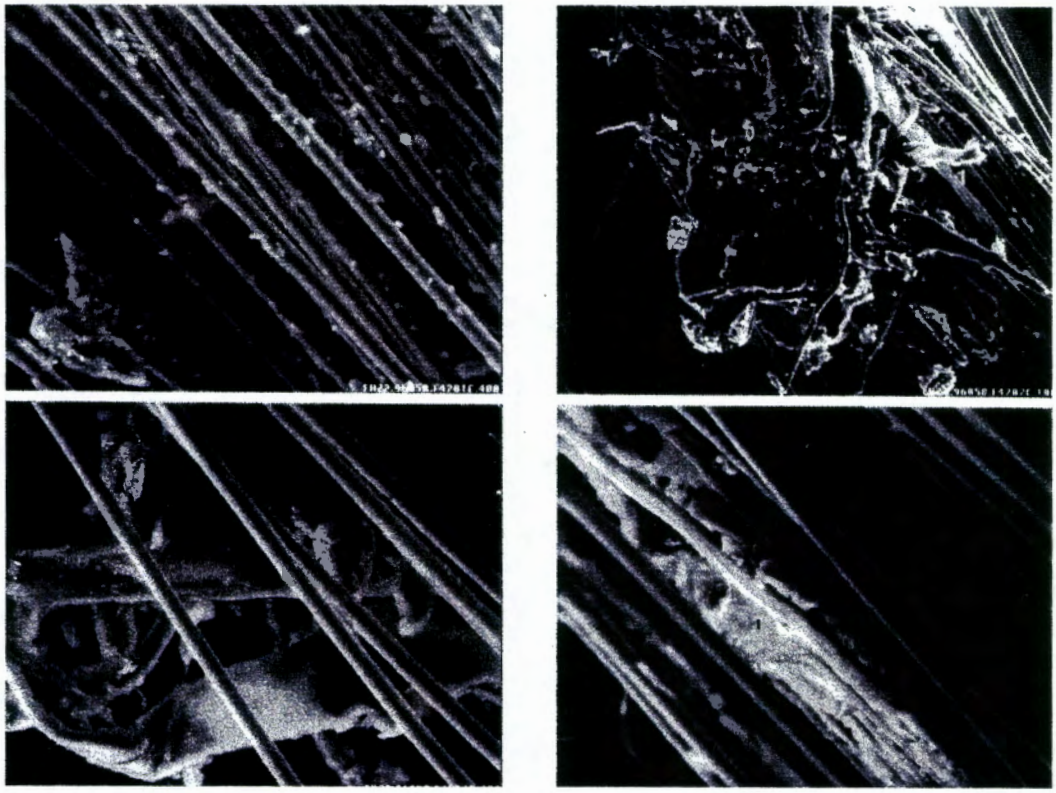
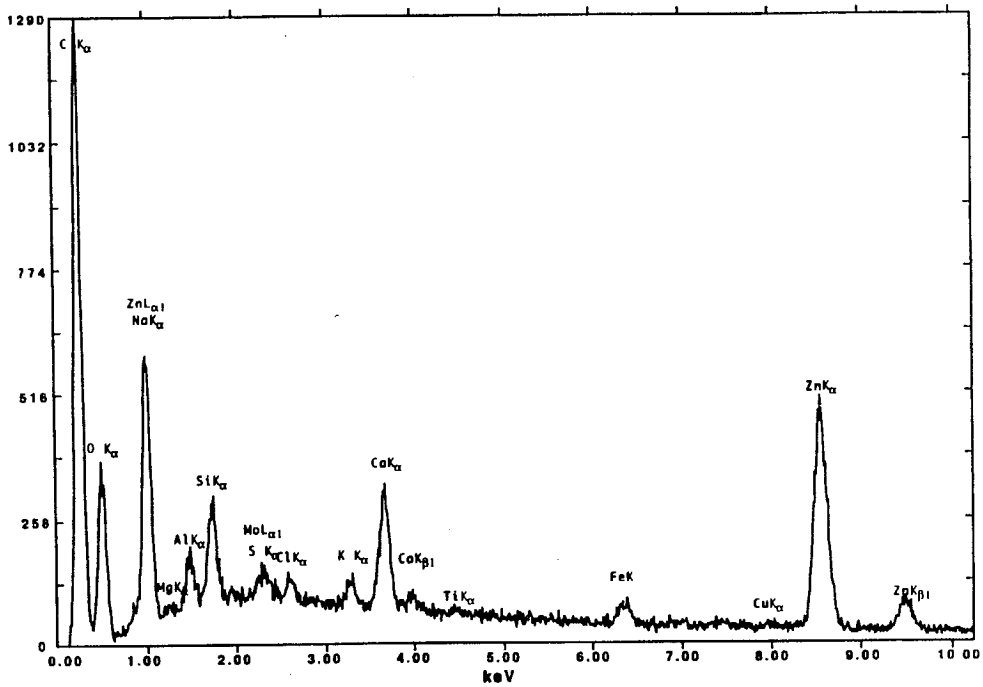
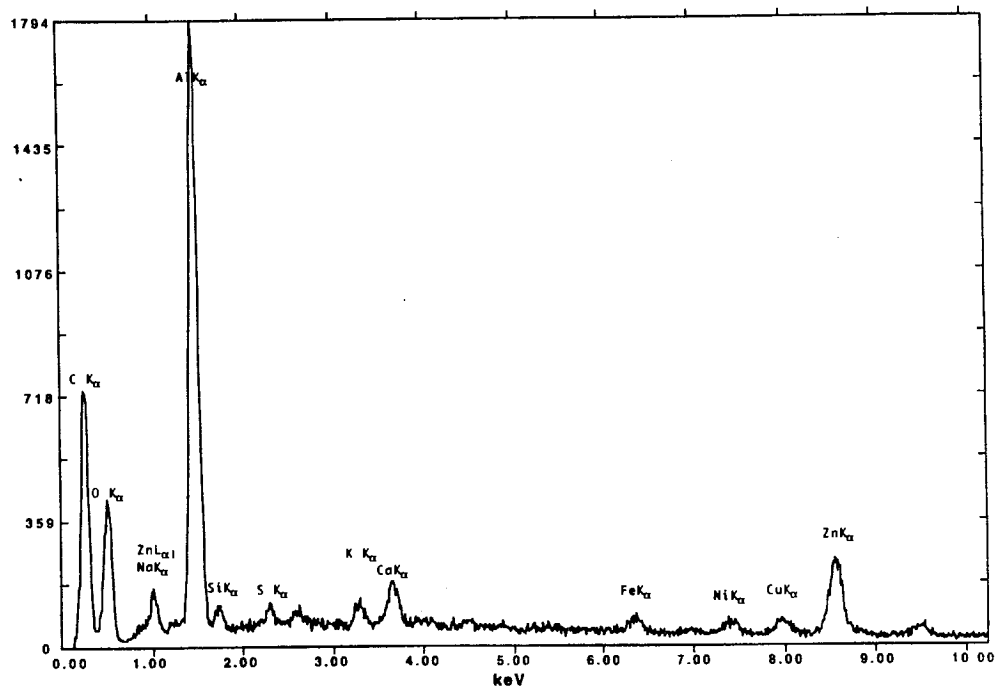


Figure 3.2-14 — R5 Kevlar 1 Analysis Areas



R5 KEVLAR 1
LARGE MASS ON FIBERS (E4202) #1
Analyst: COSTON keV: 25.00 Current: 0.00 Live Time: 100.00 eV/Channel= 10.00
Detector Resolution: 148.50 eV Take-off angle= 40.00

Figure 3.2-15a — EDS Analysis of R5 Kevlar 1 (dirt contaminant)



R5 KEVLAR 1
RIBBON (E4204) #1
Analyst: COSTON keV: 25.00 Current: 0.00 Live Time: 100.00 eV/Channel= 10.00
Detector Resolution: 148.50 eV Take-off angle= 40.00

Figure 3.2-15b — EDS Analysis of R5 Kevlar 1 (aluminum trace)

d) Bumps were found on the FEP surface as discussed above with the first bump being at the failed end. The second bump-pair was located 1.374 m from the failed end and had a maximum height of approximately 0.18 mm. Lacerations in the FEP were noted about 0.25 mm away from the bump. These lacerations were examined using SEM and the maximum depth appeared to be on the order of 0.075 mm. Definite signs of Kevlar indentations were noted at this bump location. The crevice between the bumps extended at least 0.05 mm into the FEP. This site also contained an externally visible Kevlar fiber tuft protrusion and extensive blue/black streaking (see paragraph e) on the outer surface of the Kevlar (anomaly 46).

The third bump-pair was located at 3.770 m from the failed end and had a maximum height of approximately 0.15 mm. The crevice running between the bumps went into the FEP about 0.15 mm or less. A few lacerations were noted within 50 mm of this bump, but none were as severe as the other two bump sites. Kevlar tow/fiber marks were embedded in this region also. At all of the bumps, the copper wire underneath was perturbed in proportion to the size of the bump.

e) Blue/black streaks composed of some material in the Kevlar/Nomex fibers were found between the failed tether end and 13.67 m from that end (figure 3.2-16). No further streaking was found past the 13.67 m point. Heating of a length of tether or heating a local spot on the tether did not duplicate the blue/black streaks. This phenomenon is not completely understood, but is a post-failure mechanism, and did not contribute to the failure.

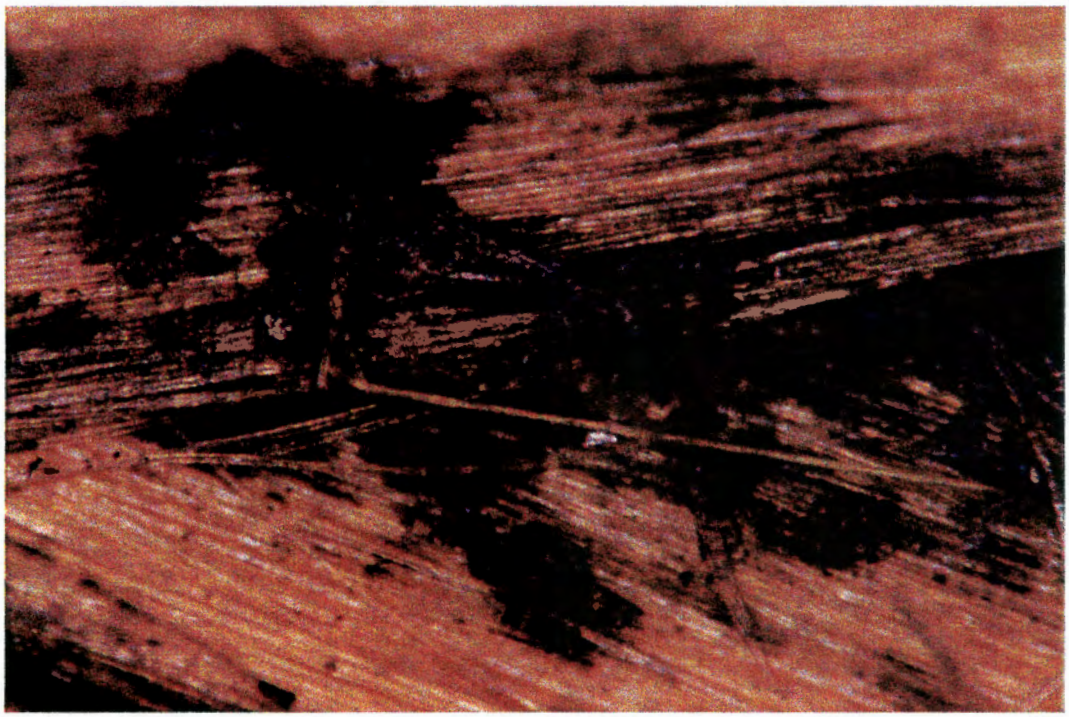


Figure 3.2-16 — Blue/Black Streaks

f) Examination of the 9 m section adjacent to the failed end revealed no butt welds in the wires. The insulation in the entire 27 m length had an oval shaped cross section. This ovality is discussed in another section 3.2.3.3 of this report.

- Contamination was found within the FEP and within the Kevlar-Nomex layers of the 27 m of tether immediately adjacent to the failed end.

- Kevlar protrusions and blue/black streaking on the Kevlar, under undamaged Nomex occurred near areas marked by the hot spots on the LTCM pulleys. A chemical reaction between the Kevlar and Nomex sizing is suspected as the cause.

- Bumps were found at approximately 1.3 m and 3.8 m from the failed end with FEP lacerations suggestive of twisting and kinking.

- No copper conductor butt welds were found in the 9 m adjacent to the failed end.

3.2.2.3 Remaining 1989 Meters of Flight Tether

The final length of 1,989 m of tether was visually inspected when it was removed from the flight reel. Several noteworthy points were observed and photographed. These included:

- crossovers and overlapped tether, in the middle of reel
- turnarounds and overlapped tether at the reel flanges
- Kevlar protruding through the Nomex layer in several places
- a large bump

This entire length of flight tether passed a special spark test conducted during the investigation. A detailed laboratory inspection revealed evidence of kinks that appeared to be partially straightened out. Some of these features were similar to those that resulted from forced kinking on specimens of tether in the laboratory. The large bump was found to be a "nest" of Kevlar, which is called "pilling" in textile manufacturing. The FEP insulation layer under this area was not damaged.

A 10 m section of this long tether was subsequently analyzed microscopically. Numerous sub-millimeter foreign particles were discovered in the Nomex cover, in the Kevlar tows, inside the FEP insulator walls, and inside the copper-Nomex core. (reference Appendix F-1)

Although the returned 1989 m flight tether section passed the spark test it showed signs of mechanical stress and contained numerous contaminants.

3.2.2.4 Tether Separated from the Orbiter

The Board viewed the various video taped sequences of the upper tether moving away from the orbiter. It was observed that the lower portion of the tether had coiled considerably by the time this end moved into the field of view of the video camera. Figure 3.2-17 is a still image taken from the video tape a few seconds after the coiled section came into view.

The coils were estimated by a JSC photo analysis to be on the order of 0.3-0.5 m, and the extensive coils were estimated to propagate several tens of meters up the tether. Beyond this point, there appeared to be fairly uniform twisting to the limit of visual discrimination on the video.

The coiled section moved away from the orbiter at an initial velocity of 3 m/s, increasing to 10 m/s, which was the satellite differential velocity. The data also showed that the net torque on the satellite was near zero at the time of the failure. The observed untwisting motion of the tether indicates that the torque on the tether near the orbiter was not zero.

The extreme coiling action of the lower part of the upper tether section was not modeled and is not understood. However, no evidence was found to connect this phenomenon with the failure.

3.2.3 Post Flight Analyses and Tests

During the course of the investigation numerous tests and analyses were conducted in connection with the fault tree path that contained the failure modes indicated by inspection of the tether. These included duplication of original tether qualification tests as well as focused tests associated with the fault tree.

Satellite with Broken-End of Tether

Digitized Image from Tape Title: STS-75 H-8mm Onboard ID#06

Image Science and Analysis Group
Earth Science Branch / SN5 /JSC

Figure 3.2-17a — Satellite with Broken End of Tether

Satellite with Broken-End of Tether

A

B

Digitized Images from Tape Title: STS-75 H-8mm Onboard ID#01

Image Science and Analysis Group
Earth Science Branch / SN5 /JSC

Figure 3.2-17b — Satellite with Broken End of Tether

3.2.3.1 Breakdown Voltage Test With and Without Insulation Violation

At the time of the TSS -1R tether failure, the electrical potential on the tether conductor relative to orbiter ground was measured to be -3500 VDC. A sequence of tests were devised to determine the voltage at which the insulation breaks down (current discharge from the conductor to a ground plane or plasma) on a standard undamaged tether, and on a tether with pre-existing violations of the FEP layer. These tests were performed both in air and in a vacuum. The test setup is shown in Figure 3.2-18. A typical tether discharge is shown in Figure 3.2-19. A complete listing of results is included in F-2. Some of the most significant results are shown below.

Test Conditions	Summary of Results
Good tether; partial vacuum; -3500 VDC; no tension; close ground plane	No arcing or current discharge
Tether with pinhole; vacuum and partial vacuum; no tension; close ground plane; -3500 VDC.	Arcing occurred at 10^{-3} to 10^{-2} Torr, sustaining 0.6 A for 10's of sec.
Tether with pinhole; partial vacuum; -3500 VDC; tension 15 lb.; close ground plane	Arcing occurred at 10^{-3} to 10^{-2} Torr; 0.6 A; tether broke in 6-8 sec; failed end similar to flight end.
Tether with pinhole in a plasma; -3500 VDC; no ground plane; tension 15 lb.	Arcing occurred; 0.6 A; tether broke in 6-8 sec. Upper failed end continued to discharge for 10's of seconds.
Grounded pointed rod pushed into Kevlar, but not FEP; variable voltage; variable pressure.	No arcing with -6 kVDC to -8 kVDC at 10^{-2} Torr
Grounded pointed rod pushed partially into FEP; variable voltage; variable pressure; tension 15 lb.	Arcing started at 5×10^{-3} Torr at -3500 VDC; tether broke in 6 sec.
Grounded pointed end pushed through FEP; -3500 VDC; variable pressure; tension at 15 lb.	Arcing started at 5×10^{-3} Torr; tether broke in 6 sec.

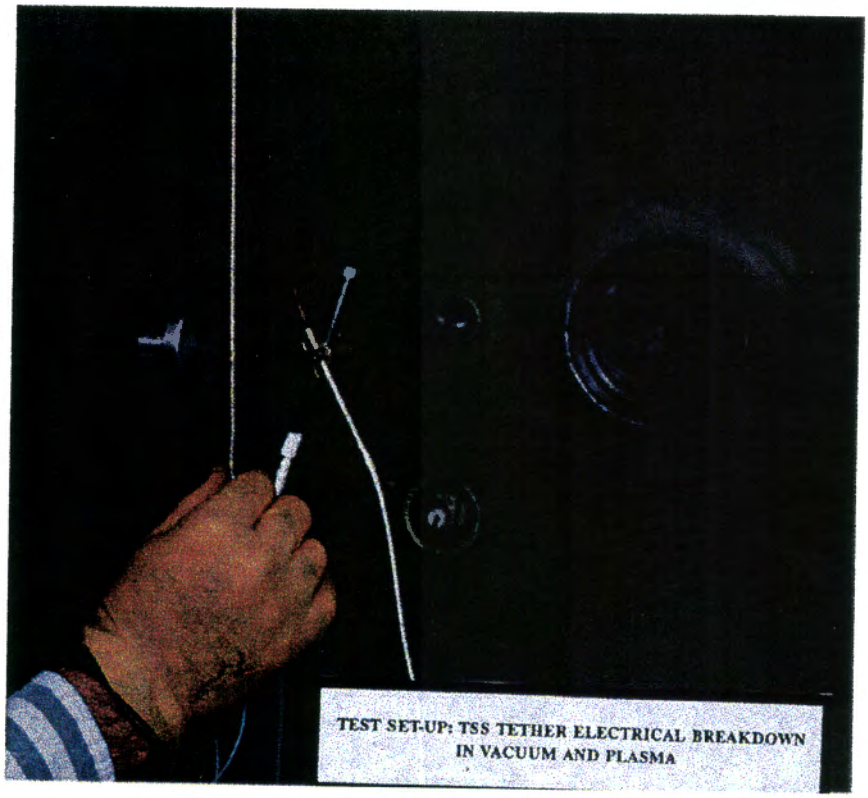


Figure 3.2-18 — Voltage Breakdown Test Setup

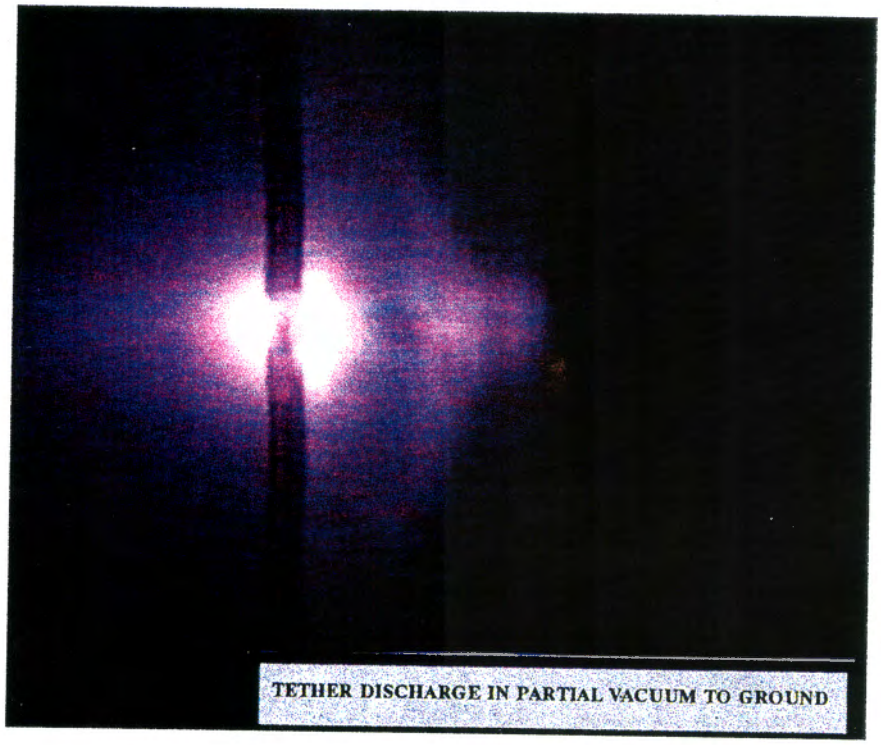


Figure 3.2-19

In summary, the voltage breakdown tests reveal that a tether with undamaged FEP insulation will not break down (flow significant current) even for very high voltage conditions and ground planes in close proximity. Breakdown readily occurred when there was a thin cut or hole (breach) through the FEP to the copper wire conductor. When there was an insulation breach, the breakdown voltage ranged from approximately -2 kVDC to -4.5 kVDC, depending on the hole size and distance from the ground plane.

3.2.3.2 Tether Strength Test

Since, in the final stages of the mishap, the tether clearly failed to carry the required load, the team performed a series of tensile strength tests. The tests focused on strength reverification of undamaged tether, establishing the strength of a tether damaged by: 1) electrical arcing/ burning, 2) various amounts of structural Kevlar removed, 3) local creep (cold flow), 4) twisting under load. A complete summary of the results can be found in Appendix F-3.

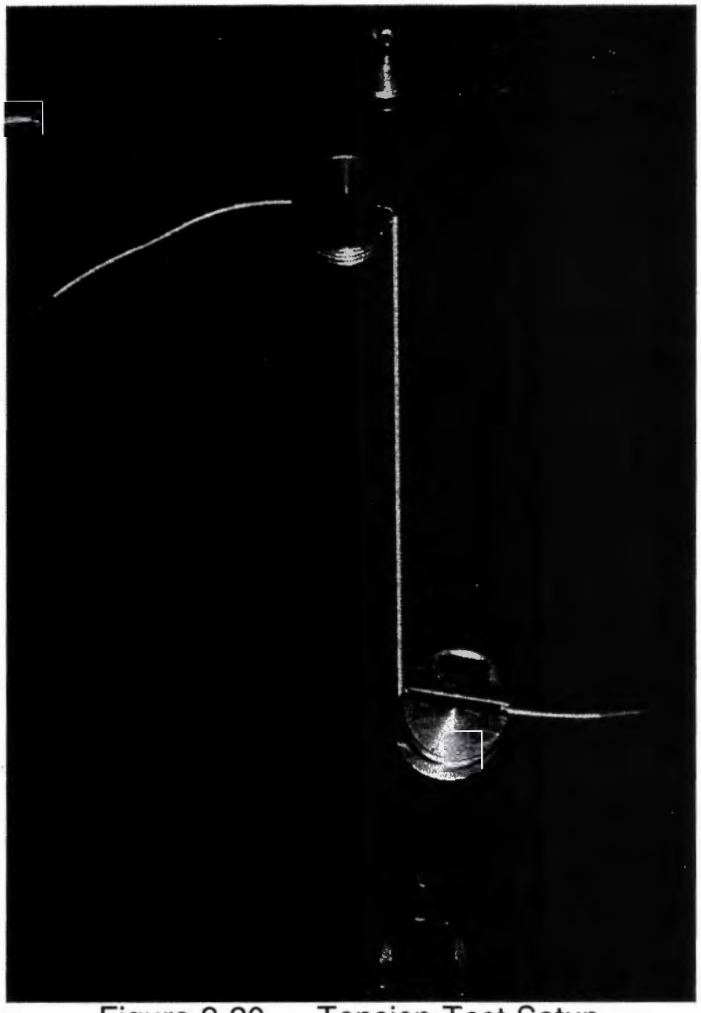


Figure 3-20 — Tension Test Setup

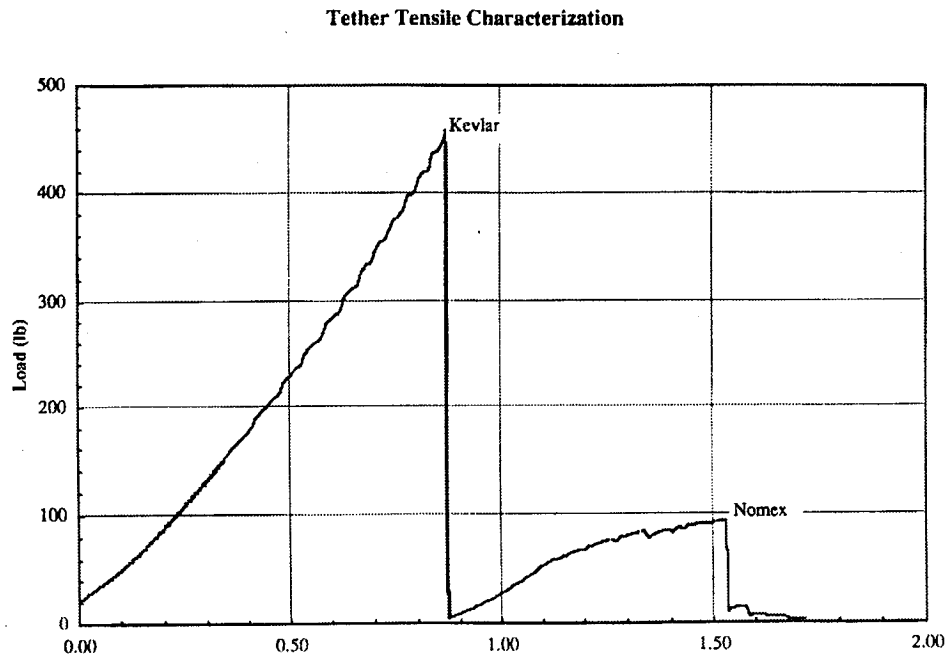


Figure 3.2-21 — Tether Axial Load vs Displacement

The test setup for tether axial tensile strength is shown in figure 3.2-20. In figure 3.2-21, the axial load (lb) is plotted against displacement (in) for a ten inch specimen of tether. The Kevlar fails first, the Nomex second, the copper conductor third, and the FEP last. The failure loads are shown in Fig. 3.2-22.

Mechanical Tests	Failure Load LB Rm Temp	Failure Load LB -100 deg C	Failure Load LB 125 deg C
Virgin Material.	431.7	463.7	320.5
After Elect Disch.	<10	N/A	N/A
12 Strand Kevlar (No Nomex)	419.1	N/A	N/A
9 Strand Kevlar (No Nomex)	309.8	N/A	N/A
6 Strand Kevlar (No Nomex)	237.9	N/A	N/A
3 Strand Kevlar (No Nomex)	142.7	N/A	N/A
No Kevlar No Nomex	37.7	N/A	N/A
Creep, No Damage	440.1	N/A	N/A
Creep w/ Damage	424.7	N/A	N/A
Twisted Tension (12 turns/m)	314.3	N/A	N/A

Figure 3.2-22 — Tether Tests Summary

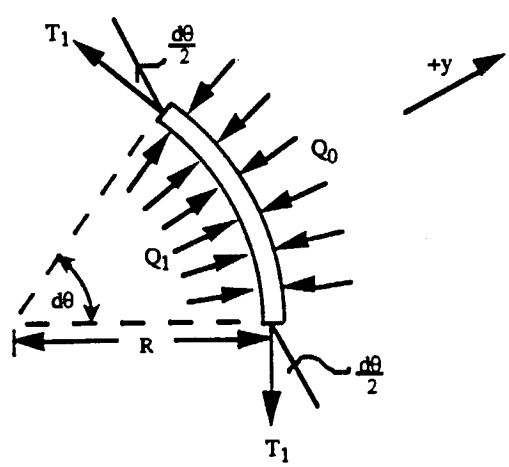
From this series of strength tests the Board concluded that:

- The strength of tether remained very high relative to the required load even when significant structural components of the tether were removed.
- Twisting of the tether, at much higher twists per meter than was seen in flight, did not significantly change the tether break strength.
- Creep did not change the tensile strength but did contribute to the cross sectional ovality without appreciably changing the insulation thickness. This latter feature is a very good feature because the tether becomes oval rather than thinning out.
- Electrical arcing/ burning dramatically reduced the strength from 1780N (400 LB) to less than 44 N (10 LB).

In summary, out of all the tests performed, including ones with severe induced structural damage, electrical arcing/ burning was the only damage that reduced the strength to a value much below the load required to physically fail the tether.

3.2.3.3 Loads Induced Into the Tether Wound on the Reel

The tether is wrapped onto the tether reel assembly with pre-load tension. As layer after layer of tether are added over previously wrapped layers, relatively high loads are induced into the under layers. In Appendix F-4 the equation is derived for computing the approximate load/unit tether length caused by this over wrapping. The Board estimated the magnitude of the forces acting on a layer of tether wrapped deep in the reel as depicted in the diagram below.



The resulting expression for the flattening load per unit length is given by:

$$Q_n = T\sum_{i=1}^{n}\frac{1}{R_i}$$

Substituting the values for the tension, the diameter of the tether, and the radius yields the linear force vs location in the reel as shown in figure 3.2-23:

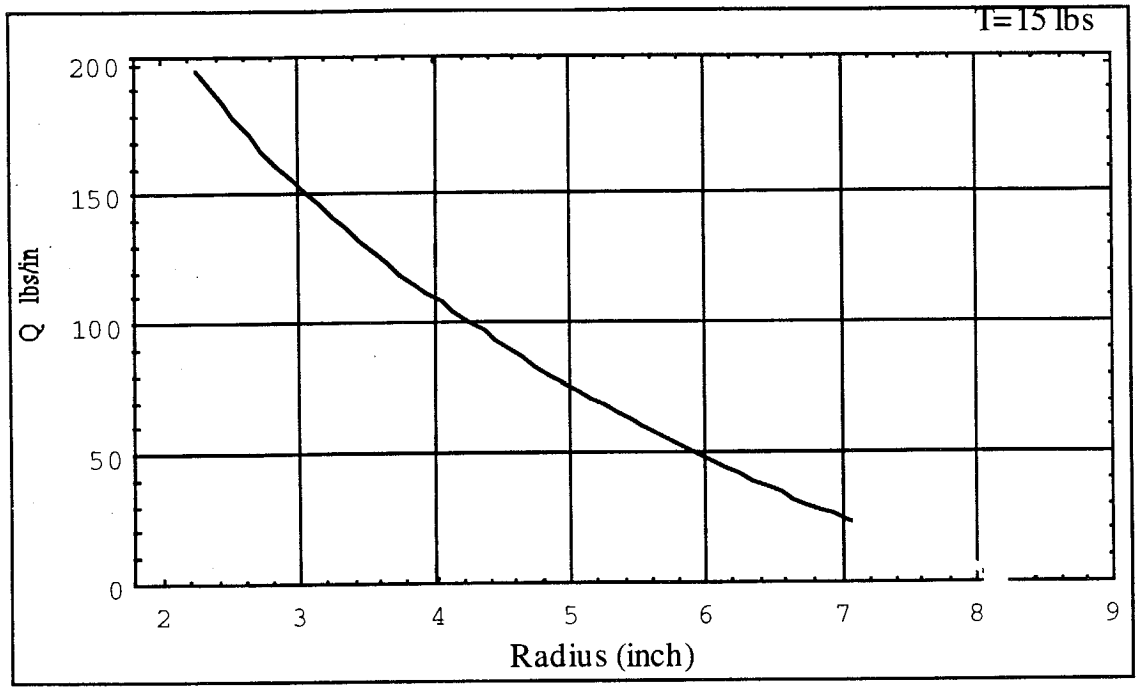


Figure 3.2-23 — Load per Unit Tether Length vs Reel Radius

It is apparent that the deeper in the wrap (i.e. smaller radius) the higher the compression load due to the wrap At the location where the failed section of tether was stored, (i.e. R=2.25 in.), the load due to wrapping is:

$$Q_{R=2.25} = 197.3\ lbs\ /\ in \qquad \text{or} \qquad Q_{R=2.25} = 345.5\ N\ /\ cm$$

The result of this load would be to flatten (see figure 3.2-24a and figure 3-24b) the cross section (make oval) but, more importantly, it would tend to force any debris into the tether, especially, if it were present at the Kevlar FEP interface. This very high load is later reduced somewhat due to cold flow and copper flattening. But by then, debris present would have already been pushed into the FEP insulation.

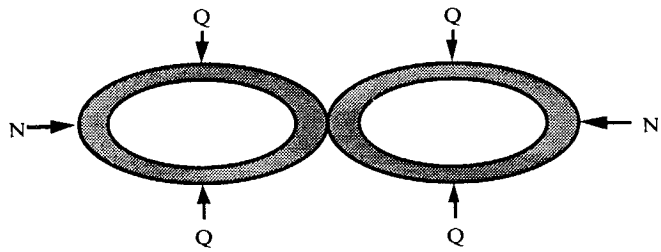


Figure 3-24a — Cross section Two Adjacent Tethers

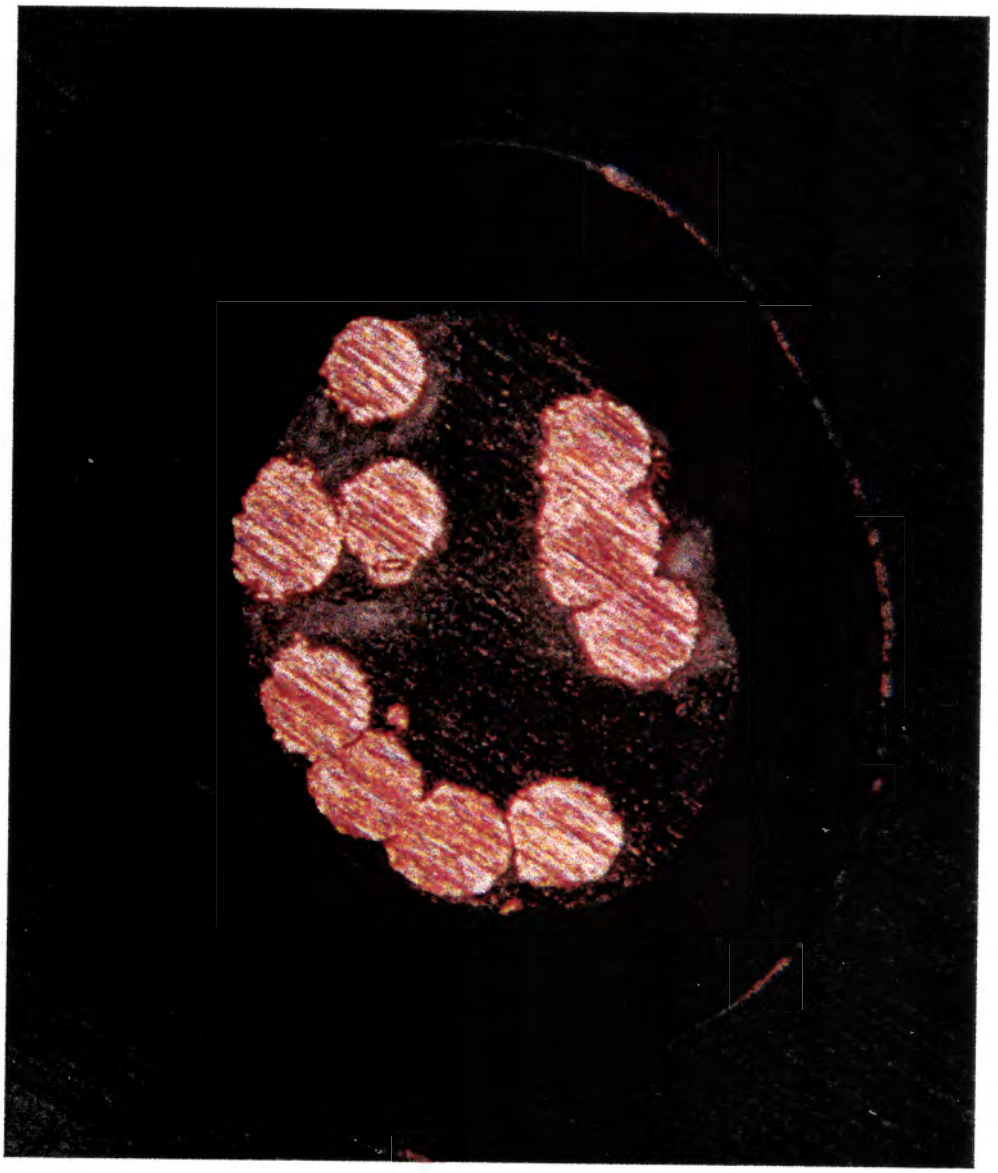


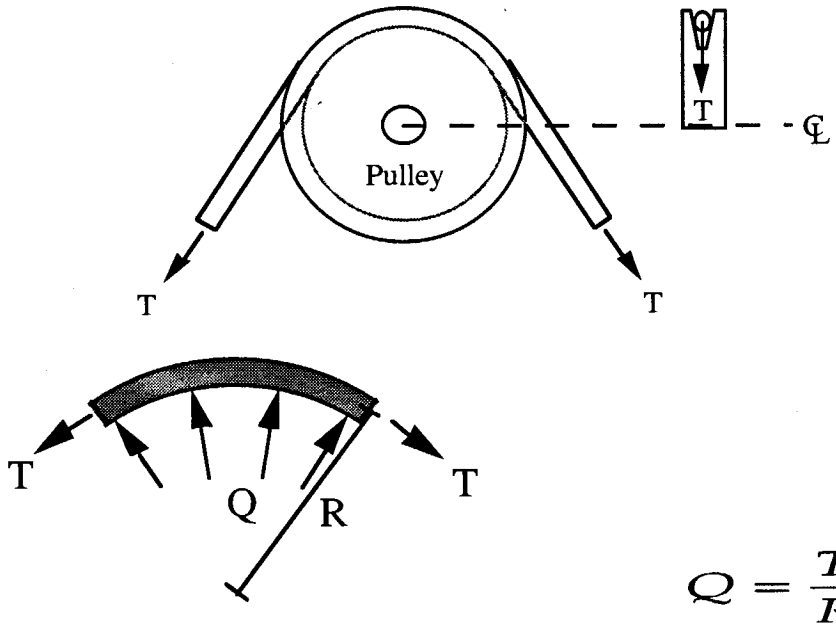
Figure 3-24b — Cross Section of TSS-1R Flight Tether

The tendency to force debris into the tether is:

- Sufficiently high to pierce the insulation but as the cross section slowly becomes oval the load is somewhat reduced. This reduction occurs after some extended period of time giving ample opportunity for debris intrusion.
- Maximum at each 90 degree of the cross section and over long lengths of tether.
- Present throughout the reel.

3.2.3.4 Load Induced into Tether by Traveling over Pulley

As the tether travels with tension over the pulleys in the LTCM, the pulley reacts the tension load by exerting a distributed load to the underside of the tether. In Appendix F -3 the derivation for that load as a function of tension and radius given.



$$Q = \frac{T}{R}$$

Free Body Diagram Tether
Over Pulley

The load per unit length, Q, that the tether experiences due to its tension is:

Q = 1.8 N/mm or Q = 10.3 lbs/in

The load / unit length exerted on a tether as it travels over a pulley is only Q=1.8 N/mm. This load is very low relative to that which is imposed on tether deep in the reel, but is high enough to force a properly positioned foreign object through the FEP.

3.2.3.6 Static Electricity Build Up Test on Pulley and Pulley Guards Relative to tether

Laboratory tests were conducted to determine the level of electrostatic charge that would build up on the LTCM pulleys and guards. The results of the tests showed that:

- In a near vacuum level, the entry LTCM pulley (which had a guard adjacent to it) charged to -1200 VDC in approximately 35 minutes.
- Once it had charged to -1200 VDC, it began to discharge, characteristic of a discharging capacitor.

- The pulley then charged to the same maximum voltage and discharged twice during the hour long test period.

This level of static charge is not high enough to cause an arc. However, a static charge of this magnitude will attract debris to the pulleys and increase the risk of foreign object damage to the tether. Further details can be found in the Appendix F - 2.

The Static Electricity Buildup Up Test showed no higher potential than -1200 VDC.

3.2.3.7 Spark Test of 1989 Meters of Flight Tether

The spark tester was re-verified by placing holes of specific sizes in the tether at various locations along the length. The set up is shown in Figure 3-25

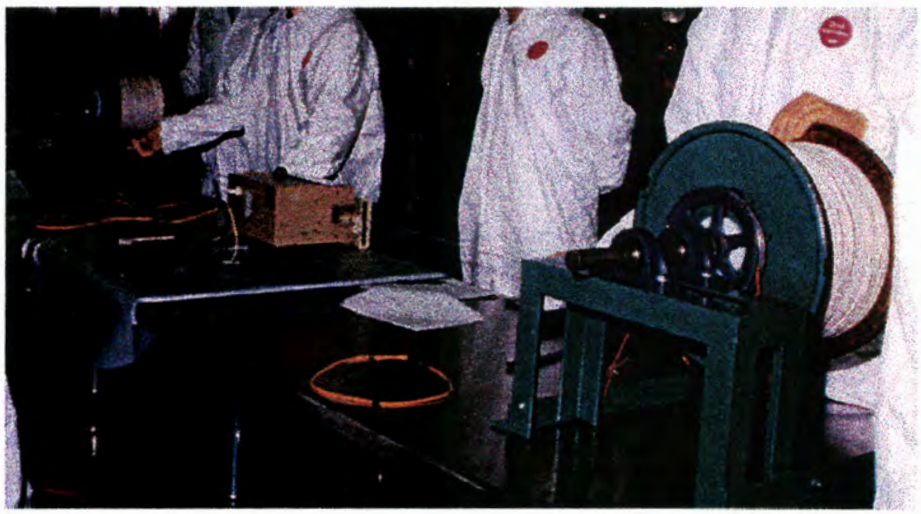


Figure 3.2-25 — Spark Test Set-up

The calibration results for the spark tester are shown in figure 3-26.

Violation Type	Dimension Diam. (mm)	Detected ?
Hole # 1	0.11	YES
Hole # 2	0.13	YES
Hole # 3	0.25	YES
Hole # 4	0.46	YES
Hole # 5	0.76	YES
Slit	Closed Back after Slitting	YES

Figure 3.2-26 — Spark Tester Results

The spark tests revealed each flaw (artificially induced) even the closed slit was detected easily. The entire 1989 m was spark tested using this very sensitive test setup. No breaches in the FEP insulation were found.

A special test was conducted to verify the 15 kVDC breakdown protection of the tether insulation. No arcing was seen at potentials up to 40 kVDC, indicating that the design of the tether was satisfactory, and that an undamaged tether would meet the design requirments for breakdown voltage.

- The 1989 m of flight tether on the flight reel had no breaches in the insulation through to the copper conductor, or near-through breaches.

- An undamaged tether substantially exceeds the 15 kVDC breakdown voltage requirement

3.2.3.8 Ease of Creating a Breach in Insulation by Debris

To establish the relative ease with which a small piece of debris can be made to penetrate the FEP insulation a qualitative test was performed. A small piece of #34 (.16 mm/.0063 in) wire, serving as debris, was pushed against FEP insulation and held. The wire did not penetrate at first but, after holding the force for a short time the, FEP parted and allowed the wire to penetrate. The result of this test can be seen in figure 3.2-27. A confirmation and further approximate quantification of those initial result is shown in figure 3.2-28

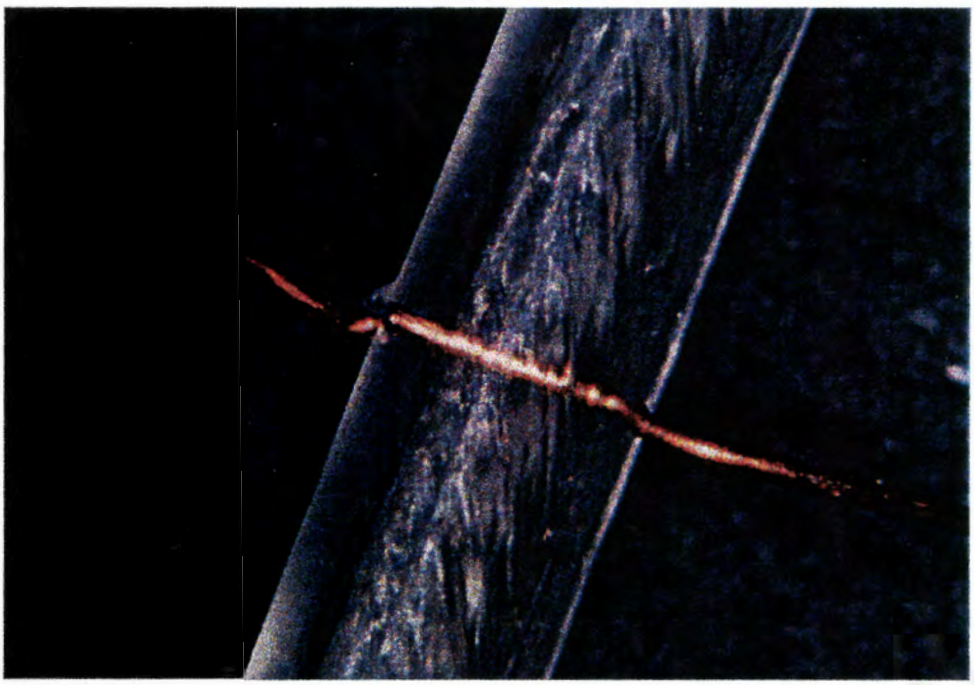


Figure 3.2-27 — Test to Determine the Ease of FEP Penetration

LOAD(N) Wedge end	TIME(sec) to penetrate	LOAD(N) Flat end	TIME(sec) to penetrate
1.08	> 300		
1.47	109		
1.58	36	1.58	>300
1.67	11	1.77	56
1.77	10	1.96	14
1.96	8		

Figure 3.2-28 — Force and Time Combinations to Penetrate FEP

- Low forces can easily force small, sharp objects into and through the FEP insulation layer.

3.2.3.9 Tether Manufacturing History

In reviewing the manufacturing history of the tether (Appendix C) it is clear that there were numerous opportunities for critical defects to be introduced into the FEP. The insulated copper wire was spark tested just after the FEP was extruded over the wire and any pinholes found were marked and repaired later. After the repair (installing heat shrink FEP tubing over hole) was complete it was locally spark tested for insulation integrity. This would be expected to provide a tether with insulation integrity, but, as the Kevlar was being woven onto the insulated conductor, a device used to check for diametrically oversized FEP can, itself, cause cuts or abrasions. The records show that one pinhole was found in the flight tether and two were found in the qualification tether.

There were recorded instances during Kevlar braiding where large bumps were seen as they were coming from the feed reel. These bumps were too large to feed through the braiding machine, so an attempt was made to reduce their size by heating and applying radial pressure. During this process the extruded FEP insulation completely parted at one end of the bump. This had to be repaired by a complete conductor splice. Numerous other smaller bumps in the FEP were also noted. There was also the potential of the bump checker doing superficial damage to the FEP.

Numerous manufacturing difficulties were encountered during the fabrication of the tether, including anomalies in the FEP insulation layer.

3.2.3.10 Special Spark Test on a Section of Qualification Tether

A 12 km length of qualification tether was spark tested again during the investigation. This tether had seen considerable use and testing since its manufacture in 1986-87. The spark test revealed two failed insulator areas. These failed regions were examined in the laboratory. One of the failures was

due to cracking of the insulator area. This area showed signs of mechanical stress, and could have been the result of the high utilization in the past 9 years.

The second failure area, however, almost certainly was the result of a manufacturing defect. (Fig. 3.2-29). Two copper conductors were broken, and one of them, turned nearly 180 degrees from its path, had worked its way through the FEP layer. Lab tests showed that very small forces over short periods of time can force a conductor through the FEP. Within 2 m of the failed end of the flight tether, copper conductors were nicked up to 1/3 of their diameter under undamaged FEP. This indicated a manufacturing defect.

- A spark test of a 12 m length of qualification tether showed only tow breaches of the insulator layer after 9 years of heavy use, indicative of a robust tether, in general. However, one of the faults involved the copper conductor which was indicative of a manufacturing defect.

3.2.3.11 Analyses and Tests Summary

The most significant results of the tests and analyses conducted on the tether are summarized as follows:

- Significant amounts of contamination were found at the Kevlar/FEP interface, in the Kevlar weave, and some in the FEP itself. Indentations and bumps were found on and in the FEP insulation and there were some nicks found in the wire strands under undamaged FEP.

- An electrostatic charge of -1200 VDC was built up on a Vespel pulley with a tether loop. This level of charge would not result in an arc to the tether conductor.

- Undamaged FEP insulated tether will not break down even for very high voltage conditions (40 kVDC) and very close ground planes. Breakdown easily occurred with an insulation breach at approximately -2.5 kVDC to -4.5 kVDC.

- Tether strength was very high relative to that required even with most of the elements removed. Electrical arcing/ burning was the only damage that reduced the strength to a value below the load required .

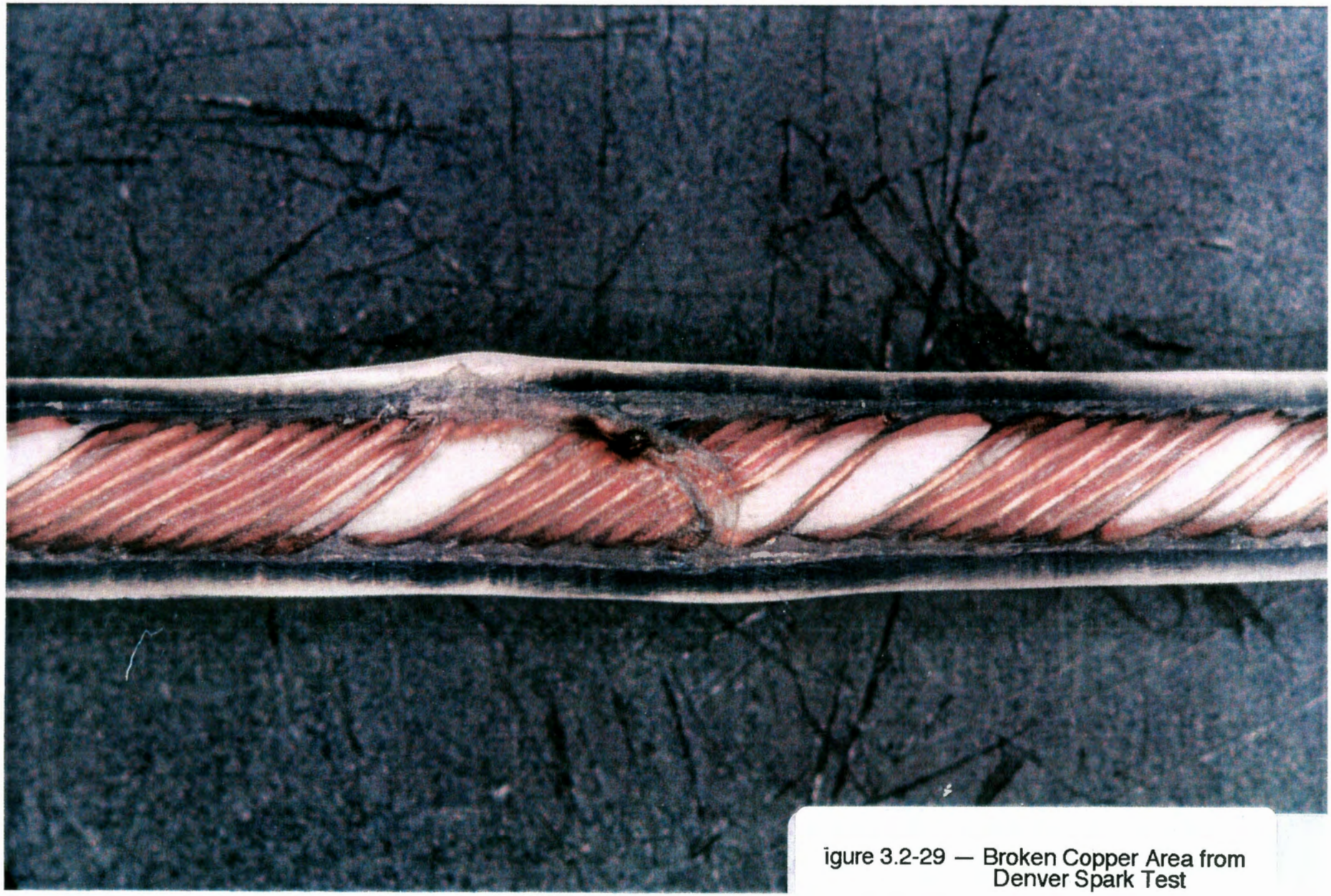
- Very low forces are required to push debris into the tether especially the FEP insulation.

- Very high forces existed (due to wrap on the reel) for several days after winding, over large lengths of the tether. These forces were orders of magnitude higher than that required to force debris into the tether.

- The forces on the tether while on a pulley were considerably lower than those imposed in the reel, but were high enough to cause a properly positioned foreign object to penetrate the FEP insulation.

- Manufacturing difficulties had the potential of producing a defect in the tether that later resulted in a breach of the FEP through reel wrap forces, pulley forces, or handling.

- Failure areas on the qualification tether, along with similar copper conductor damage under undamaged FEP in the flight tether, indicate the potential of defects in the manufacturing process.



igure 3.2-29 — Broken Copper Area from Denver Spark Test

3.3 Deployer Test and Analysis Results

3.3.1 Reel Assembly

Background/Pre-Mission Certification

Prior to the TSS-1R flight, numerous modifications and refurbishments were made to the reel assembly (reference. Section 1.3). The reel assembly was re-certified by review of the TSS-1 reel assembly certification documentation and review of the TSS-1R refurbishment and modifications. Functional testing of the reel occurred during the deployment/retrieval 4S08 tests. The reel assembly was observed and video taped during these tests and found to be operating normally.

Post-Flight Inspection

To minimize impact on the TSS-1R hardware, post flight inspection of the reel assembly was performed in-situ at KSC's Operations and Checkout building.

The reel assembly cover was removed and the reel area inspected (figure 3.3-1). Debris, found on the bottom of the reel housing, consisted mostly of shedded Nomex fibers from the tether and some small metallic particles. The level wind mechanism was partially disassembled and inspected. Particular attention was focused on the condition of the pulleys, pulley guards and rollers. All of the level wind components were found to be in nominal condition.

The reel mechanism operated normally during the mission and did not contribute to the failure. Small metallic debris were found in the reel housing which could contribute to foreign object damage to the tether.

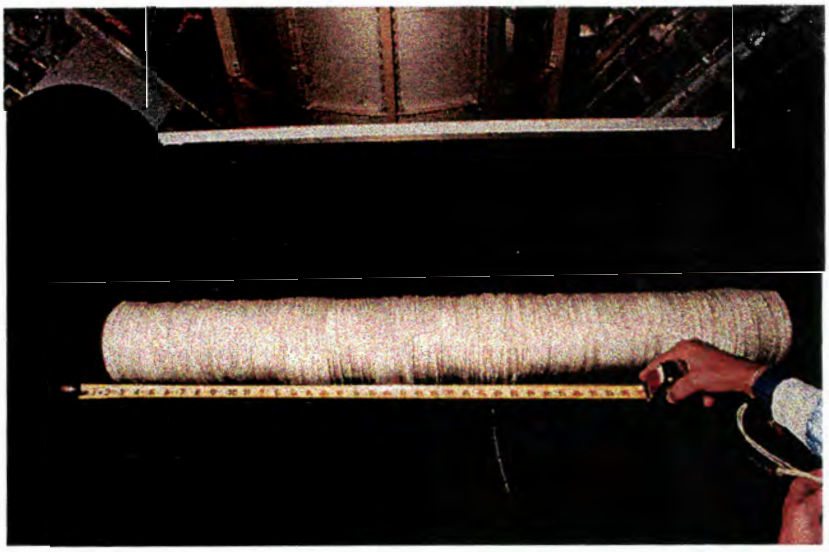


Figure 3.3-1 - Reel Assembly

3.3.2 LTCM

Background/Pre-Mission Certification

The LTCM was fully qualified prior to the TSS-1 mission (STS-46). Testing included random vibration and thermal/vacuum tests at the component level, as well as normal functioning during system-level testing. All test results were nominal. No modifications, disassembly, or inspections were performed on the LTCM between the TSS-1 and TSS-1R flights (reference. Section 1.3). The last time the LTCM had been visually inspected was prior to TSS-1. The TSS-1R mission certification included a review of the original data and an assessment that the original certification was valid and that no changes were required. The LTCM again performed nominally during system-level testing (4S08) prior to TSS-1R. The flight tether was run through the LTCM a total of 5 times in ground testing (single retrieve before TSS-1, and 2 full deploy/retrieve cycles before TSS-1R) prior to the flight failure. There were no reported or observed anomalies during any of these operations. A photo of the LTCM is shown in Figure 3.3-2. A description of the LTCM operation is provided in Section 1.2.2 of this document.

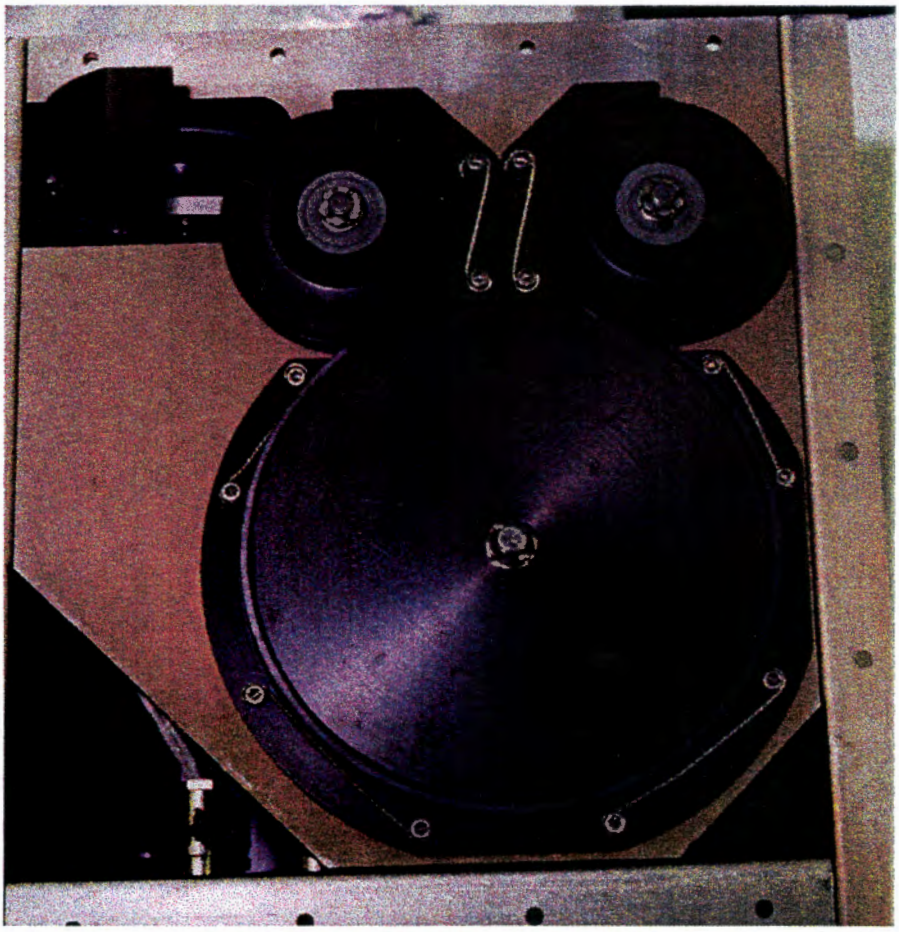


Figure 3.3-2 - Lower Tether Control Mechanism (LTCM)

Post-Flight Inspection

The LTCM was removed from the SSA and shipped to MSFC for inspection and analysis. The disassembly and inspection was performed in a Class 30,000 clean room.

All four of the LTCM pulleys were observed to have a single spot on the pulley where the pulley material, Vespel SP-3, appeared pyrolyzed. Data from the manufacturer indicated that this occurs at approximately 600°C. The pyrolyzed spots and oxidation interference fringe patterns are clearly visible on the pulleys in figures 3.3-3 through 3.3-5. Close observation of a photo of the second idler pulley showed a helical shaped particle in the root of the pulley (Figure 3.3-5). The particle was not found on the pulley when examined later and is presumed to have been lost.

The four pulley guards had oxidation along their surfaces adjacent to the tether path (Figures 3.3-6 through 3.3-8). The streak on the first idler pulley guard had a definite start position (Figure 3.3-6), which corresponds to approximately the tether's tangent point as it entered into the first idler pulley, and continued along the remaining path. The remaining guards had streaks along their entire length.

Scanning Electron Microscope (SEM) and Engergy Dispersive Spectroscopy (EDS) analysis of the idler pulleys and guards indicated the only foreign material found was a small amount of copper deposit on the first idler pulley. The encoder wheel and encoder wheel guard were too large to fit in the SEM/EDS chamber. Therefore, a small sample of the pyrolyzed area was scraped off and analyzed with X-ray Fluorescence Spectroscopy (XFS). The results did not indicate the presence of any foreign material.

The aluminum guide tube was cut in half to inspect and analyze its interior. The guide tube was isolated from orbiter ground by its mounting and its interior was anodized. Erosion of the guide tube material was found at its entrance and exit (Figure 3.3-9).

The interior walls of the LTCM are coated with an electrically conductive black paint and were therefore at orbiter ground. There were several places of bare aluminum on the housing visible, where the black paint had flaked off. There were no arc marks found on the LTCM painted surfaces or on the metallic (orbiter grounded) pulley shafts. The black painted surfaces were mottled and arc marks would be difficult to identify.

The interior of the LTCM contained a significant amount of debris (figure 3.3-10). The majority of the debris was non-metallic and consisted of shedded Nomex fibers from the tether. The metallic debris (up to 1 mm size) were analyzed and the images are presented in figures 3.3-11 and 3.3-12. EDS analysis identified most of the metallic particles as aluminum; a nickel particle

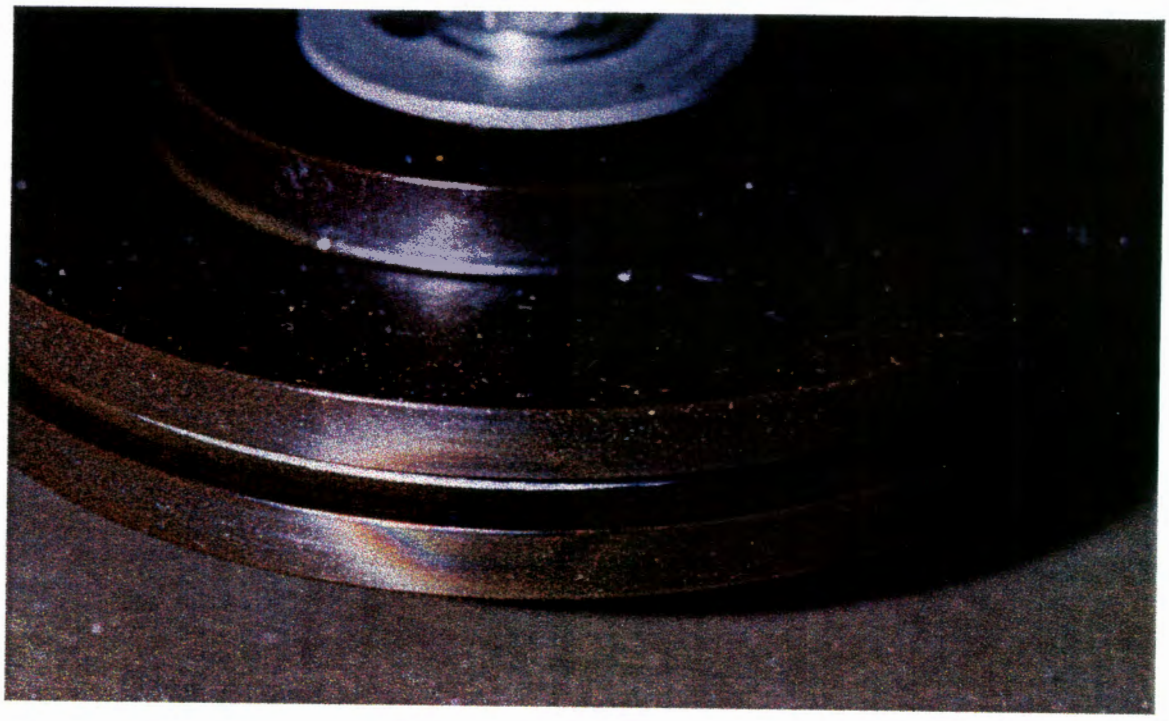


Figure 3.3-3 - LTCM First Idler Pulley

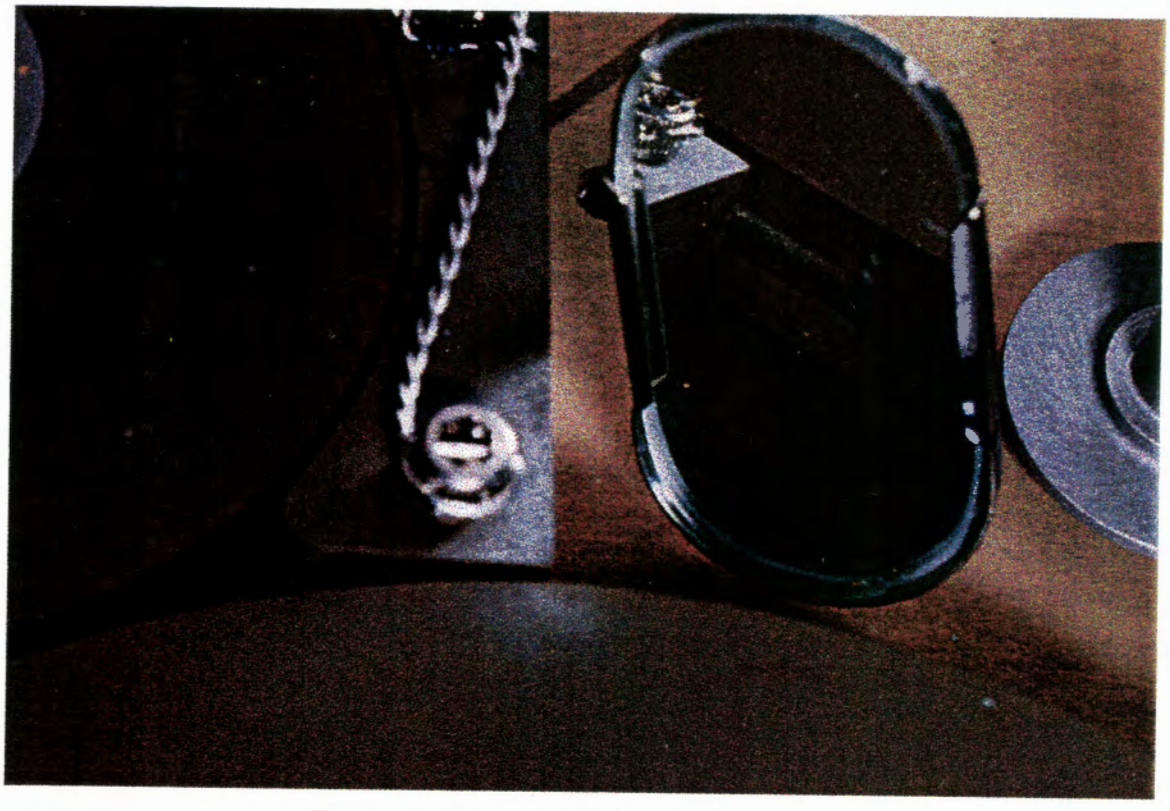


Figure 3.3-4 - LTCM Encoder Pulley

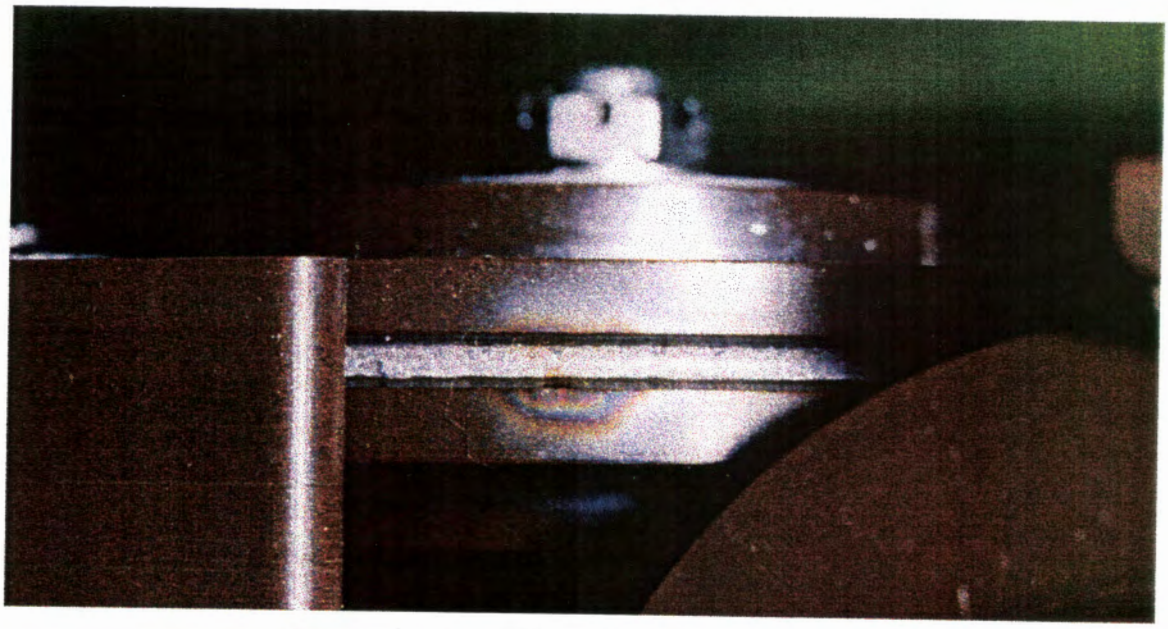


Figure 3.3-5 - LTCM Second Idler Pulley

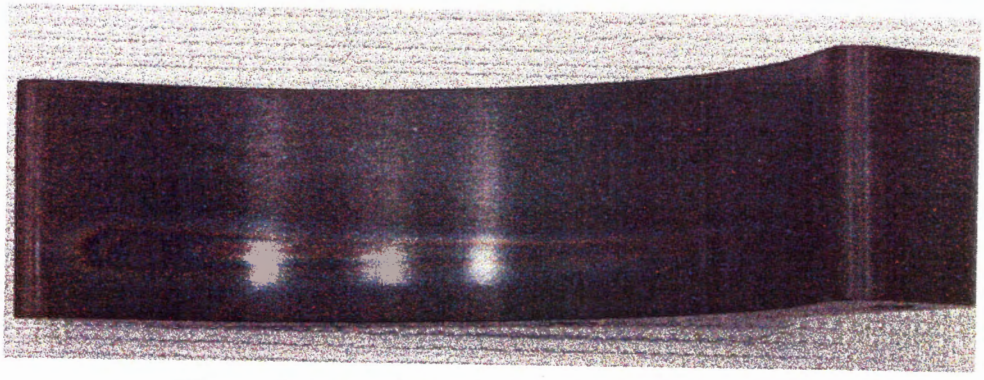


Figure 3.3-6 - LTCM First Idler Pulley Guard

Figure 3.3-7 - LTCM Encoder Pulley Guard

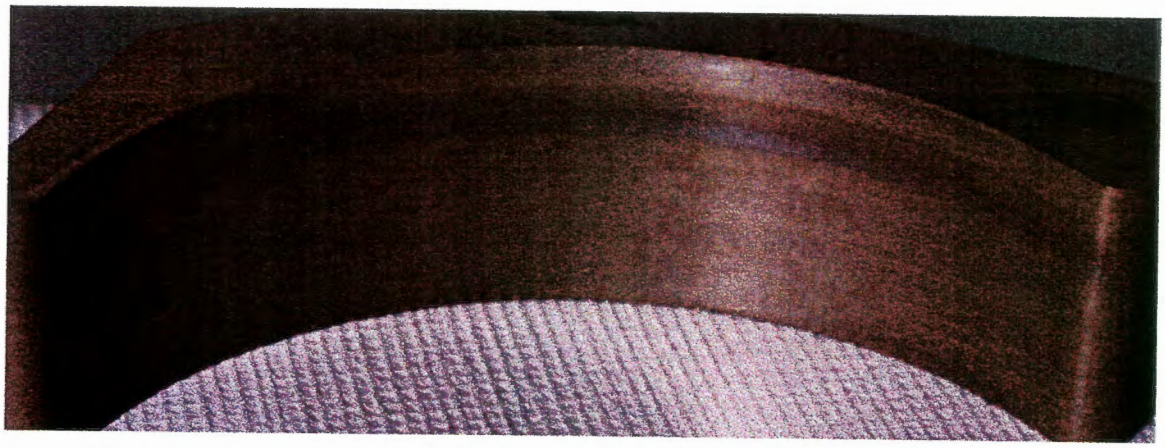


Figure 3.3-8 - LTCM Second Idler Pulley Guard

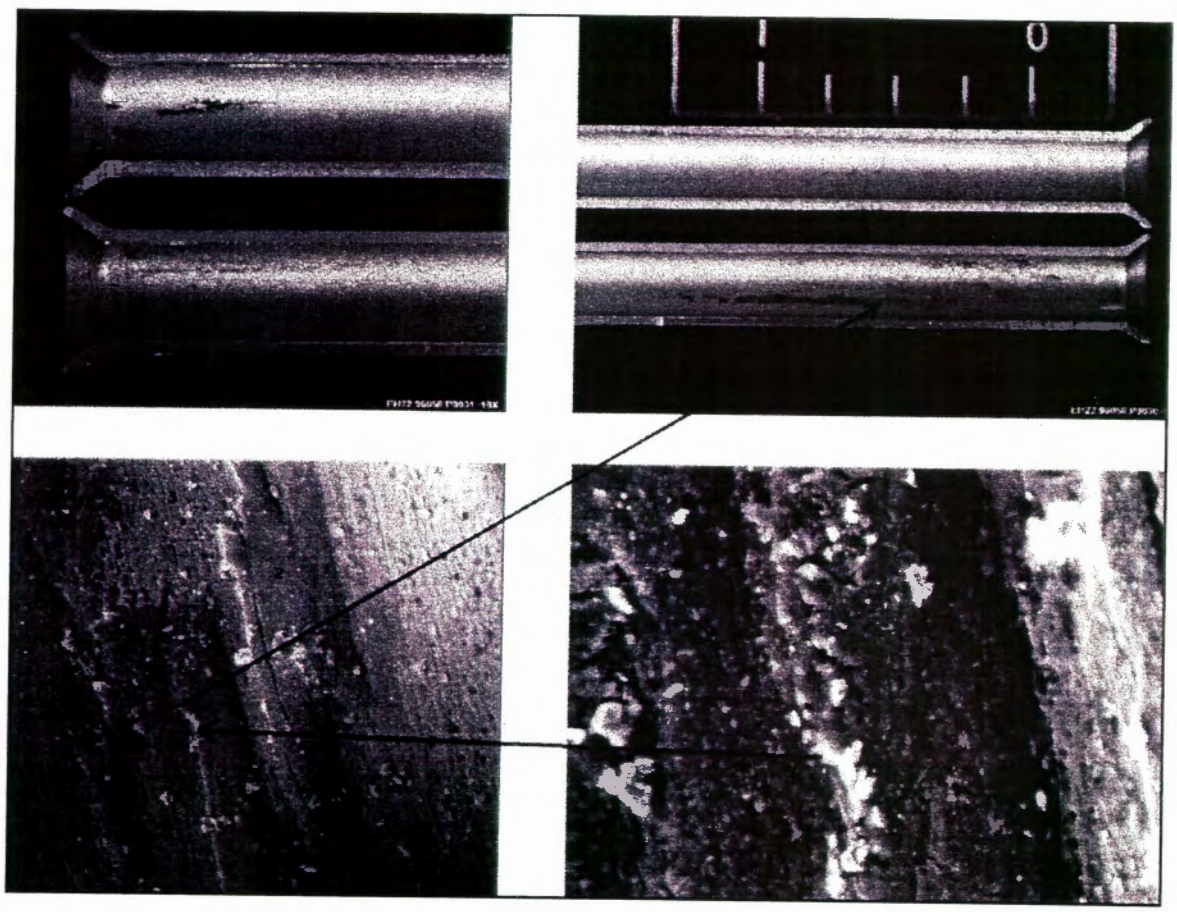


Figure 3.3-9 - LTCM Guide Tube

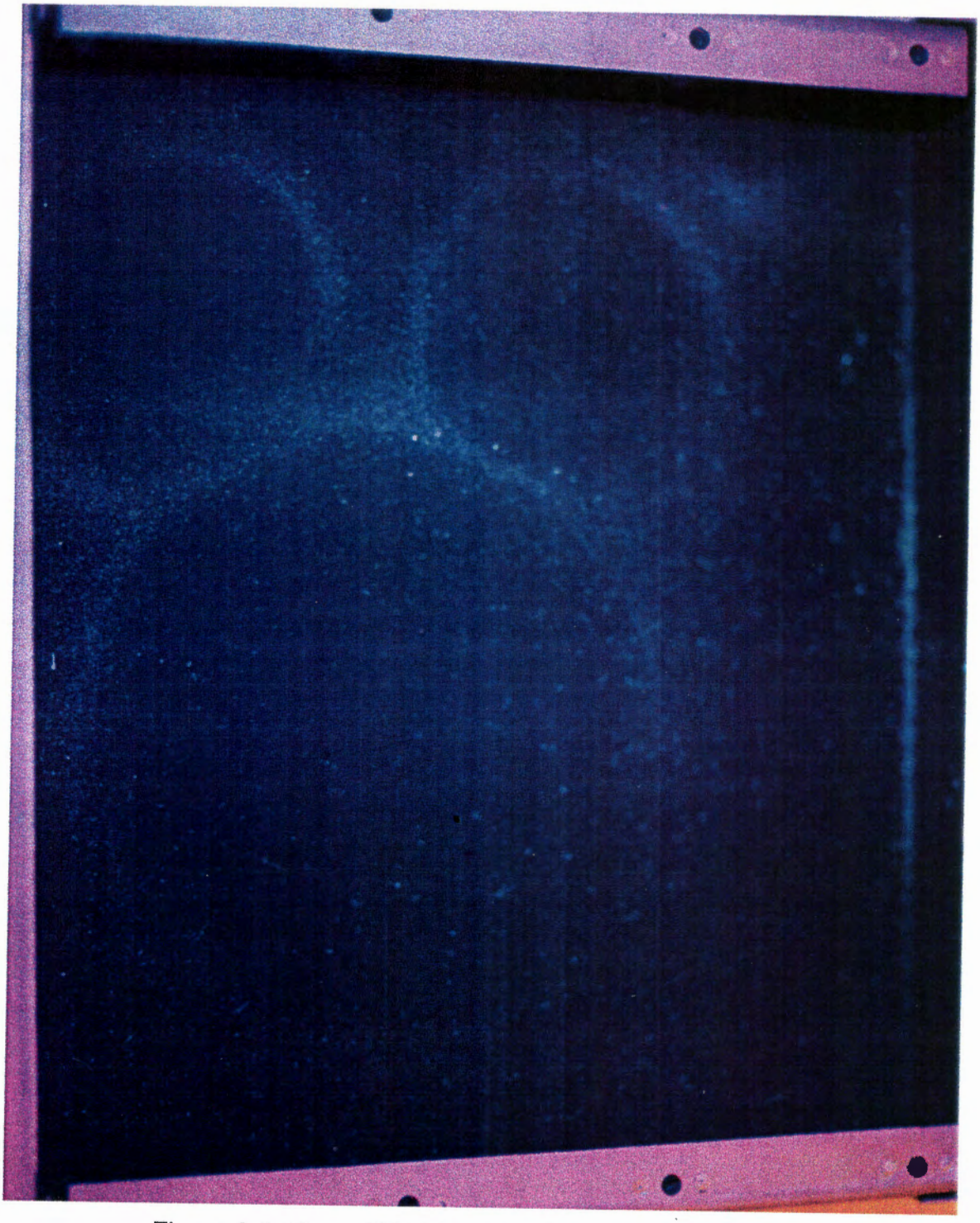


Figure 3.3-10 - LTCM Cover Debris under Black Light

Figure 3.3-11 - SEM image of LTCM Metallic Debris (~1mm Size)

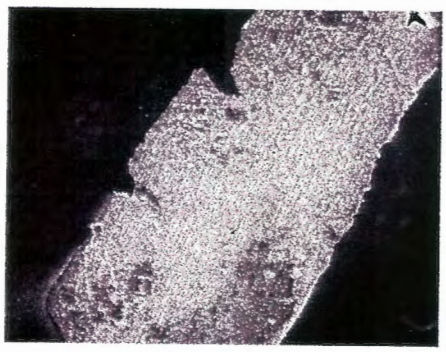


Figure 3.3-12 - SEM image of LTCM Metallic Debris (~1mm Size)

and a silver coated copper wire were also found. There was an expected buildup of white Nomex fiber residue in the root of all of the pulleys.

The encoder and tensiometer were re-calibrated to confirm their proper operation during the flight.

- The physical evidence clearly indicates that the arc began as the damaged FEP portion of the tether entered into the first idler pulley and pulley guard. This evidence is collaborated by the flight data (reference Section 3.6) which indicated that the failed end of the tether was within the LTCM when the arcing first occurred.

- The flight data indicated that the arcing extinguished as the tether entered the guide tube and started again just prior to exiting the tube. This data is consistent with the erosion of the aluminum guide tube only at its entrance and exit.

- Based on the initiation of the arcing in the LTCM, and the negative findings of MMOD damage the MLI, MMOD damage to the tether was eliminated as a cause of the failure.

- Numerous metallic particles were found within the LTCM housing. In a zero-g environment, these particles would float and be attracted toward the tether or the Vespel pulleys by electrostatic forces. It is possible that a metallic particle could be forced into the tether and breach the FEP insulation by getting captured between the pulley and the tether.

3.3.3 Tether Cutters

Background/Pre-Mission Certification

The deployer system has two tether cutters. One, the Lower Tether Cutter (LTC) assembly is mounted at the bottom of the SSA near the bottom of the boom canister. The assembly consists of a Vespel pulley, two ceramic guards, an aluminum mounting bracket and the LTC. The LTC is a small aluminum housing through which the tether passes. The LTC contains a cutter blade which is restrained by a shear pin until it is pyrotechnically actuated. The second tether cutter, which is of the same construction as the LTC, is located at the top of the boom inside the UTCM.

Prior to flight, the tether cutters were tested by conducting a resistance check on the pyrotechnic circuit to confirm that the NASA Standard Initiators (NSI) were in a nominal condition.

Post-Flight Inspection

Telemetry indicated that neither tether cutter was activated, or operated during the mission. Post flight examination of these cutters also indicated that neither had operated. Therefore, inadvertent operation of the tether cutters was ruled out as a possible cause. Both tether cutters were also examined for sharp edges and cutters not fully recessed. The cutters themselves were in the proper configuration and would not have introduced sharp edges into the tether path.

Neither the upper or lower tether cutter pyrotechnics were fired, nor did either tether cutter provide sharp edges protruding into the tether path.

3.3.4 Deployer Boom

Background/Pre-Mission Certification

Prior to TSS-1, the twelve meter deployer boom was subjected to strength, vibration, and thermal testing. The Engineering Development Unit was also subjected to life cycle testing. The boom was operated on the first mission and performed satisfactorily. To prepare the boom for the TSS-1R mission, the boom was returned to the manufacturer for refurbishment (reference. Section 1.3). After refurbishment, the boom and UTCM were subjected to a thermal test and vibration test. The boom can not be deployed in a one-g environment without special GSE, therefore, functional testing of the boom occurred at the manufacturer prior to re-integration into the TSS hardware. A strength test was performed on the boom flexible battens and the results were satisfactory. The boom was considered qualified for TSS-1R.

Post-Flight Inspection

After the TSS-1R mission, the boom was de-integrated from the hardware at Kennedy Space Center's Operations and Checkout building and shipped to its manufacturer. The tip can, located at the top of the boom, was de-integrated from the boom and shipped to MSFC.

At the manufacturer, the boom was inspected and deployed. Periodically the deployment was halted for detailed inspections. A listing of the findings are as follows:

- Three scratches, approximately 4 to 5 cm long, were found inside the Vespel bushing at the bottom of the boom.

- Metallic slivers were found on the end of the pivot screws for the cable diagonals. These slivers appeared to be the result of the pivot screw pushing the metal shavings generated during the initial machining, from the receiving through-hole in the longeron fitting.

- Debris was found on a fiberglass batten (bay 22). The debris appeared to have been imbedded in the epoxy coating during manufacture.

- Particulate was observed at several locations on the boom. The particulate was collected for analysis.

- Strength tests were performed on the flexible battens. The batten strength had degraded by approximately three pounds but this was expected and still within a nominal value.

- Electrical continuity measurements were also made. No unexpected findings were identified.

There was no evidence of arcing on any of the boom's components.

At the top of the boom rests the salad bowl. The bowl was observed to have a yellow discoloration on one quadrant near the tether exit bugle where the tether passed closest to the salad bowl. Attempts to identify the constituents of the due to the small amount of material deposited. The board concluded that this was probably due to outgassing of the failed end of the tether as it exited the boom.

- The 12 m deployer boom operated normally during the mission and did not contribute to the tether failure.

- The boom had attached metallic debris behind some screw holes.

- Metallic slivers contributed to a contaminated environment.

3.3.5 UTCM

Background/Pre-Mission Certification

For TSS-1R, several modifications were performed on the UTCM to rectify the tether jam anomaly experienced on TSS-1 (reference. Section 1.3). The UTCM was re-certified by review of the TSS-1 UTCM certification documentation and review of the TSS-1R UTCM refurbishment and modifications. The UTCM performed nominally during the deployment/retrieval tests (4S08 test).

Post-Flight Inspection

The UTCM, located inside the tip can at the top of the boom, was shipped with the boom to the boom manufacturer. The tip can was subsequently removed and shipped to MSFC. The electrostatic discharge resistors resistance were measured and found to be within specification. Since the arc and subsequent failure of the tether occurred prior to entering the UTCM, additional inspection and analysis of this mechanism was not considered necessary for purposes of this investigation.

All in-flight data indicated the UTCM performed satisfactorily during the TSS-1R Mission.

3.4 Mission Operations Summary

Immediately prior to the tether break, satellite deployment operations were proceeding nominally. On the ground, flight controllers and members of the science teams were monitoring their data displays to verify that the satellite and deployer systems were working properly. The crew members on board the orbiter were visually monitoring the tether and satellite's dynamic behavior. The deployment rate was slowly decreasing in preparation for stopping at the predetermined distance of 20.7 km. No actions were being taken, nor had any been executed which would have impacted the reel out process . The orbiter was performing normally. There were no satellite or orbiter reaction control jet firings, fuel cell purges, water dumps, flash evaporator operations or other types of venting operations in progress. Figure 3.4-1 illustrates the orbiter's attitude and summarizes the operational status of the orbiter and satellite at the time of the failure.

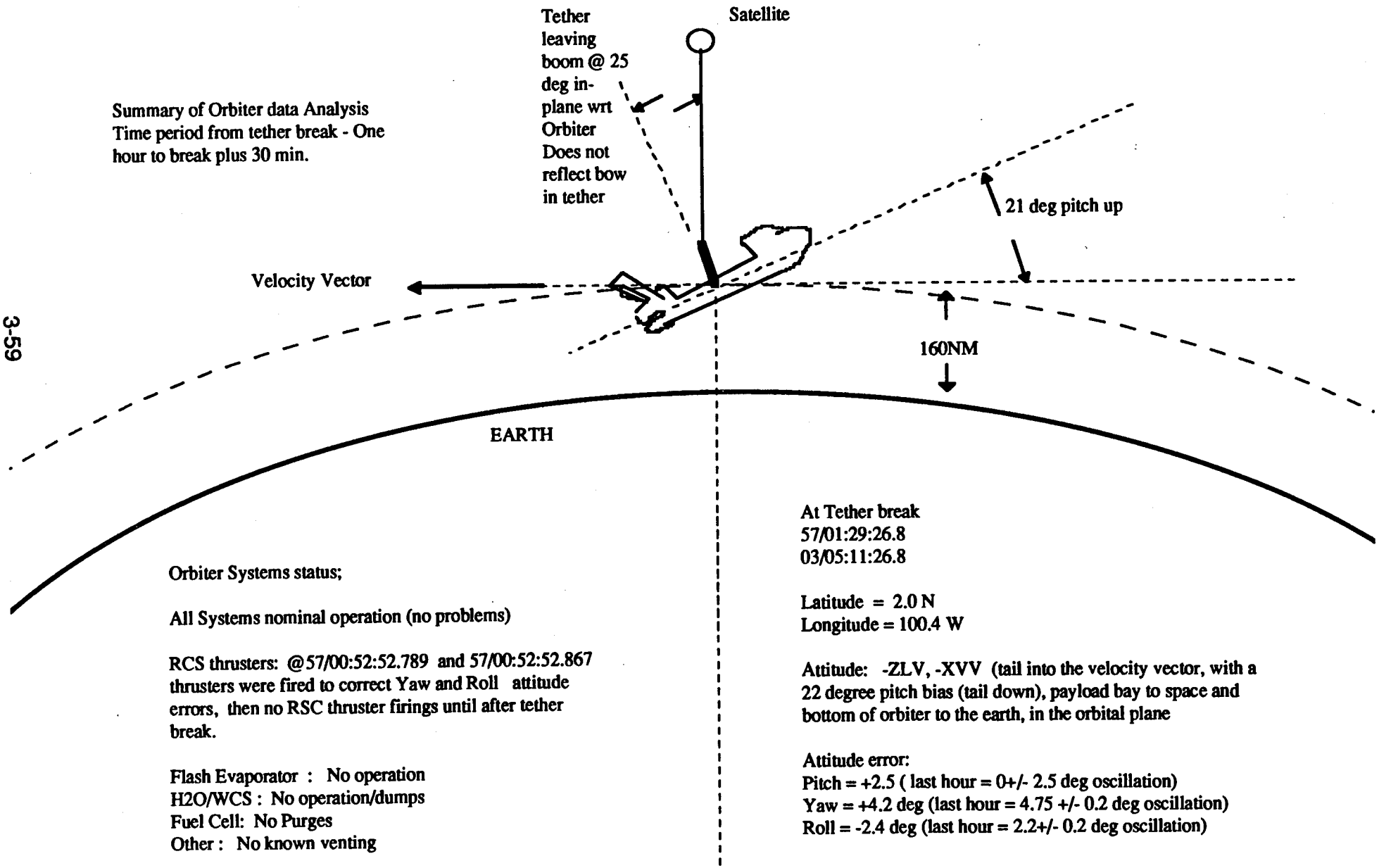
The broken tether was first noted by one of the orbiter crew visually monitoring the tether. The initial indication of a problem was a series of small ripples in the tether followed by larger tether motion corresponding to loss of tether tension. The tether failure was immediately verified on the ground and on-board the orbiter by telemetry data of satellite and deployer parameters. According to procedure, the crew members checked for problems at the deployer boom, and noticed the tether had failed at the orbiter end. Because of the location of the tether break, no immediate orbiter maneuvers or on-board actions were required.

Review of the telemetry data showed spurious voltage and current indications 9 s prior to the tether separation. These data showed that it was only 9 s from the first indication of spurious electrical activity to the time of the tether break. Considering the 6 s delay in telemetry data sent to the ground and the sampling rate of the crew's on-board data, there was insufficient time to see the data, evaluate it, and take action before the tether failure occurred.

The planned response to tether arcing was for the crew to connect the tether to orbiter ground through a shunt resistor, thereby reducing the voltage potential driving the arc. Since the measured tether voltage had already dropped to less than -200 VDC because of the arc, it is uncertain that this action would have prevented the tether break, even if the crew could have acted instantaneously when the arc occurred.

After the failure, the orbiter crew and ground team began the effort to make sure the orbiter was in a nominal condition, gather data for determining the cause of the break, reel-in the broken tether, and reconfigure the deployer system for entry. Numerous in-flight images of the failed tether end and deployer were taken to characterize the problem. Imagery collected on orbit provided the first indication that there had been burning or charring at the failed end. Comparison of the inflight images with inspection of the tether postflight confirmed that no damage was done to the failed tether during the reel-in process.

Summary of Orbiter data Analysis
Time period from tether break - One hour to break plus 30 min.



Orbiter Systems status;

All Systems nominal operation (no problems)

RCS thrusters: @57/00:52:52.789 and 57/00:52:52.867 thrusters were fired to correct Yaw and Roll attitude errors, then no RSC thruster firings until after tether break.

Flash Evaporator : No operation
H2O/WCS : No operation/dumps
Fuel Cell: No Purges
Other : No known venting

At Tether break
57/01:29:26.8
03/05:11:26.8

Latitude = 2.0 N
Longitude = 100.4 W

Attitude: -ZLV, -XVV (tail into the velocity vector, with a 22 degree pitch bias (tail down), payload bay to space and bottom of orbiter to the earth, in the orbital plane

Attitude error:
Pitch = +2.5 (last hour = 0+/- 2.5 deg oscillation)
Yaw = +4.2 deg (last hour = 4.75 +/- 0.2 deg oscillation)
Roll = -2.4 deg (last hour = 2.2+/- 0.2 deg oscillation)

Figure 3.4-1 — STS-75/TSS-1R Operations Summary

An Extra Vehicular Activity (EVA) to retrieve a sample of the broken tether was considered but not performed. This action may have accelerated post flight analysis, but would not have materially affected the investigation schedule, and would not have affected the outcome of the investigation.

Satellite weather photographs of the orbiter ground track taken within 30 minutes of the failure indicated that there was no cloud cover or thunderstorm activity in the immediate vicinity.

3.5 Science Operations

During the deployment phase the science operations were carried out according to the nominal science timeline loaded on the science computer on the orbiter.

The experiments data were monitored in real time by the Science Operation Center (SOC) at MSFC with a delay time of a few seconds.

The science timeline makes use of three TSS science electrical configurations. Two of these configurations allowed controlled current circulation in the tether (active mode), while the third is designed to have no current flowing in the tether (passive mode).

Each of these configurations is operated alone, with the other two disabled, but all the instruments on the satellite and the orbiter are operated in a coordinated and controlled way to characterize the system at both the satellite and the orbiter. The two active experiments, DCORE and SETS experiments, each have different tether current values, range/control, and circuit closure paths.

3.5.1 DCORE Mode

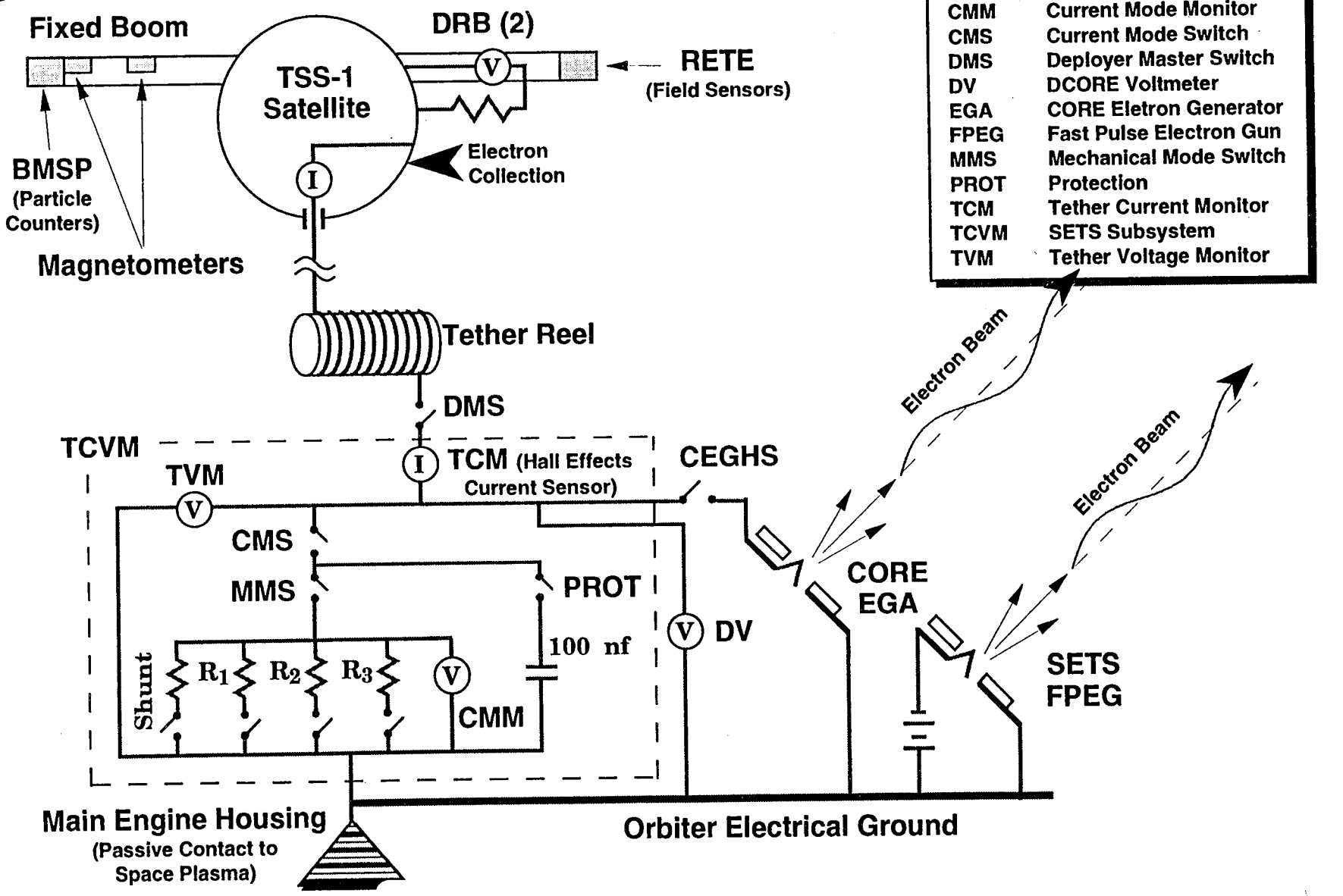
In this mode the configuration is described in Fig. 3.5-1. The DCORE experiment is operating while the SETS experiment is electrically disconnected from the tether via a series of high voltage switches.

The lower end of the tether is connected through the DMS and CEGHS switches to the cathode-filament of a diode, the Electron Generator Assembly (EGA), whose anode in connected to the orbiter ground. The electron current collected on the satellite skin flows in the tether and is re-emitted, as an electron beam, into the ionosphere by the EGA. The EGA uses part of the EMF produced across the TSS in its motion through the Earth's magnetic field to accelerate the electron beam. (Fig. 3.5-2)

The tether current value is limited and controlled by the EGA which has an internal feed-back current loop in the range of 10 m A to 750 m A.

Using the space plasma potential as the reference ground, the satellite potential value is expected to be positive while the orbiter potential is close to zero, because the orbiter is not in the tether current path, and therefore, no orbiter charging would take place.

TSS SCHEMATIC

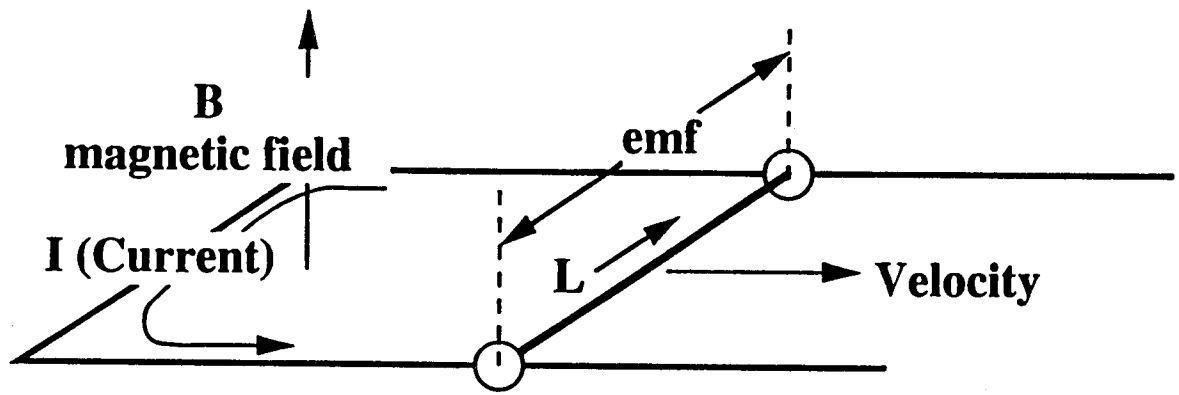


Acronyms Table	
CMM	Current Mode Monitor
CMS	Current Mode Switch
DMS	Deployer Master Switch
DV	DCORE Voltmeter
EGA	CORE Eletron Generator
FPEG	Fast Pulse Electron Gun
MMS	Mechanical Mode Switch
PROT	Protection
TCM	Tether Current Monitor
TCVM	SETS Subsystem
TVM	Tether Voltage Monitor

Figure 3.5-1 — TSS Schematic

TSS Electric Generator Analogy

1. The motional electro motive force (emf)



2. The Tethered Satellite System Generator

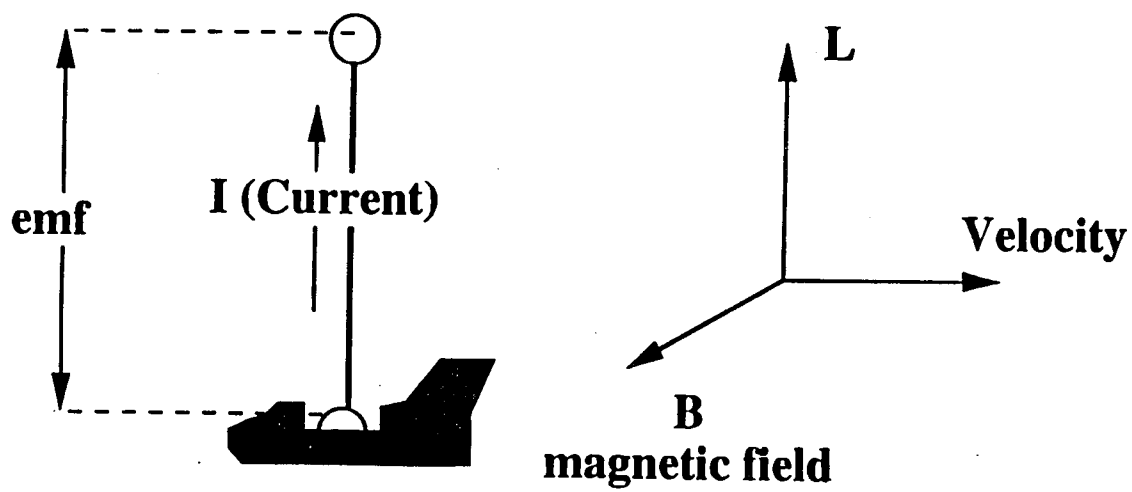


Figure 3.5-2 — TSS Electric Generator Analogy

3.5.2 SETS Mode

In this mode, described in Fig. 3.5-1, the SETS experiment is operating, while the DCORE experiment is electrically disconnected from the tether via the high voltage CEGHS switch.

The orbiter end of the tether is directly connected through the DMS, CMS, and MMS switches to orbiter ground through a resistor. The value of 25 Ohm (shunt), 25 k Ohm (R1), 250 k Ohm (R2), and 2.5 M Ohm (R3), is switched through a preprogrammed timed sequence.

The electron current collected on the satellite skin flows in the tether and is reemitted into the ionosphere by using the ion passive collection on the conductive area of the orbiter (engine bell). The expected satellite potential value is positive, while the orbiter is negative since it is electrically connected to the tether current path.

The sequence of resistor switching is repeated having the electron accelerator (FPEG) firing a 100 m A beam. While the DCORE requires the tether EMF voltage to operate, the FPEG has its own high voltage DC power supply of 1 kVDC. When the FPEG fires, the tether current increases. The tether current value is limited by the total resistance in series with the tether in the range of 1 m A up to 1.5 A

When the FPEG is firing, the orbiter potential is expected to become less negative, reaching a positive value when the tether current value is less than the FPEG beam current .

It was known that during the resistor switching, a voltage transient across the resistor/switch will be produced due to the inductance of the remaining tether wound on the reel.

3.5.3 Passive Mode

This mode described in Figure 3.5-1 makes use of both the DCORE and SETS experiment to electrically disconnect the orbiter end of the tether from the orbiter ground. No electrons are collected on the satellite, and no current is flowing in the tether.

Both satellite and orbiter expected potential values are very close to zero, and therefore, the orbiter end of the tether has a negative potential relative to orbiter ground, whose value equals the EMF voltage present at that time across the system.

3.5.4 Conclusions on Science Operations

a) DCORE Mode

During the DCORE operations no anomalies were detected by any of the instruments on the satellite and the orbiter .

Tether current values were measured according to the commanded sequences.

No induced voltage spikes were produced during the EGA firings due to the relatively long rise time (tens of ms) which allows the current in the inductor (the tether wound on the reel) to be changed relatively slowly.

No orbiter charging occurred during any of the EGA firings, indicating no beam impingement with the orbiter. The expected orbiter negative charging of 150 VDC was observed during one minute of EGA firing when the orbiter was at the equator crossing.

The cargo bay pressure was as expected, below 1×10^{-6} Torr all during the tether deployment, and approximately at 1×10^{-4} Torr during the initial part of deployment when both satellite in-line thrusters where on.

The Core Science Equipment hardware, and operations did not contribute to the tether failure.

b) SETS Mode

During the SETS operations no anomalies were detected by any of the instruments on the satellite and the orbiter, with the exception of the RETE experiment. This experiment automatically entered a reconfiguration mode due to an upset occurring during LOS approximately 1 hour prior to the tether break. This disabled the operation of its AC electric field measurements but the AC measurements operated nominally after being reset by a power cycle after the tether break.

A post flight analysis on a representative data set of the switching voltage transients produced by the SETS operation indicates that no voltage transients above 4.4 kVDC occurred during TSS-1R due to the relay switching, well below the rated tether stand-off voltage of 10 kVDC.

The SETS experiment hardware, and operations did not contribute to the tether failure.

c) Passive mode

During the passive operations no anomalies were detected by any of the instruments on the satellite and the orbiter until the tether separated.

The tether failure occurred after the system had been in the passive mode for approximately three minutes.

3.5.5 Summary of Science Operations

The science timeline being executed up to the time of the break was nominal and could not have initiated the tether failure because more than three minutes prior the break, the system had been commanded into passive mode where no electron guns were powered on. The tether circuit was open, and no current was being commanded in the tether. No further changes to the system were executed until after the break had occurred.

The satellite and the experiments on board were operating nominally also after the tether break. The satellite science data that was telemeter to the orbiter, has provided key information to the Board, on the circumstances just prior to, during, and just after the tether break. This data has been crucial to the Board in understanding what happened.

The operations immediately preceding the break consisted of the first five steps of an IV24 FO (see Fig. 3.5-3). This FO steps rapidly through a range of the currents in order to establish the satellite current-voltage characteristic. In steps 1 and 4, the tether current is controlled by the DCORE mode. In steps 2 and 5, current is limited by SETS mode, and steps 3 and 6 are passive mode with no current flow. As an example the DCORE nominal operation during the last IV24 FO prior to the tether break is shown in Figure 3.5-4 and 3.5-5. The Satellite current-voltage characteristics during step 1 and 4 are reported along with the electron density and temperature. The satellite potential was computed by using the TSS circuit equation and the current and voltage measurements provided by the DCORE experiment.

The measured values (solid circles) are compared with the expected value by the Parker and Murphy (PM) model (open squares). The results indicate that the satellite commanded current values have been obtained with a corresponding satellite potential less than the expected theoretical values by a factor of about ten. The satellite voltage quoted in parenthesis in each plot is the computed value required by the PM model

IV-24 Operating Cycle

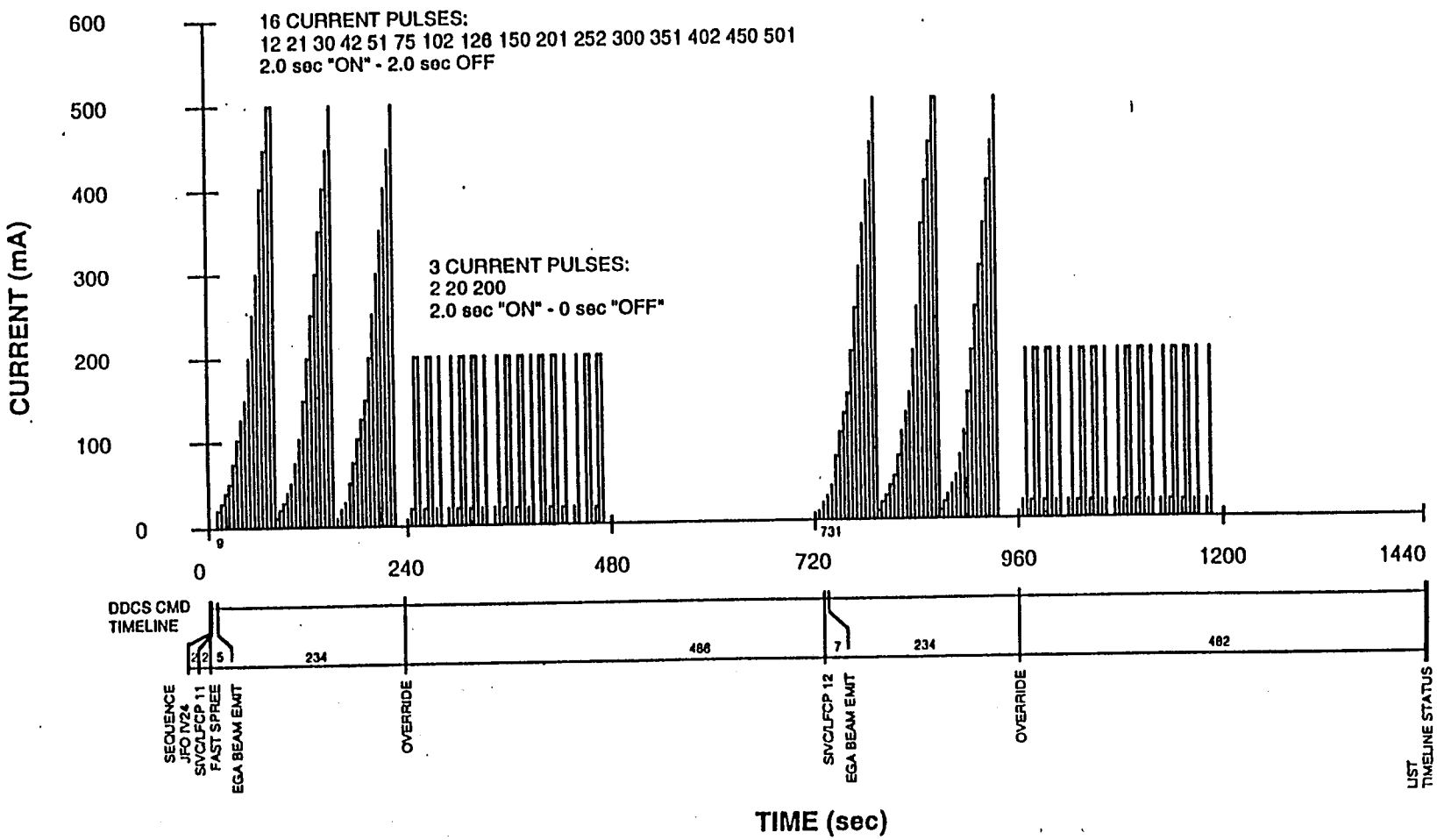


Figure 3.5-3 — IV-24 Operating Cycle

TSS 1R Electrodynamics

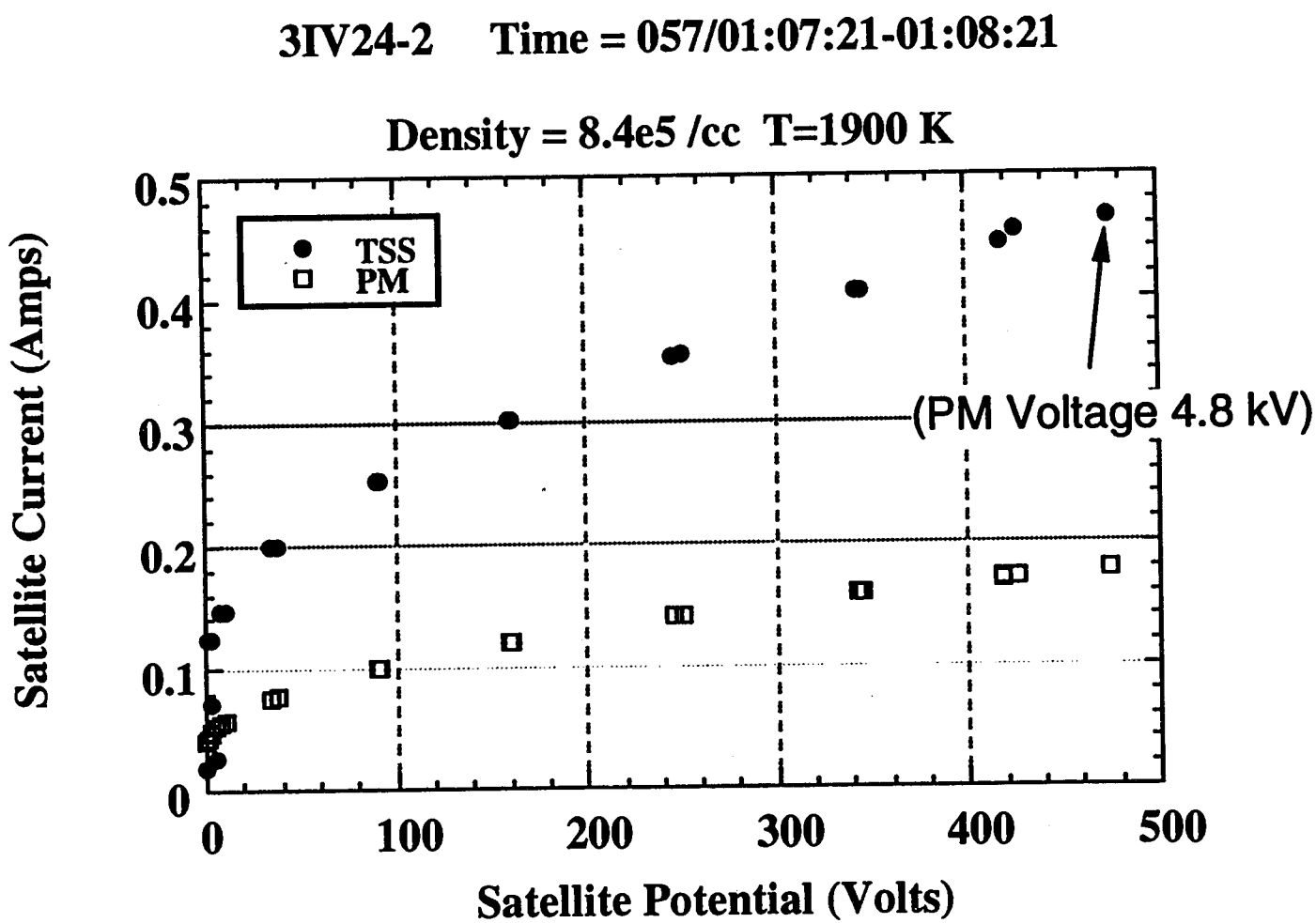


Figure 3.5-4 — TSS-1R Electrodynamics

TSS 1R Electrodynamics

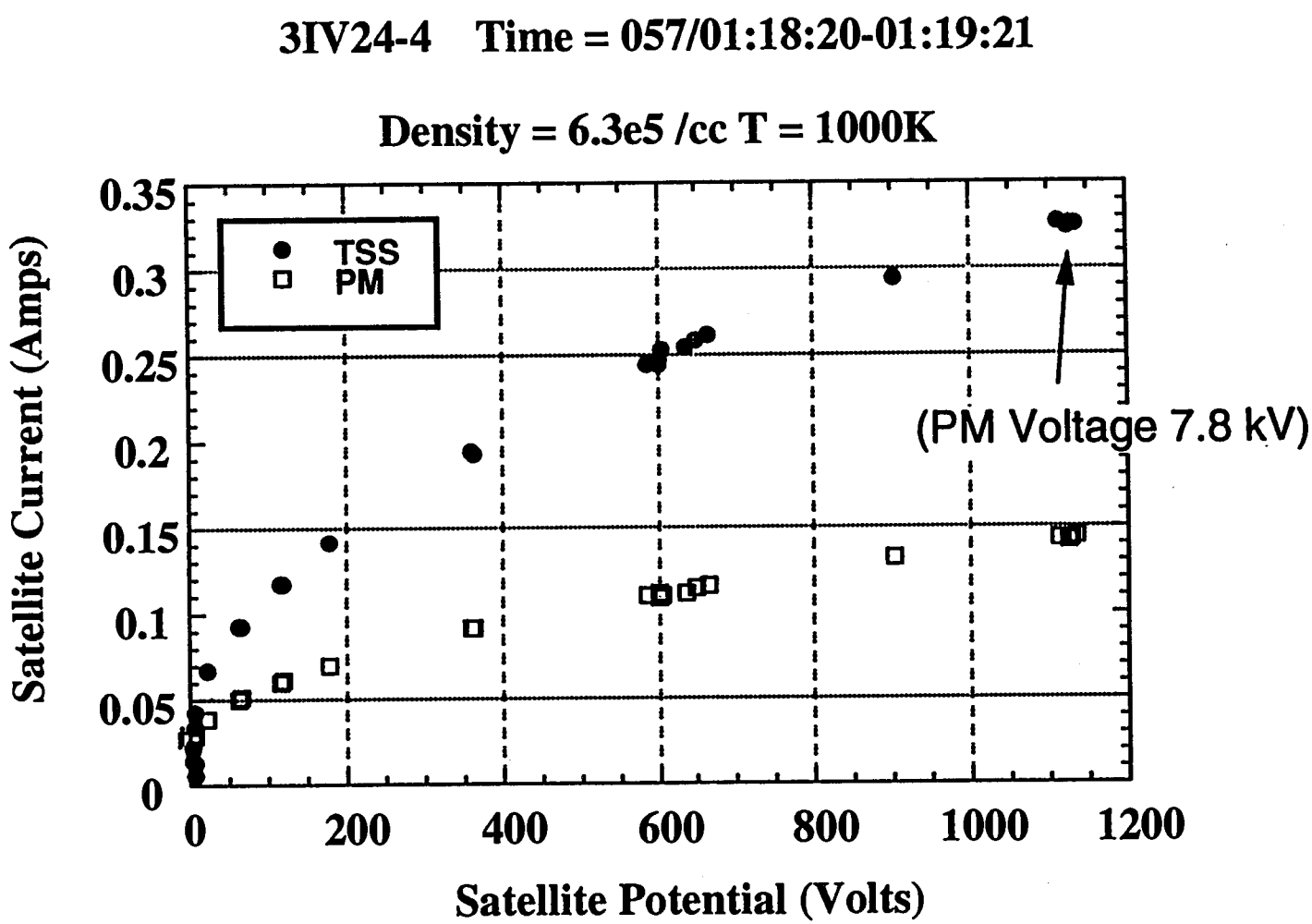


Figure 3.5-5 — TSS-1R Electrodynamics

TSS-1R TETHER MEASURED CURRENT and VOLTAGE

maximum current:	580 m A	for a few seconds
	480 m A	for 4 minutes continuously
maximum voltage:	3500 V	(EMF)
	4400 V	(EMF+ overvoltage due to SETS operations).

The Satellite hardware, the satellite experiments and their operations did not contribute to the tether failure

3.6 Timeline of Key Events

The following sequence of events was put together to establish the time relationship of key events surrounding the tether failure. The figures are excerpts from a continuous video timeline originally created at the MSFC. The timing of events is based on the fact that the tether started arcing at the first pulley in the LTCM. Aligning this event with the first spurious current flow establishes the time-location relationship of the failed spot on the tether. A detailed timeline of other events is contained in Appendix B.

The following notes apply to each of the figures:

- "GMT" and "Distance to break" relate to the point where plotting stopped, i.e., right hand side of page. So the upper figure shows the location of the tether when the plot ends on the right hand side of the page.

- Distance along tether path is a linear scale. The distance that the spot on the tether travels around each pulley has been "straightened out" to convert it to a linear distance.

- The sample rate of the current is 16 Hz and had a 2 Hz filter applied to it at the experiment (from satellite SCORE). It is a linear scale.

- The sample rate of Voltage is 196 Hz (from SETS) . It is a log scale, which means that at lower magnitudes, the variations are exaggerated.

- The sample rate of the tension is 8 Hz (from Deployer). It is a linear scale, and essentially is constant during the entire arcing sequence, up to the time of the break.

- The individual pulleys, guide tubes, and other in-line mechanisms are scaled to represent their relationship with each other.

Note that the science experiments were in the passive mode, with no commanded current flow. The voltage on the lower end of the tether was at -3500 VDC with respect to orbiter ground.

Figure 3.6-1: As the damaged point of the tether entered the LTCM and contacted the first pulley, at 57/01:29:16.9, the tether voltage decreased in magnitude from -3500 VDC to approximately -200 VDC and the current increased from 0.0 A to approximately 0.8 A as the initial arc began.

The voltage varied sharply as the damaged point on the tether proceeded through the LTCM. When the damaged tether point exited the first pulley, the voltage increases in magnitude slightly to approximately -300 VDC. However, the tether current continued to increase to the value of approximately 1 A.

At 57/01:29:17.1, as the damaged tether point contacted the LTCM encoder wheel, the tether voltage decreased to approximately -200 VDC and remained steady while the satellite current remained steady at 1 A.

At 57/01:29:17.4, the damaged tether point exited the LTCM encoder. The tether voltage oscillated between -200 VDC and -50 VDC while the satellite current remained at 1 A.

At 57/01:29:17.5, the damaged tether point contacted the second "idler" pulley in the LTCM. The current was steady at 1 A, the voltage was erratic at approximately -100 VDC to -40 VDC. As the damaged tether point left this pulley, the voltage recovered to approximately -200 VDC.

At 57/01:29:17.6, the damaged there point contacted the last direction change pulley in the LTCM. The current remained steady while the voltage decreased to approximately -40 VDC as the damaged tether point left the pulley at 57/01:20:17.7.

At 57/01:29:17.8, the damaged tether point entered the exit guide tube of the LTCM. At this time, the satellite current decreased to approximately 0 A and the satellite voltage recovered to -3500 VDC.

Figure 3.6-2: At 57/01:29:17.9, the damaged tether point leaves the LTCM exit guide tube. The current remains steady at 0 A and the voltage at -3500 VDC.

After the damaged tether point exited the LTCM guide tube, the voltage and current remained steady at -3500 VDC and 0 A, except for one voltage spike at approximately 57/01:29:18.3 and a slight associated current increase, however, the voltage recovered to -3500 VDC.

At 57/01:29:18.6, the damaged tether point entered the turnaround pulley (TAR). The satellite current was increasing from the 0 A level to approximately 0.6 A and the voltage decreased to approximately -50 VDC to -200 VDC while in contact with the TAR.

At 57/01:29:18.6, just after the damaged tether point exited the TAR, the boom base was entered. There were two recoveries of the satellite voltage in a very short period of time with a slight recovery of the current as well. Just after the damaged there point entered the boom can base, the satellite voltage and current decreased to -3500 VDC and 0 A, respectively.

Figure 3.6-3 and 3.6-4: At 57/01:29:19.5, the damaged tether point entered the snocone. The voltage decreased in magnitude from -3500 VDC to approximately -300 VDC with a short recovery to -3000 VDC. The current increased to 1.0 A and stayed steady. While the damaged tether point was in the snocone (part of the housing structure for the 12 m deployer boom assembly), there were at least five spikes and recoveries of the voltage before it dropped to -100 VDC and remained steady. This was while the damaged tether point was passing the U1 connector. At 57/01:29:20, the battery heater current

measurement indicated a current spike, responding to the spurious voltage/current situation. The U1 connector was open.

Figure 3.6-5: At 57/01:29:20.4, the damaged tether point exited the snocone, and the current remained steady at 1 A. The voltage remained at approximately -100 VDC, except for five or more spikes/recoveries until the damaged tether point exited the SSA and entered the boom.

Figure 3.6-6: The current remained at approximately 1 A after the damaged tether reached the space plasma and entered the 12 m open boom assembly. The arcing burned away sufficient Kevlar, that the normal tension load of 65 N was enough to fail the tether. The tether separation is indicated by the drop in tension .

This sequence of events indicates that numerous arcing paths existed for the current to flow from the tether conductor directly to orbiter ground, until it entered the boom area. Then, the current discharge could be to the boom, or to the space plasma itself.

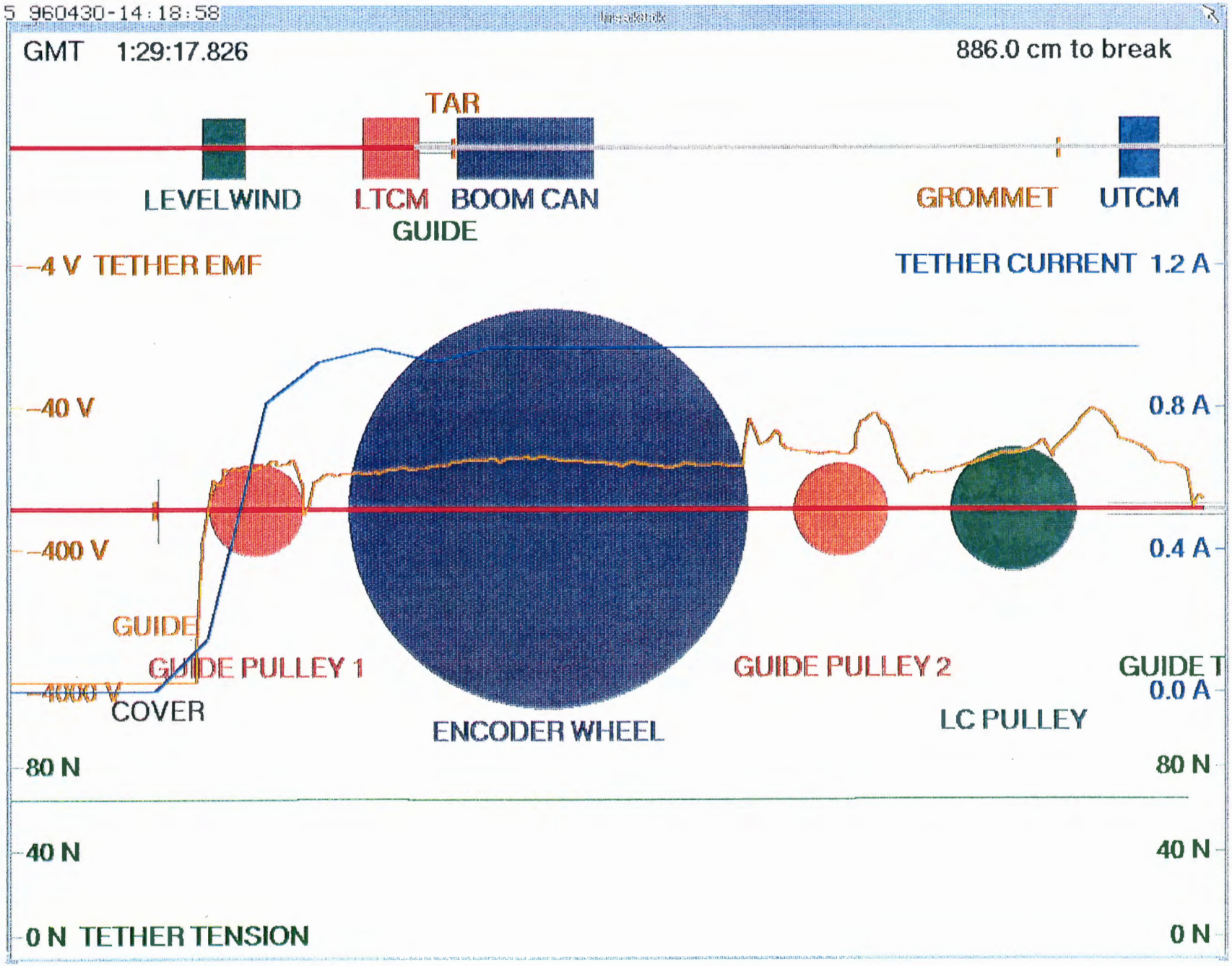
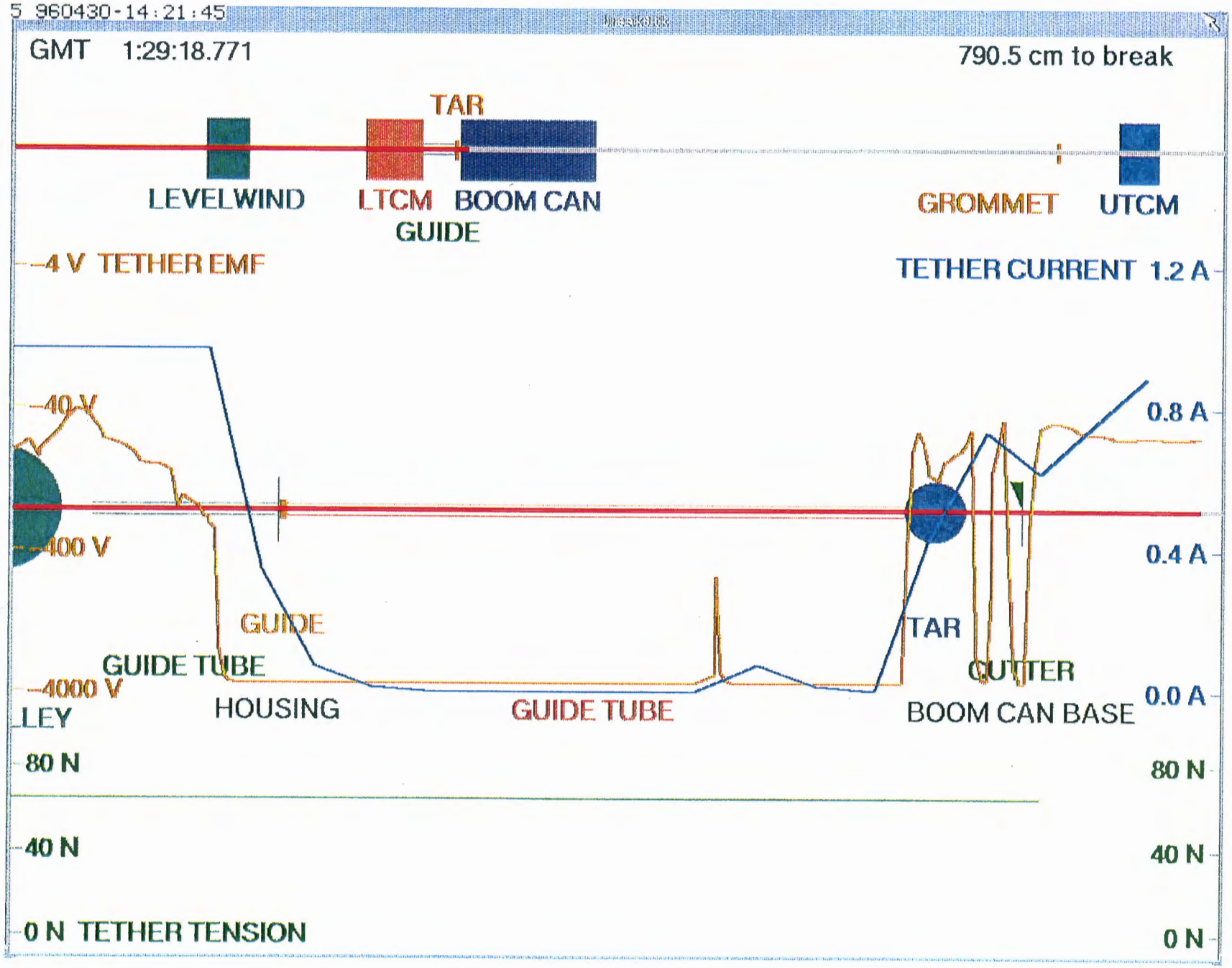

5 960430-14:18:58
GMT 1:29:17.826
886.0 cm to break
TAR
LEVELWIND
LTCM
BOOM CAN
GUIDE
GROMMET
UTCM
-4 V TETHER EMF
TETHER CURRENT 1.2 A
-40 V
0.8 A
-400 V
0.4 A
GUIDE
GUIDE PULLEY 1
GUIDE PULLEY 2
GUIDE T
0.0 A
-4000 V
COVER
ENCODER WHEEL
LC PULLEY
80 N
80 N
40 N
40 N
0 N TETHER TENSION
0 N

Figure 3.6-1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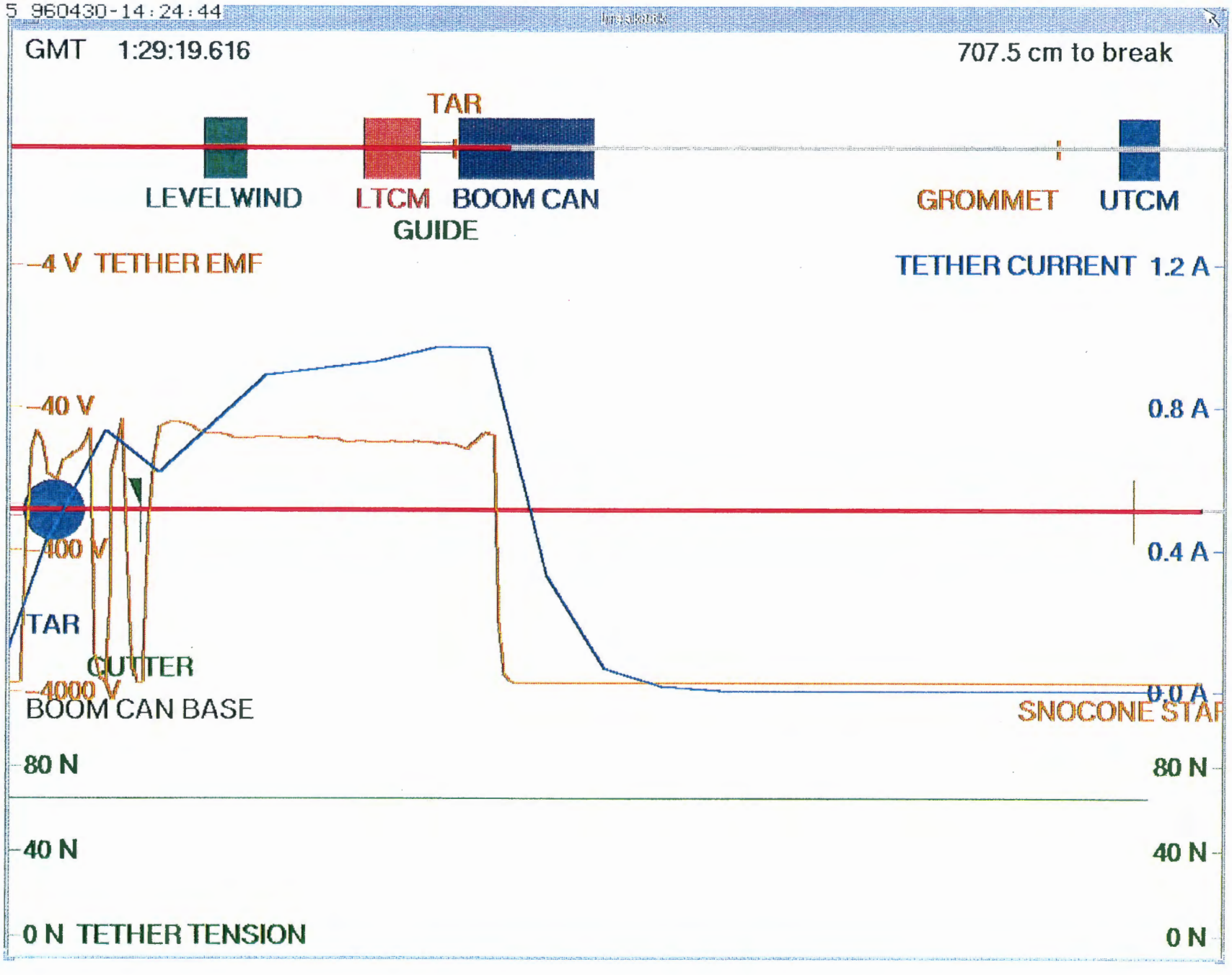
790.5 cm to break
TAR
LEVELWIND
LTCM
BOOM CAN
GUIDE
GROMMET
UTCM
-4 V TETHER EMF
TETHER CURRENT 1.2 A
-40 V
-400 V
-4000 V
LEY
GUIDE
GUIDE TUBE
HOUSING
GUIDE TUBE
TAR
GUTTER
BOOM CAN BASE
0.8 A
0.4 A
0.0 A
80 N
40 N
0 N TETHER TENSION
80 N
40 N
0 N

Figure 3.6-2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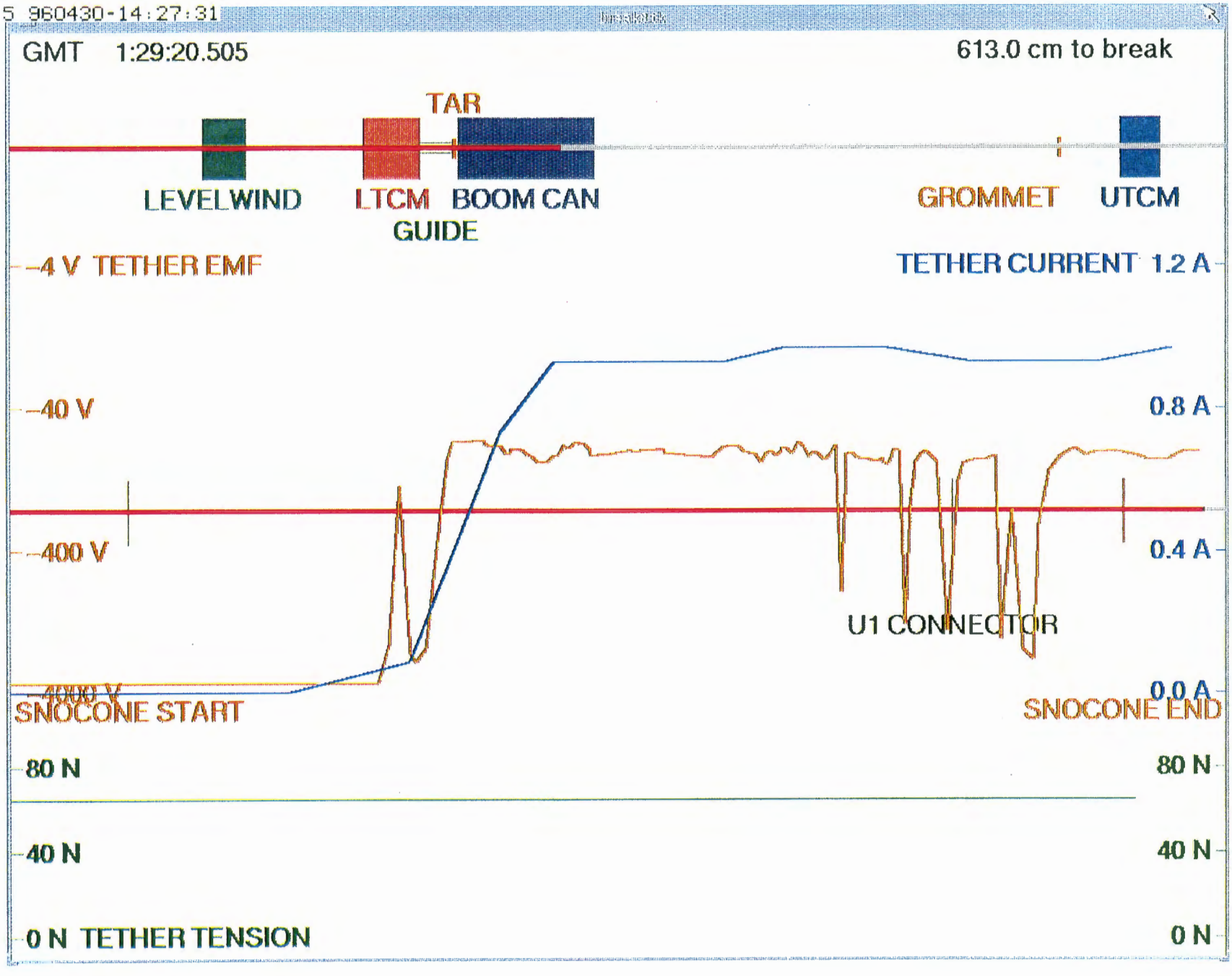
707.5 cm to break
TAR
LEVELWIND
LTCM
BOOM CAN
GUIDE
GROMMET
UTCM
-4 V TETHER EMF
TETHER CURRENT 1.2 A
-40 V
0.8 A
-400 V
0.4 A
TAR
CUTTER
-4000 V
0.0 A
BOOM CAN BASE
SNOCONE STAF
80 N
80 N
40 N
40 N
0 N TETHER TENSION
0 N

Figure 3.6-3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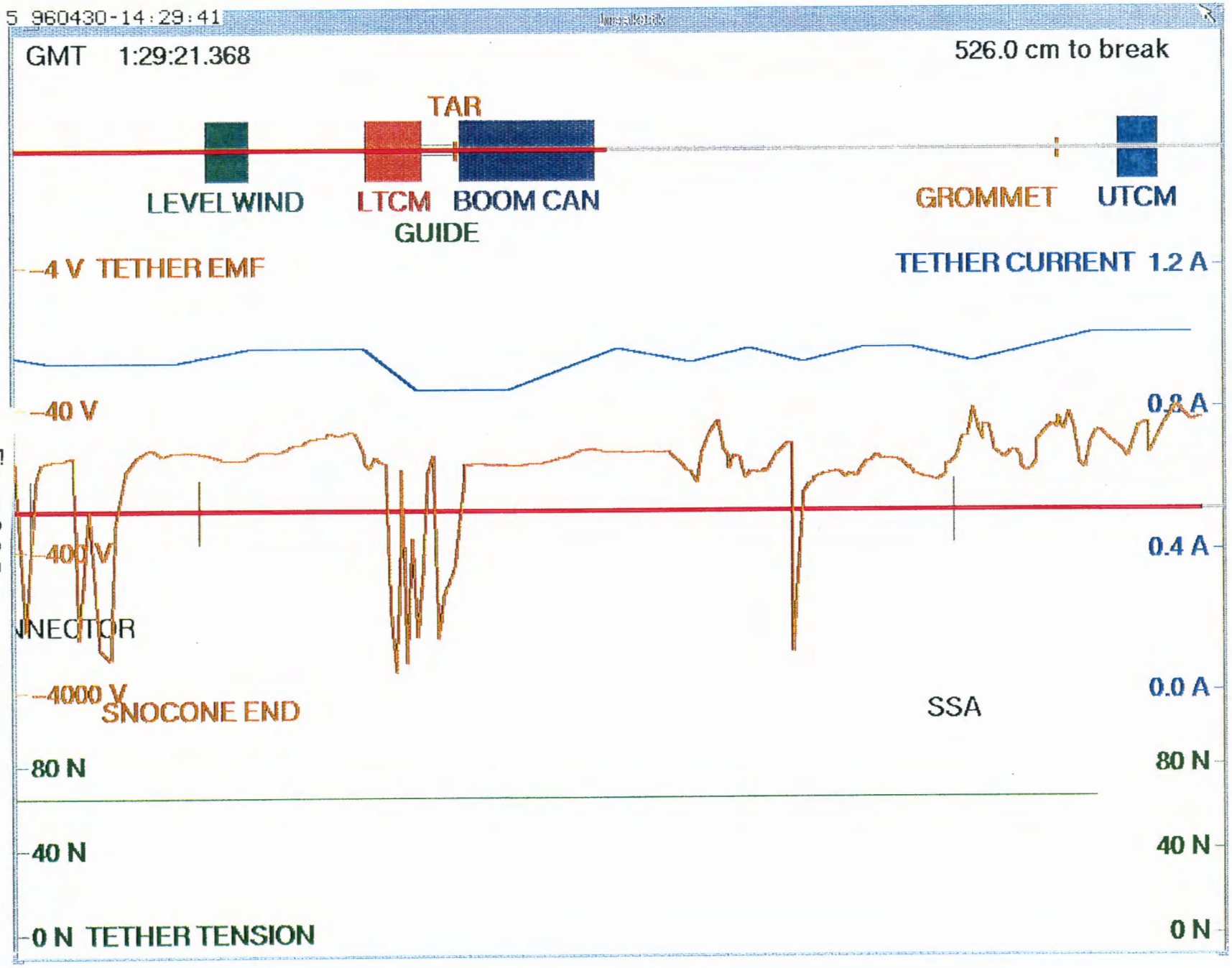
613.0 cm to break
TAR
LEVELWIND
LTCM
BOOM CAN
GUIDE
GROMMET
UTCM
-4 V TETHER EMF
TETHER CURRENT 1.2 A
-40 V
0.8 A
-400 V
0.4 A
U1 CONNECTOR
-4000 V
0.0 A
SNOCONE START
SNOCONE END
80 N
80 N
40 N
40 N
0 N TETHER TENSION
0 N

Figure 3.6-4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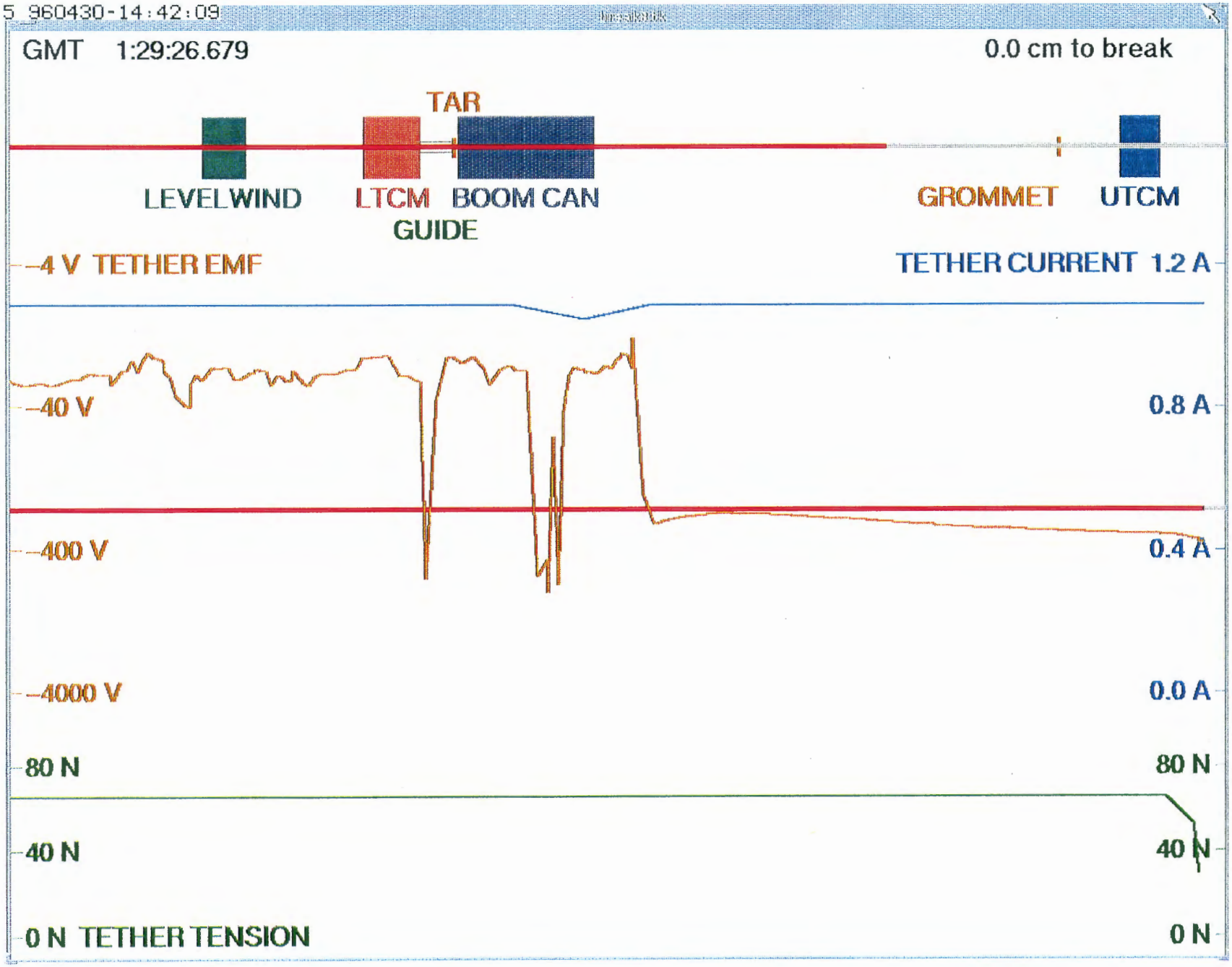
526.0 cm to break
TAR
LEVELWIND
LTCM
BOOM CAN
GUIDE
GROMMET
UTCM
-4 V TETHER EMF
TETHER CURRENT 1.2 A
-40 V
0.8 A
-400 V
0.4 A
INECTOR
-4000 V
SNOCONE END
0.0 A
SSA
80 N
80 N
40 N
40 N
0 N TETHER TENSION
0 N

Figure 3.6-5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0.0 cm to break
TAR
LEVELWIND
LTCM
BOOM CAN
GUIDE
GROMMET
UTCM
-4 V TETHER EMF
TETHER CURRENT 1.2 A
-40 V
0.8 A
-400 V
0.4 A
-4000 V
0.0 A
80 N
80 N
40 N
40 N
0 N TETHER TENSION
0 N

Figure 3.6-6

4.0 Causes, Findings, Recommendations, and Observations

4.1 Primary Causes

4.1.1 The tether failed in tension under nominal loads due to the degradation of the Kevlar strength member by arcing and burning.

Findings:

a) Most of the Kevlar (strength member) burned away during the arcing, and the remaining Kevlar failed in tension, separating the tether

The failed end displayed evidence of burning or charring as observed on orbit. The analysis of the failed end showed conclusively that a significant portion of the tether material had burned away, and that the final failure was a tensile failure of the few remaining Kevlar fibers. The load on the tether was at a nominal level, approximately 65 N.

b) Arcing and current discharge continued intermittently as the tether traversed through the deployer systems

Once the initial arc had occurred, products of combustion would have provided a rich charge carrier environment to sustain current flow within the LTCM. The arc continued intermittently for 9 seconds as this part of the tether traversed at 1 m/s through the remaining deployer mechanisms and into the 12 m deployer boom, where the space plasma provided the current path return. The tether failed within the 12 m deployer boom. The upper tether section was pulled through the UTCM, away from the orbiter at a speed of 3 m/s due to tether dynamics and the satellite movement away from the orbiter. The lower section of the tether remained within the boom, was reeled in and recovered after the flight.

c) The science experiments were in a passive mode, and did not contribute to the anomaly

The TSS science experiments were in the passive mode such that no current was being commanded, and the EMF level on the tether was -3500 VDC with respect to orbiter ground as expected, as a result of tether length and orbital location. The previous current command sequence had been completed approximately 4 minutes prior to the failure. The satellite and orbiter based experiments operated normally prior to, during, and for up to one hour after the tether failure. The satellite and orbiter based experiments provided telemetry data critical to identifying the cause of the failure.

4.1.2 External foreign object penetration, or a defect in the tether, caused a breach in the FEP insulation layer, resulting in arcing.

Findings:

a) Arcing started when the tether breach was in the LTCM where a favorable pressure environment and paths to orbiter ground existed

Inspection of the LTCM and correlation of current flow with the length of the tether remaining in the boom showed that the initial arcing of the tether conductor occurred between the entry pulley and the pulley guard in the LTCM. The tether potential was at the expected level of -3500 VDC. The Board estimated the internal pressure of the LTCM to be greater than

1×10^{-4} Torr, which provided a favorable pressure-distance relationship to support an arc from a breach in the FEP insulator. The "tunnel" environment between the pulley and pulley guard would have been at an even higher pressure, which would have enhanced arcing at this point. There are numerous ground planes (to orbiter ground) within the LTCM at distances from the tether to support an arc, based on pressure-distance relationships (Paschen's Law).

b) Forces in the reel were sufficient to cause penetration of an object through the FEP insulation

The Board found that the tether would be compressed significantly, deep in the reel by the winding of the tether on the reel under tension. The Board calculated this compressive force to be approximately 35 N/mm in the area where the part of the tether that failed was located within the reel. This force would last for several days after winding, and is sufficiently high to force either contamination within the tether, or debris in the windings, into the 0.3 mm insulator layer.

c) A significant amount of contamination was found in the returned flight tether

Metallic and non-metallic contamination was found within the FEP insulator layer of the flight tether, including the 9 m that had gone through the lower deployer mechanisms prior to the failure. Non-metallic and metallic contamination was also found between the Nomex and insulator layers of several samples of flight tether. EDS analysis revealed foreign material near the failed end.

d) Metallic and non-metallic debris was found in LTCM, reel housing, and the 12 m deployer boom.

In addition to the contamination found within the tether, debris was found in several locations within the deployer mechanism. Metallic debris, large enough to breach the FEP, was found in the LTCM, the boom assembly, and

the reel housing. In the LTCM, a small piece of very fine silver plated wire, aluminum shavings, and unidentified non-metallic debris was found. Small metallic shavings were found attached to the back of small screw holes in the deployer boom assembly.

e) Significant manufacturing problems occurred during fabrication of the tether

Manufacturing and inspection records show that the tether fabrication task was very difficult, and that numerous problems were encountered in the extrusion and braiding processes of this very long tether. The fabrication of the tether was carried out under normal manufacturing shop conditions which exposed it to foreign contamination.

f) It was not possible to cause an arc with an undamaged tether at design voltage levels

The tether was designed to a 15 kVDC breakdown specification, and was qualified to 10 kVDC on the conductor. A variety of laboratory tests were conducted during the investigation in an attempt to produce an arc from an undamaged tether with from -3 to -8 kVDC on the conductor. A section of grounded tether was also subjected to a 40 kVDC potential level. The tether did not break down in any of these tests. The Board concluded that an undamaged flight tether would meet all of its design specifications. The fact that more than 19 km of tether was successfully deployed, and that for the 45 minutes prior to the failure, the tether was carrying a potential of between -2500 VDC and -3500 VDC, underscores this fact.

4.2 Contributing Causes

The TSS project was the first attempt to develop a space-qualified, flight weight, integrated load bearing electrodynamic tether for deployments of tens of kilometers. The precise nature of the problems that were going to be seen in this experiment were not known.

The tether, itself, was an experimental system. It is quite easy to identify the weak link in the system after a failure. It is not as apparent where resources should be allocated in experimental flights before one fully understands the environment. For example, the dynamic response of the tether drew a significant amount of attention and resources before the TSS-1 and TSS-1R mission. Failure is one of the products of exploratory development.

The most important post-failure activity is gleaning all of the information from the failure to improve or otherwise modify processes to prevent similar failures from occurring in the future. The Board identified contributing causes to the tether failure as a backdrop to its recommendations for the future.

4.2.1 The degree of vulnerability of the tether insulation to damage was not fully appreciated

The design of the tether-deployer system depended almost solely on the ability of the tether to insulate the conductor high voltage from orbiter ground. With this approach, however, a single breach through the tether insulator would make the tether extremely vulnerable to arcing due to the conductive environment within the LTCM, leading to catastrophic failure of the tether.

Arcing was understood by the development engineering staff to be a serious threat to tether integrity. The requirements for fabrication and test processes were not always consistent with the vulnerability of the tether insulation, however. Post-flight inspection of the flight and qualification tethers revealed insulator and conductor damage that is indicative of both manufacturing defects and handling forces.

The manufacturing process was carried out under normal shop environment conditions, which exposed the tether to contamination. The manufacturing problems encountered were closely scrutinized by project staff, and corrective actions were taken for all known anomalous conditions.

The spark test and repair of one pinhole showed the flight tether insulator to be sound at the time of fabrication. However, the test was not repeated after subsequent manufacturing steps and several years of handling. A high voltage potential test was conducted prior to flight, but is considerably less sensitive than the spark test .

The environment that the tether saw in storage and in flight, which included foreign debris, partial pressure in enclosed areas, and high compressive forces within the reel, were all significant threats to insulator integrity. This environment was not identified in any risk assessment. The Failure Modes and Effects Analysis (FMEA) of the deployer system did not include the failure mode which actually occurred.

4.2.2 High Voltage Effects on the Insulator

Application of high voltage over long periods of time reduces the dielectric strength of an insulator. This effect is exacerbated if the insulation has voids or contamination. Given the findings of contamination within the tether, and the known presence of air gaps between the conductor and the FEP layer, a partial discharge, or glow discharge phenomena could have degraded a marginal area of the insulator, previously damaged or contaminated.

4.3 Major Areas Which Did Not Contribute to the Failure

Because of the many interrelated systems and factors associated with this mission, the Board decided to summarize the major factors exonerated as causative to the failure.

- Satellite Hardware and Operations
- Core Science Equipment and Operations
- Hardware and Operations of the Experiments
- Mission Operations (Ground and Flight)
- Induced Loads (static or dynamic)
- Pyrotechnic Tether Cutters
- Heating of the Tether During Commanded and Controlled Current Flow
- Design Changes Made to TSS-1
- Aging of the Components (shelf life)
- Micrometeoroid or Orbital Debris Collision
- Electrical Storm Activity

4.4 Recommendations

The following recommendations are applicable to reuse of the TSS-1R hardware, and to new electrodynamic tether systems developments as well. These recommendations do not apply to use of the TSS-1R deployer system for non-conducting tethers, for which the system appears to be satisfactory.

4.4.1 Manufacturing of the tether should be to rigid standards used for high voltage cables.

Standards and design approaches for high voltage cable in other industrial applications should be examined for applicability to electrodynamic tethers, in terms of conductor protection, insulator-to-conductor interfaces, contamination, and handling.

4.4.2 Ensure that the deployment path is free from debris

Foreign objects must be filtered or cleaned out of the path and operating environment for a high voltage tether. Besides the direct threat of penetration, foreign objects can distort local electric fields and increase the possibility of arcing.

4.4.3 Reduce the possibility of arcing during tether deployment.

The potential for arcing can be minimized by reducing the potential difference between the tether and orbiter ground (e.g. flowing tether current while the tether is deploying), and insulating areas which provide convenient arc termination points. Closed areas which would provide a favorable pressure-distance combination (Pashen's Law) for arcing could also be vented.

4.4.4 Conduct electrical integrity tests after final integration and as close as possible to flight.

Spark tests should be conducted as part of the final reeling procedure, and as close as possible to flight. Retest policies should be developed as part of the contingency plans for long delays in the mission. Care should be taken, however, to observe guidelines for multiple spark tests, to avoid weakening the insulation by repetitive high voltage testing.

4.4.5 Conduct high fidelity tests on critical subsystems to verify design or operating margins.

Because many high voltage effects are difficult to model in complex hardware applications, high fidelity tests should be conducted to assure the integrity of the design or actual hardware in flight-like conditions.

4.4.6 Strengthen the integrated systems development approach.

Because electrodynamic tether systems requirements, design, fabrication, test, and operations are so highly interdisciplinary in nature, it is crucial to establish an integrated team of specialists in the various disciplines that will be able to provide continuity throughout the development and operational process. This would ensure that critical design features and assumptions are not defeated by subsequent steps in the development process, and that the required testing is accomplished throughout the process to assure that the integrity of the overall system has been maintained throughout the entire developmental process.

The oversight of such complex systems is also a challenge. The practice of having a large number of reviews by generalists should be reduced in favor of more focused reviews by specialists. This should include the cross-review of the engineering products (design, FMEA, etc.), operations plans, and constraints by the science PI's; and the review of the science experiments by the systems engineers and operations team. This would enhance the understanding of potential threats to overall mission success.

In the quality surveillance of critical steps in system fabrication and test, the system specialists should provide oversight of process integrity.

4.5 Observations

The Board has included the following observations it concluded were significant:

4.5.1 The tether failure is not indicative of a fundamental problem in using electrodynamic tether systems.

The TSS hardware and science experiments comprised an advanced space research endeavor with many unknowns. The overall design of the tether and deployer mechanisms was based on a very demanding set of requirements for science data, weight, volume, safety, operational constraints, and flexibility. This was not a routine mission. The lessons learned in TSS-1R, along with the science data, have provided an enormous amount of new understanding of the environment and the real characteristics of electrodynamic tether operations in space. Aggressive and advanced experiments of this kind will occasionally experience failures.

4.5.2 A significant amount of science data was secured prior to, and after the tether separated.

The Board became aware of the significant data and discoveries made during the TSS-1R mission in the course of its meetings and deliberations. The operations and science planning teams should be commended for the science mission planning which secured data all during the deployment, thus acquiring invaluable data. The Board also noted the extreme amount of interest in the satellite data immediately following the tether failure. The current flow characteristics following the tether failure has also produced significant scientific data according to the science team.

4.5.3 The TSS science, engineering and support teams were highly competent, motivated, and committed to the experiment.

The Board also noted the close working relationship between the U.S. and Italian members of the project. The successful operation of a very complex experiment up to the point of tether failure, and the improvised operations after the tether failure is indicative of a high degree of teamwork and skill.

4.5.4 The load paths of the tether are complex

The internal load paths of the composite tether as a function of twisting, tension, and temperature are quite complex. For example, the Board noted that the tether was susceptible to kinking at low tension. In addition, the temperature gradients in the deployed tether also varied significantly during the mission. It may be of value to more accurately model the tether to be able to precisely define the operating envelope.

4.5.5 The length of time between manufacture and use of the deployer/tether increased its exposure to damage.

The long time that transpired between the deployer/ tether development and fabrication, and the actual flight missions increased the exposure of the deployer/tether to contamination and damage. It is also more difficult to maintain continuity of staff over several years. Shorter development-to-fly cycles may reduce the overall risk to the hardware and mission.

4.5.6 The tether configuration was affected by the winding loads on the reel.

The winding loads created by the multiple layers of tensioned tether onto the reel were large enough to permanently deform the tether cross-section from round to oval. This represented an uncontrolled configuration change which could adversely affect the tether's design margin.

4.5.7 There are data which could not be explained fully during the investigation.

The blue/black spots and streaking in the Kevlar was not fully explained. The Board suspects that this was due to a chemical reaction of the sizing material on the Nomex and/or the Kevlar. The extreme coiling action of the lowest tens of meters of the tether end that was closest to the orbiter after the separation was unusual. This coiling action did not seem to continue as significantly out toward the satellite. Both of these anomalies were post-failure.

4.5.8 Electrostatic charge build-up could be an issue on future missions

The Board noted that a static charge could build up quite readily on several deployer components due to tether motion. A high electrostatic charge could contribute to arcing. Even if the magnitude of the charge is not significant relative to the high voltage breakdown levels, static charge on pulleys and other mechanisms can attract debris into the tether path.

4.5.9 The documentation provided by the project to the Board was appropriate.

The quality of the documentation was consistent with the standards of space systems development and resulted in a strong contributing element to support the Board investigation activities.

5.0 Minority Reports

None

Appendix A:

Appointment Letters

C

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

Reply to Attn of: M

FEB 27 1996

TO: Dryden Flight Research Center
Attn: X/Director

FROM: M/Acting Associate Administrator for Space Flight

SUBJECT: Appointment Letter for STS-75 Tethered Satellite System Reflight (TSS-1R) Mission Failure Investigation Board

1. Purpose

This establishes the Mission Failure Investigation Board (hereafter referred to as the Board) for the STS-75 Tethered Satellite Reflight mission failure which occurred February 25, 1996.

2. Establishment

a. The Board is hereby established in accordance with NMI 8621.1F, "Mishap Reporting and Investigating," in the public interest to gather information, analyze, and determine the facts as well as the actual or probable cause(s) of the mission failure in terms of: (1) primary cause(s), (2) contributing cause(s), and (3) pertinent observations, and to recommend preventive and other appropriate actions to preclude recurrence of a similar mishap.

b. The Board is considered a "project-oriented technical team."

c. You, as Chairperson of the Board, will report to the Associate Administrator for Space Flight.

3. Authorities and Responsibilities

The Board will:

a. Obtain and analyze whatever evidence, facts, and opinions it considers relevant by relying upon reports of studies, findings, recommendations, and other actions by NASA officials and contractors or by conducting inquiries, hearings, tests, and other actions it deems appropriate. In so doing, it may take testimony and receive statements from witnesses.

b. Impound property, equipment, and records to the extent that it considers necessary.

c. Determine the actual or probable cause(s) of the mission failure and document and prioritize their findings in terms of: (1) the primary cause(s) of the mishap, (2) contributing cause(s), and (3) pertinent observations.

d. Develop recommendations for preventive and other appropriate actions.

e. Provide a final written report to the Associate Administrator for Space Flight within 75 days. The report should follow the format outlined in NMI 8621.1F, including a proposed Corrective Action Implementation Plan and a Lessons Learned Summary for further review.

4. Membership

The Chairperson, members of the Board, and supporting staff are designated in the enclosure.

5. Duration

The Board will be dismissed upon final approval of the report.

6. Cancellation

This appointment letter is automatically canceled one year from effective date of the publication unless otherwise specifically extended by the establishing authority.

Wilbur C. Trafton
Associate Administrator
for Space Flight (Acting)

Enclosure

ENCLOSURE

TSS-1R Mission Failure Investigation Board

Chair:	Kenneth J. Szalai	DFRC
Members:		
	J. Robert Lang	KSC
	Robert J. Schwinghamer	MSFC
	David Walker	JSC
	David W. Whittle	JSC
	William Schneider	JSC
	Paul M. Joyce	JSC
	John H. Stadler	LaRC
	Dr. Carlo Bonifazi	Italian Space Agency (ASI)
Consultants:		
	Harold F. Battaglia	JSC
	John W. Young	JSC
	Peter Banks	ERIM
Observers/Advisors:		
	Richard J. Howard	HQS
	Louis R. Durnya	MSFC/Legal
	Gerald H. Berg	MSFC/PAO
	Dr. Marino Dobrowolny	ASI
	Prof.Francesco Angrilli	Univ. of Padua
Ex-Officio:		
	Bill J. Comer	HQS
Executive Secretary:		
	Sandra Meske	DFRC

cc:

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AI/Gen. Dailey
AT/Mr. Mott
AE/Dr. Mulville
AO/Mr. West
AS/Dr. Cordova
B/Mr. Holz
E/Mr. Reese (Acting)
F/Gen. Armstrong
G/Mr. Frankle
H/Ms. Lee
I/Mr. Schumacher
J/Ms. Cooper
K/Mr. Thomas
L/Mr. Lawrence
O/Mr. Force
P/Mr. Boeder
Q/Mr. Gregory
R/Dr. Whitehead
S/Dr. Huntress
U/Dr. Holloway
W/Ms. Gross
X/Dr. Mansfield
Y/Dr. Kennel
Z/Mr. Ladwig

Directors, NASA Field Installations:

ARC/Dr. Henry McDonald
GSFC/Mr. Rothenberg
JSC/Mr. Abbey
KSC/Mr. Honeycutt
LaRC/Mr. Holloway
LeRC/Mr. Campbell
MSFC/Dr. Littles
SSC/Mr. Estess

Director, Jet Propulsion Laboratory:

Dr. Stone

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

Reply to Attn of: M

MAR 4 1996

TO: Dryden Flight Research Center
Attn: X/Director

FROM: M/Acting Associate Administrator for Space Flight

SUBJECT: Amendment to Appointment Letter for STS-75 Tethered Satellite System Reflight (TSS-1R) Mission Failure Investigation Board

This letter amends the subject Board appointment letter dated February 27, 1996, to appoint Mr. Robert D. White, Johnson Space Center, as a consultant to the Board in lieu of Mr. Harold Battaglia.

Wilbur C. Trafton

Enclosure

ENCLOSURE

TSS-1R Mission Failure Investigation Board

Chair:	Kenneth J. Szalai	DFRC
Members:		
	J. Robert Lang	KSC
	Robert J. Schwinghamer	MSFC
	David Walker	JSC
	David W. Whittle	JSC
	William Schneider	JSC
	Paul M. Joyce	JSC
	John H. Stadler	LaRC
	Dr. Carlo Bonifazi	Italian Space Agency (ASI)
Consultants:		
	Robert D. White	JSC
	John W. Young	JSC
	Peter Banks	ERIM
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	Louis R. Durnya	MSFC/Legal
	Gerald H. Berg	MSFC/PAO
	Dr. Marino Dobrowolny	ASI
	Prof.Francesco Angrilli	Univ. of Padua
Ex-Officio:		
	Bill J. Comer	HQS
Executive Secretary:		
	Sandra Meske	DFRC

cc:

Officials-in-Charge of Headquarters Offices:

A/Mr. Goldin
AI/Gen. Dailey
AT/Mr. Mott
AE/Dr. Mulville
AO/Mr. West
AS/Dr. Cordova
B/Mr. Holz
C/Mr. Christiansen
E/Mr. Reese (Acting)
F/Gen. Armstrong
G/Mr. Frankle
H/Ms. Lee
I/Mr. Schumacher
J/Ms. Cooper
K/Mr. Thomas
L/Mr. Lawrence
O/Mr. Force
P/Mr. Boeder
Q/Mr. Gregory
R/Dr. Whitehead
S/Dr. Huntress
U/Dr. Holloway
W/Ms. Gross
X/Dr. Mansfield
Y/Dr. Kennel
Z/Mr. Ladwig

Directors, NASA Field Installations:

ARC/Dr. McDonald
DFRC/Mr. Szalai
GSFC/Mr. Rothenberg
JSC/Mr. Abbey
KSC/Mr. Honeycutt
LaRC/Mr. Holloway
LeRC/Mr. Campbell
MSFC/Dr. Littles
SSC/Mr. Estess

Director, Jet Propulsion Laboratory:

Dr. Stone

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

Reply to Attn of: M

MAR 29 1996

TO: Dryden Flight Research Center
Attn: X/Director

FROM: M/Associate Administrator for Space Flight

SUBJECT: Amendment to Appointment Letter for STS-75 Tethered Satellite System Reflight (TSS-1R) Mission Failure Investigation Board

Mr. David Walker will leave NASA service April 12, 1996. I am hereby appointing Mr. Kenneth Bowersox, JSC, to replace him as a voting member of the TSS-1R Mission Failure Investigation Board effective April 13, 1996. Effective immediately, Mr. Bowersox is authorized to participate in Board activities to effect an orderly transition.

Wilbur C. Trafton

cc:
Q/Mr. Gregory
JSC/AA/Mr. Abbey
CB/Mr. Bowersox
Mr. Walker

National Aeronautics and
Space Administration
Dryden Flight Research Center
P.O. Box 273
Edwards, CA 93523-0273

MAY 0 9 1996

Reply to Attn of:
X

TO: M/Associate Administrator for Space Flight

FROM: DFRC/Director

SUBJECT: Request for 7 Day Extension on TSS-1R Report Submittal

The analysis and interpretation work of the TSS-1R Board has been completed. In our review yesterday (5/8), I realized that a proper review by all Board Members will require one more iteration. I therefore request an extension of 7 calendar days for the submittal of the Report to you. You would receive the report NLT 5/20/96.

Thank you,

Kenneth J. Szalai

cc:
Q/F. Gregory

National Aeronautics and
Space Administration
Dryden Flight Research Center
P.O. Box 273
Edwards, CA 93523-0273

Reply to Attn of: X

May 1, 1996

For: The Record

From: DFRC/Chairperson, TSS-1R Mission Failure Investigation Board

Subject: Record of Resignation from Board

Mr. J. Robert Lang, KSC, left NASA during the latter stages of the investigation to join a private company. He resigned his membership on the Board effective April 19, 1996. He contributed significantly to the Board's deliberations and to the deintegration planning for TSS-1R in support of the investigation.

Kenneth J. Szalai

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

Reply to Attn of: M

MAY 10 1996

TO: Dryden Flight Research Center
Attn: X/Director

FROM: M/Associate Administrator for Space Flight

SUBJECT: Request for a Seven-Day Extension on TSS-1R Report Submittal

In response to your request, subject as above, dated May 9, 1996, you are granted the additional seven days in whch to submit the TSS-1R report. I shall expect your input by May 20, 1996.

Wilbur C. Trafton

cc:
AT/Mr. Mott
Q/Mr. Gregory
QS/Mr. Comer
JSC/AA/Mr. Abbey

National Aeronautics and
Space Administration
Headquarters
Washington, DC 20546-0001

MAY - 8 1996

Reply to Attn of: M

TO: Dryden Flight Research Center
Attn: X/Director

FROM: M/Associate Administrator for Space Flight

SUBJECT: Change in Board Member Status

Per your request, Mr. Robert D. White is appointed as a Member of the TSS-1R Mission Failure Investigation Board, changing his status from Advisor. This is as a result of his role in the investigation and report.

Wilbur C. Trafton

cc:
Q/Mr. Gregory
QS/Mr. Comer
JSC/AA/Mr. Abbey

Appendix B:

Integrated Timeline

APPENDIX B

Integrated Timeline

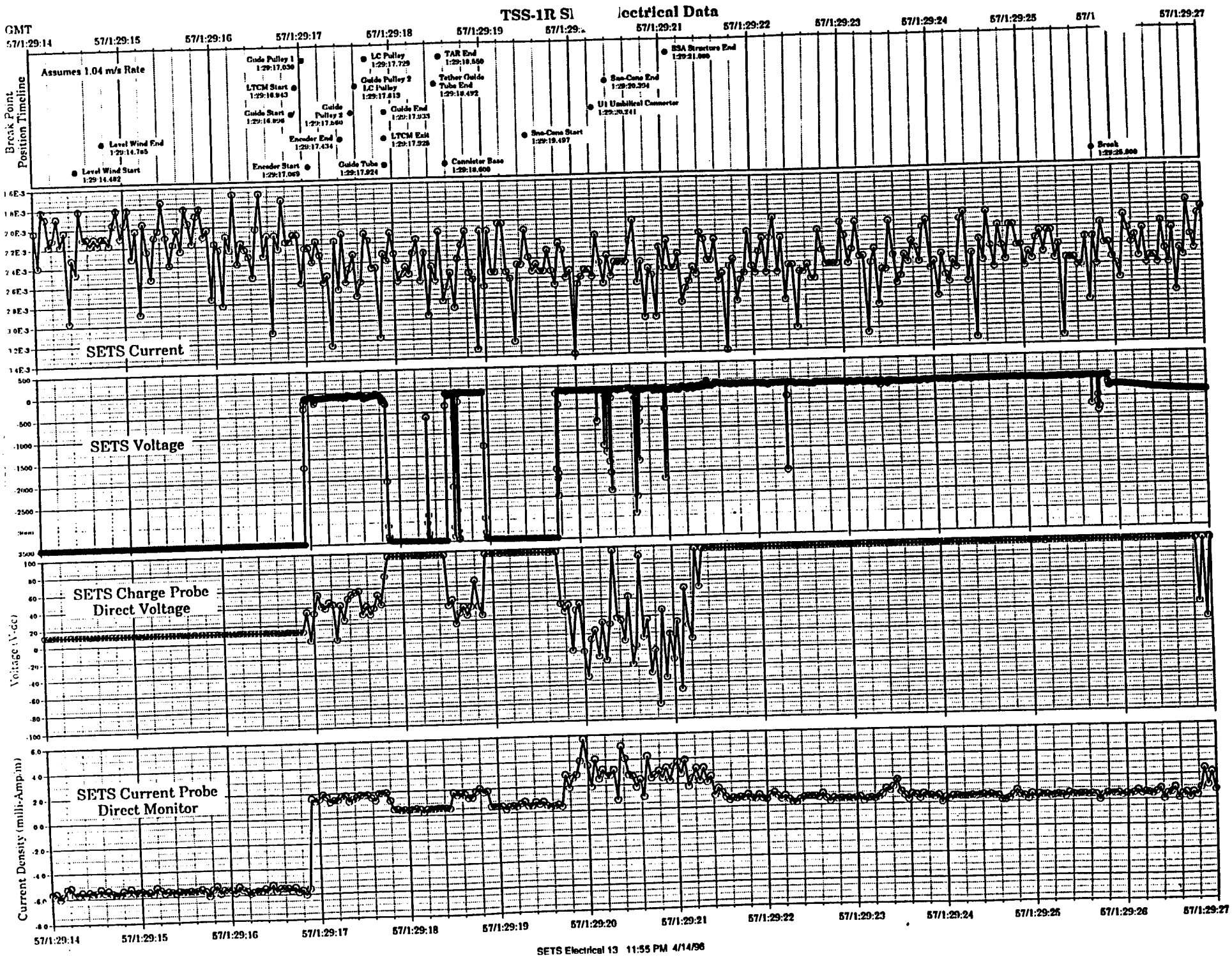
TIME(GMT)	EVENT
53/20:18	Launch
53/22:23	Carrier activation
53/23:09	SETS initial activation
54/07:28	SET FO1B
54/12:50	SPREE Check-out begin
54/12:55	DCORE Checkout Begin
54/17:08	Satellite Power on, and checkout in external power
54/17:43	Satellite Orbiter RF Link Test
54/18:12	Satellite experiments power on and checkout (TEMAG,ROPE,RETE,SCORE)
56/19:14:00	Satellite latches open
56/19:20:00	Satellite in internal power
56/19:46:00	U1 retraction
56/19:51:00	Deployer 12 meter boom deployment start
56/20:43:00	Satellite In-line Thrusters on
56/20:45:50	Satellite release
56/20:47:29	First tether current flow
56/20:48:00	Satellite in-line 1 off
56/21:27:00	SETS first FPEG beam firing
56/22:11	Satellite in-line 2 off

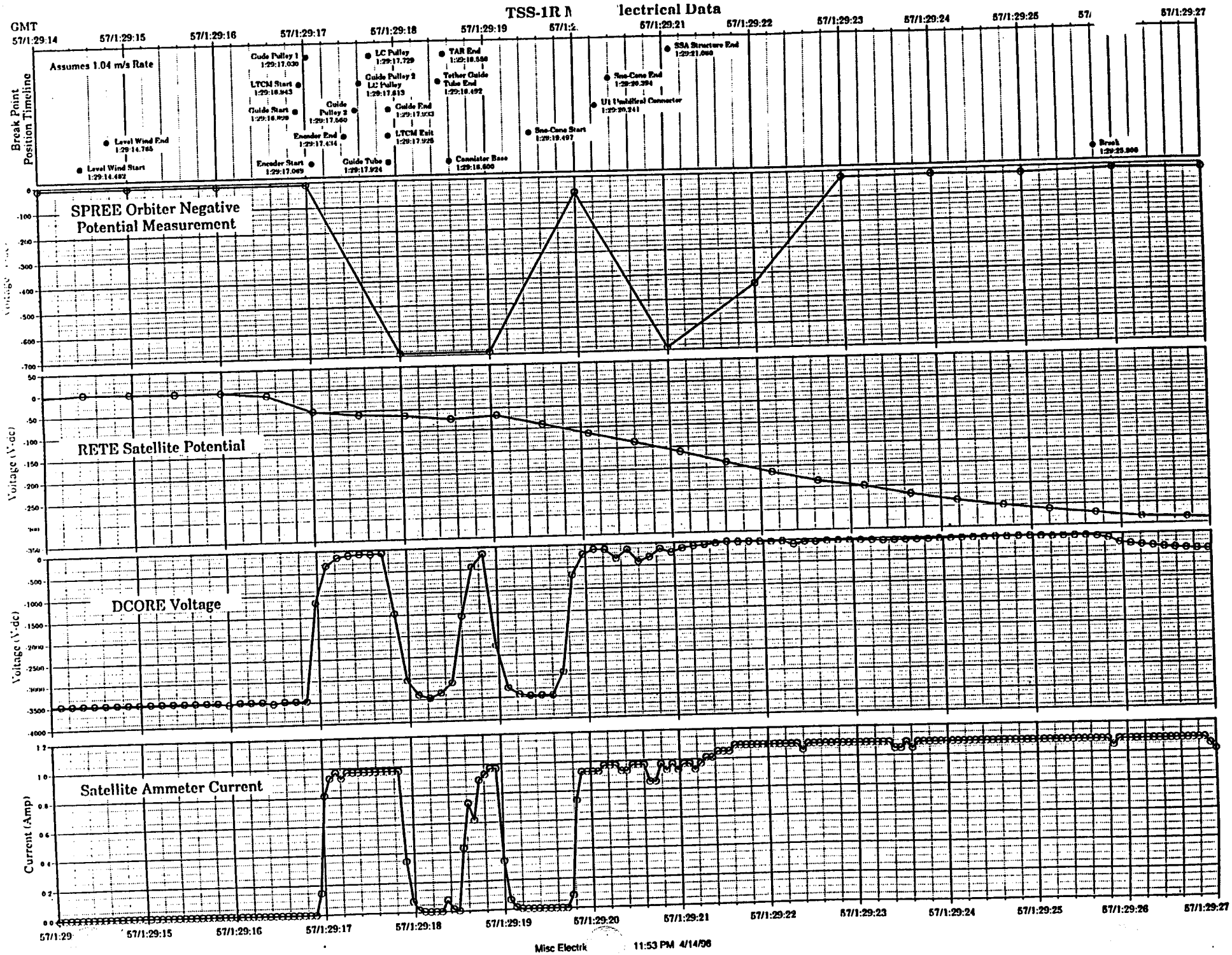
56/22:18	Satellite in free-spinning
56/22:35:24	First DCORE EGA beam firing
56/23:19:30	Satellite at 0.25 rpm controlled spin
57/01:21:30	Last DCORE beam firing prior tether break
57/01:24:00	Reversal of direction of the tether torque
57/01:25:55	Last FPEG beam firing prior to tether break
57/01:26:02	Last passive configuration

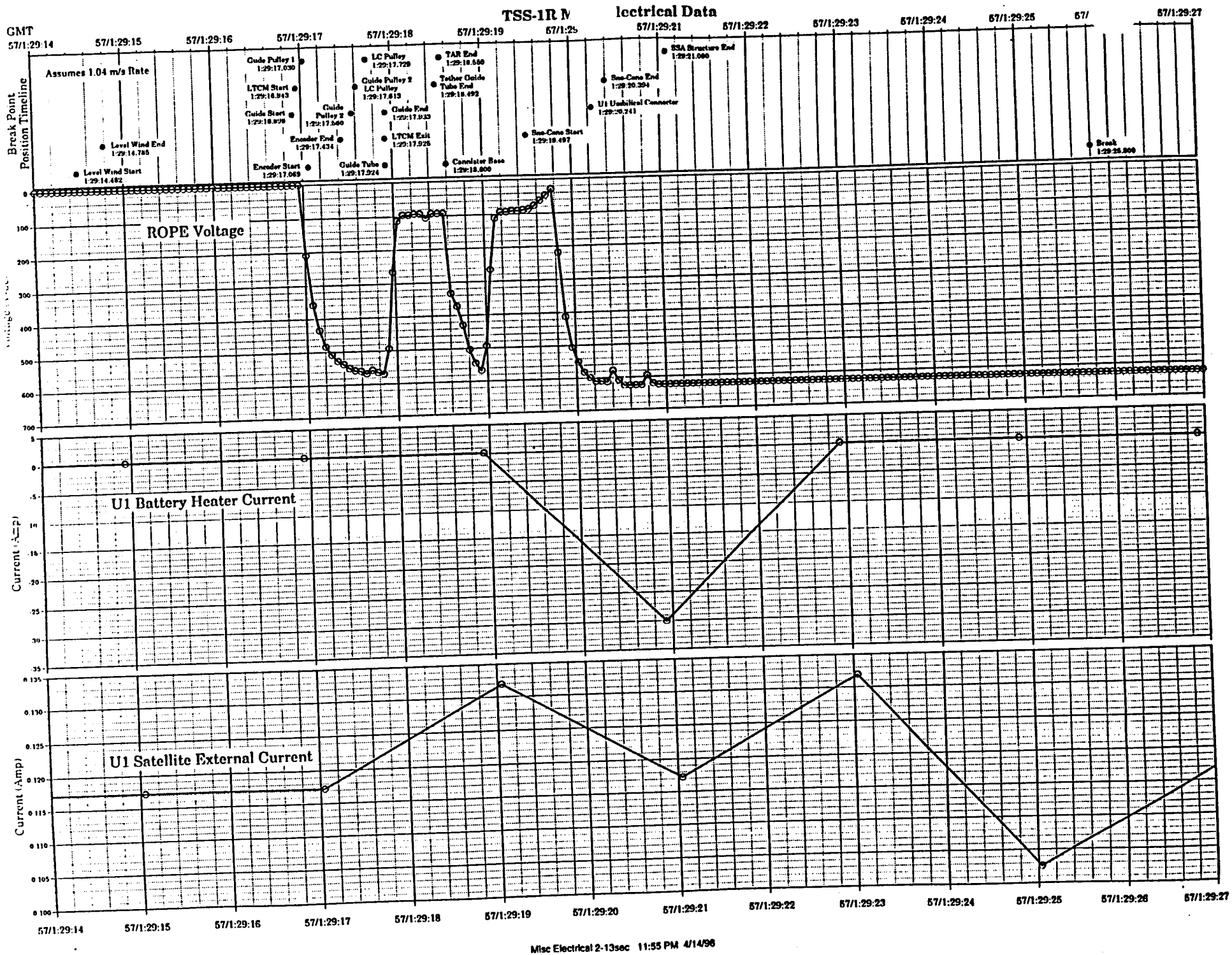
The following references to "enter" and "exit" apply to the point on the tether that had a breach in the insulator, which ultimately became the point where the tether failed.

57/01:29:14.4	Breach in tether enters level wind
57/01:29:14.8	Breach in tether exits level wind
57/01:29:16.9	Breach in tether enters LTCM
57/01:29:16.9	First unexpected high voltage drop
57/01:29:16.9	First unexpected tether current flow
57/01:29:17	Enter guard/pulley 1
57/01:19:17.1	Enter encoder
57/01:29:17.4	Exit encoder
57/01:29:17.5	Enter guard/pulley 2
57/01:29:17.5	Exit guard/ pulley 2
57/01:29:17.6	Enter LC pulley
57/01:29:17.7	Exit LC puley
57/01:29:17.8	Enter guide tube
57/01:29:17.9	Exit guide tube

57/01:29:17.9	Exit LTCM
57/01:29:18	First high voltage recovery
57/01:29:18.1	Enter guide tube 2
57/01:29:18.5	Exit Guide tube 2
57/01:29:18.6	Enter turn around pulley
57/01:29:18.6	Second voltage drop
57/01:29:18.6	Enter cannister base
57/01:29:18.7	Enter lower tether cutter
57/01:29:19.2	Second high voltage recovery
57/01:29:19.5	Third tether voltage drop
57/01:29:19.5	Enter snow cone
57/01:29:20.2	Pass by U1 connector
57/01:29:20.4	Exit snow cone
57/01:29:21.1	SSA structure end
57/01:29:26	Tether break
57/01:29:27	Tether end exited UTCM
57/01:29:36	Crew reports tether break
57/01:30:40	Current flow in tether ceases
57/01:44:00	Radar contact with satellite lost
57/14:13:00	Contact with satellite is reestablished
79/22:55:00	Satellite reentry


TSS-1R Sl lectrical Data
GMT
57/1:29:14
57/1:29:15
57/1:29:16
57/1:29:17
57/1:29:18
57/1:29:19
57/1:29:20
57/1:29:21
57/1:29:22
57/1:29:23
57/1:29:24
57/1:29:25
57/1:29:26
57/1:29:27
Break Point Position Timeline
Assumes 1.04 m/s Rate
Level Wind Start 1:29:14.482
Level Wind End 1:29:14.785
Guide Pulley 1 1:29:17.030
LTCM Start 1:29:16.943
Guide Start 1:29:16.896
Encoder Start 1:29:17.069
Encoder End 1:29:17.434
Guide Pulley 2 1:29:17.560
Guide Tube 1:29:17.924
LC Pulley 1:29:17.729
Guide Pulley 2 LC Pulley 1:29:17.813
LTCM Exit 1:29:17.928
Guide End 1:29:17.933
TAR End 1:29:18.550
Tether Guide Tube End 1:29:18.492
Canister Base 1:29:18.600
Sno-Cone Start 1:29:19.497
Sno-Cone End 1:29:20.394
UI Umbilical Connector 1:29:20.241
RSA Structure End 1:29:21.000
Break 1:29:25.000
SETS Current
SETS Voltage
SETS Charge Probe Direct Voltage
Voltage (V-dc)
SETS Current Probe Direct Monitor
Current Density (milli-Amp/m)
SETS Electrical 13 11:55 PM 4/14/96


TSS-1R M lectrical Data
GMT
57/1:29:14
57/1:29:15
57/1:29:16
57/1:29:17
57/1:29:18
57/1:29:19
57/1:29:20
57/1:29:21
57/1:29:22
57/1:29:23
57/1:29:24
57/1:29:25
57/1:29:26
57/1:29:27
Assumes 1.04 m/s Rate
Break Point Position Timeline
Level Wind Start 1:29:14.482
Level Wind End 1:29:14.785
Guide Pulley 1 1:29:17.030
LTCM Start 1:29:16.943
Guide Start 1:29:16.909
Encoder Start 1:29:17.069
Encoder End 1:29:17.414
Guide Pulley 2 1:29:17.560
LC Pulley 1:29:17.729
Guide Pulley 2 LC Pulley 1:29:17.613
Guide Tube 1:29:17.924
Guide End 1:29:17.933
LTCM Exit 1:29:17.926
TAR End 1:29:18.580
Tether Guide Tube End 1:29:18.492
Canister Base 1:29:18.600
Sun-Cone Start 1:29:19.497
Sun-Cone End 1:29:20.394
UI Umbilical Connector 1:29:20.241
SSA Structure End 1:29:21.000
Break 1:29:25.000
SPREE Orbiter Negative Potential Measurement
RETE Satellite Potential
Voltage (V-dc)
DCORE Voltage
Voltage (V-dc)
Satellite Ammeter Current
Current (Amp)
Misc Electrk
11:53 PM 4/14/96


TSS-1R M lectrical Data
GMT
Assumes 1.04 m/s Rate
Break Point Position Timeline
Level Wind Start 1:29:14.482
Level Wind End 1:29:14.785
Encoder Start 1:29:17.069
Encoder End 1:29:17.434
Guide Pulley 1 1:29:17.030
LTCM Start 1:29:16.943
Guide Start 1:29:16.976
Guide Pulley 2 1:29:17.560
Guide Tube 1:29:17.924
LC Pulley 1:29:17.729
Guide Pulley 2 LC Pulley 1:29:17.613
Guide End 1:29:17.933
LTCM Exit 1:29:17.925
TAR End 1:29:18.550
Tether Guide Tube End 1:29:18.492
Canister Base 1:29:18.600
Sun-Cone Start 1:29:19.497
Sun-Cone End 1:29:20.394
U1 Umbilical Connector 1:29:20.241
SSA Structure End 1:29:21.090
Break 1:29:25.800
ROPE Voltage
U1 Battery Heater Current
Current (Amp)
U1 Satellite External Current
Current (Amp)
57/1:29:14
57/1:29:15
57/1:29:16
57/1:29:17
57/1:29:18
57/1:29:19
57/1:29:20
57/1:29:21
57/1:29:22
57/1:29:23
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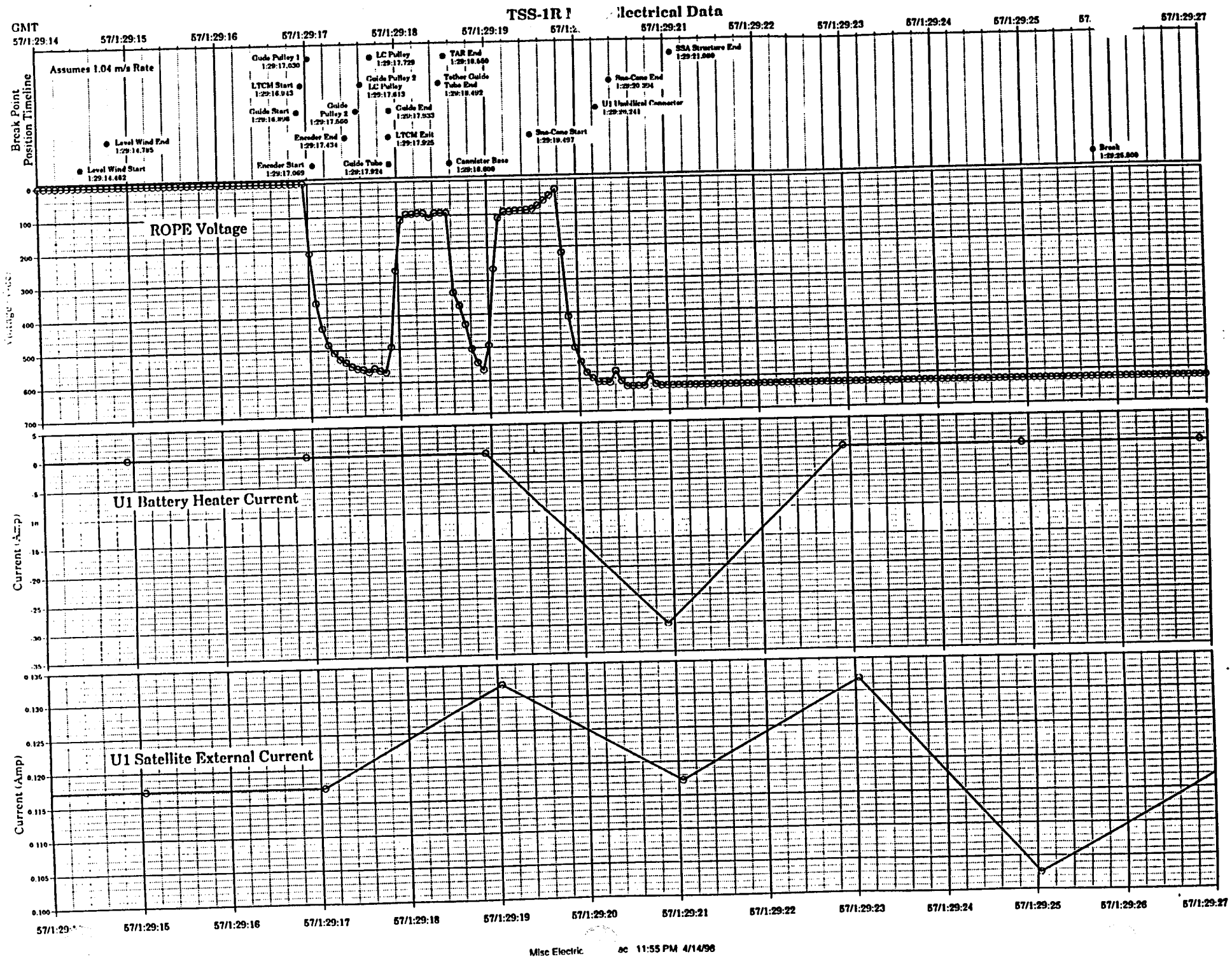
57/1:29:25
57/1:29:26
57/1:29:27
Misc Electrical 2-13sec 11:55 PM 4/14/96


TSS-1R
Electrical Data
GMT
57/1:29:14
57/1:29:15
57/1:29:16
57/1:29:17
57/1:29:18
57/1:29:19
57/1:29:20
57/1:29:21
57/1:29:22
57/1:29:23
57/1:29:24
57/1:29:25
57/1:29:26
57/1:29:27
Assumes 1.04 m/s Rate
Break Point Position Timeline
Level Wind Start 1:29:14.462
Level Wind End 1:29:14.785
Guide Pulley 1 1:29:17.030
LTCM Start 1:29:16.943
Guide Start 1:29:16.898
Encoder Start 1:29:17.069
Encoder End 1:29:17.434
Guide Pulley 2 1:29:17.500
Guide Tube 1:29:17.924
LC Pulley 1:29:17.729
Guide Pulley 2 LC Pulley 1:29:17.613
Guide End 1:29:17.933
LTCM Exit 1:29:17.925
TAR End 1:29:18.660
Tether Guide Tube End 1:29:18.492
Canister Base 1:29:18.806
Sun-Cone Start 1:29:19.497
U1 Umbilical Connector 1:29:20.241
Sun-Cone End 1:29:20.394
SSA Structure End 1:29:21.000
Break 1:29:26.800
ROPE Voltage
U1 Battery Heater Current
Current (Amp)
U1 Satellite External Current
Current (Amp)
Misc Electric
11:55 PM 4/14/96

Appendix C:

1. *History of the TSS Conducting Tether*

1. *Background*
2. *General Design Considerations*
3. *TSS-1 and TSS-1R Tether Design*
4. *Tether Fabrication Procedure Overview*
5. *Tether Testing*
6. *Tether Shipping/Handling and Testing*
7. *Tether History Summary*

Reference 1: Tether Manufacturing Timeline/Events
Reference 2: TSS-1 and TSS-1R Deployer Systems Test (4S08)
Reference 3: Manufacturing Mapping Data

2. *TSS-1R Deployer Detailed Schedule and Task*

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A History of the TSS Conducting Tether

1.0 Background

2.0 General Design Considerations for the TSS Tether

3.0 TSS-1 and 1R Tether Design

4.0 Tether Fabrication Procedure Overview

5.0 Tether Testing
5.1 Engineering Test
5.2 Acceptance Test
5.2.1 Conductor Resistance
5.2.2 Insulation Voltage Withstand Capability
5.2.3 Strength Member Braiding
5.2.4 Tether Preconditioning
5.3 Qualification Test
5.3.1 Tether Witness Sample Breakstrength
5.3.2 Tether Witness Sample Voltage Withstand
5.3.3 Thermal Vacuum
5.3.4 Post-Thermal Vacuum Breakstrength
5.3.5 Post-Thermal Vacuum Voltage Withstand
5.3.6 Acceptance/Qualification Test Summary
5.4 Special Test on the Flight Tether (Post TSS-1 and TSS-1R Missions)
5.4.1 Post TSS-1 Testing
5.4.2 Post TSS-1R Mission Testing

6.0 Tether Shipping/Handling and Testing (Post Manufacturing Phase)
6.1 Tether Shipping/Handling 1987 thru Post-TSS-1
6.2 Tether History/Pedigree 1993 - 1994

7.0 Tether History Summary

Reference 1 - Tether Manufacturing Timeline/Events
Reference 2 - TSS-1 and TSS-1R Deployer Systems Test (4S08)
Reference 3 - Manufacturing Mapping Data

B TSS-1R Deployer Detailed Schedule and Task

History of the Tethered Satellite System (TSS) Conducting Tether

History of the Tethered Satellite System (TSS) Conducting Tether

This report provides a historical description of the design, development, fabrication and test phases of the TSS electromechanical tether flown on the TSS-1 (STS-46) and TSS-1R (STS-75) missions. A narrative description is included for the each of the phases, with references to key figures and tabular summaries that have been developed for TSS-1R investigation board presentations and action item responses.

Three reference packages are attached to this report in order to provide a single integrated tether history package. A detailed review/timetable of the tether manufacturing activity is included and presented in tabular format in Reference 1, Tether History. A summary of the TSS-1 and TSS-1R Deployer System Test (4S08) activities and areas of interest pertaining to the tether is provided in Reference 2. Reference 3 contains the Manufacturing mapping data.

1.0 Background

Satellite and balloon tethers up to 100 km in length have been deployed for many years using Kevlar lines manufactured by Cortland Cable Company, the TSS tether manufacturer. In addition to these mechanical tethers, electromechanical cables (EMCs) have been deployed in a variety of applications, ranging from short harnesses to 10 km undersea sonobuoys, using Kevlar strength members and special conductor cores.

There are a myriad of wire and cable designs used in the electronics, construction and transportation industries. Typically, these cables are made to meet commercial or military specifications which control electrical and physical properties, and are intended for use in fixed (static) installations. The electromechanical cables (EMCs) discussed in this section are designed for dynamic applications; towing, mooring, and working cables that are repeatedly deployed and retrieved, or subjected to shock loads. The design and material aspects of these EMCs have been applied to the fabrication of the TSS electromechanical tether which contains an #24 AWG equivalent conductor, and can withstand applied voltages in excess of 10 kV. This tether has a nominal breakstrength rating of 400 lb and can be deployed to a maximum length of 20.7 km.

For many years, scientists have envisioned the possibility of flying tethers in space to learn about plasma processes and characteristics. In addition, electrodynamic power generation with a tether was a key area of interest which led to the development of a conducting tethered satellite system.

In 1984, NASA MSFC awarded Martin Marietta Denver Aerospace a contract to develop the Deployer and the conducting tether for the TSS.

2.0 General Design Considerations for the TSS Tether

Specialty cables in existence today range from tried-and-true designs to ingenious assemblies arrived at by design team consensus. Most EMCs that have critical mechanical functions use steel for the strength member, taking advantage of the inherent high modulus/low elongation characteristics and the high tensile strength per unit cross section.

The simplest EMC design, when tensile stresses are high, consist of an insulated conductor wrapped loosely around a steel core or messenger. This is the standard procedure for routing power lines to homes and buildings. Since bulk or cable cross-section are not important in this application, the design offers a reliable, low-cost means of decoupling the conductor from the strength member.

When a non-metallic, non-magnetic or low weight requirement exists, a high strength fiber such as Kevlar is utilized as the cable strength member. In addition, when the application calls for a minimum cross section (as is the case for the TSS tether), the strength member becomes a concentric and integral part of the cable. Basic EMC designs with minimized cross sections include copper-clad steel wire or precipitation-hardened copper alloy for use in telephone line/overhead signal systems. These are the most efficient single conductor/high strength designs for conditions with uniform tensile loading and no cyclic bending or shock loads.

Proposals were requested by Martin Marietta from industry for a tether design and fabrication approach, with responses being received from Cortland Cable Co. and a German subsidiary of GM Packard Electric Division. In December 1985, Cortland Cable Co. was selected to design, build and test the electrodynamic cable which was to fly on the TSS-1 and TSS-1R missions.

A tether design PDR (Preliminary Design Review) was held at MSFC in March, 1985 and a CDR (Critical Design Review) was conducted at MSFC in late October, 1985. The major items identified at the PDR included: selection of insulation application for proper high voltage rating (tape wrap vs. extrusion), definition of minimum tether bend radius, deletion of load-carrying requirement for tether conductor, and the addition of a engineering tether torsion test to quantify tether twist/torque. These items were resolved at the CDR: extrusion was selected as the insulation application method, minimum tether bend diameter was identified as 30X the tether diameter, the conductor load carrying requirement was deleted and tether torsion was seen to be low (approximately 16 oz-in) for 10 turns per meter of tether length.

The geometry of the conductor used for the TSS electrodynamic tethers was a design developed over fifty years ago to allow the incorporation of a hard-wired communication link between a glider and the towing aircraft through the nylon tow rope. The finished three stand rope was capable of being elongated to 150% of its initial length without a change in the resistance of the three embedded conductors. In the early 1980's, the Navy revived this design for another application and Cortland Cable developed the equipment to fabricate and deliver half a million feet per month of this conductor.

In 1985, Cortland Cable Company registered the trademark name, "HiWire" (High impact Wire), and proposed its use in applications where dynamic loading is too severe for conventional insulated wires to survive the mechanical stress. In addition to several marine towing applications, this conductor proved to be very successful as an electrical component in polar ice coring cables. The design of the conductor decouples the thermal expansion behavior of the copper from the synthetic fiber components of the cable. This unique resistance to mechanical fatigue induced by thermal stresses made HiWire an ideal candidate for the TSS tether. The helical path of the copper provides the compliance necessary to accommodate not only rapid changes in tension (high impact), but also mitigates the effect of thermal expansion and contraction that might otherwise buckle the copper conductors.

The general guidelines for conductor design in cables subject to stresses and cyclic loading are: (1) use the smallest conductors possible for the required power and voltage requirements of the system; (2) use stranded wire only (#34 AWG to #40 AWG individual sizes are preferable); (3) use the maximum twist per unit length for the individual stranded conductors; (4) larger conductors should be cabled, rather than bunched, when forming the helixed core to permit better packing and to avoid the twisting of conductors; (5) use the optimum geometric pattern for packing the conductors; and (6) protect the core and successive layers with braided or extruded jackets.

Heavy cyclic loading over drums or sheaves will tend to compress, twist and break up almost any type of jacketing. The use of properly grooved sheaves that support the cables and avoid excessive local deformation is extremely important. The sheave to cable diameter ratios must be as large as possible, preferably over 20:1. Finally, the tensile loads on the cables should not be over 20% of the rated breakstrength, or no greater than 10% of the breakstrength when many thousands of cycles over sheaves are involved. Special attention is required to assure that the cable and its associated mechanical system are designed in conjunction.

In situations where high impact, snap loading or severe vibrations are expected, there are special designs required both for the strength member and the conductors. Steel or Kevlar, with their high elastic moduli, would transmit the shock and vibrations to the payload and be unacceptable. The conductors can also fail if coupled to the strength member. In spite of the ductility of the copper, even a stranded copper conductor will

buckle and fail with a successive compression and tension loading occurring from a snap load or release. This is frequently experienced with the center conductor of a coaxial cable even when assembled in a multiconductor design.

For very long continuous lengths, the Cortland HiWire is a design of high helix angle copper wires over an elastic fiber core, finished with an outer extruded insulation. These have been successfully within nylon ropes and in multiconductor cables for tow systems in underwater and arctic environments. The sizes and types of elastic core, conductors, and insulation are selected according to the deployment problems that range from airplane-towed magnetometers to missile launch systems. In addition to impact loads with cable elongations over 10%, these conductor designs survive extensive cycling.

For multiconductor cables, the most common approach that lends itself to efficient production methods is to helix, or bunch, the insulated conductors over a central strength member. When many conductors are involved, the twisted pairs are shielded with aluminum foil, aluminized Mylar, or braided copper, plus an outer insulating layer. Overall jacketing is required to protect the cables if operating conditions can damage the insulation. These multiconductor cables are often used, however, without jackets (even underwater) to permit easy access for breakouts or pigtails.

The use of an outer strength member which encloses the electrical conductors is desirable for applications requiring protection of the conductors. Examples include the conventional steel armored cable or the Kevlar equivalent braided counter-helix design. Fillers may be used to retain a smooth circular cross section and uniform loading, particularly when the number of conductors do no pact into a concentric arrangement

The basic geometry of the HiWire provides for a concentric ring of copper strands wrapped around a parallel bundle of multifilament fibers. It is important that this concentric band of copper elements does not fill the available space, so that when the cable bends over a pulley or on a spool there is room for the copper elements to slide closer together at the inside of the bend where the cable goes into compression without being forced out of the annulus they occupy. At the same time, the outside of the bend sees these copper strands spread apart. The configuration is similar to a spring (or a Slinky) turning a corner, and uses the space between the coils to allow the structure to bend.

The HiWire conductor is stranded with about 80% coverage at a twist rate of five turns per inch. Since there is no way to keep the strands of copper evenly spaced during the conductor stranding process, several strands can group together leaving random gaps where the Nomex fiber core is seen. The majority of the cable displays a pattern where all ten strands are adjacent to each other, with a gap between the group of strands at an approximate interval of 0.20 in (0.51 cm). The stranding process left the coiled wires free to group together or have slight separations, with a consistent count of fifty copper coil

wraps per inch. The gaps are necessary to maintain cable flexibility, and the non-symmetrical appearance is the nature of the design.

3.0 TSS-1 and -1R Tether Design

The TSS tether uses a composite design consisting of an FEP-insulated copper conductor located concentrically within a Kevlar ® strength member and a Nomex ® braided protective jacket. The conductor is comprised of ten #34 AWG copper strands wrapped around a Nomex core in a high helix angle. This configuration decouples the conductor from the Kevlar strength member, thus allowing the strength member to carry all of the mechanical load applied to the tether. A detailed description of the tether configuration is provided in Table 1 and a pictorial view in Figure 1.

Key design requirements include a minimum tether breakstrength of 1780 N (the maximum worst-case system level requirement is 980 N), a voltage withstand rating of 10 kV and the ability to survive thermal excursions in a vacuum between -100°C and +125°C. The maximum weight per unit length is specified as 8.2 kg/km, while the maximum allowable resistance is 0.122 ohm/m.

Table 1 TSS Conducting Tether Configuration

Item	Cumulative Dia (mm/in)	Description
Core	0.51/0.020	12 strands, 200 denier Nomex
Conductor	0.86/0.034	10 strands, #34 AWG (#24 AWG equivalent) bare, electrolytic tough pitch, annealed copper wire, helixed around core
Insulation	1.47/0.058	FEP, 0.3 mm/0.012 in wall thickness, 10 kV voltage breakdown specification, (15 kV qualification level)
Strength Member	1.88/0.074	12 strands, 1000 denier braided Kevlar, 1780 N breakstrength rating
Jacket	2.54/0.100	8 strands, 1200 denier braided Nomex

The tether strength member acts as the structural attachment between the TSS Deployer mechanism and the deployed satellite. Nominal loads on the tether were estimated to be approximately 55 N, with maximum loading around 100 N during boom extension. The tether conductor served as one leg of the electrical circuit between the Deployer and satellite for electrodynamic experiments. The insulation layer was designed to withstand applied voltages of 10 kV.

4.0 Tether Fabrication Procedure Overview

This section contains a general overview of the tether fabrication procedures. The procedures are discussed in more detail in conjunction with the acceptance tests (Section 5.2), which were an integral part of the fabrication activity. Cortland Cable Co. developed specific procedures for fabricating the TSS qualification and flight tethers. The in-line tether assembly for the flight tether is summarized below:

Activity	Location	Duration	Length (m)
Conductor Stranding	Cortland Cable Co.	3/86 - 4/86	24,500
Insulation Extrusion	Tensolite, Inc.	5/86	~24,400
Strength Member Braiding	Cortland Cable Co.	7/86 - 12/86	24,056
Protective Jacket Braiding	Cortland Cable Co.	1/87 - 3/87	22,756

All stranding/braiding operations took place under controlled low tension, with automatic machine shutdown capability if line tension or cable diameter tolerance parameters were exceeded. Splices in the conductor, strength member and protective jacket were staggered to reduce the probability of single point failures in the tether (see Figure 2 for more information on conductor buttweld arrangement).

The FEP insulation layer was applied to the conductor as part of a continuous extrusion process. A 10 kV spark test was employed during this operation to give a 100% verification of insulation integrity. Any pinholes that were detected were marked and later repaired during the Kevlar braiding process.

The Kevlar braiding operation used a special off-line verification process that tested each spool of Kevlar as part of a test braid prior to being spliced onto the tether strength member. Pull tests were conducted on the test braid to verify that the 1780 N minimum breakstrength requirement was met. Visual inspections were performed on a regular basis to verify that proper braid configuration was maintained.

The final manufacturing process applied a Nomex protective jacket to the tether. A pre-conditioning device (PCD) was placed between the Nomex braiding machine and the final take-up reel to eliminate constructional stretch of the tether. In addition, this device served to proof load the entire tether length to an approximate load of 445 N. Full jacket coverage of the internal tether components was verified visually by checking the wrap appearance of the finished tether as it was wound onto the take-up/shipping reel.

The tether breakstrength rating of 1780 N represents a safety factor of about 18.0 for the maximum expected load and over 32.0 for the nominal mission loads. All tether materials, including the FEP insulation, have high temperature operating capabilities (in excess of 200°C).

The HiWire conductor configuration allows the conductor to act independently of the Kevlar strength member during mechanical and thermal cycling of the tether. The helixed copper over the Nomex core has been seen to retain electrical continuity for elongations up to 30% of the core material. The FEP insulating material does not change the mechanical behavior of the conductor/core significantly because of its low modulus and thin wall dimension (0.3 mm).

As a finished tether, with Kevlar and Nomex braids, the total stretch is limited to approximately 4% elongation (controlled by the Kevlar) at over 1780 N breakstrength. Tether pre-stretching during production (0.5% to 1.0% elongation) was performed to reduce the constructional stretch of the Kevlar braid, with no effect on the conductor electrical properties. Subsequent cyclic loading up to 445 N would involve only about 1% elongation, again with no effect on the conductor. Length changes due to thermal excursions of greater that 200°C, would be on the order of 0.1% , and would be controlled by the Kevlar strength member.

The Nomex jacket is used to protect the internal tether components from abrasion as the tether cycles through the TSS mechanisms. In addition, the jacket thickness was sized to minimize the atomic oxygen degradation effects on the other tether components during the 38-hour mission.

Two electromechanical tethers measuring 22 km and 25 km, respectively were completed in April 1987. Several sample lengths taken from each completed tether were used in mechanical, electrical, and environmental tests to verify the tether design capability.

5.0 Tether Testing

5.1 Engineering Tests

Martin Marietta tested several hundred meters of engineering tether samples identical in configuration to the TSS-1 tether design prior to flight tether production. The key test results are presented in Table 2 and Figure 3. Note that the mean breakstrength value of the tethers (approximately 30 test points total) exceeds the minimum required breakstrength by 135 N. No sample was seen to break below the required value of 1780 N. Electrical continuity measurements performed during the breakstrength tests verified that the conductor did not break until after failure of the strength member.

Three thermal cycling tests were performed on 5 m tether sections, loaded to 120 N to determine the effective thermal expansion coefficient of the composite tether. Temperature limits ranged from -100 °C to +125 °C for a total of twenty-four cycles per test. Tether deflection vs. temperature was measured throughout the test period. The negative thermal expansion coefficient shown in Table 2 indicates that the Kevlar was acting as the primary load-carrying member.

Table 2 Test Results: Engineering Version of TSS Tether

Physical Properties		
o	Nominal Diameter (mm) at 52 N tension	2.54
o	Mass Per Length (kg/km)	8.2
Electrical Properties		
o	Resistance at 20°C (ohm/meter)	0.10
o	Insulation Breakdown at 20°C (kV)	15+
Mechanical Properties		
o	Mean Breakstrength at 20°C (N) (1780 N required)	1915
o	Elongation Constant at 20°C 120 N (cm/N/km)	6.3
o	Elongation at 120 N Load (%)	0.35
o	Creep at 24 hours, 120 N Load (%)	0.06
o	Thermal Expansion Coefficient (PPM/C)	-6.1

5.2 Acceptance Tests

The following acceptance tests were performed during tether production by Cortland Cable Co., Cortland, NY and Tensolite, Inc., Buchanan, NY under the contractual direction of Martin Marietta. These acceptance tests were performed to verify proper workmanship during the tether fabrication procedures. The fabrication procedures and associated acceptance tests were performed concurrently. A detailed description of the fabrication procedures is included in this section for completeness.

5.2.1 Conductor Resistance

The full length conductors for the 22 km flight tether and 25 km qualification tether were comprised of ten strands of #34 AWG copper wire wrapped in a high helix configuration

around a continuous Nomex core. Since the maximum length of the individual copper strands was approximately 3600m, it was necessary to join strands end-to-end to make up the total required length for each tether conductor. A special buttwelding procedure was developed to join the #34 AWG wire strands without increasing the overall conductor diameter. Seven (7) buttweld "sets" were required for the qualification tether conductor, while six (6) "sets" were made for the flight tether conductor. a given buttweld set contained ten individual joints staggered 1.8 m apart, resulting in a total end-to-end length of 16 m between the buttwelds in the first and tenth conductor strands. This staggered arrangement of joints was used to decrease the possibility of a single point failure in the conductor.

Acceptance testing consisted of a magnified visual inspection to ensure no joint laps, applying a dead load of 6.7 N to the buttweld joint to check mechanical integrity, and a resistance measurement to verify the 0.122 Ω/m maximum requirement was met. All seventy (70) buttweld joints in the qualification tether conductor showed resistances under the 0.12 Ω/m value (0.10 - 0.11 Ω/m). Similar results were seen for the flight tether. The final flight tether conductor resistance was 0.101 Ω/m, with an uncertainty factor of 2%. This uncertainty was primarily driven by inaccuracies in the length measurement device used during the manufacturing process. Subsequent resistance measurements of the TSS tether were on the order of 0.098 - 0.099 Ω/m when using the highly accurate Deployer encoder for measuring installed tether length.

5.2.2 Insulation Voltage Withstand Capability

Following fabrication of the tether conductors, an extruded layer of FEP was applied to the qualification and flight conductors to serve as an electrical insulator. Tensolite, Inc. was contracted to perform this extrusion operation which was constrained by several unique and challenging requirements. Typical industry requirements for extruded wire insulation lengths are on the orders of several hundred meters; the TSS tether conductors needed continuous lengths up to 25 km. In addition, the tether insulation layer was required to have a high voltage rating of 10 kV, but was constrained to a wall thickness of 0.3 mm (0.012 in) in order to minimize the overall diameter of the finished tether. The nominal rating of FEP was 1500 V/mil, or a total of 18 kV for a 0.012 inch wall thickness.

After several months of development, Tensolite used a tension-controlled tube extrusion process to insulate the qualification and flight tether conductors. The tube extrusion setup was chosen due to its inherent feature of providing a relatively uniform wall thickness over the conductor. Fluorinated Ethylene Propylene (FEP) was selected as the insulation material on the basis of its excellent dielectric strength, high temperature rating and favorable extrusion characteristics.

Acceptance testing during the insulation extrusion process consisted of a continuous high voltage impulse spark test on the insulated conductor. The spark tester was located

between the extruder and the conductor take-up reel to detect pinholes in the FEP insulation layer. The test voltage was set at the design requirement level of 10 kV. Conductor velocity through the extruder and spark tester was 0.25 m/s.

Two pinholes were detected in the qualification tether insulation layer, while one pinhole was found in the flight tether. The general location of the flight tether pinhole was near the midpoint of the conductor length (see Ref. 1 for more information). The extrusion operation did not allow immediate repair of the pinholes since a constant conductor velocity through the extruder is required to maintain a uniform insulation wall thickness. Stopping the conductor movement through the extruder terminates the extrusion operation, therefore, no interruptions can occur after the extrusion is initiated. The pinhole locations were marked by Tensolite with a paper tag inserted onto the take-up reel insulated conductor windings. Subsequent repair of the pinholes occurred during the strength member braiding process at Cortland Cable Co. The pinhole repair procedure consisted of sliding a short section of FEP shrink tube (3.8 cm in length) over the conductor during the Kevlar braiding process until the pinhole marker was reached. At that point a heat gun was used to shrink the tube down tightly over the parent FEP insulation layer. Mechanical integrity of the shrink tube adherence to the parent FEP was checked, and the dielectric strength of the tube was tested to 3 kV, then 10 kV.

Interference of the shrink tube with oversized sections of FEP parent material (larger than the nominal specified diameter of 0.058 inches) during the Kevlar braiding process prevented sliding the shrink tube to the known pinhole location (this occurred approximately 2000 meters prior to reaching the pinhole). The oversized areas were detected with a plastic go/no-go gauge with a diameter of 0.060 in. Cortland Cable Co. stopped the operation at this point and notified Martin Marietta. A combined Cortland/Martin Marietta/MSFC team met at the Cortland facility to discuss possible repair options. Some options included: 1) reflowing the damaged/oversized FEP, 2) building new tether conductor and sending to Tensolite for new insulation extrusion, and 3) removing damaged insulation and performing conductor repair. The group agreed after a week-long study, that the damaged FEP should be cut out of the flight tether conductor, and that the conductor should be repaired at this point before continuing with the Kevlar braiding operation. Samples of conductor repairs were fabricated by Cortland and tested by Martin Marietta before proceeding with the flight conductor repair. Removal of the damaged insulation layer and a successful repair of the flight tether conductor was accomplished (see Ref. 1 for length location).

Results from the tether insulation extrusion process for the qualification and flight tethers indicate that the longest lengths of pinhole-free sections attained were on the order of 13000 m. These results were encouraging since they represent lengths that are several orders of magnitude greater than normal industry achievements during standard wire manufacturing runs. One possible approach to producing a defect-free extrusion length in the future would involve the use of a conductor several times longer than the required final tether length. For example, a 25 km tether might make use of a 100 km conductor during application of the insulation layer. The 100 km insulated conductor may have an increased probability of containing a 25 km section without any pinholes; this section could be cut out and used as the conductor for the tether. Present-day extrusion tooling and mechanisms would need to be modified, however, to accommodate conductor lengths of 100 km.

5.2.3 Strength Member Braiding

In order to verify the tether breakstrength requirement of 1780 N, an off-line verification method of each Kevlar spool was employed prior to strength member braiding start-up. The verification method tested the Kevlar spools as part of a woven test braid identical in configuration to the tether strength member braid pattern. The test braids, measuring 9m in length, contained twelve strands (one strand per spool) of 1000 denier Kevlar. Three breakstrength tests were conducted on each test braid length. Following successful completion of the breakstrength tests, a given set of twelve Kevlar spools was moved into the production area for subsequent usage in the strength member braiding sequence. Each spool contained approximately 2400m of Kevlar material.

The results of the breakstrength tests are summarized in Table 3. No test braids failed to meet the 1780 N requirement. The lowest breakstrength reading of 1891 N represents a 6% margin over the minimum requirement. The standard deviation of the test data is approximately 4% of the mean value (2093 N).

Table 3 Kevlar Test Braid Breakstrength Results

Qualification Tether

Test Braid No.	Test 1	Test 2	Test 3
1	2136	2069	2047
2	2047	2114	2069
3	2092	1936	2003
4	2158	2225	2225
5	2136	2181	2225
6	2136	2136	2181
7	1891	2047	2025
8	2158	2092	2092
9	2092	1980	2092

Avg.= 2096 N, Low 1891 N, Standard Deviation = 84 N

Flight Tether

Test Braid No.	Test 1	Test 2	Test 3
1	2069	1980	1980
2	2003	2092	2047
3	1891	1958	2047
4	2136	2136	2225
5	2136	2225	2181
6	2136	2136	2181
7	2092	2003	1958
8	2181	2225	2092
9	2092	2092	2136
10	2003	2136	2136

Avg.= 2090 N, Low = 1891 N, Standard Deviation = 87 N

Total (Qualification and Flight Tether)
Avg. = 2093 N, Low = 1891 N, Standard Deviation = 85 N

5.2.4 Tether Preconditioning

A tether preconditioning device (PCD) was implemented during the final tether jacketing operation. The PCD served two purposes: 1) removal of constructional stretch from the Kevlar strength member, thus offering improved predictability of tether load vs. elongation behavior during the mission, and 2) continuous proofloading of the tether to a level approximately two times greater than the maximum expected flight load under system failure conditions.

The PCD was comprised of two horizontal rollers, each containing a step diameter increase from 50.8 mm to 53.3 mm. The centerline distance between the two rollers was 203.2 mm, thereby creating a tether elongation of about 1.4% as it passed through the diameter increase step-up on each roller. This elongation corresponds to a load of approximately one-fourth the rated tether breakstrength, or 445 N.

The PCD was installed in-line between the Nomex jacket braiding machine and the tether take-up reel for both qualification and flight tether jacketing operations. A force gauge was used to read the tether line-tension in the PCD for proof-loading verification.

Results indicate that the PCD tension ranged between 445 N and 668 N for 98% of the production time. Several tension readings fall as low as 334 N due to loosening of drive motor belts, however, this value is still 114 N over the worst-case flight load of 220 N. Momentary PCD tensions were recorded as high as 779 N, but no tether degradation was evidenced due to the 1780 N rated capability of the strength member.

The permanent set on tether samples passed through the PCD was measured a 0.20% to 0.25%. This was a direct result of removing the Kevlar braid constructional stretch as it was loaded to 445 N in the PCD. The non-linearity of load vs.-elongation behavior of the tether at low loads (0 to 55 N) was greatly reduced, thus making it less difficult to predict tether load/elongation Characteristics during the TSS mission.

A chart summary of the splices/repairs in the completed flight tether is contained in Figure 4.

5.3 Qualification Tests

Martin Marietta completed the following qualification tests on tether samples taken from the beginning and end of the production runs for both tethers in 1987. The qualification test summary is presented in Figure 5.

5.3.1 Tether Witness Sample Breakstrength

A total of thirty-two (32) witness from the qualification and flight tethers were tested for breakstrength to verify the design requirement rating of 1780 N. All samples were approximately one meter in length. Results are listed in Table 4. All thirty-two samples met the minimum breakstrength value. Average breakstrengths for the qualification and flight tether samples were 1885 N and 1906 N, respectively. The standard deviation was approximately 3% of the mean breakstrength value for both sets of samples.

Table 4 Tether Witness Sample Breakstrength Test Results
(Breakstrength in N)

Sample #	1	2	3	4	5	6	7	8
Sample Origin								
Qual Beginning	1936	2003	1927	1825	1887	1914	1927	1896
Qual End	1927	1802	1847	1922	1811	1816	1816	1905
Flight Beginning	1838	1900	1878	1945	1940	1811	1980	1922
Flight End	1878	1869	1847	1958	1936	1882	1980	1936

Qualification Tether: Avg. = 1885 N, Low = 1802 N, Standard Deviation = 59 N

Flight Tether: Avg. = 1906 N, Low = 1811 N, Standard Deviation = 51 N

5.3.2 Tether Witness Sample Voltage Withstand

Tether samples were subjected to a 15 kV dc qualification-level voltage (50% higher than the design requirement of 10 kV) for a minimum of thirty-eight (38) hours. The purpose of this qualification test was to verify the insulation integrity at a voltage level above the design rating for an extended period of time.

Thirty-two (32) samples total were immersed in a salt water bath to simulate the conductive medium of the space plasma environment for the TSS-1 flight. The salt water conductivity was measured as 500 $\Omega \pm 10$ % between two bus bars in the bath located approximately 1 meter apart.

The positive lead of a high voltage tester was connected to a copper bus bar in the salt water solution, and the negative lead was connected to the tether conductors outside of the water bath. Tether leakage current was measured continuously with a sensitive ammeter/strip chart recorder arrangement.

The 15 kV potential was actually applied for a total accumulated time of seventy-six (76) hours - with no insulation failures occurring in any of the tether samples. One leakage current anomaly was noted during the test; troubleshooting was performed and the cause was determined to be a facility power transient. The full 15 kV potential was successfully reapplied to all tether samples, with no further problems. Peak leakage currents for the full complement of samples ranged from 1 to 3 microamps. This results in a leakage per unit length value of approximately 0.094 microamps per meter. It is suspected that the leakage current peaks seen on the strip chart plot were attributable to facility power and that the actual value of tether leakage current is very close to zero. This conclusion was based on the observation that the current peaks were seen primarily during daylight test periods when the facility was fully occupied. The current peaks were not seen during test periods between midnight and 6:00 A.M.

5.3.3 Thermal Vacuum

Four (4) tether samples measuring 1.8 m in length were subjected to a thermal vacuum cycling test between the temperature extremes of -100°C and +125°C, at a pressure of 10-5 Torr. Four (4) cycles total were completed, with a twelve hour dwell at each temperature extreme. The total test time was 120 hr. each sample had a tensile load of 110 N applied at one end (approximately two times the nominal flight load). Conductor resistance was monitored continuously throughout the test.

The tether samples showed no visual degradation at the completion of the thermal vacuum cycling sequence. Conductor resistance readings remained below the maximum allowable value of 0.122 Ω/m. Following the completion of the thermal vacuum exposure,

the samples were removed from the chamber and subjected to post-thermal vacuum breakstrength and voltage withstand tests.

5.3.4 Post-Thermal Vacuum Breakstrength

Two (2) each samples (measuring approximately one meter in length) from the qualification and flight tether were tested for breakstrength following exposure to the thermal vacuum conditions described above. Results are summarized in Table 5.

Table 5 Post-Thermal Vacuum Tether Witness Sample Breakstrength Test Results

Sample	Breakstrength (N)
Qualification Beginning	2047
Qualification End	2114
Flight Beginning	1869
Flight End	1914
Qualification Tether:	Avg. = 2081 N, Low = 2047 N
Flight Tether:	Avg. = 1892 N, Low = 1869 N

All four tether samples met the minimum breakstrength requirement of 1780 N. The flight tether sample average breakstrength value (post-thermal vacuum) was about 1% lower than the mean value of samples that had not been exposed to thermal vacuum cycling. The qualification tether samples had an average breakstrength of 2081 N (post-thermal vacuum), which actually represented an increase over the average value of 1885 N for qualification tether samples not subjected to thermal vacuum conditions. These results indicate that a thermal vacuum environment does not degrade the strength member properties any appreciable amount.

5.3.5 Post-Thermal Vacuum Voltage Withstand

Two (2) each sections from the qualification and flight tether thermal vacuum samples were subjected to the salt water-bath voltage withstand test described earlier. No insulation failures were noted during the thirty eight (38) hour test period. Leakage

current values for all four tether samples ranged from 0.5 to 1.0 microamps (peak). Once again, these peak leakage current spikes were noted primarily during daylight test periods when facility power transients were more prominent. The actual tether leakage current was approaching zero during second and third shift work periods. These test results verified the ability of the FEP conductor insulation layer to retain its dielectric strength after exposure to a thermal vacuum environment.

5.3.6 Acceptance/Qualification Test Summary

Acceptance and qualification testing was successfully completed on the 22 km flight tether and 25 km qualification tether. Tether breakstrength and voltage withstand capability have been shown to exceed tether design requirements on multiple test samples. Furthermore, the tests demonstrated that thermal vacuum conditions do not degrade tether breakstrength or insulation dielectric strength properties significantly. After qualification testing, the qualification tether was used in several tests identified in Figure 6. The qualification tether was an important element in the development of the Deployer mechanisms and tether thermal/electrical characterizations.

5.4 Special Tests on the Flight Tether (Post TSS-1 and TSS-1R Missions)

5.4.1 Post TSS-1 Testing

Following the TSS-1 mission in 1992, a 300 meter section of flight tether was removed (at the satellite end) and subjected to tests at Martin Marietta in 1993. This section of tether included the 256 meters that was deployed and exposed to the free space environment during the mission, as well as approximately 44 meters that had remained on the reel. The purpose of the test program was to verify the acceptance of the remaining tether for the TSS-1R mission. A meeting was held at Martin Marietta in March 1993 with MSFC TSS Program Office representatives to develop a test and inspection plan for this purpose. The attendees agreed that several visual inspections as well as verification of tether breakstrength, dielectric strength and resistance would be needed to recertify the tether for the TSS-1 mission.

The tether samples in this program were observed to meet the requirements of a new tether, thus it was determined that the remaining tether length was acceptable for reflight. Results are presented in Figure 7.

5.4.2 Post TSS-1R Mission Testing

A high voltage spark test was performed on the remaining ~1890 m of tether which was removed from the flight reel assembly in April 1996. The entire length of tether passed

through the 10 kV potential without a breakdown. This indicates that the tether insulation in general maintained its integrity, and was not degraded due to long term reel storage effects or exposure to the flight environments.

Table 6 provides a comparison of this test to the original spark test which was performed on the qualification and flight tethers immediately after the FEP was extruded onto the copper conductor.

6.0 Tether Shipping/Handling and Testing (Post-Manufacturing Phase)

A line-item summary of tether shipping, handling and testing after completion of the tether build at Cortland Cable Co. is presented in Figures 8 through 12. This activity covers the period from the original shipment of the tether to Martin Marietta in 1987, through the final testing at KSC in the CITE stand in November 1995 for the TSS-1R mission.

Figure 8 documents the tether shipping and handling pedigree from shipment in 1987 through installation onto the flight reel in 1991. Tether testing at KSC prior to the TSS-1 mission in 1992 is presented in Figure 9 (Tether Circuit Instrumentation Test) and Figure 10 (Tether Path Testing). Tether testing after the TSS-1 mission was previously described in Section 5.

A number of Deployer modifications were performed after the TSS-1 mission. Figure 11 addresses the tether control during the off-line Deployer modification activity performed by Martin Marietta. Figure 12 identifies all testing that was performed on the flight tether following the TSS-1 mission.

7.0 Tether History Summary

Two overview summaries are provided in Table 7 which lists the pertinent procedures used during tether fabrication, and Table 8 which lists a chronological event summary of major milestones in the tether development activity. Figure 13 provides an overview of the reeling and unreeling of the tether from manufacturing to the TSS-1R mission.These tables are provided to enable a quick-look at the major processes and milestones.

Table 6 Comparison Between 1996 Manufacturing Spark Test and Spark Test on Recovered TSS-1R Tether

Spark Test Parameters	1986 Manufacturing Production Set-Up	1996 Spark Test of TSS-1R (MSFC Test Set-Up)
Line Speed	30 to 40 feet per minute Based upon total length and run time during the mfg. effort.	30 to 40 feet per minute
Tether Tension	Between 5 and 15 lb A minimum of 5 lb tension is required to overcome system friction during extrusion. More than 15 lb would stretch the wire core.	Between 2 and 15 lb
Voltage	10 kV dial setting Verified by Tensolite (ltr of 3/86) and specified in CCC-TSS-004 Process Procedure for FEP Insulation	10 kV dial setting Max Breakdown Current 4 mA
Spark-Tester Type	Clinton DC Impulse Sparker In the past 16 years, Tensolite has not seen any high voltage spark testers other than those from Clinton Instruments. Impulse tester referenced in 3/86 ltr.	Clinton Instruments Model IT-25B DC Impulse Spark Tester
Detectability	Based upon the success of finding one defect in flight tether and two defects in qual tether (relocated with 10 kV), Tensolite claims that the 10 kV spark test with this device is 100% reliable in detecting mfg. defects	100% reliable in detecting the smallest engineered defect as proven by tests at MSFC on April 11, 1996

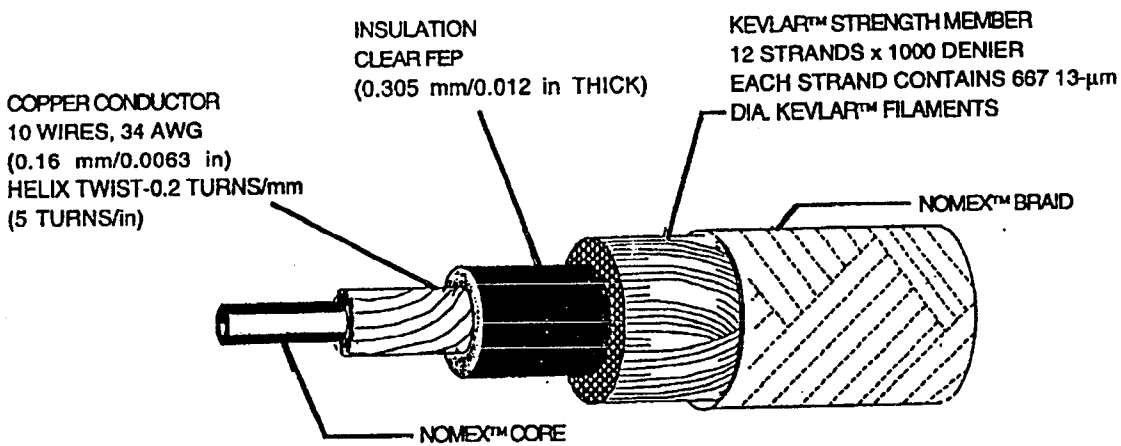
Table 7 List of Procedures Pertaining to TSS Tether Fabrication

1. PD9100050	Procurement Document for Tether
2. CCC-TSS-001	Flow Chart of Tether Construction Activity
3. CCC-TSS-002	Procured Material Inspection for Nomex Yarn
4. CCC-TSS-DP-002	Receiving Inspection for Nomex Yarn
5. CCC-TSS-201	Calibration Procedures
6. CCC-TSS-003	Procured Material Inspection for #34 AWG Conductor
7. CCC-TSS-DP-003	Receiving Inspection for Conductor Material
8. TSS-QAS-016	Source Inspection Requirement for PD9100050
9. CCC-TSS-101	Process Procedure for Conductor Stranding
10. TSS-86-REH-008	Limited QA Approval for Cortland Cable Co.
11. CCC-TSS-DP-101	Daily Inspection Log for Conductor Stranding
12. CCC-TSS-BW-101	Permanent Record for Buttweld Sections
13. CCC-TSS-004	Process Procedure and Receiving Inspection for FEP
14. CCC-TSS-004A	Process Procedure for Repair of FEP Insulation
15. CCC-TSS-004B	Process Procedure for Repair of Severed or Damaged Tether
16. CCC-TSS-005	Procured Material Inspection for Kevlar Yarn
17. CCC-TSS-103	Process Procedure for Strength Member Braiding
18. CCC-TSS-DP-103	Daily Log for Kevlar Braiding Operations
19. CCC-TSS-104	Process Procedure for Protective Jacket Braiding
20. CCC-TSS-DP-104	Daily Log for Protective Jacket Braiding
21. CCC-TSS-401	Process Procedure for Repair of Fully Severed Tether
22. CCC-TSS-105	Process Procedure - Final Inspection of Tether
23. CCC-TSS-DP-105	Final Inspection Report
24. CCC-TSS-301	Process Procedure - Tether Pack & Ship

Table 8 Chronological Event Sequence for TSS Flight Tether

3/85	Tether Preliminary Design Review (PDR) at MSFC
7-8/85	Cortland Cable Co. Builds 4000 ft. Engineering Tethers
10/85	Tether Critical Design Review (CDR) at MSFC
12/85	Production Authorization Granted for Cortland Cable Co.
3/86	Tether Fabrication Starts at Cortland Cable Co.
3-4/86	Copper Stranding Over Nomex Core at Cortland Cable Co.
5/86	FEP Extrusion at Tensolite, Inc.
7-12/86	Kevlar Braiding at Cortland Cable Co.
1-3/87	Nomex Braiding at Cortland Cable Co.
3/87	Pre-Ship Review at Cortland Cable Co.
4/87	Ship Tether from Cortland Cable Co. to Martin Marietta-Denver
5-6/87	Qualification Testing of Tether Samples at Martin Marietta
7/87 - 8/90	Store Flight Tether at Martin Marietta
9/90	Ship Flight Tether from Martin Marietta to KSC
9/90 -8/91	Store Flight Tether at KSC
9/91	Load Flight Tether on Flight Reel at KSC
10/91	Flight Tether Motion Test at KSC (~ 30 meters for low tension flyaway)
11/91	TSS-1 Tether Circuit Instrumentation Test (TCIT) at KSC
7-8/92	TSS-1 (STS-46) Mission - 256 meter Flight Tether Deployment
8/92 - 4/93	Store Flight Tether at KSC
4/93	Remove 300 m Flight Tether/Ship to Martin Marietta for Testing
5/93 - 8/94	Store Flight Tether at KSC
8/94	Perform 2 Full Deploy/Retrieve Cycles During Deployer 4S08 Test/KSC
6/95	TSS-1R Tether Circuit Instrumentation Test (TCIT) at KSC
7/95	Deployer Motor Power Conditioner (MPC) Overtorque Test at KSC
7/95	Tether Eyesplice/Satellite Connector Rework at KSC
8/95	Tether to Satellite Connection at KSC
2/96	TSS-1R (STS-75) Mission - 19695 meter Flight Tether Deployment
3-4/96	Post TSS-1R Inspection/Spark Testing of Remaining Flight Tether

Fig. 1 Tether Design Description



DIAMETER	2.54 mm (0.1 inch)
MAX MASS	8.2 kg/km (0.0055 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% AT 1780 N
ELEC BREAKDOWN VOLTAGE	10 kV (SPECIFIED), 15 kV (QUAL)
ELEC RESISTANCE	0.12 Ω/m (SPECIFIED), 0.15 Ω/m (ACTUAL AT ROOM TEMP)
LEAKAGE CURRENT	5 mAmp (Max) AT 10 kV-dc

Fig. 2 Manufacturing Processes - Conductor

- Copper Conductor (10 #34 AWG Strands) Over Nomex
- Copper Strands Available in ~3600 m Length
- Strands Joined End to End to Minimize Diameter Change
  - Butt Welding Process Used for Individual Copper Strands
  - Six (6) Butt Weld Sets in Flight Tether
    - 1 Set Includes 10 Joints Staggered at ~1.8 m Linear Intervals
  - Finished Distance: 1.6 m Between Joints Due to Helical Wrap
- Total Length of Buttweld Set ~ 16m Linear/14.4m in Helix

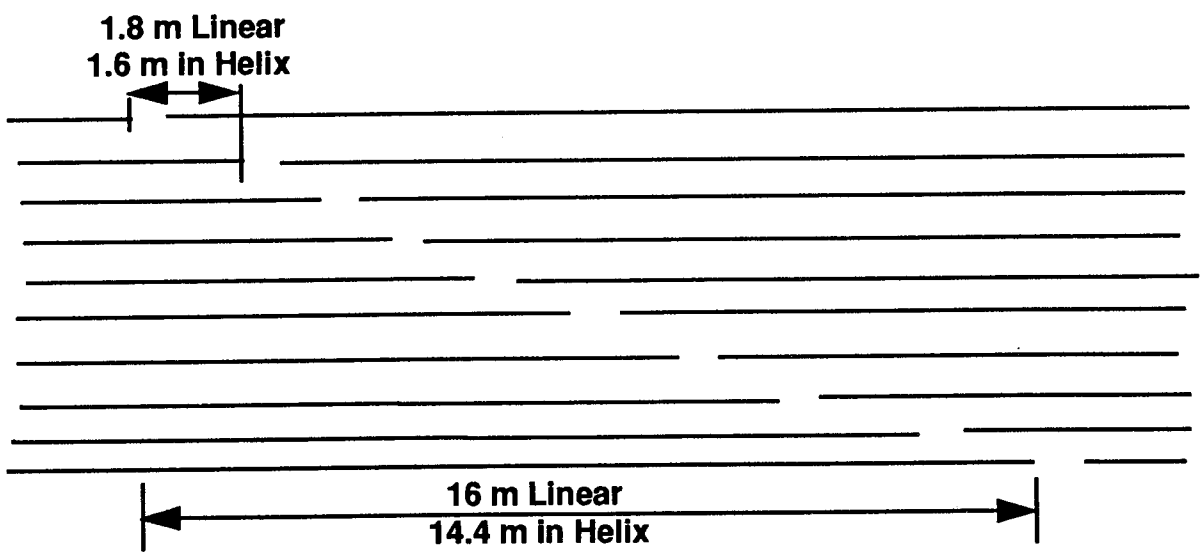


Fig. 3 Pre TSS-1 Testing - Engineering Tests

- Numerous Engineering Tests Performed on Flight-Like Tether Prior to Flight Tether Production (Aug. 1985 - Jan. 1986)
  - Breakstrength (Ambient, -100°C, +125°C)
  - Insulation Breakdown (Salt Water Tests, Foil Tests, High/Low Temps)
  - Insulation Chafing Tests (Translation/Bending of Insulated Conductor Over Sharp Edge, 100 Cycles, Breakdown at 24 kV)
  - Thermal Coefficient Testing (Elongation as Function of Temp)
  - Low Temperature Flexibility
  - Damping
  - Elongation/Hysteresis
  - Torsional Spring Rate

Fig. 4 Mfg Processes - Splice/Repair Summary

- Staggered Splices of Conductor, Kevlar and Nomex As Previously Described (Normal Manufacturing Processes)
- Full Tether Splice Joining Flight Tether to Tether Pigtail In Reel (Normal Installation Sequence - Location 9 m from Reel)
- Insulation Pinhole Repair (Deployment Distance ~11.8 km
  - Pinhole Found During Spark Test/Repaired During Kevlar Braiding
  - Repaired with Shrink Tube per Controlled Process/Retest to 10 kV
- Conductor Repair (Deployment Distance ~ 9.3 km)
  - Secondary Effect Caused by Pinhole Repair Sequence
  - Shrink Tube for Pinhole Repair Caused Braid Machine Jam
  - Repaired per Controlled Process/Retest Continuity and 10 kV
- Post TSS-1 Full Length Flight Tether Inspection
  - Nomex Jacket Fuzz Observed/Trimmed (L = 2.8 km)
  - Nomex Jacket Discoloration Inspected (L = 20.2 km)
  - No Internal Components Exposed/No Tension Spikes - Use As Is

Fig. 5 Pre TSS-1 Testing - Qualification Tests

- Qualification Testing Performed May - June 1987 at Martin Marietta
- Breakstrength (1780 N Requirement)
  - 16 Samples Flight Tether 1885 N/424 lb Avg.
  - 16 Samples Qual Tether 1906 N/428 lb Avg.
- Insulation Dielectric Strength (15 kV, 38 hr Requirement)
  - 16 Samples Qual & Flight Tether (32 Total)
  - No Breakdown in Salt Water Bath at 15 kV for 76 hr
- Thermal Vacuum (-100°C to +125°C, 10 E-6 Torr)
  - 2 Samples Qual & Flight Tether (4 Total)
  - Samples Installed in Chamber and Loaded to 110 N
  - Conductor Continuity Measured Continuously
  - 4 Cycles with 12 Hour Dwells at Each Temp Extreme

Fig. 5 Pre TSS-1 Testing - Qualification Tests (Cont)

- Post-Thermal Vacuum Breakstrength (1780 N/400 lb Requirement)
  - 2 Samples Flight Tether 1869 N/420 lb & 1914 N/430 lb
  - 2 Samples Qual Tether 2047 N/460 lb & 2114 N/475 lb

- Post-Thermal Vacuum Insulation Dielectric Strength (15 kV, 38 hrs)
  - 2 Samples Qual & Flight Tether (4 Total)
  - No Breakdown in Salt Water Bath at 15 kV for 38 hr

Fig. 6 Pre TSS-1 Testing - Qual Tether Usage

- After Qualification Sample Testing, Qual Tether Used for:
  - Tether Impedance Testing (Inductance, Capacitance) ~1988
  - Thermal Testing/Reel Wrap Temperatures ~ 1988
  - System Test Bed Software/Profile Verification Runs 1988-89
  - Flight Deployer System Development/Profile Verification 1989-90

- Qual Tether Currently Installed on System Test Bed

Fig. 6 Pre TSS-1 Testing - Qual Tether Usage (cont)

- Thermal Testing on Qualification Tether (1988 at Martin Marietta)
- Ten Layers (~2060 m) Qual Tether Installed on Reel
- Current Injected at 0.3 A, 0.5 A and 0.8 A
  - Thirty (30) Thermocouples Installed to Measure Temperatures
- Thermal Model Verified With This Test
  - Model Predicted Nodal Temperatures to Within 3.9°C or Better
- Flight Predictions Generated from Model After Accounting for Vacuum Environment
  - For Full Tether Wrap on Reel 0.45 A Could Be Run for 10 hr
  - At 20 km Deployment, 1.2 A Could Be Run for 10 hr

Fig. 7 Post TSS-1 Tether Inspection/Test Tasks

- Inspections/Tests Completed in April 1993
  - Inspection of Full 300 Meters (Gross Inspection - 100% Visual)
  - Tether Weight Measurement/Electrical Continuity
  - Breakstrength Tests (Nine (9) Samples + Control)
  - High Voltage Tests (Seven (7) Samples + Control)
  - Detailed Visual Inspection
    (Two Samples at 8X Magnification)
- Samples Taken From Both Satellite-End and Deployer-End of 300 Meter Section
  - Satellite-End:
    - Exposed to Space Environment
    - Realized Additional Ground Test/On-Orbit Mechanical Cycles
  - Deployer-End: Remained on Reel During TSS-1

Fig. 7 Post TSS-1 Tether Inspection/Test Tasks (cont)

- Tether Electrical Tests
  - All Samples (Including High Voltage Connector) Passed 10 kV
  - Resistance of 0.115 Ω/m (0.122 Ω/m Maximum Requirement)
    - This Section Had Been Subjected to UTCM Jams During Flight
  - Pre-Flight Measurement Was 0.098 Ω/m
  - Flight Tether Resistance (On Reel) Measured At 0.099 Ω/m
- Tether Weight
  - Weight of 7.36 kg/km (8.2 kg/km Maximum Requirement)
  - Approximate 3% Decrease from Pre-Flight Measurement
- Detailed Inspections
  - Two (2) Samples Measuring 0.5 m Each Inspected at 8X
  - No Degradation of Tether Components Observed
  - Minor Cosmetic Changes in Nomex Jacket in Isolated Sections
  - No Concerns

Fig. 8 Tether Shipping/Handling Pedigree

- Flight Tether Shipment (Cortland to Martin Marietta) - April 1987
  - Flight Tether Wrapped with Plastic
  - Desiccant Bags Installed Inside Plastic Wrap &Shipping Crate
  - Shipping Reel Installed in Crate
  - Shipping Mode (Ground)
- Tether Stored in Humidity and Temperature Controlled Stock Room (1987 - 1990)
  - Same Room Used for Storage of Other Flight Hardware
  - Stored Inside Shipping Crate
- Flight Tether Shipment (Martin Marietta to KSC) - Sep 1990
  - Flight Tether Wrapped with Plastic/Desiccant & Humidity Indicator Cards Installed
  - Shipping Mode (Ground Dedicated Truck)

Fig. 8 Tether Shipping/Handling Pedigree (cont)

- Flight Tether Transfer at KSC (Aug 27, 1991 to Sep 11, 1991)
  - Tether Transferred from Shipping Reel to EGSE Takeup Reel
  - Motor/Controller Installed on EGSE Takeup Reel
  - Transfer Operation Controlled to Maintain 10 to 12 lb Tension
- Tether Manually Routed from EGSE Takeup Reel Through:
  - EGSE Compliance Tower/Pulley
  - Deployer Flight Mechanisms
- In-Line Splice of Flight Tether to Tether Pigtail in Reel
- Remaining Tether Transfer to Flight Reel per 4S08 Test Procedure
  - Spooled 20 m Length Manually Onto Reel After In-Line Splice
  - Transferred 2020 m Under "EGSE Spooling Software" Control
  - Controls Flight & Takeup Reels, V = 0.6 m/s, Tension = 50 N
  - Transferred 19971 m Under Flight Software Control (Soft Stop Resume)

Fig. 9 Pre TSS-1 Testing - TCIT

- Tether Circuit Instrumentation Test (November 1991)
  - Full Tether Circuit Characterization (Flight Tether + Instruments)
  - Capacitance and Inductance Measurements
  - Continuity Test
  - High Voltage Proof Test to 5 kV

Fig. 10 Pre-TSS-1 Testing - Tether Path

- Mechanism Testing at Component Level With Qual Tether from 1987 through 1989
- Qual Tether Used for Mission Profile Deploy/Retrieve Ops at KSC (4S08) Testing August 1991
- Flight Tether Loaded from EGSE Tether Takeup Reel
  - Aug 27, 1991 to September 11, 1991
- Low Tension Flyaway During EMP IVT (Weight Drop Method)
  - Testing Occurred Approximately Sep - Oct 1991 Timeframe
  - Approximately 30 m Flight Tether Moved
- Flight Tether Deployed/Retrieved ~ 30 m for Satellite Eyesplice Fab and Installation
  - November 1991

Fig. 11 Tether Control During Offline Activities

- Modification Kit Installation (March 1994 - July 1994)
  - Installation Activities Performed By Trained Lockheed Martin Technicians
  - Installation Support Provided by Engineering and Product Assurance Personnel (Lockheed Martin and MSFC/KSC)
- Tether Handling Not Required for All Modifications
  - Tether Remained on Flight Reel/LTCM for Most Activities
- Multiple Technicians/Engineers Used for Manually Routing Tether As Required (Experienced Personnel)
  - Level Wind
  - LTCM/Lower Tether Cutter Mod
  - Boom Installation
  - Tether Eyesplice (Test Only - Flight Eyesplice Performed by MSFC in 1995)
- Note: Tether Handled During These Operations Was Removed Prior to Flight Eyesplice Termination in 1995

Fig.11 Tether Control During Offline Activities (cont)

- Deployer System Testing (O & C North Rails) - July to Sep 1994
  - Tether Deployment/Retrieval Operations Performed With Proven Software Controls
  - Security Level of Test Setup Consistent With O & C Practices
    - KSC Monitor
    - Badge Station

- Experienced Personnel Operating System
  - Heritage from Deployer Development Tests in Denver (Pre-TSS-1)

Fig. 11 Tether Control During Offline Activities (cont)

- Summary:
- Lockheed Martin Off-Line Activity Included:
  - Deployer Modification Activity (O & C Processing Room B)
  - Deployer System Testing (O & C North Rails)
- Security Measures Consistent With O & C Practices
- Hardware Installation/Test Procedures Coordinated With MSFC/ KSC
- Operations Performed by Experienced Lockheed Martin Personnel
- Tether Length Handled Manually During Mod Kit Installation Was Removed Prior to Flight (Prior to Flight Satellite Eyesplice)

Fig. 12 Post-TSS-1 Testing

- Tether Defined as One Mission Item for TSS-1 (CEI-02/MSFC-SPEC-2409)
- Testing on 300 m Section Removed from Reel (April 1993)
  - Included 256 m Section That Was Deployed/Retrieved
  - All Mechanical and Electrical Requirements Were Met
- Two Full Deployments/Retrievals at KSC (4S08 Test 1994)
  - One Deployment Went to Final Wrap on Reel
  - Aided in Inspection of Full Tether and Length Measurement
- Tether Circuit Instrumentation Test at KSC (1995)
  - Tether + Instruments Tested
  - Full Circuit Characterization
  - Continuity
  - High Voltage Proof Test to 5 kV

Fig. 12 Post-TSS-1 Testing (cont)

- Tether Path Testing (July - August 1994 at KSC):
- Two Full Deploy/Retrieve Profiles per Design Reference Mission
  - Included One Deploy to Final Wrap for Length Measurement
- Flyaway With Satellite Simulator (Nominal Thrust/Low Thrust)
- Low-Tension Flyaway (Weight Drop Method)
- Low-Tension Docking
- On-Station Yo-Yo (Control Law Capability Verification)
- Brake Circuit Trip (Length, Rate)
  - Brake Calipers Disabled/Verified Cutoff Circuitry

FLIGHT TETHER MANUFACTURING/TRANSFER SEQUENCE

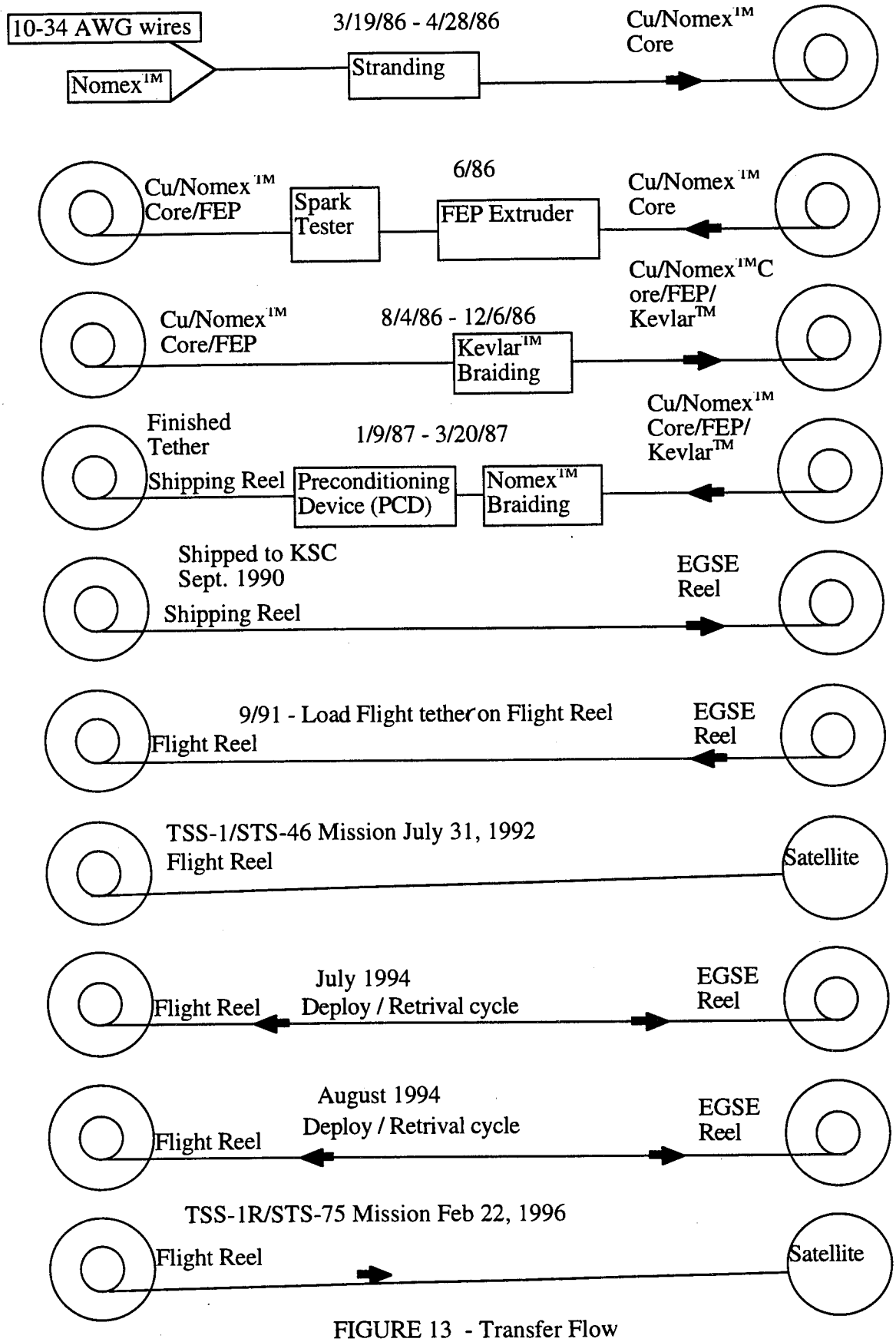


FIGURE 13 - Transfer Flow

Appendix C:

History of the TSS Conducting Tether

1. *Background*
2. *General Design Considerations*
3. *TSS-1 and TSS-1R Tether Design*
4. *Tether Fabrication Procedure Overview*
5. *Tether Testing*
6. *Tether Shipping/Handling and Testing*
7. *Tether History Summary*

Reference 1: Tether Manufacturing Timeline/Events

Reference 2: TSS-1 and TSS-1R Deployer Systems Test (#505)

Reference 3: Manufacturing Mapping Data

TSS-1R Deployer Detailed Schedule and Task

DATE	ACTIVITY	REMARKS
7/11/85	PD9100050, TETHER, CONDUCTING	NOTE: COMPARE PD9100050 DEVELOPMENT TESTS TO STANDARD HIGH VOLTAGE INSULATED WIRE TEST ACTIVITIES.
4/4/86	STATEMENT OF WORK (SOW) FOR "TETHER, CONDUCTING", PD9100050	
1/15/86	CCC-TSS-001, PROCEDURE WITH ACCEPT/REJECT CRITERIA	FLOW CHART OF TETHER CONSTRUCTION ACTIVITIES
1/15/86	CCC-TSS-201, CALIBRATION PROCEDURE	PROCEDURE TO CONTROL ACCURACY OF MEASURING AND TEST EQUIPMENT RELATIVE TO TETHER FABRICATION ACTIVITIES (SPARK TESTER IS NOT INCLUDED).
12/3/85	E.I. DuPONT DeNEMOURS & CO. CERTIFICATE OF CONFORMANCE NOMEX 200 DENIER 100-R79 ARAMID YARN ROTOSET BRIGHT TYPE 430	CUSTOMER ORDER # 86615 DuPONT ORDER # EL-9680 PI
2/15/86	CCC-TSS-002, PROCURED MATERIAL INSPECTION FOR NOMEX YARN	
1/15/86	CCC-TSS-DP-002, RECEIVING INSPECTION FOR NOMEX YARN	MERGE 1X006 200 DENIER NOMEX 430
12/12/86	OWL WIRE & CABLE: FINAL INSPECTION TEST REPORT 100-10-02	DIMENSIONAL INSPECTION
12/15/86	OWL WIRE & CABLE: CERTIFICATION OF COMPLIANCE: #34 AWG SOFT SOLID BATE COPPER	ASTM B374, QQ-W-343
4/1/86	CCC-TSS-003, PROCURED MATERIAL INSPECTION FOR #34 CONDUCTOR	

DATE	ACTIVITY	REMARKS
12/18/85	CCC-TSS-DP-003, RECEIVING INSPECTION FOR CONDUCTOR MATERIAL	NOTE: "SPOOLS DIRTY, BUT NOT DAMAGED., VERY UNIFORM. ALL REELS (STEEL SPOOLS) CLEANED, AND ALCOHOL WIPES INSTITUTED IN ALL TRANSFER OPERATIONS FROM BULK REELS TO STRANDING BOBBINS."
2/13/86	TSS-QAS-016, SOURCE INSPECTION REQUIREMENTS FOR PD9100050	REFERENCE: CONTRACT # NAS8-36000 PD 9100050 IS THE TETHER CONDUCTING SOURCE CONTROL DRAWING
2/15/86	CCC-TSS-101 PROCESS PROCEDURE STRANDING	
3/5/86	SPECIFICATION PD 9100050, COMPLIANCE CHECKLIST FOR CONDUCTING TETHER	CHECKLIST OF REQUIREMENTS AND METHODS OF ACCOMPLISHMENT @ CORTLAND CABLE CO.
1/16/86	TSS-86-REH-008, LIMITED QA APPROVAL FOR CORTLAND CABLE CO.	REFERENCE: PD9100050 TETHER, CONDUCTING MMC MEMO IDC # TSS-85-LSM-1040 11/4/85 NASA MEMO FA31 (349-85) 11/8/85
1/22/86	S/N 5321 "LIMITED APPROVAL" CORTLAND CABLE FOR PD9100050 ONLY	APPROVAL LIMITED TO MIL-I-45208A REQUIREMENTS

DATE	ACTIVITY	REMARKS
1/15/86	CCC-TSS-DP-101, STRANDING OPERATION DAILY INSPECTION LOG	**QUALIFICATION TETHER:** DATE: 3/19/86 TO 4/30/86 STRANDING MACHINE: 1 OPERATORS: DAVIS, BENTLY, EUSON, FIELD **FLIGHT TETHER:** DATE: 3/19/86 TO 4/25/96 STRANDING MACHINE 1 OPERATORS:DAVIS, EUSON

FLIGHT TETHER STRANDING OPERATION DAILY INSPECTION NOTES:

DATE	LENGTH/YD	OBSERVATIONS
3/19/86	0	STRANDING BEGINS
3/20/86	363	CUT OFF "FIX TRAVERSE"
3/20/86	700	SHORT SECTION OF NOMEX CORE EXPOSED
3/21/86	778	EXPOSED COMPARED TO WORKMANSHIP STD 301 (WS3
3/21/86	865	CUT OFF (CHECK WIRES)
3/21/86	1202	CUT OFF (CHECK WIRES)
3/22/86	1651	PLASTIC TUBE BROKE (REMOVED)
3/22/86	1653	FILE FLAT SPOTS ON SHAFT
3/24/86	2432	STOP FOR ADJUSTMENTS
3/25/86	2949	CUT OFF TO FIX MOTOR
3/25/86	3863	CUT OFF TO CHANGE BOBBINS/BUTT WELD SET 1
4/1/86	7818/7889	BUTT WELD SET 2
4/1/86	7924	BROKEN WIRE BUTT WELD FIX
4/2/86	8956	BROKEN WIRE BUTT WELD FIX (SEE SHEET)

4/5/86	11549	CUT OFF (RUNNING LOW)
	11812/11835	BUTT WELD SET 3
4/7/86	11812	BROKEN WIRE BUTT WELD FIX (RE-BUTT WELDED)
4/9/86	14340	CUT OFF TO CHANGE DIE
4/10/86	15454/15485	BUTT WELD SET 4
4/11/86	16386	CUT OFF TO REPLACE DIE
4/11-14/86	16553	CUT OFF FOR WEEKEND CHANGE DIES/4/14/86 4/14/86
4/14/86	17351	CUT OFF TO REPLACE DIE
4/16/86	18882/18921	BUTT WELD SET 5
4/18/86	21159	CUT OFF TAKE-UP REEL PROBLEM (REPAIRED)
4/22/86	22789/22800	BUTT WELD SET 6
4/28/86	26726	SLACK LINE TAKE UP TENSION INCREASE 45 TO 50
4/28/86	26780	CABLE ENDS
4/28/86	26793	FINISHED LENGTH

GROSS WEIGHT	SPOOL	NET STRANDED ASSEMBLY WEIGHT
131.0	11.6	119.4

DATE	ACTIVITY	REMARKS
12/15/96	CCC-TSS-BW-101, PERMANENT RECORD OF BUTT WELD SECTIONS	**QUALIFICATION TETHER:** DATE: 3/26/86 TO 4/29/86 STRANDING MACHINE: 1 OPERATORS: STEVE DAVIS, STAN EVSON, DOUG BENTLEY **FLIGHT TETHER:** DATE: 3/26/86 TO 4/22/86 STRANDING MACHINE: 3 OPERATORS: STEVE DAVIS, STAN EVSON
11/25/86	CERTIFICATION OF DAIKIN-NEOFLON FEP N-20 PRIME VIRGIN, SUMITOMO CORP.	
5/9/86	CCC-TSS-004 PROCESS PROCEDURE AND RECEIVING INSPECTION OF FEP INSULATION OF TETHER CONDUCTOR	
6/23/86	CCC-TSS-004A PROCESS PROCEDURE FOR REPAIR OF FEP INSULATION OF TETHER CONDUCTOR	
10/30/86	CCC-TSS-004B, PROCESS PROCEDURE FOR REPAIR OF SEVERED OR DAMAGED TETHER CONDUCTOR	
2/15/86	CCC-TSS-005, PROCURED MATERIAL INSPECTION FOR KEVLAR YARN	

DATE	ACTIVITY	REMARKS
12/6/86	E.I, DuPONT DeNEMOURS, INC. TEXTILES DEPT. KEVLAR 29, 1000 DENIER 666 ARAMID TYPE 964 (1) PACKAGE 284.9 LB.	SHIPPING PAPERS "KEVLAR"
12/15/86	CCC-TSS-005, PROCURED MATERIAL INSPECTION FOR KEVLAR YARN	
6/23/86	CCC-TSS-103 PROCESS PROCEDURE: STRENGTH MEMBER BRAIDING	

DATE	ACTIVITY	REMARKS
7/23/86	CCC-TSS-DP-103, BRAIDING OPERATIONS, DAILY INSPECTION LOG "KEVLAR BRAIDING"	**QUALIFICATION TETHER: 7/28/86 TO 12/4/86** MATERIAL/BRAID: KEVLAR 29, TYPE 960, 1000 DENIER (12) STRANDS BRAIDED @ 6 PPI BRAIDING MACHINE 12-301 OPERATORS: STEVE DAVIS, WILLARD FIELD, DOUG BENTLEY, WALLACE CARSON DAVE GIUMENTO **FLIGHT TETHER: 7/30/86 TO 12/6/86** MATERIAL/BRAID: KEVLAR 29, TYPE 960, 1000 DENIER (12) STRANDS BRAIDED @ 6 PPI BRAIDING MACHINE: 12-302 OPERATORS: W. FIELD, S. DAVIS, D. GIUMENTO, D. BENTLEY

FLIGHT TETHER DAILY INSPECTION LOG "KEVLAR BRAIDING"
NOTES:

DATE	LENGTH/YD.	OBSERVATIONS
8/4/86	3,483	M.S. TRIPPED EXCESS KEVLAR
8/6/86	5,360 5,453	BOBBIN LOAD
8/8/86	8,090 8,124	KEVLAR SPLICE
8/11/86	8,892	FEP LUMP
8/12/86	9,666	KEVLAR BRAKE AWAY FROM BOBBIN
8/12/86	9,738	BOBBIN REMOVED, CHECKED & RE-SPLICED

FLIGHT TETHER DAILY INSPECTION LOG "KEVLAR BRAIDING"
NOTES:

DATE	LENGTH/YD.	OBSERVATIONS
8/12/86	10,247	EXTRA TAKE-UP BELT ADDED
8/13/86	10,890 10,963	BOBBIN LOAD
8/13/86	11,259	FEP LUMP TRIPPED MS SENSOR DUE TO WIRE CROSS OVER". LUMP DIA. = .075 LUMP
8/13/86	11283	RESTARTED AFTER LUMP CHECK
8/13/86	11,563	VISIBLE LUMP ON PAY OFF OUTER (SEE SITE AT 11,763 YD.) LAYER IS A 3 "TO 4" LONG LUMP". NOTE THAT LUMP IS SEVERAL HUNDRED FEET AWAY AND SHOULD TRIP MS.
8/14/86	11,763	LUMP IN FEP 4.5" LNG., O.D. = 0.80" (TRIPPED MICROSWITCH) TETHER PRODUCTION HALTED PENDING MRB REF. MARS G44634 AND CCC-TSS-DP-004B CONDUCTOR REPAIR."
11/13/86	11,929	REPLACED LEVEL WIND WITH INDEPENDENT UNIT FOR BRAIDING MACHINE 12302
11/13/86	12,148	COLLAR FELL OFF "SHAFT STICKING"
11/13/86	12,346	SHUT DOWN DUE TO LEVEL WIND
11/14/86	12,350	CHANGE BACK TO COMMON LEVEL WIND
11/14/86	13,277	KEVLAR RAN OUT

FLIGHT TETHER DAILY INSPECTION LOG "KEVLAR BRAIDING"
NOTES:

DATE	LENGTH/YD.	OBSERVATIONS
11/15/86	13,277 13,299	LOAD BOBBIN
11/16/86	13,874	REPLACED TANGLED BOBBIN
11/16/86	13,998	LOCATED FLAG INDICATING PINHOLE MARKED AT TENSOLITE
11/16/86	14,122	STOPPED TO OBSERVE FLAG POSITION PENDING FEP INSULATION REPAIR
11/17/86	14,389	STOPPED PENDING PINHOLE REPAIR (REPAIR PROCEDURE). SEE CCC-TSS-DP-004A INSULATION REPAIR RESULTS (11/19/86)
11/19/86	14,396	PINHOLE REPAIRED PER CCC-TSS-DP-004A
11/19/86 11/20/86	14,954	STOPPED---CABLE WAS OUT OF ALIGNMENT "CHECK OUT FOUND ALIGNMENT WAS OKAY"
11/21/86	15,970 15,994	(12) BOBBIN CHANGE OUT AT (2) YARD INCREMENTS
11/21/86	16,723	STOP--BOBBIN TANGLED
11/22/86	16,773	BAD BOBBIN REPAIRED
11/24/86	18,301	STOP
11/25/86	18,660	SPLICED IN BOBBIN

FLIGHT TETHER DAILY INSPECTION LOG "KEVLAR BRAIDING"
NOTES:

DATE	LENGTH/YD.	OBSERVATIONS
11/25/86	18,710	BUMP @ 18,727 AND 18,744 SMALL BUMPS VISIBLE UNDER MAGNIFICATION
11/26/86	19,050	BUMPS @ 19,086 THRU 19,089
11/26/86	19,515	STOPPED---MICROSWITCH SHUT OFF
11/26/86	19,565	@ 19,579 (6) MICROSWITCH TRIPS IN 15 MINS. CAN NOT FIND PROBLEM. CHECKED MICROSWITCHES
11/28/86	19,707	SPARE BOBBIN SPLICED IN TO COVER FOR SHORT LENGTH BOBBIN
11/28/86	19,781	APPROX. 1 FT. LONG SWELL IN FEP. O.D. = 0.965" CAUSED REPEATED MICROSWITCH TRIP. O.D. RESURVEYED NO MORE DETAILS
12/1/86	19,982 20,004	SPLICE
12/2/86	21,979	OUT OF KEVLAR
12/3/86	22,513 22,535	SPLICE BOBBINS
12/3/86	22,557	BUMP
12/3/86	22,654	LUMP
12/5/86	24,905 24,925	SPLICE

FLIGHT TETHER DAILY INSPECTION LOG "KEVLAR BRAIDING"
NOTES:

DATE	LENGTH/YD.	OBSERVATIONS
12/5/86	25,261	LUMP
12/5/86	25,451	NO KEVLAR
12/6/86	25,451	BUMP @ 25,556
12/6/86	25556	BUMP. SWITCH TRIPPED SLIGHT DIAMETER INCREASE.
12/6/86	26,308	KEVLAR BRAIDING COMPLETE

DATE	ACTIVITY	REMARKS
9/22/86	TSS-86-LM/CL-386, TRIP REPORT INVESTIGATION OF TETHER INSULATION DEFECTS AT CORTLAND	DETAILS OF PROPOSED REPAIR TO AN INSULATION LUMP (APPROX. 4" LONG DEFECTIVE AREA) ON FLIGHT. TETHER
9/26/86	MAJ-86-0252, CONCERNS/RECOMMENDATIONS	CONCERNS AND RECOMMENDATIONS AS TO THE MFG. OF PD9100050, TETHER, CONDUCTING @ CORTLAND CABLE CO.

DATE	ACTIVITY	REMARKS
10/4/86	CCC-TSS-DP-004B, CONDUCTOR REPAIR INSPECTION RESULTS NOTE: EVIDENTLY THE TENSOLITE VS. CORTLAND LENGTH DISAGREEMENT BEGINS WITH THESE REPAIR ACTIVITIES.	**QUALIFICATION TETHER:** DATE: 11/6 TO 7/86 FAULT LOCATION: 12,364 YD BRAIDING MACHINE: 12-301 REFERENCE: MMDA MARS 682717 DATE: 11/13/86 FAULT LOCATION: 41,800 FT./13,933 YD. TENSOLITE 38,988 FT./12,996 YD. CORTLAND BRAIDING MACHINE: 12-301 NOTE: CONTAMINATION UNDER FEP. DATE: 12/4/86 FAULT LOCATION: 83,136 FT./27,712 YD. TENSOLITE 78,924 FT./26,308 YD. CORTLAND NOTE: FOREIGN MATTER IN NOMEX CORE **FLIGHT TETHER:** DATE: 11/7/86 FAULT LOCATION: 11,769 YDS. BRAIDING MACHINE: 12-302 REF. MARS G44634 CONDUCTOR REPAIR DATE: 11/17/86 FAULT LOCATION: 46,362 FT./15,454 YD. TENSOLITE 43,188 FT./14,396 YD. CCC BRAIDING MACHINE: 12-302 NOTES: OBVIOUS FAULT, CONTAMINATION IN FEP WALL, COPPER STRANDING CLEAN AND UNIFORM

DATE	ACTIVITY	REMARKS
12/16/86	MAJ-86-0387, AUTHORITY TO PROCEED QUALIFICATION TETHER NOMEX BRAIDING	REFERENCE: MMC CONTRACT # RH5-401004
1/7/87	MAJ-87-0002, AUTHORITY TO PROCEED FLIGHT TETHER NOMEX BRAIDING	REFERENCE: MMC CONTRACT # RH5-401004
12/27/85	E.I. DuPONT DeNEMOURS & CO. CERTIFICATE OF CONFORMANCE FOR NOMEX 1200 DENIER 600-0 ARAMID YARD BRIGHT TYPE 430	CUSTOMER ORDER # 86-616 DuPONT ORDER # EL9679 PI
12/17/86	CCC-TSS-104, PROCESS PROCEDURE PROTECTIVE JACKET BRAIDING	

DATE	ACTIVITY	REMARKS
12/18/86	CCC-TSS-DP-104, PROTECTIVE JACKET BRAIDING "DAILY INSPECTION LOG"	**QUALIFICATION TETHER:** 12/17/86 TO 3/17/87 MATERIAL/BRAID: NOMEX 430 1200 DENIER (8) STRANDS BRAIDED @ 16 ppi BRAIDING MACHINE: 8401 OPERATORS: BENTLEY, SAMPSON, DAVIS, CARSON, BARROWS **FLIGHT TETHER:** 1/8/87 TO 3/20/87 MATERIAL/BRAID: NOMEX 430 1200 DENIER (8) STRANDS BRAIDED @ 16 ppi BRAIDING MACHINE: 8402 OPERATORS: DOUG BENTLEY, T. SAMPSON, BRIAN BARROW, STEVE DAVIS, WALLACE CORSON **FLIGHT TETHER NOMEX BRAIDING "DAILY INSPECTION LOG" NOTES:**

DATE	LENGTH/YD.	OBSERVATIONS
1/9/87	830	BOBBIN RAN OUT
1/12/87	837	CHANGE 8 BOBBINS
1/12/87	1169	STICK TRIPPED MICROSWITCH
1/13/87	1682	STOPPED LEVEL WIND
1/14/87	1717	CHANGE BOBBINS
1/15/87	2471	TAKE UP TROUBLE
1/16/87	2644	RETRACK LEVEL WIND
1/16/87	2732	FIX MICROSWITCH
1/20/87	3798	STOPPED FOR TROUBLE

			"UNKNOWN NATURE" BAD COPY
		1/22/87	4522	SPLICE BOBBINS
		1/23/87	5176	STOPPED BECAUSE OF LEVEL WIND
		1/27/87	5475	SPLICE BOBBINS
		1/27/87	5979	STOPPED FOR LEVEL WIND
		1/28/87	5983	HAD TO FIX LEVEL WIND ON REEL
		1/28/87	6223	BROKEN LEVEL WIND
		1/29/87	6405	OUT OF NOMEX
		1/30/87	6422	SPLICE BOBBINS
		1/30/87	6560 6579	MARS H 52671 ITEM 2
		2/2/87	7200	ADJUST LEVEL WIND. BOTH UNITS STOP WHEN SOLENOID FAILS ON 8402 (FLIGHT BRAIDER)
		2/3/87	7369	BOBBIN CHANGE
		2/4/87	7402	SPLICING IN BOBBINS
		2/5/87	8373	LOAD BOBBINS
		2/9/87	9412	SPLICING IN BOBBINS
		2/10/87	10313, 10329	STOPPED
		2/11/87	10333	BRAIDER # 8402 SHUT DOWN FOR REPAIRS

		2/11/87	10679	PINHOLE REPAIR TRIPPED DIAMETER GAGE 2633 YD TO FULL REPAIR = 13,312 YD REFERENCE: MARS H52671
		2/12/87	10981	SPLICE BOBBINS
		2/12/87	11194	SPOOL RAN OUT
		2/13/87	11265	SPLICE BOBBINS
		2/17/87	12190	SPLICE BOBBINS
		2/19/87	13150	OFF-LINE PROOF LEAD PERFORMED
		2/19/87	13192	SPLICE IN BOBBINS
		2/19/87	13289	TETHER REPAIR MARS 52671
		2/20/87	14036	SPLICE BOBBINS
		2/20/87	14107	STOPPED (SWITCH)
		2/23/87	14152	LINE OFF METER
		2/24/87	14996	SPLICED (2) BOBBINS
		2/25/87	15596	FIXED LEVEL WIND
		2/26/87	15820	SPLICE BOBBINS
		2/26/87	15891	TAKE-UP SLIPPING (TIGHTEN)
		2/27/87	16264	FIX TAKE-UP TENSION CONTROL ARM
		2/27/87	16710	STOPPED
		3/2/87	16987	SPLICE IN BOBBINS

		3/3/87	17529	REPLACE SOLENOID
		3/4/87	17961	BOBBIN RAN OUT/SPLICING IN BOBBINS
		3/4/87	18305	STOP-SPOOLS BROKE OFF
		3/5/87	18711	STOP
		3/6/87	19045	SPLICE BOBBINS
		3/9/87	20032	STOP SPLICE BOBBIN
		3/9/87	20064	SPLICE BOBBIN
		3/9/87	20084	SPLICE BOBBIN
		3/10/87	20121	SPLICE BOBBINS
		3/11/87	21072	WITNESS BRAID. SPLICE BOBBINS
		3/11/87	21120	BACK-UP TO TAKE OUT KEVLAR BALL < 0.10"
		3/13/87	22101	SPLICE IN BOBBINS
		3/16/87	23105	CHANGE BOBBINS
		3/18/87	24172	SPLICE IN BOBBINS
		3/19/87	24723	STOPPED
		3/20/87	24886	NOMEX BRAID OPERATION COMPLETE

DATE	ACTIVITY	REMARKS
8/13/86	CCC-TSS-401, PROCESS PROCEDURE FOR REPAIR OF FULLY SEVERED TETHER	
7/27/86	CCC-TSS-105, PROCESS PROCEDURE--FINAL INSPECTION TETHER, CONDUCTING	CORTLAND CABLE CO.,--FINAL INSPECTION
1/30/87	S/N 6674 "LIMITED APPROVAL": FOR PD9100050 ONLY	
3/25/87	INTEROFFICE MEMO: L. MARSHALL TO JACOBS, WAGNER, AND WISSERT; MMDA/CORTLAND CABLE CO. VERIFICATION RESPONSIBILITIES: REF. TETHER	DELINEATES SPECIFIC VERIFICATION REQUIREMENTS PERFORMED AT CORTLAND AND THOSE TO BE PERFORMED AT MARTIN MARIETTA
3/20/87	CCC-TSS-DP-105, FINAL INSPECTION REPORT	**QUALIFICATION. TETHER:** RESULTS DATED 4/1/87 "IN FILE" **FLIGHT TETHER:** DATE: 4/2/87 LENGTH: 72,495 FT. DIAMETER: "IN SPEC" W/EXCEPTIONS (SEE MARS) DISCREPANCY POINTS: MARS H52671 GROSS WT.: 585 LB. (TETHER + REEL) REEL: 205 LB. TETHER NET: 380 LB. LINEAR DENSITY: 5.09 LB./M FT. FLIGHT TETHER RESISTANCE: 2242 Í /30.0 Í /1000 FT. SPARK TEST DURING EXTRUSION: DONE SPARK TEST REPAIRS: DONE SUMMARY OF VISUAL INSPECTION: SEE MARS H52671

DATE	ACTIVITY	REMARKS
3/20/87	CCC-TSS-301, PROCESS PROCEDURE: PACKAGING/SHIPPING	
3/20/87	CCC-TSS-DP-301, PACKAGING AND SHIPPING FORM	QUALIFICATION TETHER: 4/2/87 FLIGHT TETHER: 4/2/87
6/12/87	TSS-010 CORRECTIVE ACTION PROBLEM SUMMARY	MARS: H52671 AND H74148 CONDUCTING, TETHER (PD9100050-010) FLIGHT. **PROBLEMS:** **1.)** O.D. > 0.10" IN (2) LOCATIONS FAILED PRECONDITIONING TENSION (100-150 LB.) **2)** EXCESSIVE LEAKAGE CURRENT IN TEST SYSTEM (HYPOT TESTER) TSS-2E11-01, PARA. 4.3.19
6/20/87	MARS B13928, TEMPERATURE OUT OF SPEC (-106 ∞C TO -94 ∞C)	ITEM: PD910050V010 FLIGHT TETHER TEST PROCEDURE: TSS 2E12-01, PARA. 4.3.15
3/31/87	MARS B 13936, FLIGHT TETHER O.D. OUT OF SPEC	ITEM: PD9100050V010, FLIGHT TETHER
8/19/86	MARS G44634, FLIGHT TETHER OVERSIZED AND IRREGULAR O.D. IN EXTRUDED INSULATION	ITEM: PD9100050V010, FLIGHT TETHER REPAIRED PER CCC-TSS-004B QUESTION: A REGULAR SYMMETRICAL FEP SURFACE IS VERY IMPORTANT. WHY WERE OTHER IRREGULARITIES NOT EXAMINED CLOSELY?
8/23/91	TSS-9M44-01, ENGINEERING TEST ORDER; TAKE-UP REEL TETHER CHANGE OUT	OFFICIAL TEST COPY (FROM KSC) 8/27/91 QUAL TETHER IS SPOOLED OFF TETHER TAKE-UP REEL (TTUR) ONTO THE SYSTEM TEST BED REEL AND THE FLIGHT TETHER IS SPOOLED OFF THE FLIGHT TETHER SHIPPING REEL ONTO THE TTUR.
5/6/94	NSP 00461, FABRICATION OF SHORT TETHER-TO-SATELLITE EYE SPLICE	7/21/95: "AS -RUN PROCEDURE"

DATE	ACTIVITY	REMARKS
3/2/95	EYE SPLICE SAMPLES; BREAKING STRENGTH RESULTS	
5/95	MSFC-PROC-2531, NONSTANDARD PROCEDURE , TERMINATION OF TETHER HIGH VOLTAGE CONNECTOR	
1990-1992?	TSS-4S08-01, DEPLOYER POST INTEGRATION FUNCTIONAL TEST (KSC) TSS-1 (MANY ACTIVITIES)	TSS-1/STS-46 THIS PROCEDURE PROVIDES INFORMATION NECESSARY TO VERIFY TSS DEPLOYER FUNCTIONAL OPERATION AFTER DEINTEGRATION FROM THE EH PALLET AND INTEGRATION ONTO THE FLIGHT PALLET AT KSC.
11/1/91	T1-TSS-1-005, TETHER CIRCUIT INSTRUMENTATION TEST/TEST & ASSEMBLY PROCEDURE (TAP)	TSS-1/STS-46 THE OBJECTIVE OF THIS TEST IS TO MEASURE THE ELECTRICAL CHARACTERISTICS OF THE INTEGRATED TSS-1 CONDUCTING TETHER CIRCUIT @ KSC.
1994-1996?	TSS-4S08-01, DEPLOYER POST INTEGRATION FUNCTIONAL TEST (KSC) TSS-1R	TSS-1R/STS-75 THIS PROCEDURE PROVIDES INFORMATION NECESSARY TO VERIFY TSS DEPLOYER FUNCTIONAL OPERATION AFTER DEINTEGRATION FROM THE EH PALLET AND INTEGRATION ONTO THE FLIGHT PALLET AT KSC.
11/1/95	T1-TSS-1-005, TETHER CIRCUIT INSTRUMENTATION TEST/TEST & ASSEMBLY PROCEDURE (TAP)	TSS-1R/STS-75 THE OBJECTIVE OF THIS TEST IS TO MEASURE THE ELECTRICAL CHARACTERISTICS OF THE INTEGRATED TSS-1 CONDUCTING TETHER CIRCUIT @ KSC.

Exclusions

Historical information excluded from this publication at this time include:

1. The extrusion process performed at Tensolite.
2. Inspection log or observation reports regarding the extrusion process at Tensolite.
3. A comprehensive listing of individual test events where the directly involving the tether at Tensolite (the FEP extrusion facility, Martin Marietta, and KSC).

4. Existing video records of tether spooling activities should be available through the TSS Project Office,

Appendix C:

History of the TSS Conducting Tether

1. *Background*
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5. *Tether Testing*
6. *Tether Shipping/Handling and Testing*
7. *Tether History Summary*

Reference 1: Tether Manufacturing Timeline/Events

Reference 2: TSS-1 and TSS-1R Deployer Systems Test (4S08)

Reference 3: Manufacturing Mapping Data

TSS-1R Deployer Detailed Schedule and Task

Timeline of TSS 1 4S08 Test

DATE	SECTION	DESCRIPTION	PURPOSE
8/06/91	4.3.1	Deployer Isolation	Verify Deployer Power and Signal Returns and Isolations
8/8/91	4.3.2	Power Systems	Verify power polarity to Deployer
8/8/91	4.3.3	Communications	Verify EGSE/DACA/MCA Communications links
8/8/91	4.3.4	Tension Operations	Verify tether tension readings are operational.
8/8/91	4.3.5	Brake and Launch Lock functional	Verify Reel Brake and Launch Lock functions.
8/9/91	4.3.6	Brake Test Manual Operations	Verify Brake Manual Engagement and Disengagement.
8/12/91	4.3.7	Brake Test- Trip on Length and Rate	Verify MCA Brake circuits correctly trip on length and rate.
8/13/91	4.3.8	Brake Test-Trip on Power Off	Verify brake activates when power is removed
8/13/91	4.3.9	Brake Test-Tension	verify Reel Brake will slip at Specified Tension
8/13/91	4.3.10	Satellite Interface	Verify Satellite ICD

Timeline of TSS 1 4S08 Test

DATE	SECTION	DESCRIPTION	PURPOSE
8/15/91	4.3.12	Design Ref Mission -	Verify System Operations during
8/17/91		Deploy	Nominal Deploy
8/16/91	4.3.11	Heaters/Temperature Sensors	Verify Deployer Thermal Control System Operation
8/17/91	4.3.13	Design Ref Mission Operations during On Station Activities	Verify System Operations during on station activities.
8/19/91	4.3.14	Design Ref Mission-Retrieval	Verify system operations during nominal retrieval
8/20/91	4.3.15	Design Ref Mission-Low tension flyaway	Verify system operations through simulated satellite flyaway
8/20/91	4.3.16	Low tension docking control laws enabled	Verify system operations through simulated satellite docking.
8/20/91	4.3.17	Design Ref Mission Low tension docking	Verify system operations through simulated satellite docking.
8/20/91	4.3.18	Contingency-Low Tension flyaway Brake Recovery	Verify Reel Brake recovery during flyaway
8/20/91	4.3.19	Contingency-Low Tension flyaway Vernier off before next station	Verify contingency method of Satellite Low tension flyaway

Timeline of TSS 1 4S08 Test

DATE	SECTION	DESCRIPTION	PURPOSE
8/20/91	4.3.20	Contingency Low Tension flyaway measure slump	Measure tether slump that occurred between LTCM and reel.
8/20/91	4.3.21	Contingency Low Tension flyaway run spike vs delay time	Measure run spike that occurs when Vernier on command is delayed after deploy command
8/22/91	4.3.24	Detail Ops-Latches	Verify SRL operations and preload
8/22/91	4.3.26	Pyro functions-Energy	Verify level of energy at Pyro
8/22/91	4.3.25	Satellite Docking Ring Rotation	Verify Docking ring rotation
8/26/91	4.3.27	Pyro functions - S&A	Verify Pyro resistance & S&A plug
8/27/91 9/10/91	4.3.23	Load Flight Tether	(Tether failed post splice continuity test, KSC PR PC-2-000453)
9/10/91	4.3.28	Load Flight Tether to on station	
9/11/91	4.3.29	Design Ref Mission-Soft Stop/Resume Retrieve	Verify system operations during soft stop/resume during retrieval

Timeline of T[illegible]R 4S08 Test

DATE	SECTION	DESCRIPTION	PURPOSE
7/27/94	4.3.1	Deployer Isolation	Verify Deployer Power and Signal Returns and Isolations
7/29/94	4.3.2	Power Systems	Verify power polarity to Deployer
7/29/94	4.3.3	Communications	Verify EGSE/DACA/MCA Communications links
7/29/94	4.3.4	Tension Operations	Verify tether tension readings are operational.
7/29/94	4.3.5	Brake and Launch Lock functional	Verify Reel Brake and Launch Lock functions.
8/1/94	4.3.6	Brake Test Manual Operations	Verify Brake Manual Engagement and Disengagement.
8/1/94	4.3.7	Brake Test- Trip on Length and Rate	Verify MCA Brake circuits correctly trip on length and rate.
8/3/94	4.3.8	Brake Test-Trip on Power Off	Verify brake activates when power is removed
8/3/94	4.3.9	Brake Test-Tension	Verify Reel Brake will slip at Specified Tension
8/5/94	4.3.40	Satellite Simulator Flyaway at Low Thrust	Verify Satellite Flyaway with 2 Newton Thrust.
8/8/94	4.3.41	Satellite Simulator Flyaway-Nominal	Verify Satellite Flyaway with 4 Newton Thrust.

Timeline of T[illegible]R 4S08 Test

	SECTION	DESCRIPTION	PURPOSE
8/9/94	4.3.11	Heaters/Temperature	Verify Deployer Thermal Control
8/10/94		Sensors	System Operation
8/11/94	4.3.12	Design Ref Mission - Deploy	Verify System Operations during Nominal Deploy
8/12/94	4.3.13	Design Ref Mission Operations during On Station Activities	Verify System Operations during on station activities. (Last three steps performed on 8/15/94)
8/12/94	4.3.50	Tether Measurement	Measure the amount of tether on the Reel
8/16/94	4.3.14	Design Ref Mission-Retrieval	Verify system operations during nominal retrieval
8/17/94	4.3.15	Design Ref Mission-Low tension flyaway	Verify system operations through simulated satellite flyaway
8/17/94	4.3.16	Low tension docking control laws enabled	Verify system operations through simulated satellite docking.
8/17/94	4.3.17	Design Ref Mission Low tension docking	Verify system operations through simulated satellite docking.
8/22/94	4.3.22	Design Ref Mission-Soft Stop/Resume Deploy	Verify system operations during soft stop/resume during deployment

Timeline of TSS 1R 4S08 Test

DATE	SECTION	DESCRIPTION	PURPOSE
8/23/94	4.3.60	Profile Deploy 20 km-20.7 km	Verify system operations from 20 km to 20.7 km
8/23/94	4.3.61	Manual Pulse, 20km to 20.7 km	Verify system operations from 20 km - 20.7 km using manual pulse control
8/24/94	4.3.29	Design Ref Mission-Soft Stop/Resume Retrieve	Verify system operations during a soft stop resume during retrieval.
8/25/94	4.3.24	Detail Ops-Latches	Verify SRL operations and preload
8/25/94	4.3.26	Pyro functions-Energy	Verify level of energy at Pyro
8/28/94	4.3.10	Satellite Interface	Verify Satellite ICD
8/28/94	4.3.30	Launch Lock Reset Reel Cover Installation	
8/29/94	4.3.25	Satellite Docking Ring Rotation	Verify Docking ring rotation
8/30/94	4.3.51	Umbilical Test	Verify U1 can be mated and demated using STM
8/31/94	4.3.27	Pyro functions - S&A	Verify Pyro resistance & S&A plug
9/1/94	4.3.52	Tether Isolation	Verify Tether resistance and isolation

TSS-1 4S08

- During the flight tether loading (4.3.23);
- The flight inboard tether side was exposed to the O&C building during the 8/27-9/10 period. The tether break area was buried by approximately 2400 meters of tether.

- During the overnight period 9/10 - 9/11 (Between 4.3.28 - 4.3.29); Tether was loaded to on station position of overnight. The next day 19479 m of tether was loaded on the reel. The location of the break was on the outer layer of the TUR overnight.

- After Design Reference Mission- Deploy (4.3.12) and before the Operations on station (4.3.13)
- Tether was loaded to on station position overnight (8/11-8/12). 20674M was left on the take-up reel overnight (4.3.12.64). Depending on reel timing, the break location was on the outer layer of the Reel or TUR.

- From the completion of tether measurement (4.3.50) to the start of retrieval (4.3.14)
- From 8/12 to 8/16, 21449 m of tether was left on the take up reel. The location of the break was buried on the TUR.

- From the completion of the soft stop deploy (4.3.22) to the start of the 20km to 20.7 km profile deploy (4.3.60).

- Overnight (8/22-8/23), 19971 m of tether was left on the take up reel overnight. The break location was on the outer wrap of the TUR.

- From the completion of manual pulse deploy from 20 to 20.7 km (4.3.61) to the start of Soft stop retrieval (4.3.29)

- Overnight (8/23 - 8/24), 20678m of tether was left on the take-up reel overnight. Depending on the reel timing, the break location was on the outer layer of the Reel or TUR.

- After Design Reference Mission- Deploy (4.3.12) and before the Operations on station (4.3.13)
- Tether was loaded to on station position overnight (8/11-8/12). 20674M was left on the take-up reel overnight (4.3.12.64). Depending on reel timing, the break location was on the outer layer of the Reel or TUR.

- From the completion of tether measurement (4.3.50) to the start of retrieval (4.3.14)
- From 8/12 to 8/16, 21449 m of tether was left on the take up reel. The location of the break was buried on the TUR.

- From the completion of the soft stop deploy (4.3.22) to the start of the 20km to 20.7 km profile deploy (4.3.60).
- Overnight (8/22-8/23), 19971 m of tether was left on the take up reel overnight. The break location was on the outer wrap of the TUR.

- From the completion of manual pulse deploy from 20 to 20.7 km (4.3.61) to the start of Soft stop retrieval (4.3.29)
- Overnight (8/23 - 8/24), 20678m of tether was left on the take-up reel overnight. Depending on the reel timing, the break location was on the outer layer of the Reel or TUR.

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History of the TSS Conducting Tether

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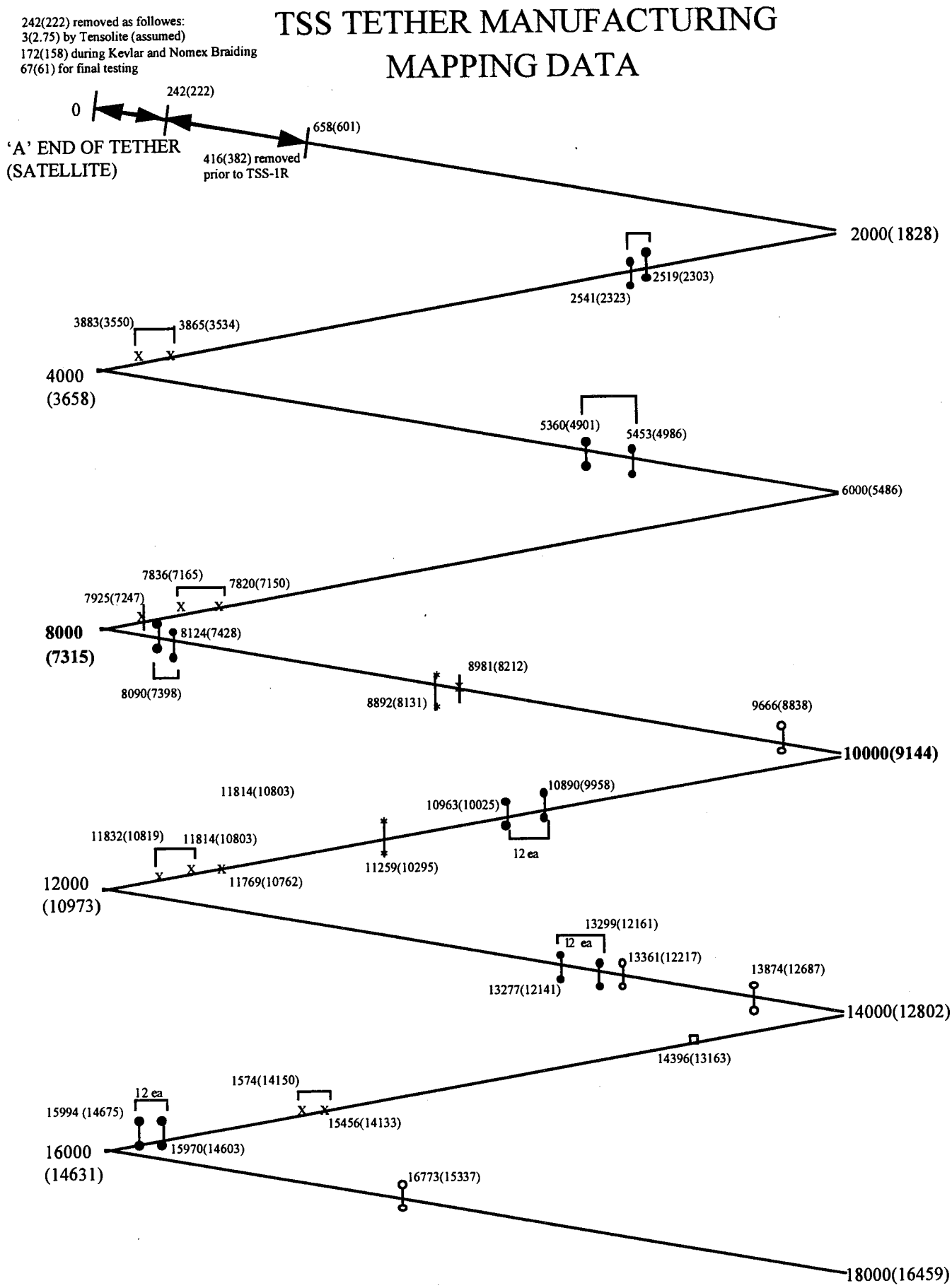
Reference 1: Tether Manufacturing Timeline/Events

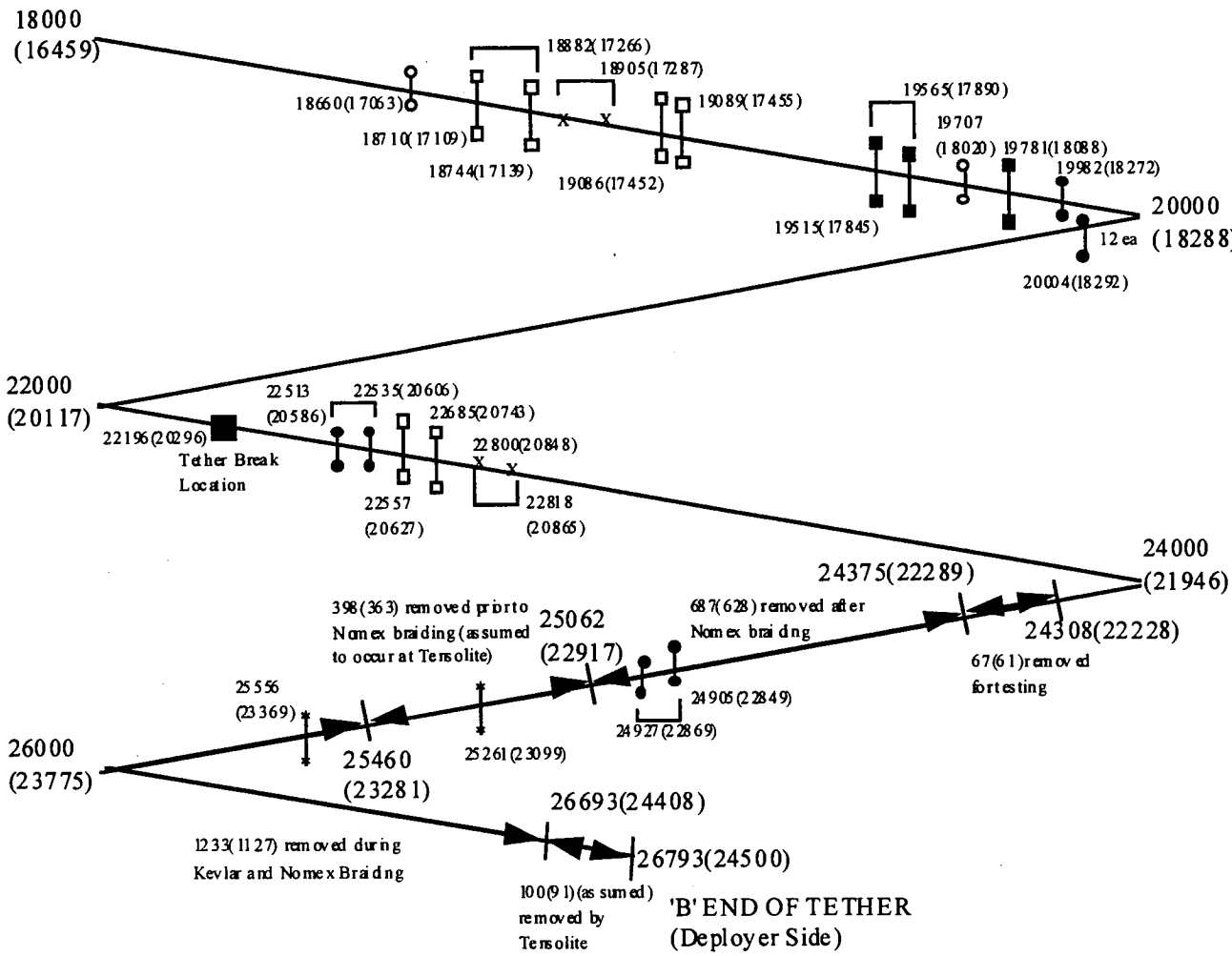
Reference 2: TSS-1 and TSS-1R Deployer Systems Test (4S08)

Reference 3: Manufacturing Mapping Data

TSS-1R Deployer Detailed Schedule and Task

TSS TETHER MANUFACTURING MAPPING DATA





SYMBOL KEY:

x - Copper Welds

- Kevlar Seams/Splices

- Set of Kevlar Seams/Splices

- Kevlar Seams/Splices (One strand only)

- Copper (Cu) Repair (One strand only)

x x - Set of Welds

- Lumps

- Pinhole Repair

- FEP Bumps

- OD Oversize

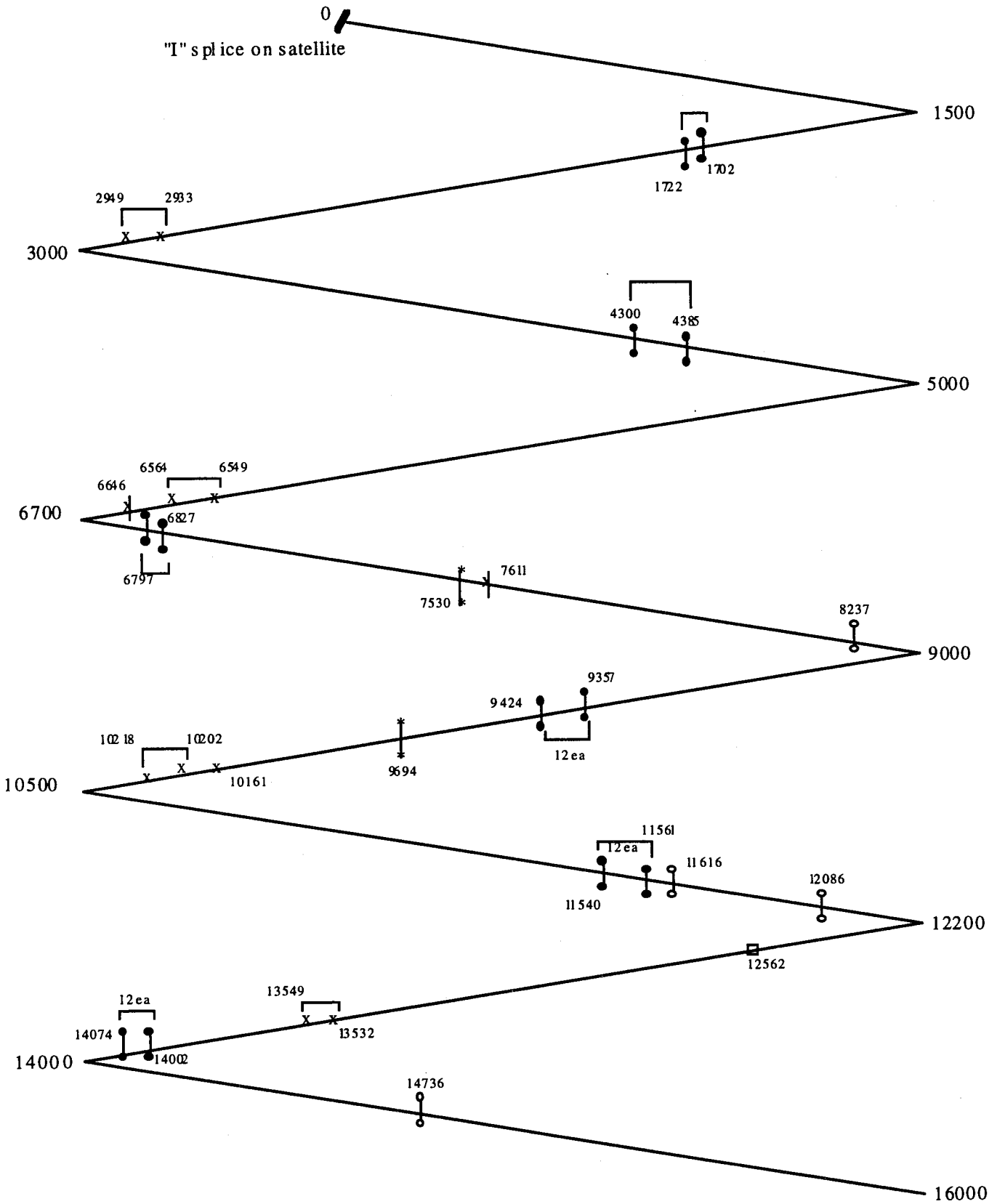
NOTES:

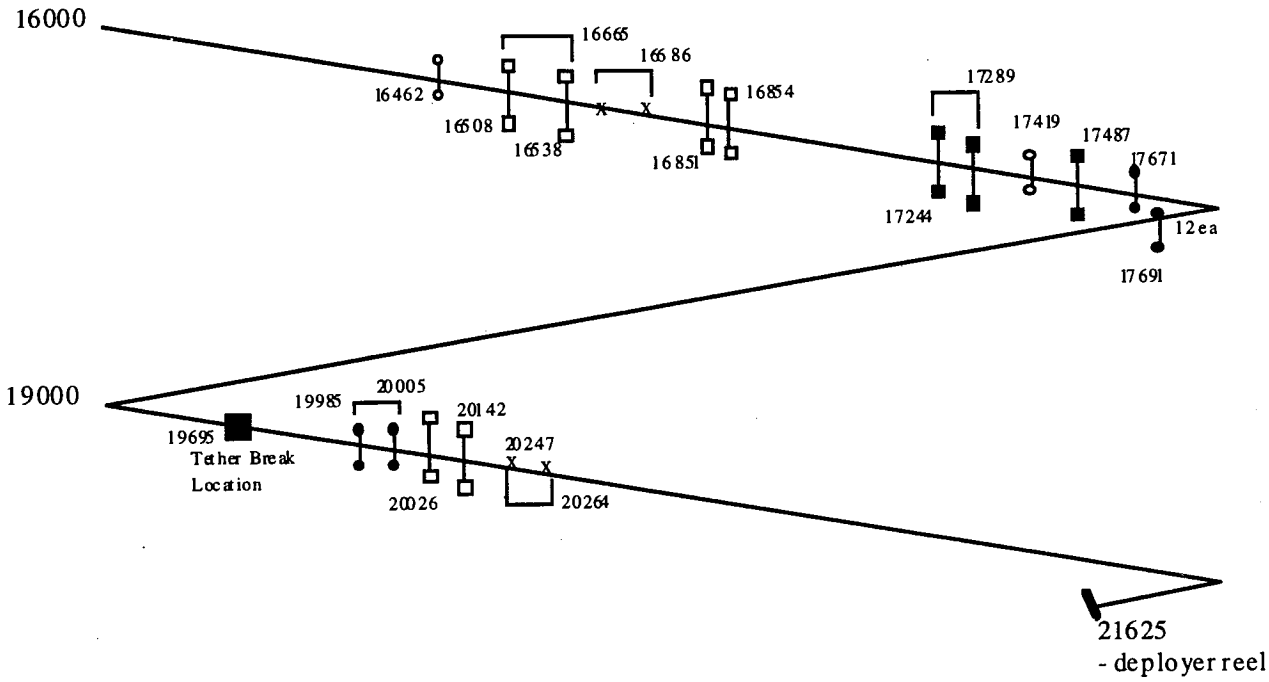
1) THIS DOCUMENT IS NOT TO SCALE.

2) LOCATIONS OF ANOMALIES, ETC. ARE BASED ON DATA PROVIDED FOLLOWING A REVIEW OF TETHER BUILD RECORDS.

3) ALL DIMENSIONS STATED ARE IN YARDS (METERS).

TSS 1R FLIGHT TETHER MAPPING DATA (METERS)





SYMBOL KEY:

x - Copper Welds

- Kevlar Seams/Splices

- Set of Kevlar Seams/Splices

- Kevlar Seams/Splices (One strand only)

- Copper (Cu) Repair (One strand only)

x x - Set of Welds

- Lumps

- Pinhole Repair

- FEP Bumps

- OD Oversize

NOTES:

1) THIS DOCUMENT IS NOT TO SCALE.

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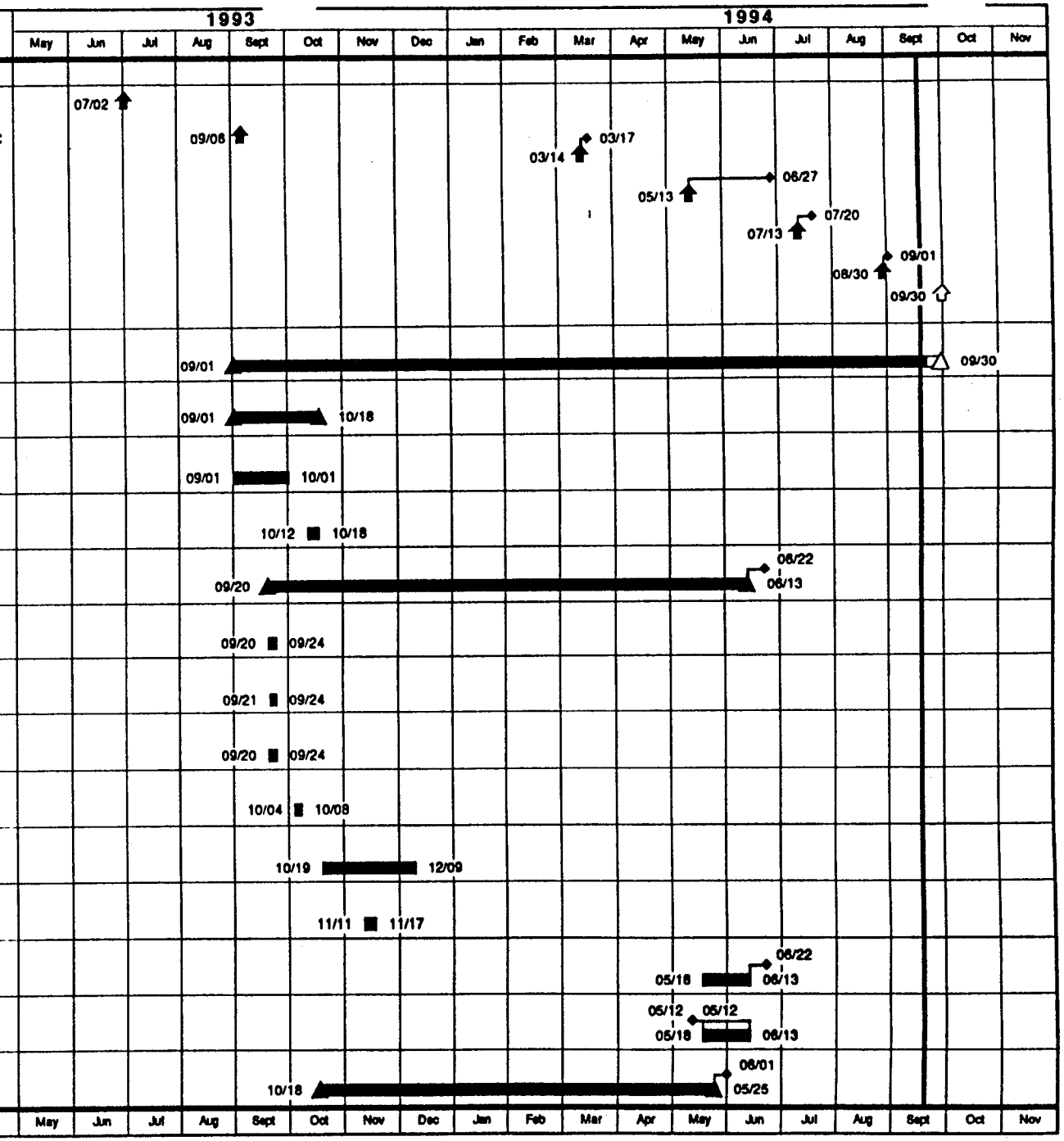
Reference 1: Tether Manufacturing Timeline/Events

Reference 2: TSS-1 and TSS-1R Deployer Systems Test (4S02)

Reference 3: Manufacturing Mapping Data

TSS-1R Deployer Detailed Schedule and Task

Task No.	Activities
	MAJOR MILESTONES
0.1	• INITIATE DEPLOYER HARDWARE MODIFICATIONS
0.2	• INITIATE MMA TASK TRANSITION TO MSFC
0.3	• INITIATE DEPLOYER HARDWARE INSTALLATION OPERATIONS AT KSC
0.4	• COMPLETE HARDWARE MOD KIT PACK AND SHIP
0.5	• COMPLETE DEPLOYER H/W MOD INSTALLATION AND TEST
0.6	• COMPLETE DEPLOYER SYSTEMS TEST
0.7	• COMPLETE DEPLOYER HARDWARE TURNOVER TO MSFC
1.0	KSC DEPLOYER OPERATIONS
1.1	DEPLOYER TRANSFER TO MMA
1.1.1	Conduct Deployer Hardware Audit
1.1.2	Transfer Deployer to MMA
1.2	DEPLOYER MAINTENANCE AND INSPECTION
1.2.1	Inspect Satellite Restraint Latches
1.2.2	Inspect Level Wind
1.2.3	Inspect Pallet Mounted Equipment
1.2.4	Troubleshoot Level Wind
1.2.5	Conduct Dye Penetrant Inspection
1.2.6	Inspect Reel Brake
1.2.7	Test Motor Shield
1.2.8	Test Docking Ring Motor Shield
1.3	DEPLOYER INSTALLATION PROCEDURES



Task No.	Activities	1993 May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	1994 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov
1.3.1	Update Procedures to Remove MCA						10/18	11/05												
1.3.2	Develop U1 Mechanical Installation Procedures							12/15	01/17											
1.3.3	Develop U1 Resistor Bypass Installation Procedures							12/23	01/07											
1.3.4	Develop U2 Function Transfer Installation Procedures								01/17	02/14										
1.3.5	Develop Level Wind Installation Procedures										03/07	03/11								
1.3.6	Update MCA Installation Procedures									01/25	02/14									
1.3.7	Update GSE Checkout Procedures											03/23	04/19							
1.3.8	Review GSE Checkout Procedures												04/20	05/03	05/16					
1.3.9	Release GSE Checkout Procedures													05/04	05/17	05/16	06/01			
1.3.10	Develop Lower Tether Cutter Installation Procedures											03/14	03/16	04/05	04/07					
1.3.11	Develop U2 Mechanical Installation Procedures											03/21	04/15	04/13						
1.3.12	Update Deployer Boom Installation Procedures (MMC Inputs Complete)											04/04	04/21							
1.3.13	Develop Eye Splice Installation/Validation Procedures												04/28	05/25	05/06					
1.4	DEPLOYER MODIFICATION INSTALL AND TEST						10/19								06/20	07/20				
1.4.1	LEVEL WIND REFURBISHMENT						10/19						03/25							
1.4.1.1	Remove and Ship Connecting Rod To Denver						10/19	10/22												
1.4.1.2	Level Wind Mod On-Dock											03/14	03/16							
1.4.1.3	Install Level Wind Mod											03/14	03/17	03/18	03/21					
1.4.1.4	Set LW Timing, Align Gearbox and Install Chain (Preliminary)											03/21	03/25							
		May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov

Task No.	Activities
1.4.2	RESISTOR BYPASS MODIFICATION
1.4.2.1	Resistor Bypass Modification On-Dock
1.4.2.2	Install Resistor Bypass Modification
1.4.2.3	Test Resistor Bypass Mod
1.4.3	PYRO CIRCUIT REFURBISHMENT
1.4.3.1	Pyro Circuit Equipment on Dock
1.4.3.2	Perform Primary Pyro Circuit Refurbishment
1.4.3.3	Test Primary Pyro Circuit
1.4.3.4	Perform Secondary Pyro Circuit Refurbishment
1.4.3.5	Test Secondary Pyro Circuit
1.4.4	U2 UMBILICAL FUNCTION TRANSFER MODIFICATION
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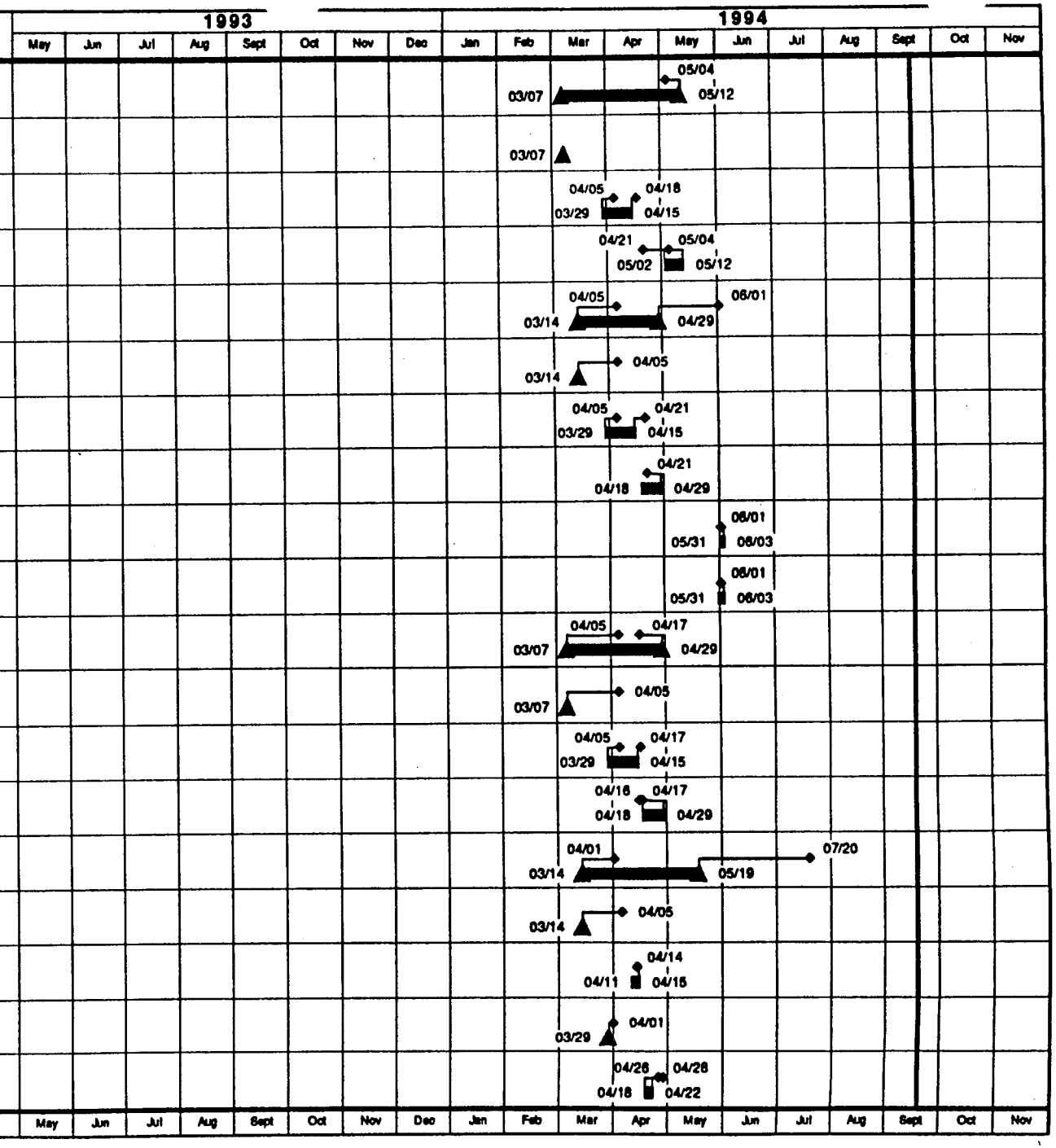
1.4.5.2	Modify STM U1 Bracket (Alenia)
1.4.5.3	Structural Test Model On-Dock
1.4.5.4	Install Structural Test Model on Deployer



Task No.	Activities
1.4.5.5	Install and Test U1 Mechanism Mod
1.4.5.6	Evaluate Pull Test Data and Verify Vlier Pins
1.4.5.7	Remove Structural Test Model
1.4.5.8	Conduct U1 Vlier Pin Engineering Evaluation
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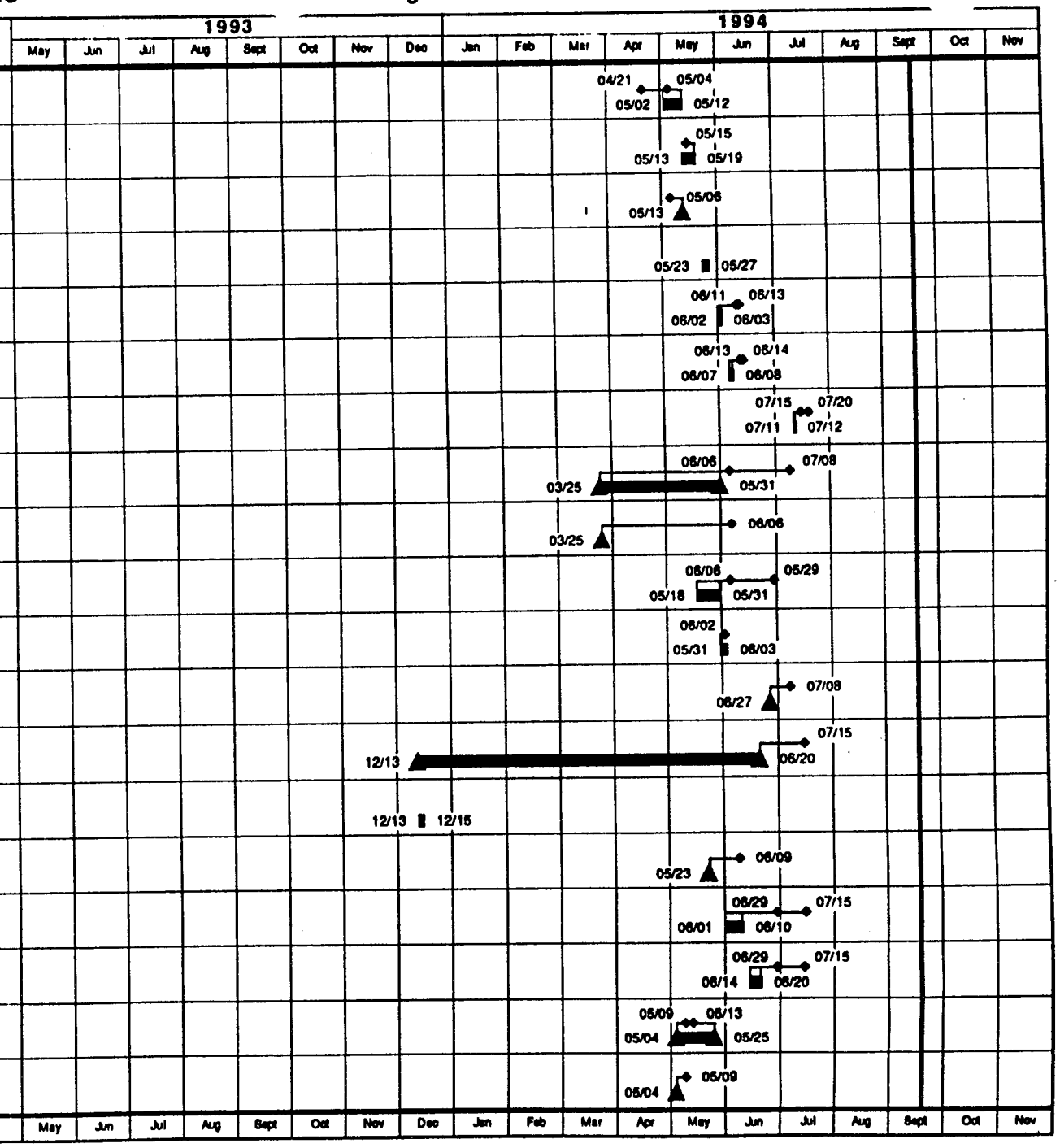
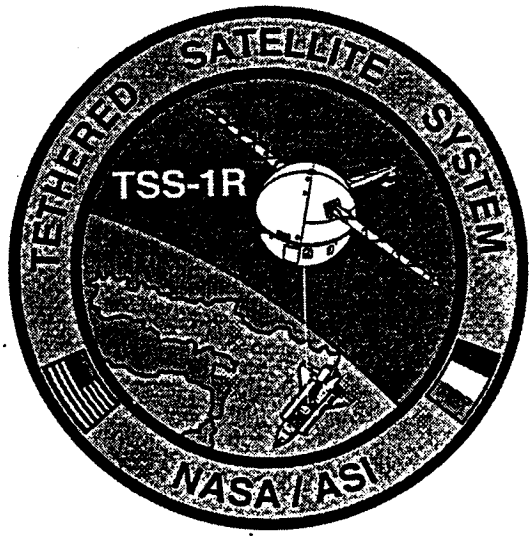
1.4.7.1	Remove MCA from Pallet and Ship to Denver
1.4.7.2	MCA Mod On-Dock
1.4.7.3	Install MCA Mod
1.4.7.4	Test MCA Mod
1.4.8	**LOWER TETHER CUTTER MODIFICATION**
1.4.8.1	Lower Tether Cutter Mod On-Dock



Task No.	Activities	1993 May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	1994 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov
1.4.8.2	Install and Test Lower Tether Cutter Mod												05/10 05/12	05/13 05/25						
1.4.9	SUPPORT SKIP ROPE DAMPER TEST											04/11	04/13 04/15							
1.4.10	INSTALL DOCKING RING ASSEMBLY												05/25	06/06 05/31	07/08					
1.4.11	REDUNDANT POWER PATH MODIFICATION													06/27 07/01	07/15					
1.4.11.1	Redundant Power Path Mod Kit On-Dock													07/01	06/27					
1.4.11.2	Fabricate Redundant Power Path EGSE Cable													07/05	07/07 07/08					
1.4.11.3	Fabricate, Install and Test Redundant Power Path Mod													07/05	07/15					
1.5	DEPLOYER BOOM INSTALL AND TEST												05/13	05/23 06/20	07/20					
1.5.1	Boom/Tip Can On-Dock												05/13	05/23						
1.5.2	Replace Boom Separation Nuts													06/16	06/13 06/15 06/21					
1.5.3	Install Boom/Tip Can													05/31	06/22 06/13	07/20				
1.5.4	Test Boom/Tip Can													06/14	06/27 06/20	07/20				
1.6	DEPLOYER SYSTEM TEST (4S08)					10/19												09/01 08/30		
1.6.1	SYSTEMS TEST GSE PREPARATION					10/19										07/22 07/08				
1.6.1.1	Ship GSE From KSC to Denver					10/19	10/29													
1.6.1.2	GSE On Dock												05/13		06/13					
1.6.1.3	Conduct GSE Inventory												05/16	05/17	06/16 06/17					
1.6.1.4	Install and Checkout GSE												05/18		06/20 07/06 07/08					
1.6.1.5	Fly Wheel and Weldment On Dock												05/31		06/22					
		May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov



Appendix D:

KSC Deintegration Plan

1.0 KSC Anomaly Investigation Deintegration Plan
2.0 KSC Payloads Summary Report
3.0 KSC Photo documentation and Radiographic Procedures
4.0 Photo of Salad Bowl Yellow Spot
5.0 Photo of Micrometeorite Hit

KSC Deintegration

The TSS-1R Deintegration function included all activities at Kennedy Space Center associated with the inspection of the flight hardware and the removal and shipment of appropriate hardware to MSFC and various vendors. All activities were performed in accordance with the Deintegration Plan developed by the MSFC /KSC Deintegration Team and approved by the TSS-1R Mission Failure Investigation Board (See Attachment 1).(Copy on the MSFC file server)

The inspection effort began with the opening of the Orbiter Payload Bay doors (See Attachment 2 KSC Payloads Summary Report of The TSS-1R Mission Failure Investigation report) for chronological details of KSC deintegration activities.). After orbiter radiator inspection, a detailed photo inspection and video taping of the TSS-1R payload was performed to compare with pre-flight photos. The only off-nominal condition noted was a yellow (see photo attachment 4) discoloration of the "salad bowl" within the boom. (does not cover detailed inspections ordered by the Board)

Special electrical bond checks were performed between the pallet and orbiter and between the MPESS and the pallet. All results were nominal.

The remaining payload removal preparations, removal and installation in the Operations and Checkout (O&C) building test stand were performed per normal operating procedures.

Initial inspections, prior to removal of any hardware, including the multiple layer insulation (MLI) blankets, were performed by the MSFC and KSC Inspection Team, including micrometeroid inspection. One micrometeroid impact on the upper outside rail area of the TSS structure was found (see photo attachment 5). This impact was outside of the MLI cover therefore was not a factor in the failure of the tether.

The pyrotechnic devices were tested and found to be intact proving that there was no inadvertent firing of any of the devices. All inspections were augmented by photographic and video documentation. *(All Videos and Photos will be retained at KSC)*

The transportation canister was inspected for debris. All debris was collected, bagged, tagged and delivered to the MSFC Materials Laboratory for analysis.

The MLI blankets were systematically removed for more detailed inspections. No blanket damage was noted and no anomalous conditions under the blankets, including the tether path within the deployer and the reel cover, were noted.

The reel cover was removed to allow access to the separated tether end. The cover, fasteners and shims were tagged and impounded at KSC facilities. The configuration and position of the tether or the reel were recorded, photographed, and video taped. Both normal and magnified photographs of the tether end were taken. Tether end protection was installed and 27 meters of tether were manually unspooled from the reel and cut off.

The removed section of the tether was inspected, photographed, photographed under a microscope, video recorded and x-rayed. (See attachment 3 Photodocumentation and Radiographic Procedures for TSS-1R Tether report). The tether portion was then bagged, packaged and hand-carried to the MSFC Materials Laboratory for more detailed analysis.

TSS-1R payload power isolation checks were performed. All readings were within specification and essentially equal to the pre-flight data with the exception of the main DC positive and return to MPESS structure readings. Post-flight readings of 122 Kohms and 119 Kohms were recorded versus the pre-flight readings of 2.2 Mohms and 2.2 Mohms. The change in resistance is explained by the Science Power Control Box (SPCB) relays remaining closed during the last on-orbit deactivation.

The Lower Tether Control Mechanism (LTCM) was visually inspected, photographed and video recorded. No anomalous conditions were noted on the external surfaces. A visual inspection into the openings (without penetrating the openings) revealed what appeared to be residue characteristic of arcing on at least one pulley guide. The LTCM was removed from the SSA, packaged and shipped to MSFC for disassembly, inspection and analyses.

A deployer boom to pallet bond check was performed with nominal results. The deployer boom was removed from the Satellite Support Assembly (SSA). The tipcan to docking ring structure bond check was performed indicating proper isolation. The docking ring, salad bowl, and U2 umbilical assembly were removed from the boom assembly and shipped to MSFC for further analyses. The SSA and U1 umbilical connector were inspected with no anomalies noted. The boom assembly was packaged and shipped to the vendor, Abel Engineering in Golita, California for a deployed inspection.

The approximate 2 kilometers of tether remaining on the reel was tested for continuity from the tether end to the slip ring with the expected reading of 182.35 ohms. Proper isolation of tether conductor to ground was also verified.

The Lower Tether Cutter was removed, NASA Standard Initiators (NSIs) removed, packaged and shipped to MSFC. The interior of the tether reel assembly was inspected and some amount of debris was noted. The debris locations was documented and photographed. The debris was removed, bagged, labeled and shipped to the MSFC material Laboratory for analysis.

The remaining tether (approximately 2 kilometers) was transferred from the reel assembly to an 8-inch diameter reel. The transfer was performed by hand while using a manual level wind technique onto the take-up reel. The tether transfer operation was photographed and video taped. the entire length was inspected during the transfer process and care was taken to capture all debris. The tether was packaged and shipped to MSFC for spark testing and other analysis.

Attachments:

1 - KSC Anomaly Investigation Deintegeration Plan (On the MSFC file server)

2 - KSC Payloads Summary Report (Final Report to be here Wed 4 (5/1/96) from KSC)

3 - KSC Photodocumentation and Radiographic Procedures for TSS-1R Tether report

4- - Photo of Salad bowl Yellow spot

5 - Photo of Micro Hit

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4.0 Photo of Salad Bowl Yellow Spot

5.0 Photo of Micrometeorite Hit

Tethered Satellite System

Anomaly Investigation Deintegration Plan

(Revision A)

TETHERED SATELLITE SYSTEM
ANOMALY INVESTIGATION DEINTEGRATION PLAN
(Revision A)

Prepared By:

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Tether Satellite System
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Approved By:

_____

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ABBREVIATIONS AND ACRONYMS

ASI	Agenzia Spaziale Italiana
DCE	Direct Current Electronics
DCORE	Deployer Core Equipment
EGA	Electron Generator Assembly
EGSE	Electrical Ground Support Equipment
FU	Flight Unit
GSE	Ground Support Equipment
KSC	Kennedy Space Center
MMI	Marshall Management Instruction
MPE	Mission Peculiar Equipment
MPESS	Mission Peculiar Experiment Support Structure
MSFC	Marshall Space Flight Center
O&C	Operations and Control facility
PED	Payload Element Developer
SETS	Shuttle Electrodynamic Tether System
SPREE	Shuttle Potential and Return Electron Experiment
TOP	Tether Optical Phenomena
TSS	Tethered Satellite System
TSSPO	Tethered Satellite System Project Office

APPLICABLE DOCUMENTS

This section contains a listing of documents that serve as references only for this document. Latest revision is applicable unless otherwise noted.

K-PSM-11.50.2 Launch Site Support Plan
K-STSM-14.1.14 O&C Building Payload Processing and Support Capabilities
KHB-1700-7A Space Transportation System Payload Ground Safety Handbook

MSFC-STD-126E Inspection, Maintenance, Proof Testing and Certification of Handling Equipment
MSFC-DOC-2311 Tethered Satellite System to Shuttle Electrodynamic Tether System Operations and Integration Agreement
MSFC-DOC-2282 Tethered Satellite System to Satellite Operations and Integration Agreement
MSFC-DOC-2302 Tethered Satellite System to DCORE Operations and Integration Agreement
MSFC-DOC-2403 Tethered Satellite System to Deployer Operations and Integration Agreement
MSFC-RQMT-2310 Tethered Satellite System Ground integration Requirements Document
NASA Contract NAS8-39381

1.0 INTRODUCTION

There will be three phases to the Tethered Satellite System (TSS) anomaly investigation deintegration and test activity. Phase 1 & 2 cover the anomaly investigation activities at Kennedy Space Center (KSC) and Phase 3 covers the deintegration and test activity required at other facilities.

1.1 PURPOSE

This plan serves as the basis for planning deintegration, testing, handling, packaging, transportation, and storage requirements for the TSS elements and associated equipment during the anomaly investigation period.

1.2 SCOPE

All deintegration and test aspects with regard to the TSS elements, support equipment, and associated supply support are covered by this plan. This plan is the official information source within the Anomaly Investigation Board for guiding deintegration and test activities for TSS items.

2.0 KSC DEINTEGRATION/TEST (Phase 1&2 "Anomaly Investigation")

Phase 1 will begin once the Orbiter is placed in the Orbiter Processing Facility (OPF) and payload bay doors have been opened. All activity associated with Phase 1 will be documented on Interim Problem Report (IPR) SL-TSS-01R-0029. This phase is non-intrusive and includes photographic survey of the payload prior to its removal from the Orbiter and continues with visual inspection and photography through out the O&C activity, see figure 1. The photographic requirements are contained in KSC Photographic Plan. Security around the payload will be required and is covered in KSC Security Plan.

Phase 2 begins in the O&C after KSC has safed the TSS and the Closed Circuit Television Cameras have been removed. During this phase the Investigation team will begin "Intrusively" inspecting, investigating and testing the TSS hardware, see figure 2. The Marshall Space Flight Center (MSFC) Deintegration and Test Engineering Team will provide assistance, expertise, and consultation to support the KSC Payload Processing Team in the

development of processes and procedures to implement approved investigation requirements, to be executed by KSC's engineers and technicians who perform the deintegration activity.

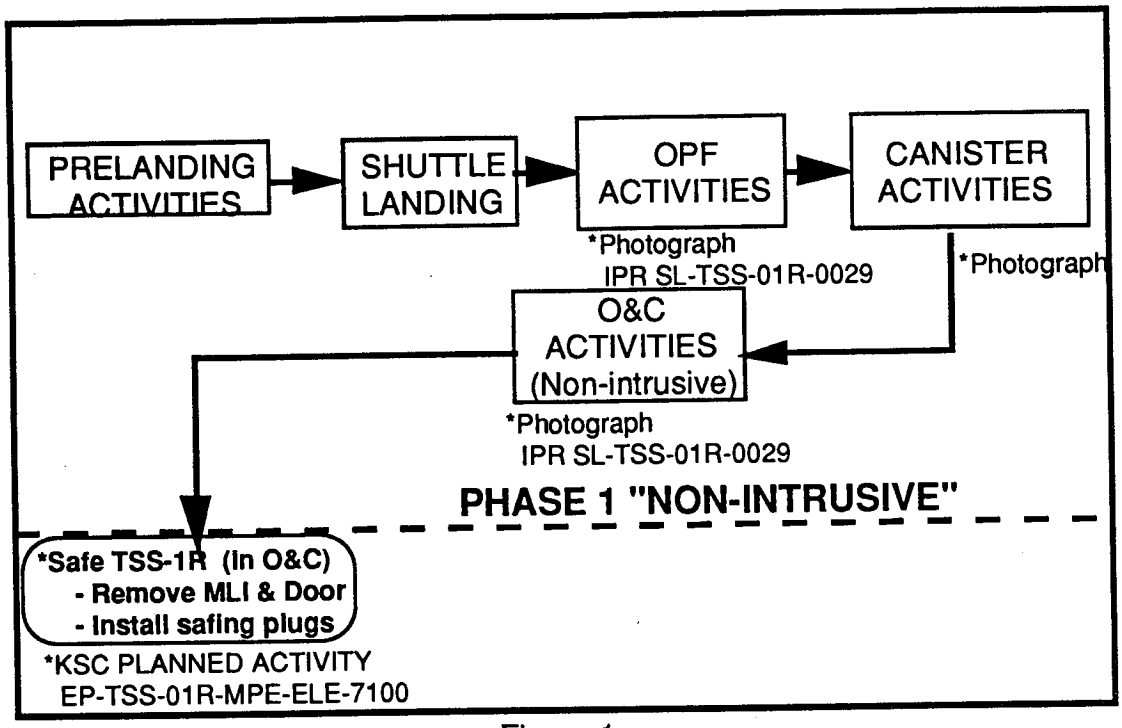

Figure 1
Phase 1 "Non-intrusive" flow.

Once the TSS hardware has been removed by KSC, per IPR SL-TSS-01R-0029, it will be moved to a KSC off-line area. MSFC Personnel/representative will be responsible for off-line operations at KSC, which will be performed under KSC Quality surveillance for safety considerations. MSFC personnel/representatives or other subject matter experts will perform "hands-on" work as determined by the Board and/or MSFC. Off-line hazardous operations will be controlled by KSC. The Tethered Satellite System Project Office (TSSPO) will provide appropriate logistics support relative to payload hardware and GSE. The deintegration and test team will provide deintegration and test requirements as well as procedure inputs to KSC.

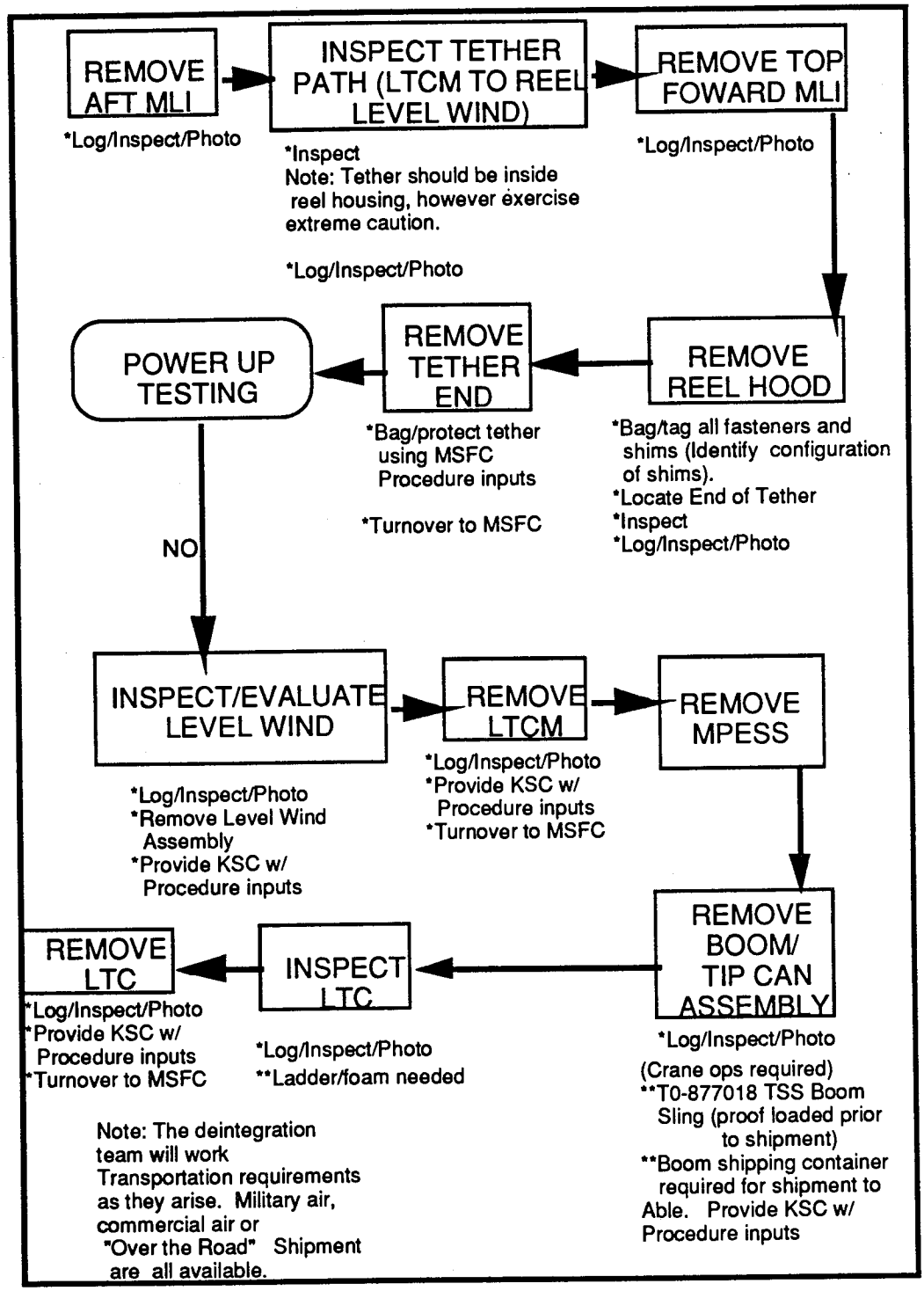

Figure 2
TSS-1R DEINTEGRATION FLOW
O&C ACTIVITIES
(Phase 2 Intrusive)

2.1 REQUIREMENTS

The anomaly investigation requirements flow is shown in figure 3. The requirements have been categorized as either a deintegration or test requirement. Deintegration requirements include all physical deintegration of TSS hardware. Test requirements include, but are not limited, to interface and verification testing (IVT), calibration and alignment testing. The requirements form to be submitted to the board is shown in figure 4. Once the investigation has concluded the residual payload hardware requirements will use the process in place prior to the anomaly.

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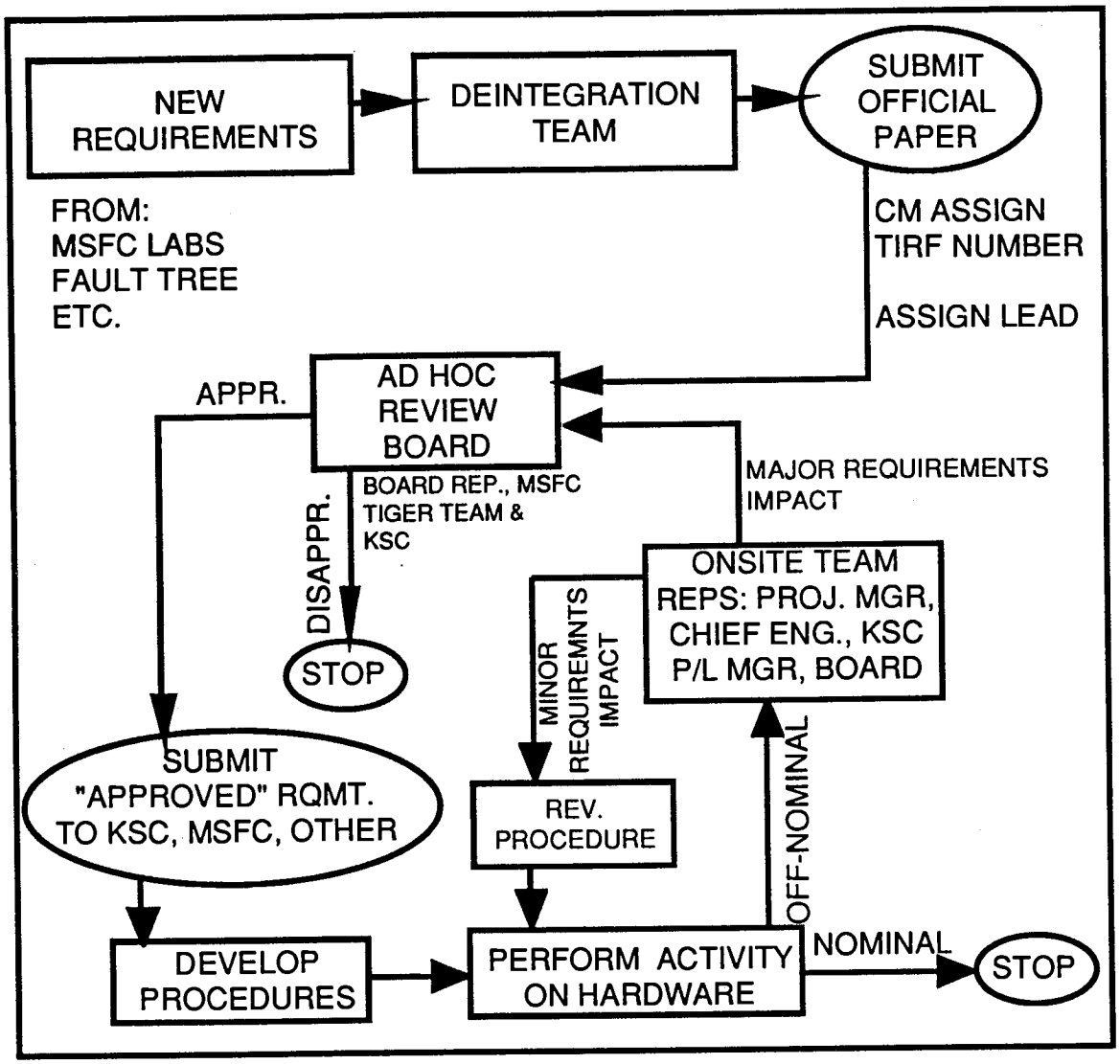

Figure 3
Requirements Flow

TIRF Number:	Test/Inspection Requirements Form (TIRF) Sheet	Page ____ of ____
Related Fault Tree Block Number:		

Descriptive Title of Test/Inspection:

Detailed Description of Test/Inspection:

Location, Resources, Time Estimate (if applicable):

Rationale for Test/Inspection:

Submitted by (Signature):	Phone Number:	Organization:	Date:

I&T Team Impact Evaluation:

I&T Team Lead (Signature/Date):

TIRF Chairman (Signature):	Date:

Figure 4
TIRF Sheet

2.2 HARDWARE HANDLING

Hardware will be handled as "flight" hardware to assure protection from damage during all phases of deintegration. During packaging all flight and GSE equipment will be inspected and bought off by Quality Assurance for both **count** and **condition.** If needed the deintegration and test team will provide inputs to existing handling procedures. Where no procedures exist the deintegration and test team will work with KSC to develop these procedures.

2.3 FIXTURES AND STANDS

KSC will provide all scaffolding required to deintegrate the TSS-1R payload while at KSC.

2.4 HOISTS AND SLINGS

The Payload Element Developers (PEDs) will provide tested and proof loaded hoists and slings at KSC to support deintegration activity of their payload element. Lockheed Martin, in Denver will proof load and ship to KSC all slings in their inventory which were developed for the TSS. Any new hoists or slings required will be worked through the TSSPO.

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TSS-1R Slings	Part Number
Deployer	
TSS Boom Sling	T0-877018
Reel Structure Assy. Sling	87770000031-009
Reel Spindle Sling & Container	T0-877001 - T0-877002
MCA Sling	87770000035-009
Truss Member Sling	8770000028-009
Pyro Initiator Controller Assembly/Data Aquisition and Control Assembly Sling	87770000800-009
Reel Motor Sling	87770000400-009
Satellite Support Structure Sling	87770000030-009
Docking Ring Handling Sling	T0877021
SETS Lifting Sling	DIL No. 01-501

Table 1.
TSS-1R Hoists and Slings

2.5 PACKAGING

2.5.1 PACKAGING AND MARKING

The packaging process shall be implemented to minimize damage and/or deterioration due to vibration, thermal, vacuum, and other environmental conditions during transportation. All unique requirements must be identified. The deintegration and test team will supply KSC, through the TSSPO, drawings and/or procedures necessary to pack hardware for shipment.

Package marking should include references to the mission (TSS-1R), the black box, (LTCM, LTC, etc.), and the exact contents (part number, S/N) and the value of each item.

2.5.2 CONTAINERS

Reusable containers will be utilized for packaging whenever possible. If the PED/PI has dedicated shipping containers for their hardware, the containers should be called out in the packing

drawings/procedures and delivered to KSC through the TSSPO. Any nonstandard or specialized containers required will be worked through the TSSPO.

2.6 TURNOVER

As hardware is removed from the MPESS and/or pallet, it will be taken to an off-line area. Hardware turnover during the anomaly investigation will be decided on a case-by-case basis. All items turned over will use official paperwork similar to that provided during hardware turnover to KSC. Scheduled, formal, turnover meetings are not required for this activity. At the time of element hardware turnover, Quality Assurance will provide paperwork which describes the results of their visual inspection of the deintegrated hardware element. This paperwork will also certify the **count** and **condition** of each hardware element. The IPR paperwork will be provided during this time as well. Upon completion of turnover, the hardware will be prepared for off-line testing and/or shipment to the appropriate facility as the case may be.

2.7 TRANSPORTATION

During the investigation phase deintegrated hardware will be hand carried when practical. Transportation for TSS hardware is provided by using the most cost effective means available given program requirements and time constraints. Currently there are two principal modes of transportation available, government furnished transportation systems and best commercial practices. Any special transportation requirements will be coordinated through the TSSPO.

2.8 STORAGE

Storage of TSS hardware shall provide a safe and secure environment in which items are protected from damage, deterioration, loss, and maintains flight hardware status. Requirements for special storage considerations will be worked through the TSSPO.

3.0 REMOTE FACILITY DEINTEGRATION/TESTING

A Remote facility is any facility other then KSC where deintegrated TSS hardware may be sent for detailed deintegration and/or test.

3.1 DEINTEGRATION/TEST REQUIREMENTS

All requirements concerning deintegration and/or test at remote facilities will be handled using the same process described in section 2.1. Reference figure 3, for requirements flow.

3.2 HARDWARE HANDLING

Hardware will be handled as flight hardware to assure protection from damage during all phases of deintegration and test. During packaging all flight and GSE equipment will be inspected and bought off by Quality Assurance for both **count** and **condition.** If needed the TSS project will provide inputs to existing handling procedures. Where no procedures exist the TSSPO will work with KSC to develop these procedures.

3.3 FIXTURES AND STANDS

Any fixtures and stands which need to be developed to support the anomaly investigation should be worked through the TSSPO.

3.4 HOISTS AND SLINGS

The PEDs will provide tested and proof loaded hoists and slings to support deintegration activity of their payload element. These hoists and slings will be made available, if needed, to support remote facility activities. Any new hoists or slings required will be worked through the TSSPO.

See Table 1. TSS-1R Hoists and Slings, in section 2.4.

3.5 PACKAGING REQUIREMENTS

3.5.1 PACKAGING AND MARKING

The packaging process shall be implemented to minimize damage and/or deterioration due to vibration, thermal, vacuum, and other environmental conditions during both transportation and storage. The PED will supply the remote facilities, through the TSSPO, drawings and/of procedures necessary to pack their hardware for shipment.

3.5.2 CONTAINERS

Reusable containers will be utilized for packaging whenever possible. If the PED has dedicated shipping containers for their hardware, the containers should be called out in the packing drawings/procedures. Once these containers arrive at the remote facility they will be retained for future use. Any nonstandard or specialized containers required will be worked through the TSSPO.

3.6 TURNOVER

At the time of element hardware turnover, Quality Assurance will provide paperwork which describes the results of their visual inspection of the deintegrated hardware element. This paperwork will also certify the **count** and **condition** of each hardware element. The IPR paperwork will be provided during this time as well. Upon completion of turnover, the hardware will be shipped to the designated remote facility . Once at the remote facility all approved work done on the hardware will continue to be documented.

3.7 TRANSPORTATION

During the investigation phase deintegrated hardware will be hand carried when practical. Transportation for TSS hardware is provided by using the most cost effective means available given program requirements and time constraints. Currently there are two principal modes of transportation available, government furnished transportation systems and best commercial practices. Any special transportation requirements will be coordinated through the TSSPO.

3.8 STORAGE

Each remote facility will be responsible for storage of TSS deintegrated hardware in their inventory. Storage of TSS hardware shall provide a safe and secure environment in which items are protected from damage, deterioration, or loss and maintains flight hardware status. Requirements for special storage considerations will be worked through the TSSPO. Items will be packaged as required to protect them against natural and induced environments per paragraph 3.5 during storage.

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KSC PAYLOADS SUMMARY REPORT
OF
THE TSS-1R MISSION FAILURE INVESTIGATION

1. Reason for Report

This report identifies the activities and operations that were required to support the TSS-1R Mission Failure Investigation. The time frame begins with the tether breaking to the removal of the Tethered Satellite System deployer and experiment flight hardware from the space shuttle Columbia; transporting the hardware to the Operations & Checkout Building ; the safing of the hardware; and the subsequent examination and deintegration at the direction of the TSS-1R Mission Failure Investigation Board.

2. Protection of Data

Per the Mission Management Team request and authorization, information and data that covered TSS-1R (STS-75) ground processing from March, 1995, to present, the processing activities for STS-75 at LC-39B, and the time prior to March, 1995, that includes the ground processing for TSS-1 (STS-46) were impounded. Information and data impounded encompasses Work Authorization Documents (includes Operation & Maintenance Instructions, Test and Assembly Procedures, Problem Reports, Interim Problem Reports, and Field Engineering Changes), Closeout photographs, 14-track analog data tapes (116), 7-track analog data tape, 9-track digital tapes (115), Optical disks (65), Video Tapes (297), Digital recording tapes of the Operational Intercommunication System (OIS) during ground processing at the O&C building from September 8, 1995, to December 20, 1995, and numerous miscellaneous items.

3. Post-Flight Payload Operations

Post-flight operations required the removal of the Tethered Satellite System deployer and experiment flight hardware from the space shuttle Columbia, transportation of the hardware to the Operations and Checkout Facility, safing the hardware, and securing it for subsequent examination and deintegration at the direction of the of the TSS-1R Mission Failure Investigation Board.

These operations represented the minimum activities required to secure the hardware in a safe configuration without disturbing interfaces and mechanisms relevant to the investigation prior to further direction by the Board, and consisted of the following:

- Payload bay doors opening
- Orbiter radiator inspections
- Payload photographic survey
- Payload/Orbiter interfaces demates
- Payload removal from the Orbiter

- Payloads transported to the Operations & Checkout Building
- Pyrotechnics safing after an initial inspection team survey of the payload

In anticipation of the requirements of the Board, additional plans and procedures were jointly developed by the KSC payload processing team and the MSFC TSS Project Office to provide required deintegration and access to assemblies and components as were requested by the Board. These plans/procedures were submitted to and approved by the Board.

In summary the following examinations and deintegration was performed at KSC:

- Inspected the tether path from the Lower Tether Control Mechanism to the Reel Level Wind
- Removed the Reel Hood
- Examined the Tether End prior to its removal from the Reel and shipped to MSFC
- Inspected and evaluated the Reel Level Wind
- Removed the Lower Tether Control Mechanism and shipped to MSFC
- Removed the Boom/Tip Can Assembly and shipped to MSFC
- Removed the Lower Tether Cutter and shipped to MSFC
- Removed and inspected the Level Wind Pulley Assembly
- Removed the remaining 2 km of flight tether and shipped to MSFC.

No further deintegration requirements are anticipated.

4. Payload Assess Control

The orbiter processing facility was open 24 hours per day. Payload bay entry was prohibited while the payload bay doors were closed. An access monitor was on station when the payload bay doors were opened and the payload was in the payload bay. The monitor was stationed on either the 7 or the 13 platforms at all times. The Lockheed-Martin Orbiter Integrity Clerk logged in all personnel entering the orbiter midbody. The MDS&DS access monitor logged in only those personnel who performed hands-on work with the payload.

During all phases of TSS-1R deintegration in the Operations & Checkout Building , an access control list was in effect. The access control monitor ensured that only those personnel who were on the access control list were allowed into the controlled payload area.

Additions or changes to the access control list were made through the MDS&DS Operations Engineer, the NASA Mission Operations Engineer, and/or the NASA Payload Manager. All additions were approved by the Mission Failure Investigation Board Chairperson and/or the NASA Payload Manager, acting by the chairpersons' authority.

5. Requirements Review Team

To ensure the proper execution of all Operations and Maintenance Requirements Specifications Document (OMRSD) requirements, the Requirements Allocation Matrices (RAMs) for both TSS-1 and TSS-1R were reviewed to ensure all requirements were satisfied.

Proper identification of all OMRSD exceptions and waivers within the RAMs was verified. The affect of the exceptions and waivers on the deployer/tether operations were reviewed and evaluated. In addition to the RAM review, all requirements related to tether testing and handling operations were identified and verified to have been completed through a review of the performing procedures. Attachment 1 is a listing of the waivers, exceptions, and tether related requirements.

6. Problem Reporting and Corrective Action Review Team

To ensure proper disposition of anomalies which occurred during payload processing, a review of all Problem Reports (PRs) and Interim PRs (IPRs) for both TSS-1 and TSS-1R was performed to identify any which could have had a direct or indirect affect on the tether or its deployment system. An in-depth review of these PRs was then conducted to evaluate the soundness of the work performed and the subsequent disposition used for closure.

7. Tethered Satellite System-1 and Tethered Satellite System-1R Tether Handling Review Team

A team was appointed to review all tether handling and test operations, to identify testing, verify test satisfaction, report relevant results, and categorize for subsequent board review. The team's review did not reveal any anomalous conditions or test results. The complete history of the tether while at the Kennedy Space Center is contained in a report submitted to the board in response to RFI K-24.

8. Hardware Examination and Deintegration

The following is an overview of the STS-75 TSS-1R payload examination and deintegration operations performed at KSC, as related to the TSS-1R mission failure investigation, starting from shuttle landing on 3/9/96 through 3/28/96. To date, all specific KSC requirements mandated by the TSS-1R Mission Failure Investigation Board have been satisfied (reference attachment 2 "TSS-1R Anomaly Investigation Requirements Matrix.

Saturday, 3/9: Columbia landed at KSC and was rolled into OPF Bay 2.
Monday, 3/11 through Wednesday, 3/13: No payload activities occurred. The payload bay doors were opened, and their radiators inspected.
Thursday, 3/14: A detailed photo inspection and video taping of the TSS-1R payload within the orbiter payload bay was performed. Yellow discoloration on the "salad bowl" within the boom was noted. Experiment protective covers and lens caps were installed. Bond checks between the pallet and the orbiter, as well as between the MPESS and the pallet, were performed and were nominal. The TSS-1R and USMP-3 fluid and electrical systems were then demated from the orbiter.
Friday, 3/15: The payload was removed from the orbiter and installed into the transportation canister. Canister doors were locked and integrity sealed. The canister was then moved to the SSPF airlock.

Saturday, 3/16: The canister was moved to the O&C building, and TSS-1R was installed into Test Stand 4.
Monday, 3/18: Access GSE was configured and the initial inspection of TSS-1R by the MSFC Inspection Team was performed, including a micrometeoroid inspection. Pyro safing was performed; all NSIs were tested and found to be intact. Pyro safing plugs were then installed.
Tuesday, 3/19: The KSC procedure for analyzing and cutting the tether was reviewed and approved by the Mission Failure Investigation Board. The aft MLI was removed, and more non-intrusive photos were taken. The transportation canister was inspected for debris and photographed. Debris was collected using a filtered vacuum cleaner.
Wednesday, 3/20: The tether path within the Deployer was inspected. The forward MLI was removed to gain access to the reel. The reel cover was then inspected, and most of the securing bolts removed to facilitate an early reel cover removal 3/21.
Thursday, 3/21: The reel cover was removed, and the tether inspected. The configuration and position of the tether on the reel were recorded and photographed. Both normal and magnified photos of the tether end were taken. Tether end protection was installed, and 26.99 meters of tether was manually unspooled from the reel and cut off. Following this, X-ray imaging of the tether end was performed. The tether was then packaged for shipping.
Friday, 3/22: TSS-1R payload power isolation checks were performed. All readings were within specification; however, both main DC positive and return to MPESS structure readings were less than the preflight data (122 and 119 kohms (post-flight) vs. 2.2 and 2.2 Mohms (preflight)). KSC suspects that the Science Power Control Box (SPCB) relays were left closed during the last on orbit deactivation. The Lower Tether Control Mechanism (LTCM) was deintegrated and packaged. It, along with the tether end, were transported to MSFC for further analysis.
Monday, 3/25: No payload activities were performed.
Tuesday, 3/26: In preparation of the Deployer boom removal, a bond check between the boom and the pallet was successfully performed. Also, pyro Faraday caps were installed.
Wednesday, 3/27: The Deployer boom was removed from the Satellite Support Assembly (SSA). The tip can to docking ring strut bond check was performed. This check indicated isolation of the docking ring from the tip can. This data was forwarded to MSFC. Following boom removal, the docking ring, salad bowl, and U2 umbilical assembly were deintegrated from the boom assembly. The SSA and U1 umbilical connector were inspected.
Thursday, 3/28: Tether continuity (tether end to slip ring) and isolation were measured (182.35 ohms and infinity, respectively). The Lower Tether Cutter was removed, and the NSIs removed from it. The LTC was packaged for shipment on 3/29.
Friday, 3/29
The boom, salad bowl, LTC, and all debris collected to date were shipped to MSFC for analysis. The proposed level wind inspection procedure inputs from MSFC were reviewed by KSC.
Monday, 4/1
MLI bond strap resistance checks were completed.
Tuesday, 4/2

The reel level wind pulley housing was inspected. Its cover was bond checked to the reel housing (5.35 Mohm), and then removed. Two pulley assemblies were then removed and inspected. The inside of the housing and the fair lead rollers were inspected. No apparent evidence of an electrical discharge were visible (only the expected Nomex debris).

Wednesday, 4/3, through Friday, 4/5

No payload activities occurred.

Monday, 4/8

Emblems, flags, and logos were removed from multi-layer insulation (MLI).

Tuesday, 4/9

Both pallet mounted Closed Circuit Television Cameras (CCTVs) were deintegrated.

Wednesday, 4/10

Both Shuttle Potential and Return Electron Experiment (SPREE) Flight Data Recorders (FDRs) were removed. The FDRs were hand carried from KSC to MSFC. Debris in the area below the tether reel assembly was inspected, mapped, photographed, and collected.

Thursday, 4/11

The tether remaining on the reel was manually removed and respooled onto a Cortland supplied take up reel. The spool was packaged for a return to MSFC on 4/13/96.

Friday, 4/12

Debris in the area below tether reel assembly was collected again (post tether removal).

9. Malfunction Analysis

The KSC Material Science Division provided photographed and X-rays per the request of the Mission Failure Investigation Board. A report from the KSC Material Science Division will not be produce since they were not requested by the Board to analyze any of the components.

10. Conclusions

- A review of the STS-75/TSS-1R Operations & Maintenance Requirements & Specifications requirements allocation matrix has been completed, and no unsatisfied requirements were identified.
- All applicable exceptions and waivers have been reviewed and evaluation has not identified any relevancy to the mission failure.
- All Interim Problem Reports / Problem Reports have been reviewed, and significant problems were reviewed in-depth. The soundness of all work performed and subsequent dispositions were verified. There were no indication that any of these Interim Problem Reports / Problem Reports were related to the in-flight anomaly.
- Observations during the deintegration of the tether control mechanisms at KSC indicated residue characteristic of arcing on the Lower Tether Control Mechanism and the Lower Tether Cutter. These components and residue marks are being further analyzed by MSFC.

Prepare by:

Glenn E. Snyder
STS-75 Payload Manager

Approved by:

P. Thomas Breakfield, III
Director, Payload Flight Systems

---- ATTACHMENT 1 ----

TSS-1/TSS-1R EXCEPTIONS/WAIVER SUMMARY AND TETHER RELATED REQUIREMENTS SUMMARY

1. TSS-1 EXCEPTION AND WAIVER SUMMARY

NUMBER	DESCRIPTION
EKP0279	SATELLITE SERVICING GSE WAS NOT CALIBRATED
EKP0287	SATELLITE 60 DAY PERIODIC MAINTENANCE SCHEDULE WAS NOT MET
EKP0295	DEPLOYER MLI DID NOT MEET CLASS 'S' BONDING SPECIFICATION OF 1 OHM (ALL WERE < 10 OHMS, PER ICD-2-19001)
EKP0297	COULD NOT INSPECT MULTI-LAYER INSULATION (MLI) AT TWO LOCATIONS DUE TO ACCESS/COLD PLATE INSTALLATION
EKP0298	COULD NOT VERIFY THERMAL PROPERTIES ON TOP OF MPESS DUE TO EXPERIMENT BUILDUP
EKP0299	SFMDM INTERFACE CHECKS INVALIDATED DUE TO SFMDM REMOVAL AND REPLACEMENT
EKP0303	COULD NOT MEET 1 Mohm PAYLOAD POWER FAULT BOND ISOLATION (THIS EXCEEDENCE IS DOCUMENTED IN ICD-A-21286)
EKP0311	SHUTTLE POTENTIAL & RETURN ELECTRON EXPERIMENT (SPREE) ELECTROSTATIC ANALYZER (ESA) PURGE NOT USED - GSE COVER USED INSTEAD
EKP0323	POST-FLIGHT SATELLITE GN2 PURGE TEMPORARILY SUSPENDED DUE TO INVESTIGATION TEAM OPERATIONS
WKP0315	PALLET STATIC ENVELOPE RADII EXCEEDED SPEC AT FOUR LOCATIONS
WKP0236	SMALL PALLET DENTS IDENTIFIED

2. TSS-1 DEPLOYER/TETHER RELATED REQUIREMENTS SUMMARY

DESCRIPTION	OMRS REQ	PROCEDURE
DEPLOYER INTERFACE VERIFICATION TEST	H411DEPT.010	T1-TSS-1-0010
PYRO CIRCUIT CHECKOUT	H411DEPT. 015	TPS TSS-1-MPE-ELE-015, L0100, & L0102
DEPLOYER POST ASSEMBLY FUNCTIONAL	H411DEPT.020	T4-TSS-1-0011
TETHER CIRCUIT INSTRUMENTATION TEST	H411IPLT.032	T1-TSS-1-0005

VERIFY TETHER CONTINUITY AND CONNECT TO SATELLITE	H411SATT.010	T1-TSS-1-1028
SATELLITE SUPPORT ASSEMBLY INSPECTION	H411DEPM.040	T1-TSS-1-1028

3. TSS-1R EXCEPTION AND WAIVER SUMMARY

NUMBER	DESCRIPTION
WKP0555	PALLET PANEL DENT
WKP0591	MAXIMUM FREON PUMP REVERSE DELTA PRESSURE LIMIT EXCEEDED DURING INTEGRATED ONE PUMP ON TESTING
WKP0596	DEPLOYER MOTOR POWER CONDITIONER RELAYS ON DURING CLOSED LOOP TESTING TO ALLOW FOR PARALLEL SATELLITE OPERATIONS
WKP0601	FREON LOOP OPERATING PRESSURE EXCURSION
WKP0602	STATIC ENVELOPE CLEARANCE CHECK FAILURE

4. TSS-1R DEPLOYER/TETHER RELATED REQUIREMENTS SUMMARY

DESCRIPTION	OMRS REQ	PROCEDURE
DEPLOYER INTERFACE VERIFICATION TEST	H286DEPT.010	P7572
PYRO CIRCUIT CHECKOUT	H286DEPT. 015	TPS EP-TSS-01R-MPE-ELE-T002, L0100, & L0102
TETHER CIRCUIT INSTRUMENTATION TEST	H286IPLT.032	P7576
VERIFY TETHER CONTINUITY AND CONNECT TO SATELLITE	H286SATT.010	P7556 & PR EP-TSS-01R-EXP-DPLR-P008
SATELLITE SUPPORT ASSEMBLY INSPECTION	H286DEPM.040	P7556

REQUIREMENT #	DESCRIPTION	WAD #	STEP #s	ENGINEER	ST	EST CLS DATE	CLS DATE
TS[illegible]OM-002A-T	Ground test between boom docking ring struts & SSA (open)	IPR SL-TSS-01R-0029	1.7.0	Mathis/Maynard	C	26-Mar	26-Mar
	Bond check between boom canister and SSA (1.15 Mohms)	IPR SL-TSS-01R-0029	1.7.1	Mathis/Maynard	C	27-Mar	27-Mar
TSS-GEN-001-I	Inspect items in tether path for arcing	IPR SL-TSS-01R-0029	PR-ALL*	Mathis/Maynard	C	N/A	23-Apr
TSS-GEN-002-I	Inspect, photo, collect any debris	IPR SL-TSS-01R-0029	PR-ALL*	Mathis/Maynard	C	N/A	23-Apr
TSS-GEN-004-I	Payload Canister debris recovery	IPR SL-TSS-01R-0029	1.4.1	Mathis/Maynard	C	19-Mar	19-Mar
TSS-GEN-005-I	Check tether and mechanisms for signs of rubbing; take position ref data on equip. to be removed	IPR SL-TSS-01R-0029	PR-ALL*	Mathis/Maynard	C	N/A	23-Apr
TSS-GEN-007-I	LTCM, tether path inspection	IPR SL-TSS-01R-0029	1.3.11	Mathis/Maynard	C	19-Mar	19-Mar
TSS-GEN-008-I	Borescope inspection restrictions	IPR SL-TSS-01R-0029	PR-ALL*	Mathis/Maynard	C	N/A	23-Apr
TSS-GEN-009-T	Payload power bus isolation checks	IPR SL-TSS-01R-0029	1.5.0 - 2	Franco	C	22-Mar	22-Mar
TSS-LTC-001-D	Lower Tether Cutter (LTC) removal	IPR SL-TSS-01R-0029	1.9.6	Mathis/Maynard	C	28-Mar	28-Mar
TSS-LTCM-001-D	Remove LTCM for MSFC analysis	IPR SL-TSS-01R-0029	1.6.0 - 11	Mathis/Maynard	C	22-Mar	22-Mar
TSS-MLI-001-I	Inspect for meteoroid/debris impacts	IPR SL-TSS-01R-0029	1.3.2 & 10	Mathis/Maynard	C	18-Mar	18-Mar
T [illegible]I-002-T	Inspect MLI bond straps	IPR SL-TSS-01R-0029	1.3.25	Mathis/Maynard	C	19-Mar	19-Mar
	Perform resistance chk on straps	IPR SL-TSS-01R-0029	1.3.25	Mathis/Maynard	C	1-Apr	1-Apr
TSS-PALLET-001-I	Collect debris from pallet	IPR SL-TSS-01R-0029	PR-ALL*	Mathis/Maynard	C	N/A	23-Apr
TSS-PYRO-001-T	Pyro pre-safe plug instl resistance test (UTC &LTC) - done 3/18	TPS EP-TSS-01R-MPE-ELE-T004	TPS-ALL	Lacher	C	18-Mar	18-Mar
	Pyro faraday cap installation	TPS EP-TSS-01R-MPE-ELE-T004	TPS-ALL	Lacher	C	26-Mar	26-Mar
TSS-REEL-001-I	Inspect reel housing for debris	IPR SL-TSS-01R-0029	1.3.47	Mathis/Maynard	C	21-Mar	21-Mar
	Initial under reel hood debris collection	IPR SL-TSS-01R-0029	1.3.34	Mathis/Maynard	C	26-Mar	26-Mar
	Pre-remaining tether removal debris collection	IPR SL-TSS-01R-0029	1.13.0	Mathis/Maynard	C	10-Apr	10-Apr
	Debris mapping/collection per M/K-69 (post remaining tether removal)	IPR SL-TSS-01R-0029	1.14.1	Mathis/Maynard	C	12-Apr	10-Apr
TSS-REEL-002-I	Tether end position measurements & photos	IPR SL-TSS-01R-0029	1.3.35	Mathis/Maynard	C	21-Mar	12-Apr
TSS-REEL-003-I	Inspect reel before removing cover	IPR SL-TSS-01R-0029	1.3.27	Mathis/Maynard	C	20-Mar	20-Mar
TSS-REEL-005-D	Reel Level Wind inspection	IPR SL-TSS-01R-0029	1.10.0-11	Mathis/Maynard	C	2-Apr	2-Apr

REQUIREMENT #	DESCRIPTION	WAD #	STEP #s	ENGINEER	ST	EST CLS DATE	CLS DATE
TSS-SSA-001-I	Inspect top of SSA and U1	IPR SL-TSS-01R-0029	1.9.0	Mathis/Maynard	C	27-Mar	27-Mar
TETHER-001-D	Tether end/sample removal	IPR SL-TSS-01R-0029	1.3.41	Mathis/Maynard	C	21-Mar	21-Mar
	Remaining tether removal to take-up reel	IPR SL-TSS-01R-0029	1.14.0	Mathis/Maynard	C	11-Apr	11-Apr
TSS-TETHER-005-I	Photo tether end prior to cut (hi mag.)	IPR SL-TSS-01R-0029	1.3.36	Mathis/Maynard	C	21-Mar	21-Mar
TSS-TETHER-007-T	Measure tether cond continuity & iso.	IPR SL-TSS-01R-0029	1.8.2	Tilson/Lacher	C	28-Mar	28-Mar
TSS-TETHER-008-I	Xray tether end after removal	IPR SL-TSS-01R-0029	1.3.45 & 46	Mathis/Maynard	C	21-Mar	21-Mar
TSS-U1-001-I	U1 inspection	IPR SL-TSS-01R-0029	1.9.0	Mathis/Maynard	C	27-Mar	27-Mar

*Denotes general requirement satisfied throughout all other investigation work without specific step numbers within the work authorization document.

Appendix D:

KSC Deintegration Plan

1.0 KSC Anomaly Investigation Deintegration Plan

2.0 KSC Payloads Summary Report

3.0 KSC Photo documentation and Radiographic Procedures

4.0 Photo of Salad Bowl Yellow Spot

5.0 Photo of Micrometeorite Hit

NASA
John F. Kennedy Space Center
Logistics Operations Directorate
Materials Science Division (MSD)

Photodocumentation and Radiographic Procedures for TSS-1R Tether

March 22, 1996

On March 21, 1996, at the request of the TSS-1R Investigation Board, the MSD performed a photographic inspection at magnification of the broken end of the TSS-1R tether immediately after the subject tether was unreeled from the tether reel assembly. Subsequent to the removal of approximately 24 meters of tether, a real-time radiographic inspection of the broken end of the tether was performed. These tasks correspond to item no. 2 from the nondestructive failure analysis (FA) activities and item no. 2 from the destructive FA activities, respectively, listed on the MSD Proposed FA Plan for TSS-1R (Draft) previously provided to the Board. The detailed procedures associated with these tasks are listed below. The entire operation started on 3/21/96 at 9:00 am; the MSD started photography (step no. 1 below) at approximately 1:00 pm, and the real-time radiography (step no. 3 below) was completed by approximately 9:00 pm. Note: Only NASA/MSFC personnel handled the subject tether; all other tasks described below were performed by NASA/KSC MSD personnel.

1) The tether was unreeled and the broken end was placed on a table immediately in front of the reel assembly. A Nikon SMZ-2T stereomicroscope was placed on this table, along with various ring and fiber optic light sources and a laptop computer. The tether was photographed at different orientations at magnifications between 10X and 63X. For each orientation and magnification, a series of photographs was obtained as follows:

a. A Polaroid Microcam camera was attached to the eyepiece of the Nikon SMZ-2T microscope, and multiple Polaroid photographs were immediately obtained for each view. Initially five photographs were obtained for each view; as time constraints were imposed, the number of photographs obtained for each view was reduced to two or three.

b. The Polaroid camera was removed from the eyepiece and a Kodak DCS 200ci digital camera was attached to the turret of the Nikon SMZ-2T microscope. One digital photograph for each view was captured and stored on the laptop computer.

c. The Kodak digital camera was removed and a Nikon F3 35mm camera was attached to the turret of the Nikon SMZ-2T microscope. Various numbers of photographs were obtained for each view using various exposure settings. ASA 200 and 800 color negative film was used.

2) The Nikon SMZ-2T microscope was removed from the table and replaced with a Sony DXC 760MD digital camera with a RAM Optical Extended Depth of Field (EDF) lens. A video monitor and a Sony UP-7000 video printer was also attached to the Sony digital camera. The broken end of the tether was photographed at various orientations and magnifications (approximately 1X - 60X). For each photograph, one image was captured on the monitor and one hardcopy was immediately printed (some hardcopy prints contained a total of four images). It should be noted that there were two distinct regions of the tether that were photographed using this EDF lens that were not previously photographed using the procedure described in step 1: the very end of the tether break containing only a few fibers (i.e., the tips of the fibers far removed from the blackened copper wire ends); and two "black spots" visible on the tether some distance away from the actual break.

3) After completion of the photography described in steps 1 & 2, approximately 24 meters of the tether was cut, removed from the reel assembly, and packaged for shipment. This tether segment was then transported to the MSD Electrical/Electronics laboratory for a radiographic examination of the broken end (while still inside the shipping container). This real-time radiographic examination was performed using an IRT Fluroscan 1200 unit. The tether container was placed on a Plexiglas platform located inside the Fluroscan 1200 cabinet; the platform was manipulated to allow radiographic examination of the tether end at various magnifications and orientations. Video hardcopy printouts were obtained for selected views; the entire radiographic examination was recorded on videotape.

4) All Polaroid photographs, 35mm film, digital and video printouts, and videotapes were impounded by NASA/RO-PAY personnel at the request of the Board. Copies of these photographs can be made by MSD (film prints can be scanned into digital formats from which copies are easily obtained; additionally, multiple 35mm prints can be developed by Bionetics personnel) when authorized by the Board. All digital images (including scanned digital images of film prints) were placed on a CD-ROM by EG&G personnel; five copies of this CD-ROM were made and impounded by RO-PAY. Additionally, the Board authorized MSD to place all digital images on an MSD ftp site that allows the images to be viewed (via the internet) anywhere in the world with the use of a proper username and password; the proper username and password have been provided to the Board.

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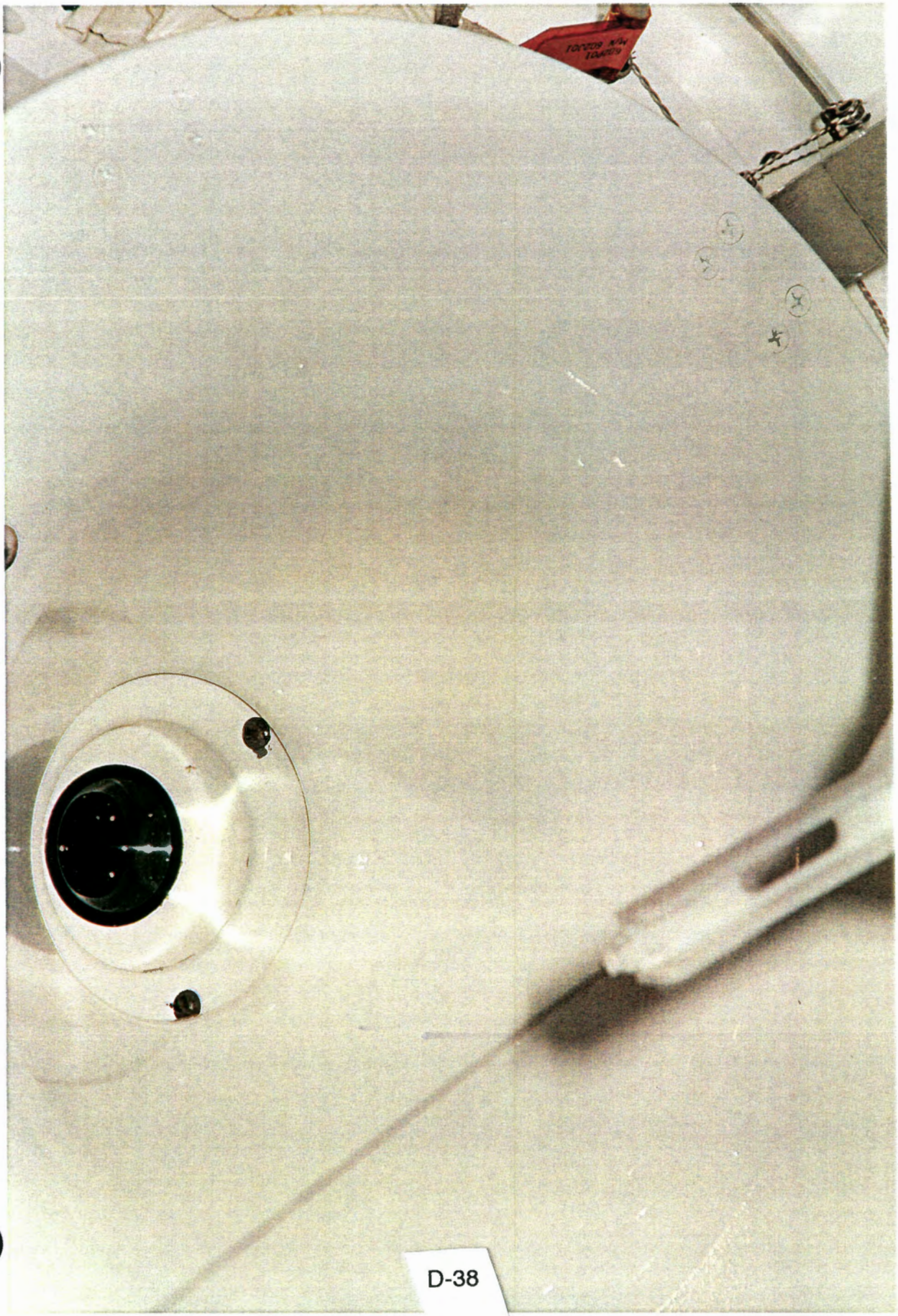
5.0 Photo of Micrometeorite Hit



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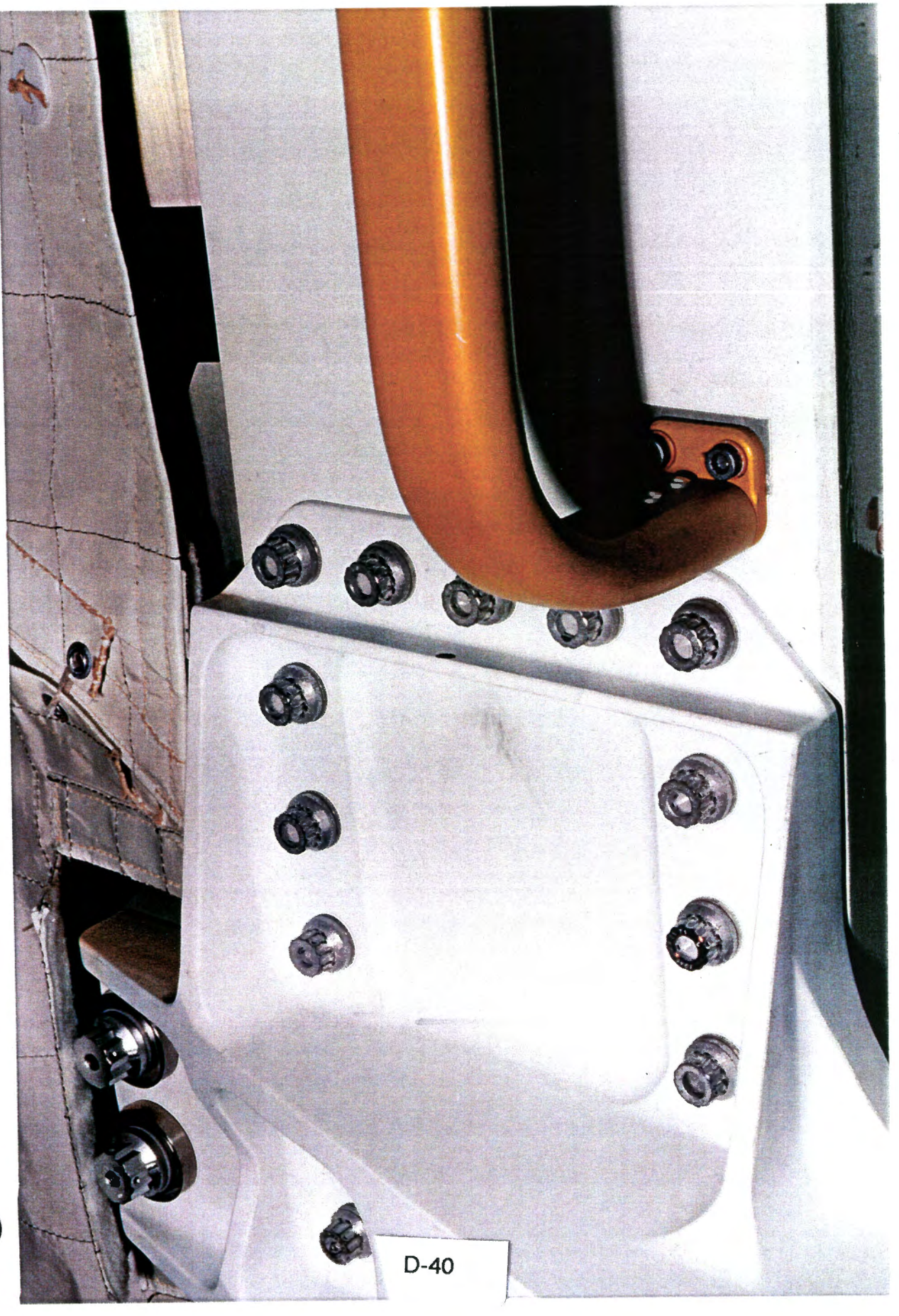
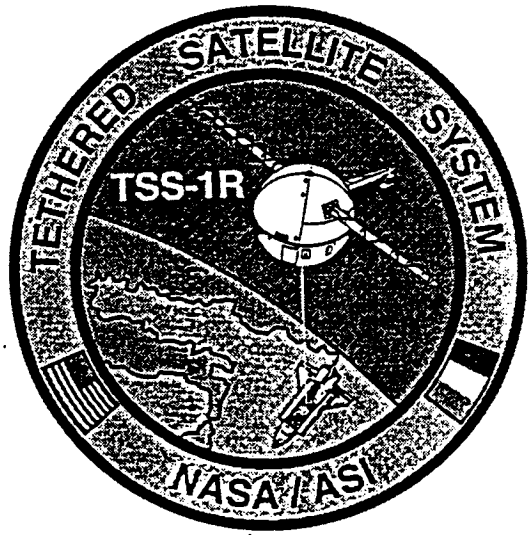
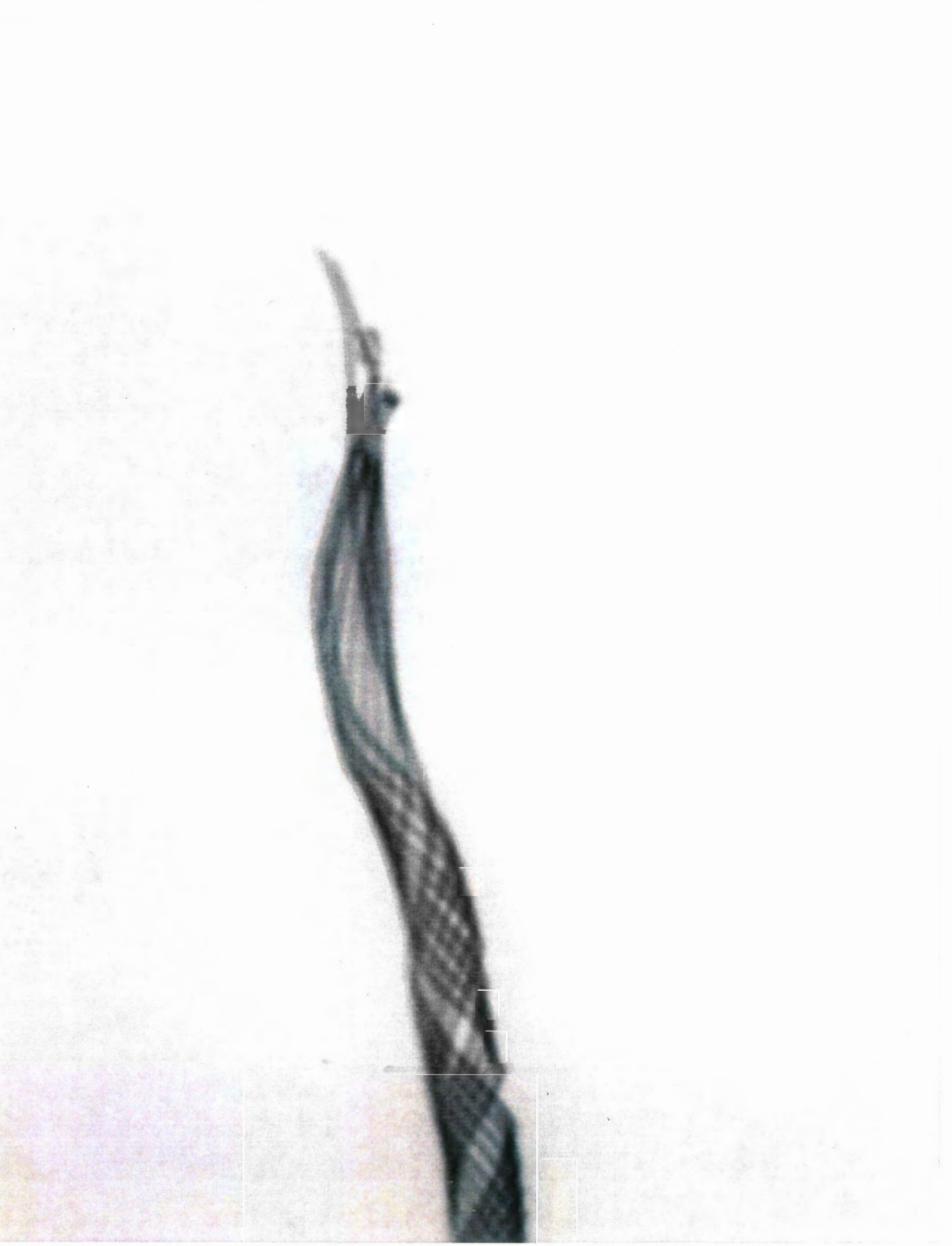
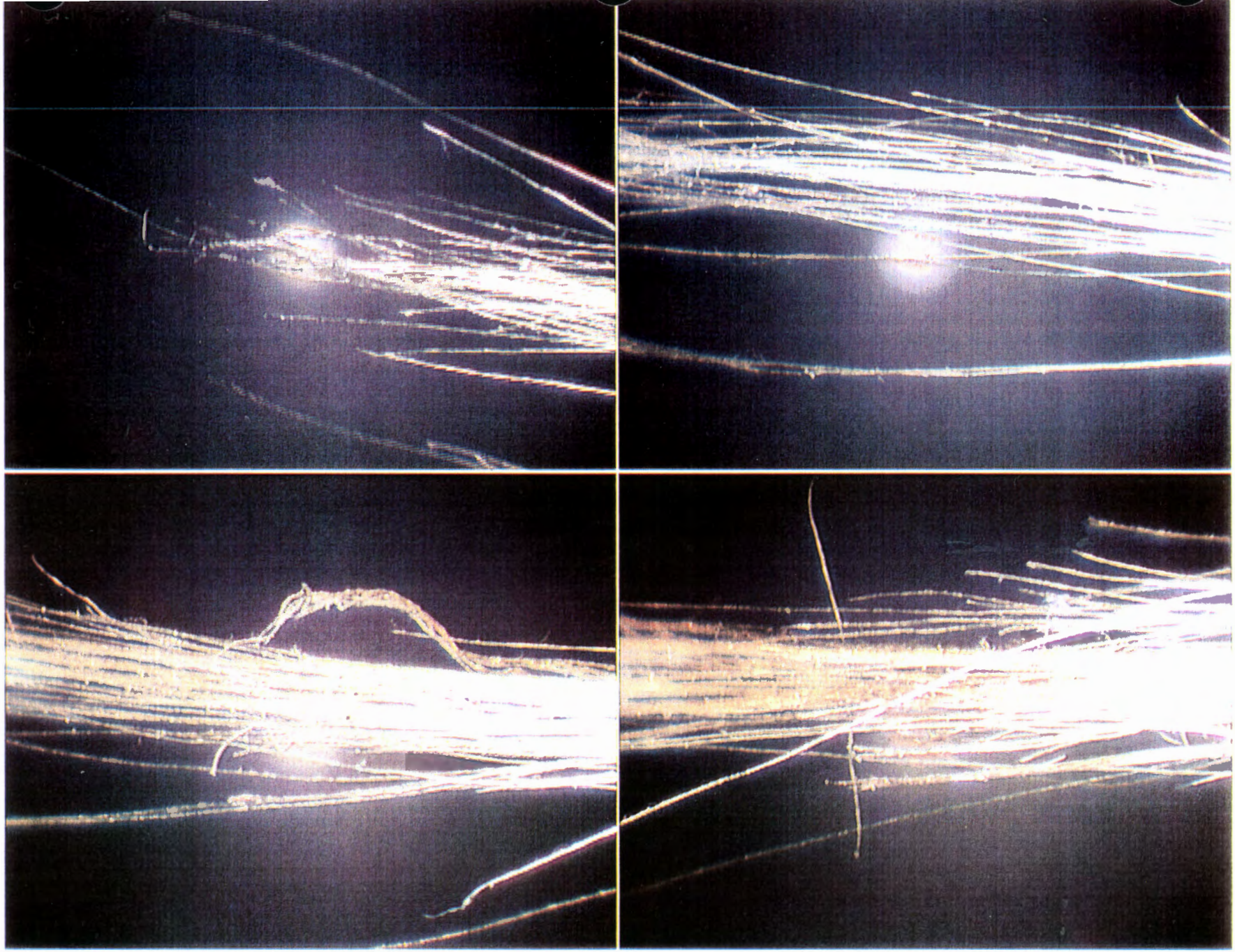




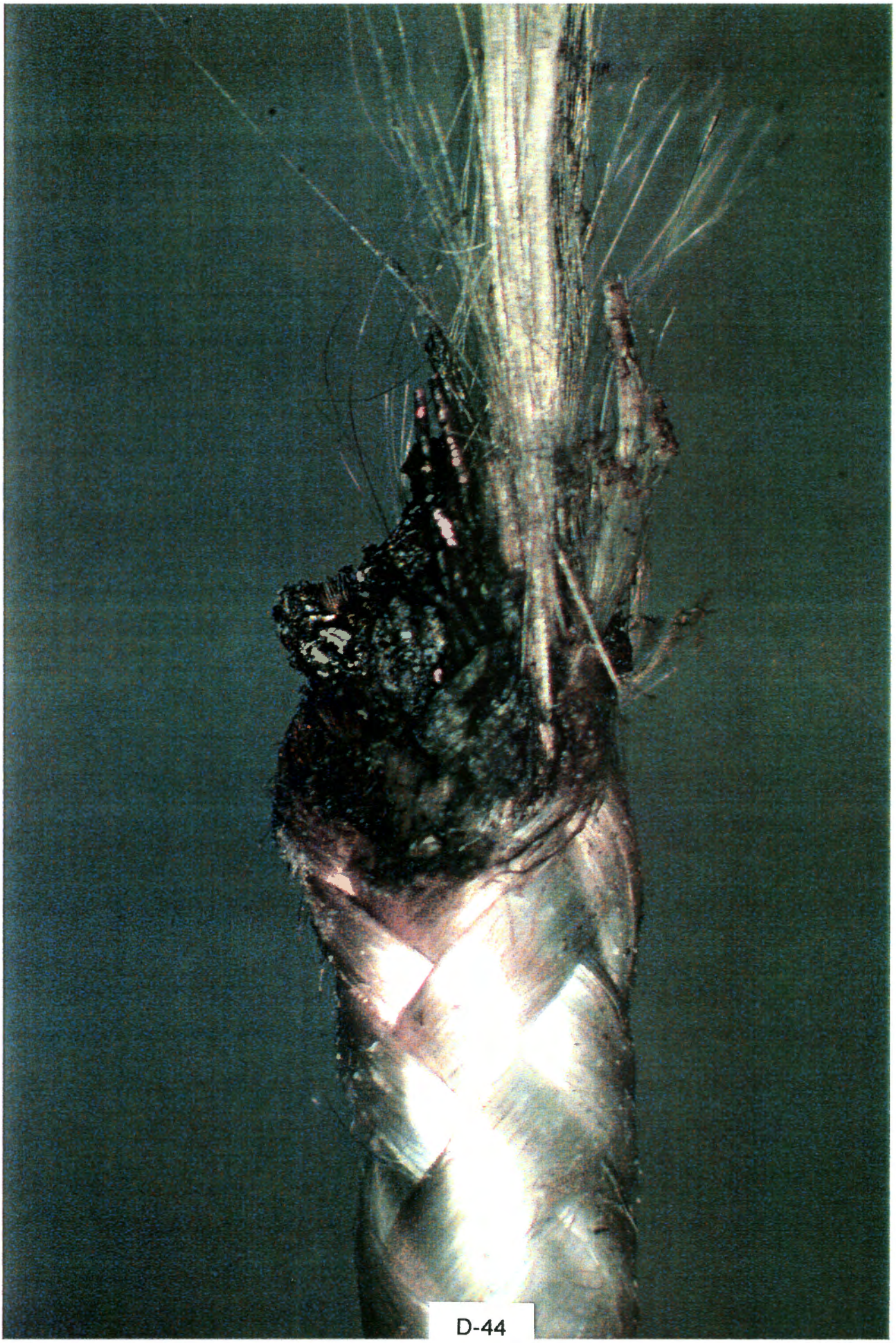
Appendix D:

Additional Tether Photos Taken by KSC





NASA/KSC Materials Science Laboratory



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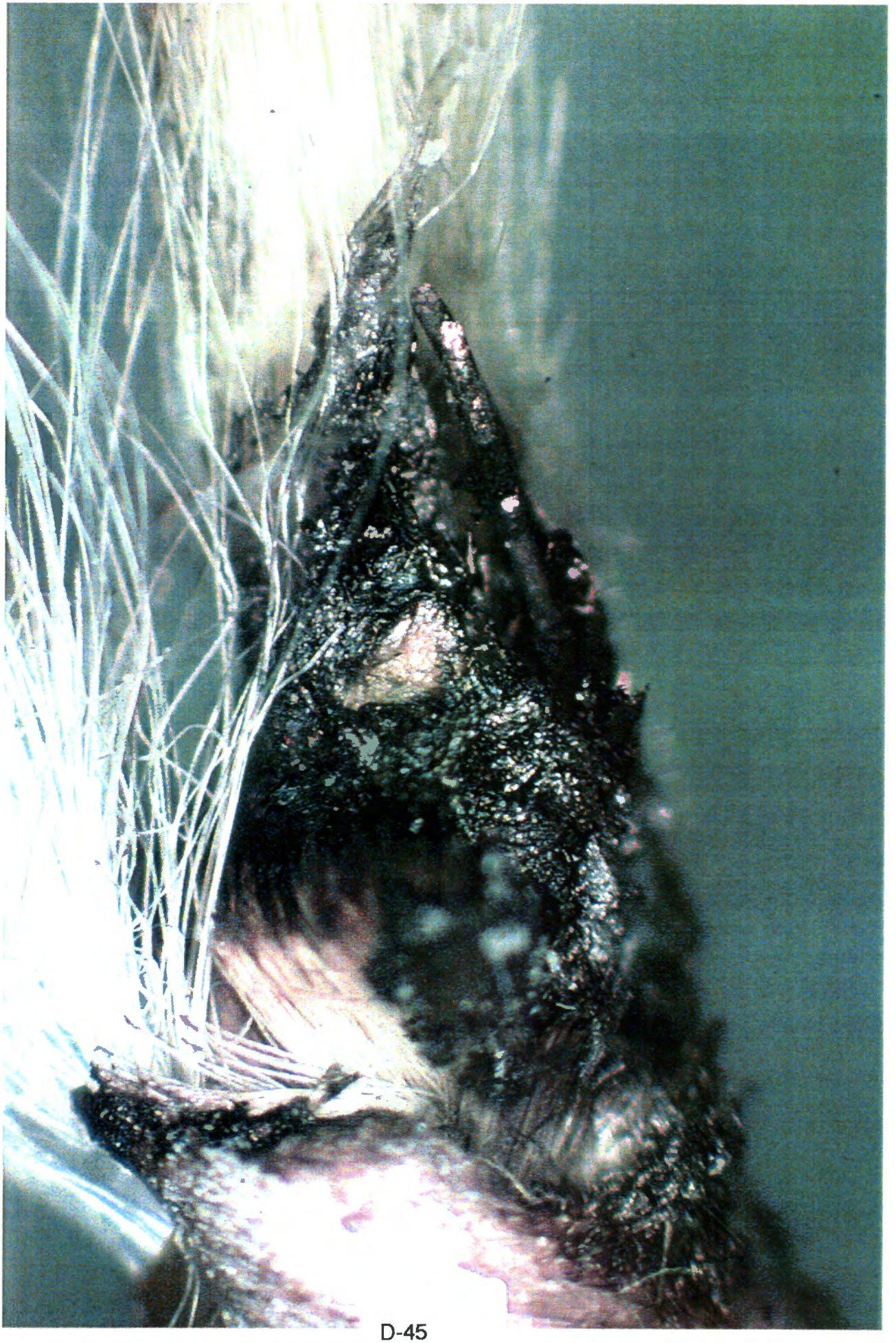

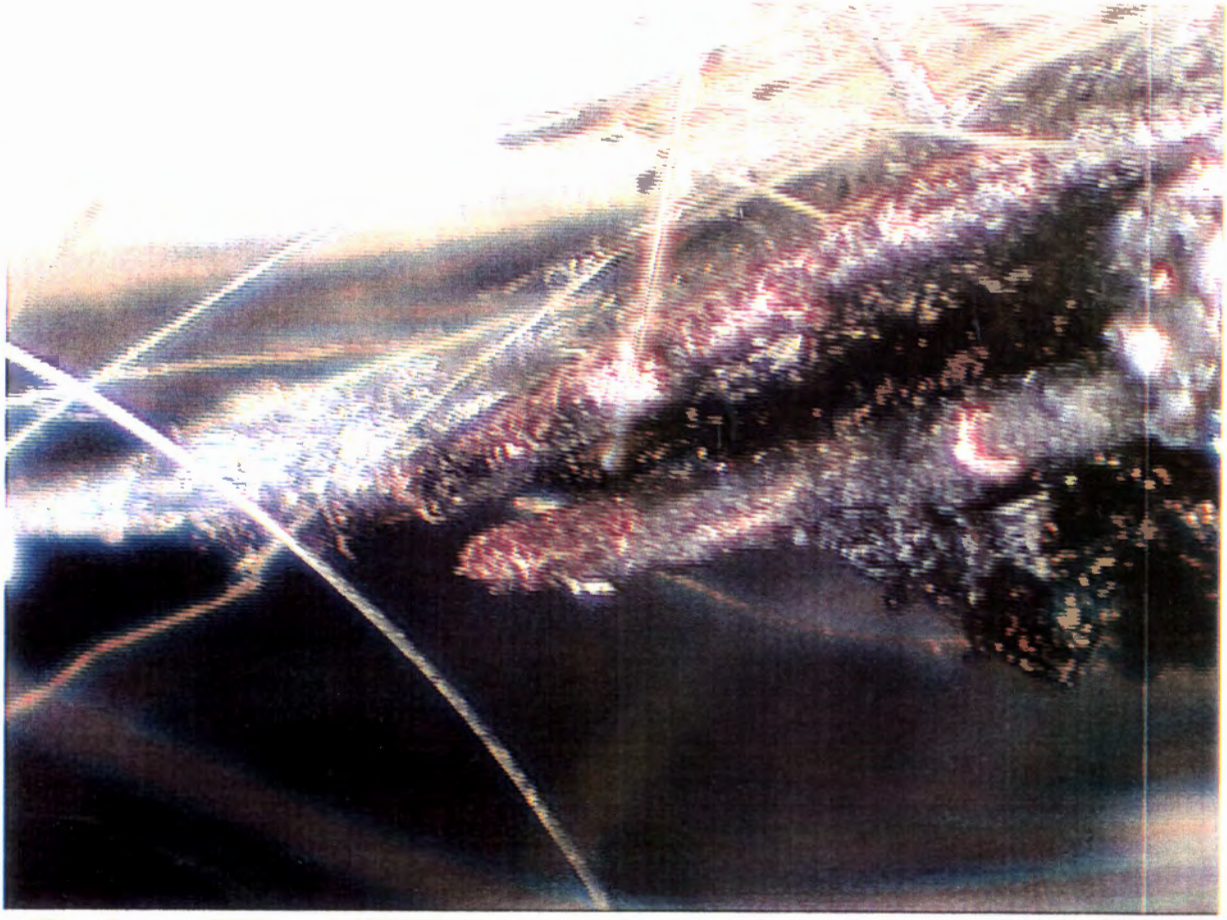

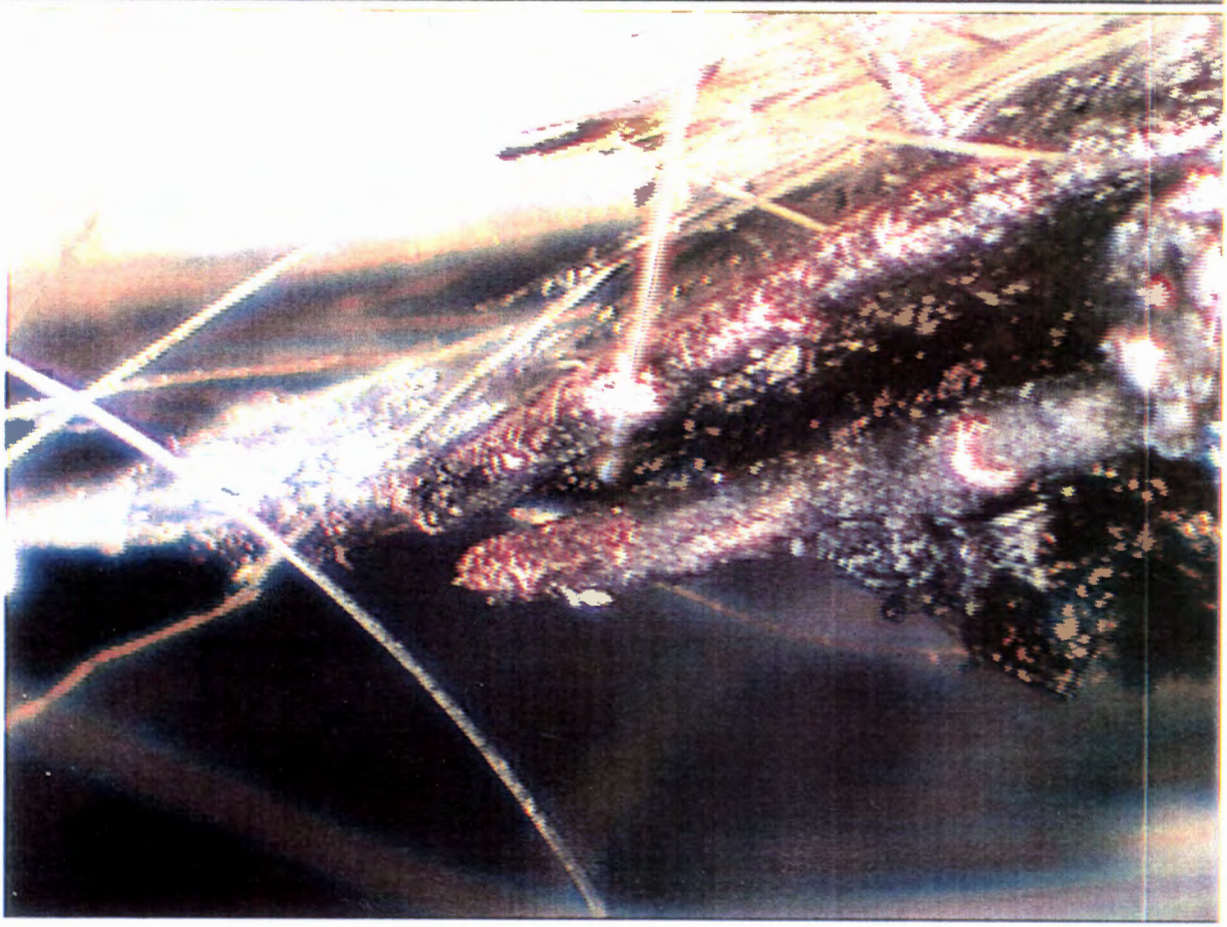

NASA/KSC Materials Science Laboratory

Appendix E:

Equipment, Tools, and Resources Used for Investigation

The following tools were used for the TSS-1R Failure Investigation analysis and tests:

MSFC

Electroscan Environmental Scanning Electron Microscope (ESEM) (model E-3, serial number E31079393) - used to acquire high magnification images of laboratory generated tether samples, flight tether and associated hardware.

4Pi Spectral Engine II data acquisition interface system (serial number 4473) - attached to the ESEM and performed elemental analysis of selected areas of laboratory generated tether samples, flight tether and associated hardware.

VG Scientific Scanning Auger Microscope (SAM) (model Microlab 310-D) - provided elemental surface analysis (depths of less than 50 Angstroms) on flight tether samples.

Pantak x-ray source, model Mark II, serial # $72834, film processor model AFP-24OHC, serial # I-IC-1030,, Kodak Type M radiographic film, batch # 204 4112 (exp. date 10/97), for radiographic testing of flight tether.

ACTIS+ system, software revision 14.2, used for CT scans of flight tether segments.

Perkin-Elmer 1800 Fourier-Transform Infrared Spectrophotometer (FT-IR) (Control 8808) interfaced to a Spectra Tech IR-Plan Infrared Microscope Accessory (Model # 0043-232, SN 595), to a Perkin-Elmer 7700 Professional Computer (SN 889801), to a Win 386 computer (SN AT90041430) on which Sadtler IR Searchmaster software (containing libraries of approximately 30,000 infrared spectra for reference) is installed.

Perkin-Elmer 2000 FR-IR interfaced to a Digital 433dx computer.

Impulse Spark Tester. Electrode Cabinet Model IT-25-B, S/N 840.

LaRC

Scanning electron microscope (SEM): JEOL JSM-6400

EDS system on the SEM: Princeton Gamma-Tech (PGT) IMIX-IID

X-ray Flourescence Spectrometer: Spectrace Model 6000

Appendix F:

Tether Test a nd Analysis

1. *LaRC TSS-1R Tether Failure Analysis*
2. *Summary of Electrical Testing*
3. *Tether Failure Analysis Structural Tests*
4. *Derivation of Average Load/Unit Length for Tether Over Wrap on Reel*

Appendix F:

Tether Test a nd Analysis

1.0 LaRC TSS-1R Tether Failure Analysis

2.0 Summary of Electrical Testing

3.0 Tether Failure Analysis Structural Tests

4.0 Derivation of Average Load/Unit Length for Tether Over Wrap on Reel

NASA Langley Research Center
Materials Division
TSS-1R Tether Failure Analysis

On April 5, 1996, a section of the flight tether was delivered to the Materials Division at LaRC. This piece of tether was labeled "cut 6" and was 31.9 cm long. Anomalies #40, #41, and #42 were located on this section of tether. Cut 6 was 25.436 m from the scissors-cut end of the flight tether and had traveled through the Lower Tether Control Mechanism (LTCM) during satellite deployment prior to tether failure. In addition, on May 3, 1996, a 10-m long piece of flight tether from the spool was delivered the LaRC Materials Division. This piece of tether was not deployed during the TSS-1R mission, and had x-ray flag #18 located 1.25 m from one end.

Analysis of tether from "cut 6" section:
The anomalies were photographed at magnifications ranging from 6X to 40X. Anomalies #40 and 42 were associated with deposits from the pulleys. Anomaly #41 had a blue tint and was out of phase with the pulley marks.

The tether was dissected in sections. A 1-cm long piece was cut from the end remote from cut 6. This piece was sectioned into its components: Nomex cover, Kevlar, FEP insulator, copper wires, Nomex core. The Nomex cover had no foreign matter on it or within the braid. The Kevlar, however, contained a large amount of a foreign substance distributed throughout the braids. No anomalous features were detected in the FEP insulator, copper wires, and Nomex core. Chemical content of each of these tether components was measured using X-ray Fluorescence Spectroscopy (XFS). Table 1 shows the elements detected in each component of the tether. In addition, one of the Kevlar braid was examined using scanning electron microscopy (SEM) and Energy Dispersive X-Ray Spectroscopy (EDS). Regions of the Kevlar braid that contained the foreign substance had Ca, Fe, Ti, Al, Si, K, S, and Cl present.

Table 1: X-ray fluorescence analysis of tether components near "cut 6".

	Elements Detected
Nomex cover	Cl; (trace of Fe and Ni)
Kevlar tows	Fe, S, K; (trace of Cu and Ni)
FEP insulator	Cu; (trace of Fe and Ni)
copper wires	Cu; (trace of Fe)
Nomex core	Cu; (trace of Fe, Ni, and Cl)

A 2.5-cm long piece of tether, with Anomaly #40 centered along the length, was dissected. The anomaly on the Nomex cover consisted of a distribution of small particles. The remainder of the Nomex cover was "clean". The Kevlar in this region also had foreign matter distributed throughout the braids. This section of Kevlar was analyzed using XFS. The elements detected were the same as those shown for the Kevlar in Table I. Examination of the FEP insulator

indicated that a particle, approximately 60 μm in size, was located below the outside surface. The FEP tube was halved lengthwise to allow examination of the inside surface. The particle was not located on the inside surface, but was an inclusion located within the wall of the FEP tube. This particle was excised from the FEP and analyzed using EDS. The particle contained Co, Ni, Fe, Cr, and Mn. These elements are commonly found in superalloys. A quantitative chemical analysis will be conducted in an attempt to identify the specific alloy to which this particle corresponds.

The rest of this piece of tether was dissected and the FEP was examined in an attempt to locate any other particulate inclusions within the FEP tube wall. One small particle, approximately 40 μm in size, was discovered within the FEP insulator wall between Anomalies #41 and #42. Chemical analysis was not conducted on this particle.

The Nomex core also contained several small particles. EDS analysis showed that these particles had the same elemental content as did the foreign matter found in the Kevlar tows.

Analysis of 10-m length of tether from spool:
The 10-m length of tether was cut into 33 segments. Segments 1-32 measured 0.3 m and Segment #33 measured approximately 0.4 m. X-ray flag #18 was centered on the cut between Segments #29 and #30. Examination involved microscopic (10X to 30X) characterization of the Nomex braid, removal of the Nomex, microscopic characterization characterization of the Kevlar, removal of the Kevlar, and microscopic characterization of the FEP/copper/Nomex assembly.

To date, a total of 3 m of tether (Segments 1-10) have been examined. The Nomex cover and the Kevlar tows had a collection of small (< 50 μm) particles distributed along the length of each segment. In addition, the Kevlar tows had several large brown discolored regions (~ 1 mm in size) on each segment. Segment #6 had a chip (~ 1 mm in size), metallic in appearance, in the Kevlar tows. Examination of the FEP/copper/Nomex assembly revealed numerous small particles (< 50 μm) and several larger particles, with size on the order of the copper wire diameter, within the assembly. In addition, numerous flakes with the appearance of copper were observed within the assembly. Many of these particles and flakes appear to be inclusions within the FEP tube wall, but they may be enclosed inside the FEP tube along with the copper wires and Nomex core. None of these particles have been excised to determine their exact location relative to the FEP wall thickness nor have the been chemically analyzed.

Summary

Examination of more than 3 m of the flight tether has revealed the presence of foreign matter located in each component of the tether: in the Nomex cover, in

the Kevlar tows, inside the FEP insulator tube walls, and inside the copper/Nomex core. These particles could have been co-extruded with the FEP, or they could have been on the surface of the copper/Nomex assembly during the extrusion process and become embedded in the FEP wall. The particles found inside the FEP tube wall lend some credence to the scenario of a particle possibly breaching the insulator and allowing arcing. However, no particles large enough to span the entire wall thickness (~ 0.012 inch) causing a hole all the way through the insulator have been found to date.

Appendix F:

Tether Test a nd Analysis

1. *LaRC TSS-1R Tether Failure Analysis*
2. ***Summary of Electrical Testing***
3. *Tether Failure Analysis Structural Tests*
4. *Derivation of Average Load/Unit Length for Tether Over Wrap on Reel*

Summary Electrical Testing for TSS Tether Investigation

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Date of Test	Name of Test	Fault Tree WBS	Description
3/12/96	Good Tether Biased in Vacuum, Partial Vacuum, and Plasma	1.2.1.1.1.5	A complete tether sample was placed in a vacuum ($7x10^{-7}$ Torr), partial vacuum ($1x10^{-4}$) by backfilling with argon, and an argon plasma. The inner conductor was biased from -1kV to -8 kV in increments of -0.5 kV and held for 10 minutes. During each test no discharge was detected. Tether was not under tension.
3/14/96-3/26/96	Tether with Pinholes in a Vacuum and Partial Vacuum with No Tension.	1.2.1.1.2.2.1.2 1.2.1.1.1.4	The purpose of these tests was to see if a tether with a pinhole under the right conditions could start and sustain a 1 A discharge. A tether sample with pinholes exposing the conductor were placed in the vacuum at pressures ranging from ($1x10^{-7}$ to $1x10^{-4}$ Torr) no electrical discharge was detected at -3.5 kV. The pressure was varied by back filling the chamber with argon gas. Once the pressure was raised to ($1x10^{-3}$ to $1x10^{-2}$ Torr), a 0.6 A discharge was started and sustained for 10's of seconds. During these tests the tether was not under tension.

3/26/96-3/28/96	Tether with Pinholes in a Vacuum and Partial Vacuum with 14 to 17 lbs Tension.	1.2.1.1.2.2.1.2 1.2.1.1.1.5	The purpose of these tests was to see if a tether under tension would break, reproducing the same type of failure observed on TSS flight tether. Some questions were raised as to the validity of backfilling the chamber with argon. During these tests the chamber was only roughed out to the correct pressure range ($1x10^{-3}$ to $1x10^{-2}$ Torr), a 0.6 A discharge was started and sustained for all pinhole diameters tested (20 mil to 60 mil dia.). Once the discharge started the tether would break between 6 and 8 seconds. The failed end in all cases resembled the flight TSS tether end.
3/28/96-4/2/96	Tether with Pinholes in Plasma with 14 to 17 lbs tension.	1.2.1.1.2.2.1.2 1.2.1.1.1.5	The purpose of this test was to see if a pinhole in a tether exposed to the ambient plasma could sustain a 1 A discharge. A 8 mil to 25 mil dia hole was placed in the tether and the sample placed in a simulated LEO plasma. Once -3.5 kV was placed on the inner conductor of the tether, a 0.6 A discharge was started immediately, and the tether broke in about 6 to 8 seconds. Also, the tether end sustained a discharge for 10's of seconds after the tether break.
4/3/96	Hermetically Sealed Tether in Vacuum with Tension	1.2.1.1.2.2.2.5	The purpose of this test was to see if the trapped air inside a 19 km tether would discharge when -3.5 kV DC voltage was applied. The chamber was pumped down to a rough vacuum of $4x10^{-3}$ Torr. The tether inner conductor was biased starting at -3.5 kV and increase to -6 kV in increments of -0.5 kV. During the test no discharge was observed.

4/4/96	Hermetically Sealed Tether in Plasma with Tension	1.2.1.1.2.2.2.5	The purpose of this test was to see if the trapped air inside a 19 km tether would discharge when -3.5 kV DC voltage was applied in a plasma. The tether was placed in a plasma under 15 lb tension, and the inner conductor was biased starting at -3.5 kV and increase to -8 kV in increments of -0.5 kV. During the test no discharge was observed.
4/9/96	Hermetically Sealed Tether with a 0.5" Dia Tungsten Grounded Rod in Vacuum	1.2.1.1.2.2.1.2	The purpose of this test was to see if a sharpened tungsten grounding rod placed inside the Nomex/Kevlar braid would cause a discharge to initiate. The chamber was pumped down to a rough vacuum of $7x10^{-3}$ Torr. The tether inner conductor was biased starting at -3.5 kV and increased to -8 kV in increments of -1 kV. During the test no discharge was observed.
4/10/96	Hermetically Sealed Tether with 5 mil Tungsten wire touching inner conductor of tether.	1.2.1.1.2.2.1.2	The purpose of this test was to see if a foreign object touching the inner conductor of the tether could cause a discharge to initiate. The chamber was pumped down to a rough vacuum of $8x10^{-3}$ Torr. The tether inner conductor was biased -3.5 kV and a 0.5 A discharge was initiated which lasted for 6 seconds until the tether broke in two due to the 15 lb tension.
4/11/96	Hermetically Sealed Tether with 5 mil Tungsten wire protuding into FEP not touching inner conductor of tether.	1.2.1.1.2.2.1.2	The purpose of this test was to see if a foreign object protruding into the FEP but not touching the inner conductor of the tether could cause a discharge to initiate. The chamber was pumped down to a rough vacuum of $5x10^{-3}$ Torr. The tether inner conductor was biased starting at -3.5 kV and raised to -6 kV in increments of -1 kV. At -6 kV a 0.5 A discharge was initiated which lasted for 7 seconds until the tether broke in two due to the 15 lb tension.

4/12/96	Hermetically Sealed Tether with Al wire protuding touching FEP	1.2.1.1.2.2.1.2	The purpose of this test was to see if a foreign object resting on the surface of the FEP could cause a discharge to initiate. The chamber was pumped down to a rough vacuum of $3x10^{-3}$ Torr. The tether inner conductor was biased starting at -3.5 kV and raised to -8 kV in increments of -1 kV. No discharge was initiated during this test.
3/19/96	Static Test of Tether Running Over Vespel Pulleys	1.2.1.1.2.4	The purpose of this test was to get an inital feel for the static potential developed by running the tether over vespel pulleys at 1 m/s for the same length of time as the deployment of the TSS system. The test was ran in a general lab environment at room temperature (70 F). The voltage on the pulley was measured as - 2750 V after 10 min of operation.
3/21/96	Static Test of Tether Running Over Vespel Pulleys	1.2.1.1.2.4	The purpose of this test was to get an inital feel of the static potential developed by running the tether over vespel pulleys at 1 m/s for the same length of time as the deployment of the TSS system. The test was ran in controlled environment room at room temperature (70 F) and 37 % relative humidity. The voltage on the pulley was measured as - 800 V after 7.5 hrs of operation.
3/21/96	Static Test of Tether Running Over Vespel Pulleys in Vacuum	1.2.1.1.2.4	The purpose of this test was to get an inital feel of the static potential developed by running the tether over vespel pulleys at 1 m/s for the same length of time as the deployment of the TSS system. The test was ran in a vacuum chamber pumped to $7x10^{-4}$. The voltage on the pulley was measured as -1.2 kV.

TSS Board Action Item Closure
(M-96)

- A 0.013 cm (0.005") dia pinhole place in a good tether which was put in the vacuum chamber.
- Ground plane was place 1.59 cm (0.625") from the tether.
- Chamber was evacuated to 1×10^{-5} Torr.
- Tether was biased to -3500 V and the pressure was varied from 1×10^{-4} to 1×10^{-2} by backfilling with air over a 12 min period. No discharge occurred.
- Bias was increased by -500 V, until a discharge at -4500 V was initiated. Once discharge was initiated, 0.55 A discharge was sustained for 22 s even though the tether broke after 7 s.

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5-3-96

TSS Board Action Item Closure
(Continued)
(M-96)

- A 0.039 cm (0.015") dia pinhole place in a good tether which was put in the vacuum chamber.
- Ground plane was place 1.59 cm (0.625") from the tether.
- Chamber was evacuated to 5×10^{-3} Torr.
- As the tether was being biased to -3500 V, a discharge was initiated at -3300 V. discharge occurred.
- Once discharge was initiated, 0.55 A discharge was sustained for 13 s even though the tether broke after 6 s.

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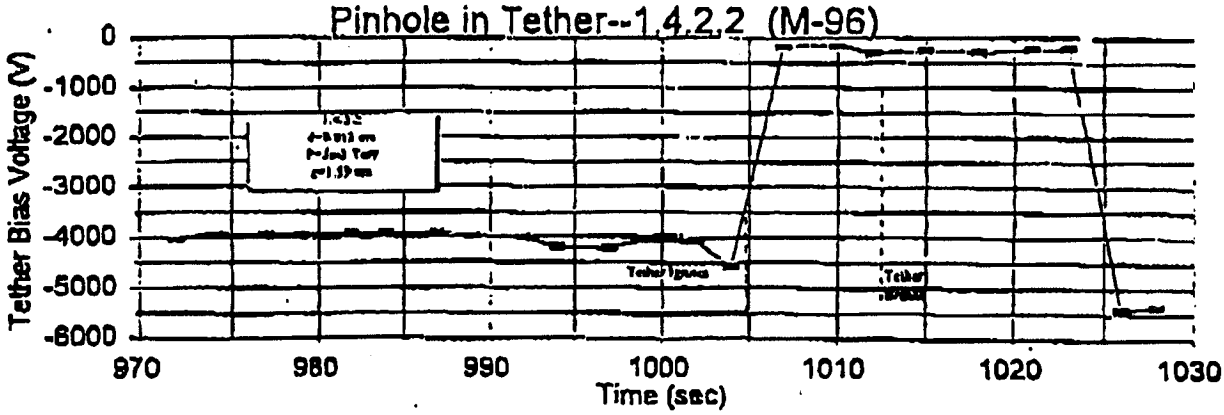
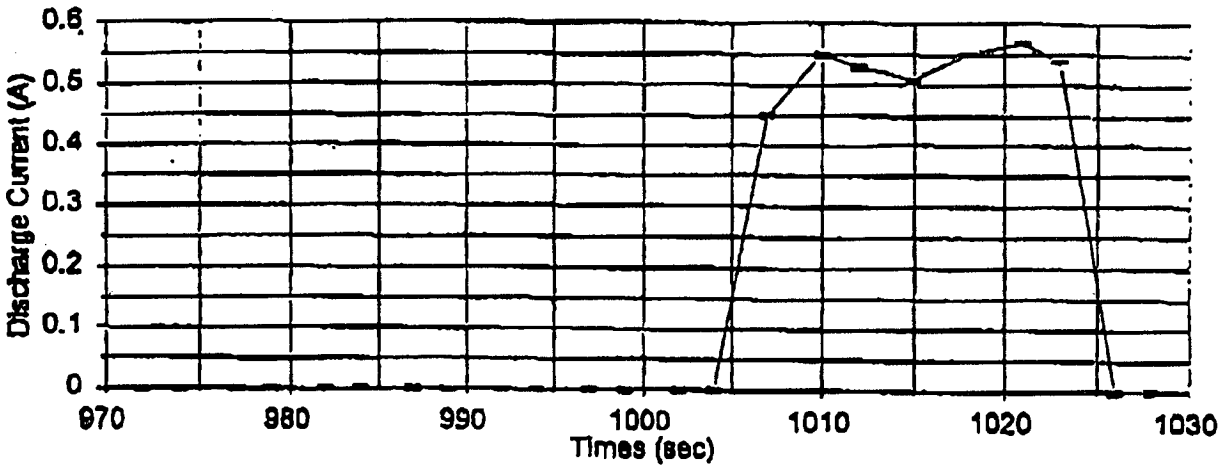
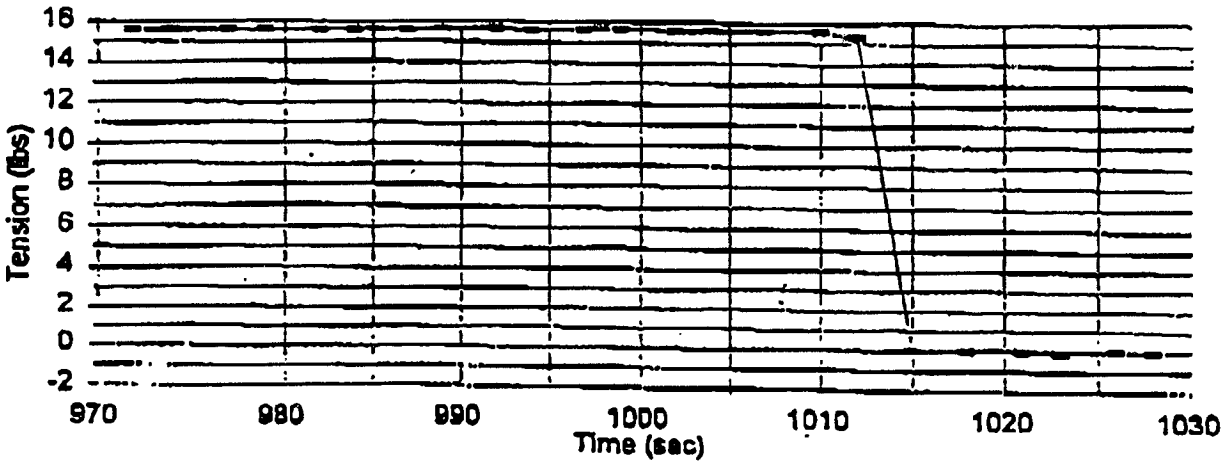
5-3-96

TSS Tether Investigation

Pinhole in Tether--1.4.2.2 (M-96)







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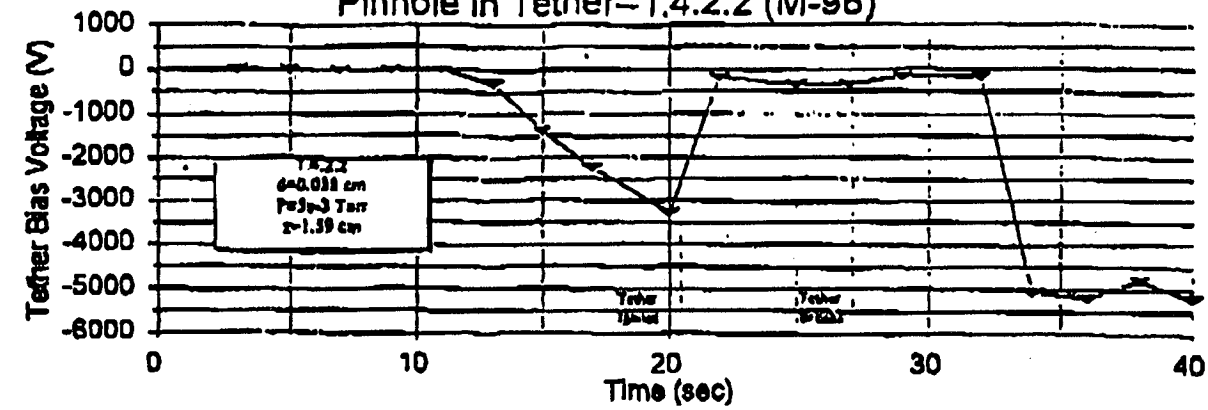
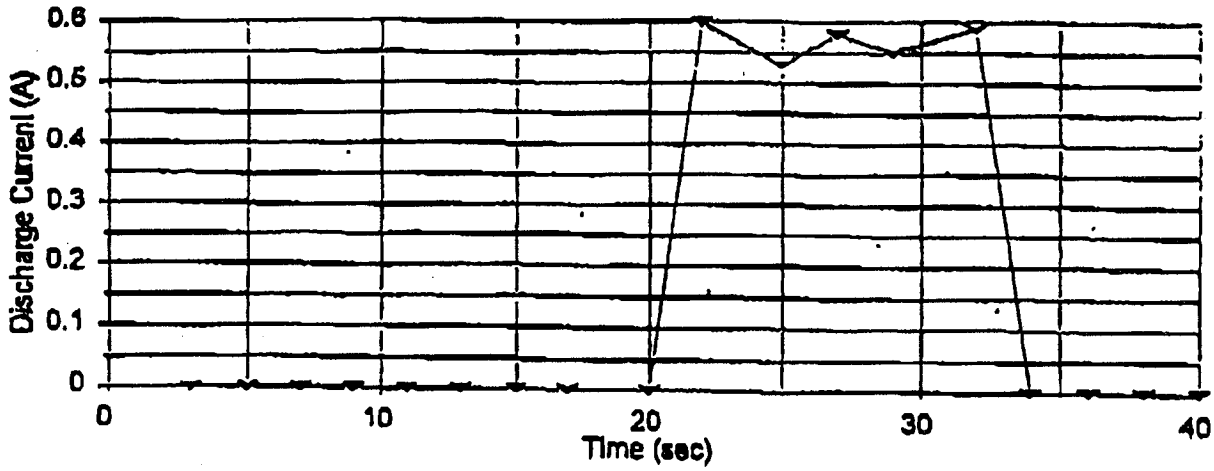
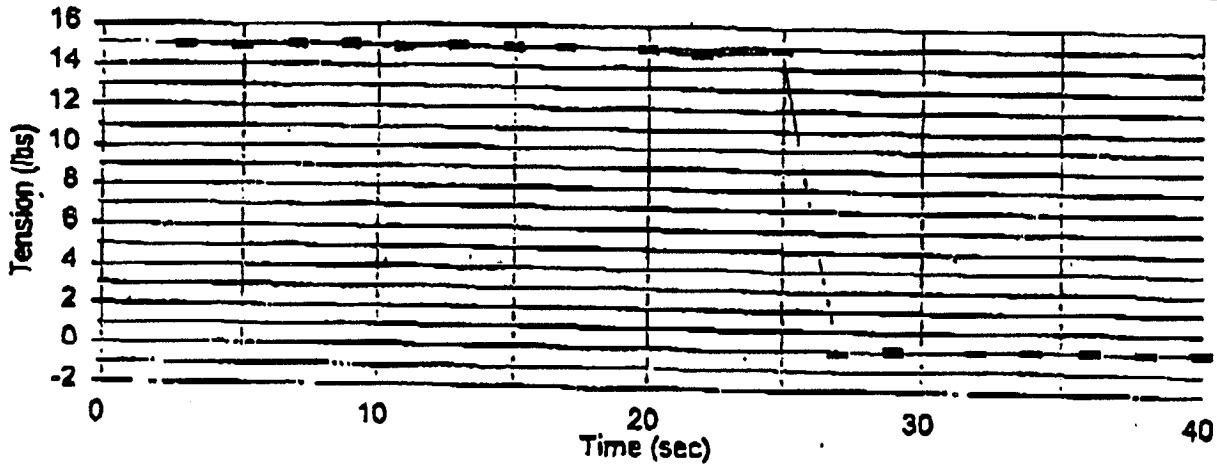
TSS Tether Investigation

Pinhole in Tether–1.4.2.2 (M-96)







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Appendix F:

Tether Test a nd Analysis

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2. *Summary of Electrical Testing*
3. ***Tether Failure Analysis Structural Tests***
4. *Derivation of Average Load/Unit Length for Tether Over Wrap on Reel*

TSS-1R TETHER F. LURE ANALYSIS

WBS 1.4.1 MECHANICAL TEST STATUS

TEST MATRIX/SUMMARY

		Tensile Failure Load (lb)			Status
1.4.1	**Mechanical Tests**	**RT**	**-100 °C**	**125 °C**	
1.4.1.1	Virgin Material	431.7	463.7	320.5	• Complete
1.4.1.2	Electrical Discharge	<10 (1)	N/A	N/A	• Complete
1.4.1.3	12 Strand Kevlar (No Nomex)	419.1	N/A	N/A	• Complete
	9 Strand Kevlar (No Nomex)	309.8	N/A	N/A	• Complete
	6 Strand Kevlar (No Nomex)	237.9	N/A	N/A	• Complete
	3 Strand Kevlar (No Nomex)	142.7	N/A	N/A	• Complete
	No Kevlar or Nomex	37.7	N/A	N/A	• Complete
1.4.1.4	Creep, No Damage	440.1 (2)	N/A	N/A	• Post-test activities continue - pending
	Creep w/Damage	424.7(2)	N/A	N/A	further Board actions
1.4.1.5	Twisted Tension	315.3	N/A	N/A	• Complete

(1) Two specimens.
(2) One specimen.

- NOTE: all tests were conducted on tether removed after first flight (TSS-1)

1.4.1.1 VIRGIN TETHER TENSION

- Objectives: Pull standard specimen lengths of tether in tension until breakage occurs, (1) to establish a baseline for all other mechanical testing, (2) for comparison to tether qualification data to assess aging effects, (3) to provide visual evidence of fracture modes and appearance, valuable for comparison to actual flight tether failure(s), and (4) to verify tether tensile strengths at design temperature extremes

- Results: Thirty specimens pulled at room temperature
  Statistically no different from tether qualification data

  Three specimens each tested at temperature extremes
  No significant change in structural performance

- Observations: Aging is not an issue (pending any additional testing on recovered flight tether)

  Temperature is not an issue (tether was operating at ~5 °C at time of failure) - recommend no additional testing at temperatures other than room temperature

1.4.1.2 ELECTRICAL DISCHARGE TENSION

- Objective: Simulate arcing on standard specimen lengths of tether, then pull in tension until breakage occurs - compare breaking load to known capability of tether

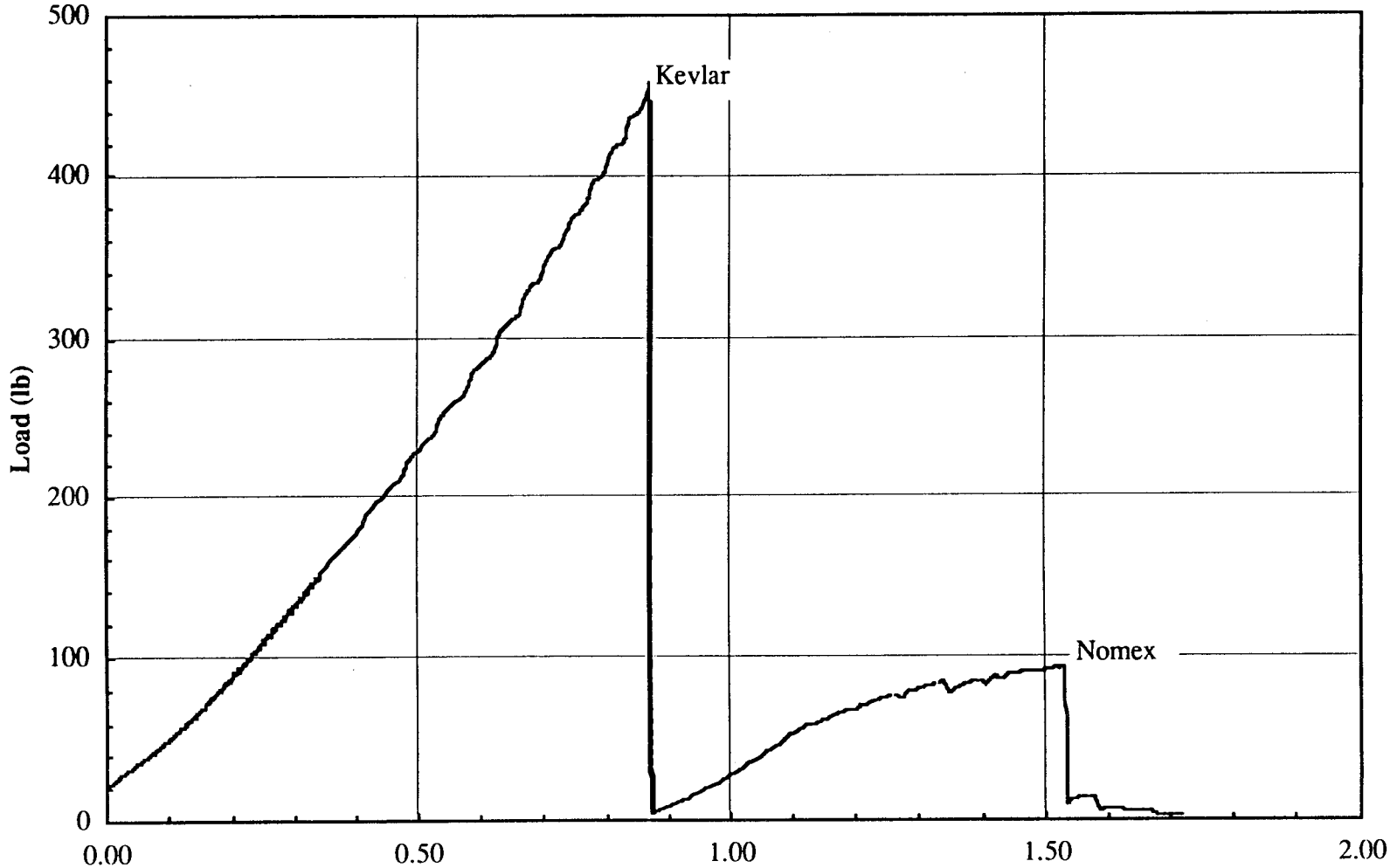
- Results: Two test specimens tested
  Significant charring on tether specimens
  Failures occurred at less than ten pounds force

- Observations: Recommend closure of this test series - electrical testing under simulated flight loads are better indicators of tether performance

TSS-1R TETHER F LURE ANALYSIS

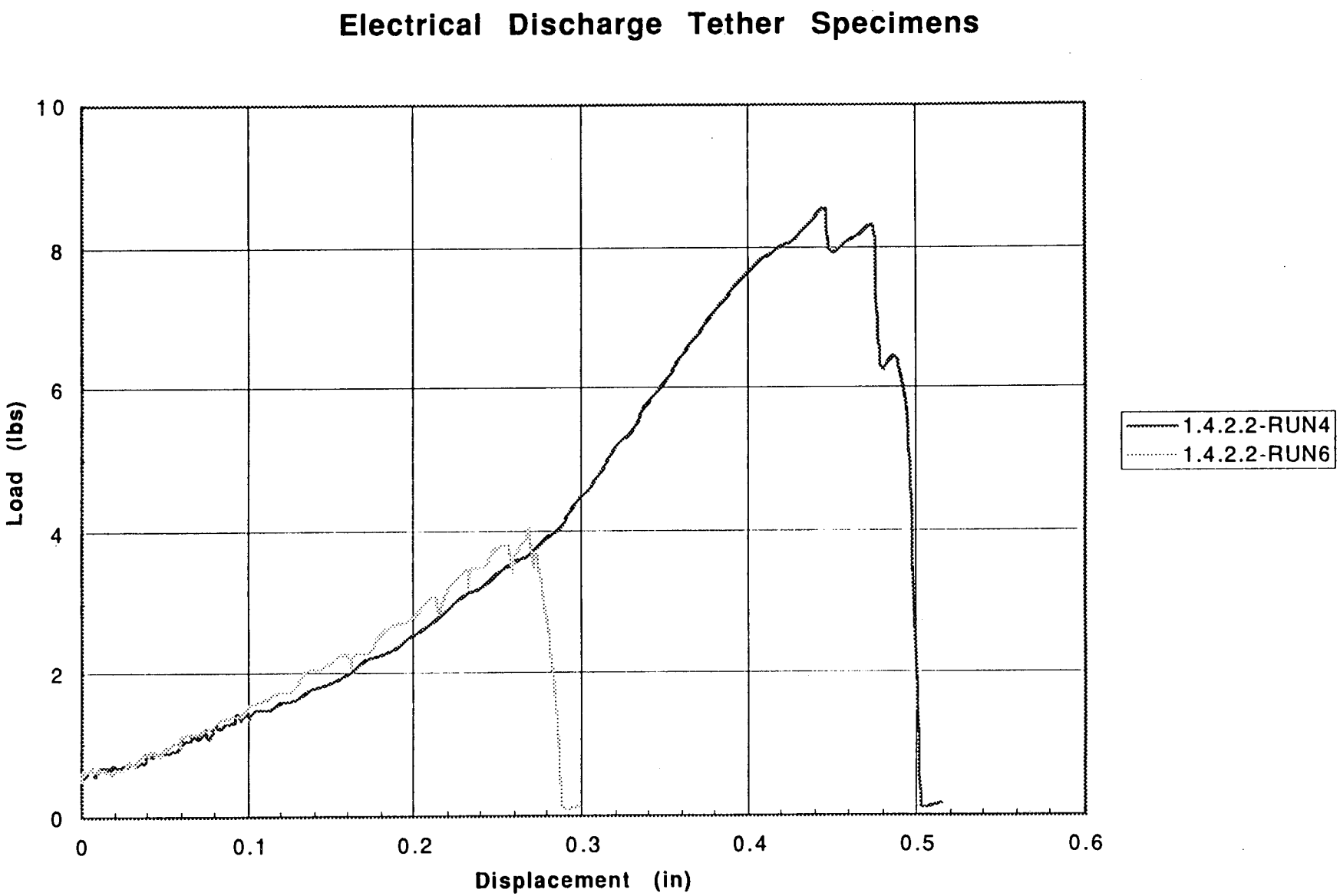
WBS 1.4.1 MECHANICAL TEST STATUS

Tether Tensile Characterization



TSS-1R TETHER F LURE ANALYSIS

WBS 1.4.1 MECHANICAL TEST STATUS

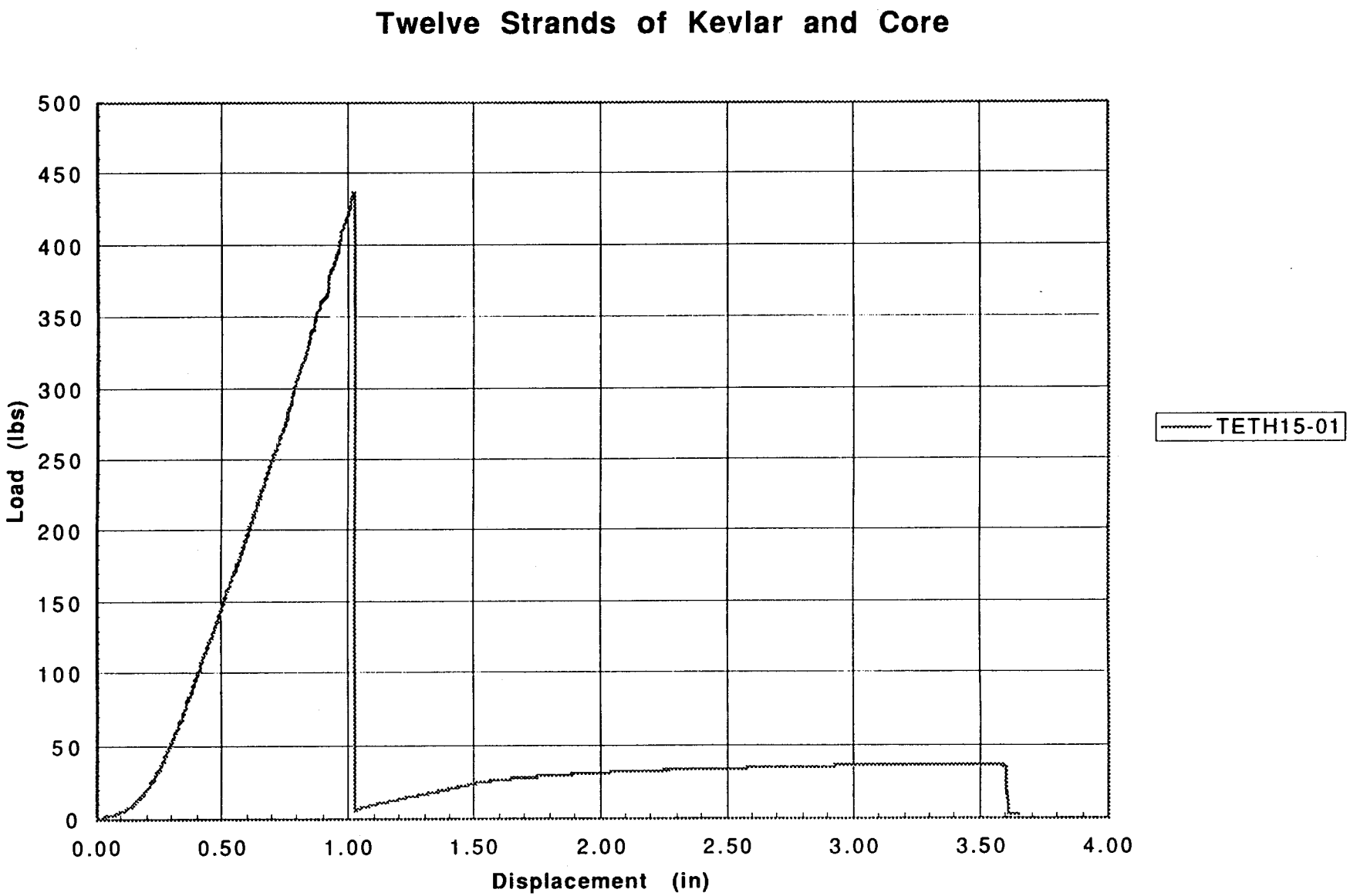


1.4.1.3 MATERIAL REMOVAL TENSION

- Objective: Remove known quantities of material from tether specimens, then pull in tension until breakage occurs - compare breaking load to known capability of tether

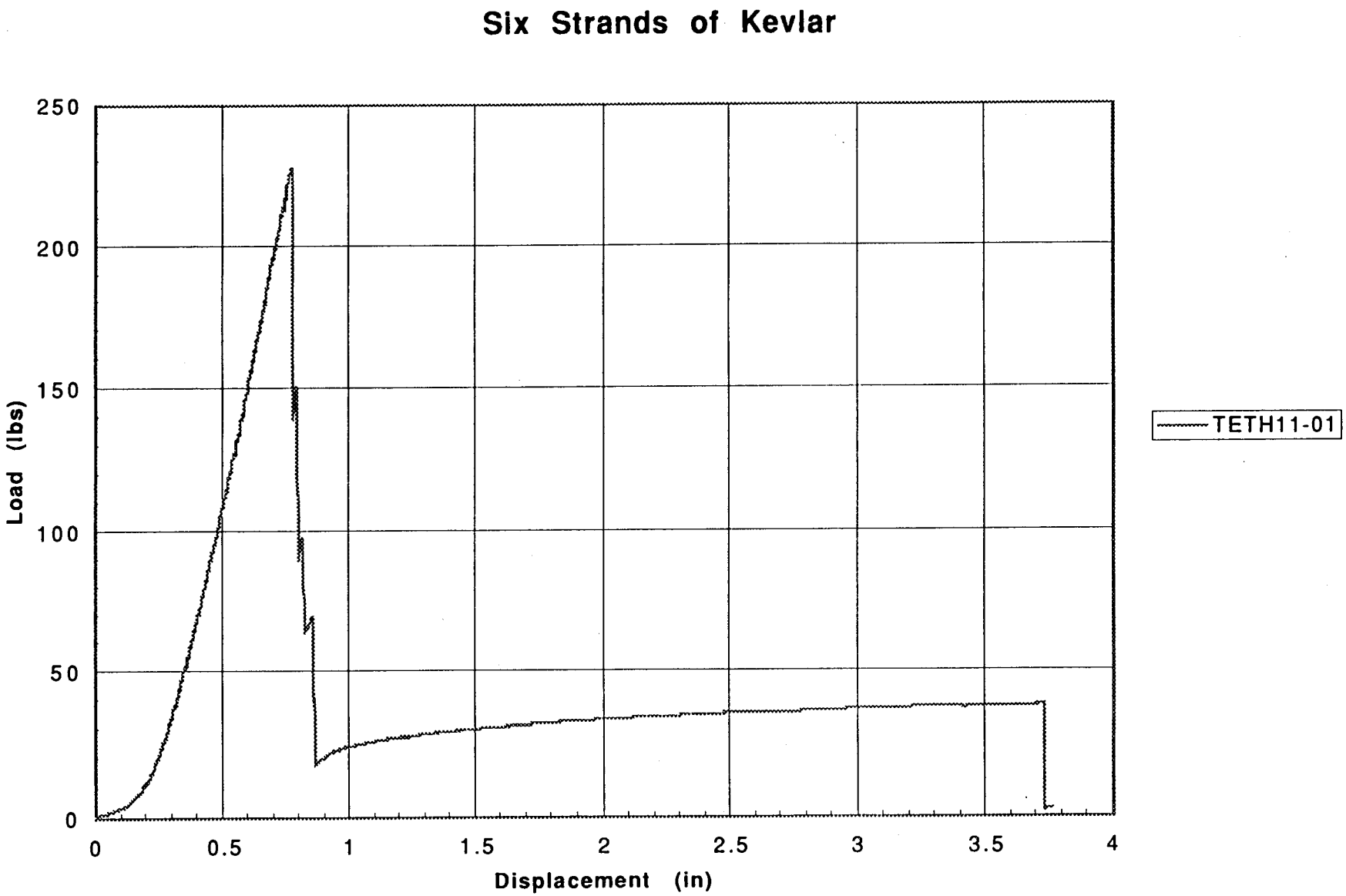
- Results: Three test specimens per condition tested
  Successive material removal led to lower strength
  All failures occurred well above known flight loads

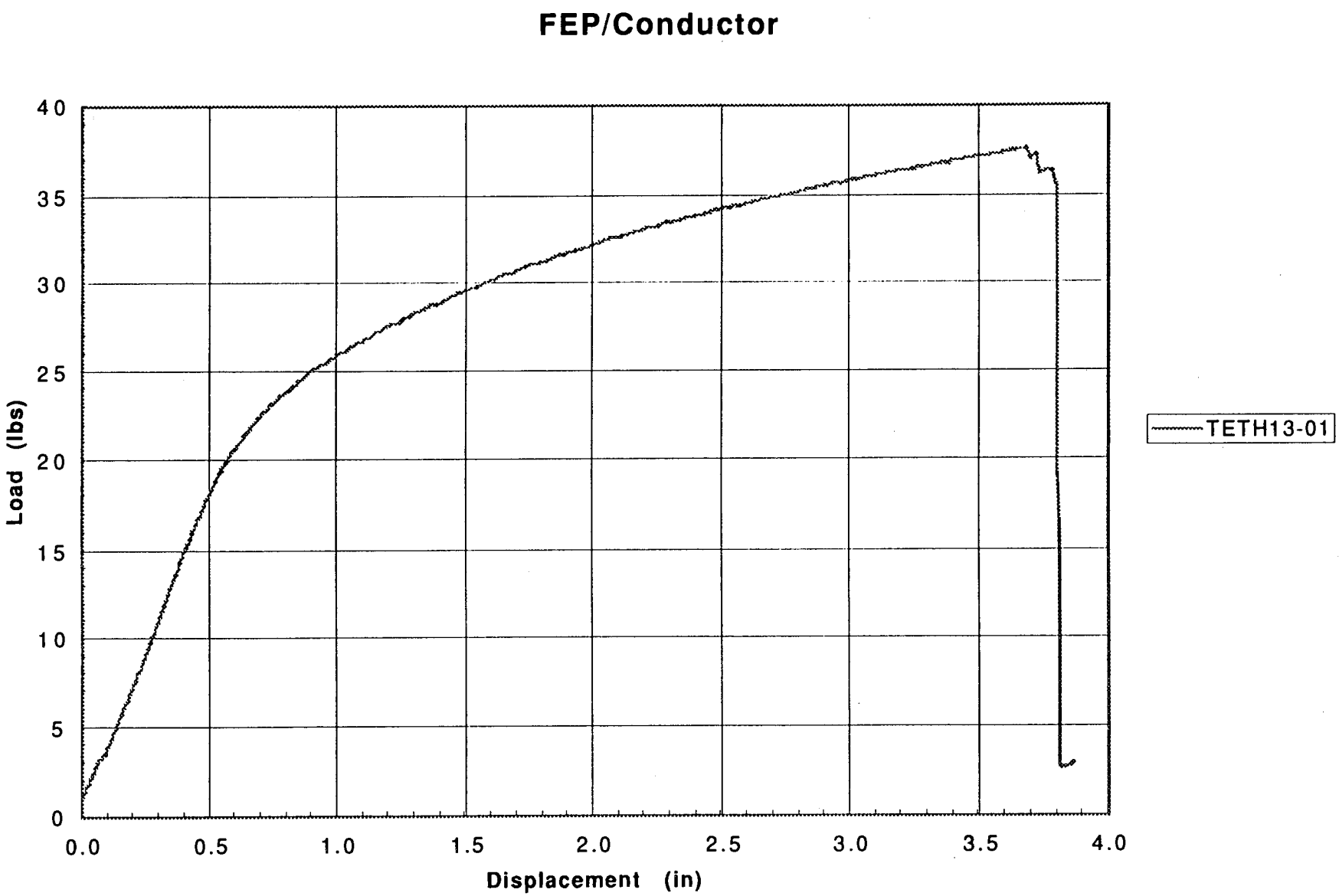
- Observations: Recommend closure of this test series


Twelve Strands of Kevlar and Core
Load (lbs)
500
450
400
350
300
250
200
150
100
50
0
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Displacement (in)
TETH15-01

TSS-1R TETHER F LURE ANALYSIS

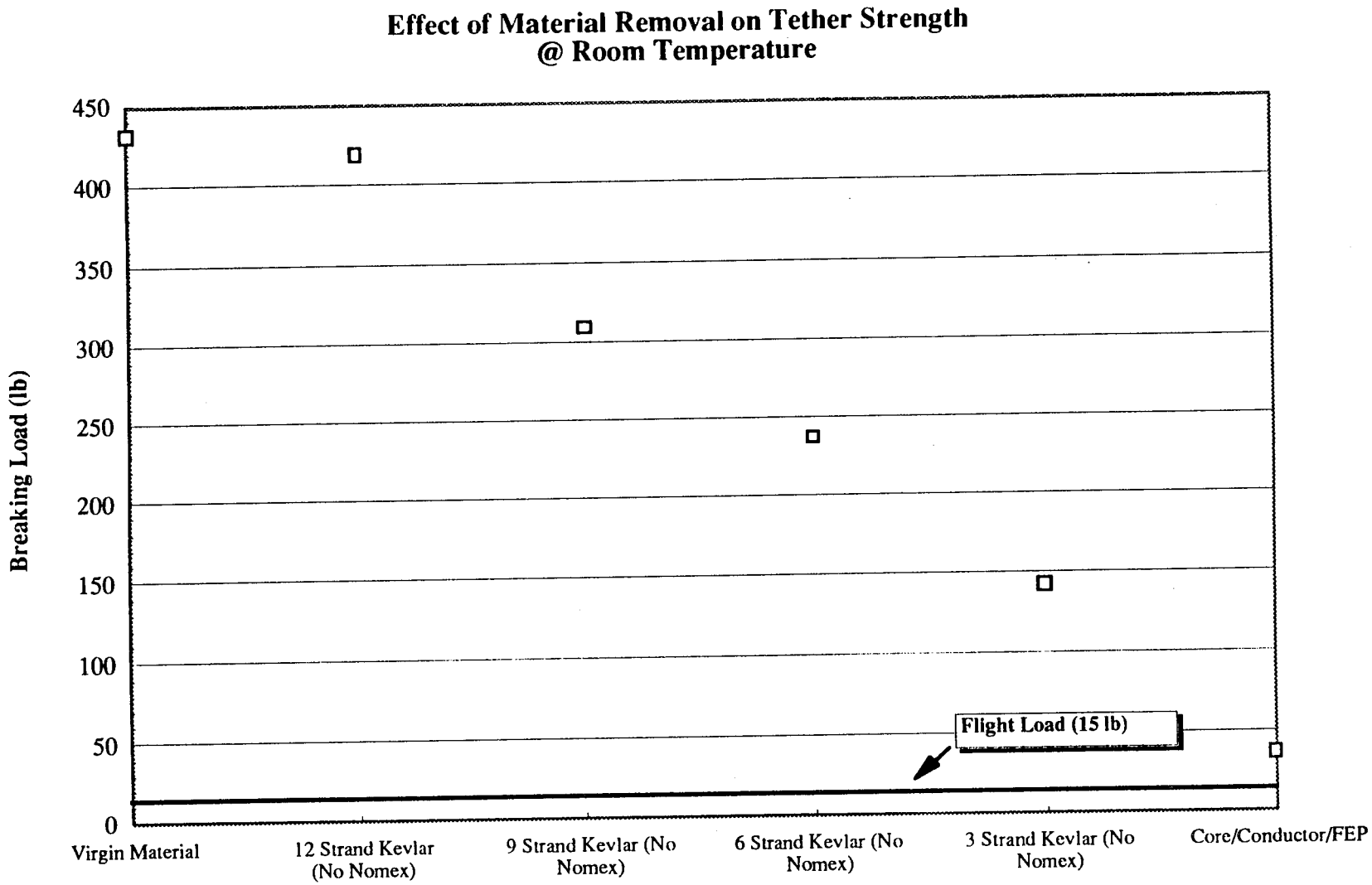
WBS 1.4.1 MECHANICAL TEST STATUS




FEP/Conductor
Load (lbs)
40
35
30
25
20
15
10
5
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Displacement (in)
TETH13-01

TSS-1R TETHER F. LURE ANALYSIS

WBS 1.4.1 MECHANICAL TEST STATUS



1.4.1.4 CREEP ("COLD FLOW")

- Objective: Subject tether specimens to loading representative of an overlap - measure deformation versus time - post-test evaluations should include dimensional check and dielectric breakdown

- Results: Six test specimens subjected to creep (three with pinholes, three without)
  Total change in FEP wall thickness is at most 2 mils in 48 hours

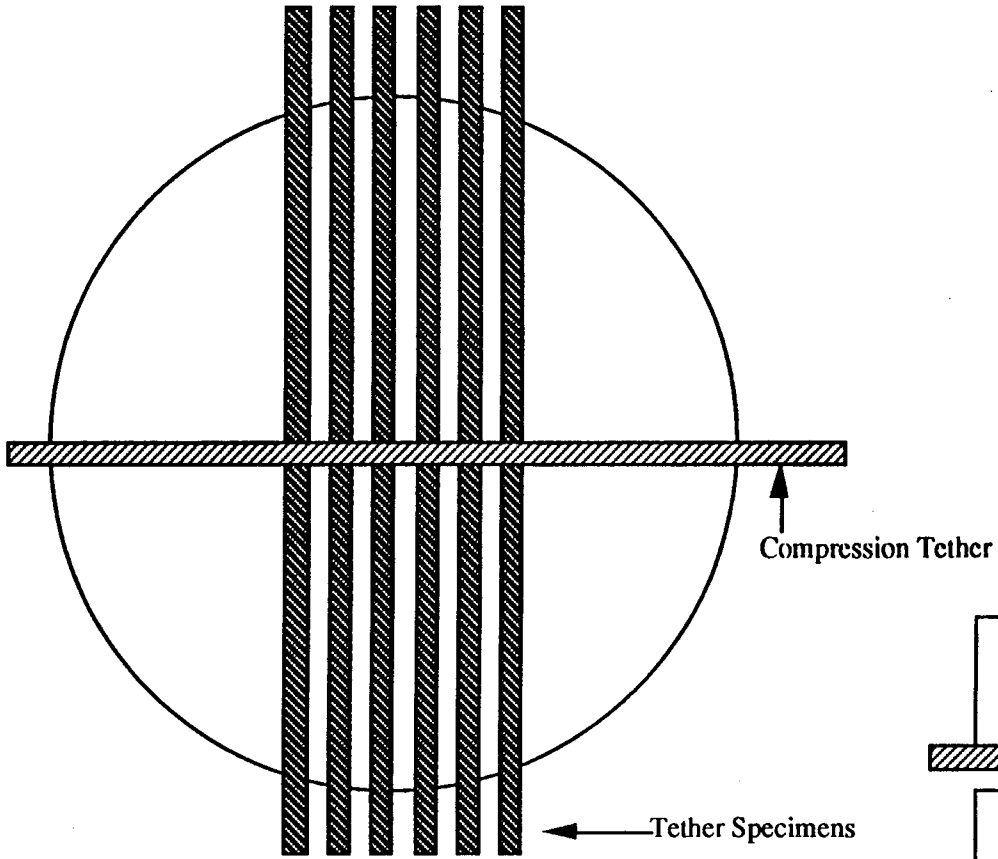
  Two specimens (one each with and without pinholes) tested in tension
  No effect on structural capability

  Remaining specimens to be subjected to electrical breakdown, X-ray, and cross-sectional examination

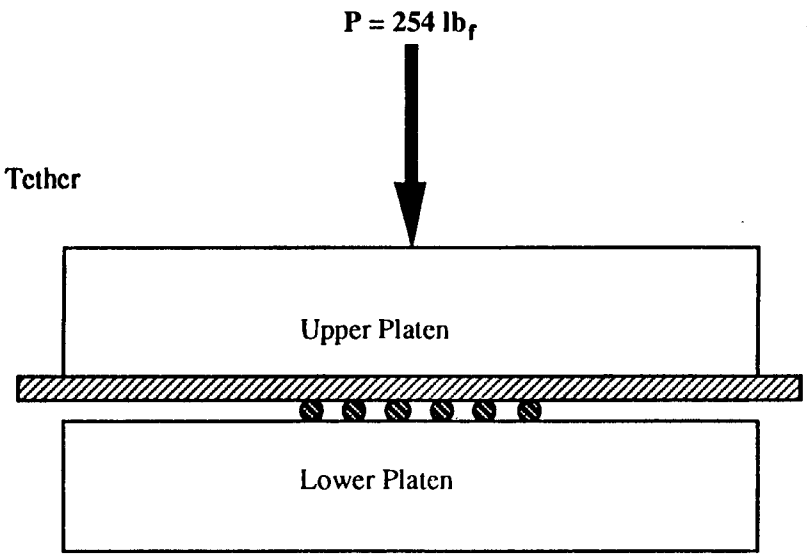
- Observations: Creep alone does not appear to be an issue
  Additional tests pending Board actions/recommendations

TSS-1R TETHER F LURE ANALYSIS

WBS 1.4.1 MECHANICAL TEST STATUS

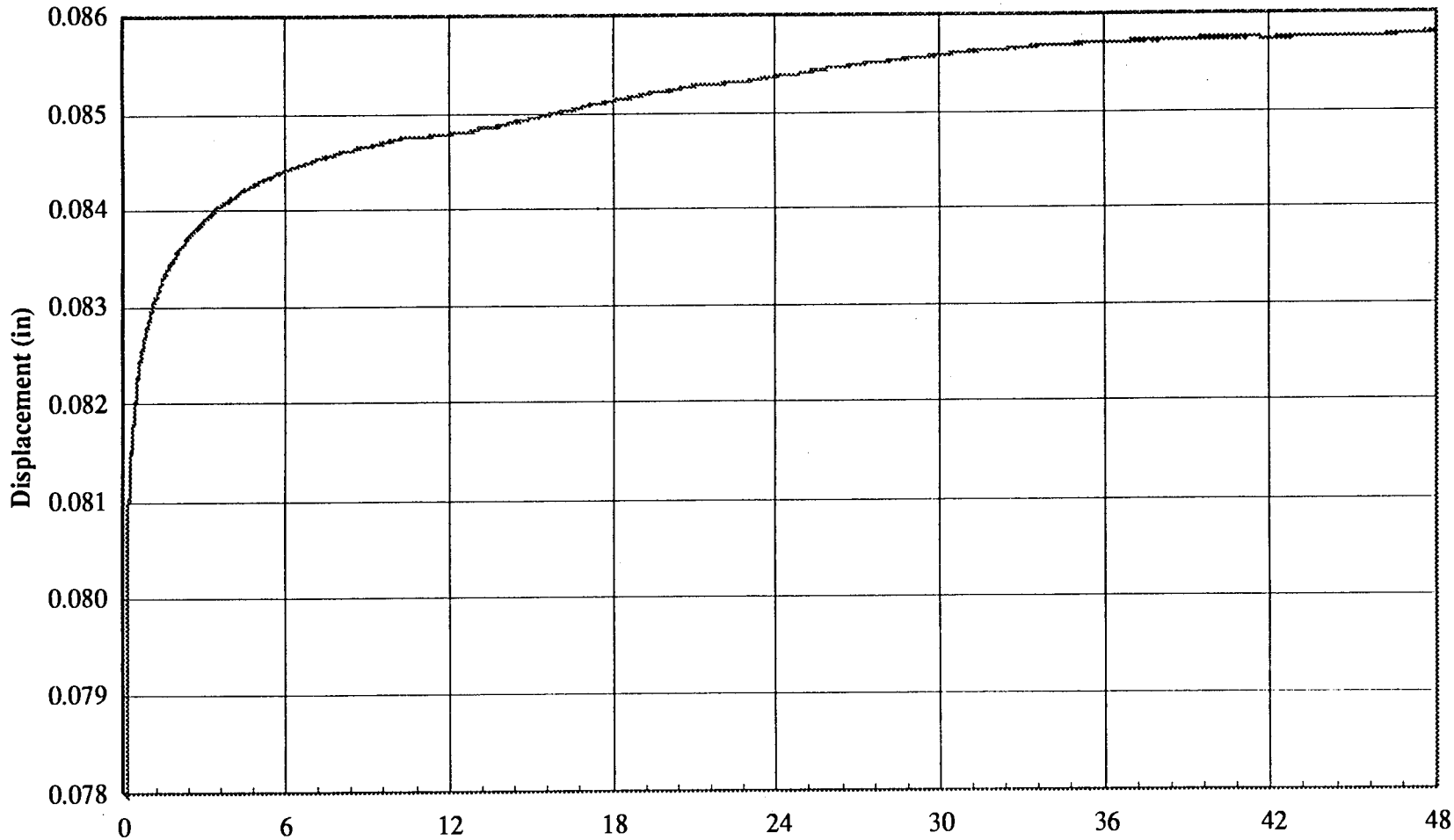


TOP VIEW

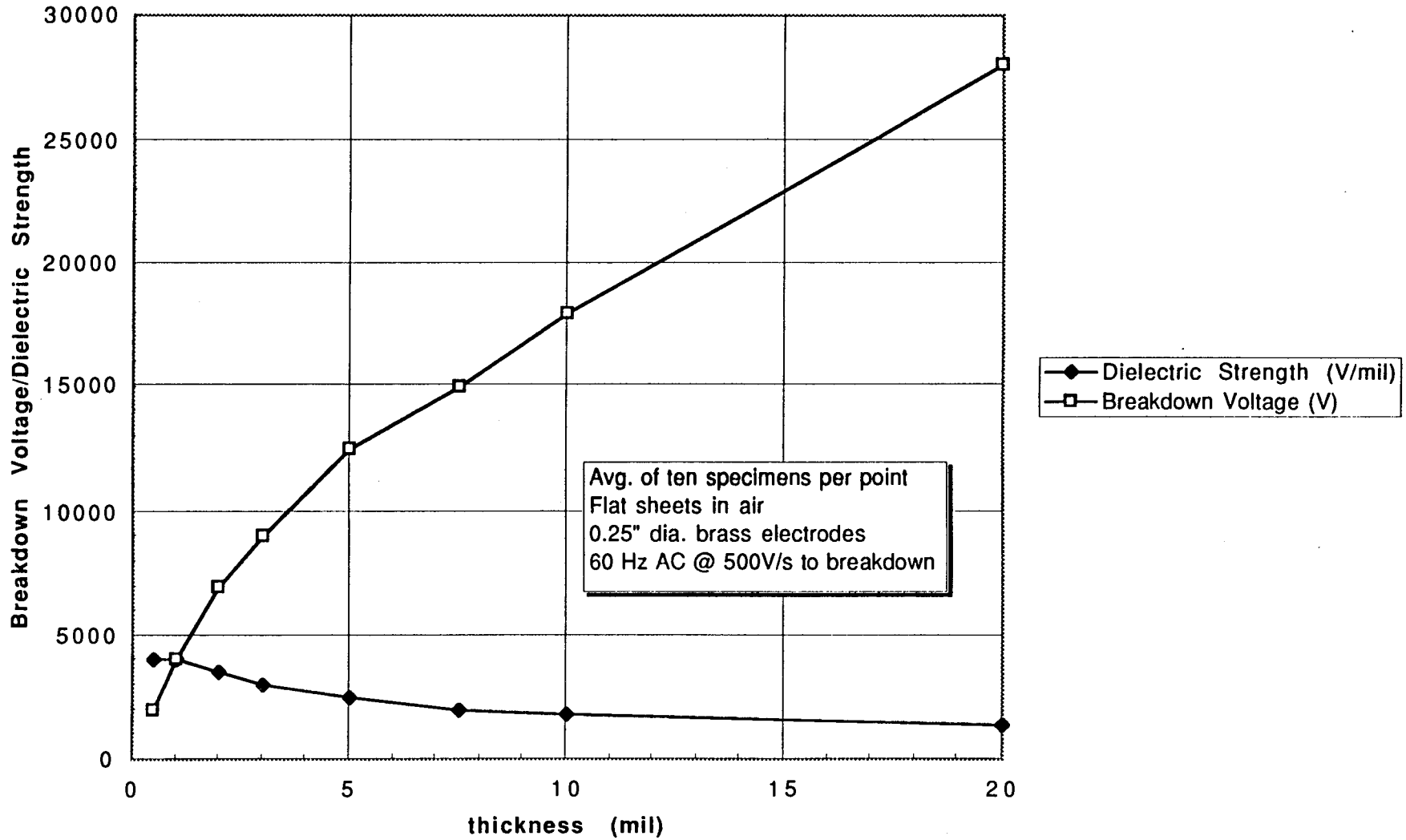


SIDE VIEW

Compressive Creep Test (254 lbs)



Breakdown Voltage vs Thickness, FEP film



1.4.1.5 TWISTED TETHER TENSION

- Objective: Evaluate effect of torsion on structural capability of tether
- Results: Three specimens subjected to torsion of 3 revs/10 inches
  No significant change in tensile strength
- Observations: Recommend closure of this test series - very conservative case tested
  (flight tether had a twist of ~0.5 °/m)

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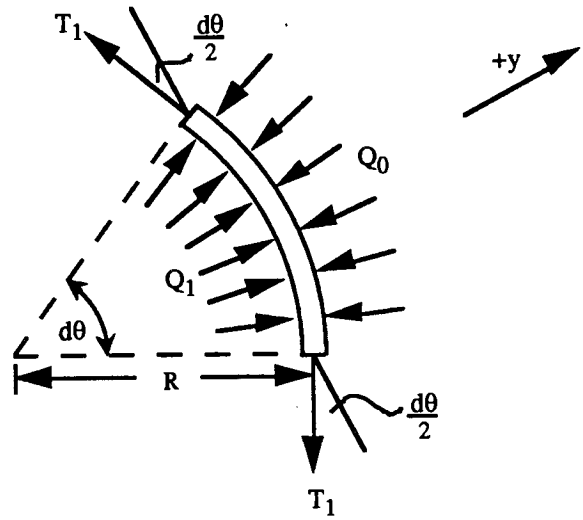
Derivation of Average Load/ unit Tether length Due to Tether Being Wrapped on Reel



$$\sum F = 0$$

$$(Q_1 - Q_0)R_1\, d\theta - 2T_1 \sin\left(\frac{d\theta}{2}\right) = 0$$

$$\sin\left(\frac{d\theta}{2}\right) \cong \frac{d\theta}{2}$$

Therefore

$$(Q_1 - Q_0)R_1\, d\theta - 2T_1\left(\frac{d\theta}{2}\right) = 0$$

or

$$Q_1 - Q_0 = \frac{T_1}{R_1}$$

Therefore

$$Q_1 = \frac{T_1}{R_1} + Q_0$$

Assuming the outside layer has $Q_0 = 0$

$$Q_1 = \frac{T_1}{R_1}$$

Similarly

$$Q_2 = \frac{T_2}{R_2} + Q_1$$

or substituting for P_1

$$Q_2 = \frac{T_2}{R_2} + \frac{T_1}{R_1}$$

Similarly

$$Q_3 = \frac{T_3}{R_3} + Q_2$$

or substituting for Q_2

$$Q_3 = \frac{T_3}{R_3} + \left(\frac{T_2}{R_2} + \frac{T_1}{R_1}\right)$$

similarly the general term for the pressure at each layer is given by:

$$Q_n = \sum_{i=1}^{n} \frac{T_i}{R_i}$$

It is assumed that the tension is the same at each layer, so

$$Q_n = T\sum_{i=1}^{n} \frac{1}{R_i}$$

If there were 60 wraps on top of the failed region then:

$$R = 2.25 + 60(0.1)$$

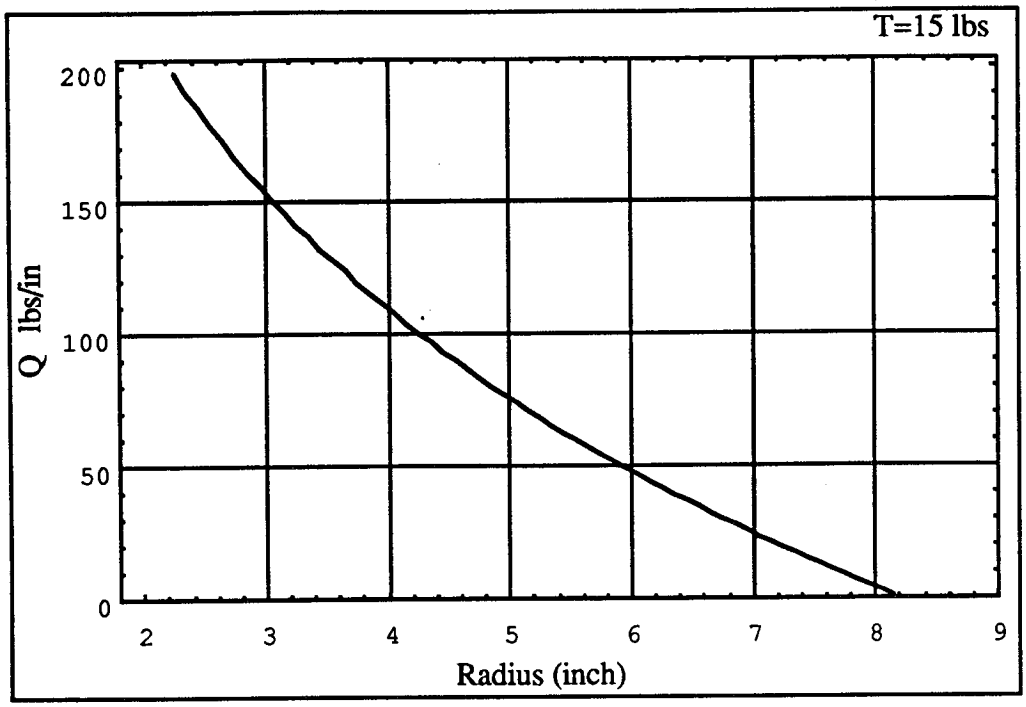
$$R = 8.25$$

So, written in general form:

$$R_i = 8.25 - i(0.1)$$

Substituting gives:

$$Q_n = T\left[\sum_{i=1}^{n} \frac{1}{8.25 - i(0.1)}\right]$$



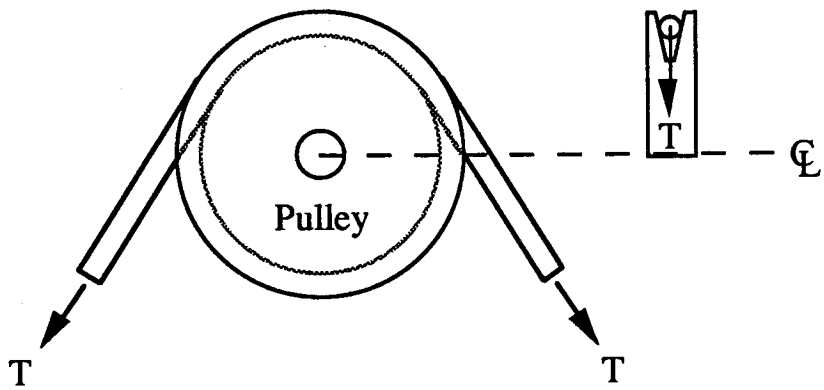
At location where failed tether was stored $(R = 2.25\ in)$

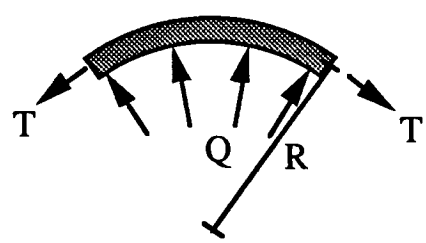
$$\boxed{Q_{R=2.25} = 197.3\ lbs\ /\ in \qquad \text{or} \qquad Q_{R=2.25} = 345.5\ N\ /\ cm}$$

W.C.Schneider

Derivation of Average Load/unit tether length for tether over pulley

As a tether with tension travels over a pulley the pulley exerts a load on the underside. The derivation for an approximation of this load is given .





The above is a free body diagram of the a tether section with tension T over a pulley of radius R being reacted by a force/ unit length Q. The derivation is similar to that of the over wrap which proceeds from equilibrium. The result is given by:

$$Q = \frac{T}{R}$$

Considering the tether to have fifteen pounds of tension and the radius to the tether centerline to be 1.45 in. (for a 3 inch diameter pulley), the load Q is :

$$Q = \frac{15\ lbs}{1.45\ in}$$

or

$$Q = 10.3\ lbs / in \quad \text{or} \quad Q = 18.0\ N / cm$$

W.C.Schneider

Appendix G:

TSS-1R Fault Tree Analysis

1. *Introduction*
2. *Management*
3. *Fault Tree Action Item/Closure*
4. *Analyses Documentation*

Appendix G:

TSS-1R Fault Tree Analysis

1. *Introduction*
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4. [illegible]

TSS-1R Fault Tree

3.1.1 Introduction

The genesis of the fault tree method of failure investigation has an impressive background. Constructed originally (early 1960's) by business strategy planners and called a decision tree, this technique was adopted early on by engineers faced with the problem of determining reasons for failure and mishaps involving complex, sophisticated engineering systems. Hence the name, fault tree, evolved.

Fault trees are especially beneficial when failed systems have significant complexity, with multiple opportunities for synergistic effects, which can contribute to the ultimate failure. When significant complexity or synergism is involved (contingent elements conspiring to cause failure), the resulting complex logic demands a methodical, orderly approach that accommodates all the rational probabilities that can contribute to the ultimate failure. The tethered saellite had this level of complexity.

Fault trees for complex sophisticated systems are, in themselves, and by necessity, complex diagnostic systems. Hence, they are frequently viewed with alarm by investigators looking for a quick solution, the early finding of the "smoking gun." When a duly qualified fault tree team does not find the smoking gun within a few weeks of full time, diligent pursuit, the failure may have involved multiple (synergistic) events, the true evidence may have been destroyed in the failure, or the cause may have been so subtle that it escaped inclusion or recognition during the initial construction of the fault tree. The latter event is unlikely if the team, constructing the tree, truly represents the "best minds"

on the subject. In this instance, we believe that we had such participation in construction of the tree used, and the cause or causes of the event were ultimately identified on the fault tree.

Modus Operandi

As note above, the fault tree begins with the event itself (the tree trunk). Major blocks then have designated leaders (called blockheads) whose responsibility it is to develop the scenario leading up to the major block events. This tactic assigns different personnel individual responsibility for the element development items (tree branches). Each of the blocks on the fault tree is coded according to the standard NASA work breakdown structure (WBS) code (1.0, 1.1, 1.2, etc.). By this means, each element is uniquely identified so that action items and closures of the blocks can be readily related back to the master fault tree diagram. Closure procedures involve either indicting or exonerating the item in the block by means of analysis, test, or legitimate logical inference. The fault tree is usually used to drive the investigation; i.e., the team meets once each day giving status of action items, assessment of tree construction accuracy, and closure according to the master fault tree diagram. Thus the fault tree approach avoids redundancy, wasteful pursuit of random events and "pet" scenarios, and ultimately provides the solution in the most expeditious manner, if the problem is characterized by sophistication, subtlety, or complexity. Simple failures do not usually warrant the full fault tree approach. However, if the fault tree technique is used, a philosophy of "No Eurekas" must be used throughout the entire endeavor and rigidly adhered to by the participants.

Each rational remaining scenario must be worked with equal emphasis. Premature zeroing in on a "pet" scenario is counterproductive to the team effort. A team environment is mandatory. In this sense, a fault tree is very much like a Product Development Team. Figure 1 shows how the fault tree system functions.

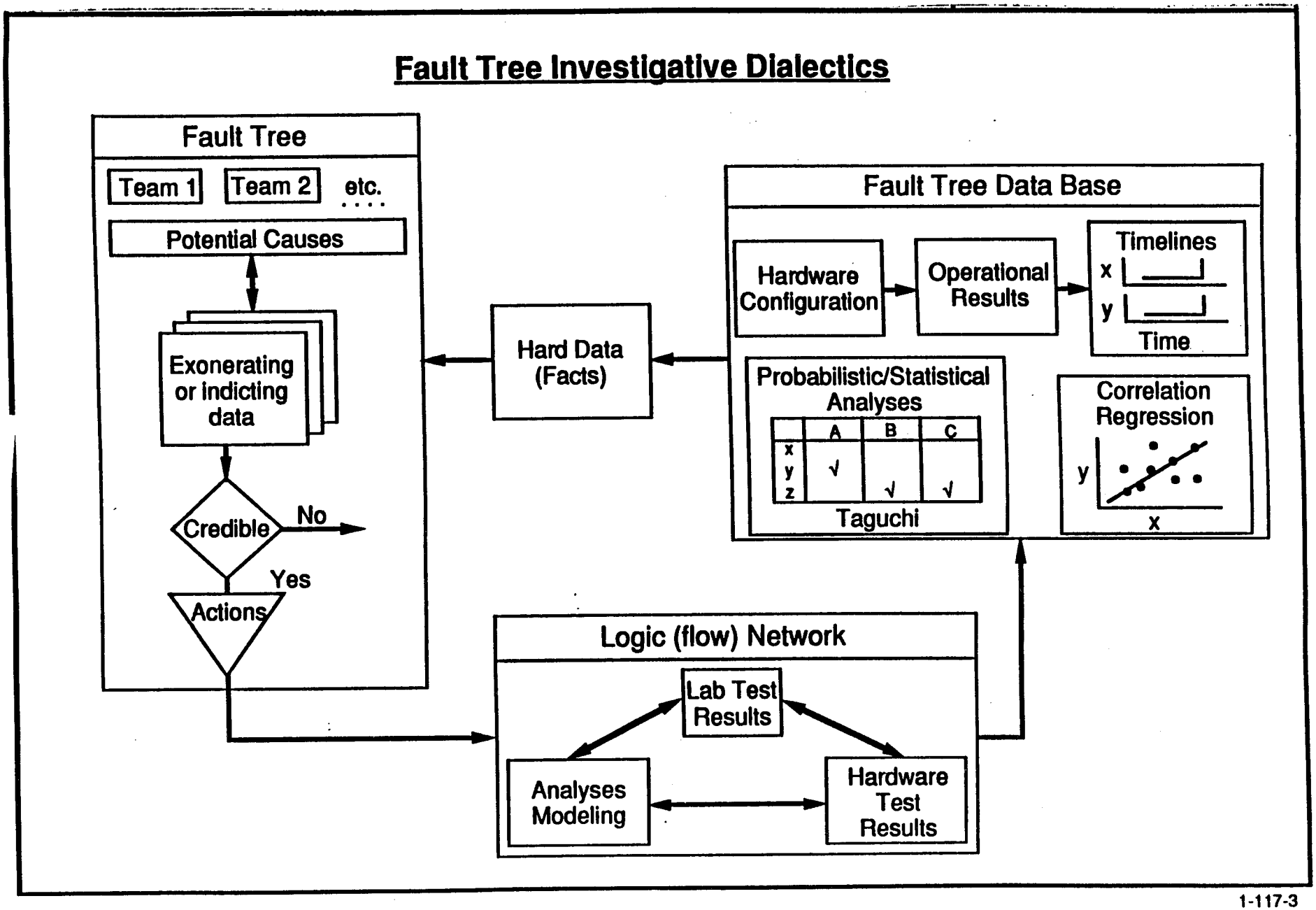
Fault Tree Investigative Dialectics
Fault Tree
Team 1
Team 2
etc.
Potential Causes
Exonerating or indicting data
Credible
No
Yes
Actions
Hard Data (Facts)
Fault Tree Data Base
Hardware Configuration
Operational Results
Timelines
x
y
Time
Probabilistic/Statistical Analyses
A
B
C
x
y
z
√
√
√
Taguchi
Correlation Regression
y
x
Logic (flow) Network
Lab Test Results
Analyses Modeling
Hardware Test Results
1-117-3

Figure 1

Appendix G:

TSS-1R Fault Tree Analysis

1. *Introduction*
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Fault Tree Management

The Tiger Team began the fault tree construction on 3/3/96. The Fault Tree leads and participants were as follows:

MSFC TSS-1R Failure Tiger Team Leads

NAME	FUNCTION	ORGANIZATION
R. J. Schwinghamer/DA01	Chairman	MSFC Director Office
Ron Mize/CR85	Executive Secretary	Safety & Mission Assurance Office
Robert McBrayer/JA71	TSS Project Manager	Payloads Project Office
Tony Lavoie/EJ61	TSS-1R Chief Engineer	Space Systems Chief Engineers
Dennon Clardy/EJ61	Deployer Engin./Ops	Systems Analysis & Integ. Lab
Mike Galuska/CR80	Safety & Mission Assurance	Safety & Mission Assurance Office
Amanda Harris/CR01	Impounded Data Control	Safety & Mission Assurance Office
Chris Hauff/EB46	Software	Astrionics Lab
Ed Litkenhous/EP43	Mechanisms	Propulsion Lab
Todd MacLeod/EL62	Dep. Chief Engineer/Sys.	Systems Analysis & Integ. Lab
Lee Marshall/LMC	Lockheed Program Manager	Lockheed Martin Company
Ron McIntosh/EH31	Materials	Materials & Processes Lab
Tina Melton/EO02	Payload Operations Dir.	Mission Operations Lab
Charlie Morris/EB33	Avionics	Astrionics Lab
Paolo Mussi/ALENIA	Satellite & Support Equip.	Alenia (Italian Sat. Contractor)
Sam Ortega/ED25	Structures	Structures & Dynamics Lab
Keith Presson/ED63	Thermal	Structures & Dynamics Lab

NAME	FUNCTION	ORGANIZATION
Robert Ryan/ED01	Fault Tree Manager	Structures & Dynamics Lab
Charles Simonds/EO01	Operations Representative	Mission Operations Lab
Nobie Stone/ES83	TSS-1R Mission Scientist	Space Sciences Lab
Jim Strickland/EL01	Deinteg & Test Planning	Systems Analysis & Integ. Lab
Don Tomlin/ED12	Dynamics & Control	Structures & Dynamics Lab
Dawn Trout/EL23	EMI/EMC	Systems Lab

OTHERS ASSISTING THE TSS-1R FAILURE TIGER TEAM LEADS

NAME	ORGANIZATION	NAME	ORGANIZATION
Ettore Allais	ALENIA	Jeff Anderson	EL23
Robert Bechtel	EB11	Tom Bechtel	EJ42
Ralph Carruth	EH11	Dennon Clardy	EJ61
Rick Deppish	LeRC	Andy Gamble	EB23
John L. Frazier	JA71	Jason Vaughn	EH15
Matt McCollum	EL54	Carlton Foster	EP43
Zac Galaboff	ED12	Rhega Gordon	EO36
John Harbison	EP41	Joe Kerr	EJ61
Tony Lavoie	EJ61	Frank Ledbetter	EH33
Allen Long	HEI	Vernon Lunsford	LMC
Steve Meacham	EJ42	Coy Newton	HEI
Patrick Molloy	EO37	Pam Nelson	EB43
Alan Nettles	EH32	Dick Parr	EH22
Steve Pearson	EL23	Ed Ricks	ED23
Steve Robbins	JA71	Noel Sargent	LeRC
Wendell Sherbert	CR80	Jeanette Skinner	EJ61
Jan Smith	S^3	Sid Smith	HEI
L. D. Stewart	EB14	Becky Soutullo	JA71
Marion Teal	EB31	John Vickers	EH33
Carole Wagner	EH43	Ken Welzyn	ED12
Bob Wingate-Retiree	LaRC	Randy Williams	HEI
Jim Zwiener	EH12	Mike Mitchell	EH43

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3. ***Fault Tree Action Item/Closure***
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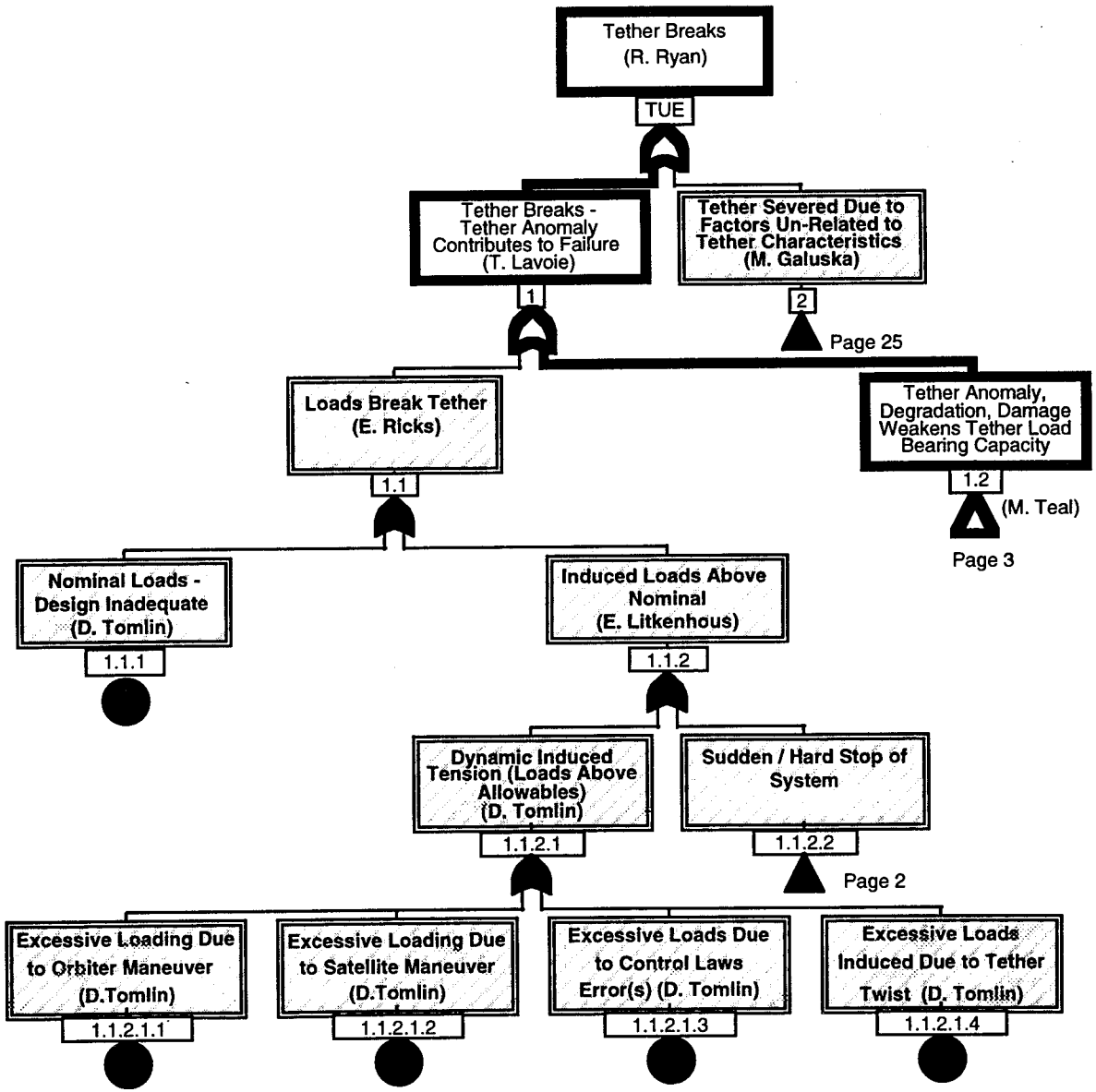
TSS Tether Anomaly Fault Tree Action Item / Closure

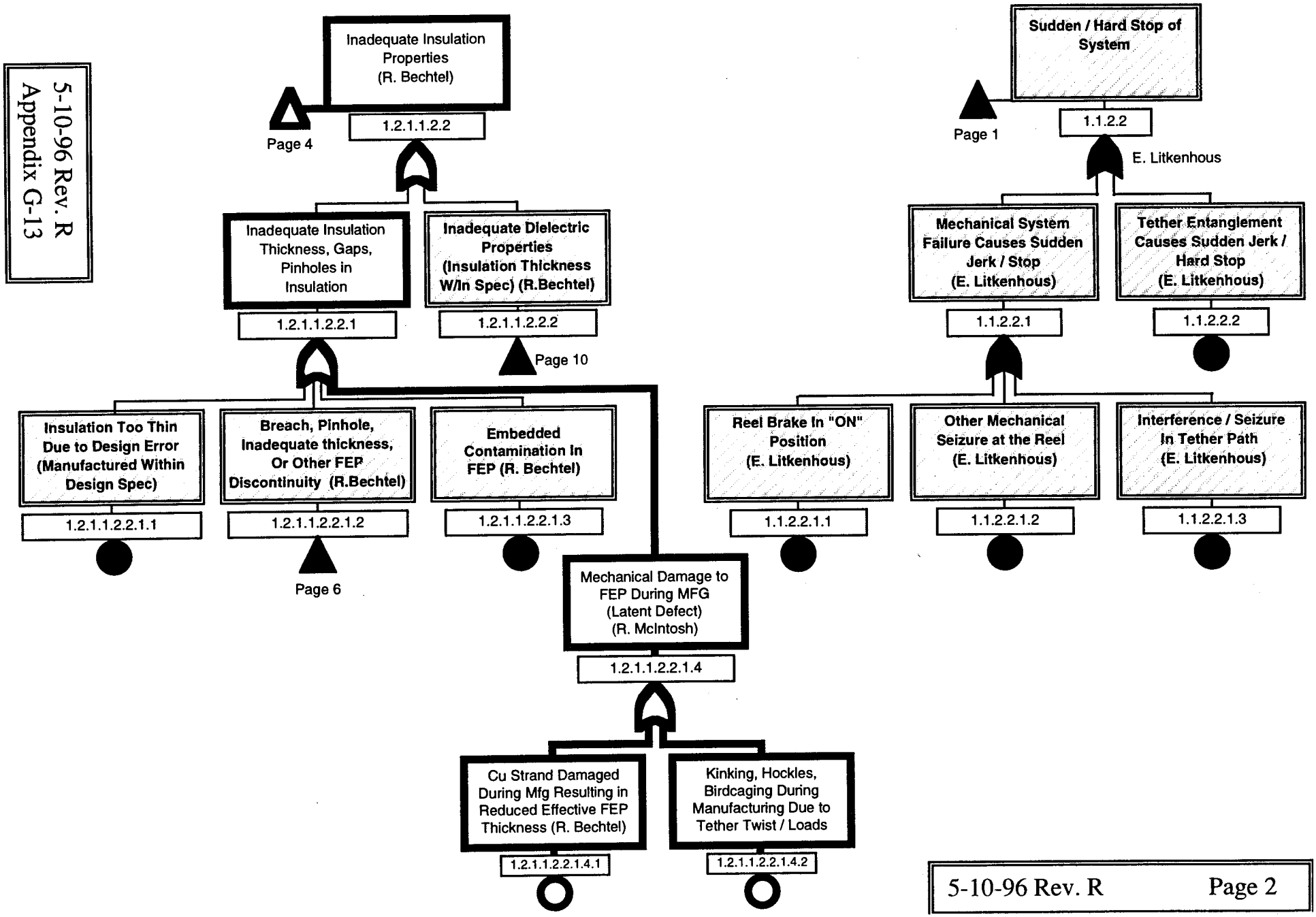


Likely Cause

Open

Closed

TSS Tether Anomaly Fault Tree Action Item / Closure



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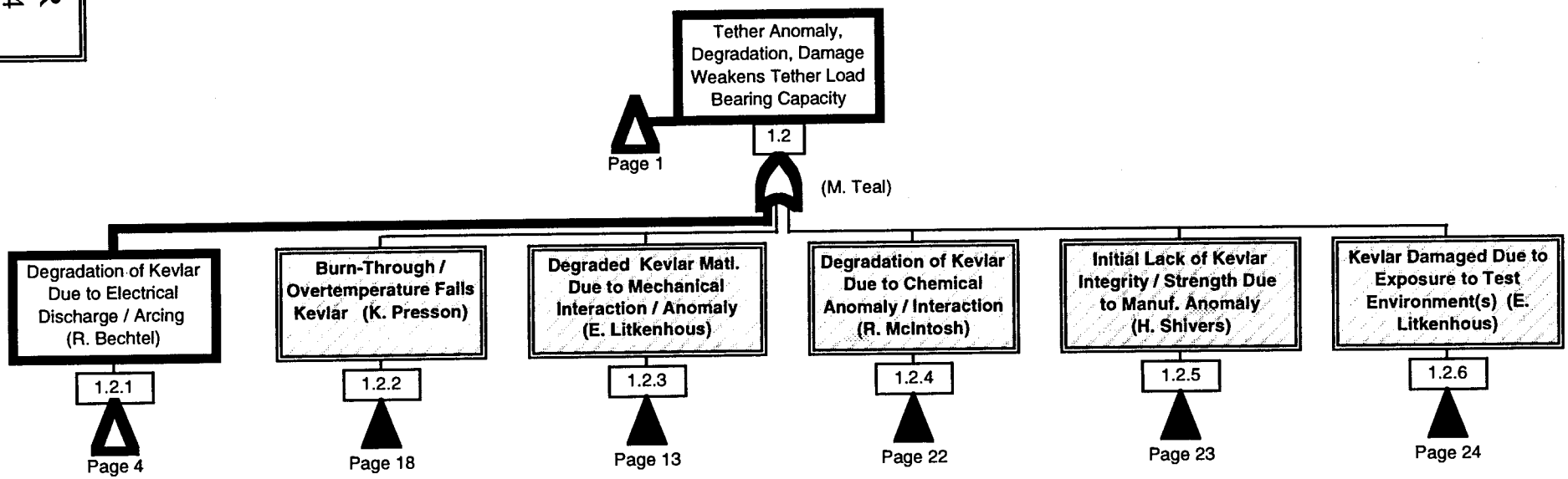

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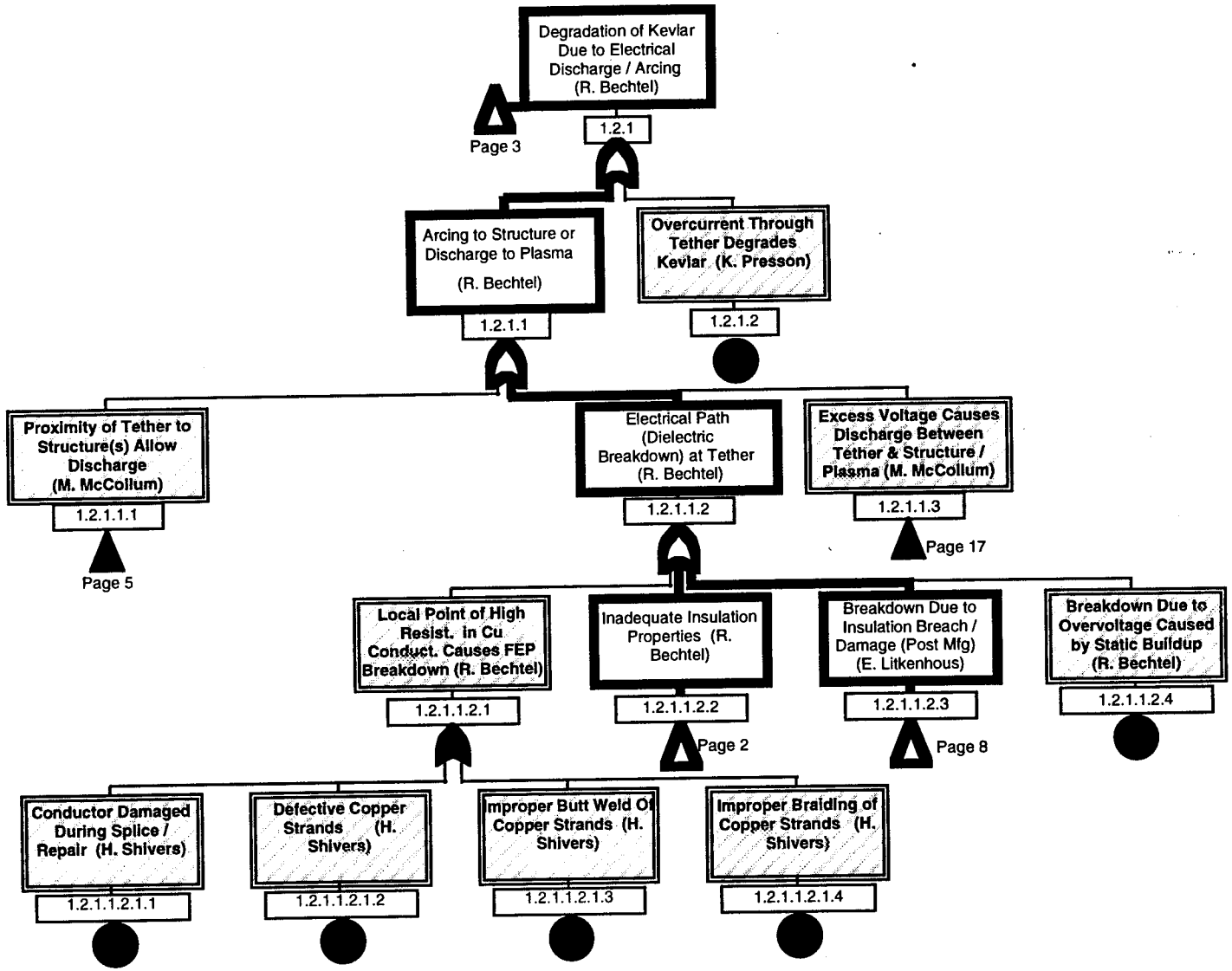

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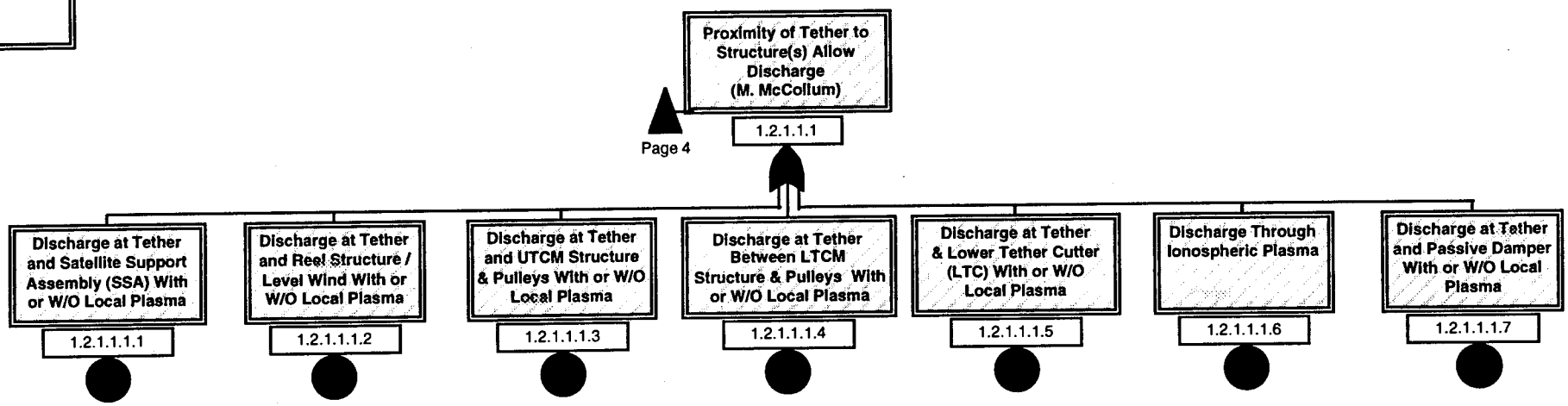

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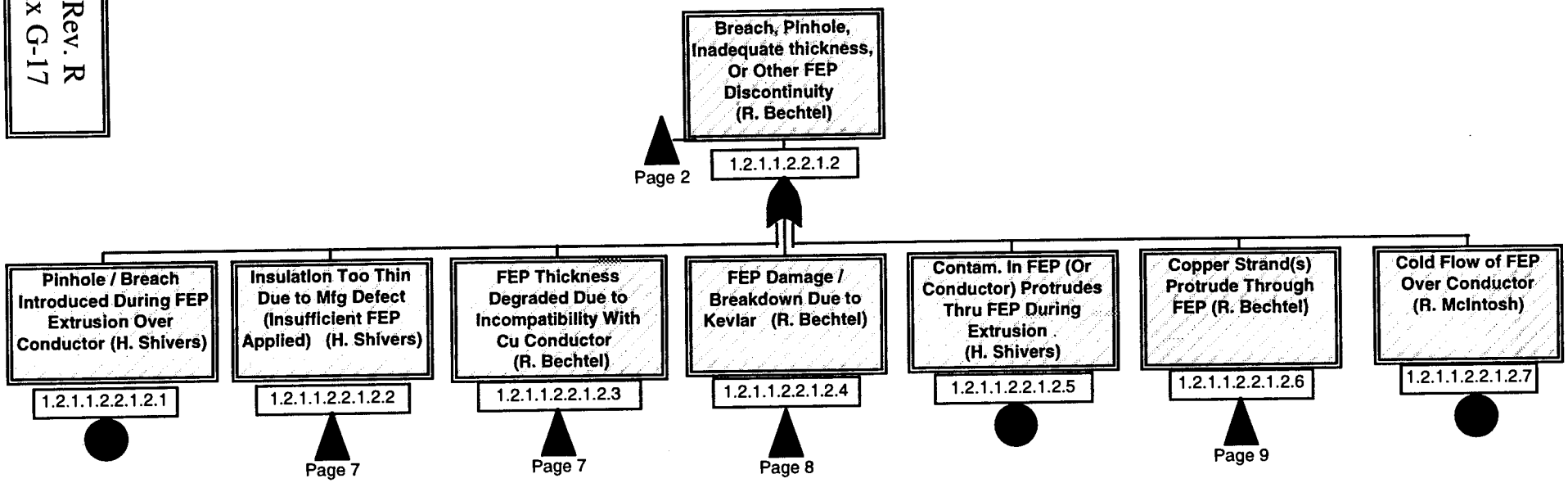

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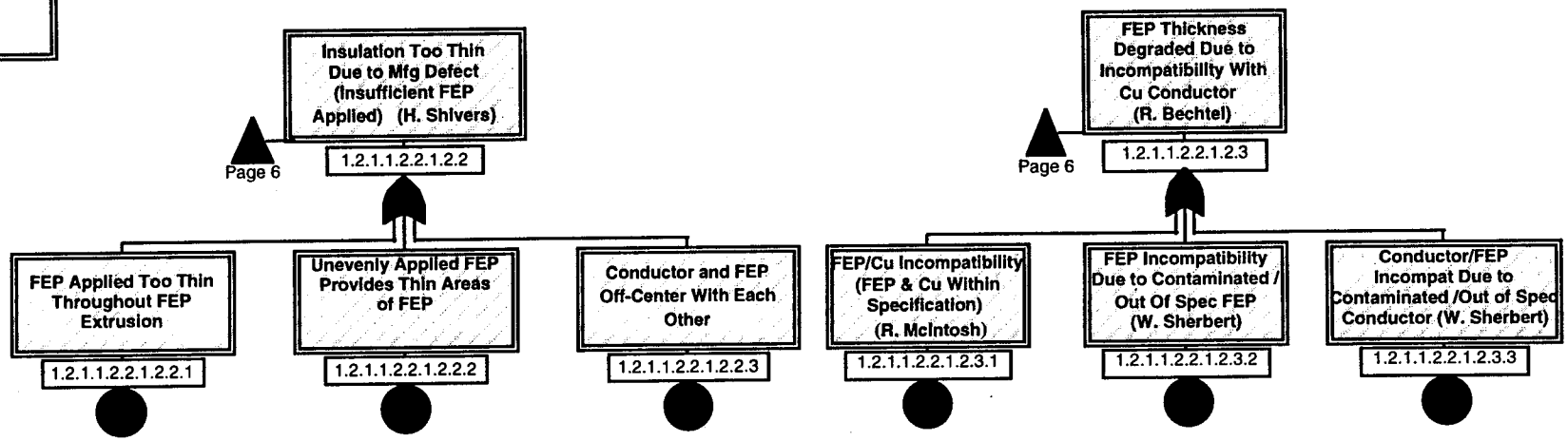

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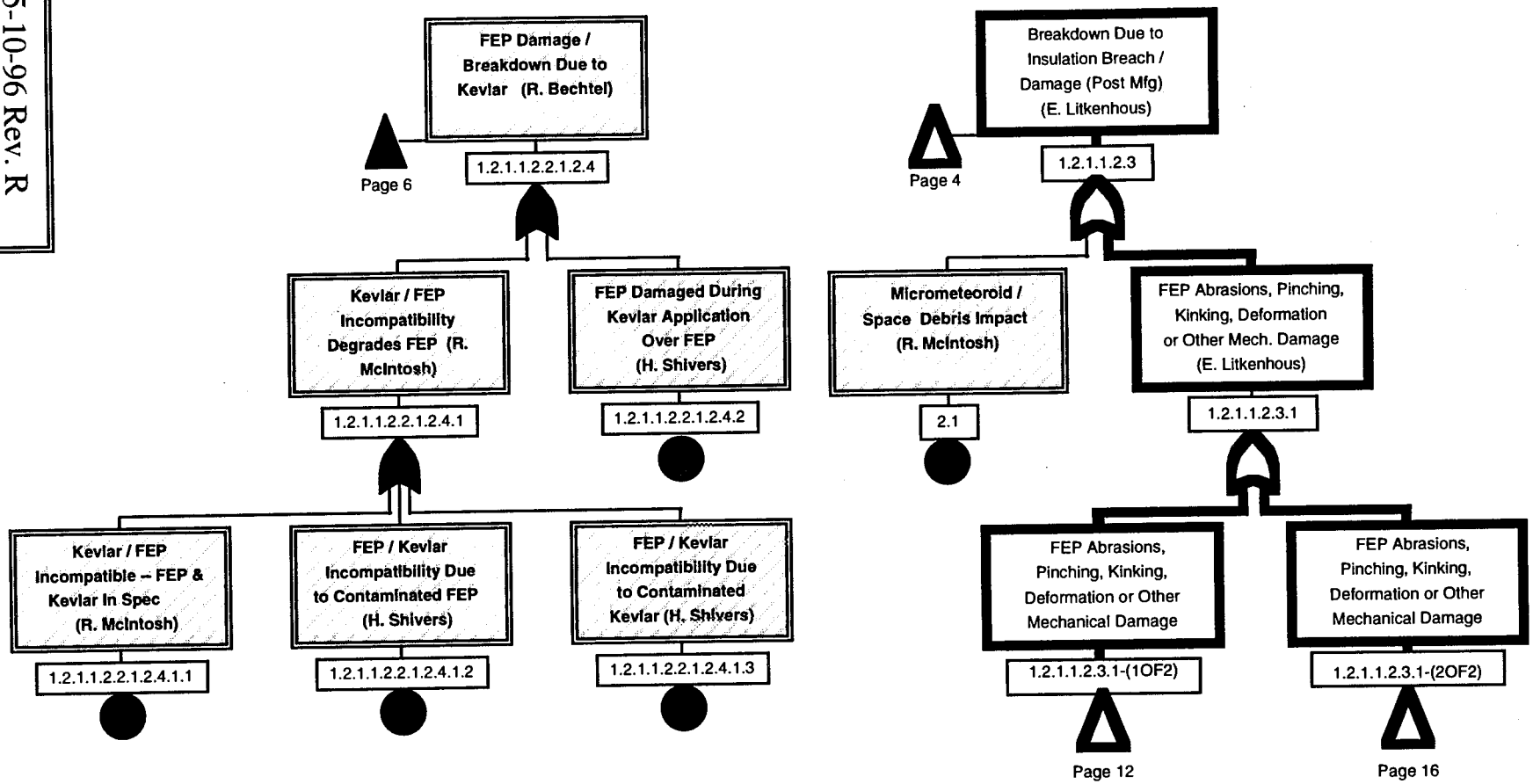

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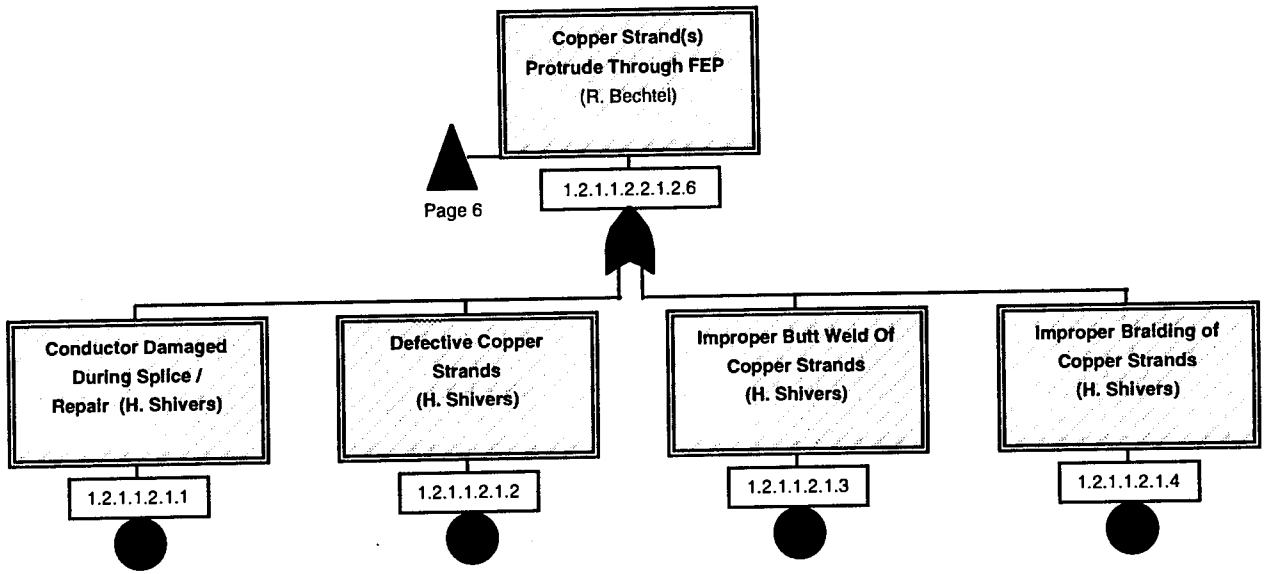

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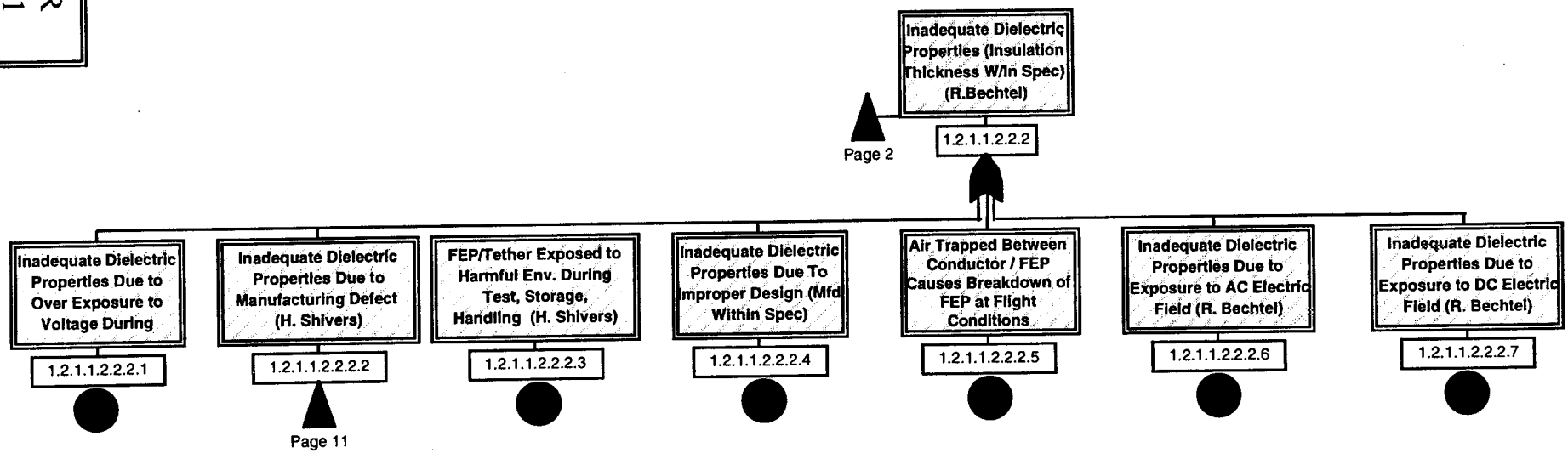

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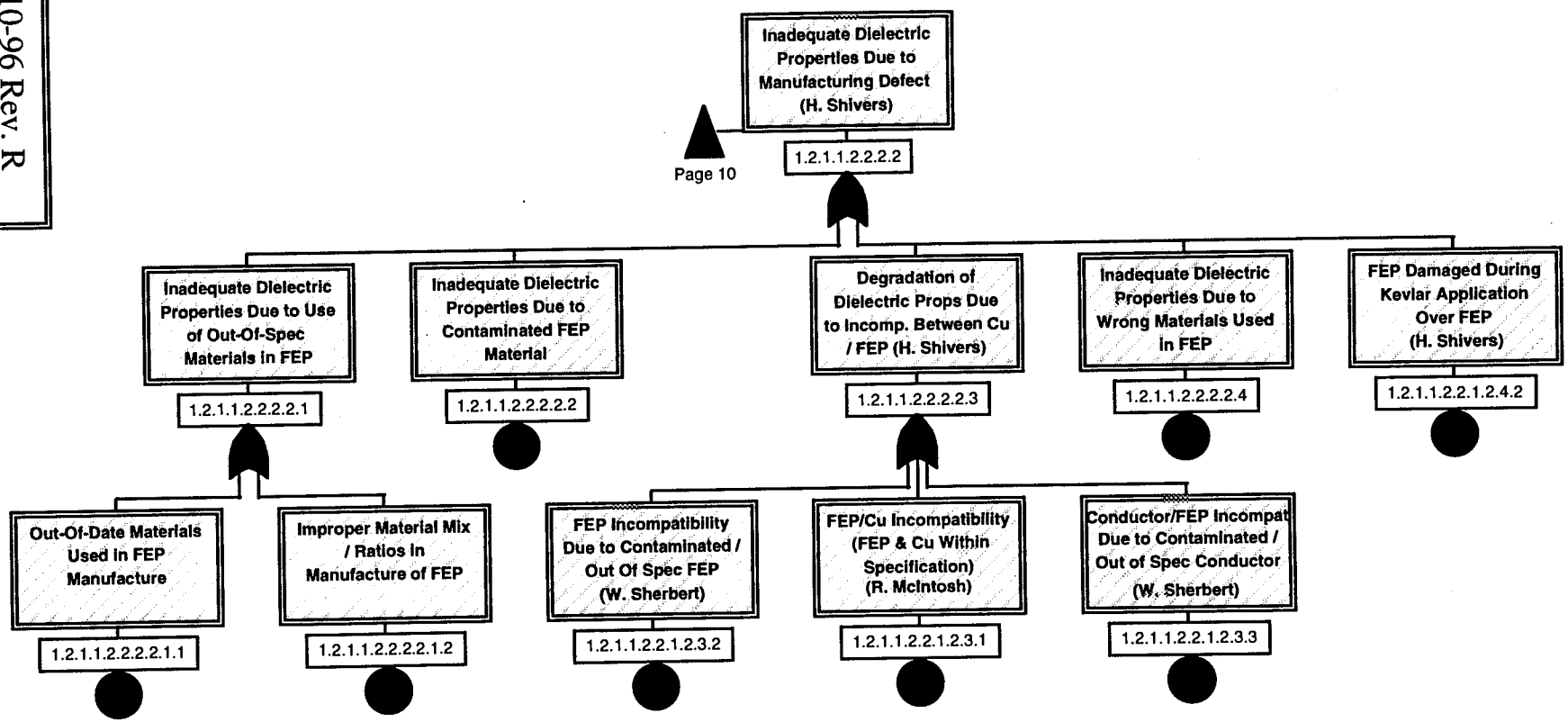

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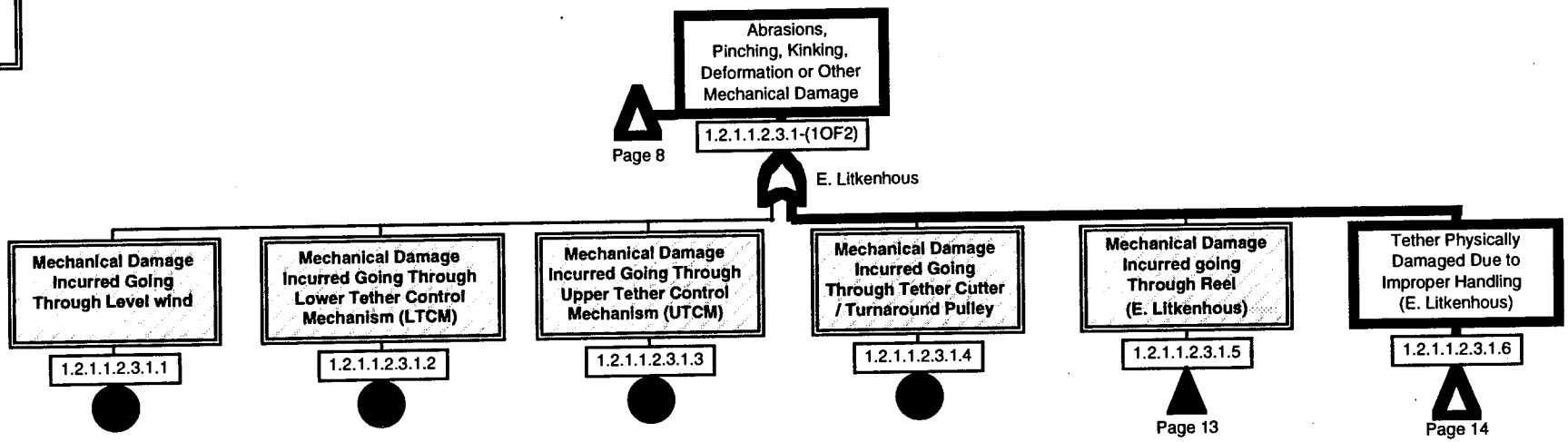

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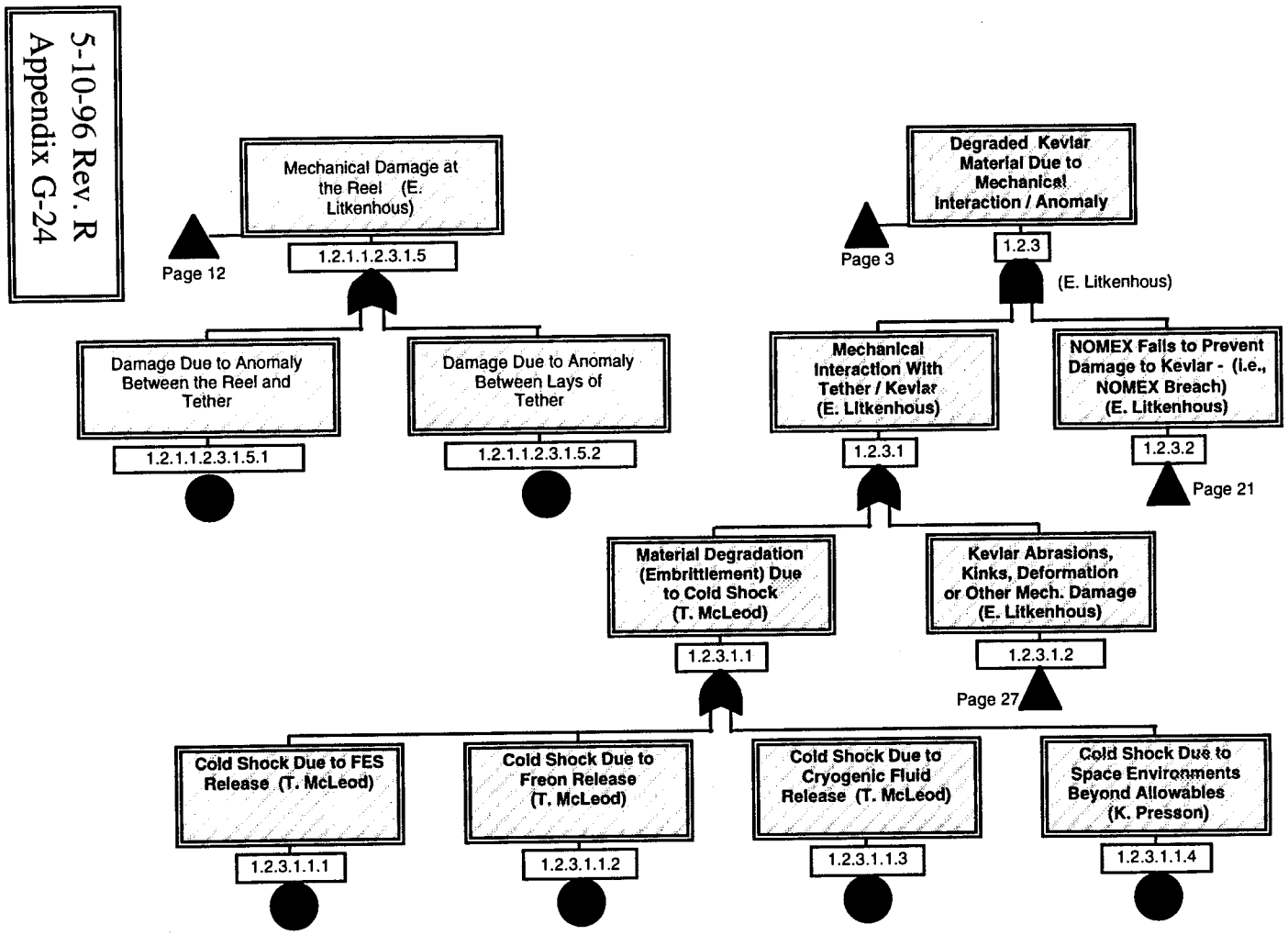

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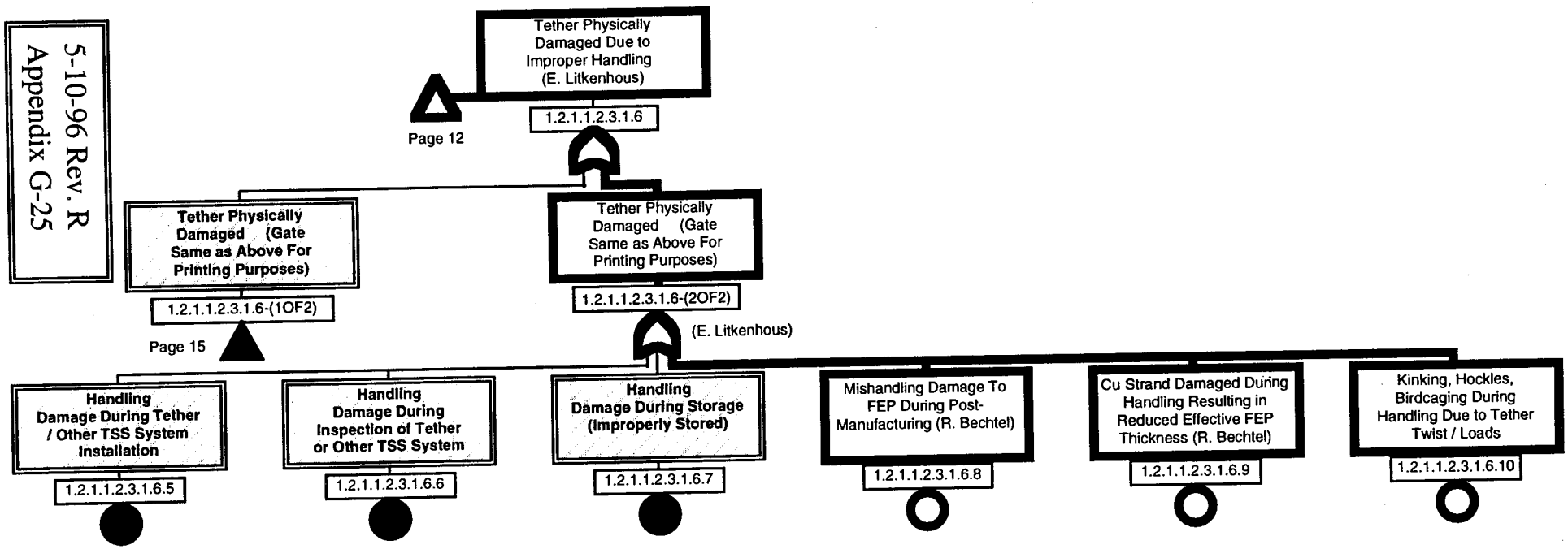

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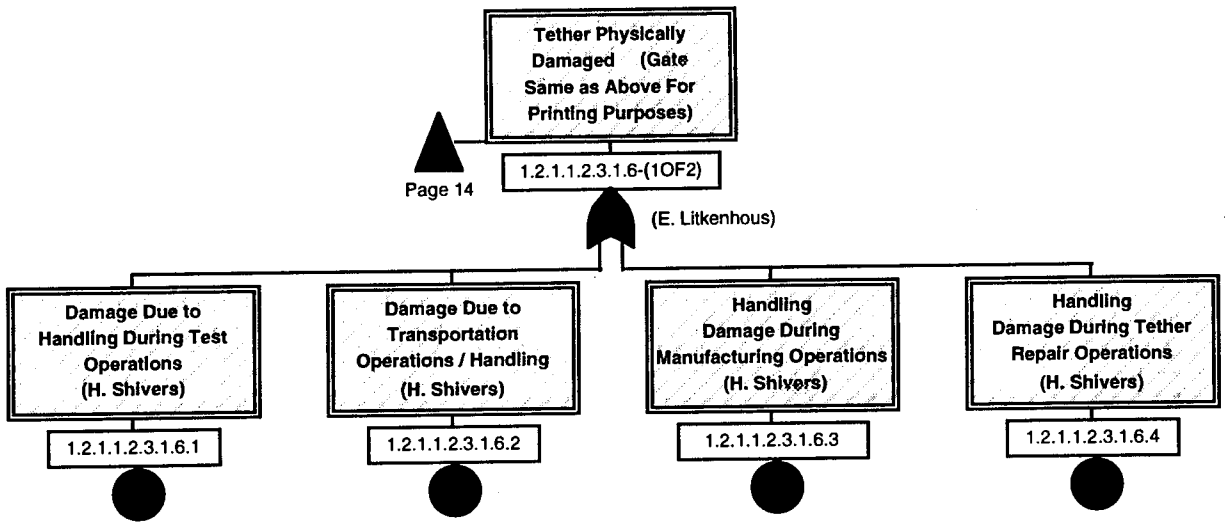

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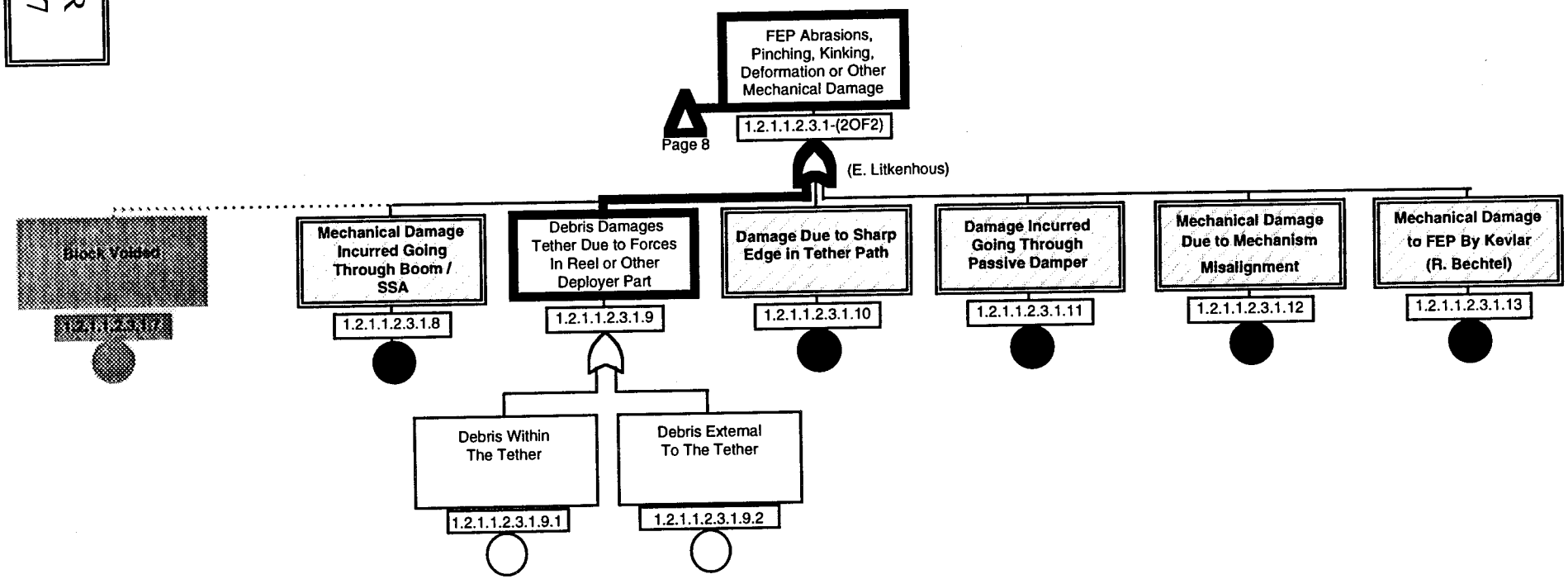

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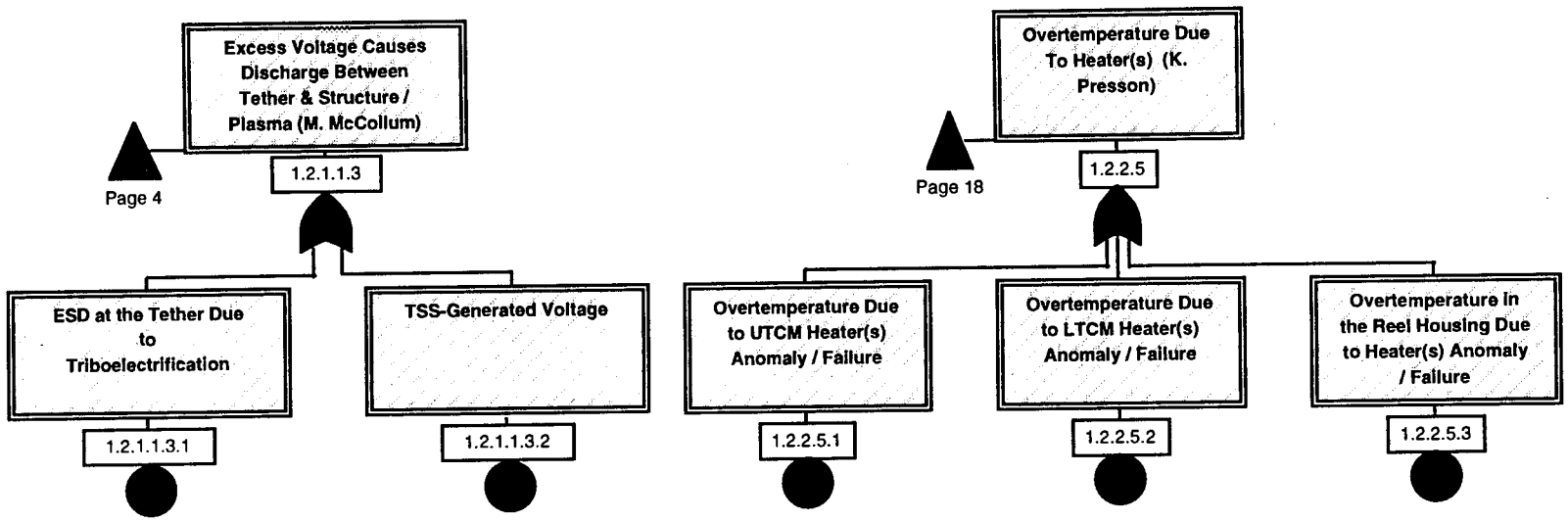

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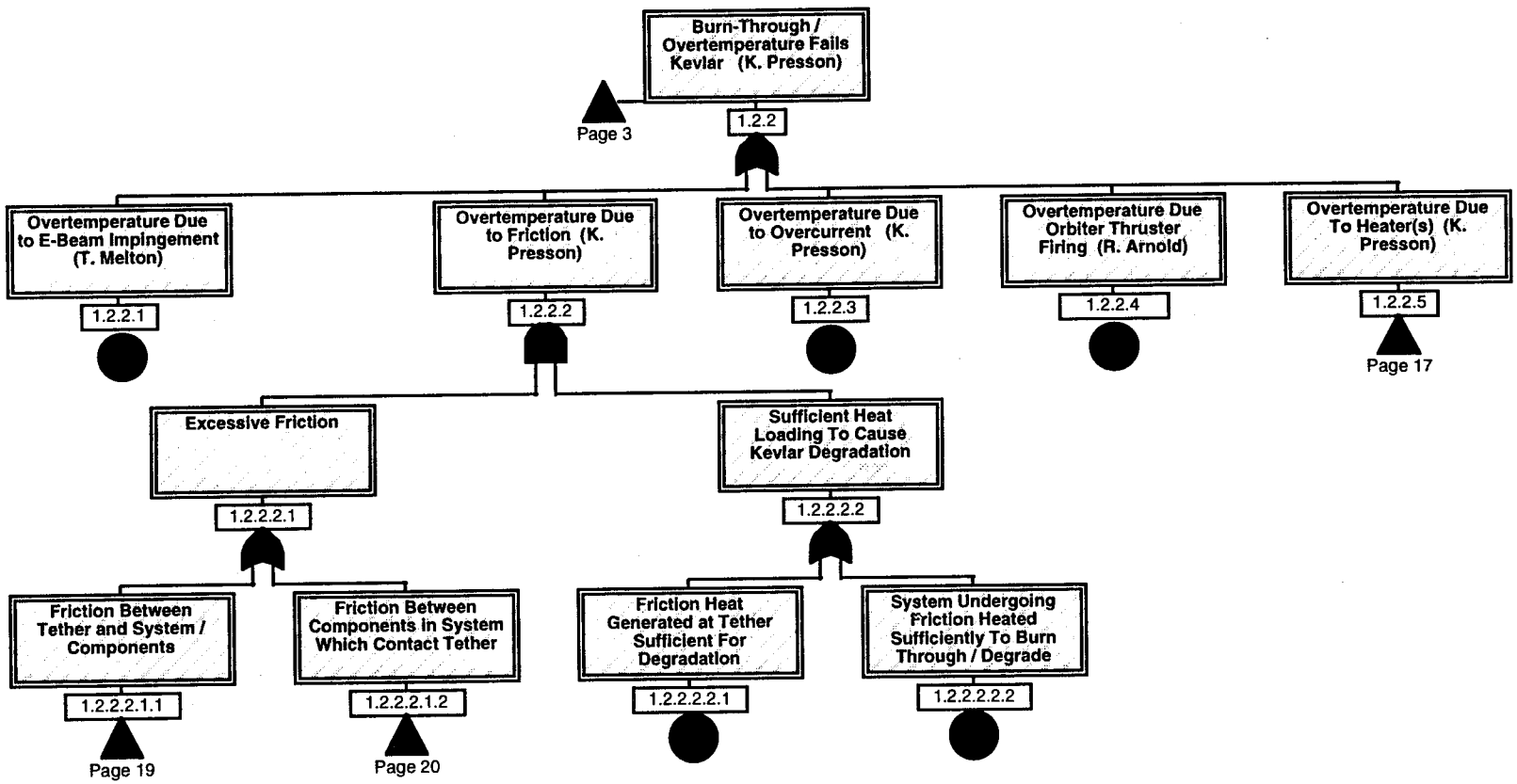

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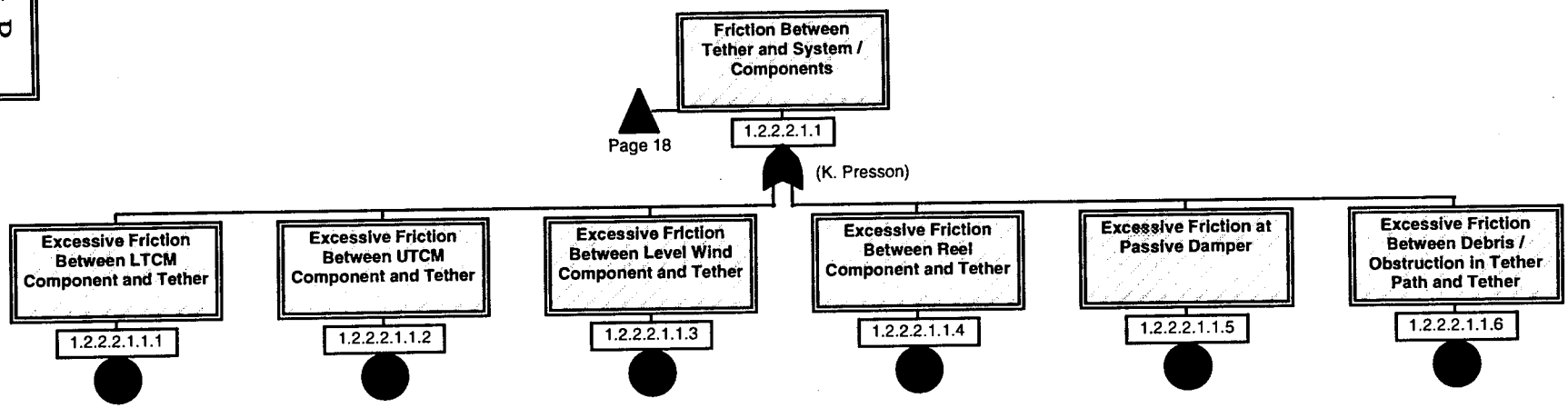

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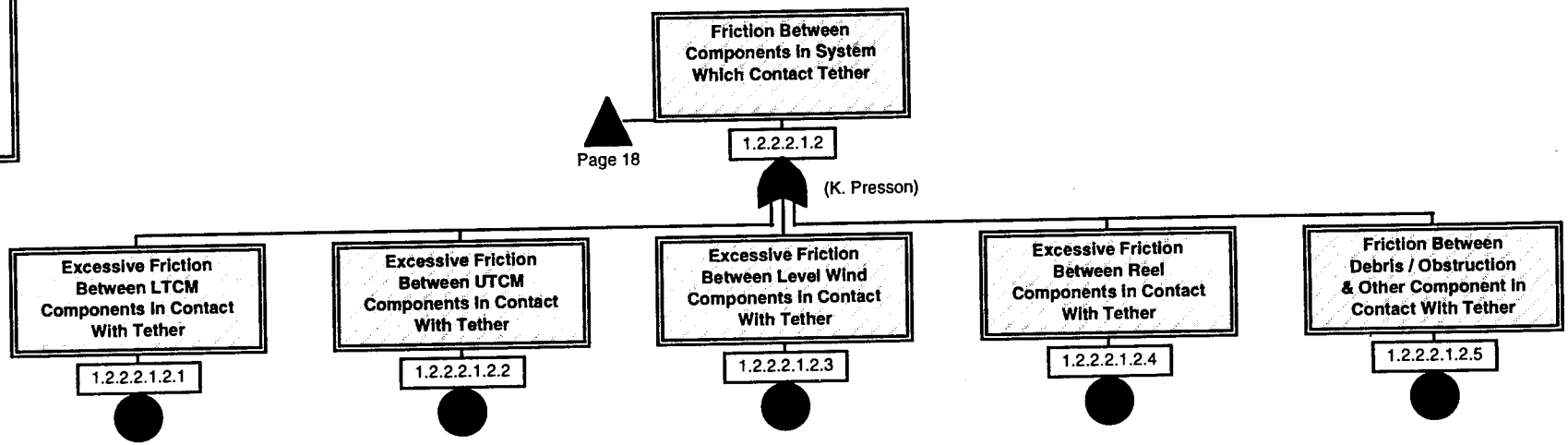

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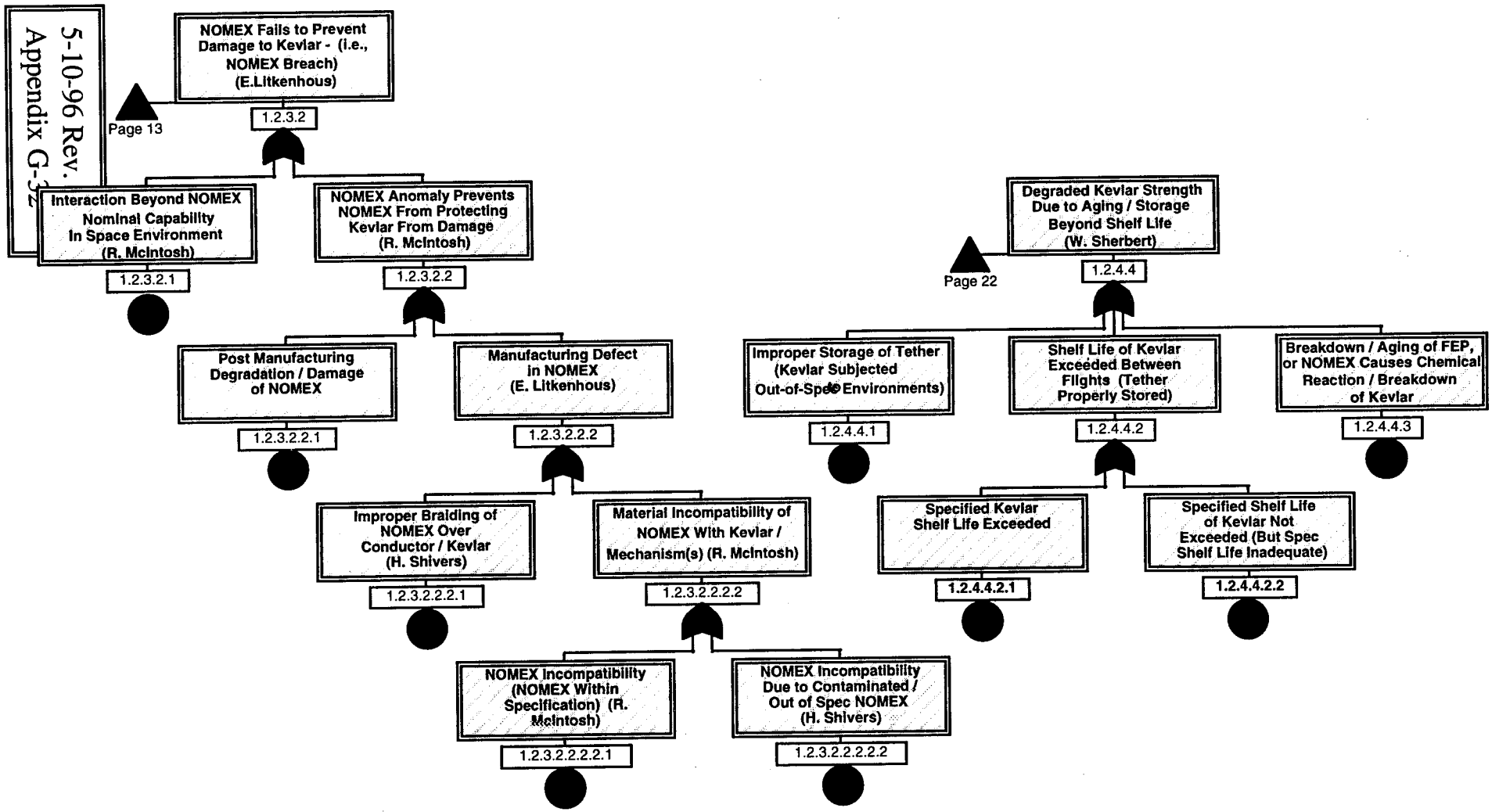

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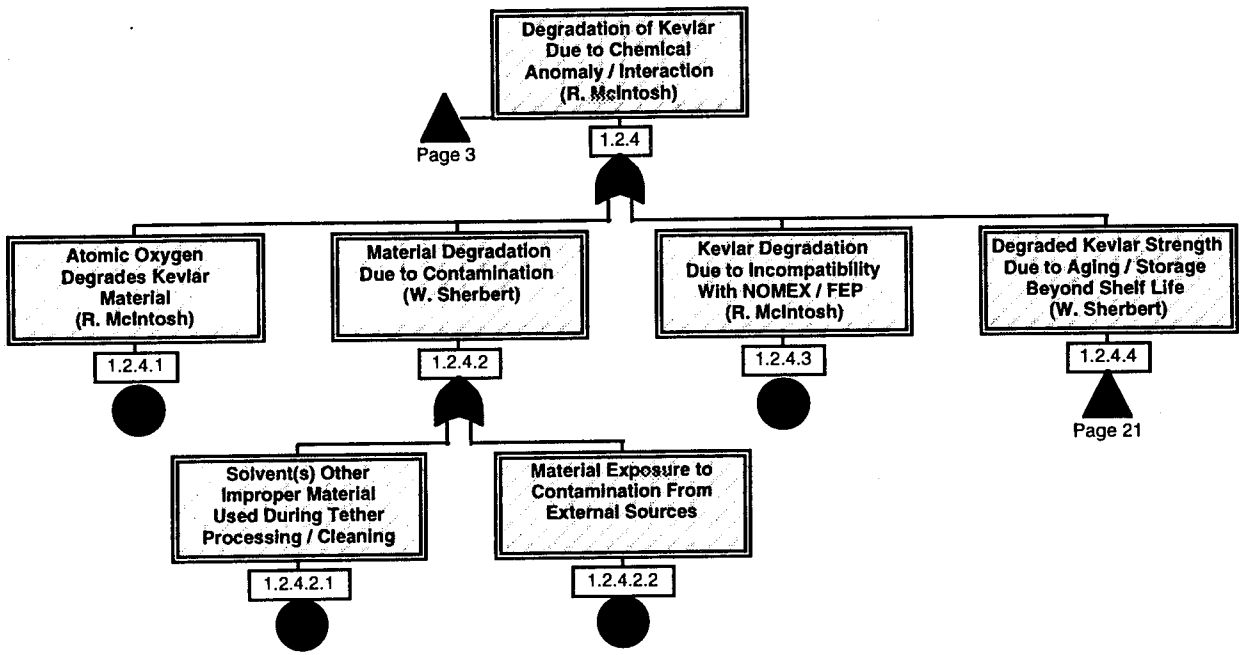

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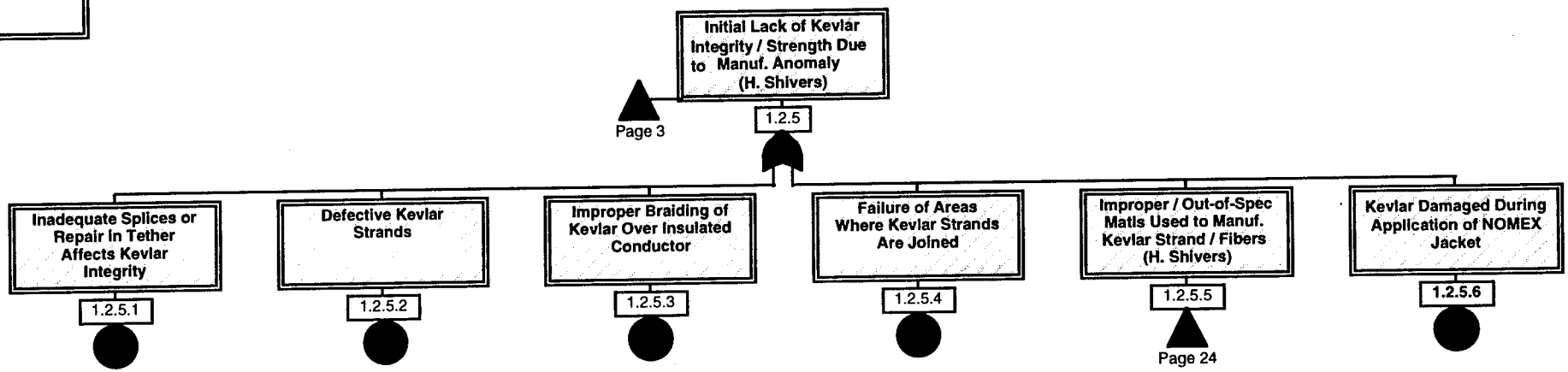

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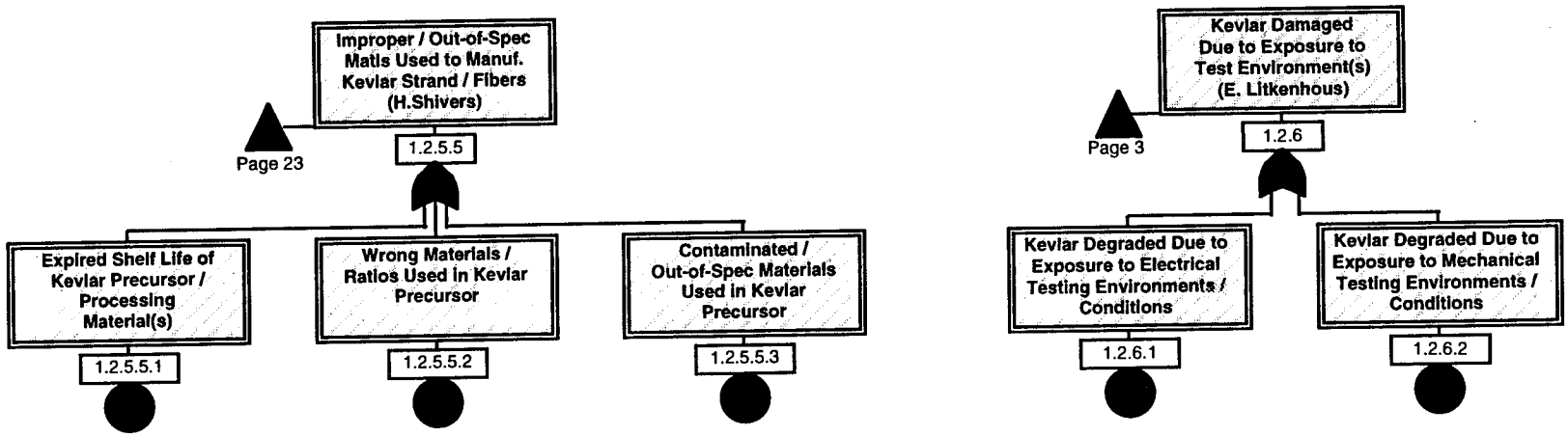

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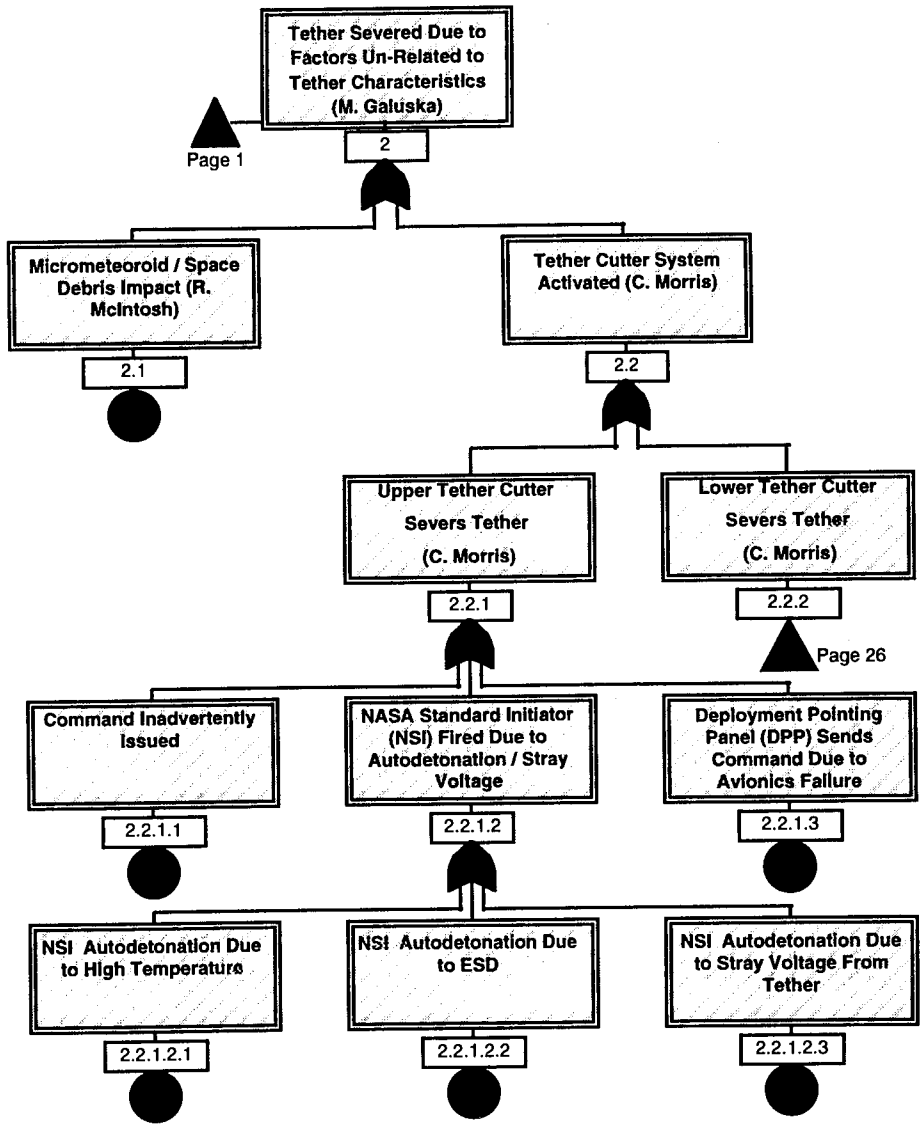

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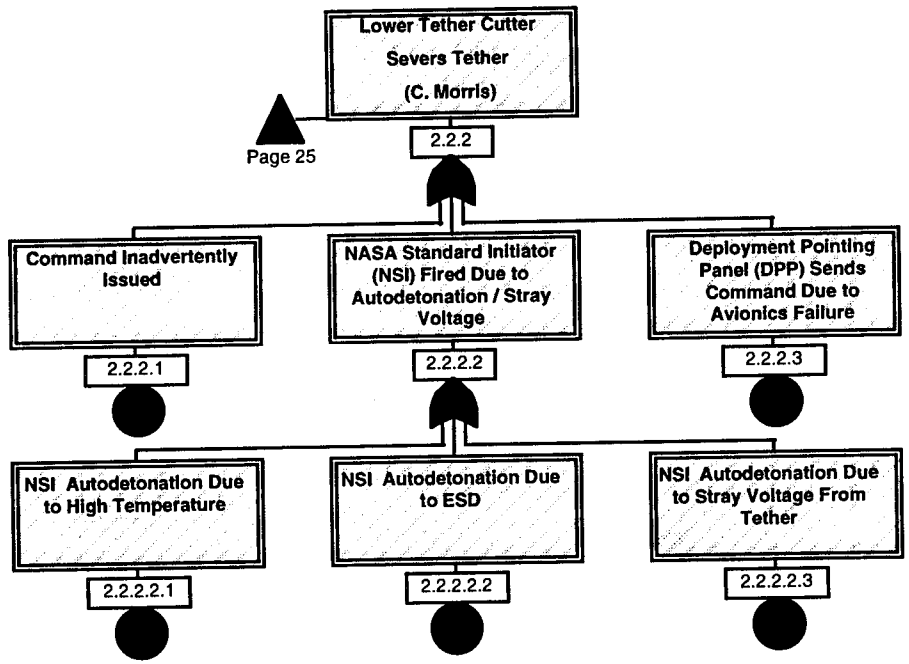

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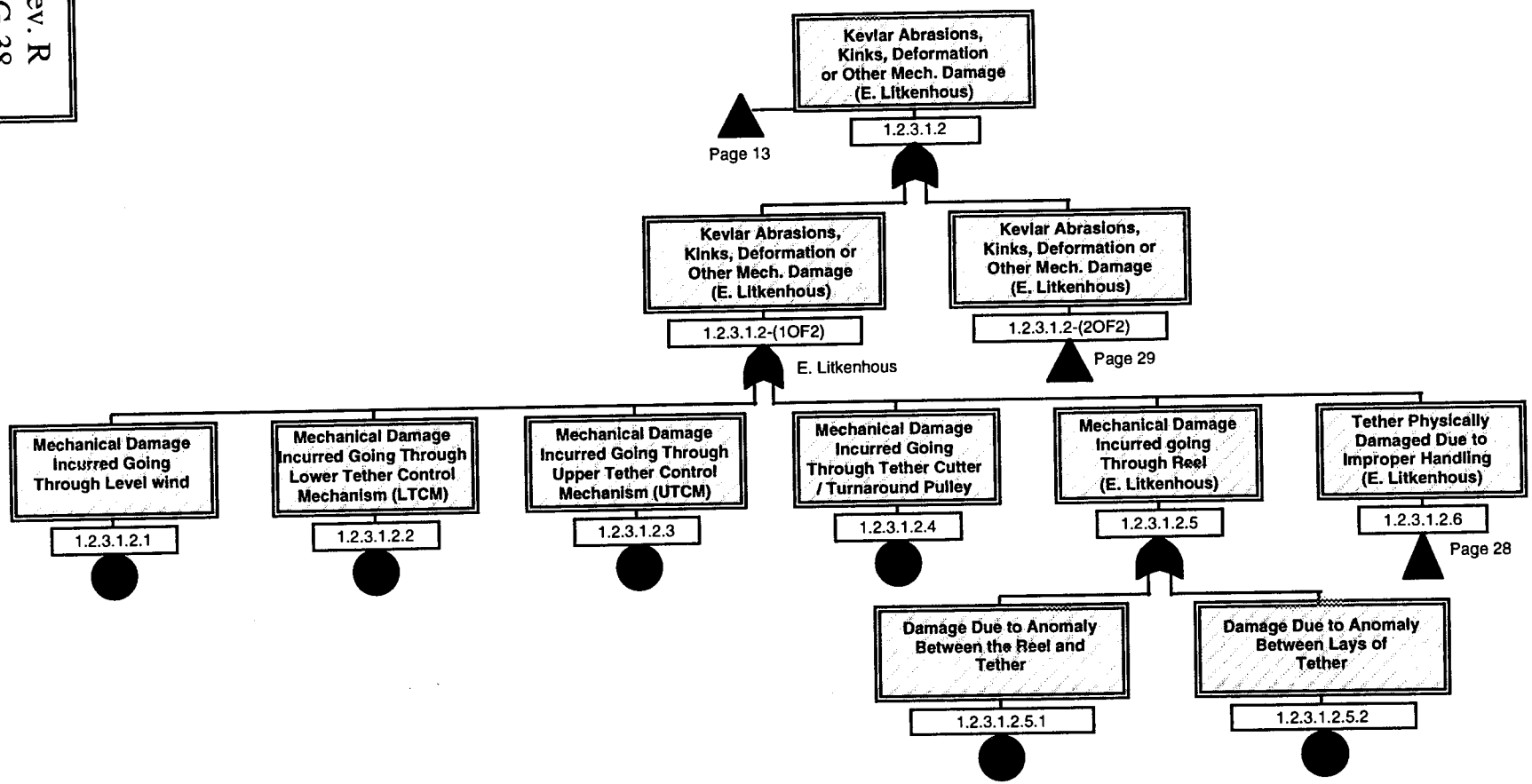

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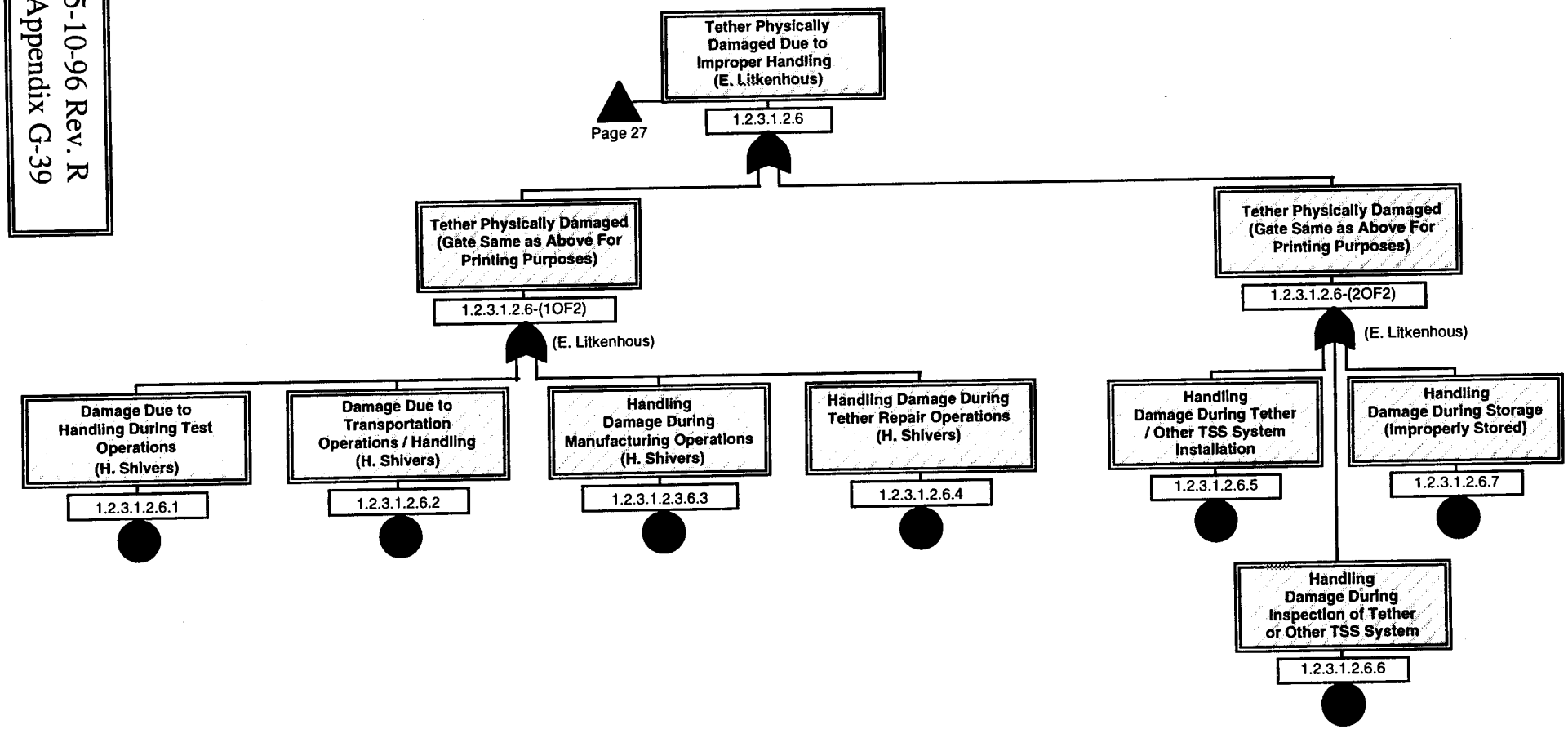

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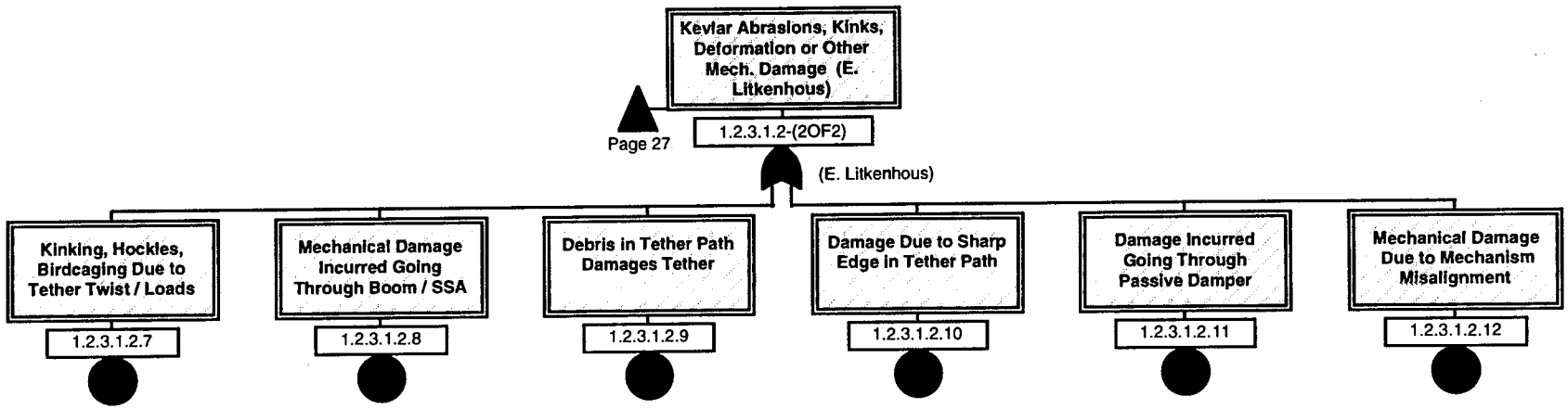

Appendix G:

TSS-1R Fault Tree Analysis

1. *Introduction*
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ANALYSES DOCUMENTED IN THE TSS-1R FAULT TREE
(Block Number and Title in Bold Type)

1.1.1 Nominal Loads
Listing of nominal tether loads @ 19695 m predicted vs flight

1.1.2.1.1 Excessive Loading Due to Orbiter Maneuver
Draper Laboratory Report TBD "STS-75 Flight control System (FCS) Report", Mark Jackson, Draper Laboratory JSC Houston, 3/12/96

1.1.2.1.2 Excessive Loading Due to Satellite Maneuver
Accelerometer data and rate gyros data on the satellite

1.1.2.1.3 Excessive Load Due to Control Laws Error
Analysis as to why the control effectors and the control laws did not contribute to the failure of the tether.

1.1.2.1.4 Excessive Loads Introduced due to Tether Twist
LMC report relative to twist induced loads.

1.1.2.2 Sudden/Hard Stop of System
Accelerometer data from the satellite

1.2.1.1.1.3 Arcing Between Tether and UTCM Structure and Pulleys
Analysis of graph of encoder data

1.2.1.1.1.5 Discharge at Tether and Lower Tether Cutter With or Without Local Plasma
Post-flight inspection of TSS hardware and correlation of science data.

1.2.1.1.1.6 Discharge Through Ionospheric Plasma
Post-flight inspection of TSS hardware and correlation of science data.

1.2.1.1.1.7 Arcing Between Tether and Passive Damper
Analysis of graph of encoder data

1.2.1.1.2 Discharge at Tether and Reel Structure/Level-wind With or Without Local Plasma
Correlation of science data and encoder data showing that first arc occurs when point at which tether broke is in the LTCM.

1.2.1.1.2.1 Local point of High Resistance in Cu Conductor Causes FEP Breakdown

Thermal Analysis to bound the physical evidence of marking the tether (Ref: Team Action TSS-0046)

1.2.1.1.2.2.1.1 Insulation Too Thin Due to Design Error (Manufactured Within Design)

Review of all tests of flight FEP to verify standoff capability to 15K V

1.2.1.1.2.2.1.2.1. Pinhole/Breach Introduced During FEP Extrusion Over Conductor

Analysis of tether build records and re-spark test of remnant of flight tether.

1.2.1.1.2.2.1.2.2.1 FEP Applied Too Thin Throughout FEP Extrusion

Tests on samples of flight tether

1.2.1.1.2.2.1.2.2.2 Unevenly Applied FEP Provides Thin Areas of FEP

Verified calibration of spark tester for the tether

1.2.1.1.2.2.1.2.2.3 Conductor and FEP Off-Center With Each Other

Tests on samples of flight tether

1.2.1.1.2.2.1.2.3 FEP Thickness Degraded Due to Incompatibility with Copper Conductor

Tests on samples of flight tether

1.2.1.1.2.2.1.2.4 FEP Damage/Breakdown Due to Kevlar

Tests on samples of flight tether

1.2.1.1.2.2.1.2.4.2 FEP Damaged During Kevlar Application over FEP

Analysis of manufacturer's build records for the tether.

1.2.1.1.2.2.1.2.5 Contamination in FEP (or Conductor) Protrudes Through FEP During Extrusion

Analysis of manufacturer's build records for the tether and re-spark test of remnant of flight tether

1.2.1.1.2.2.1.2.6 Copper Strand(s) Protrude Through FEP

Verified calibration of spark tester for tether.

1.2.1.1.2.2.1.2.7 Cold Flow of FEP Over Conductor

Performed creep test in laboratory to check FEP tube thinning in addition to microscopic inspection of anomaly #1 (bend) in flight tether.

1.2.1.1.2.2.2. Air Trapped Between Conductor/FEP Causes Breakdown of FEP at Flight Conditions

Laboratory test of samples of tether under flight conditions

1.2.1.1.2.2.2.1. Inadequate Dielectric Properties Due to Over Exposure to Voltage During Testing

Tests on samples of flight tether

1.2.1.1.2.2.2.2. Inadequate Dielectric Properties Due to Manufacturing Defect

Tests on samples of flight tether

1.2.1.1.2.2.2.3 FEP/Tether Exposed to Harmful Environment(s) During Test, Storage & Handling

Tests on samples of flight tether

1.2.1.1.2.2.2.4 Inadequate Dielectric Properties Due to Improper Design

Tests on samples of flight tether

1.2.1.1.2.2.2.6 Inadequate Dielectric Properties Due to Exposure to AC Field

Tests on samples of flight tether

1.2.1.1.2.2.2.7 Inadequate Dielectric Properties Due to Exposure to DC Field

Tests on samples of flight tether

1.2.1.1.2.3.1.1 Mechanical Damage Incurred Going Through Level Wind

Analysis of flight data relative to 27 m of flight tether which traveled through Level Wind during TSS-1R

1.2.1.1.2.3.1.2 Mechanical Damage at the Lower Tether Control Mechanism (LTCM)

Inspection of the hardware along the tether path

1.2.1.1.2.3.1.3 Mechanical Damage Incurred Going Through UTCM

Inspection of the hardware along the tether path

1.2.1.1.2.1.3.1.4 Mechanical Damage at the Lower Tether Outer/Turnaround Pulley

Inspection of the hardware along the tether path

1.2.1.1.2.3.1.5 Mechanical Damage at the Reel

1.2.1.1.2.3.1.5.1 Damage Due to Anomaly Between Reel and Tether

Witnessed removal process and visually verified location of broken end of tether

1.2.1.1.2.3.1.5.2 Damage Due to Anomaly Between Lays of Tether

Performed creep test in laboratory to check FEP tube thinning in addition to microscopic inspection of anomaly #1 (bend) in flight tether.
(Ref: 1.2.1.1.2.2.1.2.7 & !.2.1.1.2.3.1.9)

1.2.1.1.2.3.1.6.1 No Known Damage Due to Handling during Test Operations

Analysis of manufacturer's build records for the tether.

1.2.1.1.2.3.1.6.2 Damage Due to Transportation Operations/Handling

Analysis of the finished tether shipping records

1.2.1.1.2.3.1.6.3 No Known Handling Damage During Manufacturing Operations

Analysis of manufacturer's build records for the tether

1.2.1.1.2.3.1.6.4 No Known Handling Damage During Tether Repair Operations

Analysis of manufacturer's build records for the tether

1.2.1.1.2.3.1.6.5 No Known Handling Damage During Tether/Other TSS System Installation

Analysis of test records, problem reports and flight installation records at KSC

1.2.1.1.2.3.1.6.6 No Known Handling Damage During Inspection Tether/Other TSS System

Analysis of test records, problem reports and inspection records of tether at KSC.

1.2.1.1.2.3.1.6.7 Handling Damage During Storage

Analysis of handling and storage records of flight tether while at LMC/Denver and at O&C Building at KSC

1.2.1.1.2.3.1.7 Kinking, Hockles, Birdcaging Due to Tether Twist/Loads

Analysis of flight data for TSS-1R

1.2.1.1.2.3.1.8 Mechanical Damage Incurred Going Through Boom/SSA

Inspection of the hardware along the tether path.

1.2.1.1.2.3.1.10 Damage Due to Sharp Edge in Tether Path

Inspection of the hardware along the tether path.

1.2.1.1.2.3.1.11 Mechanical Damage Incurred Going Through Passive Damper

Inspection of the hardware along the tether path.

1.2.1.1.2.3.1.12 Mechanical Damage Due to Mechanisms Misalignment

Inspection of the hardware along the tether path

1.2.1.1.2.3.1.13 Mechanical Damage to FEP by Kevlar

Performed laboratory test on FEP with Kevlar filament.

1.2.1.1.3.1 ESD at Tether Due to Triboelectrification

Analysis of science data from TSS-1R

1.2.1.1.3.1 TSS - Generated Voltage

Analysis of science data from TSS-1R

1.2.1.2 Overcurrent Through Tether Degrades Kevlar

Performed analysis of tether assuming conditions of the tether for both intact and 9 of 10 copper conductor strands broken.

1.2.2.1 Beam Impingement

Analysis of the science data for TSS-1R

1.2.2.2 Overtemperature Due to Friction

Analysis of the TSS Pulley/Roller/Guide Tube Worst Case Friction Heating Assessment

1.2.2.3 Overtemperature Due to Over Current

SINDA Thermal Analysis

1.2.2.4 Overtemperature Due to Orbiter Thruster Firing

Analysis of flight data of TSS-1R near time of tether break

1.2.2.5.1 Overtemperature Due to UTCM Heaters Anomaly/Failure

Analysis of flight data of TSS-1R

1.2.2.5.2 Overtemperature Due to LTCM Heaters Anomaly/Failure

Analysis of flight data of TSS-1R

1.2.2.5.3 Overtemperature in the Reel Housing Due to Heater Anomaly/Failure

Analysis of flight data of TSS-1R

1.2.3 Degraded Kevlar Material Due to Mechanical Interaction/Anomaly

Tests on samples of flight tether

1.2.3.1.1.1 Cold Shock due to FES Release

Analysis of flight data of TSS-1R near the time when the tether broke

1.2.3.1.1.2 Cold Shock Due to Freon Release

Analysis of flight data of TSS-1R near the time when the tether broke

1.2.3.1.1.3 Cold Shock Due to Cryogenic Release

Analysis of flight data of TSS-1R near the time when the tether broke

1.2.3.1.1.4 Cold Shock Due to Space Environment Beyond Allowables

Analysis of flight data of TSS-1R near the time when the tether broke

1.2.3.2 Nomex Fails to Prevent Damage to Kevlar (i.e. Nomex Breach)

Tests on samples of tether

1.2.3.2.2.2.2.2 Nomex Incompatibility Due to Contaminated/Out of Spec Nomex

Review of manufacturer's build records for the tether

1.2.4 Degradation of Kevlar Due to Chemical Anomaly/Inspection

Review of manufacturer's data sheet for Kevlar and visual inspection of the flight tether

1.2.4.1 Atomic Oxygen Degrades Kevlar Material

Review of manufacturer's data sheet and flight data for TSS-1R

1.2.4.4.2 Shelf Life of Kevlar Exceeded Between Flights

Review of materials shelf life requirements with tether manufacturer

1.2.5 Initial Lack of Kevlar Integrity/Strength Due to Manufacturing Anomaly

Developed a mapping of all the splices and repairs for the tether from the build records. (Ref: Board Actions M-03, M-16, M-21)

1.2.5.2 Defective Kevlar Strands

Reviewed manufacturer's build records and tensile tested tether remnant from STS 46.

1.2.5.3 Improper Braiding of Kevlar over Insulated Conductor

Reviewed manufacturer's build records and tensile tested tether remnant from STS-46. (Ref: Board Action M-07)

1.2.5.4 Failure of Areas Where Kevlar Strands are Joined

Reviewed manufacturer's build records and tensile tested tether remnant from STS-46. (Ref: Board Action M-07)

1.2.5.5.1 Expired Shelf Life of Kevlar Precursor/Processing Material(s)

Reviewed manufacturer's build records with company representatives and tensile tested tether remnant from STS-46.

1.2.5.5.2 Wrong Materials/Ratios Used in Kevlar Precursor

Reviewed manufacturer's build records and tensile tested tether remnant from STS-46

1.2.5.5.3 Contaminated Out of Spec Materials Used In Kevlar Precursor

Reviewed manufacturer's build records and tensile tested tether remnant from STS-46

1.2.5.6 Kevlar Damaged During Application of Nomex Jacket

Reviewed manufacturer's processes and build records.

1.2.6 Kevlar Damaged Due to Exposure to Test Environment

Tests of flight tether from TSS-1

2 Tether Severed Due to Factors Unrelated to Tether Characteristics

Closed by the Tiger Team

2.1 Micrometeoroid/Space Debris Impact

Analysis of flight data and visual inspection of TSS hardware prior to removal of MLI and other inspections

2.2 Tether Cutter System Activated

Analysis of post-flight data