Shuttle Ground Support Equipment (GSE) T-0 Umbilical to Space Shuttle Program (SSP) Flight Elements Consultation

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<table>
<thead>
<tr>
<th>Version</th>
<th>Description of Revision</th>
<th>Office of Primary Responsibility</th>
<th>Effective Date</th>
</tr>
</thead>
<tbody>
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<td>Initial Release</td>
<td>NESC Deputy Director’s Office</td>
<td></td>
</tr>
</tbody>
</table>

NESC Request No. 05-012-E
# TABLE OF CONTENTS

**Volume I: Technical Consultation Report**

1.0 Notification and Authorization ........................................................................................................ 5

2.0 Signature Page.................................................................................................................................. 6

3.0 Team List ........................................................................................................................................ 7

4.0 Executive Summary ......................................................................................................................... 8

5.0 Consultation Plan ............................................................................................................................. 9

6.0 Problem Description and NESC Initial and Follow-On Activities .................................................. 10
   6.1 Problem Description ................................................................................................................... 10
   6.2 Initial NESC Activity ............................................................................................................... 15
   6.3 Follow-On NESC Activity ........................................................................................................ 16

7.0 Data Analysis .................................................................................................................................. 17

8.0 Findings, Observations and Recommendations .............................................................................. 19
   8.1 Findings .................................................................................................................................. 19
   8.2 Observations ............................................................................................................................ 20
   8.3 Recommendations .................................................................................................................... 20

9.0 Alternate Viewpoints ....................................................................................................................... 20

10.0 Other Deliverables ......................................................................................................................... 20

11.0 Lessons Learned ............................................................................................................................ 20

12.0 Definition of Terms ......................................................................................................................... 21

13.0 Acronym List ................................................................................................................................... 21

14.0 References .................................................................................................................................... 22

NESC Request No. 05-012-E
List of Figures

Figure 6.1-1. SRB HDP Pyrotechnic Interfaces ................................................................. 10
Figure 6.1-2. HDP/ETVAS Command Path ................................................................. 11
Figure 6.1-3. LH₂ T-0 Interface showing J61 ................................................................. 12
Figure 6.1-4. T-0 Connector Corrosion and Pin Degradation ......................................... 13
Figure 6.1-5. T-0 Connector Plug Assembly ................................................................. 14

Volume II: Appendices

A. ITA/I Request Form (NESC-PR-003-FM-01)
B. NESC White Paper, Review of the Space Shuttle T-0 Interface Anomaly Resolution, 23 Mar 05
C. NESC Presentation to Shuttle Program Requirements Change Board, GSE T-0 Umbilical to SSP Flight Elements Assessment, 31 Mar 05
D. Space Shuttle T-0 Umbilical Dynamic Displacements and Forces, Rocketdyne, 22 Aug 05
E. Report Q50299FA, Connector Failure Analysis, Goddard Space Flight Center Parts Analysis Laboratory
F. GSE T-0 Umbilical to SSP Flight Elements Assessment Project Status, 13 Oct 06
G. Quad-redundant Failure Analysis
### Volume I: Technical Consultation Report

#### 1.0 Notification and Authorization

The request to conduct a real-time consultation was submitted to the NASA Engineering and Safety Center (NESC) by the NASA Associate Administrator for Safety and Mission Assurance on March 17, 2005. The T-0 umbilical to Space Shuttle Program (SSP) flight elements assessment was approved by the NESC Director in an out-of-board action on March 17, 2005. The NESC previously participated in T-0 review activities while conducting the Space Shuttle Recurring Anomalies assessment (Part I), and this activity is summarized in NESC report RP-05-10, Appendix B.8 [ref. 4].
2.0 Signature Page

Consultation Team Members
Original signatures on file

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4.0 Executive Summary

The NASA Engineering and Safety Center (NESC) was tasked with assessing the validity of an alternate opinion that surfaced during the investigation of recurrent failures at the Space Shuttle T-0 umbilical interface. The most visible problem occurred during the Space Transportation System (STS)-112 launch when pyrotechnics used to separate Solid Rocket Booster (SRB) Hold-Down Post (HDP) frangible nuts failed to fire. Subsequent investigations recommended several improvements to the Ground Support Equipment (GSE) and processing changes were implemented, including replacement of ground-half cables and connectors between flights, along with wiring modifications to make critical circuits quad-redundant across the interface. The alternate opinions maintained that insufficient data existed to exonerate the design, that additional data needed to be gathered under launch conditions, and that the interface should be further modified to ensure additional margin existed to preclude failure.

The NESC reviewed the data gathered during the various investigations, including the results of vibration tests and a finite element analysis performed by the Space Shuttle Program (SSP). Four initial recommendations were documented in a white paper released March 23, 2005 (see Appendix B). These focused on implementing hardware and process control improvements, changing interface assembly procedures to increase the force margin on the mated interface connection, collecting data to anchor the finite element models, and performing a high-fidelity system-level test of an assembled interface connector to establish the design margin. In lieu of the system-level test, the NESC undertook a follow-on effort to expand the finite element analysis the SSP had already performed. Failure analysis of GSE cabling removed from the T-0 interface was also conducted and an independent risk assessment performed.

The expanded finite element analysis indicated that sufficient margin existed at the interface and the failure analysis was successful at duplicating a corrosion-induced intermittent electrical failure. Consequently, the NESC concurred with launching STS-114 and subsequent vehicles with no redesign of the T-0 interface.
5.0 Consultation Plan

The scope of this consultation was initially limited to a review of the documentation and test and analysis results collected in conjunction with the STS-112 T-0 interface failure investigation [ref. 1 through 9]. The scope was later expanded to include additional modeling of the T-0 interface, failure analysis of a T-0 interface cable including testing to duplicate a corrosion-induced intermittent connection, and an independent risk assessment. Boeing-Rocketdyne performed the initial T-0 modeling work in support of the SSP and was contracted by the NESC to perform the expanded analysis [ref. 10]. The T-0 cable failure analysis was undertaken by the Goddard Space Flight Center (GSFC) [ref. 11]. The risk assessment was performed by Dr. K. Preston White of the University of Virginia [ref. 12].
6.0 Problem Description and NESC Initial and Follow-On Activities

6.1 Problem Description

The T-0 umbilicals provide fluid and electrical connections between the Shuttle Orbiter and the ground. One umbilical on the left-hand side of the Orbiter aft carries liquid hydrogen (LH₂) and related fluid lines along with a set of electrical connections. One umbilical on the right-hand side carries liquid oxygen (LO₂) and a second set of electrical connections. Connectors on each side pass through a ground-side umbilical carrier plate and mate to flight-half connectors on an Orbiter-side plate. The umbilicals are disconnected at launch by commands from the Orbiter Primary Application Software Set (PASS) through General Purpose Computers (GPC). Redundant (Systems A and B) signals across the LH₂ and LO₂ interfaces also arm and fire pyrotechnic charges that release the SRB HDP frangible nuts and disconnect the External Tank Vent Arm System (ETVAS). Refer to Figures 6.1-1 and 6.1-2. The LH₂ side T-0 interface is depicted in Figure 6.1-.3 and a typical electrical connector assembly is depicted in Figure 6.1-5.
During the STS-112 launch, System A pyrotechnics failed to fire the release mechanism of the HDP frangible bolts and ETVAS. System B functioned normally and the launch was successful. However, failure of one-half of the redundant system was considered a “near-miss” launch failure and a Standing Accident Investigation Board (SAIB) was convened at KSC to determine the root cause. The problem was closed as an unexplained anomaly and attributed to an intermittent failure at the T-0 interface [ref. 2]. An Independent Assessment Team (IAT) was formed to review the SAIB report and to provide recommendations [ref. 3]. The SSP Program Requirements Change Board (PRCB) subsequently directed Systems Engineering and Integration (SE&I) to form and lead a Tiger Team to address all findings related to GSE interfaces with Space Shuttle flight elements, including not only the STS-112 failure, but other intermittent signal dropouts that had been documented and attributed to connections through the T-0 [ref. 5]. The Tiger Team’s charter included identifying common failure causes, understanding the multiple environments, and developing corrective actions. An NESC Recurring Anomalies Splinter Team was formed to participate in a review of the SSP’s response to the consultation team’s findings (held at KSC on 28 October and 3 November 2004) [ref. 4].
The various investigations eventually pointed to an electrical connection at the T-0 interface as the most likely point of the STS-112 failure. Visual inspection using 10X magnification detected contamination and missing gold plating on the ground-side connector pins. Laboratory failure analysis showed isolated areas of discontinuity and pin degradation (Figure 6.1-4). In addition, a spring used to apply force to the mated contact assembly and hold the ground and flight halves together was found out-of-tolerance with a spring constant of 30.5 lbs/in versus a minimum required of 34.9 lbs/in. (see Figure 6.1-5). Finally, it was determined the mating procedure being employed had potential for misalignment of the connector mating halves. Testing showed that a misaligned connector can result in individual signal dropout at the outer connector pins during vibration. A course of action to address these issues was outlined by the PRCB Tiger Team and a plan for corrective action implemented. The plan included not only specific procedural changes to address the potential for corrosion and connector mis-assembly, but also component-level vibration testing and finite element modeling of the interface. The NESC Recurring Anomalies Splinter Team concurred with the actions proposed [ref. 4].
Figure 6.1-4. T-0 Connector Corrosion and Pin Degradation
Figure 6.1-5. T-0 Connector Plug Assembly

Two IAT members responsible for reviewing the original SAIB investigation and findings generated an alternate opinion (below) in response to the SSP’s proposed corrective actions. The opinion was based on weaknesses in the original certification testing program and a general lack of data regarding the behavior of the interface at launch [ref. 10, pg 1]:

“Many umbilical mechanical retention system improvements have resulted from this Independent Assessment and the SE&I Tiger Team activity, which adds rigor, controls, and robustness. However, after reviewing the Shuttle Program’s final SE&I Tiger Team actions and responses to the IAT’s risk mitigation recommendations, the IAT has concluded that there still remains a level of uncertainty due to the undetermined root cause by the Tiger Team / Standing Accident Investigation Board (SAIB) and lack of controls for the...
Support Equipment] GSE T-0 umbilical to SSP flight element interfaces posing high risk to future Shuttle flights. Primary residual risks / concerns include: (1) Vibration testing non-representative of flight configuration; (2) Inadequate connector pin/socket electrical engagement design margin; (3) Finite Element Model (FEM) modeling deficiencies; (4) Inadequate qualification / certification of electrical umbilical portion of [Tail Service Mast] TSM umbilical system; (5) Risk documentation inadequate to address causes for T-0 signal losses; (6) Lack of adequate instrumentation to quantify and certify the TSM T-0 system; (7) Inadequate full scale flight verification.”

The IAT made eight recommendations to address these concerns [ref. 10, pg. 19]:

“(1) Increase the electrical pin length 1 mm to accommodate the unknown dynamic extraction potential; (2) Maximize effort to obtain suitable instrumentation and certify it for use during launch; (3) Perform T-0 Umbilical Electrical System Delta Certification; (4) Update the [Finite Element Model] FEM to include considerations of the issues identified; (5) Continuation of the mandatory instrumentation / data review of the T-0 signals active across the T-0 Umbilical from T-7 seconds to T-0. A subset of these measurements that are relatively stable during this time period [should] be recorded at 100 or 200 samples per second; (6) Install [Linear Voltage Displacement Transducers] LVDT’s on the LO₂ electrical connectors J56, J60, & J64 for the [STS-114] tanking test; (7) Reclassify GSE associated with the SRB HDP system to a different criticality category because it performs CRIT 1 and CRIT 1R launch functions; (8) Properly update risk documentation to reflect the deficiencies noted.”

The SSP objected to several of these recommendations, especially the first and third which would have required a full-up, system-level test of the T-0 interface before flight. The NESC was asked to review the data already collected and make pertinent recommendations.

6.2 Initial NESC Activity

The initial NESC effort is summarized in the white paper which is provided in Appendix B. The NESC concurred with the SSP’s efforts and with the corrective actions already implemented to address weaknesses in the processing and flight-to-flight hardware maintenance. The NESC T-0 Assessment Team concluded those actions were adequate to address the most probable cause of the failures observed at the interface (corrosion of electrical connections leading to intermittent contact) and, given the redundancy designed into the system, sufficient to ensure
safe flight. At the same time, the NESC T-0 Assessment Team concurred with several of the concerns voiced in the IAT alternate opinion and noted that the modeling conducted to that point was not test-validated and did not address at the excitations due to Space Shuttle Main Engine (SSME) startup. The SSP’s vibration testing was found adequate to characterize performance of an individual connector, but not representative of the integrated, dual carrier plate assembly being flown. Four recommendations to the SSP were generated as a result of the initial NESC work:

R-1. Fully implement planned hardware and process control changes.

R-2. Revisit the 0.25-inch connector nut gap requirement and consider increasing to 0.38 - 0.5 inches to increase force margin on the mated connector assembly.

R-3. Collect data suitable for anchoring system-level finite element models, optimally by instrumenting the ground-side of the T-0 interface through launch.

R-4. Verify the connector frequency response is in the 300-500 Hz range and conduct a conservative vibration test of the assembled connector using a composite spectrum that bounds both the 16C and 21 environments. The use of instrumented nominal and undersized pins of varying lengths across the full spectrum will help establish design margin.

6.3 Follow-On NESC Activity

After release of the initial white paper and consultation with stakeholders, the NESC undertook three additional activities:

1. Conduct finite element modeling to help characterize the response of the T-0 interface to the launch startup transient. The NESC T-0 Assessment Team agreed that a well-developed finite element analysis that incorporated all system elements and addressed low-frequency response (less than 20 Hz) could be conducted in lieu of the system-level test recommended in the white paper (Recommendation R-4).

2. Conduct failure analysis and testing of a cable assembly removed from the Mobile Launch Platform (MLP) at KSC to better understand the corrosion-induced failure postulated for STS-112.

3. Develop a quantitative risk estimate assuming failure of the entire HDP firing circuit (i.e., a quad-redundant failure).

In the initial review, the NESC T-0 Assessment Team noted that although the finite element
modeling prepared by the SSP was well-formulated, the model did not: couple the vehicle and ground carrier plates, incorporate cryogenic quick disconnects, or address the system response to frequencies below 20 Hz.

In the follow-on activity, Boeing-Rocketdyne was asked to perform a more comprehensive analysis by building an integrated model coupling the LH$_2$ umbilical carrier plate (ground-side) and the LH$_2$ umbilical Orbiter plate (vehicle-side). All mass elements including cryogenic quick disconnects and electrical connectors would be included. Low frequency response of the system was to be evaluated and the sensitivity to modeling assumptions assessed. Results of the Boeing-Rocketdyne finite element modeling are provided in Appendix D and are discussed in Section 7.0.

A T-0 cable assembly was removed from the KSC MLP and transferred to GSFC where a detailed examination and analysis of corrosion by-products were performed. These analysis results are provided in Appendix E. GSFC also assessed whether the “wiping action” of the pins in their sockets was sufficient to remove corrosion and ensure good electrical contact. The NESC T-0 Assessment Team also attempted to demonstrate an intermittent connection. Results of the GSFC work are documented at Appendix F and discussed in Section 7.0.

A quantitative risk assessment was performed, assuming failure of the entire quad-redundant HDP firing circuit. This analysis is provided in Appendix G.

### 7.0 Data Analysis

The NESC Recurring Anomalies Splinter Team and NESC T-0 Assessment Team both concurred with the findings of the SAIB and the SSP: that the most likely cause of the STS-112 HDP failure was corrosion-induced intermittent electrical contact at the T-0 umbilical, and it is unlikely a generic or design flaw exists.

Failure history of the T-0 electrical connections is summarized on page 8 of Appendix C. Eleven incidents were documented over five missions beginning with STS-105. Four were recurrences of the same problem at different times in the Vehicle Assembly Building (VAB) or pad processing flow, so there were seven distinct failures including the STS-112 incident. At least one failure occurred per mission from STS-105 through STS-112 with exception of STS-109. It is important to note that not every connection through the T-0 is continuously monitored, and those that are may not be monitored at a high enough sampling rate to detect a short-duration intermittent failure. Thus, it is possible some intermittent failures occurred and escaped detection. The failures recorded in Appendix C are failures documented in the Problem Reporting and Corrective Action (PRACA) system. Onset of the problems began shortly after a
The processing decision to start re-using MLP T-0 cables rather than replace them after each flow was implemented. The ground-side MLP J71 connector and cable which carry certain Launch Data Bus (LDB) signals (see Appendix C, page 16) were replaced after erratic signals were noted during STS-110 and no failures of those signals were noted after that time. No failures at all have been noted since STS-112 when routine cable replacement was re-instituted. This includes missions processed since the data in Appendix C was collected (STS-114, STS-121, and STS-115).

A review of PRACA documentation revealed that signals could sometimes be restored by de-mating and re-mating connectors. In other instances, signals disappeared and reappeared with no action taken. Failure signatures were not all identical. In some cases, complete loss of signal was reported, but in seven instances degraded signals (distorted waveforms) typical of high-resistance connections were documented. There is no consistent pattern in the timing of the failures, although five occurred during dynamic conditions (SSME start through T-0) and two during tanking or de-tanking. Four incidents were documented with the vehicle under static conditions, at ambient temperature and with no dynamic activity underway. Failed J61 connections were positioned along the outer edges of the connector and those in J71, J60, and J64 were all routed through the connector center.

The involvement of multiple vehicles and subsystems appears to exonerate vehicle-side wiring. Additionally, the successful operation of the umbilical interface from STS-26R to STS-105 points to a process or hardware change, not a design problem. As noted above, the onset of failures after STS-105 is consistent with a change to pad preventive maintenance processes. At the time the first failure occurred, GSE-side cables were not being replaced after each launch, but were cleaned with isopropyl alcohol (IPA), inspected, and re-used. GSFC failure analysis of a MLP cable removed from the pad after STS-112 found non-conductive corrosive compounds consistent with SRB exhaust by-products (Appendices E and F). The corrosive materials were persistent, not readily dislodged from the pins, and were robust enough to survive multiple mate/de-mate cycles. The “wiping action” of the connector socket as it engaged the pin was not sufficient to remove the materials and ensure electrical contact. GSFC was able to duplicate intermittent opens on four of the ten connector pins that were electrically connected.

While the above evidence builds a strong circumstantial case for corrosion as a probable cause of the T-0 failures, the possibility that random vibration at launch could cause intermittent contact remained. If the SSME startup transient is capable of exciting the coupled interface sufficiently, the ground- and flight-side plates might move apart from one another enough to separate the connector halves. Dynamic loads placed on the mated assembly combined with the connector assembly’s internal resonance might also overcome the mating spring force with a similar result.
Dynamic response of the coupled system was assessed through a combined finite element model that augmented existing plate models to create a single, integrated finite element model suitable for structural dynamic analysis. The integrated model accounted for connector mass, stiffness, and pre-load and was subjected to the loading conditions expected between T-6.6 seconds and T-0, bracketing the period from SSME start to vehicle launch. Combined relative displacements of the ground- and flight-side connector mounting plates were as expected with a worst-case plate displacement of slightly over 0.050 inches predicted (Appendix D). Plate separation of more than 0.25 inches would be required before the connector halves would begin to de-mate. Analysis of the dynamic load at the connector interface also showed that considerable margin exists with a worst-case dynamic load of less than 4 pounds predicted (note these values apply to the J71 connector – the “worst-case force” occurs at the J51 connector, about 8 pounds). This force would have to overcome a worst-case (lowest) spring force of approximately 40 pounds before the connector halves would begin to separate. Given the margin already existing at the interface as suggested by this analysis, re-design of the electrical connections to incorporate additional pin-socket engagement or increase force margin on mated connections is not warranted (Refer to Appendix B, Recommendation 2).

While this analysis indicates a properly-assembled T-0 connection has considerable margin against separation, and thus minimal potential for a vibration-induced intermittent connection, the modeling performed is not anchored with the exception of test data collected through modal tests of the Vandenberg Air Force Base T-0 plate (see Appendix D). Modeling uncertainties exist with regards to the loading environment and the interconnecting elements between the Orbiter and ground-side plate.

Details of the failure probability estimate are provided in Appendix G. Assuming the connector failures experienced are independent and identically distributed across the 113 Space Shuttle missions flown at the time of the analysis, dual redundancy affords 226 independent opportunities to observe a single failure. Given the seven independent events seen, probability of a single connector failure on any launch can be estimated at 7/(2 x 113) = 0.03. For the quad-redundant SRB HDP firing circuit, the corresponding loss of fire function is 9.20 x 10-7.

8.0 Findings, Observations and Recommendations

8.1 Findings

F-1. Corrosion of electrical pins in ground-side interface connectors is the most probable proximate cause of the T-0 failures observed from STS-105 through STS-112.
F-2. The T-0 interface is a robust design with considerable margin against vibration-induced intermittent electrical connection.

F-3. Given the margin already existing at the interface, re-design of the electrical connections to incorporate additional pin-socket engagement or increase force margin on mated connections is not warranted.

8.2 Observations

O-1. Interface failures began shortly after a decision was implemented to stop replacing T-0 interface cables. This hardware is exposed to a corrosive environment at launch, and this change in the cable reuse increased the likelihood that corrosion would damage the interface with subsequent failure of electrical connections.

8.3 Recommendations

R-1. The SSP should fully implement hardware and process control changes to minimize the potential for future failures at the T-0 interface. (F-1, F-2, F-3)

R-2. The SSP should collect data suitable for anchoring finite element models by instrumenting the ground-side T-0 umbilical plate through at least one launch. (F-1, F-2, F-3)

9.0 Alternate Viewpoints

There were no alternative or dissenting opinions identified within the NESC T-0 Assessment Team in the submission of this report.

10.0 Other Deliverables

Finite element models, analyses, and results produced by this effort will be delivered to the SSP.

11.0 Lessons Learned

During the course of this consultation, the following lesson was learned:

LL-1. Electrical interfaces should be protected against the deposition of nonconductive corrosive environments. Presence of gold plating on connector pins and sockets is insufficient, in and of itself, to ensure corrosion will not occur with subsequent loss of circuit function.
12.0 Definition of Terms

Corrective Actions  Changes to design processes, work instructions, workmanship practices, training, inspections, tests, procedures, specifications, drawings, tools, equipment, facilities, resources, or material that result in preventing, minimizing, or limiting the potential for recurrence of a problem.

Finding         A conclusion based on facts established during the assessment/inspection by the investigating authority.

Lessons Learned Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.

Observation    A factor, event, or circumstance identified during the assessment/inspection that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur.

Problem        The subject of the technical assessment/inspection.

Requirement    An action developed by the assessment/inspection team to correct the cause or a deficiency identified during the investigation. The requirements will be used in the preparation of the corrective action plan.

Root Cause     Along a chain of events leading to a mishap or close call, the first causal action or failure to act that could have been controlled systemically either by policy/practice/procedure or individual adherence to policy/practice/procedure.

13.0 Acronym List

ETVAS       External Tank Vent Arm System
GPC         General Purpose Computers
GSE         Ground Support Equipment
GSFC        Goddard Space Flight Center

NESC Request No. 05-012-E
HDP  Hold-Down Post
IAT  Independent Assessment Team
IPA  Isopropyl Alcohol
KSC  Kennedy Space Center
LaRC  Langley Research Center
LDB  Launch Data Bus
LH₂  Liquid Hydrogen
LO₂  Liquid Oxygen
LPS  Launch Processing System
LVDT  Linear Voltage Displacement Transducers
MEC  Master Events Controller
MLP  Mobile Launch Platform
NASA  National Aeronautics and Space Administration
NDE  NESC Discipline Expert
NESC  NASA Engineering and Safety Center
PASS  Primary Application Software Set
PIC  Pyro Initiated Charge
PRACA  Problem Reporting and Corrective Action
PRCB  Program Requirements Change Board
SAIB  Standing Accident Investigation Board
SE&I  Systems Engineering and Integration
SRB  Solid Rocket Booster
SSME  Space Shuttle Main Engine
STS  Space Transportation System
TSM  Tail Service Mast
VAB  Vehicle Assembly Building

14.0 References

1.  PRACA Report P-V6-391545, During the Launch Sequence, a Signal from the PIC Rack was not Received at the SRB Bolts, 17 Oct 02

2.  Hold Down Post System A Pyrotechnics Failure, SAIB Team E Report, 23 Jan 03


NESC Request No. 05-012-E
5. PRCB Action S062323, Separation Interfaces Tiger Team Review Summary to PRCB, March 04

6. KMJ-3011, Independent Assessment of KSC GSE Interfaces with SSP Flight Elements, IAT Dissenting Opinion, 16 Mar 05


8. Space Shuttle T-0 Umbilical Dynamic Displacement, Miller, Tsai, Pilkey, and Davis, Rocketdyne, 18 Mar 05

9. KSC-MSL-0608-2002, Analysis of T-0 Connector and Hardware Associated with the SRB Hold Down Post Pyrotechnics, 7 Feb 03.

10. Independent Assessment of KSC GSE Interfaces with SSP Flight Elements, IAT Dissenting Opinion, revision 2, update 3, 16 Mar 05.
Volume II: Appendices

A. ITA/I Request Form (NESC-PR-003-FM-01)
C. NESC Presentation to Shuttle Program Requirements Change Board, *GSE T-0 Umbilical to SSP Flight Elements Assessment*, 31 Mar 05
D. *Space Shuttle T-0 Umbilical Dynamic Displacements and Forces*, Rocketdyne, 22 Aug 05
E. Report Q50299FA, *Connector Failure Analysis*, Goddard Space Flight Center Parts Analysis Laboratory
F. *GSE T-0 Umbilical to SSP Flight Elements Assessment Project Status*, 13 Oct 06
G. Quad-redundant Failure Analysis
Appendix A. ITA/I Request Form (NESC-PR-003-FM-01)
# Shuttle GSE T-0 Umbilical to Space Shuttle Program Flight Elements

## NASA Engineering and Safety Center Request Form

**Section 1: NESC Review Board (NRB) Executive Secretary Record of Receipt**

<table>
<thead>
<tr>
<th>Received (mm/dd/yyyy h:mm am/pm)</th>
<th>Status</th>
<th>Reference #:</th>
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<tbody>
<tr>
<td>3/17/2005 12:00 AM</td>
<td>New</td>
<td>05-012-E</td>
</tr>
</tbody>
</table>

**Initiator Name:** Bryan O'Connor  
**E-mail:** bryan.oconnor@nasa.gov  
**Center:** NASA HQ  
**Phone:** (202)-358-2699, Ext.  
**Mail Stop:**

**Short Title:** GSE T-0 Umbilical to SSP Flight Element Assessment

**Description:** This is to provide an assessment precipitated by a dissenting opinion from the Independent Assessment Team (IAT) review, Independent Assessment of KSC GSE Interfaces with SSP Flight Elements. After reviewing the Shuttle Program's final SE&I Tiger team actions and responses to the IAT's risk mitigation recommendations, the IAT has concluded that there still remains a level of uncertainty due to the undetermined root cause by the Tiger Team/Standing Accident Investigation Board (SAIB) and lack of controls for the GSE T-0 umbilical to SSP flight element interfaces posing high risk to future Shuttle flights. IAT is providing this dissenting opinion as a constraint to flight.

**Source:** email  
**Type of Request:** Assessment

**Proposed Need Date:** 3/23/2005

**Date forwarded to Systems Engineering Office (SEO):** (mm/dd/yyyy h:mm am/pm):

---

**Section 2.1 Potential IIA/I Identification**

- **Received by SEO:** (mm/dd/yyyy h:mm am/pm): 3/17/2005 12:00 AM
- **Potential IIA/I candidate?** Yes [ ] No [X]
- **Assigned Initial Evaluator (IE):**
- **Date assigned (mm/dd/yyyy):** 3/22/2005
- **Due date for IIA/I Screening (mm/dd/yyyy):**

**Section 2.2 Non-ITA/I Action**

- **Requires additional NESC action (non-ITA/I)?** Yes [X] No [ ]
  - **Description of action:** There is no initial evaluation required this was approved Out-of-Board to proceed with Tim Wilson leading. This is fast turn-around, high priority with a Special NR13 on 3/23/05 for Tim Wilson to present the NESC position

**Action:** Tim Wilson

- **Is follow-up required?** Yes [X] No [ ]
  - **If yes: Due Date:** 3/23/2005
  - **Follow-up status/date:**
  - **If no:**

**NESC Director Concurrence (signature):**

**Request closure date:**

---

NESC Request No. 05-012-E
**Title:** Shuttle GSE T-0 Umbilical to Space Shuttle Program

**Flight Elements**

### Section 3: Initial Evaluation

- **Received by IE:** (mm/dd/yyyy h:mm am/pm):
- **Screening complete date:** 
- **Valid ITA/I candidate?** [ ] Yes [ ] No
- **Initial Evaluation Report #:** NESC-PN-
- **Target NRB Review Date:**

### Section 4: NRB Review and Disposition of NCE Response Report

- **ITA/I Approved:** [ ] Yes [ ] No
- **Date Approved:**
- **Priority:** - Select -
- **ITA/I Lead:** , Phone ( ) - , x

### Section 5: ITA/I Lead Planning, Conduct, and Reporting

- **Plan Development Start Date:**
- **Plan Approval Date:**
- **ITA/I Start Date** | **Planned:** | **Actual:**
- **ITA/I Completed Date:**
- **ITA/I Final Report #:** NESC-PN-
- **ITA/I Briefing Package #:** NESC-PN-
- **Follow-up Required?** [ ] Yes [ ] No

### Section 6: Follow-up

- **Date Findings Briefed to Customer:**
- **Follow-up Accepted:** [ ] Yes [ ] No
- **Follow-up Completed Date:**
- **Follow-up Report #:** NESC-RP-

### Section 7: Disposition and Notification

- **Notification type:** - Select - | **Details:**
- **Date of Notification:**
- **Final Disposition:** - Select -
- **Rationale for Disposition:**
- **Close Out Review Date:**

---

NESC Request Form
NESC-RP-003-PM-01, v1.0

NESC Request No. 05-012-E
Form Approval and Document Revision History

<table>
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<tr>
<th>Version</th>
<th>Description of Revision</th>
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<td>1.0</td>
<td>Initial Release</td>
<td>Principal Engineers Office</td>
<td>29 Jan 04</td>
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Approved: NESC Director

Date
Appendix B. NESC White Paper, Review of the Space Shuttle T-0 Interface Anomaly Resolution, 23 March 05

NASA Engineering and Safety Center

Background

Standing Accident Investigation Board (SAIB) Team E was convened at KSC in October, 2002 to determine the root cause of failure of System A pyrotechnics to fire frangible nuts and release the Solid Rocket Booster Hold-Down Post (HDP) studs and External Tank Vent Arm System (ETVAS) during the STS-112 launch. The problem was closed as an unexplained anomaly and attributed to an intermittent failure at the T-0 interface (references 1 and 2).

An Independent Assessment Team (IAT) was formed to review the SAIB report and provide recommendations (reference 3). The Program Requirements Change Board (PRCB) subsequently directed Systems Engineering and Integration (SE&I) to form and lead a Tiger Team to address all findings related to ground support equipment interfaces with Space Shuttle flight elements. The Tiger Team’s charter included identifying common failure causes, understanding the multiple environments, and developing corrective actions.

A NESC Recurring Anomalies Splinter Team was formed to participate in a review of the Program response to the IAT findings held at KSC on 28 October and 3 November 2004. At that time, the NESC T-0 Assessment Team concurred with actions the Program was taking to resolve the issue pending completion of forward work (reference 4, appendix 8). NESC was again asked to render an opinion on the issue in response to an IAT dissenting opinion which had been forwarded to the HQ Director of Safety and Mission Assurance in March 05. The NESC splinter team was reformed to review work accomplished since the November meeting. The team was joined by the NESC Discipline Expert (NDE) for mechanisms, John McManamen, NDE for electrical power and avionics, Bob Kichak, NDE for mechanical analysis, Julie Kramer-White, and NDE for structures, Ivatury Raju. Team members reviewed the work accomplished by the Program and the dissenting opinion submitted by the IAT (references 5 - 6), some of the Program Tiger Team data summarized at the team’s website (reference 7), and the Rocketdyne dynamic analysis (reference 8). No NESC-chartered tests or independent technical analyses were performed. This follow-on review was hampered by the short time permitted for the work and lack of visibility by some team members into the actual hardware configuration.

NESC Request No. 05-012-E
Hardware and Processing Changes

The Program has made significant changes to hardware and processes since the STS-112 incident, mostly to address the most probable causes of the failure cited in the unexplained anomaly and SAIB reports. These changes include:

(1) Redesign of Orbiter-side wiring to provide for redundant HDP fire signals routed through two separate connectors on both the Liquid Hydrogen (LH2) and Liquid Oxygen (LO2) T-0 plates. This provides for dual redundant channel A and B signal paths (quad redundancy against loss of function) from the Orbiter MEC to the ground PIC racks. While the system has been so-modified, it is important to note the redundant copper paths cannot be verified by test and redundancy could be susceptible to common cause effects if any exist.

(2) Replacement of ground-side interface cables and connectors each flight. Cables were previously re-used and were thus subject to a buildup of corrosion and contamination. Corrosion of the interface connectors was singled out as a contributor to the STS-112 incident (reference 2). The intermittent and random nature of the failures is considered to be consistent with the presence of corrosion by-products on electrical hardware. KSC Malfunction Lab tests (reference 9) showed that the contamination provided insulation sufficient to register as an open circuit on a multi-meter.

(3) Improvements to the connector mating process including Videoscope inspection of the interface after mating, specification and measurement of driving nut engagement, verification of connector spring force, verification of connector saver bayonet pin engagement, and improved configuration control of tolerances to minimize the potential for stack-up. Weaknesses in the connector mating process were thought to contribute to the STS-112 incident (reference 2).

(4) Redesign of interface cables to incorporate Teflon instead of polyimide insulation to minimize the potential for wiring damage or short circuit.

The NESC review team concurs with these actions.

Testing

The Program conducted vibration testing with an instrumented connector mounted in a test fixture intended to represent the GSE-Orbiter T-0 configuration. IAT concerns that this test setup did not fully model the interface because it did not permit relative motion between the two umbilical plates are not without merit, and confidence in the integrity of the connection could be improved by unrestrained multi-axis testing. Such testing might highlight response coupling.
between the plates and connector assembly, if any exists, especially at the low frequencies characteristic of SSME startup. Presence of this coupling would reduce the pin engagement margin.

While initial dynamic response could be better simulated, the NESC T-0 Assessment Team notes that the most critical operating time from the perspective of commands crossing the T-0 interface is not at SSME start-up, but in the few seconds just prior to T-0 when the engines are operating at steady-state. It is at this time that HDP arm and fire commands are sent. The configuration tested does provide visibility into performance of the connector interface independent of the plates. Assuming that the frequency response of the spring connector is significantly higher than the frequency response of the plates, then this is a reasonable simulation of the interface during the critical operating phase. The fact the tests were conducted with a worst-case (minimal) load on the connector provides some confidence that the mated connector will operate properly during the period before T-0. The Program subjected the entire assembly to forcing inputs several orders of magnitude above those seen by the flight vehicle in the low frequency region of the engine steady-state spectrum in an attempt to create a worst-case environment. However the Program has indicated that the frequency response of the spring connector is somewhere between 300 -500 Hz and this specific test used the 16C zone environment which ramps down to low levels well before 300 Hz, suggesting this test was not as conservative as the Program maintains. A more conservative test would have used a composite spectrum that bounds both the zone 16C and 21 environments. Since the whole pin engagement margin hinges on the response of the connector (currently assumed to be above 300 or 500 Hz) under this dynamic loading environment this test should be conducted and a more definitive assessment of connector frequency response obtained. This will improve confidence in the integrity of the mated assembly during the period before T-0.

Modeling

The NESC T-0 Assessment Team reviewed the Finite Element Model (FEM) prepared by the Program to analyze the relative motion between the Orbiter and GSE umbilical plates. The team found the plate model to be well-formulated and concurs with the analysis performed, but notes the analysis is based on the fundamental assumption that low-frequency system response (that below 20 Hz) is not critical. This is not a crucial flaw if one assumes, as above, that the critical operating period for the interface is not during the dynamic startup transient but during steady state operation just prior to T-0 and that system modeling accurately represents any low-frequency coupling with the vehicle which may occur. The NESC T-0 Assessment Team did not see evidence the integrated system models have been anchored to real-world data. Such data should be collected and the models appropriately anchored for improved confidence.

NESC Request No. 05-012-E
Safety Margin

While significant pin-to-socket margin does appear to exist, at least under steady-state conditions, the extent of that margin is difficult to quantify. Values quoted by the Program are somewhat misleading since they assume a minimum contact area of 0.001" between a pin and socket is adequate. While this is true from the perspective of current transfer, it is probably not sufficient to ensure a reliable connection and there is no existing rule-of-thumb for de-rating under these circumstances. The manufacturer’s connector current ratings are based on pin diameter rather than depth of engagement and assume proper mating of the connector halves. Boeing analysis indicates nominal pin engagement for a connector-to-connector pair with locking ring is 0.096" with a minimum of 0.035", measured beyond the radius of the tip of the pin. This is the minimum pin engagement for which the connector is certified and a more reasonable lower bound on the engagement margin than the 0.001" analytical value quoted by the Program. Vibration testing with pins of varying lengths would help establish the actual design margin.

Attempts to improve the contact margin by lengthening the connector pins are ill-advised without detailed analysis and re-certification of the hardware. This proposed change, while simple on the surface, may well have unintended consequences. The NESC T-0 Assessment Team notes additional margin could probably be gained by increasing the minimum gap proposed for the connector nut from 0.25 inches to 0.38 to 0.5 inches, thus increasing pre-load on the spring and connector assembly and reducing potential for the pins and sockets to separate, without changing the physical characteristics of the interface.

Conclusion

The Program has implemented a number of corrective actions in response to the STS-112 failure. These include increasing redundancy for critical signals across the T-0 interface, significantly improving process controls, and replacing interface cables to minimize the potential for corrosion. NESC concurs these actions are suitable to address the most probable causes of that failure and is satisfied with flight rationale based upon them. Since critical commands do not cross the interface during the SSME startup transient, and those that cross the interface shortly before T-0 have significant redundancy, NESC concurs the interface as-designed can be operated with low probability for catastrophic loss of function.

While it appears the Program has done an adequate job modeling the interface under steady-state conditions, modeling of the integrated system under dynamic conditions is not validated and only covers frequencies above 20 Hz. It could be improved by a better understanding of the system sensitivity to low frequency forcing functions of the kind seen during SSME startup. Models

NESC Request No. 05-012-E
should be anchored to real-world data. Vibration testing done to demonstrate pin engagement margin is reasonable for the connector, but is not representative of integrated system performance. Characterization of the connector could be improved with a conservative vibration test conducted using a composite spectrum that bounds both the zone 16C and 21 environments. Additional work to address these issues and better understand the actual design margin should be conducted per the recommendations below, though with exception of the first NESC does not consider these constraints to flight.

**Recommendations**

1. Program fully implement planned hardware and process control changes.

2. Program revisit the 0.25 inch connector nut gap requirement and consider increasing to 0.38 to 0.5 inches in order to increase force margin on the mated connector assembly.

3. Program collect data suitable for anchoring system level finite element models, optimally by instrumenting the ground side of the T-0 interface through launch.

4. Program verify connector frequency response is in the 300-500 Hz range and conduct a conservative vibration test of the assembled connector using a composite spectrum that bounds both the 16C and 21 environments. Use of instrumented nominal and undersized pins of varying lengths across the full spectrum will help establish design margin.

**Review Team Members**

Tim Wilson, NESC Chief Engineer, KSC (Team Lead)
John McManamen, NESC Discipline Expert for Mechanisms
Julie Kramer White, NESC Discipline Expert for Mechanical Analysis
Ivatury Raju, NESC Discipline Expert for Structures
Robert Kichak, NESC Discipline Expert for Power and Avionics
Robert Beil, NASA KSC
Robert Cherney, Orbital Sciences
John Weeks, NASA KSC
Dave McCann, Boeing

**References**

1. PRACA Report P-V6-391545, *During the Launch Sequence, a Signal from the PIC Rack was not Received at the SRB Bolts*, 17 Oct 02

NESC Request No. 05-012-E
2. *Hold Down Post System A Pyrotechnics Failure, SAIB Team E Report*, 23 Jan 03


5. PRCB Action S062323, *Separation Interfaces Tiger Team Review Summary to PRCB*, March 04

6. KMJ-3011, *Independent Assessment of KSC GSE Interfaces with SSP Flight Elements, IAT Dissenting Opinion*, 16 Mar 05


8. *Space Shuttle T-0 Umbilical Dynamic Displacement*, Miller, Tsai, Pilkey, and Davis, Rocketdyne, 18 Mar 05

9. KSC-MSL-0608-2002, *Analysis of T-0 Connector and Hardware Associated with the SRB Hold Down Post Pyrotechnics*, 7 Feb 03.

NESC Request No. 05-012-E
Appendix C. NESC Presentation to Shuttle Program Requirements Change Board, *GSE T-0 Umbilical to SSP Flight Elements Assessment*, 31 Mar 05
NASA Engineering and Safety Center (NESC)

GSE T-0 Umbilical to SSP Flight Elements Assessment

05-012-E

Tim Wilson
NESC Chief Engineer, KSC
31 March 05

This briefing is for status only and does not represent complete engineering data analysis.
T-0 Anomaly Review

- NESC assessment team assembled at the request of HQ S&MA
  - Recurring anomalies team members who participated in November and February T-0 anomaly reviews
  - NESC Discipline Experts for mechanisms, mechanical analysis, power and avionics, and structures
- Team reviewed the Program position and IAT opinion
  - PRCB presentation summarizing work performed
    - Modeling
    - Vibration Testing
  - IAT concerns package
  - Finite element model documented as Rocketdyne dynamic analysis
  - Other materials published at Tiger Team website
- NESC team did not conduct independent test or analysis other than a review of the above material

This briefing does not represent complete engineering data analysis
Conclusions

• Program has implemented a number of corrective actions in response to the STS-112 failure
  - Increased redundancy for critical signals across the T-0 interface
  - Significant improvement to process controls
  - Replacement of interface cables to minimize potential for corrosion
• NESC concurs with these corrective actions and with flight rationale based upon them
• Since critical commands do not cross the interface during the SSME startup transient, and those that cross the interface shortly before T-0 have significant redundancy, NESC concurs the interface as-designed can be operated with low probability for catastrophic loss of function. Additional work should be undertaken to better understand margins.

This briefing does not represent complete engineering data analysis

3

NESC Request No. 05-012-E
Conclusions

- Additional work should be conducted to address weaknesses in the model and vibration tests and ensure actual design margins are fully understood
  - Finite element modeling should be anchored to real-world data
  - Connector characterization should be improved with a conservative vibration test that bounds the zone 16C and 21 environments
  - Minimum value quoted for pin-socket contact (0.001") should be increased to 0.035" to ensure connector cert is not invalidated
  - Potential for increasing margin by increasing spring pre-load should be fully explored
- NESC does not consider this follow-on work a constraint to flight
Recommendations

- Program fully implement planned hardware and process control changes before return to flight
- Program revisit the 0.25 inch connector nut gap requirement and consider increasing to 0.38 to 0.5 inches to increase force margin on the mated connector assembly.
- Program collect data suitable for anchoring system level finite element models, optimally by instrumenting the ground side of the T-0 interface through launch.
- Program verify connector frequency response is in the 300-500 hz range and conduct a conservative vibration test of the assembled connector using a composite spectrum that bounds both the 16C and 21 environments. Use of instrumented nominal and undersized pins of varying lengths across the full spectrum will help establish design margin.

This briefing does not represent complete engineering data analysis
### Risk Assessment

#### NESC Risk Matrix

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<th>Consequence</th>
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<tr>
<td>2</td>
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<td>4</td>
<td>4</td>
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<tr>
<td>5</td>
<td>5</td>
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</tbody>
</table>

#### Hazardous Events

- **A** – Loss of a single circuit at the T-0 interface
- **B** – Loss of all critical circuits at the T-0 interface leading to LOCV

---

This briefing does not represent complete engineering data analysis.
Backup Charts

This briefing does not represent complete engineering data analysis.
## Combined Failure / Flight History

<table>
<thead>
<tr>
<th>Flight</th>
<th>Orbiter</th>
<th>MLP</th>
<th>Umbilical</th>
<th>Connector</th>
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<tr>
<td>STS-105</td>
<td>OV-103</td>
<td>3</td>
<td>LH2</td>
<td>J71 /</td>
<td>Distorted PCMMU signal during S0009 power-up</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>J71 /</td>
<td>LDB-1 lost during SSME start – Water in TD connector</td>
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<tr>
<td>STS-108</td>
<td>OV-105</td>
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<td>LH2</td>
<td>J61 /</td>
<td>SRB LH Bus A erratic after SSME start</td>
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<td>OV-102</td>
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<td>STS-110</td>
<td>OV-104</td>
<td>3</td>
<td>LH2</td>
<td>J71 /</td>
<td>LDB V0 errors during S0008 power-up</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LDB-1 to LDB-2 switch during scrub de-tanking</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>LDB-1 / LO2 / LO2 / J60 / SRB RH Bus A erratic after SSME start</td>
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<td>STS-111</td>
<td>OV-105</td>
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<td>J64 /</td>
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<td>J61 /</td>
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<td>STS-107</td>
<td>OV-102</td>
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</tbody>
</table>

Items in red: Troubleshooting revealed a corrupted or distorted waveform

This briefing does not represent complete engineering data analysis
Failure History Observations

- Eleven failures over five missions beginning with STS-105
  - Four are recurrences of the same problem at different times in the VAB or pad processing flow leaving seven distinct failures
  - At least one failure per mission from STS-105 through STS-112 with exception of STS-109
  - No failure of MLP J71 connection since STS-110 cable replacement
  - No failures of any connections since STS-112 cable replacements
- Failure signatures
  - Degraded signals typical of high-resistance connections noted
  - Loss of signal (open circuit) noted in some cases
  - Signals could sometimes be restored by de-mating and re-mating connectors

This briefing does not represent complete engineering data analysis
Failure History Observations

- Failures occurred at various times during the processing flows
  - Four during static conditions: ambient temperatures, no dynamic activity
  - Two during tanking / de-tanking (one was a signal recovery)
  - Four at SSME start
  - One at T-0
  - Signals sometimes disappeared or reappeared with no action taken
- Discrepant connector pin configuration
  - J71 : LH2 Plate – Failed signals in connector center
  - J61 : LH2 Plate – Failed signals along connector edge
  - J60 : LO2 Plate – Failed signals in connector center
  - J64 : LO2 Plate – Failed signals in connector center

This briefing does not represent complete engineering data analysis
Corrosion / Mate as Likely Cause

- Involvement of multiple vehicles and subsystems appears to exonerate vehicle-side wiring
- Successful operation of the interface from STS-26R to STS-105 points to a process or hardware change, not a design problem
  - PRACA research extended to STS-26R
  - Low probability of an undetected or unreported failure prior to STS-105
    - First failure (distorted PCMMU signal resulting in loss of OI data) was highly problematic and drove extensive troubleshooting
    - Identical problem detection and resolution processes have been in place since STS-26R
- Loss of individual circuits / pins instead of whole connectors or groups of pins points to a failure mechanism other than vibration or marginal pin-socket contact

This briefing does not represent complete engineering data analysis
Corrosion / Mate as Likely Cause

- Failures observed are consistent with corrosion and/or improper mating
  - Would expect corroded or contaminated connections to cause random failures
    - High resistance connections would lead to signal degradation of the type noted
    - Corroded connections would have marginal contact area resulting in connections sensitive to vibration, minor thermal transients, etc.
  - Most failures were to low-voltage signals, the ones most susceptible to high-resistance degradation
  - Several of the failures cleared when connectors were de-mated and re-mated
  - Pins associated with STS-112 fail-to-fire are near periphery of connector and thus most likely affected by a cocked or poorly mated connection

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This briefing does not represent complete engineering data analysis

12
Corrosion / Mate as Likely Cause

- Process and hardware discrepancies are known to have existed at the time of the first failure
  - GSE cables were not replaced but cleaned and re-used post-flight
    - Interface connectors were exposed to highly-corrosive environments
    - Cleaning not effective in removing corrosion products
  - Interface connectors had corrosion on pins and connector shells as confirmed by failure analysis of the J71 and J61 cables
    - Corrosion products were non-conductive in nature
    - Corrosion had breached, and caused damage to, gold plating
  - Mating process was not well-controlled until after STS-112
    - Blind mate not confirmed by visual inspection
    - Spring force not controlled
    - Parts tolerance stack-up not controlled

This briefing does not represent complete engineering data analysis
Corrosion / Mate as Likely Cause

- Problems have not recurred since likely causes were addressed
  - MLP3 J71 connection was especially problematic
    - Failures observed on both STS-105 and the following MLP3 mission, STS-110
    - No J71 failures have been observed since the cable and interface connector were replaced (one mission, STS-112)
  - No MLP1 failures were observed in the single mission processed since all interface cables on that MLP were replaced

This briefing does not represent complete engineering data analysis
# LO2 Umbilical Connectors

<table>
<thead>
<tr>
<th>Connector</th>
<th>Wired Pins</th>
<th>Active at T-0</th>
<th>Circuits</th>
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<td>0</td>
<td>Main Bus B Feed</td>
</tr>
<tr>
<td>50J54</td>
<td>4</td>
<td>0</td>
<td>Main Bus C Feed</td>
</tr>
<tr>
<td>50J66</td>
<td>50</td>
<td>20</td>
<td>ICOM, C Monitors, LO2/LH2 Press, PRSD Vlv Cmds, MEC 2 HDP Arm/Fire</td>
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<tr>
<td>50J88</td>
<td>59 Max</td>
<td>Varies</td>
<td>Payload - Mission Specific</td>
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<td>50J60</td>
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<td>10</td>
<td>Mon, Bus Pwr Cmds, RSS SRB Inhib/Reset, GSE Bus Rmt Sense</td>
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<td>50J62</td>
<td>9</td>
<td>4</td>
<td>Dump Line HR2, Pre-Flt Test Bus</td>
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<td>50J64</td>
<td>46</td>
<td>9</td>
<td>LDB2, EUU2/3, MMU, PCMMU2, P/L Signal Processor</td>
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<td>50J70</td>
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<td>FDM FMM2, PMMI1, MADS Recorder</td>
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Minimum Number Active at T-0: 52

Pins active at T-0 are those carrying > 100 uA
Connectors in red are those with a failure history

---

This briefing does not represent complete engineering data analysis

---

NESC Request No. 05-012-E
**Title:** Shuttle GSE T-0 Umbilical to Space Shuttle Program Flight Elements

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### LH2 Umbilical Connectors

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Minimum Number Active at T-0: 59

*Pins active at T-0 are those carrying > 100 uA
Connectors in red are those with a failure history*

---

This briefing does not represent complete engineering data analysis.
Appendix D. Space Shuttle T-0 Umbilical Dynamic Displacements and Forces, Rocketdyne, 22 Aug 05
Space Shuttle T-0 Umbilical

Dynamic Displacements and Forces

Prepared by: Jeff H. Miller, James Y. Tsai, Debbie F. Pilkey, Gary A. Davis, Jeff H. Christie, Chris T. Houghton

Approved by: John E. Larson

Rocketdyne

August 22, 2005
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Table of Contents

1.0 Introduction .......................................................................................................................... 6
2.0 Executive Summary ................................................................................................................. 6
3.0 T-0 Umbilical LH2 Carrier Plate Finite Element Model ........................................................... 7
3.1 T-0 Umbilical LH2 Carrier Plate Finite Elements .................................................................... 7
3.2 T-0 Umbilical Carrier Plate Mass Elements ......................................................................... 11
3.3 T-0 Umbilical Carrier Plate Material Properties and Temperature ........................................ 12
3.4 Vandenberg T-0 Umbilical Carrier Plate ............................................................................. 12
3.4.1 T-0 Umbilical Carrier Plate Density Adjustment (Vandenberg Plate) ................................ 13
3.4.2 Verification of FEM using Space Vandenberg LH2 Carrier Plate ...................................... 14
3.5 Verification of FE Model Weight Estimate for Fluid and Electrical Line Weights ............. 17
3.6 T-0 Umbilical Carrier Plate Launch Boundary Conditions ................................................ 17
3.7 T-0 Umbilical Carrier Plate Damping ................................................................................... 17
3.8 Dynamic Load ...................................................................................................................... 17
3.9 T-0 Umbilical Carrier Plate Frequency & Mode Shape (Launch Boundary Conditions) ........ 17
3.10 T-0 Umbilical Carrier Plate Displacement (Launch Boundary Conditions) ....................... 17
3.11 Sensitivity Studies ............................................................................................................ 17
3.11.1 Number of Modes Sensitivity (Sensitivity Study #1) ...................................................... 17
3.11.2 Fluid and Line Weight Sensitivity (Sensitivity Study #2) ............................................... 17
3.11.3 Effect of Fluid Line Stiffness and Spring Stiffness (Sensitivity Study #3) ......................... 17
4.0 Comparison of LH2 and LOX T-0 Umbilical Carrier Plates .............................................. 17
5.0 Orbiter LH2 T-0 Umbilical Panel Finite Element Model .................................................... 17
5.1 Element Types .................................................................................................................... 17
5.2 Material Properties ............................................................................................................. 17
5.3 Mass Properties .................................................................................................................. 17
5.4 Boundary Conditions ......................................................................................................... 17
5.5 Special Features .................................................................................................................. 17
5.5.1 Estimate of LH2 Fill-and-Drain Line Stiffness ................................................................. 17
5.5.2 Orthotropic Shell Elements ............................................................................................ 17
5.5.3 Connector Region Reinforcements ............................................................................... 17
5.5.4 Constraint Equations ..................................................................................................... 17
5.6 Damping ............................................................................................................................. 17
5.7 Applied Dynamic Loads ..................................................................................................... 17
5.8 Baseline Configuration FEM Frequencies and Mode Shapes .............................................. 17
5.9 Baseline Configuration FEM Displacements .................................................................... 17
5.10 Sensitivity Studies ............................................................................................................ 17
5.10.1 Natural Frequencies .................................................................................................... 17
5.10.2 Displacement Results .................................................................................................. 17
6.0 Integrated LH2 T-0 Umbilical FEM .................................................................................... 17
6.1 Collet Connections ............................................................................................................. 17
6.2 Shear Pin Connections ....................................................................................................... 17
6.3 Foot Connections ................................................................................................................ 17
6.4 Fluid and Electrical Connections ........................................................................................ 17
6.4.1 Fluid Line Connections .................................................................................................. 17
Shuttle GSE T-0 Umbilical to Space Shuttle Program
Flight Elements

Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson 8/22/2000

6.4.2 Electrical Line Connections ................................................................. 17
6.5 Damping .................................................................................................. 17
6.6 Applied Dynamic Load ........................................................................... 17
6.7 Baseline Configuration FEM Frequencies and Mode Shapes ................. 17
6.7.1 Modes 1 and 2 .................................................................................. 17
6.7.2 Mode 3 ............................................................................................ 17
6.7.3 Mode 4 ............................................................................................ 17
6.7.4 Mode 5 ............................................................................................ 17
6.7.5 Mode 6 ............................................................................................ 17
6.7.6 Mode 7 ............................................................................................ 17
6.7.7 Mode 8 ............................................................................................ 17
6.7.8 Mode 9 ............................................................................................ 17
6.7.9 Mode 10 ......................................................................................... 17
6.7.10 Mode 11 ....................................................................................... 17
6.7.11 Mode 12 to 15 ................................................................................ 17
6.7.12 Modes 16 to 30 .............................................................................. 17
6.8 Sensitivity Study Configurations ............................................................... 17
6.9 Dynamic Relative Displacement and Spring Forces .............................. 17
7.0 Conclusion ............................................................................................. 17
8.0 References ............................................................................................ 17
Appendix A. Modal Test Report .................................................................... A-17
Appendix B. Material Properties Data .......................................................... B-17
Appendix C. Connector Spring Damping Ratio Sensitivity Study .................. C-17

NESC Request No. 05-012-E
Shuttle GSE T-0 Umbilical to Space Shuttle Program
Flight Elements

Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

List of Figures
Figure 1. Electrical Connectors Dynamic Relative Displacement and Force ........................................ 6
Figure 2. LH2 T-0 Umbilical Plate Mated To Orbiter ........................................................................ 7
Figure 3. View Looking at the LH2 T-0 Umbilical Carrier Plate from the Orbiter ....................... 8
Figure 4. View Looking At GSE Side of Plate .................................................................................. 8
Figure 5. View Looking At Orbiter Side of GSE Plate .................................................................... 9
Figure 6. T-0 Umbilical Carrier Plate FE Model .............................................................................. 10
Figure 7. T-0 Umbilical Carrier Plate FEM Collect .......................................................................... 10
Figure 8. T-0 Umbilical Carrier Plate FEM Mass Elements ............................................................... 11
Figure 9. T-0 Umbilical Carrier Plate FEM Materials and Drawing Numbers ............................... 12
Figure 10. Vandenberk Spare T-0 Umbilical Carrier Plate ............................................................. 13
Figure 11. Instrument Modal Test Hammer ....................................................................................... 15
Figure 12. Vandenberk Plate Modal Test Data (Free-Free B.C.) .......................................................... 16
Figure 13. Vandenberk FE Model Modal Frequency and Shape ....................................................... 16
Figure 14. T-0 Umbilical Carrier Plate Partially Retracted ................................................................. 17
Figure 15. T-0 Umbilical Carrier Plate Partially Retracted FE Mode Shapes .................................... 17
Figure 16. T-0 Umbilical Carrier Plate FEM Launch Boundary Conditions ...................................... 17
Figure 17. T-0 Umbilical Carrier Plate Wire Braided Hoses ............................................................... 17
Figure 18. T-0 Umbilical Damping Ratio vs. Data Window Size T-0 Umbilical Carrier Plate .......... 17
Figure 19. T-0 Umbilical Carrier Plate Base Excitation Spectra ...................................................... 17
Figure 20. T-0 Umbilical Carrier Plate Mode Shapes (1st and 2nd Mode) ....................................... 17
Figure 21. T-0 Umbilical Carrier Plate Mode Shapes (3rd and 4th Mode) ....................................... 17
Figure 22. T-0 Umbilical Carrier Plate 3d Connector Displacement ................................................. 17
Figure 23. T-0 Umbilical Carrier Plate 3d Connector Displacement .................................................... 17
Figure 24. T-0 Umbilical Carrier Plate Sensitivity Study #1 ............................................................. 17
Figure 25. T-0 Umbilical Carrier Plate Sensitivity Study #2 ............................................................. 17
Figure 26. T-0 Umbilical Carrier Plate Sensitivity Study #3 Artificial Flat PSD ............................. 17
Figure 27. T-0 Umbilical Carrier Plate Sensitivity Study #3 Displacement ....................................... 17
Figure 28. Location of LH2 T-0 UmbilicalPanel on Orbiter ............................................................. 17
Figure 29. Orbiter LH2 T-0 Umbilical Panel Exterior ............................................................ 17
Figure 30. Orbiter LH2 T-0 Umbilical Panel Connector Numbering Scheme .................................. 17
Figure 31. Orbiter LH2 T-0 Umbilical Panel Interior ..................................................................... 17
Figure 32. Orbiter LH2 T-0 Umbilical Panel Interior ............................................................. 17
Figure 33. Orbiter LH2 T-0 Umbilical Panel Finite Element Model ................................................ 17
Figure 34. Mass, Spring, and Rigid Elements .................................................................................... 17
Figure 35. Materials in Finite Element Model .................................................................................. 17
Figure 36. In-Plane Boundary Conditions ...................................................................................... 17
Figure 37. Out-of-Plane Boundary Conditions ................................................................................. 17
Figure 38. FEM Used in Estimating LH2 Fill-and-Drain Line Stiffness .......................................... 17
Figure 39. Orthotropic Shell Elements ............................................................................................. 17
Figure 40. FEM Representation of Connector Reinforcement Regions ........................................... 17
Figure 41. Effect of Including Connector Region Reinforcement in FEM ....................................... 17
Figure 42. Constraint Equations in FEM ......................................................................................... 17
Figure 43. Use of Constraint Equations at Panel Edge ................................................................. 17
Figure 44. FEM Representation of Mid-Panel Frame Beam ............................................................ 17
Figure 45. Constraint Equations at Mid-Panel Frame Beam ............................................................ 17
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2003

Figure 46. Effect of Constraint Equations at Mid-Panel Frame Beam
Figure 47. Orbiter T-0 Umbilical Panel Random Base Excitation PSD Function
Figure 48. First Mode Shape (56 Hz) - Baseline
Figure 49. Second Mode Shape (62 Hz) - Baseline
Figure 50. Third Mode Shape (114 Hz) - Baseline
Figure 51. Fourth Mode Shape (147 Hz) - Baseline
Figure 52. Orbiter Panel 3-σ Out-of-Plane Displacement - Baseline
Figure 53. Orbiter Panel Baseline FEM Electrical Connectors & Shear Pins 3-σ Out-of-Plane Displacement
Figure 54. Orbiter Panel Sensitivity Studies Electrical Connectors & Shear Pins 3-σ Out-of-Plane Displacement
Figure 55. Orbiter Panel 3-σ Out-of-Plane Displacement - Case 1
Figure 56. Orbiter Panel 3-σ Out-of-Plane Displacement - Case 2
Figure 57. Orbiter Panel 3-σ Out-of-Plane Displacement - Case 3
Figure 58. Orbiter Panel 3-σ Out-of-Plane Displacement - Case 4
Figure 59. Orbiter Panel 3-σ Out-of-Plane Displacement - Case 5
Figure 60. Orbiter Panel 3-σ Out-of-Plane Displacement - Case 6
Figure 61. Integrated T-0 Umbilical FEM
Figure 62. Side Views of Integrated T-0 Umbilical FEM
Figure 63. Collet Connection
Figure 64. Shear Pin Connections
Figure 65. Carrier Plate Foot Attachment Locations on Orbiter
Figure 66. Upper Foot Attachment Clevis FEM
Figure 67. Upper Foot Attachment
Figure 68. Lower Foot Attachment
Figure 69. Fluid Disconnect FEM Representation
Figure 70. Electrical Connector Assembly
Figure 71. Electrical Connector FEM Representation
Figure 72. Updated Orbiter T-0 Umbilical Random Base Excitation PSD Function
Figure 73. Integrated FEM 1st Mode Shape (56 Hz)
Figure 74. Integrated FEM 2nd Mode Shape (62 Hz)
Figure 75. Integrated FEM 3rd Mode Shape (65 Hz)
Figure 76. Integrated FEM 4th Mode Shape (75 Hz)
Figure 77. Integrated FEM 5th Mode Shape (85 Hz)
Figure 78. Integrated FEM 6th Mode Shape (92 Hz)
Figure 79. Integrated FEM 7th Mode Shape (106 Hz)
Figure 80. Integrated FEM 8th Mode Shape (106 Hz)
Figure 81. Integrated FEM 9th Mode Shape (107 Hz)
Figure 82. Integrated FEM 10th Mode Shape (123 Hz)
Figure 83. Integrated FEM 11th Mode Shape (127 Hz)
Figure 84. Integrated FEM 12th Mode Shape (130 Hz)
Figure 85. Integrated FEM 13th Mode Shape (130 Hz)
Figure 86. Integrated FEM 14th Mode Shape (130 Hz)
Figure 87. Integrated FEM 15th Mode Shape (130 Hz)
Figure 88. Integrated FEM 3-σ Out-of-Plane Displacement - Baseline Configuration
Figure 89. Integrated FEM Electrical Connector 3-σ Out-of-Plane Relative Displacement
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson 8/22/2003

Figure 90. Integrated FEM Electrical Connector 3-α Dynamic Spring Force.............................. 17
Figure 91. Mode Contribution to Connector 3-α Relative Displacement Response .................... 17
Figure 92. Mode Contribution to Connector 3-α Spring Force Response .................................... 17
Figure 93. Static Relative Displacement due to Connector Preload ............................................. 17
Figure 94. Integrated FEM Electrical Connector Dynamic Relative Displacement & Force ...... 17

List of Tables

Table 1. Added Mass For Vandenberg Spare Carrier Plate .......................................................... 14
Table 2. Frequency Comparison of Vandenberg Modal Test Data against FE Model ................. 17
Table 3. Frequency Comparison (Partially Retracted) Modal Test Data against FE Model ...... 17
Table 4. T-0 Umbilical Carrier Plate Modal Frequencies ........................................................... 17
Table 5. Modal Test Frequency Comparison LH2 Plate vs. LOX Plate ....................................... 17
Table 6. Connector Description .................................................................................................... 17
Table 7. Element Type List ........................................................................................................... 17
Table 8. Material Properties List .................................................................................................. 17
Table 9. Connector and Line Weight Estimates ............................................................................ 17
Table 10. Orbiter Panel Finite Element Model Configuration List .............................................. 17
Table 11. Orbiter Panel Finite Element Model Natural Frequencies ........................................... 17
Table 12. Integrated FEM Connector Parameters ......................................................................... 17
Table 13. Integrated FEM Sensitivity Study Configuration List................................................... 17

NESC Request No. 05-012-E
1.0 Introduction

A port and starboard umbilical system is used to provide fluid and electrical lines to the Space Shuttle prior to launch at T-0. Each umbilical system is composed of Ground Support Equipment (GSE) which includes an aluminum Carrier Plate that mates to an Orbiter interface panel. The orbiter interface panel is integral to the Orbiter. The port and starboard GSE including the carrier plates retract at T-0 into their own Tail Service Mast (TSM) which is equipped with a blast shield that drops to protect the GSE from launch pad environments.

On STS-112 an electrical signal did not get through the umbilical system and although a backup system did work, a question was raised as to whether dynamic loads prior to liftoff could create a displacement (gap) between the GSE and the orbiter panel that was big enough to contribute to the loss of electrical signal. This report presents the predicted dynamic displacements and dynamic forces between the GSE and the Orbiter panel in the last 6 seconds prior to liftoff.

2.0 Executive Summary

An integrated finite element model (FEM) was created incorporating both the GSE LH2 T-0 Umbilical Carrier Plate and the LH2 T-0 Umbilical Orbiter Panel. Modal testing of both the port and starboard GSE, including the Carrier Plates, helped validate the FEMs. Sensitivity studies showed that the models were insensitive to key modeling assumptions. The dynamic relative displacement between the GSE side (Carrier Plate) and the Orbiter side (Orbiter Panel) and the dynamic spring force for each electrical connector on the LH2 side are shown in Figure 1.

Analysis indicates that similar results would be expected for the LO2 side.

![Graph showing dynamic relative displacement and force](image_url)

**Figure 1. Electrical Connectors Dynamic Relative Displacement and Force**

NESC Request No. 05-012-E
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

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3.0 T-0 Umbilical LH2 Carrier Plate Finite Element Model

The LH2 T-0 Umbilical Carrier Plate is one component in the ground support equipment (GSE) that supports the Space Shuttle program. The T-0 Umbilical Carrier Plate is part of the Tail Service Mast (TSM) which is part of the Mobile Launch Platform (MLP). The MLP has two TSMs with each TSM having a T-0 Umbilical Carrier Plate. One of the T-0 Umbilical Carrier Plates is used to supply the Orbiter and Tank with LH2 and the other T-0 Umbilical Carrier Plate is used to supply the Orbiter and Tank with LOX. T-0 Umbilical Carrier Plate is mated to the Orbiter and is used to supply the Orbiter and Tank with all the electrical and fluid lines for the GSE equipment. Milliseconds after launch (T-0) the mated T-0 Umbilical Carrier Plate is automatically detached from the Orbiter and is retracted into the TSM. A blast shield on the TSM is then closed to protect the T-0 Umbilical Carrier Plate from the flame of the Space Shuttle Main Engines as the Orbiter lifts off. Figure 2 shows a view of the T-0 Umbilical Carrier Plate, the yellow rectangular shape plate, mated to the Orbiter. A view of the Orbiter side of the T-0 Umbilical Carrier Plate in a partially retracted state is shown in Figure 3. In this view, the fluid and electrical connectors that mate with matching connectors on the Orbiter can be seen. The largest fluid connector, located on the middle of the plate, is the connector for the LH2 fill-and-drain line. There are a total of twelve electrical connectors. The electrical connectors are located to the left and right of the LH2 fill-and-drain line.

To aid in the identification of the connectors, the connector numbering scheme from the Space Shuttle Operation and Maintenance Document VUML001-01 [1] is used in this report (see Figure 4). The locations of the critical electrical connectors J53, J61, and J71 are also identified in Figure 4. A picture viewing the GSE plate from the orbiter side of the plate with fluid connector labeled is shown in Figure 5. Table 6 contains a list of the connectors and their functions.

Figure 2. LH2 T-0 Umbilical Plate Mated To Orbiter

NESC Request No. 05-012-E
**Space Shuttle T-0 Umbilical Dynamic Displacements and Forces**


Approved by: John E. Larson

8/22/2003

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**Figure 3. View Looking at the LH T-0 Umbilical Carrier Plate from the Orbiter**

**Figure 4. View Looking At GSE Side of Plate**

NESC Request No. 05-012-E
The LH₂ T-0 Umbilical Carrier Plate was modeled using ANSYS 8.1. The plate was meshed from an IGES file produced by Pro/E. Rocketdyne’s design group constructed the Pro/E model from the T-0 Umbilical Carrier Plate drawings out of the SDS system. The model was meshed with 3-D tetrahedral elements with mid-side nodes. These elements have been found to be very good in bending. A fine mesh (145,000 nodes) was used for the solid geometry as can be seen in Figure 6.

The two collets near the top of the T-0 Umbilical Carrier Plate are used to mate the plate to the Orbiter before launch. The collets were modeled as beam elements. Each collet contains two different regions (Figure 7). Each region represents a different component of the collet. One region represents the non-moving outer structure of the collet and the other region represents the finger of the collet that expands to lock into the Orbiter. Each zone has different material properties and different real properties. The real properties are used to define the beam dimensions such as diameter and thickness. The collet beam elements were connected to the solid elements on the GSE side of the plate by constraint equations and couples. The constraint equations are used to transfer load along the beam axis. The couples are used to restrain the beam elements in the in-plane direction of the plate. Also for each collet, one beam node was restrained against rotation about the beam axis (again see Figure 7).
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Page 6 of 236

Tetrahedral Elements
With Mid-side Nodes
145,000 Nodes

Beam Elements Used To Model Collets

Mass Elements Used To Add Weight
• Connectors
• Fluid and electrical
• Collet Releasing Mechanism
• LH, Insulation Box

Figure 6. T-0 Umbilical Carrier Plate FE Model

Figure 7. T-0 Umbilical Carrier Plate FEM Collet

NESC Request No. 05-012-E
3.2 T-0 Umbilical Carrier Plate Mass Elements

Mass elements were used to represent the weight of the fluid and electrical connectors and a portion of the line weight. Mass elements were also used to represent the weight of the collet releasing mechanism and the LH2 insulation box. The mass elements are shown in purple in Figure 8. The weight of the electrical connector, collet releasing mechanism and the LH2 insulation box were estimated based on SDS drawings. The weight estimate of the collet releasing mechanism and the LH2 insulation box did not include all the miscellaneous parts so a 1.2 scale factor was applied to the weight estimate. The weight of the mass elements is shown on the right side of Figure 8. In this figure, “Wtf” is a parameter that can be used to scale the weights and was only used in sensitivity study #2. For the baseline case, “Wtf” was set to one. The weight parameter number corresponds to VULML001-01 [1] or Figure 4.

![Figure 8. T-0 Umbilical Carrier Plate FEM Mass Elements](image-url)
3.3 T-0 Umbilical Carrier Plate Material Properties and Temperature

The LH₂ T-0 Umbilical Carrier Plate is machined out of a solid plate of 2219 aluminum. The LH₂ T-0 Umbilical Carrier Plate foot is made out of A-286 and 17-4 PH stainless steel (see Figure 9). The collet housing is made out of A-286 and the collet fingers that mate with the Orbiter are made out of Beryllium Copper. Detailed material properties are shown in Appendix A.

The temperature of the LH₂ T-0 Umbilical Carrier Plate at T-0 is below room temperature. Thermal couple data show that at T-0 the plate temperature ranges between 0 °F and 45 °F. To be conservative, 70 °F material properties were used in the FE model. The 70 °F temperature is conservative because the elastic modulus is lower than at a colder temperature however the difference is a small amount. At 90 °F the elastic modulus is 10.16 ksi and at 20 °F the elastic modulus is 10.22 ksi which is less than 0.4 % difference.

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<td>G079-562510</td>
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<td>2 Guide</td>
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Figure 9. T-0 Umbilical Carrier Plate FEM Materials and Drawing Numbers

3.4 Vandenberg T-0 Umbilical Carrier Plate

The Space Shuttle Program has a spare LH₂ T-0 Umbilical Carrier Plate. This plate was originally to be used at the Vandenberg launch site. The Vandenberg launch site was never completed and the LH₂ T-0 Umbilical Carrier Plate for that site became known as the spare Vandenberg LH₂ T-0 Umbilical Carrier Plate.
3.4.1 T-0 Umbilical Carrier Plate Density Adjustment (Vandenberg Plate)

The Vandenberg spare plate was weighted as shown in Figure 10. The weight of the Vandenberg spare plate was 1,350 pounds. The Vandenberg spare plate does not contain any of the fluid and electrical lines. Also, as can be seen in Figure 10, the Vandenberg spare plate was missing one electrical connector socket and two fluid line connectors. The baseline FE model was copied and then modified to match the configuration of the Vandenberg plate. A comparison of Figure 8 (added mass for baseline) and Table 1 (added mass for Vandenberg spare plate) shows the modifications done to represent the Vandenberg plate. The weight calculated from the modified FE model, Vandenberg FE model, was 1,225 pounds. Comparing the weight of the actual Vandenberg plate to the Vandenberg FE model shows the FE model was approximately 10% too light. Therefore the FE model material density and mass elements were scaled up by 10% to match the Vandenberg plate weight. This was done for all three FE models, baseline with launch boundary conditions, baseline with partially retracted boundary conditions and Vandenberg configuration. All analyses were then performed with the adjusted weight.

Figure 10. Vandenberg Spare T-0 Umbilical Carrier Plate
3.4.2 Verification of FE11 using Spare Vandenberg LH2 Carrier Plate

The spare Vandenberg LH2 T-0 Umbilical Carrier Plate was modal tested using portable modal test equipment. The portable modal test equipment consisted of an instrumented hammer (see Figure 11), accelerometers, and modal processor. The Vandenberg plate was modal tested in the free-free state by suspending the plate from the rafters (see Appendix A for more modal testing information). The accelerometer data from the modal test was then processed with the X-Modal modal software. This software does a best fit to derive the modal frequencies and mode shapes. The first two significant mode shapes from the modal test data are shown in Figure 12. The X-Modal software contains only geometry information, x, y, z location of the accelerometers, therefore the plots and animations are stick figures such as that shown in Figure 12.

The Vandenberg FE model was run for modal frequency and shape. The first two significant mode shapes from the FE model are shown in Figure 13. The first mode was a torsion mode and the mode shape from the FE model (Figure 13) compares well with the mode shape from the modal test data (Figure 12). The second mode was bending in the long direction of the plate. Again, the mode shape from the FE model compares well with the modal test data. A frequency comparison for the first three modes is shown in Table 2. From this table it can be seen that the modal frequencies from the FE model closely match the modal test data therefore, the FE model has been verified by the modal test data.
Figure 11. Instrument Modal Test Hammer
Vandenber Spar Plate Modal Test Data (Free-Free B.C.)

Torsion 46 Hz  
Bending Long Direction 141 Hz

Figure 12. Vandenber Plate Modal Test Data (Free-Free B.C.)

Torsion 44 Hz  
Bending Long Direction 135 Hz

Figure 13. Vandenber FE Model Modal Frequency and Shape

NESC Request No. 05-012-E
Table 2. Frequency Comparison of Vandenberg Modal Test Data against FE Model

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>Frequency Vandenburg (Hz)</th>
<th>Frequency FE Model (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsion</td>
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<td>44</td>
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<td>Bending</td>
<td>141</td>
<td>135</td>
</tr>
<tr>
<td>2nd Torsion</td>
<td>178</td>
<td>179</td>
</tr>
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3.5 Verification of FE Model Weight Estimate for Fluid and Electrical Line Weights

The difference between the Vandenberg FE model (free-free B.C.) and the Baseline FE model (Launch B.C.) besides boundary conditions is that the Baseline FE model contains added mass for the fluid and electrical line weight. The effective fluid and electrical line weight supported by the LH₂ T-0 Umbilical Carrier Plate was estimated and applied to the model with mass elements. This increased the total weight of the Vandenberg FE model from 1,350 pounds to the Baseline FE model weight of 1,700 pounds. To verify the estimated fluid and electrical line weight the LH₂ T-0 Umbilical Carrier Plate in the partially retracted state was modal tested (see Figure 14). The plate in the partially retracted state was supported by a pair of links on both sides. The Baseline FE model was copied and then the boundary conditions were modified to match the carrier plate in the partially retracted state. The two modes, where the stiffness of the supporting links does not affect the modal frequency, are torsion of the plate top and bending in the long direction (see Figure 15 for the FE model mode shapes). Table 3 contains a frequency summary comparison between the modal test data and the FE model in the partially retracted state. The table shows a good comparison between the modal test data and the frequencies calculated from the FE model. This indicates that the estimated added mass for the fluid and electrical line weight was a good estimate. Also Sensitivity Study #2 shows that the estimate fluid and electrical line weight is not a strong driver in the dynamic out-of-plane displacement (see 3.11.2).
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson
8/22/2005

Figure 14. T-0 Umbilical Carrier Plate Partially Retracted

Mode VII (115 Hz) 
Torsion Of Top

Mode VIII (133 Hz) 
Bending Long Direction

Figure 15. T-0 Umbilical Carrier Plate Partially Retracted FE Mode Shapes
3.6 T-0 Umbilical Carrier Plate Launch Boundary Conditions

T-0 Umbilical Carrier Plate has six points of contact when the plate is mated to the Orbiter. Launch boundary conditions are the boundary conditions when the plate is mated to the Orbiter. At the top of the plate are the two collets. A rod is pushed down the center of the collet, causing the fingers of the collet to expand and make contact with the Orbiter. The collet fingers are individual thin walled small width fingers. These small fingers transfer very little shear load therefore, the FE model boundary condition at the end of the collet consist of restrained out of plane of the plate only. Located in the middle of the plane are two shear pins. At the shear pin locations, the FE model is restrained in the in-plane directions. At the bottom of the plate are the feet. The feet are restrained in the out of plane direction of the plate and in the vertical direction, long dimension of the plate (see Figure 16).
3.7 T-0 Umbilical Carrier Plate Damping

The damping ratio used in the LH₂ T-0 Umbilical Carrier Plate FE model was 3.3%. Most of the fluid lines connecting to the plate are external wire braided lines which produce a great deal of damping (see Figure 17). Damping is a function of the magnitude of the displacement. The magnitude of damping ratio will decrease if displacement is decreased. The damping value of 3.3% was based on modal testing of the LH₂ T-0 Umbilical Carrier Plate in the partially retracted state. In the modal test of the LH₂ T-0 Umbilical Carrier Plate, the plate is stung with a rubber tipped hammer. Since the plate is only stung once the vibration of the plate decays with time. Therefore the damping ratio from the modal test should decay with time. The actual damping ratio for the plate bending mode from the modal testing is shown in Figure 18 as the black line. The “x” axis of this plot is “data window size”. The larger the data window size the larger the time span that is used to calculate damping. This figure shows the modal test damping ratio decaying with time as expected. The damping of the LH₂ T-0 Umbilical Carrier Plate is over 4.2% based on the modal test when the magnitude of the vibration during the modal test is taken into account. The vibration amplitude from the SSME acoustic noise is much larger than the modal test input from a rubber tipped hammer therefore, the actual damping during launch is higher than the modal test results. The 3.3% damping used in the FE model is conservative compared to the 4.2% modal test damping. The 3.3% damping for the FE model was selected because it was conservative and because it is also the same damping ratio used on all the fluid duct line on the Space Shuttles Main Engines.
Figure 17. T-0 Umbilical Carrier Plate Wire Braided Hoses

Figure 18. T-0 Umbilical Damping Ratio vs. Data Window Size
3.8 Dynamic Load

The dynamic load used in the analysis is random base excitation in the plate out-of-plane direction. The low frequency transient loads (less than 10 Hz) are not included in this analysis. The excitation is applied, fully correlated, in the out-of-plane direction at the collets and at the feet (see Figure 16). The power spectral density (PSD) function of the excitation is obtained from Boeing Company NASA System MF 0004-014 Table 3.2.2.2d-1 [4], and a plot of that PSD function is shown in Figure 19. Two power spectral density curves are shown in this figure. The Zone 21A PSD as listed in MF0004-014 is for “aft fuselage umbilical plate (mated)” therefore, this PSD could have been used for the GSE plate. However to be conservative, the PSD for the Orbiter, Zone 16C, was used for T-0 Umbilical Carrier Plate. For T-0 Umbilical Carrier Plate the bending mode with launch boundary conditions occurs at 75 Hz. Figure 19 shows the Zone 16C curve to be a little larger in magnitude than the Zone 21A curve at the 75 Hz frequency. Also the loads people out of Houston have stated Figure 19 includes accelerations due to acoustic excitations. Consequently, no acoustic excitation is applied to the FEM.

3.9 T-0 Umbilical Carrier Plate Frequency & Mode Shape (Launch Boundary Conditions)

Plots of the first four mode shapes for the baseline case are shown in Figure 20 through Figure 21. The contour colors in these plots indicate the relative out-of-plane displacements of the modes. The first mode (75 Hz) is plate bending in the long direction of the plate. This is the mode that produces all of the out-of-plane displacements at the electrical connector locations. The second mode is a torsion mode at 103 Hz. This mode is hard to excite since it does both positive and negative work. The third mode is an in-plane shear mode. This mode is hard to
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John D. Larson 8/22/2005

The forth mode is a complex mode at 164 Hz. This mode is also hard to excite because of the positive and negative work and the mode shape is such that the minimum mode shape displacement occurs at the electrical connector location. The 9th thru 12th modes are all complex modes and are hard to excite. A complete list of the first twelve frequencies is shown in Table 4.

Bending Long Direction
75 Hz

Torsion
103 Hz

Figure 20. T-0 Umbilical Carrier Plate Mode Shapes (1st and 2nd Mode)

NESC Request No. 05-012-E
In-plane Shear
156 Hz

Complex Mode
169 Hz

Figure 21. T-0 Umbilical Carrier Plate Mode Shapes (3rd and 4th Mode)

Table 4. T-0 Umbilical Carrier Plate Modal Frequencies

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<td>11</td>
<td>362</td>
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<tr>
<td>12</td>
<td>415</td>
</tr>
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</table>

3.10 T-0 Umbilical Carrier Plate Displacement (Launch Boundary Conditions)

The LH2 T-0 Umbilical Carrier Plate 3-sigma out-of-plane displacements were calculated using the first twelve modes. The deflection shape is shown in Figure 22. This figure shows that the maximum deflections occur at the electrical connector locations. A bar graph showing the 3-sigma out-of-plane maximum displacement at electric connector plus the shear pin locations is
shown in Figure 23. The maximum 3-sigma out-of-plane displacement for all the electrical connectors is 0.045 inches and occurs at connector J61, which is one of the three critical connectors. The out-of-plane displacement at the shear pins is approximately the same value as the electrical connectors.

Figure 22. T-0 Umbilical Carrier Plate 3σ Displacement Shape

Figure 23. T-0 Umbilical Carrier Plate 3σ Connector Displacement
3.11 Sensitivity Studies

Three dynamic sensitivity studies were performed on the T-0 Umbilical Carrier Plate. The first sensitive case was to study the effect of the number of modes included in the FE model dynamic deflection calculation. The second sensitivity case was to study the effect of different fluid and electrically line weights. The last sensitivity case was to study the effect of the fluid line stiffness.

3.11.1 Number of Modes Sensitivity (Sensitivity Study #1)

The LH$_2$ T-0 Umbilical Carrier Plate 3-sigma out-of-plane displacements for the baseline case were calculated using the first twelve modes (green bars shown in Figure 24). Note that the displacement magnitudes of the green bars in Figure 23 are the same as those of the green bars in Figure 24. The red bar in Figure 24 is the 3-sigma out-of-plane displacement with only the first mode (bending in the long direction at 75 Hz) included in the FE model calculation. From this figure it can be seen that all of the out-of-plane deflections are produced by the first mode.

![Figure 24. T-0 Umbilical Carrier Plate Sensitivity Study #1](image)

3.11.2 Fluid and Line Weight Sensitivity (Sensitivity Study #2)

The portion of the fluid and electrical line weight that would be effectively supported by the LH$_2$ T-0 Umbilical Carrier Plate was estimated therefore, a sensitivity study of this estimated effective line weight was performed. Again, the LH$_2$ T-0 Umbilical Carrier Plate 3-sigma out-of-plane displacements for the baseline case are shown as green bars in Figure 25. For the baseline...
case, the total weight of the plate, connectors, and the estimated portion of the line weights was 1,700 pounds. For this sensitivity study, an extra 500 pounds of weight was added to the line weights to give a total weight of 2,230 pounds. The 3-sigma out-of-plane displacements with the modified weight of 2,230 pounds are shown as red bars in Figure 25. The difference in displacement between the two weight cases is only 0.005 inches. On top of the fact that the 0.005 inches is a small amount out of the 0.250 inches allowable, the modal testing of the LH₂ T-0 Umbilical Carrier Plate in the partially retracted state indicates that the baseline line weight estimate was good since the frequencies between modal test and FE model match.

![Figure 25. LH₂ Umbilical Carrier Plate Sensitivity Study #2](image)

3.11.3 Effect of Fluid Line Stiffness and Spring Stiffness (Sensitivity Study #3)

The LH₂ fluid fill line stiffness and the electrical connector spring stiffness are not included in the FE model based on an engineering decision to be conservative. Again the weights of fluid and connector springs are included in the model. The stiffness of the LH₂ fluid fill line is low due to the fact that at T-0 the fill line has no pressure and the fill line is made of a hose type construction. The LH₂ fluid fill line without pressure has intermittent supports since it does not have enough stiffness to support its own weight.

The reason that not including the LH₂ fluid fill line and connector spring stiffness in the FE model is conservative is because as the plate deflects, the fluid line and connector spring stiffness will resist the motion. The LH₂ fluid fill line will be dragging across the intermediate supports resisting the motion. The electrical connector spring force will also act in such a way as to reduce the relative deflection between the GSE plate and the Orbiter panel. The springs would produce
an increase in resisting force over the static force as the GSE plate and Orbiter panel came together. The reverse effect would occur as the GSE plate and Orbiter panel move away from each other. During separation, the spring force decreases compared to the static force. Both of these effects would result in less relative deflection if included in the FE model.

Furthermore the effect of the LH2 fluid fill line stiffness as it affects the acceleration load from the PSD was also explored. Including the LH2 fluid fill line stiffness would result in an increase in frequency for the 1st mode. As stated previously, the frequency of the 1st mode with launch boundary conditions was 75 Hz. Reviewing the PSD again, as shown on the left side of Figure 26, an increase in frequency from the 75 Hz would result in an increase in the acceleration. In order to band the effect of frequency change on the out-of-plane displacement of the plate, an artificial PSD was created as shown on the right of Figure 26. This PSD was a flat PSD at the actual PSD maximum magnitude. The FE model was then used to calculate the LH2 T-0 Umbilical Carrier Plate 3-sigma out-of-plane displacements with this artificially high and flat PSD. The 3-sigma displacement results comparison is contained in Figure 27. The displacement with the artificially high PSD increases the displacement by only .005 inches. This is a small amount out of the allowable .250 inches. Also remember that if the fluid line and spring stiffness were included, the total effect of the increase in resisting force and frequency would be a reduction in the displacement. In conclusion, the connector spring and fluid line stiffness were not included in the FE model so that the FE results would be conservative.

**Actual PSD**  
MF 0004-014 Table 3.2.2.2d-1  

**Artificially Flat PSD**

![Figure 26. T-0 Umbilical Carrier Plate Sensitivity Study #3 Artificial Flat PSD](image-url)
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson
Page 29 of 29
8/22/2005

4.0 Comparison of LH₂ and LOX T-0 Umbilical Carrier Plates

The LOX T-0 Umbilical Carrier Plate has the same global dimensions as the LH₂ T-0 Umbilical Carrier Plate. Both LOX and LH₂ carrier plates are made out of the same material. The main difference between these two plates is that the LOX plate has three extra medium size fluid hoses located at the bottom of the plate near its feet. Frequency comparison from modal testing the LH₂ T-0 Umbilical Carrier Plate versus the LOX T-0 Umbilical Carrier Plate is shown in Table 5.

Table 5. Modal Test Frequency Comparison LH₂ Plate vs. LOX Plate

<table>
<thead>
<tr>
<th>Mode Shape</th>
<th>LH₂ Retracted Frequency (Hz)</th>
<th>LOX Retracted Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torsion</td>
<td>116</td>
<td>109</td>
</tr>
<tr>
<td>Bending</td>
<td>113</td>
<td>125</td>
</tr>
</tbody>
</table>

The frequencies from the two plates are similar, with the LOX plate having slightly lower frequencies, most likely due to the weight of the aforementioned three extra fluid lines. Because the extra weight in the LOX plate is located at the bottom of the plate near the feet, its effect on the out-of-plane deflection of the electrical connectors locations should be relatively small. Furthermore, sensitivity study #2 showed only a 0.005 inches increase in deflection due to an extra 500 pounds of weight. The bending stiffness of the plates is governed by the ribbed portions rather than by the webbed portions. Differences between the two plates in their webbed portions due to cut-outs for fluid lines should not cause significant differences in their bending stiffness. For these reasons, the dynamic out-of-plane deflection of the LOX T-0 Umbilical Carrier Plate is expected to be similar to that of the LH₂ T-0 Umbilical Carrier Plate.
5.0 Orbiter LH\textsubscript{2} T-0 Umbilical Panel Finite Element Model

The Space Shuttle Orbiter LH\textsubscript{2} T-0 Umbilical Panel is a trapezoidal shaped panel located on the port (left) side of the orbiter aft fuselage (see Figure 28). As viewed from the orbiter exterior (see Figure 29), the panel contains connectors for attaching fluid and electrical umbilical lines. The largest connector, located on the forward portion of the panel, is the connector for the LH\textsubscript{2} fill-and-drain line. The electrical connectors are located above and below the LH\textsubscript{2} fill-and-drain line.

Figure 28. Location of LH\textsubscript{2} T-0 Umbilical Panel on Orbiter

Figure 29. Orbiter LH\textsubscript{2} T-0 Umbilical Panel Exterior
To aid in the identification of the connectors on the orbiter panel, the connector numbering scheme from the Space Shuttle Operation and Maintenance Document VULML001-01 [1] is used in this report. A picture of the panel with connector number labels is shown in Figure 30. The locations of the critical electrical connectors J53, J61, and J71 are also identified in the Figure 30. Table 6 contains a list of the connectors and their functions.

The stiffening ribs on the LH₂ T-0 Umbilical Panel can be seen from the orbiter interior as shown in Figure 31. The panel is bolted to the orbiter structural frame along its four edges, as well as along a vertical beam located just aft of the LH₂ fill-and-drain line. Fluid lines and electrical wire bundles emanate from the connectors on the panel. Also evident from Figure 31 is that many of the connectors are capped and not used.

In Figure 32, an interior view of the Orbiter LO₂ T-0 Umbilical Panel is shown. The main difference between the LO₂ and LH₂ panels is the existence of three medium sized lines at the aft region of the LO₂ panel. The forward regions of the two panels, where the electrical connectors are located, are very similar. Both panels also have vertical beams located in the panel’s middle region. Due to their structural similarities at the forward region, the out-of-plane displacements of the electrical connector location of both panels are expected to be comparable.
Figure 31. Orbiter LH₂ T-0 Umbilical Panel Interior

Figure 32. Orbiter LO₂ T-0 Umbilical Panel Interior
## Table 6. Connector Description

<table>
<thead>
<tr>
<th>Index Number</th>
<th>Type</th>
<th>Reference Designator</th>
<th>Function</th>
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<tbody>
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<td>Fluid</td>
<td>S0517P0P7</td>
<td>LH2 fill &amp; drain</td>
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<td>EPDC, C&amp;W systems</td>
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* Numbering scheme is obtained from VUM100.001 [1], page 1-6, figure 1-3. Refer to Figure 30 in this report for connector locations.

NESC Request No. 05-012-E
The Orbiter LH₂ T-0 Umbilical Panel finite element model, shown in Figure 33, is a linear elastic ANSYS model. It includes not only the umbilical panel itself but also portions of the surrounding structure. The model extends from the aft heat shield shell structure aft of the panel to the \( x_c = 1421.000 \) (refer to MD-V70 for orbiter coordinates) vertical frame beam forward of the panel. Included in the model are portions of the orbiter frame beams, skin panels forward and aft of the umbilical panel, and the LH₂ fill-and-drain disconnect, valve, and line assembly. The attachments for the T-0 Umbilical Carrier Plate, located at the collet assemblies and at aft attachment points, are also included in the model. Various aspects of the model will be discussed in the following sections.

5.1 Element Types

The model uses six different types of elements as listed in Table 7. As shown in Figure 33, the umbilical panel, skin panels, and the LH₂ fill-and-drain disconnect are represented by shell elements. Beam elements are used for the orbiter frame beams, and pipe elements for the LH₂ fill-and-drain valve body.

The masses of the LH₂ fill-and-drain line and those of other lines and connectors are represented by mass elements as shown in Figure 34. A mass element located above the valve body pipe elements represents the mass of the valve actuator. The total mass of the valve assembly is assumed to be evenly distributed between the valve body and the valve actuator. Three spring elements connect the node at the most inboard end of valve body pipe elements to a coincident node. The spring elements represent the relative translational stiffness of the LH₂ fill-and-drain
line. The estimated stiffness of the line is described in detail in section 5.5.1. Finally, rigid elements are used to connect the umbilical panel to the aft skin panel because the two panels do not share an edge at their mutual boundary.

Figure 34. Mass, Spring, and Rigid Elements

The ANSYS SHELL181 element is a 4-node quadrilateral shell element incorporating first-order transverse shear deformation (Mindlin-Reissner) theory. The full integration with incompatible modes option is used for these shell elements in the FEM. These elements allow for layered sections, whose use in the model is described in sections 5.5.2 and 5.5.3.

The ANSYS BEAM188 element is a 2-node beam element. As used in the model, the beam elements include warping degree of freedom. The FEM uses the beam’s first-order transverse shear deformation (Timoshenko) theory option. The actual geometric cross-sections of the beams, along with the appropriate nodal offsets, are used in the model.

Table 7. Element Type List

<table>
<thead>
<tr>
<th>Element Type</th>
<th>ANSYS Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell</td>
<td>SHELL181</td>
<td>4-node Mindlin-Reissner shell element</td>
</tr>
<tr>
<td>Beam</td>
<td>BEAM188</td>
<td>2-node Timoshenko beam element with warping degree of freedom</td>
</tr>
<tr>
<td>Pipe</td>
<td>PIPE16</td>
<td>2-node Euler-Bernoulli beam element with circular cross-section</td>
</tr>
<tr>
<td>Mass</td>
<td>MASS21</td>
<td>1-node concentrated mass element with translational inertia only</td>
</tr>
<tr>
<td>Spring</td>
<td>COMBIN14</td>
<td>2-node translational spring element</td>
</tr>
<tr>
<td>Rigid</td>
<td>MPC181</td>
<td>2-node rigid beam element</td>
</tr>
</tbody>
</table>

NESC Request No. 05-012-E
5.2 Material Properties

As shown in Figure 35, the major structural components included in the FEM are made of aluminum alloys. The elastic material properties of the aluminum alloys are listed in Table 8. All properties are obtained from Rocketdyne's material properties database accessed through the MVISION computer program. Since the temperature of the panel at the time of Main Engine Ignition is expected to be near room temperature, the values of the material properties are evaluated at 70 °F. MVISION printouts of the material properties are included in Appendix A.

![Figure 35. Materials in Finite Element Model](image)

### Table 8. Material Properties List

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Property</th>
<th>Value (70 °F)</th>
<th>Source</th>
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<td>Elastic Modulus</td>
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<td></td>
<td>Poisson’s Ratio</td>
<td>0.33</td>
<td>MPM 3203.01.01.01-02</td>
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<td></td>
<td>Density</td>
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<td>MPM 3203.01.01.01-02</td>
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<td>2024-T62</td>
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<td>MPM 3202.21.10.01.01B</td>
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<td>Poisson’s Ratio</td>
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<td>MPM 3203.01.01.01-02</td>
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<td>Density</td>
<td>0.1 lbs/in^3</td>
<td>MPM 3202.01.01.01-02</td>
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<tr>
<td>2219-T852</td>
<td>Elastic Modulus</td>
<td>19.65 x 10^6 psi</td>
<td>MPM 3215.21.10.01.01</td>
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<td>Poisson’s Ratio</td>
<td>0.325</td>
<td>MPM 3215.01.01.01-02</td>
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<td></td>
<td>Density</td>
<td>0.103 lbs/in^3</td>
<td>MPM 3215.01.01.01-02</td>
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<tr>
<td>Inconel 718*</td>
<td>Elastic Modulus</td>
<td>29.6 x 10^6 psi</td>
<td>718.ALL,ALL,EMOD,MPM,JUN77,TYP</td>
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</tbody>
</table>

*Inconel 718 is used for fill-and-drain line stiffness estimation FEM (see section 5.5.1).
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

5.3 Mass Properties

The weight of the Orbiter LH2 T-0 Umbilical Panel is estimated as 82.5 pounds based on a CAD model supplied by Boeing Huntington Beach. The estimated weights of the connectors and lines, as shown in Table 9, are based on the appropriate disconnect specifications and line drawings. The weights of the electrical connectors and lines, as well as those of the unused fluid lines, are assumed to be 1 pound. The weights are converted into masses for use in the FEM. As discussed later in section 5.8, these baseline mass estimates are used in the FEM baseline case. The masses of the connectors and lines used in the FEM are varied from their baseline estimates for the sensitivity cases.

Table 9. Connector and Line Weight Estimates

<table>
<thead>
<tr>
<th>Index Number*</th>
<th>Installation Drawing</th>
<th>Disconnect Specification</th>
<th>Line Drawing</th>
<th>Estimated Weight (lbs)</th>
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<tr>
<td>1</td>
<td>V070-415704-008</td>
<td>MC276-0005-0041</td>
<td>MC276-0006-0021</td>
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<td>9</td>
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</table>

* Numbering scheme is obtained from VUML00-001 [1], page 1-6, figure 1-3. Refer to Figure 30 in this report for connector locations.
5.4 Boundary Conditions

The in-plane boundary conditions used in the FEM are illustrated in Figure 36, while the out-of-plane boundary conditions are shown in Figure 37. Since the orbiter skin panels extend beyond the upper, lower, and forward boundaries of the FEM, the FEM is restrained along these edges in the in-plane translational direction that is normal to the respective edge. No in-plane restraint is applied at the aft edge of the FEM since there is no structure further aft of the edge.

However, the aft edge of the FEM is restrained in the out-of-plane translational direction due to the presence of the aft heat shield shell structure. The shell structure is oriented perpendicular to the aft skin panel along the skin panel’s aft edge. The rotations about the local x-axis at the upper aft and lower aft corners are also restrained because of the aft shell structure’s presence. A short portion of the upper edge at the FEM’s upper aft corner is restrained in the out-of-plane translational direction. A longitudinal fitting at this location limits out-of-plane motions.

The four corners of the umbilical panel, along the upper and lower ends of the mid-panel frame beam (located just aft of the LH2 fill-and-drain line), are restrained in the out-of-plane translational direction due to orbiter frame beams that pass through these locations and continue beyond the upper and lower boundaries of the FEM. Orbiter frame beams that continue beyond the upper, lower, and forward boundaries of the FEM at the upper forward and lower forward corners of the FEM limit out-of-plane motions these locations. Consequently, both the out-of-plane translation and the rotation about the local x-axis at these locations are restrained.

In-of-plane restraints are set along edges where skin panels continue beyond the boundaries of the FEM.

Figure 36. In-Plane Boundary Conditions
5.5 Special Features

The Orbiter LH₂ T-0 Umbilical Panel finite element model includes several special features that are discussed in the following sections.

5.5.1 Estimate of LH₂ Fill-and-Drain Line Stiffness

Out-of-plane restraints are set at locations where frame structures continue beyond the boundaries of the FEM.

Figure 37. Out-of-Plane Boundary Conditions

Figure 38. FEM Used in Estimating LH₂ Fill-and-Drain Line Stiffness
The stiffness of the LH\textsubscript{2} fill-and-drain line was estimated using an ANSYS linear elastic finite element model, as shown in Figure 38. The line is modeled using ANSYS PIPE16 elements for the straight sections and PIPE18 elements for the curved sections. Inconel 718 material properties are used for the line in the FEM. The flexibility factors from the ASME NB-3686.2 [3] are used in the curved pipe sections. The inboard end of the fill-and-drain line is restrained in all translational and rotational directions. Unit translations are applied at the outboard end of the line in each direction, in one direction at a time. The resulting reaction forces due to each applied unit translation are used as the baseline stiffness constants of the spring elements in the Orbiter LH\textsubscript{2} T-0 Umbilical Panel FEM (see Figure 34). The spring elements' stiffness constants in the Orbiter Panel FEM are varied from their baseline values for the sensitivity cases, as described in section 5.8.

### 5.5.2 Orthotropic Shell Elements

The orbiter skin panels that are included in the Orbiter Panel FEM contain stiffening ribs, similar to those on the LH\textsubscript{2} T-0 Umbilical Panel. Shell elements, with the actual geometry of the ribs, are used to represent explicitly the ribs on the T-0 Umbilical Panel. However, since such level of detail is not necessary for the skin panels, equivalent orthotropic shell elements are used to represent the combined rib-and-web structure of the skin panels in order to facilitate model construction. The locations of these orthotropic shell elements are shown in Figure 39.

These orthotropic shell elements contain two layers, with the first layer representing the panel web and the second layer the stiffening ribs. The first layer has isotropic material properties, and its thickness is equal to the panel web’s thickness. The thickness of the second layer is equal to the height of the stiffening ribs. The second layer contains orthotropic material properties, in which the reduced elastic modulus value in each direction accounts for the stiffness of the ribs in the corresponding direction. The elastic modulus of the second layer is factored by the ratio of the rib thickness to the rib spacing distance in each of the two principal in-plane directions.

![Orthotropic Shell Elements](image.png)
5.5.3 Connector Region Reinforcements

At connector locations on the panel, there are extra materials providing reinforcement, as seen in the left portion of Figure 40. These reinforcements are represented by thickened shell elements as seen in the center of Figure 40. These thickened elements have two layers. The first layer, representing the panel web, has its thickness equal to the web thickness. The second layer represents the reinforcement. Its thickness is equal to the reinforcement height, and its elastic modulus value is reduced by the ratio of the actual volume reinforcement material to the volume of the second layer. Because of the mass elements located at the connector regions representing the masses of connectors and lines (see Figure 34), the connector regions in the FEM deform excessively if the reinforcement stiffness are not included (see Figure 41). Including the reinforcement stiffness prevents such excessive deformation at the connector regions.

![Figure 40. FEM Representation of Connector Reinforcement Regions](image)

![Figure 41. Effect of Including Connector Region Reinforcement in FEM](image)
5.5.4 Constraint Equations

The Orbiter Panel FEM includes many constraint equations which couple the motions of various nodes. The locations of the constraint equation nodes are shown in Figure 42. There is a set of constraint equations which ties the LH₂ disconnect flange to the corresponding flange on the T-0 Umbilical Panel. Another set of equations ties the LH₂ disconnect shell elements to the LH₂ valve body pipe elements. The mass element representing the LH₂ valve actuator mass (see Figure 34) is also tied to the LH₂ valve body pipe elements using constraint equations. For the above three sets of constraint equations, all translational and rotational degrees-of-freedom (DOF) are coupled.

Since the beam elements used in the FEM include the warping DOF, the warping DOF must be decoupled at nodes where beam elements intersect. Warping, unlike the translations and rotations, is not coupled at beam intersections in which beams connect at sharp angles. In the FEM, two coincident nodes exist at each beam intersection, with one node belonging to each of the intersecting beam elements. The translational and rotational DOF of the two coincident nodes are coupled, while the warping DOF is left uncoupled.

The constraint equations between the orbiter frame beam and the umbilical panel edge, and those between the mid-panel frame beam and umbilical panel ribs, are described in detail in the following sections 5.5.4.1 and 5.5.4.2 respectively.

Figure 42. Constraint Equations in FEM
5.5.4.1 Panel Edge Constraint Equations

The T-0 Umbilical Panel is bolted to the flanges of the orbiter frame beams along strips along the panel’s edges. In the FEM, the beam elements representing the orbiter frame beams are one-dimensional elements and therefore do not actually have flanges. Consequently, the panel may separate from the beam flanges at the bolted joints in the FEM, as shown in the top left portion of Figure 43. Constraint equations, shown in the bottom portion shown in the bottom portion of Figure 43, are used to tie the panel web to the beam flange. The constraint equations couple the out-of-plane translation of the slave nodes on the panel shell elements to the out-of-plane translation and beam-axis rotation of the beam elements. In addition, rotation about the beam axis at the panel shell nodes is coupled to that of the beam element. By using the appropriate constraint equations, the panel remains attached to the beam flange at the bolted joint as shown in the top right portion of Figure 43.

5.5.4.2 Mid-Panel Frame Beam Constraint Equations

The mid-panel frame beam is bolted to a rib on the Umbilical Panel just aft of the LH2 fill-and-drain line, as shown in the left portion of Figure 44. In the FEM, the beam and the rib to which it is attached are combined into a single entity represented by beam elements (see the right portion of Figure 44). This approach is used in the FEM because the beam and rib, when bolted together, will tend to act as a single beam entity.
Since the beam elements do not actually have webs or flanges, constraint equations are used to couple the motions of the beam elements to those of the perpendicular rib shell elements. The appropriate constraint equations for the mid-panel frame beam elements and the rib shell elements are shown in Figure 45. The in-plane translation (in the rib longitudinal direction) of
the rib shell nodes is coupled to the translation in the same direction and rotation about the beam-axis of the beam node. The out-of-plane translation (with respect to the rib) of the rib shell nodes is coupled to the translation in the same direction and rotation about the rib longitudinal axis of the beam node. In addition, all rotations of the rib shell nodes are coupled to those of the beam node. Without the use of the constraint equations, the ribs separate from and slide relative to the beam, as shown in the left portion of Figure 46. However, with the appropriate constraint equations, the ribs remain connected to the beam (see the right portion of Figure 46).

Figure 46. Effect of Constraint Equations at Mid-Panel Frame Beam

5.6 Damping

Based on the results of the T-0 Umbilical Carrier Plate modal test (section 3.7), a damping ratio value of 3.3% is used in the analysis of the Orbiter T-0 Umbilical Panel.

5.7 Applied Dynamic Loads

The load used in the analysis is random base excitation in the out-of-plane direction. The low frequency transient loads are not included in this analysis. The excitation is applied, fully correlated, at all out-of-plane translational restraints shown in Figure 37, including the LH fill-and-drain line and the entire aft edge. The power spectral density (PSD) function of the excitation is obtained from MF0004-014 [4], and a plot of that PSD function is shown in Figure 47. James Lambert, in his presentation to the T-0 Separation Interface Tiger Team on October 26, 2004 [5], identifies this PSD function as the appropriate one to use for the Orbiter T-0 Umbilical Panel. In the same presentation, Mr. Lambert also indicates that this PSD function...
already includes accelerations due to acoustic excitations. Consequently, no acoustic excitation is applied to the FEM.

![Figure 47. Orbiter T-0 Umbilical Panel Random Base Excitation PSD Function](image)

5.8 Baseline Configuration FEM Frequencies and Mode Shapes

Plots of the first four mode shapes for the baseline case are shown in Figure 48 through Figure 51. The contour colors in these plots indicate the relative out-of-plane displacements of the modes.

The first two modes, which are the rocking modes of the LH2 fill-and-drain line, do not contribute significantly to the out-of-plane displacement of the electrical connectors. The third mode, shown in Figure 50, is the full panel bending mode and is the primary contributor to the out-of-plane displacement at the electrical connector locations. The frequency of the third mode for the baseline FEM configuration (114 Hz), is located at the peak value of the base excitation PSD in Figure 47. The fourth mode, shown in Figure 51, has significant out-of-plane displacements at the aft region of the panel, but none at the electrical connector locations.

The higher frequency modes, whose mode shape are not shown in this report, have complex out-of-phase deflections, and are difficult to excite. In addition, the input base excitation values decreases rapidly for frequencies above 200 Hz. Consequently, the higher modes do not contribute significantly to the out-of-plane displacement at the electrical connector locations.
Figure 48. First Mode Shape (56 Hz) - Baseline

Figure 49. Second Mode Shape (62 Hz) - Baseline
Figure 50. Third Mode Shape (114 Hz) - Baseline

Figure 51. Fourth Mode Shape (147 Hz) - Baseline
5.9 Baseline Configuration FEM Displacements

Using the first 15 modes along with the base excitation PSD, the orbiter panel 3-sigma out-of-plane displacements are calculated, as shown in Figure 52. A bar graph showing displacements at electrical connector and shear pin locations is shown in Figure 53. For the baseline case, the maximum out-of-plane displacement on the entire panel occurs at the LH2 fill-and-drain line. The electrical connectors, which are located above and below the LH2 line, have 3-sigma out-of-plane displacements that range from 0.008" to 0.016". The three critical connectors (J53, J61, and J71), being located on the outer rows of electrical connector, have slightly smaller displacements that range from 0.007" to 0.012".

![Baseline Configuration FEM Displacements](image)

Figure 52. Orbiter Panel 3-σ Out-of-Plane Displacement – Baseline
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson
8/22/2005

Figure 53. Orbiter Panel Baseline FEM Electrical Connectors & Shear Fins 3-σ Out-of-Plane Displacement

5.10 Sensitivity Studies

Table 10. Orbiter Panel Finite Element Model Configuration List

<table>
<thead>
<tr>
<th>Configuration</th>
<th>FILL &amp; DRAIN Line Weight Factor</th>
<th>Connectors Weight Factor</th>
<th>Connector Region Stiffness</th>
<th>FILL &amp; DRAIN Line Stiffness Factor</th>
<th>X-rotation Restraints at Panel Corners</th>
<th>Number of Modes</th>
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<tr>
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1. The weight factor applies only to the weight of the L11 fill-and-drain line assembly (121 lbs) in Table 9.
2. The weight factor applies to the all connector weights in Table 9 except for the L11 fill-and-drain disconnect, valve, and line assembly.
3. See section 5.5.3 for the discussion on the incorporation of connector region stiffness in the FEM.
4. See section 5.5.1 for the discussion on the use of spring elements for fill-and-drain line stiffness.
5. See Figure 37 for the locations and the direction of the boundary conditions.

The analysis includes sensitivity studies in which the model's weight, boundary conditions, and the number of modes are varied. A list of the FEM configurations and the parameters used in the sensitivity study are shown in Table 10. Damping ratio of 3.3% is used for all cases.

NESC Request No. 05-012-E
6.10.1 Natural Frequencies

The natural frequencies of the first 15 modes for each of the FEM configurations are listed in Table 11. The natural frequencies of the third mode, which is primary contributor to out-of-plane displacements at the electrical connector locations, range from 109 Hz to 134 Hz. This frequency range resides within the maximum value region of the input base excitation PSD (Figure 47).

<table>
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<tr>
<th>Mode No.</th>
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Modes in shaded cells are not used in subsequent displacement calculations.

5.10.2 Displacement Results

The 3-sigma out-of-plane displacement values at the electrical connectors and shear pins as calculated by the FEM are presented in Figure 54. Color contour plots of the 3-sigma out-of-plane displacements across the entire Orbiter T-0 Umbilical Panel for each of the FEM sensitivity study configurations are shown in Figure 55 through Figure 60.
For case 1, the weight of the connectors (except for the LH₂ fill-and-drain line) is doubled and the LH₂ fill-and-drain line stiffness is halved from their baseline values. These changes caused a minor increase to the displacement of the electrical connectors with respect to the baseline case displacements. However, the maximum displacement on the panel is significantly greater than that of the baseline case. As seen in Figure 55, the location of the maximum displacement on the panel has shifted from the LH₂ line in the baseline case towards the aft panel region. The shift is a result of increased weight of the connectors located in the aft panel region. Since the weight of the LH₂ line, the most massive component located in the forward panel region, did not change from its baseline value, the displacements of the electrical connectors did not change significantly from their baseline values.

Similar to case 1, the weight of the connectors not including the LH₂ line in case 2 is doubled. However, unlike case 1, the LH₂ line stiffness values in case 2 remain at their baseline values. The displacements at the electrical connectors change slightly from the baseline case displacements. The location of the maximum displacement also shifts from the LH₂ in the baseline case to the aft panel region (see Figure 56).

In case 3, the effective weight of the LH₂ fill-and-drain line is set to half of its total weight. All other parameters are set equal to the baseline values. For this case, there is a decrease for the
electrical connector displacements, but an increase for the maximum panel displacement, as compared with the baseline displacements. The reduction in the effective weight of the LH₂ line also shifts the location of the maximum displacement from the LH₂ line to the aft panel region (see Figure 57).

The weights and boundary conditions for case 4 are the same as those of the baseline case. However, only the third mode, the full panel bending mode (see Figure 50), is used in calculating the out-of-plane displacements. The displacements calculated for case 4 (see Figure 58), which only used one mode, are very similar to those calculated for the baseline case, which used the first 15 modes. This result indicates that the full panel bending mode is the only mode which contributes significantly to the out-of-plane displacements of the panel.

For case 5, the rotations about the orbiter longitudinal axis at the four panel corners are restrained. These rotational restraints are in addition to the in-plane and out-of-plane translational restraints that are present in the baseline case (see Figure 36 and Figure 37). In the actual orbiter, the frame beams that continue beyond the upper and lower boundaries of the FEM limit the rotation at the panel corners. With the panel corners' rotations restrained, the out-of-plane displacements for case 6 (see Figure 59) are smaller than those for the baseline case. As expected, the boundary conditions for the baseline case allow for greater out-of-plane displacements than those for case 6.

In case 6, the stiffness provided connector region reinforcements (see section 5.5.3) is not included in the FEM. All other parameters in this case are the same as those in the baseline case. The out-of-plane displacements across the whole panel for case 6 are only slightly greater than those for the baseline case. The excessive local deformations shown in Figure 41, when the stiffness connector region reinforcement is not included in the model, occur only at the higher modes. Since the higher modes do not contribute significantly to the panel's out-of-plane displacements under the applied loading, the calculated displacements are insensitive to the stiffness of connector region reinforcements (see Figure 60).

As seen in Figure 54, if considering only the out-of-plane displacements at the electrical connector and shear pin locations, the values for the baseline case are close to the maximum values for the sensitivity study cases. The values for certain sensitivity study cases are only slightly higher than those of the baseline case. Consequently, the baseline case's out-of-plane displacements at the electrical connector and shear pin location are used in the final calculation of the total relative displacement between the Orbiter T-0 Umbilical Panel and the T-0 Umbilical Carrier Plate.
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Figure 55. Orbiter Panel 3-σ Out-of-Plane Displacement – Case 1

Figure 56. Orbiter Panel 3-σ Out-of-Plane Displacement – Case 2
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson

Figure 57. Orbiter Panel 3-σ Out-of-Plane Displacement – Case 3

Figure 58. Orbiter Panel 3-σ Out-of-Plane Displacement – Case 4
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Figure 59. Orbiter Panel 3-σ Out-of-Plane Displacement – Case 5

Figure 60. Orbiter Panel 3-σ Out-of-Plane Displacement – Case 6
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

6.0 Integrated LH₂ T-0 Umbilical FEM

The stand-alone LH₂ T-0 Umbilical Carrier Plate FEM and the stand-alone Orbiter LH₂ T-0 Umbilical Panel FEM are combined to form an integrated LH₂ T-0 Umbilical FEM, as shown in Figure 61. The Carrier Plate FEM is transformed from its local coordinate system to the global orbiter coordinate system so that it is in the correct position and orientation relative to the Orbiter Panel FEM. As seen in Figure 62, the planes of the Carrier Plate and the Orbiter Panel are parallel to each other. However, the fluid disconnects and electrical connectors that span the Carrier Plate and the Orbiter Panel are not oriented perpendicular to either the Carrier Plate or the Orbiter Panel. As also shown in Figure 62, the attachments for the Carrier Plate feet on the orbiter are located inboard of the Orbiter T-0 Umbilical Panel.
The original boundary conditions of the stand-alone Orbiter Panel FEM, as described in section 5.4, are retained in the Integrated T-0 Umbilical FEM. However, since the carrier plate is attached to the orbiter panel in the integrated FEM, the original boundary conditions of the stand-alone Carrier Plate FEM (see section 3.6) are removed from the integrated FEM. In place of these boundary conditions at the collets, shear pins, and feet, constraint equations are used to tie the Carrier Plate FEM to the Orbiter Panel FEM at the aforementioned locations.

6.1 Collet Connections

Figure 62. Side Views of Integrated T-0 Umbilical FEM

Figure 63. Collet Connection
The collets are restrained in the out-of-plane direction in the stand-alone Carrier Plate FEM, as seen in Figure 16. In the integrated FEM, the collets on the carrier plate are tied to their respective receptacles on the orbiter panel using multi-point constraint equations in the out-of-plane direction, as seen in Figure 63. A single node at the end of each collet is tied to multiple nodes on the orbiter panel that are located within the collet receptacle region.

6.2 Shear Pin Connections

In the stand-alone Carrier Plate FEM, the nodes at the shear pins locations are restrained in the in-plane directions as shown in Figure 16. In the Integrated T-0 Umbilical FEM, the in-plane degrees-of-freedom of these nodes are coupled to those of the corresponding nodes on the Orbiter Panel FEM, as shown in Figure 64.

![Figure 64. Shear Pin Connections](image)

6.3 Feet Connections

The feet on the Carrier Plate latch onto the orbiter panel at two locations shown in Figure 65. The upper foot attaches to a clevis that is bolted onto the aft end of the orbiter aft fuselage frame. The lower foot attaches a horizontal frame beam that runs along the lower edge of the orbiter T-0 umbilical panel. Consequently, both feet attachment locations on orbiter are relatively stiff. In the stand-alone Carrier Plate FEM, the feet are restrained in the out-of-plane and orbiter longitudinal directions (see Figure 16).
Figure 65. Carrier Plate Foot Attachment Locations on Orbiter

In the Integrated T-0 Umbilical FEM, a beam element (BEAM4) is used to represent the upper foot attachment clevis. A detailed shell-element FEM of the clevis (see Figure 66) is used to determine the appropriate stiffness for the clevis beam element in the Integrated T-0 Umbilical FEM. As shown in Figure 67, the clevis beam element is attached to the Orbiter Panel FEM by coupling its forward end node to the upper aft corner node the Orbiter Panel FEM. The aft end node of the clevis beam element is coupled to the corresponding Carrier Plate foot nodes in the out-of-plane and the orbiter longitudinal degrees-of-freedom.

Figure 66. Upper Foot Attachment Clevis FEM
The lower foot of the Carrier Plate attaches to a horizontal frame beam of the orbiter aft fuselage. Since the attachment on the orbiter is integral to the beam frame, stiff beam elements (BEAM4) are used to connect the lower foot with the orbiter frame beam in the Integrated T-0 Umbilical FEM (see Figure 68). The out-of-plane and orbiter longitudinal degrees-of-freedom of the of these connection beam element inboard nodes are coupled to those of the Carrier Plate lower foot nodes.
6.4 Fluid and Electrical Connections

In the stand-alone Carrier Plate FEM and the stand-alone Orbiter Panel FEM, the weights of the connectors (the components which span between the Carrier Plate and Orbiter Panel) are all concentrated on the Carrier Plate. For the Integrated T-0 Umbilical FEM, the weights of these connector components are distributed between the Carrier Plate and Orbiter Panel as shown in Table 12. The stiffness and preload for each line are also listed in Table 12.

Table 12. Integrated FEM Connector Parameters

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1. Numbering scheme is obtained from VUM00-0031 [1], page 1-6, figure 1-3.
2. Refer to Figure 30 in this report for connector locations.
3. Spring weights represent only the active coils.
6.4.1 Fluid Line Connections

In the Integrated T-0 Umbilical FEM, each fluid connection is represented by two mass elements and a single truss (LINK8) element as shown in Figure 69. The two mass elements represent the weights of a fluid connection placed onto the Carrier Plate and Orbiter Panel respectively. For the LH2 fill-and-drain line, 90% of the disconnect weight and a portion of the line weight are placed on the Carrier Plate. The remaining 10% of the disconnect weight is placed on the Orbiter Panel. The weights of the other fluid lines are evenly distributed between the Carrier Plate and the Orbiter Panel. The zero-mass truss element represents the stiffness of the fluid disconnect. The nodes at each end of the truss element are connected to nodes on either the Carrier Plate or the Orbiter Panel with constraint equations.

![Figure 69. Fluid Disconnect FEM Representation](image)

6.4.2 Electrical Line Connections

For the electrical connectors, the weight of the connector sleeve (see Figure 70) and a 4-foot portion of the electrical cable are placed on the Orbiter Panel. The weights of the remaining components, other than the spring, are placed on the Carrier Plate. The weight of the active coils (coils that actually flex) of the spring are placed on elements that span the Carrier Plate and Orbiter Panel.
Since the focus of this analysis is on the electrical connectors, the electrical connections have more detailed representations in the Integrated T-0 Umbilical FEM than those of the fluid connections. Each electrical connector in the Integrated T-0 Umbilical FEM is represented by two mass elements and 20 beam elements (see Figure 71). The two mass elements represent the weights of an electrical connection placed onto the Carrier Plate and Orbiter Panel respectively. The stiffness of the spring and weight of the active spring coils are represented by the 20 beam elements (BEAM44). The axial stiffness of these beam elements is set to a value such that their
combined axial stiffness is equal to that of the spring. Because the connector sleeve can only slide but not rotate relative to the outer sleeve, the bending stiffness of the electrical connector is much greater than its axial stiffness. In the FEM, the bending stiffness of the electrical connector beam elements is set to a value lower than that of the physical connector, but the value is high enough so that the beam bending mode frequencies are above the frequency range of interest. As with the fluid disconnects, the nodes at the ends of the spring beam elements are tied to nodes on either the Carrier Plate or the Orbiter Panel with constraint equations.

6.5 Damping

Based on the results of the T-0 Umbilical Carrier Plate modal test (section 3.7), a damping ratio value of 3.3% is used in the analysis of the Integrated T-0 Umbilical FEM. A sensitivity study of the effect of the local damping value for the electrical connector springs on the dynamic spring forces is presented in Appendix C.

6.6 Applied Dynamic Load

The load used in the analysis is random base excitation in the out-of-plane direction. The excitation is applied to the Orbiter Panel, fully correlated, at all out-of-plane translational restraints shown in Figure 37, including the LH fill-and-drain line and the entire aft edge. The power spectral density (PSD) function of the excitation, shown in Figure 72, is obtained from MF0004-014 [4], but with an update that includes values from 1 Hz to 20 Hz. Details of this update is contained in Brent Mann and Dan Paul's presentation [6] to the Space Shuttle Program Loads Panel on May 11, 2005.

![Updated Orbiter T-0 Umbilical Random Base Excitation PSD Function](image-url)

Figure 72. Updated Orbiter T-0 Umbilical Random Base Excitation PSD Function
6.7 Baseline Configuration FEM Frequencies and Mode Shapes

The first 15 modes of the Integrated T-0 Umbilical FEM are shown in Figure 73 through Figure 87. The contour colors in these plots indicate the relative out-of-plane relative displacements of the modes.

Figure 73. Integrated FEM 1st Mode Shape (56 Hz)
Figure 74. Integrated FEM 2nd Mode Shape (62 Hz)
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Figure 75. Integrated FEM 3rd Mode Shape (65 Hz)
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Figure 76. Integrated FEM 4th Mode Shape (75 Hz)
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Figure 77. Integrated FEM 5th Mode Shape (85 Hz)
Figure 78. Integrated FEM 6th Mode Shape (92 Hz)
Figure 79. Integrated FEM 7th Mode Shape (106 Hz)
Figure 80. Integrated FEM 8th Mode Shape (106 Hz)
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson

Figure 81. Integrated FEM 9th Mode Shape (107 Hz)
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Figure 82. Integrated FEM 10th Mode Shape (123 Hz)
Figure 83. Integrated FEM 11th Mode Shape (127 Hz)
Figure 84. Integrated FEM 12th Mode Shape (130 Hz)
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2005

Figure 85. Integrated FEM 13th Mode Shape (130 Hz)
Figure 86. Integrated FEM 14th Mode Shape (130 Hz)
Figure 87. Integrated FEM 15th Mode Shape (130 Hz)
6.7.1 Modes 1 and 2

The first two modes (Figure 73 and Figure 74) are the rocking modes of the LH₂ fill-and-drain line on the Orbiter Panel. They correspond to the first two modes of the stand-alone Orbiter Panel FEM (see Figure 48 and Figure 49). These two modes do not contribute significantly to the out-of-plane relative displacement of the electrical connectors.

6.7.2 Mode 3

The third mode (Figure 75) of the integrated FEM is the primary bending mode the Carrier Plate. This mode corresponds to the first mode of the stand-alone Carrier Plate FEM (see Figure 20), and is a significant contributor to the out-of-plane relative displacements at the electrical connectors. While the maximum deflection for the Carrier Plate on the stand-alone FEM is located on the upper (near the orbiter tail fin) side, the maximum deflection on the integrated FEM is located on the lower (near the orbiter belly) side.

In the stand-alone FEM, both collets are restrained in the out-of-plane direction. However, the upper (near the orbiter tail fin) side of the Carrier Plate is heavier than the other side, due to the presence of heavier fluid lines. Consequently, the heavier side has a slightly larger deflection in the stand-alone FEM. In the integrated FEM, the collets are attached to the Orbiter Panel. The lower collect attachment point on the Orbiter Panel is more flexible than the upper attachment, as the lower attachment is located in the middle of the skin panel while the upper attachment is located near an orbiter frame beam. Consequently, the maximum deflection of the integrated FEM is located on the upper (near orbiter tail fin) side of the Carrier Plate. Another effect of the more flexible attachments for the Carrier Plate is that the frequency of the Carrier Plate primary bending mode is reduced from 75 Hz in the stand-alone FEM to 65 Hz in the integrated FEM.

6.7.3 Mode 4

In mode 4 (Figure 76), the Carrier Plate exhibits in-plane twisting relative to the Orbiter Panel. Because of most of the motion in this mode is in the in-plane directions, this mode does not contribute significantly to the out-of-plane relative displacement of the electrical connectors.

6.7.4 Mode 5

Mode 5 (Figure 77) is the primary torsion mode of the Carrier Plate. It corresponds to the second mode of the stand-alone Carrier Plate FEM (see Figure 20). Due to its out-of-phase displaced shape, this mode is not easily excited and therefore does not contribute significantly to the out-of-plane relative displacement at the electrical connectors.

6.7.5 Mode 6

In mode 6 (Figure 78), the Carrier Plate slides in the longitudinal in-plane direction relative to the Orbiter Panel. Since the primary motion of this mode is in the in-plane directions, this mode does not contribute significantly to the out-of-plane relative displacement of the electrical connectors.

6.7.6 Mode 7

Mode 7 (Figure 79) exhibits in-plane transverse sliding of the Carrier Plate feet along with a twisting of the Carrier Plate collect region. The Orbiter Panel also exhibits bending in this mode.
However, due to its out-of-phase displaced shape, mode 7 is difficult to excite and does not contribute significantly to the out-of-plane relative displacement at the electrical connectors.

6.7.7 Mode 8
This mode (Figure 80) is the Orbiter Panel primary bending mode. It corresponds to the third mode of the stand-alone Orbiter Panel FEM (see Figure 50), and is also a significant contributor to out-of-plane relative displacements at the electrical connectors. Its frequency of 106 Hz is lower than that of the corresponding stand-alone FEM mode of 114 Hz. The drop in frequency is mainly due to the weight redistribution of the connectors (the components which span between the Carrier Plate and Orbiter Panel), which had previously been placed entirely on the Carrier Plate in the stand-alone FEM, but are distributed between the Carrier Plate and the Orbiter Panel in the integrated FEM.

6.7.8 Mode 9
Mode 9 (Figure 81) is the primary spring mode of the large electrical connector, connector number 36 (see Figure 30 for location). While this mode is not a significant contributor to the out-of-plane relative displacement of connector 36, it has a significant effect on the connector 36’s spring forces, due to closeness of its frequency to the Orbiter Panel primary bending mode frequency.

6.7.9 Mode 10
This mode (Figure 82) is coupled bending mode of the Carrier Plate and the Orbiter Panel about the short transverse axis through the LH2 fill-and-drain line. This mode is difficult to excite due to its out-of-phase displaced shape.

6.7.10 Mode 11
Mode 11 (Figure 83) is the bending of the aft region of the Orbiter Panel. It corresponds to the fourth mode of the stand-alone Orbiter Panel FEM (see Figure 51). Since this mode has very little motion at the locations of the electrical connectors, it is not a significant contributor to their out-of-plane relative displacement.

6.7.11 Mode 12 to 15
These modes (Figure 84 through Figure 87) are the primary spring modes of the small electrical connectors. They do not have a significant effect on either the out-of-plane relative displacement or the spring forces of the electrical connectors.

6.7.12 Modes 16 to 30
A total of 30 modes are used in the analysis of the baseline configuration. These higher modes have complex out-of-phase displaced shapes, and are therefore difficult to excite. Consequently, these modes do not contribute significantly to either the out-of-plane relative displacements or the spring forces of the electrical connectors.
6.8 Sensitivity Study Configurations

The analysis included sensitivity studies in which the weight, fluid and electrical connection properties, preload value, and the input PSD are varied. A list of the FEM configurations and the parameters used in the sensitivity studies are shown in Table 13. Damping ratio of 3.3% is used for all cases.

Table 13. Integrated FEM Sensitivity Study Configuration List

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Orig. 16C</td>
<td>100/0</td>
<td>(2)</td>
<td>Stand-alone Carrier Plate and Orbiter Panel</td>
<td>FEM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
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<td>100/0</td>
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<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>Updt. 16C</td>
<td>100/0</td>
<td>(2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Updt. 16C</td>
<td>50/50</td>
<td>(3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Updt. 16C</td>
<td>50/50</td>
<td>(3)</td>
<td>35</td>
<td>40</td>
<td>60</td>
<td>(1)</td>
<td>1 Elem.</td>
</tr>
<tr>
<td>6</td>
<td>Updt. 16C</td>
<td>50/50</td>
<td>(2)</td>
<td>35</td>
<td>40</td>
<td>60</td>
<td>(1)</td>
<td>1 Elem.</td>
</tr>
<tr>
<td>7</td>
<td>Updt. 16C</td>
<td>50/50</td>
<td>(3)</td>
<td>35</td>
<td>40</td>
<td>60</td>
<td>(3)</td>
<td>1 Elem.</td>
</tr>
<tr>
<td>8</td>
<td>Updt. 16C</td>
<td>(4)</td>
<td>(3)</td>
<td>35</td>
<td>40</td>
<td>60</td>
<td>(3)</td>
<td>1 Elem.</td>
</tr>
<tr>
<td>9</td>
<td>Updt. 16C</td>
<td>(4)</td>
<td>(3)</td>
<td>35</td>
<td>40</td>
<td>60</td>
<td>(3)</td>
<td>20 Elem.</td>
</tr>
<tr>
<td>10</td>
<td>Updt. 16C + 1.5 dB</td>
<td>100/0</td>
<td>(2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Updt. 16C + 1.5 dB</td>
<td>50/50</td>
<td>(3)</td>
<td>35</td>
<td>40</td>
<td>60</td>
<td>(3)</td>
<td>1 Elem.</td>
</tr>
<tr>
<td>12</td>
<td>Updt. 16C + 1.5 dB</td>
<td>(4)</td>
<td>(3)</td>
<td>35</td>
<td>40</td>
<td>60</td>
<td>(3)</td>
<td>20 Elem.</td>
</tr>
</tbody>
</table>

1. All fluid disconnect preload are set to 60 lbs except for disconnect #29, which has 100 lbs preload.
2. Electrical connector weights are as listed in Figure 8.
3. Fluid disconnect weights and preload are as listed in Table 12.
4. Connector weight distributions are as described in Table 12.
5. See Figure 72 for the applied PSD.
7. Case 9 is the baseline configuration.

In addition to the sensitivity studies of the configurations shown in Table 13, the contribution of each mode to the overall electrical connector dynamic relative displacement and spring forces is also investigated. The effect of the connector preload on the static relative displacement is also included in the sensitivity studies. Both the mode contribution and preload studies used the baseline (case 9) FEM configuration.

6.9 Dynamic Relative Displacement and Spring Forces

A color contour plot of the 3-sigma out-of-plane displacement of the baseline (case 9) Integrated FEM is shown in Figure 88. The 3-sigma out-of-plane relative displacement values between the Carrier Plate and the Orbiter Panel at the electrical connector locations as calculated by the Integrated T-0 Umbilical FEM are shown in Figure 89. The 3-sigma electrical connector spring dynamic forces are shown in Figure 90.
**Space Shuttle T-0 Umbilical Dynamic Displacements and Forces**


Approved by: John E. Larson

Page 84 of 84

8/22/2005

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**Figure 88. Integrated FEM 3-σ Out-of-Plane Displacement - Baseline Configuration**
Figure 89. Integrated FEM Electrical Connector 3-σ Out-of-Plane Relative Displacement

As seen in Figure 89, the maximum electrical connector relative displacement value of the Integrated T-0 Umbilical FEM baseline configuration (case 9) is lower than that of the stand-alone Carrier Plate and Orbiter Panel FEM. Based on the results of the sensitivity analysis, the dynamic relative displacement values are insensitive to weight, fluid and electrical connection properties, and preload. As expected, the displacement results for the higher (+1.5 db) PSD input are greater than those for the nominal PSD input.

The connector spring force results are only calculated for the cases which included electrical connections. The frequencies of the connector springs’ primary mode (107 Hz for the large connector, 130 Hz for the small connectors) are within maximum PSD excitation level frequency range, and are near several modes of the primary structure. Consequently, multiple elements are required to adequately capture the local motion of the connector springs. As seen in Figure 90, the two cases with detailed spring representation, case 9 and case 12, have significantly higher spring forces than cases with simple spring representation. The large connector, number 36 (J51), has much greater dynamic spring forces than the small connectors due to it being heavier and its primary spring mode frequency being very close the primary Orbiter Panel bending mode frequency. However, connector 36 (large connector) is powered off prior to SSME start, and the 3-sigma spring forces are all well below the minimum connector spring preload of 40 pounds.
The contribution of each mode to the overall dynamic relative displacement and spring force responses is investigated in the study. As shown in Figure 91, mode 3 (Carrier Plate primary bending mode) and mode 8 (Orbiter Panel primary bending mode) are the main contributors to the dynamic out-of-plane relative displacements of the electrical connectors. This result is consistent with the findings of the sensitivity studies for the stand-alone Carrier Plate FEM (see section 3.11.1) and the stand-alone Orbiter Panel FEM (see section 5.10).

Mode 3 and mode 8 are also the main contributors to the connector spring force responses. However, for connector number 3 (J55) and number 36 (J51), other modes also contribute significantly. As mention previously in section 6.7.8, the primary spring mode of the large connector (mode 9) is a significant contributor to its dynamic spring force response due to its frequency being very near to that of mode 8. Consequently, both modes 8 and 9 are included when calculating the “mode 8” spring forces response for the large connector as shown in Figure 92. Connector 3 (J55) spring force response also has significant contributions from modes other than mode 3 and 8, but its overall response is less than 4 pounds.

The static relative displacements of the electrical connectors due to connector preload are shown in Figure 93. The preload values of the fluid and electrical connectors are shown in Table 12. The static relative displacements due to connector preload are small, less than 0.010 inches.
Figure 91. Mode Contribution to Connector 3-σ Relative Displacement Response

Figure 92. Mode Contribution to Connector 3-σ Spring Force Response
7.0 Conclusion

An integrated finite element model (FEM) was created incorporating both the GSE LH₂ T-0 Umbilical Carrier Plate and the LH₂ T-0 Umbilical Orbiter Panel. Modal testing of both the port and starboard GSE, including the Carrier Plates, helped validate the FEMs. Sensitivity studies showed that the models were insensitive to key modeling assumptions. The dynamic relative displacement between the GSE side (Carrier Plate) and the Orbiter side (Orbiter Panel) and the dynamic spring force for each electrical connector on the LH₂ side are shown in Figure 94. Analysis indicates that similar results would be expected for the LO₂ side.
8.0 References


Appendix A. Modal Test Report

A.1 Objectives and Purpose

The objective of the modal testing conducted on the T-0 umbilical plates was to measure the natural frequencies, mode shapes, and damping of the primary vibration modes.

The purpose for conducting the tests was to validate and update existing finite element models of the plates. The frequency data was used to correct for added mass not included in the model such as lines connectors, and non-structural items. The damping values obtained from the tests were used in the dynamic response analysis.

A.2 Results Summary

Modal tests were performed on three different umbilical plates on Dec. 8, 2004. The test hardware consisted of the spare “Vandenberg” plate, an LH₂ plate, and a LOX plate. The Vandenberg plate was tested in a simulated free condition hanging from an overhead beam, while the LH₂ and LOX plates were tested as mounted in their respective tail service masts (TSM). All test objectives were met and excellent quality data was obtained.

The primary natural frequencies of the Vandenberg plate ranged from 46 Hz to 192 Hz and involved bending and torsion of the plate. Damping calculated from the data was found to range from 0.89% to 2.74%.

The primary natural frequencies of the LH₂ plate ranged from 42 Hz to 203 Hz and also involve bending and torsion of the plate. Damping was calculated ranging from 1.3% to 13.4%.

Natural frequencies were also obtained for plate rigid body motion on flexible supports. Three of these modes were found ranging from 1.75 Hz to 12.5 Hz.
A.3 Instrumentation & Excitation Method

Test equipment consists of a rubber-tipped excitation hammer, accelerometers, signal conditioning electronics, assorted cables, and a portable PC. The rubber-tipped hammer is used to input and measure the force pulse that causes structural response. The hammer, shown in Figure A-3 and Figure A-4, is equipped with 4 different rubber tips and a load cell that senses the instantaneous force applied to the structure being tested. Accelerometers are used to measure structural response and are attached to the test article with a small amount of wax or, in some instances, hot glue. The hammer force and accelerometer time histories pass through signal conditioning equipment prior to being recorded on the portable PC. The PC and signal conditioning equipment are shown in Figure A-2. All equipment is powered by standard 110 volt, AC current, but can be operated for short periods on battery power alone.

![Figure A-2. Test setup - Portable PC and Signal Conditioning Equipment](image-url)
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Page A-3 of 3
8/22/2005

Figure A-3. Excitation Hammer with Rubber Tips

Figure A-4. Excitation Hammer on Back of Plate, Accelerometers on Front
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

A.4 Test Descriptions - LH₂ Plate

A.4.1 LH₂ Plate-Test 1

The test article was the LH₂ plate in a partially deployed condition as mounted on the tail service mast (TSM). Cables were not attached to the top of plate. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-5. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction directly opposite from accelerometer 7 on the side of the plate that faces away from the orbiter. Ten hammer pulses were used for the test. Data was recorded for 0.8 seconds during each pulse with 2048 pts, 0-1000 Hz, with a frequency resolution of 1.25 Hz. The green hammer tip was used for this test.

Predominate response frequencies found during this test were 6 Hz, 55 Hz, 126 Hz, and 190 Hz.
A.4.2 LH₂ Plate-Test 2
The test article was the LH₂ plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-5. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction directly opposite from accelerometer 5 on the side of the plate that faces away from the orbiter. Ten hammer pulses were used for the test. Data was recorded for 1.6 seconds during each pulse with 2048 points, 0-500 Hz, with a frequency resolution of 0.625 Hz. The green hammer tip was used for this test.

Predominant response frequencies found during this test were 6.25, 55, 78, 116, 193 Hz.

A.4.3 LH₂ Plate-Test 3
The test article was the LH₂ plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-5. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction on the orbiter side of the plate in the location of the missing accelerometer 6. This is the side of the plate that faces towards the orbiter. Ten hammer pulses were used for the test. Data was recorded for 1.6 seconds with 2048 points, 0-500 Hz, with a frequency resolution of 0.625 Hz. The green hammer tip was used for this test.

Predominant response frequencies found during this test were 6.25, 55, 78, 116, 193 Hz, and 206 Hz.

A.4.4 LH₂ Plate-Test 4
The test article was the LH₂ plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-5. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction directly opposite from accelerometer position 2 on the side of the plate that faces away from the orbiter. Ten hammer pulses were used for all tests. Data was recorded for 1.6 seconds with 2048 points, 0-500 Hz, with a frequency resolution of 0.625 Hz. The green hammer tip was used for this test.

Predominant response frequencies found during this test were 5.6, 55, 72, 117, 126, 193, and 206 Hz.

A.4.5 LH₂ Plate-Test 5
The test article was the LH₂ plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-5. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.
The hammer pulse was input to the orbiter side of the plate in the z-direction directly between accelerometers 2 and 5. Ten hammer pulses were used for all tests. Data was recorded for 1.6 seconds with 2048 pts, 0-500 Hz, with a frequency resolution of 0.625 Hz. The green hammer tip was used for this test.

Accelerometer 3 was discovered loose at the end of the test.

Predominant response frequencies found during this test were 5.6, 6.25, 71, and 126 Hz.

**A.4.6 LH2 Plate-Test 6**

The test article was the LH2 plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were mounted on the plate at the locations shown in Figure A-6. Accelerometers 2, 3, & 4 were oriented to measure in the y-direction, accelerometer 8 measured x-direction motion and accelerometers 5 & 7 measured z-direction. Accelerometers 2, 3, 4, & 8 were mounted on the edge of the plate. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input at the edge of the plate in the y-direction near accelerometer 5. Ten hammer pulses were used for all tests. Data was recorded for 4.00 seconds with 2048 pts, 0-200 Hz, with a frequency resolution of 0.25 Hz. The green hammer tip was used for this test.

Predominant response frequencies found during this test were 1.75, 6.5, 13.5, 18.8, 55, 78, 94, 117, and 125 Hz.

![Figure A-6. Accelerometer Locations & Measurement Directions for Tests 6-7 (LH2 Plate)](image-url)
A.4.7 LH$_2$ Plate-Test 7

This test was identical to test 6 with the exception that the rubber hammer tip was changed from green to brown for a lower frequency input pulse. The test article was the LH$_2$ plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were wax mounted on the plate at the locations shown in Error! Reference source not found.. Accelerometers 2, 3, & 4 were oriented to measure in the y-direction, accelerometer 8 measured x-direction and accelerometers 5 & 7 measured z-direction. Accelerometers 2, 3, 4, & 8 were mounted on the edge of the plate. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input at the edge of the plate in the y-direction near accelerometer 5. Ten hammer pulses were used for all tests. Data was recorded for 4.0 seconds with 2048 pts, 0-200 Hz, with a frequency resolution of 0.25 Hz. The brown hammer tip was used for this test.

Predominant response frequencies found during this test were 1.75, 6.5, 12, 34.5, 47, 55, 117, and 125 Hz.

A.4.8 LH$_2$ Plate-Test 8

This test used the brown hammer tip for a lower frequency input pulse. The test article was the LH$_2$ plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were wax mounted on the plate at the locations shown in Figure A-7. Accelerometers 2 & 4 were oriented to measure in the y-direction, accelerometer 8 measured x-direction and accelerometers 3, 5, & 7 measured z-direction. Accelerometers 2, 4, & 8 were mounted on the edge of the plate. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input at the bottom edge of the plate in the x-direction between accelerometers 4 & 7. Ten hammer pulses were used for all tests. Data was recorded for 4.0 seconds with 2048 pts, 0-200 Hz, with a frequency resolution of 0.25 Hz.

Predominant response frequencies found during this test were 1.75, 11.5, 18.5, 30, 34.5, 45, 67 and 126 Hz.

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Figure A-7. Accelerometer Locations & Measurement Directions for Test 8 (LH$_2$ Plate)
A.5 Test Descriptions - Vandenberg Plate

A.5.1 Vandenberg Plate - Test 1

The test article was the Vandenberg plate in a free-free state. The plate was hanging from cables attached to top of plate as shown in Figure A-4. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-8. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction directly opposite from accelerometer 4 on the side of the plate that would face away from the orbiter. Ten hammer pulses were used for the test. Data was recorded for 0.8 seconds during each pulse with 2048 pts, 0-1000 Hz, with a frequency resolution of 1.25 Hz. The green hammer tip was used for this test.

Predominate response frequencies found during this test were 46.3 Hz, and 141 Hz.
**A.5.2 Vandenberg Plate - Test 2**

The test article was the Vandenberg plate in a free-free state. The plate was hanging from cables attached to the top of the plate as shown in Figure A-4. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-8. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction directly opposite from accelerometer 6 on the side of the plate that would face away from the orbiter. Ten hammer pulses were used for the test. Data was recorded for 0.8 seconds during each pulse with 2048 points, 0-1000 Hz, with a frequency resolution of 1.25 Hz. The green hammer tip was used for this test.

Predominant response frequencies found during this test were 46, 143, and 179 Hz.

**A.5.3 Vandenberg Plate - Test 3**

The test article was the Vandenberg plate in a free-free state. The plate was hanging from cables attached to the top of the plate as shown in Figure A-4. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-8. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction directly opposite from accelerometer position 2 on the side of the plate that would face away from the orbiter. Ten hammer pulses were used for all tests. Data was recorded for 1.6 seconds with 2048 points, 0-500 Hz, with a frequency resolution of 0.625 Hz. The green hammer tip was used for this test.

Predominant response frequencies found during this test were 23 and 183 Hz.

**A.5.4 Vandenberg Plate - Test 4**

The test article was the Vandenberg plate in a free-free state. The plate was hanging from cables attached to the top of the plate as shown in Figure A-4. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-8. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction directly opposite from accelerometer position 2 on the side of the plate that would face away from the orbiter. Ten hammer pulses were used for all tests. Data was recorded for 1.6 seconds with 2048 points, 0-500 Hz, with a frequency resolution of 0.625 Hz. The green hammer tip was used for this test.

Predominant response frequency found during this test was 46.3 Hz.
A.6 Test Descriptions - LOX Plate

A.6.1 LOX Plate - Test 1

The test article was the LOX plate in a partially deployed condition as mounted on the tail service mast (TSM). Cables were not attached to top of plate. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-9. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

Figure A-9. Accelerometer Locations & Measurement Directions for Tests 1-4 (LOX Plate)

The hammer pulse was input to the plate in the z-direction directly opposite from accelerometer 4 on the side of the plate that faces away from the orbiter. Ten hammer pulses were used for the test. Data was recorded for 1.6 seconds during each pulse with 2048 pts, 0-500 Hz, with a frequency resolution of 0.625 Hz. The green hammer tip was used for this test.

Predominate response frequencies found during this test were 5 Hz, 54 Hz, 121 Hz, and 191 Hz.
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

A.6.2 LOX Plate - Test 2
The test article was the LOX plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-9. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction directly opposite from accelerometer 2 on the side of the plate that faces away from the orbiter. Ten hammer pulses were used for the test. Data was recorded for 1.6 seconds during each pulse with 2048 pts, 0-500 Hz, with a frequency resolution of 0.625 Hz. The green hammer tip was used for this test.

Predominate response frequencies found during this test were 5, 54, 77, 109, and 189 Hz.

A.6.3 LOX Plate - Test 3
The test article was the LOX plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-9. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The hammer pulse was input to the plate in the z-direction on the orbiter side of the plate near the location of accelerometer 8. This is the side of the plate that faces towards the orbiter. Ten hammer pulses were used for the test. Data was recorded for 1.6 seconds with 2048 pts, 0-500 Hz, with a frequency resolution of 0.625 Hz. The green hammer tip was used for this test.

Predominate response frequencies found during this test were 5, 44, 69, 122, and 189 Hz.

A.6.4 LOX Plate - Test 4
The test article was the LOX plate in a partially deployed condition identical to the configuration of Test 1. Accelerometers were wax mounted on the orbiter side of the plate at the locations shown in Figure A-9. All of the accelerometers were oriented to measure in the z-direction. Accelerometer 6 shown in the figure was not installed.

The excitation was supplied by hand pushing on the plate in the z-direction directly opposite from accelerometer position 7 on the side of the plate that faces away from the orbiter. Pushing was done to excite the rigid body modes of the plate. Data was recorded for 16 seconds with 2048 pts, 0-50 Hz, with a frequency resolution of 0.0625 Hz. The hammer was not used for this test.

Predominate response frequencies found during this test were 1.75 and 4.25 Hz.
A.7 Comparing test data with numerical results

The modal assurance criterion (MAC) was used as a measure of correlation between the analytical and measured mode shape vectors. The MAC makes use of the measured mode shapes \( \phi_y \) and the analytical mode shapes \( \phi_y \).

\[
MAC_{ij} = \frac{\phi_y^T(i) \phi_y(i)}{\phi_y^T(j) \phi_y(j)}
\]

There are two measured mode shapes that are being matched with the analytical shapes. X-Modal software was used to identify the measured mode shapes, which occur at 45 and 149.9 Hz

\[
\phi_{y(45Hz)} = \begin{bmatrix} 1.9159E+02 \\ 1.5449E+01 \\ -1.4632E+02 \\ -1.8996E+02 \\ 1.3987E+02 \\ -1.7208E+00 \end{bmatrix}, \quad \text{and} \quad \phi_{y(149.9Hz)} = \begin{bmatrix} 6.5339E+00 \\ -8.3175E+00 \\ 3.6573E+00 \\ -2.2586E+00 \\ 1.4363E+00 \\ -7.3868E+00 \end{bmatrix}
\]

Displacements were taken from the finite element model to determine the mode shapes of interest at 44 and 144 Hz.

\[
\phi_{(44Hz)} = \begin{bmatrix} -0.65043 \\ 0.17526 \\ 1.0155 \\ 0.60913 \\ 0.38780E-02 \end{bmatrix}, \quad \text{and} \quad \phi_{(144Hz)} = \begin{bmatrix} 0.32295 \\ -0.70997 \\ 0.62753 \\ 0.22015 \\ 0.50992 \end{bmatrix}
\]

Using the equation above for the modes listed, the MAC is:

\[
MAC = \begin{bmatrix} 0.8511 & 0.0005 \\ 0.0438 & 0.7325 \end{bmatrix}
\]

A good correlation between analytical and measured mode shapes would show values near 1 on the diagonal of the MAC matrix and near zero on the off diagonals. The analytical and measured mode shapes are thus adequately correlated.

A.8 References


A.9 Modal Test Results – Vandenberg Plate

A.9.1 Vandenberg Plate, Test 1 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2005

A.9.2 Vandenber Plate, Test 1 – Time History Plots
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces


Approved by: John E. Larson

8/22/2005

A.9.3 Vandenberg Plate, Test 2 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

A.9.4 Vandenberg Plate, Test 2 – Time History Plots

The diagrams show the time history plots for various components of movement and force over time. The plots display oscillatory behavior, likely indicating dynamic displacements and forces acting on the umbilical during the test.
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

A.9.5 Vandenberg Plate, Test 3 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson
8/22/2005

A.9.6 Vandenberg Plate, Test 3 – Time History Plots
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2005

A.9.7 Vandenberg Plate, Test 4 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces


Approved by: John E. Larson

A.9.8 Vandenberg Plate, Test 4 – Time History Plots
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson

A.10 Modal Test Results – LH₂ Plate

A.10.1 LH₂ Plate, Test 1 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2005

A.10.2 LH₂ Plate, Test 1 – Time History Plots
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson
8/22/2005

A.10.3 LH₂ Plate, Test 2 – Frequency Response Function
A.10.4 LH₂ Plate, Test 2 – Time History Plots
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2005

A.10.5 LH2 Plate, Test 3 — Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2005

A.10.6 LH$_2$ Plate, Test 3 – Time History Plots
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson  8/22/2005

A.10.7 LH₂ Plate, Test 4 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces


Approved by: John E. Larson

A.10.8 LH₂ Plate, Test 4 – Time History Plots
A.10.9 LH₂ Plate, Test 5 – Frequency Response Function
A.10.10 LH₂ Plate, Test 5 – Time History Plots
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces


Approved by: John E. Larson  8/22/2005

A.10.11 LH₂ Plate, Test 6 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2005

A.10.12 LH2 Plate, Test 6 – Time History Plots
A.10.13 LH₂ Plate, Test 1 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

8/22/2005

A.10.14 LH₂ Plate, Test 7 – Time History Plots
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

A.10.15 LH₂ Plate, Test 8 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John L. Larson
8/22/2005

A.10.16 LH2 Plate, Test 8 – Time History Plots
A.11 Modal Test Results – LOX Plate

A.11.1 LOX Plate, Test 1 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson

A.11.2 LO2 Plate, Test 1 – Time History Plots
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson 8/22/2005

A.11.3 LOX Plate, Test 2 – Frequency Response Function
A.11.4 LOX Plate, Test 2 – Time History Plots

![Time History Plots](image-url)
A.11.5 LOX Plate, Test 3 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson

A.11.6 LOX Plate, Test 3 – Time History Plots
A.11.7 LOX Plate, Test 4 – Frequency Response Function
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2005

A.11.8 LOX Plate, Test 4 – Time History Plots
Appendix B. Material Properties Data

**DATABANK**

/databases/3e/property_database/3e/3e.dbk

**MATERIAL_ID**

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Commmercial or common name
MATERIAL_CLASS: Aluminum Alloys
Major material class
UNS_NUMBER: A92124
UNS Number

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Material form
HEAT_TREAT: All
Heat treat condition, final

**PHYSICAL_PROP**

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Curve name or MPM Page Number
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Type of test
TEST_DATE: 10-30-87
Test date
PROGRAM: Historical
Program for which curve was generated
DISTRIBUTION: User
Database distribution
BORING_SECURITY: BORING PROPRIETARY
Boring security category
DENSITY: 0.1 lbs/in³
Material density at room temperature
SPECIFIC_HEAT: 0.21 Btu/lb°F
Specific heat at room temperature
THERMAL_CONDUCTIVITY: 87.5 Btu/ft/°F
Thermal Conductivity at room temperature

January 5, 2005

1 of 2

NESC Request No. 05-012-E
**Space Shuttle T-0 Umbilical Dynamic Displacements and Forces**


Approved by: John E. Larson

8/22/2005

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January 5, 2005
## Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson
Page 3 of 3
8/22/2005

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Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Elastic Modulus vs. Temperature

Legend

- 3202.21.10.01-01B
- 3202.21.10.01-01B

Plot Set 1

3202.21.10.01-01B

Curve Segment 1

-110 11.95
-200 11.48
-40 11
50 10.75
100 10.57
200 10.13
400 8.96

January 5, 2005
### Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

**Approved by:** John E. Larson  
8/22/2005

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**CURVE SEGMENT 1**

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*January 5, 2005*
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January 5, 2005
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces
Approved by: John E. Larson
8/22/2005

THERMAL_CONDUCTIVITY_2
Thermal Conductivity (BTU/hr-ft²-°F) at different temperatures

PHYS_PROP_COM
Comments on the physical properties listed above

134 (BTU/hr-ft²-°F) for 0 TEMPER AT ROOM TEMPERATURE, 84 (BTU/hr-ft²-°F) for T3, T4, AND T361 TEMPERATURES

EMISSIVITY has range values of 0.035 to 0.07

January 5, 2005
### Space Shuttle T-0 Umbilical Dynamic Displacements and Forces


Approved by: John E. Larson

8/22/2005

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January 5, 2005
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces


Approved by: John E. Larson

January 5, 2005

Elastic Modulus vs. Temperature

Legend

3215.21.01.01-01

PLOT SET 1

3215.21.01.01-01

curve segment 1

-400 12.4
-350 11.6
-300 11.25
-250 11
-200 10.92
-150 10.86
-100 10.8
-50 10.75
0 10.6
50 10.54
100 10.34
150 9.8
200 9.37
300 9.27
400 9.24

January 5, 2005
### Space Shuttle T-0 Umbilical Dynamic Displacements and Forces


Approved by: John E. Larson

8/22/2005

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January 5, 2005
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**Space Shuttle T-0 Umbilical Dynamic Displacements and Forces**

Approved by: John E. Larson  
Page B-12 of 12  
8/22/2005

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**January 5, 2005**
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

EMODULUS/TEMP PEDIGREE DATA

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**Space Shuttle T-0 Umbilical Dynamic Displacements and Forces**


Approved by: John E. Larson

8/22/2005

---

**Elastic Modulus vs. Temperature**

Legend

ELASTIC MODULUS

---

**PLOT SET 1**

ELASTIC MODULUS

CURVE SEGMENT 1

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February 16, 2004
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson
8/22/2005

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/COM FORM= All
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A-286 AMS5731, AMS5734, AMS5737, R90160-014, R90160-047

DENSITY : 0.287 #/in^3

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Space Shuttle T-0 Umbilical Dynamic Displacements and Forces


Approved by: John E. Larson

8/22/2005

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<th>TEMP (Deg F)</th>
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<th>TEMP (Deg F)</th>
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DENSITY = 0.284 #/in^3
**Appendix C. Connector Spring Damping Ratio Sensitivity Study**

The 3.3% damping ratio used in the stand-alone and integrated T-0 Umbilical FEMs is determined from the modal test of the T-0 Carrier Plate (see section 3.7). This damping value is appropriate for global modes, in which there are motions of the primary structures and/or large fluid lines. Because of the concern that this global damping value may be too high for the local electrical connector spring modes, the effect of the local damping ratio of the electrical connector springs on the dynamic spring forces is examined.

### C.1 Local Electrical Connector Spring FEM

Local electrical connector spring FEMs are used in the damping ratio sensitivity study. A picture of the FEM is shown in Error! Reference source not found.. The local FEM consists of 50 LINK8 truss elements. All nodes are restrained in the transverse directions to allow for axial motion only. The two end nodes are also restrained in the axial direction.

**Figure C-1. Electrical Connector Spring Local FEM**

The elastic modulus, cross-sectional area, and density of the truss elements are set to values so that the overall stiffness and weight of the local spring FEM match those values shown below in Table C-1.

**Table C-1. Electrical Connector Spring Properties**

<table>
<thead>
<tr>
<th>Connector Type(^1)</th>
<th>Weight (lbs)(^2)</th>
<th>Stiffness (lb/in)</th>
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<tr>
<td>Small (No. 2-6, 25-34, 37)</td>
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<td>35</td>
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<tr>
<td>Large (No. 36)</td>
<td>0.28</td>
<td>35</td>
</tr>
</tbody>
</table>

1. Numbering scheme is obtained from VUMLOO-001 \([1]\), page 1-6, figure 1-3
2. Spring weights represent only the active coils.

### C.2 Applied Dynamic Loads

The random base excitation loads are applied to the two end nodes of the local spring FEM. The PSD functions are obtained from the response acceleration PSD from the Integrated T-0 Umbilical FEM at the appropriate electrical connector locations. The response PSD of two small connectors with the highest dynamic loads as predicted by the integrated FEM (J55 and J71), along with the large connector (J35), are examined in the study. Enveloping PSD, as shown in Figure C-2 through Figure C-10, are developed from the response PSD and used as excitation. The analysis uses the first five modes of the connector spring and a damping ratio of 1%.
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces


Approved by: John E. Larson

Page C-2 of 2
8/22/2005

Figure C-2. Small Electrical Connector 3 (J55) Carrier Plate Side Response PSD

Figure C-3. Small Electrical Connector 3 (J55) Orbiter Panel Side Response PSD

Figure C-4. Small Electrical Connector 3 (J55) Response Cross-PSD
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Figure C-5. Small Electrical Connector 34 (J71) Carrier Plate Side Response PSD

Figure C-6. Small Electrical Connector 34 (J71) Orbiter Panel Side Response PSD

Figure C-7. Small Electrical Connector 34 (J71) Response Cross-PSD
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

Approved by: John E. Larson

Figure C-8. Large Electrical Connector 36 (J51) Carrier Plate Side Response PSD

Figure C-9. Large Electrical Connector 36 (J51) Orbiter Panel Side Response PSD

Figure C-10. Large Electrical Connector 36 (J51) Response Cross-PSD
Space Shuttle T-0 Umbilical Dynamic Displacements and Forces

C.3 Connector Spring Dynamic Forces

The 3-sigma dynamic forces of the electrical connector spring as predicted by the local spring FEM are shown in Table C-2. The maximum dynamic force for the small connector springs with 1% damping is slightly higher as compared to those predicted by the integrated FEM with 3.3% damping. The large increase in the dynamic force on the large connector from the reduction in damping ratio of 3.3% to 1% is mainly due to the fundamental frequency of the large connector spring being very close to the frequency of the Orbiter Panel primary bending mode. Nevertheless, these dynamic forces are still well below the minimum spring preload of 40 pounds, and the large connector is powered off prior to SSME start.

<table>
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<tr>
<th>Connector</th>
<th>Damping Ratio</th>
<th>3-σ Force (lb) No Cross-PSD</th>
<th>3-σ Force (lb) with Cross-PSD</th>
<th>3-σ Force (lb) Integrated FEM (3.3% damping)</th>
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<td>No. 3 Small (J55)</td>
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<td>No. 34 Small (J71)</td>
<td>1%</td>
<td>3.78</td>
<td>3.82</td>
<td>3.82</td>
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<tr>
<td>No. 36 Large (J51)</td>
<td>1%</td>
<td>18.57</td>
<td>17.06</td>
<td>7.90</td>
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Appendix E. Report Q50299FA, *Connector Failure Analysis*, Goddard Space Flight Center Parts Analysis Laboratory
Intermittent signal loss was detected on a Shuttle umbilical connector. Corrosion was suspected as the root cause. Tape lifts of connector material were taken from pins at both ends of the umbilical and from a control sample. The samples were labeled ‘A’, ‘B’, and ‘C’, and submitted to the NASA GSFC Failure Analysis Laboratory for morphology and elemental analysis.

**Part Description**

The umbilical mates to the Shuttle transportation system and disconnects at time of launch. The de-mated connector then faces upward and is exposed to propulsion blast during vehicle lift-off. Sample A consists of material taken from the blast-exposed end of the connector. Sample C is the protected connector on the other end of the umbilical. Sample B is material taken from a control connector.

**Analysis and Results**

The three samples, A, B, and C—consisting of material on carbon tape, were inspected in the scanning electron microscope (SEM) and photo-documented. Samples A and C consisted largely of crushed material. Sample B consisted of many small fibers and particles, roughly similar in size but dissimilar in appearance. In general, the particles were nonconductive, making high-resolution imaging difficult. Nevertheless, gold sputtering was delayed until after initial EDS analysis had been performed.

Comparative EDS spectra were performed on groups of particles on each sample. The EDS results from sample B indicated particles of varied composition. EDS mapping found that copper, chlorine, and oxygen tracked well in Sample A, and that nickel, chlorine, and oxygen tracked in Sample C. There was also appeared to be some tracking of minor elements, such as calcium and sulfur. Iron was found in small quantities.

Quantitative analysis was performed on samples C and A. The results for C are not given here. It was found that the ratio of copper to chlorine to oxygen in Sample A material was approximately 2.3 : 1.0 : 4.0.

It is noted that the composition of the solid rocket propellant used in the Shuttle SRBs consists of aluminum powder with ammonium perchlorate and a polymeric binder. Iron is used as a catalyst in approximately the same amount as detected here.
Appendix Photographs:

Figure 1. Sample A zoom-out, showing material on carbon tape.

Figure 2. Sample A close-up of material. This image is taken at location 1 of Figure 3.

Figure 3. Sample A material. Yellow letters identify the four sites probed. Spectrum is found in Figure 4.

Figure 4. Sample A. Refer to the locations identified in Figure 3. One probed location seems to be an oddball with dominant aluminum and silicon. The other three locations track together both in appearance and spectra, showing copper, chlorine, oxygen, and calcium.
Figure 5. Sample B zoom-out, showing material on carbon tape.

Figure 6. A close-up SEM view of Sample B shows fibers and particles, some bright and some faint.

Figure 7. Arrows identify locations probed by EDS on Sample B. Yellow tags identify numbering. Site 1 is at lower right, site 5 is at upper left, and numbering follows a ‘z’ pattern. Note the diversity of particle types and fibers.

Figure 8. EDS spectra of the sites shown in Figure 7 indicates a diversity of composition.
### GODDARD SPACE FLIGHT CENTER

**Part Title:** Connector

**Manufacturer:** Unknown

**Part Number:** Unknown

**Lot Code:** Unknown

### Appended Photographs:

**Figure 9.** Sample C zoom-out SEM image.

**Figure 10.** A close-up view of material on Sample C.

**Figure 11.** This SEM image shows five sites probed with EDS. The matching spectra are found in Figure 12.

**Figure 12.** Three of five spectra track together, indicating oxygen, nickel, aluminum, and chlorine. Sulfur and...

---

**NESC Request No. 05-012-E**
Appendix Photographs:

Figure 13. Sample A spectra repeated here for comparison with Figure 14. Caution: keV scale difference.

Figure 14. Sample C spectra, repeated here for comparison to Figure 13. Caution: keV scale difference.

Figure 15. SEM image of Sample A material at 300X. Gold was sputtered in sample preparation but the irregular surface made coating difficult. Some charging is seen.

Figure 16. SEM image of Sample C material at 5000X.
Figure 17. Representative spectra of samples A and C are overlaid in this plate, where red shows material from sample A and blue indicates sample C material. Compare to Figures 13 and 14.
Figures 18. Elemental dot maps for Sample C show that most of the detected elements track together.

- Image at 5000X
- Oxygen
- Aluminum
- Nickel
- Chlorine
- Silicon
- Calcium
- Sulfur
- Iron
Appendix Photographs:

Figures 19. Elemental dot maps for Sample A show that chlorine, copper, and oxygen track together, with possible tracking of silicon, calcium, and sulfur.

- Image at 586X
- Oxygen
- Aluminum

- Nickel
- Chlorine
- Silicon

- Calcium
- Sulfur
- Copper
Quantitative Analysis:
Sample A (sample from blast exposed end)

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<td>Chlorine</td>
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<td>Silicon</td>
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<td>0.61</td>
<td>0.53</td>
<td>0.63</td>
<td>0.57</td>
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</table>

However, the results at Location 1 are noted to not agree well with Locations 2 and 3. And because aluminum would not be found in a pure form, it is assumed that an aluminum oxide exists. Likewise, iron and silicon oxides also probably use some of the oxygen found in the quantitative analysis. It is also noted that the iron exists roughly in the magnitude of the iron used in the propellant as a catalyst.

Thus, the ratio of chlorine to copper to oxygen at Locations 2 and 3 is approximately 2.3:1:4.
Appendix Photographs:

Figure 20. A copy of the NASA website with Shuttle SRB propellant information. The oxidizer is ammonium perchlorate (NH₄ClO₄). The fuel is aluminum powder. Iron is used as a catalyst. A polymer binder makes up the remaining composition.
Appendix F. GSE T-0 Umbilical to SSP Flight Elements Assessment Project Status, 13 Oct 06
GSE T-0 Umbilical to SSP Flight Elements Assessment

Project Status

13 Oct 06

N. Helmold
Code 562, GSFC

NESC Request No. 05-012-E
T-0 Anomaly Review Actions

- The NESC T-0 anomaly assessment results presented to Shuttle Program PRCB and SMARR resulted in several additional actions.
- The NESC assessment team has three activities underway.
  - Integrated plate / connector modeling
    > Improve understanding of T-0 interface
    > Assess potential for connector pin-to-socket motion
  - Connector examination and analysis
    > Examine corrosive products on a used connector assembly
    > Attempt to demonstrate corrosion-induced intermittent contact under controlled conditions
  - Determine probability of quad-redundant circuit failure
Connector Examination and Analysis

- A pre-STS-112 connector and cable assembly was located at KSC and forwarded to GSFC for detailed analysis.
  - Pins were examined for corrosion product.
  - Pin-to-socket wiping action was assessed.
  - Intermittent connections were demonstrated.
  - A corrosion-induced failure mechanism was determined.

- Results of the connector analysis are consistent with earlier failure analyses.
Corrosion Product

- Two regions of corrosion were seen on 19 of the 55 pins.
  - A narrow ring of corrosion, more or less continuous around the pin, averaging 0.5 mm from first point of electrical contact
  - Corrosion patches roughly, but not exactly, 180 degrees apart about half way down the exposed length of the pin
- The corrosion product is electrically insulative and persistent – it is not dislodged when probed.
- Analysis of corrosion product by Scanning Electron Microscope and Energy Dispersive X-Ray Spectroscopy (SEM / EDS) showed copper chlorate and trace amounts of aluminum and iron believed to be from chemical reactions with SRB combustion products.
Corrosion Bands

[Image of corroded component with labels Corrosion Patches and Narrow Corrosion Ring]

13 Oct 06

N. Helmold
Code 562, GSFC

NESC Request No. 05-012-E
Wiping Action

- Of the 19 pins with corrosion, only 10 were electrically connected.
- Continued lack of electrical continuity though the corrosion product after four mate / demate cycles of these 10 pins showed that pin-to-socket mating has limited ability to wipe the connections enough to dislodge the corrosion product.
Intermittent Connections

- Mechanically controlled mate/demate tests on the 10 electrically connected pins resulted in four intermittent opens that were robust enough to survive at least four mate/demate cycles.
Mate/Demate Test: Pin Orientation

Arrows show the two socket receptacle contact orientations checked.

13 Oct 06  

N. Helmold  
Code 562, GSFC

NESC Request No. 05-012-E
Mate/Demate Test: Optically Aligned

Zero Line

13 Oct 06

9

N. Helmold
Code 562, GSFC

NESC Request No. 05-012-E
Mate/Demate Test: Electrical Contact

Contact Region

Zero Line
Contact Line

1.62 mm

13 Oct 06

10

N. Helmold
Code 562, GSFC

NESC Request No. 05-012-E
Mate/Demate Test: Electrical Open

Contact Region
Narrow Corrosion Ring
Contact Region

Zero Line
Contact Line
Open Line

1.62 mm
0.61 mm

13 Oct 06
11

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Code 562, GSFC

NESC Request No. 05-012-E
Mate/Demate Test: Mated

2.23 mm

Contact Region

Corrosion Patches

Contact Region

Zero Line

Contact Line

Open Line

13 Oct 06

12

N. Helmold
Code 562, GSFC
Corrosion Induced Failure Mechanism

- Socket makes contact with pin in two regions 180 degrees apart.
- Fretting from launch vibration eventually wears away the gold plating at these contact points (linear displacement) and near the tip (angular displacement), exposing the underlying copper.
- Following demating, elements in the SRB combustion products (aluminum, iron, ammonia, chlorine, and oxygen) react with the bare copper to form copper chlorate, whose melting point can be as low as 65°C.
- On a subsequent mating, corrosion products lift the socket leaf off the pin resulting in loss of contact area greater in size than the corrosive patch alone – contact regions vary with socket receptacle orientation in its shell, so this is a stochastic event.
# SRB Combustion Products

## SRB Propellant Mixture

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<th>Function</th>
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<tr>
<td>Ammonium Perchlorate ((\text{NH}_4\text{ClO}_4))</td>
<td>Oxidizer</td>
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<tr>
<td>Iron Oxide ((\text{Fe}_2\text{O}_3))</td>
<td>Catalyst</td>
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</tr>
<tr>
<td>Polymer and Curing Agent</td>
<td>Binder</td>
<td>14 %</td>
</tr>
</tbody>
</table>

**SRB Combustion Products**

Aluminum, Ammonium, Iron, Chlorine, and Oxygen

---

13 Oct 06

N. Helmold

Code 562, GSFC

---

NESC Request No. 05-012-E
Exposure to SRB Combustion Products

T-0 Signal Failure Cable Enclosure

13 Oct 06

N. Helmold
Code 562, GSFC
Appendix G. Quad-redundant Failure Analysis

Probability Estimate of Failures Across the T-0 Interface
22 June 2005
K. P. White, Jr.

Conclusion: A probability estimate for loss of fire function across the T-0 interface is fundamentally hostage to assumptions regarding (i) the veracity of the diagnosis of corrosion and/or poor mating of the connectors as the failure mode and (ii) the effectiveness of the measures implemented to eliminate this failure mode. If the engineering judgment regarding the failure mode is correct, and its elimination total, then there is no reason to believe that loss of fire function (or even failure of a single connector) will be observed on any of the remaining shuttle missions, at least by this mode. If the diagnosis is incorrect, or if the measures implemented are ineffective, then there is a finite and nontrivial probability of loss of fire function.

Analysis: Based on the materials I have reviewed, the current best engineering judgment is that the loss of critical signals across the T-0 interface can be attributed to failure of the connectors resulting from corrosion and/or poor mating. For prior flights with dual redundancy, there is one such connector for PIC System A and one for PIC System B. For future flights with quad-redundancy, there will be two such connectors for the PIC System A and two for PIC System B. It is assumed that the failures are independent and identically distributed for all connectors on any given launch.

With these assumptions, the probability of observing x of t connector failures is distributed binomially Pr(x)=bin(t,p), where t is the number of connectors (t=2 for the dual-redundancy and t=4 for quad redundancy) and p is the probability of a single connector failing. Since all t connectors must fail for loss of fire function (for this failure mode) on any launch, the probability of loss of fire function is P_l=Pr(t)=p^t.

The question then is how best to estimate p. There are (at least) four alternative estimates, each based on alternate assumptions regarding the connector failure mode.

Alternative 1: If we assume that the connector failures are independent and identically distributed across all 113 shuttle missions, that with dual redundancy there were 226 independent opportunities to observe a single failure, and that seven independent failures have been observed, then p_est1=7/(2x113)=0.03097 for a single connector failure on any launch. For quad-redundancy, the corresponding probability of loss of fire function therefore is P_l=(7/113)^4=9.2036x10^-7.

NESC Request No. 05-012-E
This appears to be an unlikely estimate, given the time-sequence of connector failures over the entire program history. Specifically, there were no reported or suspected failures for STS-1 through STS-104, seven failures for STS-105 through STS-112 (one failure on each of these launches except STS-109), and no failures on STS-113. Evidence suggests that failures resulting from corrosion or poor mating first occurred on STS-105, that these same conditions persisted through STS-112, and that these conditions were corrected thereafter.

**Alternative 2:** If the judgment based on this evidence is correct, then for the 105 missions (STS-1 through STS-104 plus STS-113) where the couplings have been sound, no individual connectors have failed ($p_{\text{est}}=0$) and $P_l$ is essentially zero. This is the most optimistic, as well as the most likely, estimate, giving full weight to best engineering judgment.

**Alternative 3:** If the judgment is incorrect, however, and the cause of failures beginning on STS-105 persists and will persist into the future, then for the nine missions STS-105 through STS-113, seven failures have been observed, the estimates are $p_{\text{est}}=7/(2x9)=0.38889$ and $P_l=7/(9)^4=0.022872$. This is the most pessimistic estimate.

**Alternative 4:** All else being equal (i.e., disregarding the evidence that corrosion or poor mating is the cause of connector failures), then under the same assumptions as Alternative 3, probability of *not* observing any failure of the dual-redundant STS-113 connectors is $(1-p_{\text{est}})^2=(1-0.38889)^2=0.44437$. If this is taken as the probability that Alternative 3 is correct (as opposed to Alternative 2), then $P_l=0.022872\times0.44437=0.01016$. 

NESC Request No. 05-012-E
Shuttle Ground Support Equipment (GSE) T-0 Umbilical to Space Shuttle Program (SSP) Flight Elements Consultation

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The NASA Engineering and Safety Center (NESC) was tasked with assessing the validity of an alternate opinion that surfaced during the investigation of recurrent failures at the Space Shuttle T-0 umbilical interface. The most visible problem occurred during the Space Transportation System (STS) -112 launch when pyrotechnics used to separate Solid Rocket Booster (SRB) Hold-Down Post (HDP) frangible nuts failed to fire. Subsequent investigations recommended several improvements to the Ground Support Equipment (GSE) and processing changes were implemented, including replacement of ground-half cables and connectors between flights, along with wiring modifications to make critical circuits quad-redundant across the interface. The alternate opinions maintained that insufficient data existed to exonerate the design, that additional data needed to be gathered under launch conditions, and that the interface should be further modified to ensure additional margin existed to preclude failure. The results of the assessment are contained in this report.

GSE; HDP; NESC; SRB; SSP; STS