The final report for the Shuttle Ground Operations Efficiencies/Technologies Study is made up of five volumes.

Volume 1
Executive Summary

Volume 2
Ground Operations Evaluation

Volume 3
Final Presentation Material

Volume 4
Preliminary Issues Database (PIDB)

Volume 5
Technology Information Sheets (TIS)

Volume 1
The Executive Summary volume provides a brief overview of the major elements of the Study, reviews the findings, and reflects the development of the recommendations resulting from the Study.

Volume 2
The Ground Operations Evaluation volume describes the breadth and depth of the various Study elements selected as a result of an operational analysis conducted during the early part of the Study. Analysis techniques used for the evaluation are described in detail. Elements selected for further evaluation are identified; the results of the analysis documented; and a follow-on course of action recommended. The background and rationale for developing recommendations for the current Shuttle or for future programs is presented.

Volume 3
The Final Presentation Material volume contains the most recent version of the charts used in the Final Phase 1 Oral Briefing at KSC on April 6, 1987, and to the STAS (Space Transportation Architecture Study) IPR-5 (Interim Program Review) held at MSFC on April 8, 1987. The KSC, April 6 notation in the title block was used for both packages because the reviews were held so closely together. This volume contains all charts in their final form and any differences from charts presented are minor.

Volume 4
The Preliminary Issues Database (PIDB) was assembled very early in the Study as one of the fundamental tools to be used throughout the Study. Data was acquired from a variety of sources and compiled in such a way that the data could be easily sorted in accordance with a number of different analytical objectives. The system was computerized to significantly expedite sorting and make it more usable. This volume summarizes the information contained in the PIDB and provides the reader with the capability to manually find items of interest. How that information was used in this Study is explained in greater detail in Volumes 2 and 3.

Volume 5
The Technology Information Sheet volume was assembled in database format during Phase 1 of the Study. This document was designed to provide a repository for information pertaining to 144 OMI (Operations and Maintenance Instructions) controlled operations in the OPF, VAB and PAD. It provides a way to accumulate information about required crew sizes, operations task time duration (serial and/or parallel), special GSE required, and identification of a potential application of existing technology -- or the need for the development of a new technology item.
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ACRONYMS AND ABBREVIATIONS
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INET,INST  Idaho National Engineering Laboratory
IOC        Initial Operational Capability
IPR        Interim Problem Report
IPV        Individual Pressure Vessel
IUS        Inertial Upper Stage
JSC        Johnson Space Center
KSC        Kennedy Space Center
KW         Kilowatt
LCA        Launch Control Amplifier
LCC        Life Cycle Cost
LH         Left Hand
LH2,LH2    Liquid Hydrogen
LiSOCL2     Lithium Sulphur Oxygen Chlorine
LO2,LO2     Liquid Oxygen
LPS        Launch Processing System
LRU        Line Replaceable Unit
LSC        Linear Shaped Charge
ME         Main Engine
           Maintenance Expert
MCC        Main Combustion Chamber
MCR        Modification Change Request
MDM        Multiplex/DeMultiplex
MPM        Manipulator Positioning Mechanism
MPS        Main Propulsion System
MSFC       Marshall Space Flight Center
NaS        Sodium Sulphur
NASA       National Aeronautics and Space Administration
NDT        Non-Destructive Test
NiCad      Nickel Cadmium
NiH2        Nickel Hydrogen
NiTi        Nickel-Titanium
Nitinol     Nickel-Titanium-Naval Ordnance Laboratory
NIH        Not Invented Here
NLG        Nose Landing Gear
NSI        NASA Standard Initiator
OMI        Operations and Maintenance Instruction
OMP        Operation Maintenance Plan
OMRSD       Operational Maintenance Requirements and Specifications Document
OMS        Orbital Maneuvering System
OPF        Orbiter Processing Facility
OPS        Operations
OV         Orbiter Vehicle
PAM        Payload Assist Module
PCBS       Printed Circuit Boards
PCR        Payload Changeout Room
PDI        Payload Data Interleaver
PIC        Pyro Initiator Controller
PIDB       Preliminary Issues Database
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1.0 GROUND OPERATIONS EVALUATION

INTRODUCTION

STUDY OBJECTIVES: The overall objectives of this Study are to determine high payoff, innovative methodologies and technologies to reduce the cost of STS ground processing and manpower; and, thereby reduce life cycle costs. These objectives shall be accomplished through an overall analysis of the current shuttle ground operations functions including but not limited to: assembly, test and checkout, logistics, recovery, refurbishment, servicing, payload integration, launch operations, operations management, and ground systems operations and maintenance.

OVERALL STUDY CONCLUSIONS:

SHUTTLE

Analysis of the massive amount of ground processing-related information; and documented information and reports generated after the Challenger (51-L) loss; and management of those activities provided the basis for the conclusions reached during this Study. Those conclusions involve both the Shuttle ground processing operations and the management of those activities. All the reviewed issues and related problems were ultimately determined to be the result of either a "design" or a "management" deficiency.

Management: While it may be beyond the intended scope of this Study, the basic Program problems and the idealized future solution became evident to the Study participants. These conclusions are described graphically in Figures 1 and 2 below.

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Figure 1

Figure 2

-1-

ORIGINAL PAGE IS OF POOR QUALITY
1.0 GROUND OPERATIONS EVALUATION
Continued

Ground Operations: There is no easy answer for streamlining Shuttle ground operations. The Shuttle was not designed for ease of operations -- by limiting front-end design costs, the vehicle turned out to be a proof-of-concept vehicle that is not designed to be operationally efficient. This is a fact that is generally conceded by most everyone today. The realistic, full cost per flight, based on 10 flights per year, is over $246 million in 1985 dollars. It is only by forecasting 24 flights per year that the "full cost per flight" could even approach the advertised $100 million cost figure in 1985 dollars. Since the best flight rate achieved to date (FY-85) was 8 and with a maximum improvement of 10% in ground operations without very major block modifications to the orbiter systems, it is unrealistic to quote a full cost of $100M in 1985 dollars, much less in 1987 dollars.

Analysis shows that major block modifications to make the three Orbiters operationally efficient does not appear to be cost effective. Only those efficiency mods that could be worked in parallel with mandatory safety mods appear practical. Implementation of the IMIS (Integrated Maintenance Information System) portion of the ULCE (Unified Life Cycle Engineering) system could, by simplifying the paperwork processing systems used on Shuttle, potentially reduce life cycle costs on Shuttle by better than 4%. This would, of course, require a significant up-front investment. The investment can be shown to pay for itself in three years at a flight rate of ten flights per year.

Section 1.4 details the analyses and recommendations for Shuttle and they are summarized in Section 1.5.2.

FUTURE PROGRAMS

The operations and management lessons learned from the Shuttle Program, if used in conjunction with technology advances, can significantly reduce the operational portion of life cycle costs for new vehicles. If maximum use is not made of all these lessons and improved technology, program costs will continue to rise -- life cycle costs could prevent this Country from regaining the space leadership it once held.

ULCE/CALS (Unified Life Cycle Engineering/Computer Aided Logistics System): The most important finding of this Study is the requirement for NASA to immediately require some form of the ULCE system to be included along with the new DoD standards for data interchange (MIL-STD-1840A). Individual Centers must not be allowed to develop data formats that are unique. Systems must be developed that will allow full communications with other NASA Centers, Air Force, or Contractors: for example, the "new" Shuttle Processing Data Management System (SPDMS) currently under development at KSC. NASA should insist that it conform to the new standards that have been developed for data interchange. DoD is in the process of funding approximately $685 million (for FY-87, 88, & 89) to research and provide standards for the ULCE/CALS mentioned above. NASA could easily participate in the Standards committees for that development. Full use of ULCE/CALS in future programs can bring about a six percent reduction in total life cycle costs -- a VERY large dollar value ($1.82B for a 100 flight Shuttle Orbiter, for example).
Management Issues: A major issue stressed during the Study was the need to accept new management concepts and practices. The increasing demand by both NASA and DoD to drastically reduce the cost of operations can only be met if the designed and fabricated hardware, as delivered to the operational site, has had supportability and maintainability designed into it from the beginning of the conceptual study development. Advanced management techniques are an essential part of the "new look" required for future vehicles. The use of Design/Build Teams and Build-to-Cost concepts, along with the use of new design tools like ULCE (Unified Life Cycle Engineering) systems, will be required if one is to stay in business. It may require a change in mindset about what constitutes "good management" but cost figures for new programs are getting so huge that inefficiencies, of any nature, can no longer be tolerated. This subject is discussed in more detail in Sect. 1.4.12.

Anomaly Resolution: Full implementation of the automated anomaly resolution capabilities described in Section 1.4.6 could reduce life cycle cost by an additional five percent.

Section 1.4 describes in detail the other recommendations and they are summarized in Section 1.5.1.
1.1 STUDY TOOLS AND EVALUATION PROCESS

The Study Flow Diagram, Figure 1, shows the management scheme used to track progress of various tasks associated with the main thrust of the Study. It shows the data sources inputting to the Study the inter-relationship of various parts of the Study; and Study products.
1.1 STUDY TOOLS AND EVALUATION PROCESS

(Continued)

1.1.1 ENGINEERING TOOLS

Data Processing: In order to survey the very broad scope of the Study and select material for detailed analysis in a very short period of time, it was necessary to provide a comprehensive computer network for the Study personnel. The network shown in Figure 2 allowed us to access NASA and commercial databases; transfer text between work stations; allow personnel to simultaneously work in the same database; and to do presentation quality graphics. The Mac-XL and the Mac-512 provided good graphics capability, while the AT&T 6300+'s with a Xenix operating system provided superior data processing and database management.

STUDY DATA PROCESSING SYSTEM

Figure 2

Preliminary Issues Database (PIDB): is described at length in Section 1.2 and a 600 page printout is included as Volume 4 of this Report. It includes over 2000 different descriptions of issues or data pertinent to the Study.

-5-
Expanded Automation Technology Knowledge Base (XTKB): is the expansion of the Automation Technology Knowledge Base (ATKB) brought to this Study from the OTV Launch Operations Study. It includes some 23000 records of papers and documents related to Study subjects such as automation, expert systems, artificial intelligence, fault detection, safety, etc.

PRACA and OMRSD: arrangements were also made to access the NASA PRACA and OMRSD databases.

Database Relationship: Figure 3 illustrates the relationship of internal and external databases utilized during the Study.

![Diagram of database relationships](image-url)

 STUDY ANALYSIS SUPPORT
 Figure 3

-6-
1.1.2 TECHNICAL SURVEY TRIPS

Four technical survey trips were made in direct support of the Study during Phase 1:

* Boeing Seattle
* Wright-Patterson AFB (WPAFB)
* Rome Air Development Center (RADC)
* Naval Surface Weapon Center (NSWC) (ex NOL)

The survey trip to Boeing Seattle provided us with insight in new management techniques being implemented for the next generation of airplanes where worldwide competition is making the protection of corporate rice bowls suicidal. Section 1.4.12 describes the pertinent management techniques. Technical subjects surveyed during this trip included NDE technology including backscatter X-ray (see Section 1.4.9); integrated fault-tolerant avionics (Section 1.4.6); 767 integrated testing (Section 1.4.6); manipulative robotic systems (led to potential use of Nitinol for ordnance systems (Section 1.4.11); optical sensors and processors (Section 1.4.6).

The trip to WPAFB was a result of an XTKB search which surfaced extensive Air Force activity on ULCE (Unified Life Cycle Engineering). Results of this trip and the additional research done on this and related topics account, in large part, for our conclusions and recommendations in the area of birth-to-death computerized paperwork systems (Section 1.4.12).

The Rome Air Development Center trip provided an update on Air Force research projects of Built-In-Test (BIT) techniques and the status of recommendations to DoD on various aspects of anomaly resolution (fault detection, fault isolation, and fault resolution), see Section 1.4.6.

Our trip to the Naval Surface Weapons Center was for the purpose of investigating feasibility of using Nitinol-type devices as a substitute for certain ordnance devices. Results of this trip were positive and are referenced in Section 1.4.11.
1.2 ISSUES

Issues are items impacting operational areas such as accessibility, cannibalization, or safety which surfaced from our source documentation or operational analysis.

Forty different issue topics were defined at the beginning of the Study and all issue descriptions were placed in one of these categories in the Preliminary Issues Database (Volume 4 of this Study). The number of description entries range from a low of 3 to a high of 750. The number of entries is indicative of the degree of documented attention. Figure 1 lists the 40 different issues used and the number of description entries in the database.

The prime source of issues was documentation resulting from the loss of 51-L. There were also numerous other sources of documented problems independent of 51-L. These sources are listed below in Figure 2 with the associated block of identification numbers in the PIDB, Volume 4.
1.2 ISSUES
(Continued)

Figure 3, PIDB Information Sources provides a quantitative look at source documentation origination.

A complete of the sort capability description of the PIDB is provided in Volume 4.
1.3 STS OPERATIONS ANALYSIS

1.3.1 INTRODUCTION

Objective: The objective of the operations analysis was to first identify current Shuttle operations that historically require excessive time to complete; then to analyze these operations to evaluate suitability as candidates for reduction by applying new technology. The candidates selected have been identified as "tentpoles".

Approach: The entire ground operations spectrum of the current Shuttle system was reviewed to identify operations causing the time between flights. It was immediately apparent that the Orbiter operations was the area of greatest potential reduction in turnaround time. In all flows studied, both the SRB's and the ET was stacked on the MLP; awaiting orbiter mate. Each Orbiter operation was investigated, and timelines evaluated to see if the time required had the potential of reduction through application of technology. Note that the emphasis of this study was on technology in order to avoid duplicating the concentrated effort of the Shuttle Processing Contractor on straightforward flow improvement after the 51-L incident.

There were several prime sources of information was used to make the "tentpole" determinations. These sources were:

1. 160-hour Ground Operations Plan
2. As-Run schedules from previous flows with emphasis on the 51-L (the latest) and 61-B (the shortest) flows.
3. STS-XX OPF flow (a composite flow reflecting the best-to-date performance).
4. OMI's used to perform all operations.
5. Discussions with personnel from NASA, the SPC and Rockwell International.
6. Personal experience of Study participants in Shuttle processing.

Rationalization: The 160-hour turnaround was used as a comparison baseline because it is still the NSTS 07700 design goal for the program. This 160-hr turnaround goal is recognized, at all technical and management levels of the program, as unobtainable (by a factor of several times) with the current hardware. Nevertheless, it provided a stable baseline for the study against which all ground operations growth could be measured. As a reference, the best composite turnaround time is 1040 hours.
High Payoff Technology Potential: Figure 1 depicts the growth of processing time from the original 160-hr design goal to the pre-51-L goal of 680 hours and the pre-51-L capability of 1040 hours which combined the best as-run vehicle times for the OPF, VAB, and PAD. It should be noted that this capability will be significantly impacted by additional safety-related test and inspection requirements resulting from 51-L. High potential payoff examples from the OPF and Pad processing provide a total of 1085 hours of potential serial or parallel time improvement (through the use of technology) to meet the initial design goals.

**SELECTED EXAMPLES:**

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>POTENTIAL PAYOFF</th>
<th>EXCLUDING PAYOFF RETRIBUTION</th>
<th>HOURS (160-HR GOAL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPF</td>
<td>SAME SCHEDULED MAINT.</td>
<td>***</td>
<td>260 - 24 = 236 HRS</td>
</tr>
<tr>
<td></td>
<td>SYSTEM REVERIFICATION</td>
<td></td>
<td>360 - 50 = 310 HRS</td>
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<tr>
<td></td>
<td>PAYLOAD BAY RECONFIGURATION</td>
<td></td>
<td>368 - 32 = 336 HRS</td>
</tr>
<tr>
<td>PAD</td>
<td>HAZARDOUS SERVICING &amp; CO PREPS</td>
<td></td>
<td>212 - 12 = 200 HRS</td>
</tr>
</tbody>
</table>

POTENTIAL PAYOFF: 1085 HRS

**NOTES:**

- EXCLUDING POST 51-L OMNIBUS REVISIONS
- *** INCLUDES BOTH SERIAL AND PARALLEL TIME
- *** MPS/SAME LEAK & FUNCTIONAL TEST 214 HRS
- SAME PUMP R & R / INSPECTION 112 HRS

(PORTIONS IN PARALLEL)

---

**HIGH PAYOFF TECHNOLOGY POTENTIAL**

Figure 1
1.3 STS OPERATIONS ANALYSIS
(Continued)

1.3.2 160-Hour Turnaround vs 51-L As-run

This is a comparison between the 160-hr turnaround and the actual processing schedule for the 51-L mission. This includes both the timelines and functions for processing of the Orbiter from Roll-in at the OPF to Launch.

Level I directed that the Shuttle be designed so that it could be launched within 160 working hours after landing of the previous mission. This would be on a two-shift workday, five-days a week. Level II then divided this 160-hrs into time to be spent in the OPF, VAB, and at the Pad. All designs were to support these requirements, but due to both money and weight constraints, the operation times have been lengthened by several times. Figure 2 is the original Level II Schedule with the time allotted to perform each task. Following are sheets giving the 51-L comparison.

Letters A through W are used for each operation identified on the Level II Schedule. The Title of the block on the original schedule, with time originally allocated is used for the heading. A list of the actual operations, with timelines, will show what was required (by the ORMSD and equipment failure, repair and retest) to process 51-L.

**TURNAROUND TIME (HRS.)**

![Diagram of 160-HR. TIMELINE ALLOCATION (PAYLOAD INSTALLATION AT PAD)](image)

Figure 2
1.3 STS OPERATIONS ANALYSIS
(Continued)

## A. LANDING AREA 1.0 HR

<table>
<thead>
<tr>
<th>WAD</th>
<th>TITLE</th>
<th>HOURS</th>
</tr>
</thead>
<tbody>
<tr>
<td>V5001</td>
<td>SLF OPS/TOW TO OPF*</td>
<td>10.5 hours total</td>
</tr>
<tr>
<td></td>
<td>* Previous mission landed at DFRF and was ferried to KSC.</td>
<td></td>
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</table>

## B. SAFING AND DESERVICING 8.0 HRS

<table>
<thead>
<tr>
<th>WAD</th>
<th>TITLE</th>
<th>HRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>V5001</td>
<td>TOW ORB INTO OPF/JACK &amp; LEVEL/POWER UP PREPS</td>
<td>17.5</td>
</tr>
<tr>
<td>V1184</td>
<td>SAFING PATCHES/LOAD MMU</td>
<td>3.0</td>
</tr>
<tr>
<td>V1091</td>
<td>PRSD CRYO VENT</td>
<td>40.0</td>
</tr>
<tr>
<td>V1158</td>
<td>OMS TRICKLE PURGE &amp; OMS/RCS DESERVICING</td>
<td>96.0</td>
</tr>
<tr>
<td>V5012</td>
<td>NOSE LANDING GEAR THRUSTER REMOVAL</td>
<td>8.0</td>
</tr>
<tr>
<td>V5012</td>
<td>PYRO WIRE HARNESS R&amp;R RESISTANCE CHECK</td>
<td>48.0</td>
</tr>
<tr>
<td>V1078</td>
<td>APU LUBE OIL DESERVICING</td>
<td>24.0</td>
</tr>
<tr>
<td>N/A</td>
<td>MPS/SSME PROCESSING (ENGINE DRYING)</td>
<td>71.0</td>
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<tr>
<td>V1018</td>
<td>WATER SPRAY BOILER DESERVICING</td>
<td>24.0</td>
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<tr>
<td>V1196</td>
<td>APU POST FLIGHT FUEL SYSTEM OPS</td>
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TOTAL 416.5

## C. PAYLOAD REMOVAL PREPS 8.0 HRS

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<tr>
<td>V3512</td>
<td>INSTALL PAYLOAD ACCESS</td>
<td>8.0</td>
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<tr>
<td>V5006</td>
<td>PAYLOAD STRONGBACK INST/OPEN PAYLOAD BAY DOORS</td>
<td>17.0</td>
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</table>

TOTAL 25.0

## D. MISSION UNIQUE PAYLOAD ACCOMMODATION EQUIPMENT REMOVAL/INST. 24.0 HOURS

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<td>N/A</td>
<td>AFT FLIGHT DECK/PAYLOAD BAY DECONFIG/RECONFIG.</td>
<td>240.0</td>
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<tr>
<td>V1175</td>
<td>RMS TURNAROUND VERIF.</td>
<td>16.0</td>
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<td>V5R03</td>
<td>PRSD H2/O2 TANK SET 4 REMOVAL</td>
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<tr>
<td>N/A</td>
<td>PCP/CIU INSTALLATION</td>
<td>48.0</td>
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<tr>
<td>N0533</td>
<td>PCP/CIU CHECKOUT</td>
<td>5.5</td>
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TOTAL 429.5
### 1.3 STS OPERATIONS ANALYSIS
(Continued)

#### R. ORBITER SCHEDULED MAINTENANCE 24.0 HRS

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<tr>
<th>WAD</th>
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<tr>
<td>V6002</td>
<td>ORBITER POST FLIGHT INSPECTION</td>
<td>24.0</td>
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<tr>
<td>V1026</td>
<td>REMOVE WASH &amp; WASTE FUNCTIONAL</td>
<td>16.0</td>
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<td>V5017</td>
<td>DESTOW FCE</td>
<td>16.0</td>
</tr>
<tr>
<td>V1084</td>
<td>CAUTION &amp; WARNING SYS VERIFICATION</td>
<td>8.0</td>
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<tr>
<td>V5056</td>
<td>REMOVE GAS SAMPLE BOTTLES</td>
<td>8.0</td>
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<tr>
<td>V1134</td>
<td>WATER DRAIN (HORIZONTAL POSITION)</td>
<td>8.0</td>
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<td>V1007</td>
<td>PV&amp;D VENT FILTER/INSTL.</td>
<td>104.5</td>
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<td>V1076</td>
<td>WCCS FUNCTIONAL CHECKS</td>
<td>176.0</td>
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<td>V1062</td>
<td>AIR DATA SYSTEM</td>
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<tr>
<td>V1008</td>
<td>MSBLS TESTING</td>
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<tr>
<td>V1200</td>
<td>RECORDER DUMP</td>
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<td>V6005</td>
<td>STARTRACKER CLEAN/INSPECT</td>
<td>8.0</td>
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<tr>
<td>V6018</td>
<td>CABIN AIR/RECIRCULATE MAINTENANCE</td>
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<td>V6012</td>
<td>HYD INSPECTION</td>
<td>16.0</td>
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<tr>
<td>V1217</td>
<td>ECLSS ARPCS FUNCTIONAL TEST</td>
<td>12.0</td>
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<tr>
<td>V1178</td>
<td>KU BAND TURNAROUND C/O</td>
<td>8.0</td>
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<tr>
<td>V1184</td>
<td>LOAD MMU</td>
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<tr>
<td>V1005</td>
<td>VTR C/O</td>
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<td>V1086</td>
<td>MEC PIC TEST</td>
<td>44.0</td>
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<td>V5069</td>
<td>TRANSFER TO AFT 999 JACKS</td>
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<td>V1016</td>
<td>VENT DOOR FUNCTIONAL</td>
<td>11.0</td>
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<td>V1097</td>
<td>ET DOOR FUNCTIONAL/LATCH FOR FLIGHT</td>
<td>8.0</td>
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<td>V5069</td>
<td>TRANSFER TO AFT 570 JACKS</td>
<td>3.0</td>
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<td>V1026</td>
<td>REMOVE WASTE COLLECTION SYSTEM &amp; WASTE FLUSH</td>
<td>24.0</td>
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<td>V1153</td>
<td>APU WATER SERVICING</td>
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<td>V1099</td>
<td>STARTRACKER DOOR FUNCTIONAL</td>
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<td>V1042</td>
<td>SMOKE DETECTION &amp; FIRE SUPPRESSION FUNCTION</td>
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<tr>
<td>V5010</td>
<td>INSTALL B/C/ELBOW CCTV</td>
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<td>V1003</td>
<td>POWER SYSTEM VALIDATION</td>
<td>23.0</td>
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<td>V1180</td>
<td>FRCS FUNCTIONAL C/O (LPS)</td>
<td>14.0</td>
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<td>V1080</td>
<td>MULT CRT DISP SYS C/O (LPS)</td>
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<td>V1098</td>
<td>LANDING GEAR FUNCTIONAL</td>
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<td>V6034</td>
<td>CREW MODULE SEAT FUNCTIONAL</td>
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<td>V1005</td>
<td>CCTV SYSTEM TEST</td>
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<td>V1183</td>
<td>ORBITER ELECTRICAL SYSTEM VALIDATION (LPS)</td>
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<td>APU LUBE OIL SERVICING</td>
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<td>N2 SERVICING</td>
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<td>V9023</td>
<td>CLOSE/OPEN PAYLOAD BAY DOORS</td>
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<td>V1180</td>
<td>AFT OMS/RCS FUNCTIONAL</td>
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<td>V1037</td>
<td>NH3 SYSTEM SERVICING</td>
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<td>V1055</td>
<td>POTABLE WATER SERVICING</td>
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<tr>
<td>V1017</td>
<td>WATER SPRAY BOILER SYSTEM LEAK &amp; FUNCTIONAL</td>
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<tr>
<td>V9002</td>
<td>BRAKE FILL &amp; BLEED</td>
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<tr>
<td>V1048</td>
<td>NOSE WHEEL STEERING</td>
<td>5.0</td>
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<tr>
<td>V1065</td>
<td>BRAKE/ANTI-SKID CONTROL SYSTEM TEST (LPS)</td>
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<td>V1060</td>
<td>AEROSURFACE CHECKOUT</td>
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<td>V6034</td>
<td>GALLEY FUNCTIONAL</td>
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<td>V5050</td>
<td>FLIGHT CREW EQUIPMENT STOWAGE/CEIT/DESTOWAGE</td>
<td>19.0</td>
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<td>TPS</td>
<td>FLIGHT CREW EQUIPMENT INFLIGHT MAINT. WALKDOWN</td>
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<td>V9001</td>
<td>STOW KU BAND ANTENNA</td>
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<td>HYDRAULIC ACCUMULATOR CHECKS</td>
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<td>V1161</td>
<td>ORBITER BUS REDUNDANCY</td>
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TOTAL 1132.5
### F. PROPULSION SYSTEM SCHEDULED MAINTENANCE 24.0 HRS

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<td>HYDRAULIC POWER UP PREPS &amp; POSITION SSME'S</td>
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<tr>
<td>V5043</td>
<td>REMOVE HEAT SHIELDS</td>
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<td>MPS LEAK &amp; FUNCTIONAL</td>
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<td>SSME LEAK &amp; FUNCTIONAL</td>
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<td>NOZZLE WELD INSPECTION (VAB)</td>
<td>* 240.0</td>
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<tr>
<td>V5E06</td>
<td>SSME #1 HIGH PRESSURE FUEL TURBOPUMP R&amp;R</td>
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<td>SSME #2 HIGH PRESSURE FUEL TURBOPUMP R&amp;R (VAB)</td>
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<td>V5E29</td>
<td>SSME #2 GIMBAL BOLT R&amp;R</td>
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<tr>
<td>V5057</td>
<td>DISCONNECT SSME TVC'S/INSTALL STIFF ARMS</td>
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</tr>
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<td>V5005</td>
<td>INSTALL SSME #2</td>
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<td>V1063</td>
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<td>SSME ELECTRICAL INTERFACE VERIFICATION</td>
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<td>REMOVE STIFF ARMS/CONNECT SSME TVC'S</td>
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<td></td>
<td><strong>TOTAL</strong></td>
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* These operations were accomplished in the engine shop in the VAB.
### G. UNSCHEDULED MAINTENANCE & SYSTEM REVERIFICATION 5.0 HRS

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<td>V1053</td>
<td>REMOVE CABIN SENSOR</td>
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<td>V7253</td>
<td>WINDOW POLISHING</td>
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<td>IPR</td>
<td>TANK #1 H2 CRYO CONTROL HEATER TROUBLESHOOTING</td>
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<td>V5R01</td>
<td>FUEL CELL #1 REMOVAL</td>
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<td>IPR</td>
<td>MSBLS TROUBLESHOOTING</td>
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<td>REMOVE MSBLS</td>
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<tr>
<td>V1165</td>
<td>LANDING/BRAKE INSTALLATION</td>
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<td>R&amp;R LAUNCH CONTROL AMPLIFIER</td>
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<td>V5U01</td>
<td>REMOVE APU #3</td>
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<td>V5011</td>
<td>R&amp;R RH OMS POD</td>
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<td>V5079</td>
<td>OMS ENGINE HEAT SHIELD REMOVAL</td>
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<tr>
<td>V1164</td>
<td>ELEVON LOWER COVE SEAL PRESS LEAK RATE</td>
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<td>V5U01</td>
<td>REINSTALL APU #3</td>
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<td>V5016</td>
<td>TRANSFER RIGHHAND OMS POD TO HMF</td>
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<td>PR</td>
<td>R&amp;R HEADS UP DISPLAY UNIT</td>
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<td>AMMONIA TANK PURGE</td>
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<td>V1165</td>
<td>LANDING GEAR BRAKE INSPECTION &amp; BRAKE R&amp;R</td>
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<tr>
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<td>NH3 LEAK &amp; FUNCTIONAL</td>
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<tr>
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<td>RIGHT OMS INTERFACE TEST</td>
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<td>INSTALL NOSE LANDING GEAR TIRES</td>
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<td>AFT OMS/RCS FUNCTIONAL</td>
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<td>PR</td>
<td>INSTALL THRUSTER &amp; RETEST</td>
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<tr>
<td>V1226</td>
<td>OMS POD MATING</td>
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<td>CABIN SENSOR INSTALLATION &amp; RETEST</td>
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<td>IPR</td>
<td>REMOVE BREAK OUT BOXES</td>
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<tr>
<td>PR</td>
<td>LEFT OMS CROSSFEED LINE PROBLEM</td>
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<tr>
<td>V5011</td>
<td>R&amp;R LEFTHAND OMS POD</td>
<td>26.5</td>
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<tr>
<td>V1224</td>
<td>OMS POD ELECTRICAL CONNECT &amp; RETEST</td>
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<td>LEFTHAND OMS CROSSFEED CONNECT</td>
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<tr>
<td>V1161</td>
<td>BUS REDUNDANCY LEFTHAND OMS POD</td>
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**TOTAL** 753.5
1.3 STS OPERATIONS ANALYSIS
(Continued)

H. TPS REFURBISHMENT 40.0 HRS

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<tr>
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<td>V9024</td>
<td>ORBITER TPS MAINTENANCE/OPERATION</td>
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<td>N/A</td>
<td>ORBITER TPS WATERPROOFING</td>
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<td>V9022</td>
<td>ET DOOR CYCLES/TPS OPERATIONS</td>
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<td>V6035</td>
<td>RSI PRE ROLLOUT INSPECTION &amp; UPPER SURFACE WATERPROOFING</td>
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<td>191.0+</td>
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NOTE: The 51-L as-run schedule shows the first three above operations starting as soon as the orbiter is rolled into the OPF, but does not identify how long they continue. The STS-XX schedule allows 60 hrs for both the inspection and maintenance operation and 168 hrs for waterproofing.

I. ORBITER INTEGRATED TEST 10.0 HRS.

NOTE: The requirement for this test has been deleted from the OMRSD.

J. PREPS FOR MATING 10.0 HRS.

<table>
<thead>
<tr>
<th>WAD</th>
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<tr>
<td>V5012</td>
<td>AFT SEP HARNESS/ET UMB GSE &amp; PLUG INSTALLATION</td>
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<tr>
<td>V5012</td>
<td>FWD ET BEARING &amp; YOKE INSTALLATION</td>
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<td>V5012</td>
<td>PRE-OPS SET UP</td>
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<tr>
<td>V5012</td>
<td>POWER DOWN ORDNANCE INSTALLATION</td>
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<td>POWER ON PIC TEST</td>
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<td>PAYLOAD BAY SHARP EDGE INSPECTION</td>
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<td>ORBITER CLOSEOUT</td>
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<td>ORBITER AFT CLOSEOUT</td>
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<td>V6003</td>
<td>PAYLOAD BAY CLOSEOUT/INSPECTION</td>
<td>20.0</td>
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<td>V9021</td>
<td>DEACTIVATE TRICKLE PURGE</td>
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<tr>
<td>V1176</td>
<td>PAYLOAD BAY CLEANING</td>
<td>27.5</td>
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<tr>
<td>V5018</td>
<td>CLOSE PAYLOAD BAY DOORS &amp; REMOVE STRONGBACKS</td>
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<tr>
<td>V9002</td>
<td>HYD OPS/POSITION AEROSURFACES FOR ROLLOUT</td>
<td>4.5</td>
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<tr>
<td>V3555</td>
<td>DISCONNECT ORBITER PURGE AIR</td>
<td>5.0</td>
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<tr>
<td>V3515</td>
<td>REMOVE LH2/LO2 CARRIER PLATES</td>
<td>5.0</td>
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<tr>
<td>V5101</td>
<td>JACKDOWN WEIGH &amp; CG/PREP TO TOW</td>
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<td>TOTAL</td>
<td>359.5</td>
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-17-
### 1.3 STS OPERATIONS ANALYSIS (Continued)

#### K. TOW ORBITER TO VAB  NO TIME ALLOTTED

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<thead>
<tr>
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<td>S0004</td>
<td>ORBITER TOW &amp; MATE</td>
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#### L. TRANSFER AISLE ORBITER PREMATE OPS  5.0 HRS

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#### M. ORBITER MATE AND INTERFACE VERIFICATION  15.0 HRS

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<tr>
<td>S0004</td>
<td>ORBITER TOW &amp; MATE</td>
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<tr>
<td>S0008</td>
<td>SHUTTLE INTERFACE VERIFICATION</td>
<td>36.5</td>
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<tr>
<td>S0020</td>
<td>SRB TESTING</td>
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<tr>
<td></td>
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<td>TOTAL</td>
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#### N. SHUTTLE INTERFACE TEST  19.0 HRS

NOTE: The requirements for this test have been removed from the OMR and is no longer being accomplished.

#### O. MOVE TO PAD  7.0 HRS

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<tr>
<td>A5214</td>
<td>TRANSFER &amp; MATE TO PAD B</td>
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#### P. MLP MATE TO PAD & LAUNCH PAD VALIDATION  3.0 HRS

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<td>S0009</td>
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<td>N/A</td>
<td>POWER UP PREPS</td>
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-18- TOTAL 39.5
### Q. PAYLOAD INSTALLATION IN PCR  13.0 HRS

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<td>WIND DELAY IN INSTALLING CARGO IN PCR</td>
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<td>TDRS PROPELLANT LOAD</td>
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<td>N/A</td>
<td>IUS POWER UP/DOWN TEST</td>
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<td>IUS STANDALONE TEST</td>
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<td><strong>TOTAL</strong></td>
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### R. FUEL CELL DEWAR LOADING  10.0 HRS

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<td><strong>TOTAL</strong></td>
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**NOTE:** The 160-hr Turnaround Schedule has this activity to occur prior to the arrival of the vehicle at the pad. During the 5l-L flow, it was accomplished just prior to hyper load which caused another pad clear in the pad operation.

### S. SHUTTLE LAUNCH READINESS VERIFICATION  6.5 HRS

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<td>S0009</td>
<td>LAUNCH PAD VALIDATION WITH APU HOT FIRE *</td>
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<td><strong>TOTAL</strong></td>
<td><strong>57.5</strong></td>
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* This time includes 4.5 hrs. for emergency power down if the orbiter cooling was lost to the vehicle.
1.3 STS OPERATIONS ANALYSIS
(Continued)

T. PAYLOAD INSTALLATION AND LAUNCH READINESS VERIFICATION
9.0 HRS.

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<td>TERMINAL COUNT DEMONSTRATION TEST</td>
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<tr>
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<td>1ST MOTION CHECKS &amp; SRSS HOLDFIRE CHECKS</td>
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<tr>
<td>N/A</td>
<td>HOT GAS SYSTEM TROUBLESHOOTING</td>
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<td>V1202</td>
<td>HOT GAS POI'S</td>
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<td>AFT CAVITY PURGE</td>
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<td>PR</td>
<td>PDI R&amp;R AND RETEST</td>
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<td>R&amp;R SRB AFT IEA</td>
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<td>R&amp;R HIM 6893</td>
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<td>CHARGE CARGO BATTERIES</td>
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<td>FUEL CELL #1 SERVICING</td>
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TOTAL 273.5

U. CABIN CLOSEOUT 1.0 HR

NOTE: No serial time was allotted during pad operations to close the crew cabin prior to propellant loading.

V. HAZARDOUS SERVICING/SERVICE DISCONNECTS 8.0 HRS

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<td>S0024</td>
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<td>ET BLANKING PLATE REMOVAL</td>
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<td>R&amp;R RJDA #2 &amp; RETEST</td>
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<td>ORBITER AFT CLOSEOUT</td>
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<td>S1005</td>
<td>ET PURGES</td>
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V. HAZARDOUS SERVICING/SERVICE DISCONNECTS (Continued)

The following operations were performed during this block of time but were part of the original timelines.

<table>
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<tr>
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<th>TITLE</th>
<th>HRS</th>
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<td>V1103</td>
<td>EMU INSTALLATION &amp; TEST</td>
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<td>SSME VALVE CYCLES/FRT'S</td>
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TOTAL 543.5

W. LAUNCH FROM STANDBY 2.0 HRS

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<tr>
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</table>

TOTAL 121.5

NOTE: The length of countdown for the 51-L mission was much longer due to several delays caused mainly by weather. The first one was bad visibility at the transatlantic landing site (dust storm in North Africa). Possible adverse weather at the launch site then caused a 24 hour delay, and on the third attempt, high cross winds caused a scrub at T-9 minutes. A normal countdown is now scheduled for 56 hours.
1.3 STS OPERATIONS ANALYSIS
(Continued)

1.3.2 SUMMARY

The following summarizes the results of this timeline analysis. These are:

1. A comparison of the allocated 160-hour timelines (in 24 categories) of the actual time required to complete all the tasks included under each of these categories for the 51-L flow (preceding list).

2. A chart showing the time allotted in the 160-hour Turnaround Ground Operations Plan broken down into serial and parallel operations. (Figure 3)

3. The 51-L As-Run Schedule with tasks included under the different categories of the 160-hour turnaround broken down into serial and parallel operations. (Figure 4)

4. A comparison of the 160-hour timelines vs the 51-L operations, per 160-hour categories, showing both serial and parallel operations. (Figure 5)

The analyses summarized on Figures 3 through 5 served to highlight the operations timeline growth by procedural/hardware areas. This enabled selection of high potential savings areas by OMI.

---

**KEYS**

A. LAUNCH AREA
B. SAFETY & DECONTAMINATION
C. PAYLOAD STAGE SEPARATION
D. HABITAT UNIQUE F/L ADDRESSES, B/BRESS, M/DRS
E. ORBITER SCHEDULED MAINT.
F. PROPULSION SYSTEM MAINT.
G. MAINTENANCE, MAINT., A SYSTEM
H. TSS EQUALIZATION
I. ORBITER INTENTED VIOL.
J. AIDS FOR MAINT.
K. ISS MAINT.
L. TRANSFER ASSOCIATED PREPhase OPERATIONS
M. ORBITER VACUUM & LV PAYLOAD
N. DERMAL DERM. SETUP
O. LOW TO RED. P/T MAINT.
P. HIGH TEMPERATURE MAINT.
Q. CONS. CURRENT DATA REV.
R. L/VEU SERVICES/SUPPORT
S. ENHANCED MAINT.
T. ISS PAYLOAD MAINT.
U. LAUNCH PAYLOAD MAINT.

---

160-HOUR TURNAROUND TIMELINE ALLOCATIONS

*Figure 3*
1.3 STS OPERATIONS ANALYSIS

(Continued)

OF POOR QUALITY

51-L AS-RUN SCHEDULE
MAJOR OPERATIONS ACTIVITY
Figure 4

160-HOUR TURNAROUND vs. 51-L AS-RUN SCHEDULE
MAJOR OPERATIONS ACTIVITY
Figure 5

-23-
This resulted in the identification of seven tentpoles that were candidates for investigation for improvement by applying new technology and five candidates for improvements by incorporating operational efficiencies. When the Preliminary Issues Database was queried and the operational issues matched with the tentpoles, the following new technology candidates evolved:

A. Orbiter systems that could be redesigned to include fault detection and anomaly resolution
B. Window Cavity Conditioning System (WCCS)
C. Window Polishing
D. TPS Inspection
E. Fuel Cell Operations
F. Ordnance
G. The paper system used to control the ground operations

The timeline improvements using existing technology and operational efficiencies evolved the following candidates. Those selected are considered representative and popped out of our analyses eventhough they were not a targeted goal as explained previously.

1. SSME Repair Shop
2. Payload Bay Deconfiguration/Reconfiguration
3. Crew Cabin Air Recirculation System
4. Orbiter Weight & C.G. Determination
5. Payload Bay Cleaning
1.4 TENTPOLE AND RELATED ISSUES ANALYSIS

SUMMARY

The tentpole and related issue analysis uses the Operations Analysis and Preliminary Issues Database to define the selected efficiency/technology study targets. Figure 1 is a "funnel chart" which shows pictorially how the Ground Operations task was managed. The scope of the Study was so broad, and the information available so vast, it was necessary to quickly funnel the information, using computerized methods, into pertinent specific buckets (issues). Simultaneously, the Operations Analysis was conducted using KSC data elements shown in the figure. The resultant high-payoff operations issues were then researched for potential technology to increase efficiencies as shown in Figure 2.

GROUND OPERATIONS TASK MANAGEMENT

Figure 1
TENTPOLE AND RELATED ISSUES ANALYSIS

1.4 (Continued)

OPERATIONS ANALYSIS

Figure 2

EFFICIENCIES/TECHNOLOGIES

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<th>TECHNOLOGY</th>
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Figure 3

51-L OPF PROCESSING
Timelines to Support Identified Tentpoles
Technology & Efficiencies Candidates
TECHNOLOGY AND EFFICIENCY CANDIDATES

The Operations Analysis surfaced five tentpoles (Figure 3) in the area of "timeline improvements"; that is, efficiency items that do not require new technology to implement. Because this type of improvement is being vigorously pursued by NASA and the Shuttle Processing Contractor with literally hundreds of people, we directed our prime study effort to new technology. Nevertheless, we have included several serendipitous items as timeline improvement not related to new technology, but which need an extra push.

The main thrust of our effort centered around tentpole activities that could be made more efficient through the use of new technology. Our Operations Analysis identified seven tentpoles (A - G), Figure 3, which, when matched with related issues, provided promising candidates for technology improvement. Tentpoles A through E occur in the OPF. Tentpole F, Ordnance Operations, occurs in the VAB and at the Pad. Tentpole G, Paperwork & Operational Requirements, occurs throughout the total vehicle processing; in fact, throughout the entire life cycle.

The Tentpole Issue Summary, Figure 4 below, provides a matrix of timeline improvement, tentpoles, and technology application tentpoles versus the major issues, shifts of work, and technician manhours. This provides a quick look at the scope of each tentpole selected for detailed investigation.
TENTPOLES CONSIDERED, BUT NOT INCLUDED IN STUDY

There are four significant tentpoles that are not analyzed in this study. They are SRB Processing, Facilities, Adverse Weather, and Weather Forecasts.

SRB Processing

SRB processing is not addressed because of the intensive effort being expended by others in this arena as a result of the Challenger loss. This has not been a significant on-line tentpole since it is primarily an off-line effort. However, from an efficiency manhour and cost standpoint, there is substantial improvement potential. Nevertheless, an efficiency study of expendable vs recoverable, recoverable refurbishment at KSC, etc. would be a superficial duplication of effort already underway.

Facilities:

While the subject of facilities was not addressed in Phase 1 of the Study, they provide a significant contribution to the "operational" portion of the overall life cycle costs for a program. Facilities are one of the significant "tools" provided to the workforce at the launch site. Initial facility costs may be kept low by modifications to old facilities; however, any inefficiencies forced on the operators is not a "one time thing". It is repetitive in every flow for the entire life of the program so even a relatively small item can become large from an LCC standpoint.

The Shuttle program, for example, has had to modify available facilities at KSC. Only recently has solid rocket booster processing been moved from the VAB so that those hazardous operating conditions do not have to be imposed on other VAB located operations. Many of the Shuttle workers remain in improvised office facilities (boxcars) located a considerable distance from the VAB. Workers located in close proximity to their work stations are happier and more productive than workers that have to "check in" at one location and then go some distance to get to their work station. Facilities involved with the various operations at KSC are widely separated so any joint operations requires that at least management personnel have to travel between facilities.

Operationally efficient facilities, designed to provide the right support capabilities at the right location for the processing crews, must be provided if processing costs are to be lowered.

Adverse Weather

Modifications have already been made at the Launch Pad to minimize effects of adverse weather. Literature searches were made using the XTKB for advances made in weather control (i.e., silver iodide cloud seeding, etc.), but to no avail. Further potential does exist at this time for improvement in the area of facility design for future vehicles. This should be considered in follow-on study effort.
Weather Forecasts

It has been suggested that weather forecasting should be used in the processing scheduling to provide additional efficiency in routine work schedules. No evidence has been found that current weather forecast capability can improve current scheduling techniques. This also applies to capability in the foreseeable future. For example, the schedule of the launch of 51-1 was affected several times due to weather forecasts. The following is a list of schedule changes and the reason for the changes. Each of the weather forecasts is assessed for accuracy:

Tuesday, January 14, 1985  Launch date set for January 25

Wednesday, January 22
At 1330 hrs Launch slipped to January 26 due to dust forecast at the TransAtlantic Landing site. Forecast was accurate.

Saturday, January 25
At 2200 hrs Launch slipped to January 27 due to possible adverse weather at KSC. Forecast was inaccurate because weather at previously scheduled T-0 was excellent.

Monday, January 27
1230 hrs Launch attempt was scrubbed with the count holding at T-9 minutes due to crosswinds at the Secondary Landing Facility being out of launch commit criteria. This condition was not forecasted (inaccurate).

Tuesday, January 28,
1138 hrs 51-1 Launched even though the temperature had been below freezing for several hours and the temperature was in the high thirties at launch. The forecast for that morning was for freezing temperatures, clear skies and light winds. This forecast was accurate.

TENTPOLE ANALYSIS SUMMARY

The Tentpole Analysis Summary, presented below in tabular format, is divided into two parts: Timeline Improvements Summary and Technology Applications.

Timeline Improvements: The Summary presents a brief description of each element evaluated for the Tentpole-Related Issues, Issue Sources, Related Schedule Data, Todays Methods, Timeline Improvements, Operational Evaluation, and Recommendations.

Technology Applications: The Summary presents a brief description of each element evaluated for the Tentpole-Related Issues, Issue Sources, Related Schedule Data, Todays Methods, Technology Requirements, Cost Trades, and Recommendations.
## Tentative Analysis Summary (Timeline Improvements)

### Related Issues
- **Shuttle Ground Ops:**
  - Efficiency Study,
  - Operations Analysis,
- **Operational Status of the SMST 5:**
- **Accessibility of the SMST when INST. IN THE ORBITER:**
- **Serial Schedule Time in Dura. Cut:**
- **Cost of Removing Required to Inspect/Maintain and Modify SMST 5:**

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<th>TODAY'S METHODS</th>
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<td>DEBRISS SCREENS &amp; FILTERS IN THE CABIN AIR RECIRCULATION SYSTEM ARE CLEANED AFTER EVERY FLIGHT</td>
<td>REDESIGN THE INSTALLATION OF THE DEBRISS SCREENS AND FILTERS ALONG ACCESS</td>
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<td>POST 5th FILL M</td>
<td>PD EST</td>
<td>BUILD A NEW AREA HANGAR</td>
<td>SMALL COST OF COATING</td>
<td>BEST BET - OPTICAL COATING</td>
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<td>1. WINDOWS WOULD BE CRACKED DURING SAND SEPARATION AND CLEANING/REPAIR.</td>
<td>POST 5th FILL M</td>
<td>PD EST</td>
<td>BUILD A NEW AREA HANGAR</td>
<td>SMALL COST OF COATING</td>
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<td>POST 5th FILL M</td>
<td>PD EST</td>
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**TIPS INJECTION**

- TIPS INJECTION - TENTATIVE 1987
- INSPECTION METHODS ARE UNSATISFACTORY, UNRELIABLE, INVASIVE AND TIME CONSUMING.
- ROCKWELL LESS-EX1 STUDY DPRS ANALYSIS
- JSC RESIDENT OFFICE

**FUEL CELL OPERATIONS**

- FUEL CELL OPERATIONS - TENTATIVE 1987
- MAINTAINABILITY OF THE DODGER FUEL CELL SYSTEM IS DIFFICULT AND REQUIRES EXCESSIVE TIME AND LABOR.
- ROCKWELL LESS-EX1 HISTORICAL SCH BOOK 1978
- TANK SET 4 HR - 179 HRS

**37TH PAGE OF DOD INSTRUCTIONS**

- TANK SET 4 HR - 179 HRS
- 37TH PAGE OF DOD INSTRUCTIONS

**DEVELOP NEW, HIGH POWER-DENSITY FUEL CELLS**

- DEVELOP NEW, HIGH POWER-DENSITY FUEL CELLS ON BATTERIES THAT REQUIRE SIGNIFICANTLY LESS ON-LINE MAINTENANCE THAN THE CURRENT FUEL CELL SYSTEM.
- REPLACE THE CURRENT FUEL CELLS.

**RECOMMENDATIONS**

- DEVELOP NEW, HIGH POWER-DENSITY FUEL CELLS ON BATTERIES THAT REQUIRE SIGNIFICANTLY LESS ON-LINE MAINTENANCE THAN THE CURRENT FUEL CELL SYSTEM.
- REPLACE THE CURRENT FUEL CELLS.
## Tentpole Analysis Summary (Technology Applications)

**04/30/87**

### Related Issues

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<th>Source</th>
<th>Schedule Data</th>
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<th>Technology Requirements</th>
<th>Cost Trades</th>
<th>Recommendations</th>
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<td>Owner Compliance</td>
<td>SI-4 Findings and President's Committee Reports</td>
<td>MC Integrated Data System</td>
<td>Integrated Data System including all phases of the project: design, manufacturing, operations</td>
<td>Shuttle Processing Flow</td>
<td>Significant Savings in Operational Life Cycle Costs</td>
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<td>Accessibility</td>
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### Actions
- Replace ordnance with non-explosive devices.
- Moderate redesign and material cost savings.
- Save significant labor.
- Reduce turn-around time.
- Very significant on-line reduction.
- Would speed up entire shuttle processing flow.
- Significant savings.

**Ordinance:**
- Tentpole F4
- Ordinance devices do not lend themselves to quick turn around operations.

**Schedule Data:**
- OML V5812 installs some ordnance in blister at off.
- OML 5594 installs ordnance in sled at var.
- OML 5545 installs ordnance in ET at var.
- OML 5550 installs remaining ordnance at pad.

**Today's Methods:**
- Moderately redesign and material costs compared with significant labor savings and reduced turn-around time.
- Very significant on-line reduction.
- Would speed up entire shuttle processing flow.
- Significant savings.

**Recommends:**
- A significant reduction can be made in shuttle and future vehicle turnaround time with elimination of ordnance devices.
- National technology has potential to accomplish at least part of this for non-ignition ordnance.
- Recommend development of statement of work for NSC to provide national design parameters appropriate to design of such devices.
- Using NSC input, parameters and basic shuttle design requirements, prepare RFP for substitute ordnance devices – but not limited to inertial technology.

**Original Page Is of Poor Quality**
1.4.1 SSME PROCESSING (Tentpole 1)

1.4.1.1 Summary

At the completion of the sixth flight of the shuttle the program was declared to be operational. This would be all systems of the orbiter including the Space Shuttle Main Engines (SSME). Based on the continuing technical issues and the resulting modifications on the SSME's, the engines are still not fully operational. To perform all of the required inspections, repairs, and modifications with the engines installed in the orbiter causes many operational problems.

Due to the limited space in the aft section of the orbiter, the amount of work that can be accomplished at one time is very restricted so any work on the engines precludes any other work to be worked in parallel. Also work on the engines requires the support of almost all of the orbiter systems which means that work on these systems cannot be done at the same time. With the limited access to the engines operations require more time to complete.

To alleviate this situation, the present engine shop should be upgraded to provide space, equipment, and facilities to support total engine maintenance and modification capability. Rocketdyne has submitted a plan to accomplish this which would approximately 1.2 million dollars.

Much time could be saved if ready spare engines were provided so that all maintenance and mod work could be completed off line. Engines would be ready for installation as soon as a mission is completed. Then only serial flow time would be required in the OPF for engine R&R and interface retest.

1.4.1.2 Related Issues

1. Operational status of the SSME's. SSME's were designed to be used for 10 flights before they would require any maintenance. So far no engine has been used for more than one flight without some work being performed. Modifications are also being incorporated to correct technical problems. The engines will not be fully operational until the maintenance is reduced and modifications completed.

2. Accessibility of the SSME when installed in the orbiter. The aft section of the orbiter is a plumber's nightmare. So much equipment is installed in a small volume that access is a problem for working on any equipment. This also means that only limited systems can be worked in parallel. Damage to electrical connectors is a result of the close quarters and people entering and leaving the area.
3. **Serial schedule time during OPF processing.** Any engine operation performed while installed on the vehicle requires support of many of the Orbiter systems. This means most engine work requires serial schedule time to complete. Systems that are needed to support engine operations include: EPD&C, GN&C, PV&D, HYD, OPS and INS. (Electrical Power Distribution and Control, Guidance Navigation and Control, Purge Vent and Drain, Hydraulics, Operations, Instrumentation).

4. **Cost of manhours required to inspect, maintain, and modify SSME's.** During processing of 51-L in the OPF, 47 shifts of work were used to service on the SSME's. This required 3792 technician manhours plus support of other systems, engineers, QC and other support groups.

Following are some examples taken from the Issues database:

```
ISSUE(S): LOGISTICS/SPARES
Source: (ASAP > JAN. '85 ANNUAL REPORT, P.37)
Description:
CONCERN EXPRESSED FOR LACK OF SPARES
"NASA SHOULD CONTINUE TO GIVE HIGH PRIORITY TO ACQUISITION OF SPARE PARTS AND TO UPGRADE THE RELIABILITY (FLANGED LIFE) OF HARDWARE, ESPECIALLY ITEMS ASSOCIATED WITH SPACE SHUTTLE MAIN ENGINE."
```

```
ISSUE(S): LOGISTICS/SPARES
Source: (SSME OBS REVIEW > 7/66 TEAM A4 PREP TO STS OBS REV BD)
Description:
HARDWARE REVIEW SUMMARY
- NO NEW CRITICAL SINGLE POINT FAILURES WERE FOUND
- STRUCTURAL ITEMS RELY ON PROOF LOAD VERIFICATION FOR HAZARD ELIMINATION
  - OM1'S WEBD UPDATE
- PNEUMATIC SYSTEM USE DEPENDS ON INTERFACE FILTER AND RELIEF VALVE/GAUGE
  CALIBRATION TO CONTROL CONTAMINATION/OVERPRESSURIZATION
  - OM1'S WEBD UPDATE
  - NEW FILTER REQUIRED FOR CT9--988 FLOWMETER USE
- FLIGHT HARDWARE DAMAGE IS LIKELY DUE TO INADEQUATE ACCESS DURING LBU OPERATIONS
  - AT0--663 ENGINE SERVICE PLATFORM
  - AT0--888 OFF SWING PLATFORMS
- SSME NOZZLE THERMAL PROTECTION INSULATION (TPS) IS DAMAGED BY HT0--0568
  HORIZONTAL INSTALLER
```

-35-
1.4.1 SSME PROCESSING (Tentpole I)  
(Continued)

1.4.1.3 Schedule History

Design goal for SSME's allowed 24.0 hours for propulsion system scheduled maintenance (reference the 160 hour turnaround level II schedule). During the 51-L processing a total of 893.0 schedule hours were expended. This included 581.0 hours with the engines installed on the vehicle and 312.0 hours accomplished in the engine shop (See Figure 1 for OPF work performed.) The shortest processing flow to date was the 61-B flow and 394.5 hours were expended on engine work, all of which was done with the engines installed on the orbiter.

<table>
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<tr>
<th>EFFICIENCIES/TECHNOLOGIES</th>
<th>NOVEMBER 1980</th>
<th>DECEMBER 1980</th>
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<td>MAKE PROCESSING</td>
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* All timelines indicate 3 shift/day operations  
** Does not require new technology - but goes beyond the bandaid fix  

SCHEDULE  
Figure 1

1.4.1.4 Current STS Methods

All engine inspections, most repairs and modifications are accomplished with the engines installed on the orbiter. To gain access to the engines the base heat shields must be removed. Thompson rails are installed to remove and replace the high pressure turbopumps and support must be provided by several orbiter systems to position, power-up and test the engines. This is very costly in both time and manpower and prevents other activities being accomplished on the supporting systems while engine operations are being performed. Engines are removed for major repairs and modifications. Some of this work is performed in the current engine shop but configuration of the shop prevents many tasks. Problems include: 1. Engine stands not designed for total access to the engine 2. Shop is not a clean area 3. Lighting is not adequate 4. Space is limited 5. No office space is available 6. Access to area is not easily controlled.

The following is a list of procedures currently being used:

V1001 -- SSME ELECTRICAL INTERFACE VERIFICATION  

OBJECTIVE: Provide standard instructions to test all Engine Interface Unit (EIU) and SSME controller copper paths after engine installation, after electrical LRU replacement and after engine hot firing.
1.4.1 SSME PROCESSING (Tentpole 1) (Continued)

V1011 -- SSME DRYING AND FUNCTIONAL

OBJECTIVE: .01 - Perform post flight drying of High Pressure Fuel Turbo Pump (HPFTP) and Main Combustion Chamber (MCC) using heated GN₂.

.02 - Perform internal/external inspection of major SSME components post flight.

.03 - Verify operational integrity of internal working parts of all turbopumps required after each flight.

.04 - Verify operational integrity of hex fluid systems.

.05 - Verify operational integrity of SSME HGM, LOX and LH₂ fluid systems. Interface leak checks post installation.

.06 - Perform pneumatic checkout and leak checks and routine module checkouts of the SSME's.

.07 - Verify operational integrity of all SSME/orbiter fluid and electrical interfaces following 10 engine starts.

VO043 -- SSME HEAT SHIELD REMOVAL

OBJECTIVE: Provide instructions for installation and/or removal of SSME-mounted and orbiter-mounted heat shield segments.

V5E02 -- SSME LRU (Line Replacable Unit) COMPONENT REMOVAL/INSTALLATION HIGH PRESSURE OXIDIZER TURBOPUMP

OBJECTIVE: To provide procedures to remove SSME high pressure oxidizer turbopump (LRU) in the OPF (hor.) and VAB, PAD (vert.). SSME engine shop.

NOTE: (Under the new method this would be performed in the engine shop.)

V5E06 -- SSME LRU COMPONENT REMOVAL/INSTALLATION HIGH PRESSURE FUEL TURBOPUMP

OBJECTIVE: To provide procedures to remove or to install space shuttle high pressure fuel turbo pump (LRU).

NOTE: (Under the new method this would be performed in the engine shop.)
1.4.1 SSME PROCESSING (Tentpole 1)
(Continued)

1.4.1.5 Timeline Improvements

Rocketdyne has made a survey of the present engine shop and the adjacent space in cell 6 in the VAB and has made a proposal to modify and enlarge the present shop so that all but complete engine overhauls can be done off the vehicle at KSC (see attached sketches). They have submitted 16 Engineering Support Requests (ESR's) to accomplish the modifications. Lockheed has estimated the job to cost $1,213,092.

Estimated saving in the process time to change a High Pressure Turbopump is approximately two days of overall time and four days of serial time in the vehicle processing. This is based on the following:

1. The as-run data shows the average time required to change a high pressure turbopump, while the engine is installed in the vehicle, is six days

2. To remove and replace an SSME requires two days maximum

3. Pump removal and replacement in the shop with adequate accessibility could be accomplished in 7-8 shifts

1.4.1.6 Operational Evaluation

The processing of the SSME's is rapidly becoming one of the long tentpoles in vehicle flow. In the current environment this will only get worse. Operation time on the vehicle is affected by SSME processing and will be increasing due to additional requirements. Flow time in the OPF will grow drastically. To avoid this, and to improve later flows, improved capability of the engine shop appears to be a must.

Savings will be 4 serial days in the orbiter processing flow for a pump change and a cost savings of 2 days of shop time due to improved in accessibility.
1.4.1 SSME PROCESSING (Tentpole 1)  
(Continued)

1.4.1.7 Conclusions and Recommendations

CONCLUSIONS

Timeline improvements and cost savings can be immediately realized in this area with modification to the engine shop. Money spent to accomplish the mods will be repaid from savings in the serial processing time reduction of each vehicle, and the overall simplification in maintaining the SSME's.

RECOMMENDATIONS

1. Approve the 16 ESR's that have been submitted by Rocketdyne and accomplish the work in time to support processing of the second flow of each vehicle through the OPF after program restart. Status: Cell 5 improvements have been approved at $400K with a BOD of October 1987. $400K for FY-88 and $400K for FY-89 are in the approval cycle.

2. Provide enough spare SSME's to support engine changeouts as required for flight problems and modifications.
1.4.2 AFD/PLB RECONFIGURATION (Tentpole 2)

Aft Flight Deck & Payload Bay Reconfiguration

1.4.2.1 Summary

To satisfy the Cargo Community and to attract more space business for the Space Shuttle Program, as much flexibility as possible has been designed into the payload bay/cargo interfaces. This flexibility has caused the time required to reconfigure the payload bay from one mission to the next flight, to become one of the longest tentpoles in the Orbiter Processing Facility (OPF) flow. A total of 37 shifts were required during the OPF processing of 51-L to reconfigure and test the Aft Flight Deck (AFD) and Payload Bay (PLB), plus 8 shifts to prepare for installation of the cargo.

The original concept was to locate all cargo in a limited number of positions in the payload. The center of gravity of the vehicle would be adjusted without weights being added or subtracted in the aft section. Due to growth of the vehicle weight and its effect on the available weight for cargo, this method was discarded and provisions were made to locate cargo to allow for center of gravity (CG) adjustment. This also required that provisions be made so electrical interfaces could be located to support different locations of cargo.

The only feasible approach for the present orbiters would be to provide a strongback that could be used to remove or install all of the payload bay bridges and cargo fittings simultaneously. With two strongbacks and an extra set of bridges available, the configuration of the next mission could be established and ready prior to the landing of the previous mission. This could reduce time for this operation by 50 to 60%. Any other change would require a complete redesign of the payload bay and very costly, time consuming modifications.

A much more standard approach to the installation of cargo is needed if the time is going to be reduced in reconfiguring the payload from one mission to the next.

1.4.2.2 Related Issues

1. Time required on the vehicle to reconfigure the payload bay
2. Cost in manhours to support the reconfiguration operation
3. Design criteria that dictate the amount of work required to reconfigure the payload
4. Final design of the payload bay and aft flight deck that requires reconfiguration and retest between every flight
1.4.2 AFD/PLB RECONFIGURATION (Tentpole 2) (Continued)

Below are excerpts from the Preliminary Issue Data Base of papers that have been prepared giving examples of findings from other groups to support the recommendations for standardization and simplification of cargo-to-vehicle interfaces.

- ID: (500.00) Issue(s): COMMONALITY : INTERFACE
  Issue(s) cont.: 
  Issue Source: (ASAP) JAN. '85 ANNUAL REPORT, P.38
  Description:
  REPORT RECOMMENDS THAT WHEREVER POSSIBLE THERE SHOULD BE AN INCREASING EFFORT TO PREPARE AND CARRY PAYLOADS IN A STANDARDIZED FASHION.

- ID: (714.00) Issue(s): COST/MANHOURS : 
  Issue(s) cont.: 
  Issue Source: (NSTS) DRAFT DATED 5/86, TABLE G-1
  Description:
  "LOGISTIC SYSTEM COST DRIVER: OPERATIONAL CONCEPTS SYSTEM"
  PAYLOAD ACCOMMODATIONS: MINIMIZE PAYLOAD
  - MISSION UNIQUE MODS: UNIQUE FEATURES
  - IN-LINE FUNCTION: FUNCTIONAL CHECKS
  - ON-BOARD SERVICES: SERVICE DIFFERENCES
  P/L TO BE AUTONOMOUS FROM LAUNCH VEHICLE
  P/L TESTING OFF-LINE PRIOR TO LAUNCH VEHICLE INTEGRATION

- ID: (725.00) Issue(s): ISOLATION : INTERFACE
  Issue(s) cont.: SECURITY
  Issue Source: (AFSC/NSIA) P.O74/COST RED & CRED WORKSHOP 3/18/86
  Description:
  "TO REDUCE PAYLOAD TO VEHICLE INTERFACES TO THE ABSOLUTE MINIMUM, PAYLOADS WILL PROBABLY BE ENCAPSULATED IN SOME KIND OF MODULE AT AN OFFLINE FACILITY. THE Module will then be installed on the launch vehicle. Depending on vehicle configuration, the module shell may function as the payload fairing as on current expendable vehicles. On vehicles with integral payload bays, the module might perform a thermal shielding function and serve as cleanliness protection, like the current AWH heat shields, as well as ensure security. PROVISIONS FOR MOUNTING THE MODULE TO THE VEHICLE MUST BE STANDARDIZED ASSUMING ONLY POWER AND AIR CONDITIONING ARE PROVIDED AS BASIC STANDARD SERVICES. THIS IS TO AVOID THE CURRENT PROBLEMS OF RECONFIGURING THE PAYLOAD/VEHICLE INTERFACES. PAYLOAD CONTROL AND DATA LINES MUST BE INDEPENDENT OF LAUNCH VEHICLE INTERFACES OTHER THAN A SIMPLE ANTENNA CONNECTION, IF REQUIRED. SECURITY WILL BE ENHANCED BY SUCH A SYSTEM BECAUSE ALL ENCAPSULATED PAYLOADS HAVE SIMILAR APPEARANCE AND HANDLING."

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### 1.4.2 AFD/PLB RECONFIGURATION (Tentpole 2)
(Continued)

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<td>Issue Source: &lt;AFSC/NSIA&gt;</td>
<td>(P.075) COST &amp; CRED WORKSHOP 9/18/88</td>
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**Description:**

**POTENTIAL AREAS OF PAYLOAD PROCESSING COST REDUCTIONS:**

**ACTION:** PROVIDE ELECTRICAL & FLUID INTERFACE PLATES.

**COMMENT:** MINIMIZE THE NUMBER OF INTERFACE CONNECTORS TO BE HANDLED: *LESS CHANCE OF DAMAGE* & REDUCTION IN PROCESSING COSTS.

**ACTION:** STANDARDIZE SPACECRAFT HARDWARE. *INCORPORATE STANDARD INTERFACE FORMATTING INTO UPPER STAGE OR LAUNCH VEHICLE.* 

*MODULARIZE FOR GROWTH AND REDUCING COST.* *REDUCES INTEGRATION COSTS.*

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<td>(P.077) COST &amp; CRED WORKSHOP 9/18/88</td>
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**Description:**

---PAYLOAD COMMUNITY RECOMMENDATIONS---

* DEVELOPMENT OF DESIGN STANDARDS * DESIGN FOR MAXIMUM AUTONOMY
* PAYLOAD ENCAPSULATION * SIMPLER INTERFACES
* PROVISON OF ON ORBIT SERVICING * GREATER PERFORMANCE MARGINS

AND REPAIR
* USE OF FEWER "UNIQUE" COMPONENTS * DESIGN PERFORMANCE MARGINS
* APPLICATION OF NEW AND INNOVATIVE DESIGN AND MANUFACTURING CONCEPTS AND TECHNOLOGIES.

---PAYLOAD COMMUNITY RECOMMENDATIONS---

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<td>(P.121) COST &amp; CRED WORKSHOP 9/18/88</td>
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**Description:**

---STS PAYLOAD INTEGRATION/INTERFACE-----

* ESTABLISH COMMON ORBITER/PAYLOAD INTERFACES

+ STANDARDIZE ELECTRICAL AND ATTACH POINT FITTINGS/DEVICES
+ POWER AND CONTROL WIRING ON STARBOARD AND PORT SIDES OF THE CARGO BAY
+ ATTEMPT TO MINIMIZE OR ELIMINATE ACTIVE HEATING REJECTION REQUIREMENTS WHILE IN THE PAYLOAD BAY
+ DESIGN PAYLOADS TO FUNCTION IN NORMAL ORBITER ENVIRONMENT (AVOIDS SPECIAL ATTITUDE AND THERMAL CONSTRAINTS)

* AUTONOMOUS STS PAYLOADS

+ STANDARDIZE TT&C PACKAGES ON ALL SPACECRAFT WITH ACTIVE DOWNLINK
+ ORBITER/PAYLOAD COMMUNICATION EQUIPMENT SHOULD BE SEGREGATED
+ SEPARATE COMPUTER FOR PAYLOAD INTERFACE
+ SELF-CONTAINED POWER AND COOLING CAPABILITY FOR PAYLOADS

* CARGO INTEGRATION

+ INCREASED USE OF TELECONS (SECURE & NON-SECURE) FOR LA MEETINGS
+ ONE LAUNCH SUPPORT INTEGRATION CONTRACTOR
+ EARLY JSC/PAYLOAD CONTACT
1.4.2 AFD/PLB RECONFIGURATION (Tentpole 2) (Continued)

ORIGINAL PAGE IS OF POOR QUALITY

ID: (1788.00)  Issue(s): INTERFACE : STANDARDS
Issue(s) cont.: MISSION : REQUIREMENTS :
Issue Source: (AFSC/NSIA)  (P.108)COST RED & CBBD WORKSHOP 9/18/86
Description:

***OPERATIONS & SUPPORT FOR NEXT GENERATION STS*** (SAWAYA/FRASER/ET AL)
-----KENNEDY SPACE CENTER GUIDANCE----- (PAYLOAD ACCOMMODATION)

ACCOMMODATIONS FOR PAYLOADS/CARGOS SHALL BE DESIGNED FOR EASE OF INSTALLATION, REMOVAL, AND INTERFACE VERIFICATION.

SIMPILIFY, MINIMIZE, AND STANDARDIZE INTERFACE REQUIREMENTS BETWEEN PAYLOADS/CARGOS AND LAUNCH VEHICLES.

SIMPILIFY MISSION-TO-MISSION CARGO BAY RECONFIGURATION REQUIREMENTS.

ID: (1790.00)  Issue(s): DESIGN CRITERIA : MISSION
Issue(s) cont.: STANDARDS : INTERFACE : TRAINING/CERTIF
Issue Source: (AFSC/NSIA)  (P.309)COST RED & CBBD WORKSHOP 9/18/86
Description:

***OPERATIONS & SUPPORT FOR NEXT GENERATION STS*** (SAWAYA/FRASER/ET AL)
-----JOHNSON SPACE CENTER GUIDANCE-----

SPACECRAFT DESIGNER SHALL BE PROVIDED STANDARD HARDWARE INTERFACE DEFINITION AND STD OPERATIONS PROCEDURES EARY IN THE SPACECRAFT DESIGN CYCLE.

OPERATIONS ORBITS SHALL BE STANDARD--INCLINATION AND ATTITUDE.

FLIGHT PHASES SHALL BE STANDARD: ASCENT/PROXIMITY OPERATIONS/DEPLOYMENT/ SPACECRAFT HANDLING-EMS/SPACECRAFT SEPARATION/THermal PROFILES/RENDEZVOUS/ENTRY.

SPACECRAFT DEPLOYMENT SYSTEMS AND PROCEDURES SHALL BE STANDARD.

THE PAYLOAD MISSION REQUIREMENTS DOCUMENTATION PROCESS SHALL BE STANDARD.

PAYLOAD HARDWARE & OPS INTERFACE DESIGN REQUIREMENTS SHALL BE STANDARD--POWER, COOLING, COMMAND, DATA, INTEGRATION HARDWARE, EMS, DOCKING MECHANISMS, CREW INTERFACES.

SPACECRAFT SERVICING FUNCTIONS, INTERFACES, & PROCEDURES SHALL BE STANDARD.

FLIGHT CONTROL CENTER FLIGHT RECONFIGURATION:
+ DATA REQUIREMENTS SHALL BE MINIMUM AND STANDARD. + GENERATION & VERIFICATION PROCESS SHALL BE STANDARD.

FLIGHT AND GROUND CREW TRAINING AND SIMULATION:
+ BASED UPON STD FLIGHT PROFILES/PHASES. + SIMULATION DATA SHALL BE MINIMUM & STANDARD. + BASED UPON STD SPACECRAFT INTERFACES & OPS PROCEDURES.

NECESSARY CARGO MIX FLEXIBILITY SHALL BE INDUCED BY STD P/L INTERFACES, OPS PROCEDURES, AND STANDARD ACCOMMODATION ALLOCATION.

ID: (4111.00)  Issue(s): DESIGN CRITERIA : INTERFACE
Issue(s) cont.: STANDARDS :
Issue Source: (KSC GO-MPO)  NOI WILEY -- OCT '85
Description:

------------------------GROUND TESTING AND CHECKOUT PHILOSOPHIES------------------------

DESIGN FOR NO DESERVING DURING TURNAROUND.

ACCOMMODATIONS FOR PAYLOADS/CARGOS SHALL BE DESIGNED FOR EASE OF REMOVAL, AND INTERFACE VERIFICATION.

SIMPILIFY, MINIMIZE, AND STANDARDIZE INTERFACE REQUIREMENTS BETWEEN PAYLOADS/CARGOS AND LAUNCH VEHICLES.

SIMPILIFY MISSION TO MISSION CARGO BAY RECONFIGURATION REQUIREMENTS.

+ PROVIDE VARIOUS ATTACHMENT LOCATIONS. + PROVIDE MULTIPLE INTERFACE
+ FLI SCAB WT IN PANELS/CABLES/FLUID PANELS/CONNECTION LOCATIONS.

CONNECTIONS & ATTACH FITTINGS TO REDUCE TURNAROUND RECONFIGURATION REQ.
1.4.2.3 Schedule History

For a mission that would require cargo to be installed in the orbiter while at the PAD, the Level II 160 hour turnaround design goal allowed a total of 32 hours to remove the down cargo and install and perform a launch readiness verification test. Nine hours were allotted at the PAD to install the unique payload accommodation equipment during OPF operations. Actual schedule hours used to support the 51-L flow was 454.4 hours in the OPF and 273.5 hours at the PAD. Payload installation into the PCR was predicted to take 13.0 hours and the actual time used for 51-L was 174.0 hours. See Figure 1.

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<th>EFFICIENCIES/TECHNOLOGIES</th>
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<td>TIME LINE IMPROVEMENTS</td>
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<tr>
<td>AFD/PLB RECONFIGURATION (ELECTRICAL &amp; MECHANICAL)</td>
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</tr>
</tbody>
</table>

* All numbers indicate 3 shift/day operations
** Does not require new technology - but goes beyond the bandaid fix

1.4.2.4 Current STS Methods

Nondeployable payloads are retained by passive retention devices, whereas, deployable payloads are secured by motor driven, active retention devices.

Payloads are secured in the orbiter payload bay by means of the payload retention system or are equipped with their own unique retention systems.

The orbiter payload retention system provides three-axis support for up to five payloads per flight. After the initial orbiter development flights, the payload bay was modified to accommodate attach fittings for five payloads.

The payload retention mechanisms secure the payloads during all mission phases and provide for installation and removal of the payloads when the orbiter is either horizontal or vertical.

Attachment points in the payload bay are in 9.9-centimeter (3.933-inch) increments along the left- and right-side longerons and along the bottom centerline of the bay. Of the potential 172 attach points on the longerons, 45 are unavailable because of the proximity of spacecraft hardware. The remaining 127 may be used for carrier/payload attachment; of these, 111 may be used for deployable payloads. Along the centerline keel, 104 attach points are available, any of which may be used for payloads.
There are 13 longeron bridges per side and 12 keel bridges available per flight. Only the bridges required for a particular flight are flown. The bridges are not interchangeable because of main frame spacing, varying load capability, and subframe attachments.

The longeron bridge fittings are attached to the payload bay frame at the longeron level and at the side of the bay. Keel bridge fittings are attached to the payload bay frame at the bottom of the payload bay.

The payload bay trunnions are the interfacing portion of the payload with the orbiter retention system. The trunnions that interface with the longeron are 8.2 centimeters (3.25 inches) in diameter and 17.78 or 22.22 centimeters (7 or 8.75 inches) long, depending upon where they are positioned along the payload bay. The keel trunnions are 7.62 centimeters (3 inches) in diameter and vary in length from 10.16 to 29.21 centimeters (4 to 11.5 inches), depending upon where they fit in the payload bay.

The orbiter/payload attachments are the trunnion/bearing/journal type. The longeron and keel attach fitting have a split, self-aligning bearing for nonrelease-type payloads in which the hinged half is bolted closed. For on-orbit deployment and retrieval payloads, the hinged half fitting releases or secures the payload latches that are driven by dual redundant electrical motors.

Payload guides and scuff plates are used to assist in deploying and berthing payloads in the payload bay. The payload is constrained in the X direction by guides and in the Y direction by scuff plates. The guides are mounted to the inboard side of the payload latches and interface with the payload trunnions and scuff plates. The scuff plates are attached to the payload trunnions and interface with the payload guides.

The guides are V shaped with the forward part of the V being 5.08 centimeters (2 inches) taller than the aft part. This difference enables the operator monitoring the berthing or deployment operations through the aft bulkhead TV cameras to better determine when the payload trunnion has entered the guide. The top of the forward portion of the guide is 60.96 centimeters (24 inches) above the centerline of the payload trunnion when it is all the way down in the guide. The top of the guide has a 22.86-centimeter (9-inch) opening. These guides are mounted to the 20.32-centimeter (8-inch) guides that are a part of the longeron payload retention latches.

The payload scuff plates are mounted to the payload trunnions or the payload structure. There are normally three or four longeron latches and a keel latch for on-orbit deployment and retrieval of payloads. These latches are controlled by dual redundant electric motors with either or both motors releasing or latching the mechanism. The operating time of the latch is four seconds with both motors operating or eight seconds with one motor operating.
The latch/release switches on the aft flight deck display and control panel station control the latches. Each longeron latch has two microswitches sensing the ready-to-latch condition. Only one is required to control the ready-to-latch talkback indicator on the aft flight deck display and control panel station. Each longeron latch also has two microswitches to indicate latch and two to indicate release. Only one of each is required to control the latch or release talkback indicator on the aft flight deck display and control panel station.

The keel latch also has two microswitches that sense when the keel latch is closed with the trunnion in it. Only one of the switches is required to operate the talkback indicator on the aft flight deck display and control panel station. The keel latch also has two microswitches that verify if the latch is closed or open, with only one required to control the talkback indicator on the aft flight station display and control panel station.

It is noted that the keel latch centers the payload in the payload bay; therefore the keel latch must be closed before the longeron latch is closed. The keel latch can float plus or minus 6.9 centimeters (plus or minus 2.75 inches) in the X direction.

This flexibility requires that the electrical interfaces also have the option of location in the vicinity of the mechanical attach fittings. This is done by providing a Standard Mission Cable Harness (SMCH) that plugs into one of two interface panels on either side of the orbiter, then routed to appropriate bay where a Standard Interface Panel (SIP) is installed. This SIP provides pass-through connectors and the cargo interface cable is connected to the other side. In some cases the cargo requires a special panel which must be installed. The Inertial Upper Stage (IUS) is a cargo that requires a special panel. This operation is time consuming and requires a great deal of manpower because all the panels must be removed and reinstalled; the SMCH tie-wraps must be cut loose, repositioned and retied; and retested.

Depending on the power requirements of the cargo, the fourth Power Reactant Storage and Distribution (PRSD) tank set is installed or removed from the payload bay. If the cargo requires a lot of power, then more reactant propellants are needed for the mission and tank set 4 is installed. To save weight on missions not requiring as much power to the cargo, the tank set is removed. This is both time consuming and labor intensive.

The requirements for fluid services to a cargo can also change from one cargo to the next. Again providing this service to the cargo community greatly effects the processing time and cost of preparing the vehicle for launch.
1.4.2 AFD/PLB RECONFIGURATION (Tentpole 2)  
(Continued)

1.4.2.5 Timeline Improvements

A major redesign of the payload bay would be required to change the present orbiters to a system that would accept only standard cargos. The only minor improvements that could be made to reduce the processing time would be to:

1. Provide spare payload accommodation equipment so that all required parts could be adjusted and kitted prior to the landing of the previous mission.

2. Design and build ground support equipment that would allow all bridges and fittings to be installed at the same time.

3. Control the frequency of reconfiguration by assigning similar cargos to successive flights of the same orbiter.

To enhance the ground operations of future programs, standardization of the cargo must be one of the design criteria. Requirements imposed on cargo should include the following:

1) All cargo interfaces, both electrical and mechanical, should be standardized,

2) Power supplied from the vehicle and instrumentation through the vehicle should be kept to a minimum,

3) Containerized cargo would provide the following advantages:
   A. contamination control
   B. better security
   C. reduce ground transportation problems
   D. fixed and standard interfaces.

1.4.2.6 Operational Evaluation

If all the present problems with the orbiter are solved (or even reduced), the payload bay reconfiguration and cargo installation would become the long tentpole. A very costly redesign and modification of the payload bay would be required to completely solve this problem. Providing the strongback and the spare bridges and fittings should reduce the time required for payload bay reconfiguration by 50 to 60%. Improvements should be made in the initial design of the next generation of Space Transportation Vehicles so that it will accept standard cargo with a minimum of interfaces and services required. This could reduce the processing time and cost of preparing a vehicle for launch.
1.4.2 AFD/PLB RECONFIGURATION (Tentpole 2)
(Continued)

1.4.2.7 Conclusions and Recommendations

Based on the extent of redesign and modification required to change the present orbiters to accept standard cargo, and the cost to change cargos now designed and built, it is not feasible to change any flight hardware. Future cargos could be restricted in their requirements to improve ground operations.

STS

The area of highest payback potential would be to provide ground support equipment that could reconfigure all payload fittings at the same time. This would still be labor intensive, but could be a big saving to the processing time for each flow.

FUTURE VEHICLES

Make the design criteria for standardized cargo interfaces a primary requirement for the next generation of vehicles. Extra cost during the design and build phases of the vehicle would have favorable paybacks for the duration of the operational phase of the program.
1.4.3 CABIN AIR RECIRCULATION SYSTEM MAINTENANCE (Tentpole 3)

1.4.3.1 Summary

Accessibility of the filters in the crew module cabin air recirculation system is very poor. Little thought was given in the design phase to the operation and maintainability of the system. After every flight the debris screens and filters are removed, pictures taken and samples collected from the avionics bays, cabin fan/avionics bays and Internal Measurement Unit (IMU) screen. In each case, equipment must be removed to access the screens and filters. Since the fans must be off during this operation, power must be removed from the vehicle and no troubleshooting can be accomplished on any other Orbiter system. After all the hardware is reinstalled, all electronic boxes that were removed must be retested.

Present operation is to power the vehicle to support safing and deservicing activities then power down as soon as possible to clean the screens and filters. If processing of the vehicle requires more than two months to finish, then this operation must be repeated. Approximately 80% of the lint collected to date has been blue lint; the same shade as the blue astronauts suits.

A redesign of the system could provide accessibility to the screens and filters and reduce the time required for this operation. Also if better control of contamination in the crew cabin was maintained the requirement for this operation could be reduced.

1.4.3.2 Related Issues

1. Very poor accessibility to debris screens and filters. It would appear that no thought was given to accessibility in the initial design of the crew cabin.

2. Maintainability was not considered during the initial design.

3. On line schedule time serial to other operations. Other systems must be shut down because power must be removed any time cooling is off in the cabin. This makes this operation serial to almost all orbiter electrical testing.

4. Contamination control procedures in crew module. Contamination control was not a factor in the original design of the crew module which has resulted in quicker build up of lint and dust on the filters.

5. Retest of removed and replaced parts. Retest of the electrical boxes that have to be removed to gain access to the screens and filters adds time to the overall schedule.
1.4.3.3 Schedule History

A total of 24 hours were allotted in the 160-hour turnaround for all scheduled maintenance on the orbiter. During the 51-L flow, V6018, Cabin Air Recirculation Inspection and Maintenance, required 120 hours to complete. See Figure 1. Of this time 24 hrs. were performed with power off the vehicle and the remainder of the time with power on. The preferred method to perform this operation is to conduct all of the operations with the power removed. If time is not available for this the procedure may be accomplished by working around other activities in the crew module. This method is very hard to track and presents the shop many problems in maintaining records and supporting with manpower at the proper time.

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* All timebars indicate 3 shift/day operations
** Does not require new technology - but goes beyond the bandaid fix

51-L OPF PROCESSING
Figure 1

1.4.3.4 Today's Methods

V6018 -- CABIN AIR RECYCULATION INSPECTION AND MAINTENANCE

OBJECTIVE: To perform routine maintenance on the cabin fan, IMU and avionics bay 1, 2, 3 debris screens. In addition, the condensing heat exchanger will be inspected for corrosion and biological growth. Water samples will also be obtained from the condensing heat exchanger and analyzed for biological growth. Air cooled avionics will be inspected for cleanliness and vacuum cleaned as required.

OPERATIONS: To gain access to the debris screens and filters, close out panels must be removed. In some cases electronic boxes must also be removed. After the access is available, photos are taken of the screens and filters. If any lint or debris is present it is collected, labeled and sent to Johnson Space Center (JSC). The area is vacuumed, close out photos are taken and the panels are reinstalled.
1.4.3 CABIN AIR RECIRCULATION SYSTEM (Tentpole 3) (Continued)

1.4.3.4 Today's Methods (Continued)

This operation is repeated for the following equipment:

1. Avionics Bay 1,2,&3 inspection and cleaning
2. Cabin Fan/Avionics Bay 1,2,&3 debris screen inspection and cleaning
3. IMU screen inspection and cleaning
4. Condensing Heat Exchanger inspection
5. Flight Deck Air Cooled Avionics inspection and cleaning

1.4.3.5 Timeline Improvements

Two improvements can be made that would reduce the amount of time that is required to support this operation. The first would be to redesign the air recirculation system so that the screens and filters are accessible without removing panels and equipment boxes. If spare screens and filters were made available, the operation on the vehicle could be limited to a simple change out of the screens and filters. The photo's (if still required) and cleaning could be accomplished off line in the shop.

The second improvement would be to change the fabric of the astronaut's suits to a lint-free material or require that they change into cleanroom garments before entering the crew cabin.

1.4.3.6 Operational Evaluation

With improved accessibility to the screens and filters and the availability of spare hardware, the time required to complete this operation should be reduced to approximately 4 hours from 36 hours.

Requirements could also be reduced so the system would not have to be inspected after every flight. This would be acceptable if lint could be diminished so the build-up on the screens and filters would not restrict the air flow cooling the electronic equipment. This operation could be performed on every fifth flight or less.
1.4.3 CABIN AIR RECIRCULATION SYSTEM (Tentpole 3)  
(Continued)  

1.4.3.7 Conclusions and Recommendations  

CONCLUSIONS  

There are two factors that affect the requirement and length of operation. First is the amount of lint and dust that collects in the crew module to clog the screens and filters. The majority of this contamination (approximately 80%) is being generated by the fabric used to make the astronaut’s jump suits. Secondly, design of the system adds time to the operation by installing the debris screens and filters behind other equipment that makes accessibility very poor.  

RECOMMENDATIONS  

Redesign the air recirculation system to provide better access to debris screens and filters. The modification would have to be installed during a block mod period on each orbiter.  

Change the material of the astronaut’s suits so they are lint free.
1.4.4 WEIGHT AND CENTER OF GRAVITY DETERMINATION (Tentpole 4)

1.4.4.1 Summary

A weight log is maintained for every orbiter to account for all changes to the vehicle during processing in the Orbiter Processing Facility (OPF). Just prior to rollout to the Vehicle Assembly Building (VAB), it is weighed to verify accuracy of the log; requiring 4 to 8 hours of serial time. The actual weighings will be discontinued when the data compares favorably with the log book totals. To date these have not compared, so weighings have continued.

Weighing is presently done in the OPF using portable scales. With the limited clearance between the OPF work stands and the orbiter, many observers are required any time the orbiter is moved. This causes the weighing operation to be costly and adds serial time to the processing flow.

A better method must be developed in maintaining the weight log so this operation can be eliminated. If the weight log is tied to the new paper control system, the computer could maintain the log more accurately. Until this is accomplished, load cells could be designed into the OPF jack stands so a separate operation would not be required.

1.4.4.2 Related Issues

1. Serial time to accomplish task. Four to eight hours are required to complete this task and it is serial to rollout of the Orbiter from the OPF.

2. Manpower required to support the operation. Sixteen technicians are required as observers for the jacking and leveling operation.

3. Ground support equipment design (not including load cells in OPF jack stands). If load cells were incorporated in the OPF jack stands, the weight could be obtained any time the orbiter was in the proper attitude.

4. Inadequate method of maintaining a weight log. Current methods to maintain the weight log do not have adequate controls to track all equipment and hardware removed and installed on the vehicle.
1.4.4 WEIGHT & CENTER OF GRAVITY DETERMINATION (Tentpole 4)  
(Continued)

1.4.4.3 Related Schedule History

The Level II design goal for the close out and preps to transfer the orbiter allowed 10 hours to accomplish all work. 51-L required a total of 359.5 schedule hours of which 8.0 hours of serial time were used for the jacking and weighing operation. See Figure 1.

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* All numbers indicate 3 shift/day operations
** Does not require new technology - but goes beyond the bandaid fix

51-L OPF PROCESSING

Figure 1

1.4.4.4 Current STS Method

**V5101** -- Orbiter weight and center of gravity determination using platform scales and OPF platform lifting system

OBJECTIVE: This Operations and Maintenance Instruction (OMI) will configure and perform a three point orbiter weighing utilizing model A70-0544 electronic portable platform aircraft weighing system. The orbiter will have been previously supported on the fwd and aft body jacks with orbiter facility fluid and electric lines disconnected.

OPERATIONS: As soon as the orbiter is closed out and ready to be rolled over to the VAB, it is transferred from the OPF jacks to the aft jack set. The portable scales are then placed on the OPF jacks and the vehicle raised to the weighing position. Since the orbiter is still in the confines of the OPF work stands, 16 observers must be used every time the vehicle is raised or lowered.

A weight log is maintained, but there are so many modifications and equipment changes to the vehicles that it is impossible with the current paper system to track the weight accurately.

At the present time there is no way at KSC to calibrate the portable scales. The normal way to test them has been to ship them back to the west coast. This has normally resulted in some kind of damage to the scales in transit and has been a real problem. A request has been submitted to provide a 20,000 pound weight set used to calibrate the scales but has not been made available yet.
1.4.4.5 Timeline Improvements

This operation could be completely eliminated once a method for maintaining the weight log is proven. Since there is an effort under way to track and close out requirements by bar codes and computers, the weight data could be added to the system and have the computer maintain the log.

Until the computer log system can be verified there are two things that could be done to reduce the cost and time to support this operation. The first would be to provide the test weight so that the scales could be maintained locally. Secondly if there is a chance the computer aided log will not be available soon, load cells could be designed into the OPF jacks. This would reduce the time required during this serial operation.

1.4.4.6 Operational Evaluation

Elimination of the weighing operation completely is the preferred answer to this tentpole. It has been the experience of both the missile and aircraft industries that as the program matures that weight logs are adequate for any data required for mission planning. This method would by far have the highest payback over the remainder of the program.

Both of the other proposals would only be recommended as stop gap measures until the computer log is total operational. Providing the test weight would be less costly than installing load cells in the jack stands, but would still save the overall program time and money.

1.4.4.7 Conclusions and Recommendations

Insure that provisions are made to include the weight data in the new computer-controlled paper close out system now being implemented for Operational Maintenance Requirements and Specifications Document (ORMSD) requirements satisfaction. To fill in the gap until the computer log system is verified, the test weight should be provided.
1.4.5 PAYLOAD BAY CLEANING AND CLOSEOUT (Tentpole 5)

1.4.5.1 Summary

Design criteria for the Space Shuttle was to make the operations as much like an airline as possible. This called for no special cleanliness requirements. All facilities were to be "Good Shop Practice" only. The first thing that happened when the first orbiter arrived at KSC was to build a crude tent around the crew ingress hatch to prevent dirt from entering the crew module.

Over the life of the Shuttle Program the requirements for contamination control have become more demanding. The cargo community has imposed some very tight requirements on the payload bay. Design of the Orbiter Processing Facility (OPF) did not provide for any contamination control. Some movable curtains have been installed on the work platforms and control is maintained on people allowed into the area.

With the current requirements and facilities, several shifts (3-1/2 during 51-L processing) are required to clean and inspect the payload bay prior to cargo installation in the vehicle.

If the operational timeline is to be trimmed, one of three things must be done. The first is to modify the OPF to the standards of a clean room. Another approach would be to require cargo to be designed to accept the current conditions; or the cargo could be containerized, providing its own controlled environment.

1.4.5.2 Related Issues

1. Prior to installing cargo the payload bay must inspected and cleaned. Cleaning is performed on every mission and is requiring an average of 3-1/2 shifts per flight.

2. Payload bay is closed out during cleaning. Since people and activities generate contamination, all activities must be complete and all personnel except the inspectors must be out of the payload bay.

3. Requirements of some payloads are very demanding on contamination control. After a blackbox failed on the second Tracking and Data Relay Satellite (TDRS) while at the Pad a decision was made to return the Spacecraft to the Vertical Processing Facility (VPF) so it could be cleaned while the box was being replaced. One DOD spacecraft would like to have a cover installed on it while in the Payload Changeout Room (PCR) and Payload Bay (with doors open) to protect it from contamination.

4. Many manhours are spent on cleaning. 144 technician hours are required to support the cleaning operation.
1.4.5 PAYLOAD BAY CLEANING (Tentpole 5)
(Continued)

Below are some examples extracted from the Issues database:

************************************************************************************
ID: (1730,00)  Issue(s): MAINTAINABILITY : ACCESSABILITY
Issue(s) cont.: MODULARIZATION : REQUIREMENTS :
Issue Source: (ASPC/NSIA )  (P.OTS)COST RED & HDR WORKSHOP 9/18/86
Description:
POTENTIAL AREAS OF PAYLOAD PROCESSING COST REDUCTIONS:
 ACTION: DESIGN FOR MAINTAINABILITY.
 COMMENT: PLACE CRITICAL OR LOW MEAN-TIME-BETWEEN-FAULURE COMPONENTS IN
 ACCESSIBLE AREAS - DO NOT REQUIRE "MAJOR SURGERY" TO REMOVE AND
 REPLACE A COMPONENT.  #BUILD IN MODULAR FASHION.

ACTION: ESTABLISH CLEANLINESS REQUIREMENTS.
 COMMENT: ENCAPSULATE OR USE BAGS AND LOCAL PURGES WHENEVER POSSIBLE TO
 REDUCE DEMANDS ON FACILITIES.

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ID: (1847.00)  Issue(s): DESIGN :
Issue(s) cont.: :
Issue Source: (N2-PBO MOD LIST )  (POST 51-L PRELIM. MOD LISTING)
Description:
DESIGN ENGINEERING -- JIM PHILLIPS

STUDY/ESR/MOD

"PCR CEILING -- PAD A: NEED TO REPLACE THE PERFORATED PANELS WITH SOLID
ONES AND RTV IN PLACE, TO KEEP DEBRIS FROM ABOVE THE CEILING FALLING ONTO
THE PAYLOADS. (30/6)"

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ID: (2140.00)  Issue(s): DESIGN :
Issue(s) cont.: :
Issue Source: (N2-PBO MOD LIST )  (POST 51-L PRELIM. MOD LISTING)
Description:
PCR -- ROWLAND NOBIES

STUDY/ESR/MOD

"IMPROVE CONTAMINATION PREVENTION OF PAYLOAD CHANGEOUT ROOM, B.Q., SIDE 1 DOORS
H2O PROOFING (RAIN ENTRY). (1/1)"

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ID: (2445.00)  Issue(s): MAINTAINABILITY :
Issue(s) cont.: :
Issue Source: (DB HTM FLT MODS )  16-JUN-86
Description:
CATEGORY 3 (DESIRABLE)
"PCR PGM WHITE PAINT PADS A & B : THE EXISTING EPOXY PAINT CHIPS AND
CONTAMINATES THE PCR AND PAYLOADS. (29/13)"

************************************************************************************
1.4.5 PAYLOAD BAY CLEANING (Tentpole 5)
(Continued)

1.4.5.3 Related Schedule History

Since there was no requirement for contamination control in the original design criteria, no time was allotted in the 160 hours turnaround for this activity. For the 51-L OPF processing 27.5 hours were spent in cleaning and inspecting the payload bay. See Figure 1. During this time other operations in the payload bay were restricted. The same amount of time was used on the 61-B flow for cleaning and the cargo was two PAM's, which are the simplest cargo.

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<td>B. CLOSEOUT</td>
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* All timetabs indicate 3 shift/day operations
** Does not require new technology - but goes beyond the bandaid fix

51-L OPF PROCESSING
Figure 1

1.4.5.4 Current STS Methods and Timeline Improvements

CURRENT STS METHODS

V1176 -- PAYLOAD BAY CLOSEOUT CLEANING (STANDARD, SENSITIVE/HIGHLY SENSITIVE) - OPF

OBJECTIVE:
A. To clean accessible Payload Bay (PLB) surfaces to one of three cleanliness level options as required to support turnaround and mission requirements.

B. To qualitatively assess the types and levels of various contaminants with the intent of improving contamination controls.

OPERATIONS: Design of the OPF was based on good clean shop practice. No provisions were made for a class 100,000 clean facility. The only environmental control is a standard air conditioning system. After more requirements were imposed by the cargo community, a curtain was added around the upper platform and control is maintained on the personnel allowed into the area. Before cargo is installed in the Orbiter, or the payload bay is closed out prior to transfer to the VAB, an inspection and cleaning is performed. The entire midbody is inspected for one of the following specifications:

Visual Clean 1 - (VCI) (standard) - Absence of all particulate and non-particulate visible to the normal unaided eye at a minimum light level of 50 ft. candles at a distance of 5-10 ft.

-59-
1.4.5 PAYLOAD BAY CLEANING (Tentpole 5) (Continued)

Visual Clean IA (VCIA) (sensitive)- Absence of all particulate and non-particulate visual to the normal unaided eye at a minimum light level of 50 ft. candles at a distance of 2-4 ft.

Visual Clean 2 (VC2) (highly sensitive)- Absence of all particulate and non-particulate visible to the normal unaided eye at a minimum light level of 100 to 200 ft. candles at a distance of 6-18 in.

After the cargo bay doors are closed, the contamination is controlled by the orbiter purge air, which is maintained as class 5000, and the payload changeout room, which is maintained as class 100,000.

TIMELINE IMPROVEMENTS

If the proper facilities are provided, the time to perform the inspection and cleaning could be reduced by 90 to 95 per cent. A change in the cargo requirements to accept the original criteria of good shop practice could eliminate this timeline completely.

1.4.5.5 Operational Evaluation

Contamination control has always had a big effect on the operational timelines in processing spacecraft and launch vehicles. The initial requirement to eliminate this was an attempt to reduce the processing time between flights. When the requirements of the cargo community were accepted and no provisions were made to the facilities to maintain control of contamination, it added an extra amount of time to the flow.

Only a modification to the facility or a change of requirements can result in a reduction of time to maintain the proper cleanliness level of the payload bay.

1.4.5.6 Conclusions and Recommendations

STS

To support the present shuttle configuration and the cargos that have been designed and manufactured, the only practical solution would be to design a modification to the OPF. This design would have to provide the required contamination control plus access to the payload bay for installation of horizontal payloads in the OPF.

FUTURE VEHICLES

Future requirements for new cargo should include a provision that the cargo must be containerized to maintain the level of contamination control required by the cargo.
1.4.6 ANOMALY RESOLUTION (Tentpole A)

1.4.6.1 Summary

In the context of this study, Anomaly Resolution is considered to be the entire range of actions beginning with fault detection and including fault isolation, spares available for replacement, retest and reverification.

In today's STS ground processing environment, there is an unreasonable amount of time involved in troubleshooting anomalies, repairs, cannibalization, and system recertification. The reasons for this are based on Program decisions made during the early Orbiter design phases: (1) The state-of-the-art used fifteen years ago; (2) design compromises from the 160-hr turnaround design criteria because of funding, cost, weight, schedule, etc. (3) ignorance of operational requirements; and (4) disregard of the impact of operations manhours and on-line time on life cycle costs.

Traditionally, anomaly resolution for complex launch vehicle checkout has been a complicated, labor-intensive, time-consuming, costly task requiring extensive effort from large numbers of highly-trained system support technicians.

With on-line time costing in the neighborhood of $30K/hr during ground operations, it is imperative that the available technology be exploited to produce cohesive tools and results. This has not been done and the result is reflected in ground operations where the technician is furnished a myriad of tools and documentation, which are confusing and often contradictory. The end result of this is lengthy repair times and a significant waste of manpower and dollars.

Since the initial Orbiter design, the development curve of built-in-test(BIT) and built-in-test-equipment(BITE) has been almost vertical. It is necessary that these concepts and available hardware be incorporated in future vehicle design requirements -- otherwise, just the ground operations portion of the life cycle costs will drive us out of the Space business. The advisability of incorporating extensive mods of this type for the current shuttle is questionable from the standpoint of cost effectiveness and require specific and detailed cost trades. Weapon system development in DOD has provided the funding for this fast technology advance and NASA must take advantage of its availability. Our technology search readily revealed over 100 very pertinent papers and reports. Typical of these is the "Proceedings of the Joint Services Workshop: Artificial Intelligence in Maintenance" which includes 513 pages of relevant papers. Study recommendations for this topic of Anomaly Resolution draws heavily on these rich sources of documentation and describes the basic technology available.
During the analysis of available documentation, it became readily apparent that the technology required for a quantum jump in Anomaly Resolution (fault detection; fault isolation; fault resolution; fault-tolerant computers; fault-tolerant software; data-fault tolerance; fault-tolerant system hardware; replacement without shutdown; and spares selection) is here today with applications development proceeding at a remarkable pace. However, caution must be observed in assuming that the application of "Artificial Intelligence" is a panacea for the immediate future. Much of the applicable AI technology is still in development and not yet available for incorporation into systems; this is especially true of specific applications work.

This rapid advancement is being driven by the requirement to reduce life cycle costs — resulting in R & D maintainability funding by the Air Force, Navy, Army, and Commercial companies for equipment and aircraft such as the F-16 and the Boeing 767 and 777. This technology is readily available so that NASA and its contractors do not have to reinvent the wheel, but can readily build on the in-progress development funded by DOD and the commercial airplane companies.

A complete discussion of anomaly resolution includes the topics of spares, cannibalization, and adequate line replaceable unit (LRU) repair facilities.

1.4.6.2 Related Issues

The STS problems and inefficiencies in the process of fault detection, fault isolation, and fault resolution (all of which are combined here under the title of ANOMALY RESOLUTION) have been repeatedly documented by our Issue source documentation in:

* 51-L Findings
* Presidential Commission Report on 51-L
* Rockwell Maintenance Technology Study
* Air Force Operational & Test Evaluation Center Reports
* AFSC/NSIA Space Transportation Panel (Cost Reduction & Cost Credibility Workshop)

The specific ANOMALY RESOLUTION issues related to STS are documented in Volume 4 of this report under the categories of:

* Fault Detection
* Design
* Design Criteria,
* Expert System
* Automation
* Technology
* Cannibalization
The following related issue descriptions from the study database are typical:

1. "Approximately 24 OMI’s (Operations & Maintenance Instructions) are currently required to troubleshoot problems and retest systems during each turnaround processing of the Orbiter in the OPF."

2. "System downtime could be decreased by incorporation of both anomaly detection and fault isolation."

3. "Provide increased built-in-testing for automatic fault detection/isolation."

4. "Provide the capability for ground systems to perform diagnostic monitoring and checkout of on-board systems."

5. "High leverage technology areas for Operations & Logistics include expert systems/artificial intelligence in the areas of fault detection & isolation, vehicle checkout & launch; automated software generation; and fault tolerant avionics."

6. "High leverage technology areas applicable to future architectures for Launch Operations: Expert systems & artificial intelligence for use in subsystem fault detection & isolation, vehicle checkout & launch. Avionics system improvements such as on-board fault detection, isolation, and diagnosis."

7. "The logistics support for Challenger in the 51-L ground processing was inadequate, since it created a need to remove parts from other orbiters to continue operations. For 51-L, 45 out of approximately 300 required parts were cannibalized. These parts ranged from bolts to an OMS TVC actuator and a fuel cell. The significance to operations of cannibalization is that it creates: (1) significantly increased efforts to accomplish the same work due to multiple installation and retest requirements, (2) schedule disruption due to added work and normally later part availability, and (3) orbiter damage potential due to increased physical activity in the vehicles. These efforts make cannibalization operationally unacceptable."

8. "Spare parts are in critically short supply. The Shuttle program made a conscious decision to postpone spare parts procurements in favor of budget items of perceived higher priority. Lack of spare parts would likely have limited flight operations in 1986."

Additional detail of related ANOMALY RESOLUTION issues can be obtained from VOLUME 4 of this report: ID numbers 1194, 1703, 1722, 1743, 1358, 1748, 1752, 1753, 1755, 1773, 1774, 112, 119, 158, 200, 412, 602, 608, 620, 626, 1000, 1707, 2734, and 4102.
1.4.6.3 Schedule History

The troubleshooting and system recertification as-run schedule for 51-L is shown here as Figure 1 because it is typical, most recent, and best documented. It shows that 51-L processing during November and December of 1985, anomaly resolution involved some 48 shifts and 964 technician manhours plus engineering, QA, and support manhours. There were approximately 24 OMI's required to accomplish the troubleshooting and system recertification.

<table>
<thead>
<tr>
<th>EFFICIENCIES/TECHNOLOGIES</th>
<th>NOVEMBER 1985</th>
<th>DECEMBER 1985</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TROUBLE SHOOTING &amp; SYSTEM RECENT (ANOMALY RESOLUTION)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* All timebars indicate 3 shift/day operations

51-L OPF PROCESSING
Figure 1

1.4.6.4 Current STS Methods

The inefficiency of today's methods of anomaly resolution in the Orbiter turnaround processing is, of course, a direct result of the Orbiter design not meeting the 160-hr design criteria. Because of cost, weight, and schedule compromises and the low priority of operational requirements and life cycle cost, during the design phase of STS, even the self-test and fault tolerant technology available in the early seventies was not utilized in the design. Consequently, the 50-hrs serial time allocated in the 160-hr schedule has grown to typically 384-hrs. Whereas the original design concept relied heavily on self-test, the actual design makes it necessary to brute force the troubleshooting with poor access to test points and a requirement to remove and replace equipment with the result that extensive retests are required.

A typical example of extensive retests, as a result of inaccessibility, is in the design of the air recirculation filters and debris screens. After each flight, these screens and filters must be removed and cleaned. To gain access to these, several electronic modules must be removed, then reinstalled and retested. This is not only a time consuming operation, but also requires power be removed from the orbiter with the result that access to the crew module is restricted during this time period.

ORIGINAL PACE IS POOR QUALITY
1.4.6 ANOMALY RESOLUTION (Tentpole A)  
(Continued)

There is very limited capability to analyze anomalies that occur in flight so that fault isolation procedures can be scheduled and completed within the time frame of the next turnaround.

Of course, no anomaly resolution can take place efficiently without adequate LRU spares, replacement parts, and local KSC maintenance and repair shops. Lack of these has led to extensive cannibalization, multiple remove and replace activity, and the resulting multiple retests required. During the STS-33 flow, for example, there were extensive cannibalization actions to and from Challenger (099). Examples are listed below:

1. Engine mounted heat shields and attaching hardware (to 102) 
2. Fuel Cell #1 (from 103) 
3. Plunger on flipper door (to 102) 
4. R/H wing duct (from 104) 
5. Engine mounted heat shields & attaching hardware (from 104) 
6. Thermal barrier (from 103) 
7. NLG tires (from 103) 
8. WSB liquid sensor (from 103) 
9. ET/Orb purge system line (from 104)
10. PDI (from 103) 
11. WCS (from 104)
12. ME #2 SSMEC (to 102) 
13. 12 MPS temp transducers (from 102) 
14. Spare MDM (from 102)
15. Champ experiment camera (from 102) 
16. Gas sample bottle pyro plugs (from 102) 
17. EVA hatch cover (from 104)

1.4.6.5 Technology Application Requirements

It was an unfortunate compromise that the original STS design had to forego the available self-check and fault-tolerant capability available in the early 1970's. Since that time, the progress curve in these technical areas has been almost vertical because of DOD requirements and funding.

Even today, the full cost of Operations is not recognized by the NASA Design organizations; particularly, the fact that Design typically represents only 3 to 10 percent of the Life Cycle Costs and that it is in the Design Phase that Operational considerations can provide order-of-magnitude payoffs.

The competitive international environment and the need for a dependable, airline type schedule to meet immediate and forthcoming NASA and DOD launch requirements make it mandatory to provide fully automated anomaly resolution during the Design Phase of future vehicles and to provide where cost effective, through block changes, advanced capability for STS in the 1990's. The Technology to accomplish this exists today with the techniques of EXPERT SYSTEMS, ARTIFICIAL INTELLIGENCE, SMART BIT, BITE, REDUNDANCY, FLY-BY-WIRE, EMBEDDING, TRANSPARENCY, -- only application development is required in the areas of: * FAULT DETECTION * FAULT ISOLATION * FAULT RESOLUTION * FAULT-TOLERANT COMPUTERS * FAULT-TOLERANT SOFTWARE * FAULT-TOLERANT SYSTEM HARDWARE * LRU REPLACEMENT WITHOUT SYSTEM SHUTDOWN (WHERE LRU REDUNDANCY EXISTS) * SPARES SELECTION & AVAILABILITY

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FAULT DETECTION: A process which discovers or is designed to discover the existence of faults; the act of discovering existence of a fault. One or more tests performed to determine if malfunctions or faults are present in a unit.

FAULT ISOLATION: Where a fault is known to exist, a process which identifies or is designed to identify the location of that fault within a small number of replaceable units. Tests performed to isolate faults within the unit under test.

FAULT RESOLUTION: Where the defective replaceable unit has been identified, repaired or replaced, and system satisfactorily retested.

FAULT-TOLERANT COMPUTERS, SOFTWARE, AND SYSTEM HARDWARE: Where the computer, software, or system hardware does not fail because of an individual fault.

FAULT-TOLERANT DATA: Transient data errors must be absorbed without causing false alarms or inappropriate action.

REPLACEMENT WITHOUT SHUTDOWN: Where redundancy exists, have the capability to replace an LRU and retest without shutting the system down.

SPARES SELECTION AND AVAILABILITY: Spares must have high funding priority and be selected through a thorough technical selection process.

1.4.6.6 Technology Evaluation

After determining the anomaly resolution technology application requirements, a technology search was performed using the XTKB (Expanded Technology Knowledge Base) developed for this Study and the NASA RECON database. Approximately 200 technical papers and document abstracts were screened from various "anding" of available secondary search keys in RECON including:

AEROSPACE TECHNOLOGY TRANSFER, AIRCRAFT MAINTENANCE, ARTIFICIAL INTELLIGENCE, AUTOMATIC TEST EQUIPMENT, B-1 AIRCRAFT, BLOCK DIAGRAMS, BOEING AIRCRAFT, CHECKOUT, CYBERNETICS, DATA ACQUISITION, DIAGNOSIS, ELECTRICAL FAULTS, ELECTRONIC EQUIPMENT TESTS, EMBEDDED COMPUTER SYSTEMS, EXPERT SYSTEMS, F-15 AIRCRAFT, F-16 AIRCRAFT, FAILURE ANALYSIS, FAILURE MODES, FAILURE, FAULT TOLERANCE, GLASS FIBERS, GROUND SUPPORT EQUIPMENT, GROUND TESTS, IN-FLIGHT MONITORING, INTERFACES, ISOLATION, LEARNING, MAINTENANCE, MALFUNCTIONS, MICROPROCESSORS, ON-BOARD DATA PROCESSING, ON-LINE SYSTEMS, PATTERN RECOGNITION, R & D, SPACE MAINTENANCE, SPACE MISSIONS, SPACE SHUTTLE BOOSTERS, SPACE SHUTTLE ORBITERS, STANDARDIZATION, STATISTICAL TESTS, TECHNOLOGY ASSESSMENT, and TRADEOFFS.

Where the abstracts appeared promising, actual documents or papers were obtained and studied from an application standpoint. The results of this effort were 42 papers with direct application to this technology requirement. These are listed in the bibliography at the end of this topic.
Improvement of FAULT DETECTION, FAULT ISOLATION, and FAULT RESOLUTION techniques is based on the rapidly developing technology of COMPUTERS, SOFTWARE, EXPERT SYSTEMS, and ARTIFICIAL INTELLIGENCE applied to TESTABILITY. EXPERT SYSTEMS, with a number of commercial successes demonstrated and many military developments are currently underway. Maintenance expert systems are currently difficult to implement, but there appear to be approaches that avoid the knowledge engineering bottleneck. Metarules and machine learning have the potential to substantially reduce cost, development time, and best of all -- Life Cycle Costs. Expert systems with ability to understand circuit function and malfunction are expected within the next three years. To have a common understanding of terms it is necessary to differentiate between EXPERT SYSTEMS and ARTIFICIAL INTELLIGENCE.

EXPERT SYSTEMS (ES)-- Store the knowledge of an expert. The system is able to retrieve and process the stored knowledge to perform such functions as diagnosis, monitoring, prediction, and planning. Currently, all expert systems are "rule based", that is, the knowledge is stored in the form of if-then or situation-action rules. These rules (also called production or meta rules) form a network of inferences that are used to perform the expert functions, Section 1.4.6.9.

ARTIFICIAL INTELLIGENCE (AI)-- Automated reasoning, which is the process of drawing conclusions from facts.

Our survey included the following six possible testability improvement areas with a potential for near-term application with, or as part of, an AI approach:

1. Self-improving diagnostics
2. More effective fault detection and isolation
3. Discrimination between false alarms and intermittent faults
4. Reduction of skills required for maintenance
5. Integrated diagnostics
6. Design for testability
Potential AI solutions for these six testability areas can be adapted to eight basic applications:

1. **Computer-aided Preliminary Design for Testability (CAPDT)** provides a testability assistant directly available during preliminary design phases.

2. **Smart Built-In Test (Smart BIT)** used in boxes or cards can identify intermittent faults and reduce false alarms.

3. **Smart System Integrated Test (Smart SIT)** is a system level Smart BIT which performs testing while the system is operating.

4. **Maintenance Expert - Box (ME Box)** provides offline test management with self-improvement of functional tests.

5. **Maintenance Expert - System (ME SYS)** describes the kind of capability that can be expected in the immediate future.

6. **Maintenance Expert - Smart (ME Smart)** incorporates the benefits/risks of including learning capability in the maintenance expert system and its ability to access to Smart BIT information.

7. **Automatic Test Program Generation (ATPG)** would be able to understand circuit functional operation; however, this application has the lowest payoff.

8. **Smart Bench** is a maintenance expert system developed for use with bench test equipment controlled by an engineering work station.

Figure 2 is a matrix of Anomaly/Testability Problems vs. potential AI Solutions.
COMMERCIAL DEVELOPMENT EXAMPLE: To remain competitive in the international market, BOEING is pursuing a reliable, low-maintenance design philosophy for its new 7J7 airplane. Use of avionics incorporating large-scale integrated circuits to provide multiple function capability is expected to reduce the number of LRU's in the 7J7 by 30-50% compared with 757/767 airplanes.

In addition to size, weight, and power requirement reductions, this approach is expected to yield MTBF 3 to 20 times better than today's equipment and reduce the cost of spares by 20 to 50%. An on-board maintenance system will interface 6 or 7 DATA high-speed data buses to the central maintenance computer. Each data bus will communicate with several avionics subsystems, each containing one or more LRU's and associated BITE. Critical subsystems will interface to 3 data buses to assure redundancy in case of system failures, while less critical sub-systems will be linked with only 1 or 2 buses. The central maintenance computer for the on-board system would display subsystem status and fault information on a printer or control display unit located in the aircraft, or send it to a ground maintenance center by means of an Arinc Communications Addressing & Reporting System (ACARS) VHF.

An example of today's state-of-the-art commercial airplane checkout is the Boeing 757/767. An "on airplane" data system is provided that supports validation of the system-level operation of the Flight Management System (FMS) with built-in test equipment (BITE). The BITE test support equipment is shown in Figure 3. Figure 4 shows the relative locations of personnel and equipment during test and validation. The Study Team observed this system being used for a 767 airplane overall test conducted just prior to rollout. A semi-automatic Flightline Tester Van (SAFT van) was connected to the 767 data bus and flightdeck touchscreen control. The flightdeck technician, utilizing the touchscreen and a radio intercom was able to test, take corrective action and retest on command. All data was stored on a floppy disk in the SAFT van which provides a data trail for QA and closeout. QA was not required during testing; the floppy disk data trail was used after-the-fact for this purpose. The test was accomplished by 6 technicians over 3 regular 8-hour shifts for a total of 144 manhours. While not directly comparable to Orbiter checkout, Figure 4 makes an interesting point when compared to the OPF checkout of the Orbiter.
1.4.6 ANOMALY RESOLUTION (Tentpole A) (Continued)

AIRPLANE TEST CONTROLS
- PROBE HEATER INPUTS
- LRU CONNECTORS
- A/P HYDRAULIC PRESSURE (ELECTRIC PUMPS)
- SYSTEM CONTROLS
  - FLAP OVERRIDE
  - A/P AUTO/LOG
  - L/B MODE
  - FMC-COU DATA
  - LANDING GEAR HANDLE

AIRPLANE AVIONICS SYSTEMS
- 80 BUS
- ADC
- ILS
- PSEU

EXTERNAL TEST SUPPORT SYSTEMS
- ROT-STATIC AIR
- SAFET VAN
- ILS
- GEAR AIR/GROUND SWITCHES
- AA
- MCDS RECORDER
- ILS ANTENNA
- IFR-802 ILS TEST SET
- BITE TESTS

Figure 3

RELATIVE LOCATIONS OF PERSONNEL AND EQUIPMENT
Figure 4
Technology Breakthroughs: Three major breakthroughs have occurred that will have wide reaching effect on the productivity of maintenance expert system applications and on both developer and user interfaces. These are: (1) the comprehensive development of diagnostic meta-rules (highly organized special rules) for expert systems; (2) the proliferation of engineering work stations; and (3) the recent announcement of "Universal Pin Electronics" (UPE) developed by Giordano Associates under contract with the Army Electronics Command, Ft. Monmouth, N.J. (This UPE integrates analog and digital stimulus / measurement capability by using VLSI chips and extending that capability to every ATE pin eliminating the need for ATE switching.

Typical useful expert systems have required more than 5 manyears to develop. In order to create maintenance expert systems quickly, they must be built from generic components so that a large portion of the software can be reused on each implementation. Corporate developments, such as those at GE and DEC have created expert systems using these techniques which intelligently manage test sequences and can be adapted to a new system.

The engineering work station provides a common host for development of all the recommended AI applications. Used in conjunction with the rule structure of expert systems, it permits a synergistic development of the requirements common to many of the applications (diagnostic rules, network understanding, graphical display, etc.).

Engineering work stations have gained widespread acceptance in the aerospace industry. There are multiple sources for both hardware and software that make work stations big enough, fast enough, and cheap enough to be really useful. They provide direct, personal access to AI applications by the electronic designers. As a result, the majority of end users will be able to make use of applications in engineering work stations.

These basic applications, using developing technology, and the ready availability of engineering work stations provide the capability to drive LIFE CYCLE COSTS down significantly -- Provided NASA and AIR FORCE Program Management insist on contractual requirements to put $$$ and effort into forcing OPERATIONAL DESIGN CRITERIA (Figure 5) in the area of ANOMALY RESOLUTION.
OPERATIONAL DESIGN CRITERIA
Figure 5

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OF POOR QUALITY
1.4.6.7 Cost Trades

There are two basic justifications for expending funds to improve the automation of ANOMALY RESOLUTION. These are:

1. Reduction of LIFE CYCLE COSTS (LCC)

2. SCHEDULE IMPROVEMENT -- The tangible improvement of reducing vehicle turnaround time by eliminating or reducing anomaly resolution tentpoles, thus allowing more flights per vehicle in a given time period.

There are numerous Air Force funded studies in the areas of expert systems / maintenance technology / testability / and artificial intelligence. While these studies were performed for AF fighter activities, the maintenance function involved for fast turnaround and low LCC apply equally well to STS type activities. There are two Air Force sponsored reports which are comprehensive in their cost-trade analyses. One of these reports was sponsored by the Wright-Patterson Avionics Laboratory and the other by the Rome Air Development Center (RADC). These two reports form the basis for this Study’s cost-trade analysis:


To assess the LCC impact of improvement on testability factors for anomaly resolution, seven criteria were used in the RADC study:

1. Test time reduced
2. Hard fault detection
3. Hard fault isolation
4. Intermittent discrimination & isolation
5. False alarm reduction
6. Experience Level Reduced
7. Reduced removals
A discussion of each of these factors is appropriate as a basis for understanding how improvement lowers life cycle costs.

Test Time Reduced: Many test programs must run through the entire test sequence every time, while providing the technician with no capability to make gross tests of entire sections, loop on a particular test sequence, or slowly accumulate test information to diagnose intermittents. The use of maintenance expert systems is not necessary to make the testing more flexible and hierarchical, but their incorporation produces this effect. A reduction in test time benefits LCC by increased utilization of test equipment and the test technicians for ATE (Automatic Test Equipment) bench and system tests. Large benefits in this area could also result in fewer ATE systems being required at depot repair sites.

Hard Fault Detection: At every level of testing it is desirable to have the best fault detection coverage for hard faults possible. This is relatively easy for digital circuits, but is much more difficult for circuits or systems which have poor DFT (Design for Testability), use analog circuits or microprocessors. Improving testability during the design phase of the electronics provides the greatest benefit for the effort expended, because improved fault detection in the unit has greater LCC benefits than improved fault detection solely based on ATE. Only by improving testability is it possible to detect all hard faults.

Hard Fault Isolation: Because it is a more difficult task and a less mature capability, there is more opportunity for improvement in hard fault isolation than in their detection. Both can be improved through the use of DFT (Design for Testability) techniques and by a maintenance expert system that can learn the isolation strategies for real world faults. However, it takes a greater level of DFT to locate a fault inside a complex network that to detect a fault at its output.

Intermittent Discrimination and Isolation: Intermittent discrimination and isolation is an immature field which could provide benefits to many types of systems. The test system must allow a fuzzy description of the state of a circuit (i.e., a description covering a range of states: good, most likely good—may have suspected as intermittent, degrading—but-not-yet-bad, and bad). Products which accumulate information about an item's marginally bad performance during the time it is running provide much more help in detecting and isolating intermittents than a single slow test of performance on an ATE system. That approach also provides the basic capability needed to discriminate between intermittents and false alarms.
False Alarms Reduced: Causes of false alarms are most easily eliminated using CAD tools to help reduce false alarm causes through better designs. CAD can provide the ability to simulate full system operation with BIT and software running and to simulate various hard and soft faults. The simulation results interpreted by the designer allow him to find and then eliminate many of the causes of false alarms. Additionally, methods to acquire and record fault information during circuit and system debug (in full scale development), will find many real world/environmental causes of false alarms. This information is most easily acquired by some form of BIT that has non-volatile memory after it's fielded, hardware becomes virtually unalterable; however, the BIT test software can still be changed (under configuration control). Smart BIT with reprogrammable features allows experimentation with proposed modifications and would also ease their incorporation.

Experience Level Reduced: Much of commercial and military electronic testing has gone from bench to ATE so as to increase the reliability of testing and to reduce time. The military ATE software, however, has greatly limited the technician in what he can do. The technician is rarely able to modify the test sequence or test limits to diagnose a problem. As circuits become more complicated, especially microprocessors, there tends to be little or no information available to the test technician on their operation. ATE has also become very complex to operate and each one is different. It requires 6-12 months of training for technicians to become familiar with operations of complex ATE, and learn how to compensate for its limitations to perform the testing and diagnosis required. Skill level reduction is, based on the reality of military service experience, better expressed as "experience level reduction." Because of this, it has been the conclusion in segments of the military community that ATE should be changed so as to require less training for use in performing maintenance. As a corollary, ATE must be configured to work with the technician, rather than just having him serve as a "button pusher". Instead of having a computer-guided probe, where the technician is told where to place a probe so that the computer can make a test, there should be interactive diagnosis where both the human and the computer can suggest areas of the circuit to be tested. This is already being done with sophisticated software in some commercial card-testing ATE. At KSC, where the technician skill level is more experienced and stable, the interactive diagnosis capability is even more important.

Reduce Removals: Removing an item from a system causes a whole chain of costly actions to occur. Field maintenance data exists showing that 40% of the avionics equipment removed from an aircraft is fault-free. Using better DFT to provide less isolation ambiguity reduces removals directly. Improved fault isolation decreases the need for spares.
ANOMALY RESOLUTION (Tentpole A) (Continued)

Reduce Removals (Continued): Shotgun substitution methods break spares -- typical Boeing experience is that with a printed circuit board with 5 or more layers, there is a 50-50 chance of a layer interconnection being destroyed if the board is removed twice.

The above definitions provide a basis for understanding how the Operations and Logistics Support portion of LCC can be reduced. By looking at the distribution of costs against the DOD Life Cycle Phases, Figure 4, and identifying the element in such a way as to support cost analysis, the typical distribution of DOD is shown below:

<table>
<thead>
<tr>
<th></th>
<th>Total Weapon Sys</th>
<th>ATE Type Sys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>3%</td>
<td>10%</td>
</tr>
<tr>
<td>Fabrication</td>
<td>21%</td>
<td>30%</td>
</tr>
<tr>
<td>Operations Personnel</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>Support Spares</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>Replacement Spares</td>
<td>10%</td>
<td>60%</td>
</tr>
<tr>
<td>Maintenance Personnel</td>
<td>35%</td>
<td></td>
</tr>
<tr>
<td>Replacement Material</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>12%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Note: It should be noted that designers are often not aware that detailed design phase is typically only 3-10% of the total life cycle cost.

Cost Analysis: Specific cost analysis cannot be provided without defining the system and its operation and support concept. It is the intent of this section to provide insight into the scope of cost savings to be gained by implementation of automated anomaly resolution.

Figure 6: illustrates the distribution and time relationship of the contributions to the life cycle cost of a typical system.

Figure 7 & 8: further detail the operation and maintenance cost.
Figure 9: illustrates the LCC savings that could be realized by developing integrated testing and maintenance state-of-the-art. Shown are cost deltas to current implementation of onboard test and maintenance methods.

Figure 10: shows that testability incorporation during preliminary design has the largest potential impact (70%) on life cycle costs.

DISTRIBUTION OF LIFE CYCLE COST
Figure 6
1.4.6 ANOMALY RESOLUTION (Tentpole A)
(Continued)

TYPICAL SYSTEM LIFE-CYCLE COST
Figure 7
Source: Program Management for Functional Managers,
The Defense Systems Management College, Fort Belvoir

TYPICAL SYSTEM LIFE-CYCLE COST BREAKDOWN
Figure 8
From Program Management for Functional Managers
The Defense Systems Management College, Ft. Belvoir, Virginia
### Potential ITM Cost Impact

**Figure 9**

<table>
<thead>
<tr>
<th>LIFE CYCLE PHASE</th>
<th>% OF SYSTEM LIFE-CYCLE COST</th>
<th>ROUGH ESTIMATE OF ITM COST IMPACT</th>
<th>IMPACT OF ITM ON LIFE-CYCLE COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redesign</td>
<td>10%</td>
<td>Up 10%</td>
<td>Up 1.0%</td>
</tr>
<tr>
<td>Production</td>
<td>30%</td>
<td>Up 3%</td>
<td>Up 1.5%</td>
</tr>
<tr>
<td>Operation &amp; Maintenance</td>
<td>(60%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repair Labor Costs</td>
<td>32%</td>
<td>Down 13.1%</td>
<td>Down 4.2%</td>
</tr>
<tr>
<td>Spares &amp; Repair Material</td>
<td>14%</td>
<td>Down 15%</td>
<td>Down 2.1%</td>
</tr>
<tr>
<td>Operation</td>
<td>10%</td>
<td>Down 15%</td>
<td>Down 1.5%</td>
</tr>
<tr>
<td>Initial Logistics Support</td>
<td>4%</td>
<td></td>
<td>Down 5.5%</td>
</tr>
</tbody>
</table>

% of LCC Cost Impact on Operations and Support Costs

**Figure 10**

Testability Incorporation during Preliminary Design, Has Largest Impact

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The bottom line is that by developing and incorporating anomaly resolution techniques in the early design phases, Life Cycle Costs can be reduced by at least 5% -- a significant amount when you are dealing with $billions on STS or STAS.

Indirect Benefits: while not as apparent as the direct savings, can provide even greater benefits. Reduced processing time leads to more flights/year. Based on a 3-orbiter fleet and 12 total flights/year, an improvement in processing time sufficient to provide one additional flight of payloads would be an 8 1/2 percent gain in use of a multi-billion dollar national resource.

Anomaly Resolution technology would make a significant contribution to this end. This improvement could dwarf the direct manhour savings. DOD analyses for aircraft life cycle costs do not include this type of factor.

**COST ANALYSIS EXAMPLE OF ANOMALY RESOLUTION TECHNOLOGY APPLIED TO 51-L**

Since neither the SPC Contractor or NASA were able to provide significant manpower/manhour vs. OMI data, we have extrapolated any data available to create the following 51-L cost analysis for Anomaly Resolution with a confidence factor of 1.5. The following table provides a cost estimate from the best data available.

<table>
<thead>
<tr>
<th>OMI</th>
<th>HOURS</th>
<th>TECH(M/H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1003</td>
<td>23.16</td>
<td>234</td>
</tr>
<tr>
<td>V1005</td>
<td>3.3</td>
<td>40</td>
</tr>
<tr>
<td>V1008</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>V1022</td>
<td></td>
<td>432</td>
</tr>
<tr>
<td>V1028</td>
<td>16</td>
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<tr>
<td>V1034</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1048</td>
<td>5</td>
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<tr>
<td>V1053</td>
<td>8</td>
<td>40</td>
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<tr>
<td>V1060</td>
<td>6</td>
<td>60</td>
</tr>
<tr>
<td>V1062</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>V1065</td>
<td>8</td>
<td>56</td>
</tr>
<tr>
<td>V1080</td>
<td>4</td>
<td>32</td>
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<tr>
<td>V1084</td>
<td>8</td>
<td>64</td>
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<tr>
<td>V1086</td>
<td>44</td>
<td>220</td>
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<tr>
<td>V1098</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>V1103</td>
<td>16</td>
<td>64</td>
</tr>
<tr>
<td>V1123</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>V1161</td>
<td>19.9</td>
<td>112</td>
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<tr>
<td>V1173</td>
<td></td>
<td>15</td>
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<tr>
<td>V1177</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>V1178</td>
<td>8</td>
<td>56</td>
</tr>
<tr>
<td>V1200</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>V3500</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>TOTALS:</strong></td>
<td>222+?</td>
<td>1211+?</td>
</tr>
</tbody>
</table>

**SUPPORT M/H @ 33%**

400+?

**TOTAL M/H**

1600+?

-80-
OMI's not required on 51-L had the potential of another 100 online hours and 500+ manhours plus 150 direct support (engr, QA, etc.) manhours.

Also not included in the above figures are the additional hours brought about by lack of spares and the resulting cannibalization with its resultant time and manhours for reinstallation and retest.

1.4.6.8 Conclusions and Recommendations

1. Because of the significant investment required to develop the hardware, software and techniques in the areas of EXPERT SYSTEMS and ARTIFICIAL INTELLIGENCE for testability, NASA should join the DOD/Industry team who have been funding and developing the early progress in this area. Specifically, for the STS and STAS design agencies to develop direct contact with key AFSC personnel at the Rome Air Development Center and the Wright-Patterson Avionics Laboratory.

2. With STS activity planned for another 15 years, serious consideration should be given to incorporating some degree of improved anomaly resolution via block changes in the early 1990's when the improvements now under intensive development begin to reach fruition. Cost effectiveness would be most likely when improvements are combined with mandatory safety mods. Proof of concept mods to the current Orbiters may also be a high priority for future vehicle development. Systems which should be considered include:

- Electrical Power Distribution & Control (EPD&C)
- Power Reactant Storage & Distribution (PRSD)
- Environmental Control & Life Support System (ECLSS)
- Data Processing System (DPS)
- Communications (Comm)
- Guidance, Navigation, & Control (GN&C)
- Main Propulsion System (MPS)
- Auxiliary Power Unit (APU)
- Hydraulic System (Hyd)

3. In June 1984, an Artificial Intelligence Applications Committee with ten DOD and Industry members and chaired by Anthony Coppola, Chief of the Reliability & Maintainability Engineering Techniques section of the Rome Air Development Center developed four major recommendations in this area for DOD. Allowing for very minor changes in the past two years, these recommendations are still valid and have been implemented by DoD. The results of these actions are available for use by the NASA design agencies. Because of their comprehensiveness and currency, these recommendations are quoted below:
"Despite the fact that the members of the committee worked completely independently, there is only one area of significant disagreement in the position papers. This is the recommended language in which AI programs should be written. An area of general agreement was that expert consultant systems can, and should, be applied to maintenance now. There was even a general consensus of the development resources required for an expert system: two years time, $200,000 in computer costs, and five to ten man-years per year. However, discussions after review of the position papers would cause these to be considered minimum projections, with perhaps double the computer resources and five years of time required. The following recommendations are the chairman's consolidation of the position papers, discussions with the RADC contributors, and his derivations from the information given above.

RECOMMENDATION NO. 1

The DoD should take advantage of the relative maturity of technology for creating expert systems. Specific applications of maintenance expert systems should be started immediately, and multi-application maintenance experts developed and standardized.

The DoD should immediately develop expert systems for existing maintenance applications where maintenance is particularly troublesome. As an example, the AFIT-RADC-KRALC program would attempt to create a system to work with the F-15 analog printed circuit board test station. It would first be programmed with the knowledge required to troubleshoot only one board, the most troublesome of those – the ATE handles. This would show the value of the approach and permit debugging of the system. More knowledge would be added incrementally until the system handled every board assigned to the original ATE. At this point, it would hopefully be cost effective to scrap the original system. If not, the expert system would still earn its keep by its superior handling of problem boards. Each service could pick a promising candidate (a system which is not handled well by the ATE, and for which expert maintenance personnel are both available and willing to cooperate in creating the expert maintenance system). As it builds and refines the maintenance expert system, the service would improve the Operational readiness of the candidate system while it gains experience and confidence with the AI technology. No risk would be involved, since the existing ATE would still be in place. Resources would be two to five years calendar time, 10-20 man-years of effort and $200,000 to $500,000 in computer costs for each system. Each system would pay for itself in short order, by reducing maintenance time as much as 50%. However, the real value of these first efforts would be in the knowledge gained.
1.4.6 ANOMALY RESOLUTION (Tentpole A)

(Continued)

To permit immediate application, the first AI maintenance systems should be built in the language and architecture most convenient to the builder and user, with a blanket exemption from any current policies on languages. The only exception would be that any test sequence generated by the system for outside use would be in ATLAS. No cost involved. Will cause a proliferation of languages for first systems, but will permit earlier implementation, by years, and provide information needed for ultimate standardization. (Chairman's recommendation based on conflicting inputs in position papers.)

To improve cost-effectiveness in the longer term, the DoD should develop versatile maintenance experts for specific domains, such as digital electronics, which are used in many different systems. They would contain the necessary theory and diagnostic strategies for their specific domains. They must be user friendly (interact in a subset of English, explain their actions, and adapt to the skill of the user), and, presuming progress in computer aided instruction (CAI) techniques, each system could ultimately serve as an integrated ATE, maintenance trainer and training aid. One basic system (for one domain) could be built in two years with 10 manyears effort. System specific data bases would be incorporated during the development of the systems to be tested. Refinements would be added as developed. Benefit would be the elimination of the need for reinventing the engine for every application, easily worth millions in development and training savings. Technical risk is moderate.

Further improvements in cost-effectiveness would be made possible by developing a system building tool to automate the creation of the system specific data required by the expert system discussed in the preceding paragraph. The tool would extract the needed knowledge whether from a human expert, or, ideally, from a description of the system to be tested. This will minimize one of the major costs of the expert system. Cost would be about $200,000 a year in computer costs and ten manyears per year. A prototype could be available in two years, but it might take a five year program to complete a supportable product. Benefit would be significant savings in time and elimination of errors for every new system to which it is applied. No more than five applications, if that much would repay the costs with a dividend in earlier test system availability and easier modification as the design of the system under test changes. Technical risk is presently considered high.

Note: The expert systems would eliminate the long test programs now used in conventional ATE systems. To do so the DoD could prohibit all new ATE systems to use inflexible sequential test procedures. Instead, require the use of segmented test programs which are called out in the order needed for most rapid fault isolation using the strategies now available in LOGMOD, STAMP, and FIND. Cost will be a significant increase in effort required to program the ATE and some additional memory. Will probably permit the elimination of one maintenance shift, paying for itself in one year or two. (Chairman's recommendation)
RECOMMENDATION NO. 2

Develop "smart" BIT for digital electronic system to minimize false alarms, identify intermittent failures, improve coverage of BIT. An RADC proposed FY-84 effort hopes to provide design concepts which could be used by individual designers to construct smart BIT in their particular applications. A complete series of studies leading to the design of an on-board knowledge based monitoring system or the design and test of experimental BIT systems could run two to four years and one to six million dollars. Benefits are incalculable since they include the work of reduced mission aborts due to false alarms. More tangible benefits could be a 90% reduction in false alarms, and the decrease of the portion of units sent to repair which test good, from the present 30% to perhaps 10%. A successful application should pay for itself in two years of operation on one system, and provide a measurable improvement in the ready rate of the system using it.

RECOMMENDATION NO. 3

Fund applied Research and Development of AI for maintenance, both to improve the capabilities of maintenance expert systems and to apply AI to other maintenance applications. Some specific topics are:

1. Automating the creation and presentation of Technical Manuals.
3. Developing crisis alerting systems.
4. For expert maintenance systems, developing requirements for languages and computer systems, techniques for improving user friendliness, and more sophisticated approaches (e.g., means of forming rules from the circuit itself rather than from an expert familiar with the circuit.)
5. Developing AI systems for Automatic Test Program Generation (ATPG). The current AI programs used to develop test patterns for digital combinatorial logic should be extended to sequential logic and analog circuits. Systems should work from the circuit description and provide test vectors in ATLAS.
6. Applying AI techniques to VLSI, VHSIC design for fault tolerance and testability. This should be incorporated into the VHSIC phase three study plans.
7. Developing knowledge based computer aided instruction (CAI) systems for maintenance training. Note: this could ultimately be incorporated into the ATE itself.
8. Developing self-improving diagnostics and test program sets.
Other topics will be identified by the FY-83 studies begun by RADC, NAEC, AFHRL. Recommend 6.2 programs be started by all three services, funded at one million dollars per service per year, to begin work. Promising developments should be followed by 6.3 projects with appropriate higher funding.

RECOMMENDATION NO. 4

Foster an integrated DoD-industry approach.

Coordinate the various efforts of DoD agencies through a tri-service group on AI applications to maintenance. Recommended group would be a committee under the JLC Automatic Testing Panel. It could also be under JDL working group for AI, but seems more appropriate for the Automatic Testing Panel because of its interface with other committees. Participants would include all service agencies involved to share responsibilities and avoid duplication of efforts. It would also provide a contract point for DoD and industry. (Chairman's recommendation)

Encourage private avenues of development of AI applications to maintenance; continue to support industrial IR&D in the area, express DoD interest at appropriate meetings, provide copies of this report to industry. The NSIA Testability Committee, which parallels the JLC panel, should be encouraged to create a subgroup on AI applications to serve as an industry focal point. The close working relationship of the NSIA committee and the JLC panel would be a natural avenue for creating a dialog on AI applications. (Chairman's recommendation)
1.4.6 ANOMALY RESOLUTION (Tentpole A)
(Continued)

1.4.6.9 Bibliography
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ORIGINAL PAGE IS OF POOR QUALITY
1.4.6 ANOMALY RESOLUTION (Tentpole A)  
(Continued)  

1.4.6.9 Bibliography (Continued)  

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1.4.7 WCCS FUNCTIONAL CHECKS (Tentpole B)

1.4.7.1 Summary

The Window Cavity Conditioning System (WCCS) is designed to allow the cavity between inner and outer windows to "breathe" to prevent condensation during flight. The current system is made up of eight assemblies, each with a desiccant assembly and two check valves with interconnecting tubing. The eight are:

1. command module inner
2. command module outer
3. right hand forward inner
4. right hand forward outer
5. left hand forward inner
6. left hand forward outer
7. left hand aft outer
8. right hand aft outer

The active elements in the desiccant are buff colored with random blue beads that change to buff when the moisture limit is reached. Early in the program the designer lost confidence in the indicator beads and the units were changed after each flight. The current procedure inspects them every flight and changes them every other flight. The units are not readily accessible even for inspection because the initial design did not properly address maintainability. The leak check and flow test setup has a number of flex hoses that are susceptible to damage during testing.

Although the initial 160-hour schedule did not allow any time for this activity it took 152 hours for S1-L.

Future programs must have more consideration of maintainability in early stages of design. Maintainability and accessibility must be "designed in", not merely "tacked on" at the end of the program.

It is recommended that the desiccant/check valve assembly be redesigned slightly to allow for "quick changeout" operation and spares be stocked so serial time impact be minimized. Desiccant materials should be researched to be sure that we are still using the most effective product.

1.4.7.2 Related Issues

1. Accessibility of the units for inspection or removal/replacement.

2. Removal of some assemblies require disassembly of other orbiter components.

3. Need to have spares available.

4. Need a positive reliable indicator.

5. Requirements are not in line with frequent flight philosophy.
6. Success rate of components is not periodically factored into test rate.

7. Test set-up and tear-down cycles are wearing out flex hoses.

The following are examples from the Issues database:

```
ID: (C957.00)  Issue: DESIGN
Issue Source: (WE-POST MC LIST)  (POST 51-L PRELIM. MOD LISTING)
Description:
STUDY

"PROVIDE AN EXTRA SET OF WC5S DESICCANTS SO THAT THE DESICCANTS CAN BE
REFURBISHED OFF-LINE TO REDUCE VICTA CRITICAL PATH TIME."
(1/12)
```

```
ID: (C957.00)  Issue: REQUIREMENTS
Issue Source: (WE-POST MC LIST)  (POST 51-L PRELIM. MOD LISTING)
Description:
CATEGORIES 2 (DESIRABLE)

"PROVIDE LANFLUX FLOW DENSITY IN OFF AREA FOR WC5S REFURBISHMENT. (1/12)"
```

```
ID: (C957.00)  Issue: DESIGN
Issue Source: (WE-POST MC LIST)  (POST 51-L PRELIM. MOD LISTING)
Description:
CATEGORIES 2 (DESIRABLE)

"MODIFY WC5S USE TO ROCKLINE THE SYSTEM AS MUCH AS POSSIBLE. THE EXISTING
LONG (EXPENSIVE) FLEX HOSE ARE DAMAGED NEARLY EVERY FLOW (1/9.1)
```

1.4.7.3 Schedule History

1. No time was allotted in the original 160-hour turnaround for this task.

2. The STS-XX schedule allotted 92-hours.
1.4.7 WCCS Functional Checks (Tentpole B)  
(Continued)

3. The 51-L flow required 152-hours to complete. See Figure 1.

4. Quick-change modules without sampling could be done in 3 hours.

<table>
<thead>
<tr>
<th>EFFICIENCIES/TECHNOLOGIES</th>
<th>NOVEMBER 1985</th>
<th>DECEMBER 1985</th>
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<tbody>
<tr>
<td>TECHNOLOGY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WCCS FUNCTIONAL CHECKS</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* All timetables indicate 3 shift/day operations

**51-L OPF PROCESSING**  
Figure 1

1.4.7.4 Current STS Methods

**CMI V1076 -- ORBITER WCCS FUNCTIONAL TEST**

**OBJECTIVE:** To provide procedures to verify function of the orbiter window cavity conditioning system.

**OPERATIONS:** The current procedure inspects them every flight and changes them out every other flight. OMRSD requires retest of all portions of the system that have been opened. The units are not readily accessible, even for inspection. Forward reaction control system (FRCS) access panels 21-27 and 21-28 must be removed to access the forward inner and forward outer desiccant assemblies. The right hand payload support avionics (PSA) beam must be removed to access the aft outer cavity desiccants. The desiccant assembly is then removed from the orbiter. On alternate flights the desiccant cartridge is removed from the assembly and sent to an off-line clean room facility for refurbishment. The check valves are tested while the desiccants are being refurbished. The cartridge is then replaced in the assembly and the assembly reinstalled. A leak check and flow test is performed and dew point samples are taken.
1.4.7.5 New Technology Requirements

A long life desiccant with reliable indicators that would require less frequent change-out.

A desiccant that can be recharged in place.

Research through RECON and other databases have not uncovered anything promising in either area.

1.4.7.6 Technology Application Requirements

A rechargeable nitrogen blanket system in place of the desiccants. This could probably be accomplished with no weight penalty.

A simple, and perhaps the most practical, solution would be to redesign the assembly to be quickly and easily changed out with spare units. The desiccant could be replaced off-line, the assembly tested, and put in stores. A simple design with flat faces and a rubber-type sealing surface and easy to install fasteners could substantially reduce the change-out time. This method could even be performed every launch and still save flow time if units were tested prior to returning them to stores.

1.4.7.7 Technical Evaluation

The initial design did not properly address maintainability. Four shifts could be saved if the units could be accessed without removal of other orbiter parts. Relocating the desiccant assemblies to an accessible location (such as to the payload bay) could help here. If the initial design had been a quick-change module and spares had been provisioned to allow for off-line refurb the current test length could be reduced to a minimum. The Shuttle Processing Contractor (SPC) system engineer feels that changeout of desiccant every four or five flights would be more reasonable than the current every other flight procedure. See Figure 2 below for an example of one of the present assemblies.

---

**Figure 2**

LR/RH OUTER AFT DESSICANTS

---
The desiccant assembly could be replaced with a small GN₂ container and regulator to maintain a pressure slightly above external orbiter pressure. The container could be recharged in place. Since the unit is recharged in place and doesn't have to be removed accessibility should not be an issue.

1.4.7.8 Shuttle Cost Trades

IMPLEMENTATION DESCRIPTION: Redesign of desiccant/check valve assembly to be accessible and to allow for quick changeout for unit from spares.

<table>
<thead>
<tr>
<th>Implementation Cost Estimate:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
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<td>Design &amp; Qual. Tests</td>
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<tr>
<td>Manufacturing</td>
</tr>
<tr>
<td>Modification &amp; Installation</td>
</tr>
<tr>
<td>TOTALS</td>
</tr>
</tbody>
</table>

Savings cost for 3 vehicles

<table>
<thead>
<tr>
<th>Current</th>
<th>New</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IMPLEMENTATION DESCRIPTION: Revise requirement to allow 5 flights between changeout of desiccant cartridges.

IMPLEMENTATION COST ESTIMATE: This would be an OMEGAR paper change only.

Savings cost for 3 vehicles

<table>
<thead>
<tr>
<th>Current</th>
<th>New</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IMPLEMENTATION DESCRIPTION: Redesign of WCCS to have a small GN₂ bottle to supply a blanket purge in the cavities.

IMPLEMENTATION COST ESTIMATE:

<table>
<thead>
<tr>
<th>Test</th>
<th>Manhours</th>
<th>Material</th>
<th>Comment</th>
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<tbody>
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<td></td>
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<tr>
<td>Manufacturing</td>
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</tr>
<tr>
<td>Modification &amp; Installation</td>
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<td></td>
</tr>
<tr>
<td>TOTALS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

cost for 3 vehicles

-92-
1.4.7 WCCS Functional Checks (Tentpole B) (Continued)

GROUND OPERATIONS SAVINGS FOR FUTURE VEHICLES: The cost savings for future vehicles is approximately equal to cost avoidance of the current STS costs.

**COST ANALYSIS:** This data is presented in Section 1.6.3, COST TRADE SUMMARY.

1.4.7.9 Conclusions and Recommendations

**STS**

The Shuttle Program needs to reevaluate the philosophy of OMRSD’s. This particular example is one instance where the task time is unreasonable for an operational vehicle. We need to provide the potential for “learning curve” reduction of manual tasks. Re-evaluation of the “change out every other flow whether it needs it or not” criteria presently being used should be reviewed.

Redesign of the desiccant/check valve assemblies to allow each unit to be quickly changed is the recommended solution for this problem. Once incorporated this modification could save well over 100 hours per flow. This modification should include relocation so that the desiccants could be inspected without removal of other Shuttle components or assemblies. During the redesign, the designer should verify that we are using the best available desiccant material for this application.

**FUTURE VEHICLES**

Future programs should avoid this kind of maintenance problem by considering operations at the time of initial design. Any component with a visual indicator should be designed for inspection “at a glance”. Any component that is designed for periodic changeout should be easily accessible with fasteners designed for quick replacement. Both future and current programs could benefit from a more reliable longer-life desiccant, therefore, the search should continue.
1.4.8 WINDOW POLISHING (Tentpole C)

1.4.8.1 Summary

During SRB (Solid Rocket Booster) separation a haze of contamination forms on the Orbiter front windows. Since the most critical use of the windows is during landing this has become a plaguing problem. The requirement to clean (polish) the windows was not anticipated in the initial 160-hour turnaround schedules. The 144 hours required to prepare for 51-L launch is an unreasonable amount of time for an operational vehicle so this task is a candidate for improvement (Operations and Maintenance Instruction [OMI] V7253). The placement of the protective tent required during the cleaning operation precludes or impedes parallel work for some jobs performed at the nose of the vehicle.

A second reason this problem should be addressed is because cleaning (polishing) the windows cannot be accomplished prior to landing when it is most needed. Cleaning back on the ground merely precludes accumulation from more than one launch.

The solution therefore needs to allow the windows to be clear at the time of Orbiter landing. Redirecting the SRB separation motor exhaust would solve the problem but that would cause more problems than it solved, i.e., re-design and retest. The more logical solution then would be a non-stick surface for the windows or a jettisonable overlay. The chemical vapor deposition (CVD) of a diamond film on the outer pane appears to be a potential solution.

Future programs can avoid a similar occurrence by profiting from the lesson we have learned on the STS by careful design requirements. The data and experience gathered during the Shuttle flights provides a new baseline for future programs.

1.4.8.2 Related Issues

1. This is a slow, labor intensive operation. It is a "hand" operation that cannot be performed as precisely by any mechanized method.

2. Window contamination occurs during SRB separation and the need for clear windows is during landing. The cleaning (polishing) is accomplished after the actual need.
The following is a quote from document 84X10356, Space Shuttle Orbiter Thermal Protection System Flight Experiences:

**ORBITER WINDOW CONTAMINATION**

"The Shuttle Orbiter windows must meet normal aircraft requirements for pressure redundancy and provide optical clarity and freedom from distortion to allow for operation typical of standard aircraft and other operations. In addition, the windows must have multimission capability to survive entry heating, insure single-flight safety after a micrometeoroid strike, and endure pressure stresses for at least 100 7-day missions. To satisfy these requirements, the window configuration consists of a three-pane construction: an outer fused-silica thermal, an inner alumino-silicate pressure pane, and a center fused-silica pane to serve as a redundant pressure pane.

Contamination of the outer surface of the windshields' thermal pane has occurred after each STS flight. This deposit or haze is most pronounced on the two center windshields, and efforts to remove this deposit with standard window cleaning agents (i.e., isopropyl alcohol, deionized water) have been unsuccessful. The source of this deposit has not been specifically identified, but the prime candidate appears to be the gasses from the plume generated by the solid rocket booster separation motors. Since this buildup of haze reduces pilot visibility, each window has been evaluated for acceptability prior to each flight. A hand polishing procedure, using cerium oxide, has been developed and used after each flight starting with STS-5. However, this polishing does not remove all the deposit and still requires an evaluation of each window's acceptability for the next flight."

1.4.8.3 Related Schedule History

1. No time was allocated for this task in the original 160-hour schedule.

2. 60-hours are allocated on the STS-XX integrated operations assessment.

3. 144-hours were required to accomplish this task during 51-L processing. See Figure 1.
The placement of the protective tent required during the cleaning operation precludes or impedes parallel work for some jobs performed at the nose of the vehicle. Although this activity has not yet been a "show stopper" as the flows become shorter it could easily become a real problem.

1.4.8.4 Current STS Methods

OMI V7253 -- WINDOW POLISHING FOR CONTAMINATION REMOVAL

OBJECTIVE: This OMI is to polish the orbiter window surfaces for contamination removal. It will polish windows 2 thru 5 (L/H and R/H forward and mid). See Figure 2. It will photograph an Air Force resolution chart through windows 1 thru 6. See figure 2 below.

OPERATIONS: A tent is built around the windows with a catch bag at the lower portion. Tile protective covers are installed over window perimeter tiles on the forward and mid windows on each side. The windows are then brushed and vacuumed to remove dust and lint particles. A polishing pad is fabricated by assembling alphalap felt polishing material over a rubber pad. The windows are then polished with a ceramic oxide/deionized water mixture. The polishing compound is cleaned off the windows with deionized water/Joy soap. The window surface is inspected with a fiberoptic light source to see if the process needs repeating. After all windows have been cleaned a resolution chart is placed on the outside of the window and a photograph is taken from the nearest seat in the orbiter cockpit. The photographs are inspected to verify that the windows are now cleaned satisfactorily.
1.4.8 WINDOW POLISHING (Tentpole C) (Continued)

1.4.8.5 New Technology Requirements

Develop a new material for the windshield with surface that contamination will not adhere to. (Present outer window pane is low expansion fused silica glass chosen for its high optical qualities, 5/8 inch thick.)

1.4.8.6 Technology Application Requirements

1) Provide an overlay that could either be jettisoned after ascent or be removed after flight.

2) Apply a treatment to the windshield that the contamination will not adhere to.

3) Redesign the Solid Rocket Booster (SRB) separation motor exhaust to prevent it from impinging on the windows.

1.4.8.7 Technical Evaluation

Polishing the windows does not solve the real problem here, it merely keeps from compounding it. The windows are contaminated at the time of separation and the real need for clear windows is at landing, so the polishing comes after the need. Therefore the best solution would be a material that the contaminants could not adhere to.

Technical databases were researched for new materials that might be hard enough to resist the contaminants. Two candidates were found. First, polycrystalline magnesium aluminate spinel (MgAl$_2$O$_4$) possesses an unusual combination of optical, dielectric, physical and mechanical properties that make it an attractive candidate for windows. It is exceptionally strong and hard for an optical material, has good thermal shock resistance and moderate thermal expansion coefficient. (Refer to paper “POLYCRYSTALLINE MgAl$_2$O$_4$ SPINEL FOR HIGH PERFORMANCE WINDOWS” by D. W. Roy and J. L. Hastert.)

The second and most promising material is the diamond film. The following are excerpt taken from High Technology Magazine/April 1987:

"Initially U. S. scientists were skeptical about reports from Russia in the 1970s that investigators at Moscow’s Institute of Physical Chemistry had made true diamond films via chemical vapor deposition—a process by which a carbon vapor is deposited on a substrate. The claims "seemed almost like alchemy," says Russell Messier, associate professor of engineering science and mechanics at Penn State. The scoffing waned during the early 1980s, however, when Japan's National Research in Inorganic Materials (Ibaraki) repeated the Russian work."
"The coatings are now made either by CVD techniques or by bombarding a substrate with high-velocity carbon ions, which then form a film. In the latter method, carbon ions may be generated from a hot carbon cathode or produced by "sputtering"—that is, knocked off a solid carbon block by a high-energy beam. Various ion-beam and sputtering methods are under study at the NASA Lewis Research Center in Cleveland.

Both types of techniques have generally yielded diamond-like rather than true diamond films. The diamond-like films are perfectly adequate for many applications, according to Bruce Banks, chief of the Electrophysics Office at NASA/Lewis. For example, this could be used to make abrasion- and corrosion-resistant computer disks, and infrared-transparent windows in aircraft that would stand up against pitting and scarring from raindrops at high speeds.

Among the most important developments in the CVD are methods (based largely on the addition of hydrogen to the methane) that allow diamond to be deposited on a wide range of surfaces, including metals, silicon, and glass; early methods allowed deposition only on other diamonds. Crystallume president says his company plans to use the Penn State technology to make a variety of novel products, including cutting tools, knives, surgical scalpels, computer disks, and windows for planes and spacecraft; also in the docket are heat sinks and heat-resistant enclosures for high-temperature electronic equipment."
1.4.8 WINDOW POLISHING (Tentpole C)  
(Continued)

1.4.8.8 Shuttle Cost Trades

IMPLEMENTATION DESCRIPTION: Design outer pane with CVD diamond on outer surface.

IMPLEMENTATION COST ESTIMATE:

<table>
<thead>
<tr>
<th>Item</th>
<th>Manhours</th>
<th>Material</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design &amp; Qual. Tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modification &amp; Install.</td>
<td></td>
<td></td>
<td>cost for 3 vehicles</td>
</tr>
</tbody>
</table>

**TOTALS**

GROUND OPERATIONS COST SAVINGS PER FLIGHT AFTER IMPLEMENTATION:

<table>
<thead>
<tr>
<th>Item</th>
<th>Current</th>
<th>New</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>VH2253 Window</td>
<td>100</td>
<td>300</td>
<td>$1E</td>
</tr>
<tr>
<td>Polish Polishing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>for Contamination</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Removal</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

GROUND OPERATIONS SAVINGS FOR FUTURE VEHICLES:

The cost savings for future vehicles is approximately equal to cost avoidance of the current STS costs.

**COST ANALYSIS:** This data is presented in Section 1.5.3, COST TRADE SUMMARY.
1.4.8 WINDOW POLISHING (Tentpole C)
(Continued)

1.4.8.7 Conclusions & Recommendations

STS

A jettisonable overlay is a possible solution for this problem. Using shape-memory (Nitinol or similar material) for retainers and springs, a system could be designed to be energized by the temperature extremes of outer space. This would be automatic, with no crew involvement, and would not require penetrations through the vehicle surface for wires or linkages. Once back on the ground the shape-memory could be reset and new overlays easily installed. Jettisoning, without damaging the Orbiter is, in itself, a problem.

The best solution, however, would be the one where no flight maintenance is required. The diamond hard surface currently being developed appears to be the better solution. This study therefore recommends that the diamond surface be further investigated.

FUTURE VEHICLES

The "lesson learned" from this problem should be to analyze designs that have retro rocket plumes pointed toward surfaces that might be contaminated. Advances in Computer Aided Design and data collected by STS should allow for more accurate prediction of flow patterns on future programs.

Diamond-type coatings on windows of manned vehicles should be considered as a low cost standard procedure.
1.4.8 WINDOW POLISHING (Tentpole C)
(Continued)

1.4.8.8 Bibliography (Window Polishing)

(Each of the references listed below has its own bibliography)

1. RECON 84X10356; NASA Conference Publication 2315;
D. M. Curry, D. J. Tillian
Space Shuttle Orbiter Thermal Protection System Flight
Experiences
Advances in TPS and Structures for Space Transportation
Systems Conference
December, 1983:

2. RECON 84A13505; AD-P003 202
Donald W. Roy, James L. Hastert, Coors Porcelain Company
600 Ninth Street, Golden, Colorado 80401
POLYCRYSTALLINE MgAl: O SPINEL FOR HIGH PERFORMANCE
WINDOWS

3. RECON 84N25089;
Clete J. Siebert, Fred A. Morris, 9 pages
PASSIVE SUN SEEKER/TRACKER AND A THERMALLY ACTIVATED
POWER MODULE
Martin Marietta Denver Aerospace, Denver, Colorado

4. HIGH TECHNOLOGY Magazine
Gordon Graff
April 1987 issue
"Diamonds find new settings", pages 45-47
INTRODUCTION

The development of a reusable thermal protection system was a major technical accomplishment of the early Shuttle development. Although the current TPS is far from optimal, it has proved to be durable as well as forgiving. However, future vehicles will require or benefit from more advanced and capable TPS. This requirement is fully recognized by NASA and Industry and extensive effort is already being expended in this direction (see TPS Reference 8). Consequently, this study has concentrated on the maintenance and non-destructive testing (NDT) and flight readiness verification of TPS tiles used on the Orbiter. In the case of the current Orbiter, the NDT of over 30,000 tiles during each turnaround is not even possible. This study examines R & D effort in the area of NDT of the tiles and reduced life cycle costs.

1.4.9.1 Related Issues

From the AFOTEC Launch Rate Capability Study:

"Repairs to the TPS, especially tile, have caused launch delays. Data collected during Orbiter processing shows that time to repair or remove and replace damaged tile, and the time needed to rewaterproof after flight, are major constraints to reducing turnaround time.

The characteristics of the TPS (low-density, porous silica glass) make it susceptible to absorbing water when exposed to certain environmental conditions. Thunderstorms can cause significant amounts of water to be absorbed by the tile while the Orbiter is at the Pad. The absorbed water is added weight that is carried into orbit. This reduces the performance margin and requires Orbiter positioning to evaporate the absorbed water. Water still trapped in the tile starts to evaporate and boil off during descent as the temperature rises. With the rise in temperature and if sufficient amounts of water are present, pressure will increase in the tile and cause damage.

Problems caused by water absorption were identified early in the program and the need to rewaterproof the TPS after each flight was known and planned for. Scotchgard was applied by spraying in order to waterproof the tiles. This method proved ineffective as heavy precipitation washes off the Scotchgard. The rewaterproofing method was changed on STS-7/OV-099. The application method used involved injecting a small quantity of silane and acetic acid solution, known as DC6079, into the tile. There were no known problems associated with technique until after the STS-17 mission.
1.4.9 THERMAL PROTECTION SYSTEM (TPS) (Tentpole D)
(Continued)

Post-flight inspections of OV-99 after the STS-17 mission (sixth flight of OV-099) revealed that a thermal protection tile was missing from the lower surface of the fuselage. Inspection of the tile cavity revealed that RTV577, used as screed material and RTV560, used as an adhesion material, had softened. A decision was made to remove other tile bonded over screed in the area of the missing tile and inspect for the same condition. The RTV was found not to meet the required hardness specification, leading to the removal of approximately 4100 tiles bonded over screed. Extensive investigation and laboratory testing has concluded that the waterproofing material, DC-6079, combined with water and thermal cycles causes softening of the screed. The rewaterproofing procedure was again changed to require Scotchgard spraying over areas that has screed and to use injections with DC-6079 in other areas for near-term solution.

"Flight experience has demonstrated that inadequate TPS waterproofing can have mission impacts, as well as impact to ground processing flows. Until a more effective agent than Scotchgard can be certified for use on the Orbiter, the potential for launch delays due to water-soaked tiles as well as changes to planned on-orbit attitudes to facilitate TPS drying will exist."

From the National Space Transportation and Support Study (1995-2010), May 1986. "The TPS maintenance is a Logistic System Cost Driver. Future Operational Concepts should minimize TPS inspections & closeouts and minimize repair. System Requirements should be -- no between flight servicing and weatherproofing."

From our Operational Analysis in this study -- The turnaround time on-line required for TPS inspection, repair, and validation has decreased drastically since the first several flights; nevertheless, the on-line time and the manhours involved are still very significant.
1.4.9 THERMAL PROTECTION SYSTEM (TPS) (Tentpole D)  
(Continued)

1.4.9.2 Schedule History

The initial design criteria (160-hr turnaround) allowed 40-hours flow time for TPS refurbishment. After the first 20 flights, the TPS tile replacements are shown in Figure 1. The OPF-XX schedule show on-line TPS refurbishment time as 336 hours. Typically, total manhours would be in the range of 2000 to 3000. A significant portion of this time is associated with test and verification of tile flight readiness.

![Tile Replacement History Chart]

**Figure 1**
1.4.9 THERMAL PROTECTION SYSTEM (TPS) (Tentpole D)
(Continued)

1.4.9.3 Today's Methods

For inspection and flight readiness verification there are two remaining major inspection problems associated with the TPS tiles, moisture intrusion and bonding. Flight damage is readily detected by macro and micro visual inspection.

Evolution into a macro-micro visual inspection was brought about by insufficient time available to perform both the original overall inspection and the needed repairs. With the macro-micro inspection, the overall vehicle TPS is given a gross inspection while selected areas receive detailed inspection. If a number of discrepancies show up in the detailed inspection, the option exists to expand into other areas. Also, the macro may lead directly to micro if the conditions warrant it.

Moisture intrusion on the Orbiter's lower surface is grossly detected with the use of infrared scanners but it is not a qualitative inspection.

A major problem with the tile system is verification of the bond strength in a non-destructive manner. Currently there are no NDT methods available; this has dictated the use of proof or pull testing as a means of bond verification.

The objective of OMI V6028, "Post Flight Orbiter Reusable Surface Insulation Inspection", is to perform post-landing and pre-ferry survey/inspection of the TPS and determine if components exhibit obvious latent/mission-induced damage that would require reservicing, repair, redesign, or replacement. The tasks involved are:

(1) Post landing Orbiter debris inspection and mapping verification.

(2) Engineering macro inspection of RSI (pre-ferry flight)

(3) RSI inspection (macro and micro)

(4) Engineering inspection / additional micro inspections

(5) Micro inspection of leading edge subsystem and nose cap (internal)

(6) Micro inspection of RCC panels no. 10 and 17 (internal)

(7) Micro inspection of RCC panel no. 9 (internal OV-102)

(8) Micro inspection of RCC panel no. 16 (internal OV-099) The procedures and authorization for infrared tests for moisture and pull tests for bonding are not OMI's.
1.4.9.4 Technology Application Requirements

The requirement for improved thermal protection systems is well understood and in work; consequently, this requirement is not addressed by this report.

This study does address the requirement which exists for developing fast, dependable, qualitative, repeatable, non-destructive tests for moisture and bonding. This is critical for reducing turnaround time for the existing STS tile and blanket thermal protection systems. Depending on the future type TPS used, these new techniques will be useful in whole or part for future vehicles.
1.4.9 THERMAL PROTECTION SYSTEM (TPS) (Tentpole D)
(Continued)

1.4.9.5 Technical Evaluation

After determining the technology requirement for TPS tile non-destructive testing, a technology search was made using the XTKB (Expanded Technology Knowledge Base) developed for this Study and the NASA RECON database. Technical papers and document abstracts were screened from various "and"ing of available secondary keys in RECON including:

THERMAL PROTECTION, ABSORPTIVITY, ACOUSTIC FATIGUE, ACCEPTABILITY, ADHESION TESTS, ANOMALIES, ASSEMBLING, BONDING, CONTAMINATION, CREEP TESTS, DAMAGE ASSESSMENT, MOISTURE, MOISTURE RESISTANCE, NONDESTRUCTIVE TESTS, PERFORMANCE TESTS, PREDICTIONS, PREFLIGHT OPERATIONS, PRELAUNCH PROBLEMS, QUALITY CONTROL, RADAR EQUIPMENT, SPECTROSCOPIC ANALYSIS, TENSILE TESTS, TEST EQUIPMENT, CHALLENGER, DYNAMIC TESTS, FAILURE MODES FATIGUE TESTS, ground SUPPORT EQUIPMENT, GROUND SUPPORT SYSTEMS, GROUND TESTS, ILLUMINATING, INSPECTION, LOAD TESTS, MATERIALS TESTS, MAINTENANCE, LASER APPLICATIONS, TENSILE TESTS, VIBRATION TESTS, WAVELENGTHS, WINDOWS, X R, X RAY DIFFRACTION, X RAY SPECTROSCOPY.

Where the abstracts appeared promising, actual documents or papers were obtained and analyzed from an application standpoint. The result of this effort was papers with direct application to this technology requirement. These are listed in the bibliography at the end of this topic.

PROBLEM DESCRIPTION: The tile material is made of microscopic silica fibers that are slurried with a binder, pressed and sintered into rigid, lightweight (9#/ft³) ceramic blocks. Individual tiles are machined from the blocks. The tile dimensions are typically 6"x6" and varies in thickness from 1/2" to 4". After machining, the top and sides of the tiles are coated with a thick borosilicate glass coating impregnated with pigments to provide the coating with its high temperature emissance properties. The coating also affords limited protection against moisture pick-up and handling damage.

The attachment of the tile to the aluminum skin of the vehicle is accomplished by adhesive bonding the components of the bonded system are shown in Figure 2.
Because of the low strength of the tile material and the thermal expansion mismatch between the tile and the aluminum, they could not be bonded directly to each other. A nomex felt pad called a strain isolation pad (SIP) was bonded between the tile and the aluminum to minimize lateral strain transfer.

Needling of the nomex pad to control its thickness and stiffness resulted in fibers oriented straight through the thickness of the pad. On loading of a tile, the straight fibers created hard points or stress concentrations in the bottom of the tile. This condition is shown in Figure 3. The net result was a lower bond strength than the design had taken into account.

![Stress Concentrations in Tile](image)

**Figure 3**

The tiles are extremely critical to reentry survival of the vehicle. The loss of a single tile could have serious consequences. Because of the extreme criticality of the tiles, successful completion of a proof test, although very important and confidence building, was not considered sufficient to ensure the adequacy of the tile bond strength. An NDT technique is required to ensure no significant damage occurs to the tiles during testing.

**Acoustic Testing** (ref 86A34627): Early in the STS program, a crash test program was implemented by JSC and Rockwell/Downey, to develop and implement an acoustic emission monitored proof test system. This was implemented at KSC on a 24-hr, 7-day/week schedule. Eighteen systems (Figures 4 & 5) were used to certify approximately 30,000 tiles for the first Orbiter flight. Each test required about one hour to complete and a total of about 20,000 tests were performed overall. Although many problems were encountered in this application of acoustic emission, particularly extraneous noise sources causing high reject rates, the problems were generally solved or worked around. Application of acoustic emission in this instance was extremely beneficial in that it added confidence to an unusually critical system that was yet to be proven. Acoustic emission helped screen out tiles that had inadequate strength. Acoustic emission monitoring is no longer used in tile testing; however, to obtain a confidence level prior to the first flight, it was the only method available.
The objective of the tests was to establish a pass/fail criteria based on acoustic activity or signatures prior to failure. Full size tiles with the intermediate SIP layer were bonded to aluminum substrates. Loading conditions evaluated for acoustic emission signatures included high and low strain rates, sustained loading, and fatigue cycling. Acoustic activity could be detected long before actual failures occurred. The progressive nature or time dependency of the bondline failures were ideally suited for acoustic emission monitoring. The difficulty was establishing gain settings that were not overly sensitive and yet still provided enough conservatism to ensure that early damage signatures could be identified. A fatigue test sequence was utilized that enabled the difficulty to be overcome. The sequence consisted of the following: (1) incremental proof load with 60-second holds at each level, (2) terminate hold when significant acoustic activity occurred, (3) decrease load to 80% of maximum proof load attained and (4) fatigue cycle from zero to 80% until failure occurred or 400 cycles were reached. A typical fatigue test profile is shown in Figure 6.
The acoustic emission acceptance criteria were based on the fatigue test results. Tiles which passed the 400 cycles without failure were considered successes or good tiles and those that failed were considered failures or bad tiles. The acoustic counts that occurred during the proof test prior to the start of each fatigue were evaluated for criteria that would screen all of the bad tiles and maximize the acceptance of good tiles. The logic is illustrated in Figure 7. Criteria were established such that each failure was rejected by two or more of the acceptance criteria. The criteria that were established are shown in Figure 8.

ACOUSTIC EMISSION REJECT CRITERIA

In addition to passing the proof test, each tile had to pass the four acoustic emission criteria. Failure to meet any one of the criteria was cause for rejection.

ACOUSTIC EXCITATION-/LASER SENSING: The search for a cost-effective NDT for bond integrity led NASA/KSC, in 1984, to begin discussions with the Idaho National Engineering Laboratory (INEL) and its contractor, EG&G. The outgrowth of these discussions led to a contract to develop an experimental technique using acoustic excitation and laser measurement of the tile response.

In early tests, the tiles were excited using a variety of methods including white noise and impulses from an acoustic speaker, as well as mechanical methods. In all cases, the tiles showed characteristic spectra with several distinct vibration modes present. The two strongest modes of vibration were believed to be fundamental frequencies of two plate modes in the anisotropic composite material from which the tile is formed. The relative amplitudes of these oscillations have been shown to be directly dependent on the bond between the SIP and the tile and the SIP
and the aluminum plate used in these tests. When bond deterioration was induced, a large drop in amplitude of the second spectral peak was consistently observed as well as several less dramatic but possibly significant spectral shifts. It was a consistent observation that the spectra generated by the tile were very sensitive to variations in the bond condition.

A second phenomenon was investigated in which the tile-SIP oscillation was examined at lower frequencies where the system would behave as a simple mass-spring with the tile being the mass and the SIP as the spring. The spring constant would then depend on the total area of good bond. Tests were limited in this area, however, by the difficulty in obtaining a simple excitation method with sufficient low frequency content to give an acceptable signal/noise ratio. This approach has promise as an independent or complementary measurement.

PHASE I RESULTS from the EG&G STUDY (summarized)

1. Non-contacting acousto-optic sensing is feasible. Good agreement between laser-acoustic sensor system and standard accelerometer between 200 and 5000 Hertz. No apparent problems in sensing directly off a tile surface even after normal mission degradation.

2. Resonance vibrations of the tiles studied are affected by disbands. Both the point and image data showed the effects of bond slicing in the single tile tests.

3. Similar tiles have significantly different spectra, but all of the tiles studied show common spectral features.

4. Phase I Study results provide beginning point for complete understanding of the phenomena.

EG&G STUDY PHASE II PLANNING

1. Refine and qualify the sensor design.

2. Model and analyze the dynamic tile behavior.

3. Prototype system design.

4. Fabrication, checkout, integration into Orbiter processing. (See Figure 9).
1.4.9 THERMAL PROTECTION SYSTEM (TPS) (Tentpole D)
(Continued)

ACOUSTO-OPTIC SENSING SYSTEM CONCEPT (EG&G)
Figure 9

BACKSCATTER X-RAY TECHNOLOGY

During PHASE 2 of this STS Ground Operations Efficiencies / Technologies Study, it is planned to further investigate the potential of backscatter x-ray techniques using actual Orbiter tiles and IUS engine inspection facilities.

1.4.9.6 Conclusions and Recommendations

Extensive effort is going on the development of improved thermal protection systems. This Study was limited to investigating the problems and potential solutions for ground operations efficiencies in non-destructive testing of Orbiter tiles.

An automated non-contact NDE is required to reduce turnaround time and provide the degree of reliability necessary.

Based on the Phase 1 reported progress of the EG&G, KSC sponsored, investigation into an Acoustic Excitation/Laser Sensing System, it is recommended that this effort be accelerated to provide an on-line system to support Shuttle processing as soon as possible.

It is also recommended that bonded samples of Orbiter tiles be provided to Boeing for a preliminary check into the feasibility of using backscatter X-ray techniques currently being used on the IUS solid rocket motors.
1.4.9 THERMAL PROTECTION SYSTEM (TPS) (Tentpole D)
(Continued)

1.4.9.7 Bibliography - TPS

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ORBITER THERMAL PROTECTION SYSTEM

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NASA Langley Research Center
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EVALUATION OF SHUTTLE ORBITER THERMAL PROTECTION TILES

(7) RECON 83N30702
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SPACE SHUTTLE THERMAL PROTECTION SYSTEMS

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NASA Langley Research Center
516 page Symposium Document, December 1983
ADVANCES IN TPS AND STRUCTURES FOR SPACE TRANSPORTATION
SYSTEMS

-113-
1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)

1.4.10.1 Summary

With the existing mission requirements for STS, the fuel cell still appears the best option for the Orbiter energy storage system. If the mission duration should change drastically in either direction, however, batteries or solar systems could become viable options subject to detailed trade studies.

While the Orbiter fuel cells are several times more efficient than those for Apollo, they are not state-of-the-art. The requirement exists for development of reliable, easily maintainable, high density fuel cells to be incorporated in a Shuttle Block Modification.

For future vehicles, there are a number of promising energy storage devices in various stages of development in the areas of: regenerative fuel cell systems, Ni/H2 batteries, Na/S batteries, and Li/SOCl2 batteries. Any specific recommendations would, of course, involve detailed trade studies of performance, energy density, maintainability, life cycle costs, development risk, etc. The NaS batteries appear to be the best known bet for further development in the area of materials research.

1.4.10.2 Related Issues

Reference: N_Sub

"THE PREL GSE CHECKOUT WAS COMPLETED JUST PRIOR TO S007."
1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)

1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)

1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)

1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

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1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

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1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

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1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

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1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)

1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

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1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

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1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)

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(Continued)

1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

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1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

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1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

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1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)

1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)

1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)

1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)

1.4.10  POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  

(Continued)
1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E) (Continued)

STUDY

"FUEL CELL IMPROVEMENT MODIFICATION. DELETE END CELL HEATERS AND MODIFY START-UP HEATER."

(56/4) (N)

STUDY

"PROVIDE SUFFICIENT INSTRUMENTATION CHANNELS SO THAT FUEL CELL SINGLE CELL VOLTAGES ARE AVAILABLE."

(56/4) (N)

STUDY

"INSTALL PRESSURE TRANSDUCERS AT OUTLET OF REACTANT REGULATORS."

(57) (N)
1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)
(Continued)

**Issue(s):** DESIGN

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<th>(POST 51-L PRELIM. MOD LISTING)</th>
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<td>Location:</td>
<td>(OREITE)</td>
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<td>Or. N. Mission:</td>
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<td>Description:</td>
<td>(POST 51-L FELI LISTING)</td>
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**STUDY**

"PROVIDE COOLANT ACCUMULATOR INSTRUMENTATION WITH QUANTITY READOUT INSTRUMENTATION."

**NEW**

**STUDY**

"PROVIDE INDIVIDUAL POSITION INDICATORS AND COMMENTS TO H2 AND O2 PURGE VALVES."

**NEW**

**STUDY**

"PROVIDE A "SELF CHECK" CIRCUIT IN FUEL CELL PH SENSOR."

---

**ORIGINAL PAGE IS OF POOR QUALITY**
1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)

(Continued)

ISSUE: 14000.60
ISSUE: TIME ON-LINE
ISSUE SOURCE: BOEING IPG-G GROUND OPS. SPATR. S-1C-8F
OPERATION: N/A
LOCATION: N/A
ORIGIN/MISSION: SPACE TRANSPORTATION ARCHITECTURE STUDY
SOFTWARE/HARDWARE: N/A
REFERENCE DATA: N/A
DESCRIPTION:
"LEONORES LEARNED: PRESENT OILEITE EXHIBITS EXCESSIVE FAILURE RATES."

EXAMPLES:
1. BRAKING SYSTEM REQUIRES CONTINUOUS REPLACEMENT
2. FUEL CELLS HAVE POOR LIFE EXPECTANCY
1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  
(Continued)

1.4.10.3 Schedule History

The ground operations turnaround time for the PRSD is not consistent with the requirements for an operational capability.

Figure 1 shows the shifts of work for processing the PRSD system for 51-L at the OPF. The total time for 51-L includes the PAD time shown below:

<table>
<thead>
<tr>
<th>Task</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tank Set 4 R &amp; R</td>
<td>120</td>
</tr>
<tr>
<td>OPF Ops &amp; T/S</td>
<td>139</td>
</tr>
<tr>
<td>Pad Ops (Purge/Load)</td>
<td>36</td>
</tr>
</tbody>
</table>

(7 hrs were Pad clear and 17 hrs local clear for this operation)

1.4.10.4 Current STS Methods

The descriptions below of the current STS OMI's for the Power Reactant and Storage System (PRSD) provide a graphic view of the complications, time on-line, and manhours expended because of the current design. These descriptions represent 3794 pages of OMI’s and exclude a very significant page count for non-OMI procedures.

DESCRIPTONS:

V1091 -- ORBITER PRSD CRYO DRAIN (LPS) (407 pages)

OBJECTIVE: OMI is to provide instructions to detank and inert Orbiter PRSD LO₂ and LH₂ tanks at the OPF using the Launch Processing System (LPS). This is a hazardous OMI due to LO₂ from Orbiter through GSE to vents.

PREPARATION: Includes Pneumatic Systems Setup; Cryogenic Systems Setup; and Engineering Walkdown.

GSF/VERIFY POWER UP: LPS activated; OPF GH₂ and LH₂ Systems Power Up; HWS Power Up by instrumentation; OPF GO₂ and LO₂ Systems Power Up; Verify Orbiter Power and Cooling per Standard Power Up.

* All timebars indicate 3 shift/day operations

51-L OPF PROCESSING

Figure 1
1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)
(Continued)

OPERATIONS: GH₂/LH₂ and GO₂/LO₂ Systems Purges/Pressurization; Moisture Sample using S72-1106-1; Sample Pressure for Purity; Pressurize and Leak Check Orbiter/GSE Interface; Power Down Fuel Cell Power Plants and Start Cool Down; Drain Orbiter PRSD LH₂ System until Tanks/GSE Drain Warmup is Accomplished; Purge Orbiter T-0 Line and Lockup Static Purge in Orbiter PRSD LH₂ System; Drain Orbiter PRSD LO₂ System until Tanks/GSE Drain Warmup is Accomplished; Purge Orbiter T-0 line and Fuel Cells Lockup Static Purge in Orbiter PRSD LO₂ System.

V1022 -- FUEL CELL AND PRSD SYSTEM TEST - ORBITER
VEHICLE - LPS (810 pages)

OBJECTIVE: Provide procedures for verification of fuel cell/PRSD instrumentation and controls, including functional operation of system relief valves and control circuits on the Orbiter.

PREPARATION: Perform -- Pre-Power Switch List and Pre-Power GSE Placards and Setups.


PERFORM: H₂O RV Checks - ISOL VLVS to ECLSS Water Tanks Closed. Display VDR O₂ STS GSE and VDR29 H₂ Sys GSE.; Perform Purity and Moisture Samples as follows: Purge and Sample O₂ Sys GSE, Gas and Liquid Systems with GHe; Purge and Sample H₂ System GSE, Gas and Liquid Systems with GHe; Depress GSE to Pad Pressure. Mate Umbilical Lines at Mid-Body, T-0, Horizontal Drains, and Overboard Relief Ports. Display VDR51 - Orbiter Mechanical System. (Cont’d)

Verify Orbiter Power and Cooling per Standard Power Up; Vehicle Valve Cycle (EM) and Flow Checks Utilizing Pad Pressure from GSE; FC/Cool and Loop Instrumentation Verification; FC Heater Operational Checks: FC Heater Operational Checks; H₂O Line Strip Heaters, H₂O Valve Heaters; H₂O Relief Port Heaters; O₂/H₂ Vent Port Heaters.

DISPLAY: VDR29, H₂ System GSE and VDR51, FC Operations.

PERFORM: Modify Cryo Tank Control Logic PGMS VCR05 and 06 to Allow Checkout; Pressurize Vehicle Manifolds via Horizontal Drain Line and Perform Manifold Decay Test; Instrumentation Checks and Pod External Leak Checks; Tank CV Reverse Leakage Checks; Manifold RV Crack/Reseat Checks; Horizontal Drain Pod I/F Leak Checks at Flight Pressures; T-0 Valve Leak Check and T-0 Pod Poppet Leak Check; Pressurize T-0 Line Run and Leak Check Pod I/F at Flight Pressure; Open Gas Supply Valve and Vent Vehicle to Pad Pressure.
DISPLAY: VDR50 ORBITER H2 Electrical Control and Monitor and VDR51, FC Operations.

PERFORM: On Cryo tanks -- Vac-ion Pump Checks and Monitor vacuum Levels; Tank Quantity Checks; Modify Limits of Tank Heater Monitor Control Logic; Tank Heater Checks via Cockpit Control; Tank LO/Hi Pressure Checks Using GSE Ramp Rate with Tank Heaters Off; Tank Heater Auto On/Off Checks using GSE Ramp Rate with Tank Heaters in Auto.

DISPLAY: VDR29, H2 System GSE and VDR50, Orbiter Electrical Control and Monitor H2.

PERFORM: Modify Tank Heater Control Logic Limits and Tank Temperature Monitor Limits; Slowly Pressurize Cryo Tanks and Perform Instrumentation Checks. Lo Pressure CW Checks, Heater Turn On Check (Lo Pressure-Auto Mode) Cutoff Checks, and Heater Manual On/Off Checks above Auto Cutoff Pressure; Leak Check Mid-Body Pos I/F and FC Interface; FC Instrumentation Checks at Flight Pressures; Cryo Tank RV Crack/Reseat Checks and Post Reseat Internal Leak Check; Vent Cryo Tank to Soak Pressure.

DISPLAY: VDR22, O2 SYSTEM GSE and VDR51, FC Operations.

PERFORM: Modify VCR03 and 04 to Allow Checkout; Include leak checks for uninsulated connections on O2 System.

DISPLAY: VDR49 Orbiter Electrical Control and Monitor -- O2, FC Operations.

PERFORM: Vac-Ion Pump Checks and Monitor Vacuum Levels; Tank Quantity Checks; Modify Limits of Tank Heater Monitor Control Logic; Tank Heater Checks via Cockpit Control; Tank LO/Hi Pressure Checks Using GSE Ramp Rate with Tank Heaters Off; Tank Heater Auto ON/OFF Checks using GSE Ramp Rate with Tank Heaters in Auto; Tank Current Sensor Trip/Reset Test, Tank Heaters Off; Tank Heater Current Sensor Tests - Tank Heaters On (In Auto-Mode, Tank Pressure LO.

DISPLAY: VDR22, O2 System GSE and VDR49, Orbiter Electrical Control and Monitor -- O2.

PERFORM: Modify Tank Heater Control Logic Limits and Tank Temperature Monitor Limits; Slowly Pressurize Cryo Tanks and Perform Instrumentation Checks. Lo Pressure CW Checks, Heater Turn On Check (Lo Pressure-Auto Mode) Cutoff Checks, and Heater Manual ON/OFF Checks Above Auto Cutoff Pressure; Leak Check Mid-Body Pod I/F and FC Interface; FC Instrumentation Checks at Flight Pressures; Cryo Tank RV Crack/Reseat Checks and Post Reseat Internal Leak Check; Vent Cryo Tank to Soak Pressure; Leak Check Uninsulated LO2 Connections.
DISPLAY: VDR29, H₂ GSE, FC Operations

PERFORM: Moisture and Purity Checks from H₂ Tanks; Vent H₂ System to Pad Pressure.

V1077 -- ORBITER FUEL CELL COOLANT SERVICING AND SAMPLING (LPS) (120 pages)

OBJECTIVE: Provide procedures to measure compressibility and sample the fuel cell coolant loops.

DESCRIPTION: The supporting equipment will be set up at the Orbiter servicing Access Panel (Door 44); A Compressibility Test will be conducted, Accumulator ullage established, and the quantity of dissolved gas in the coolant measured; to meet periodic OMRS requirements to sample on board F/C 40 per SE-S-0073. Sample will be taken, dissolved gas measured, ullage established and compressibility test performed; Compressibility GSE will be disconnected from the orbiter and servicing disconnects visually leak checked prior to flight caps installation.

V1093 -- FUEL CELL SINGLE CELL VOLTAGE TEST (LPS)(575 pages)

OBJECTIVE: Provide procedure to conduct a single cell voltage test (both the TAFEL test and GN₂ Diagnostic Test) of the Orbiter fuel cells. The TAFEL Test will only be performed if a fuel cell is suspect and not as part of the normal Diagnostic Test.

TEST PREPARATION: Placard reactant GSE; placard Single Cell GSE; configure FC for Single Cell Test; prepower Switch List.

POWER UP: LPS powered up; Power up Reactant GSE; Verify Orbiter Power and Cooling per Standard Power Up.

OPERATIONS: Reactant Gas Purge Orbiter; Connect Single Cell Cables; Load Test and Voltage Scan (VAH01) -- Under LPS control, 4 calibrated loads are applied for a maximum of 15 seconds each. While each load is applied, and LPS scan of the 96 individual cells is made. A minimum of 2 minutes rest is allowed between load tests. Then with reactants in the fuel cells, the baseline GN₂ Diagnostic Test is run. The O₂ side of the fuel cells are next purged with GN₂ and the Diagnostic Test is run again; disconnect load cables; inert fuel cell. When V1091 follows the performance of V1093, the inerting will be done in V1091; inert GSE. POWER DOWN: Power down Orbiter (if required); Power down reactant GSE unless V1091 is to be run immediately after completion of V1093. In this case the GSE PNLS may be left powered up; secure Single Cell GSE; secure LPS.
V5R01 -- FUEL CELL POWER PLANT INSTALLATION/REMOVAL (620 pages)

OBJECTIVE: Provide the sequence of operations for Fuel Cell 1, 2, and 3 transfer from shipping container to vehicle and reverse procedure from vehicle to shipping container.

DESCRIPTION: This procedure contains hazardous steps since a critical flight item, fuel cell, will be lifted into and out of vehicle.

OPERATIONS: Connect vacuum pump, FC-40 canister, reg. Have and entrained gas detection unit on lvi 4E; connect test setups for fuel cell bench servicing; transfer fuel cell from shipping container to bench; remove cover from shipping container. Using overhead crane lift fuel cell from container to work bench; pressurize fuel cell O2 and H2 ports with 100psi (min) GHe supply; connect FC-40 coolant fluid canister and a vacuum pump in parallel to fuel cell coolant disconnects. Disconnect fuel cell vehicle electrical and fluid interfaces, Disconnect fuel cell vehicle electrical and fluid interfaces, Disconnect fuel cell vehicle electrical and fluid interfaces; transfer replacement fuel cell from bench to vehicle; connect fuel cell vehicle electrical and fluid interfaces; transfer fuel cell from bench to shipping container; GSE teardown.

V5R02 -- PRSD BASELINE TANK INSTALLATION/REMOVAL (462 pages)

OBJECTIVE: Task 1 - To configure and validate OPF O2/H2 GSE panels for tank removal/installation. Task 2 - To remove or install PRSD H2 tank 1 as required. Task 3 - To remove or install PRSD O2 tank 1 as required. Task 4 - To remove or install PRSD H2 tank 2 as required. Task 5 - To remove or install PRSD O2 tank 3 as required. The above brief descriptions of the related PRSD procedures are indicative of the complications induced in turnaround operations by the current design.

V5R03 -- PRSD MISSION KIT TANK SET REMOVAL/INSTALLATION (LPS) (800 pages)

OBJECTIVE: To remove or install PRSD H2/O2 Tank Sets 3, 4, & 5 as required to meet mission objectives.
1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)  
(Continued)

1.4.10.5 Technology Application Requirements

The requirement exists to drastically improve the Energy Storage System (ESS) for the current Orbiter and future vehicles. Improvement is required in energy density, reliability, and maintainability.

1.4.10.6 Technology Evaluation

The breadth and size of this Study necessarily limits depth of the technology evaluation. The goal here is to utilize previous in-depth surveys in related areas. In the case of energy storage systems, work being done for Space Station and led by the NASA Lewis Research Center (LeRC) is most appropriate. LeRC is supported by contractor teams of Rocketdyne (Ford Aerospace, Harris, Garrett, and Sunstrand) and TRW (General Dynamics and General Electric). The following information is extracted in large part from the Bibliography, Section 1.4.10.8.

In the case of the current Orbiter, we are interested in technology which would lend itself to block modifications in the time frame of the early 1990's. In the case of future vehicles we are interested in the technology extending to 2010.

In addition to the obvious requirement of meeting performance requirements, life cycle costs (LCC) must be considered with equal importance. The major LCC factors that will provide low LCC are:

* Minimal Launch Cost
  
  * Low mass
  * Low volume

* Minimal Operations Cost
  
  * Automation
  * Minimal impact on other systems
    + Power generation subsystem drag
    + Thermal control subsystem drag

* Minimal maintenance/replacement cost
  
  * High reliability and long wear-out life
  * Low replacement cost
    + Low mean-time-to-repair
    + Modularity
    + Low mass and volume (launch cost)
    + Low production cost
ENERGY STORAGE SYSTEMS FOR SPACE STATION

The energy storage options initially considered for Space Station included battery systems, regenerative fuel cell systems, and flywheels:

* Battery Systems
  + Nickel-cadmium
  + Nickel-hydrogen (CPV)
  + Nickel-hydrogen (IPV)
  + Nickel-hydrogen (Bipolar)
  + Sodium-Sulfur

* Regenerative Fuel Cell Systems
  + Alkaline/alkaline hydrogen-oxygen
  + Alkaline-FC/SPE-EM hydrogen-oxygen
  + SPE/SPE Hydrogen-oxygen
  + Hydrogen-halogen

When the characteristics necessary to meet Space Station IOC were considered (maturity, development cost, production cost, solar array cost, thermal control cost, launch cost), the initial survivors were:

* Alkaline/alkaline regenerative fuel cell (RFCS)
* Nickel-cadmium battery
* Nickel-hydrogen IPV battery

Of these options, Ni-Cad is relatively heavy and costly; Ni-H₂ appears lower in overall IOC and operational cost, and is favored for maintainability and safety. The RFCS has a mass advantage, but an overall small disadvantage in Space Station IOC cost and development risk. Bottom line is that the RFCS and the Ni-H₂ battery are apparently the finalists based on an IOC date.

Short descriptions of energy storage systems considered for Space Station follows.
OVERVIEW OF ESS DESIGNS CONSIDERED FOR SPACE STATIONS

Regenerative Fuel Cell. The alkaline regenerative fuel cell system (RFCS) consists of four identical assemblies. Each includes a fuel cell module (FCM), a water electrolysis module (WEM), a FCM accessory section, and a WEM accessory section. The accessory sections contain the valves, pumps, regulators, heat exchangers, etc., required for RFCS operation. A set of hydrogen and oxygen tanks serves two of the assemblies. The electrode areas of the FCM and WEM are sized to provide a relatively high efficiency of 62%, which includes losses associated with accessory section operation. Typical operating voltages of the FCM and WEM stacks are 155 V.

IPV Ni-H₂ battery. The individual pressure vessel (IPV) Ni-H₂ battery option consists of four batteries of 275 Ah capacity in series, distributed over five identical assemblies. These assemblies hold their 21 cells supported on structural beams that carry heat pipes for efficient heat removal. Twenty assemblies are held in two “oven-rack” type arrangements, one per utility center. Typical discharge voltage is 133 V averaged over the 35-minute, 40% DoD discharge.

Bipolar Ni-H₂ battery. The bipolar Ni-H₂ battery uses the design concept developed by Ford Aerospace and Yardney under NASA-LeRC sponsorship. It consists of four batteries, each with three assemblies in parallel. The assemblies each consist of a pressure vessel containing two cell stacks of 52 cells in series, with a capacity of 90 Ah. The cells have the long, rectangular configuration: about 12 cm wide by 160 cm long. The 16 panels are mounted in “oven-rack” type arrangements in the Station utility center.

ESS OPTIONS COMPARISON FOR SPACE STATION

Ni-Cd Battery. The Ni-Cd System consists of 16 batteries of 125 Ah capacity and with 104 series cells. Each battery is divided into four 26-cell battery packs, mounted on a honeycomb panel with embedded heat pipes. The 16 panels are mounted in “oven-rack” type arrangements in the Station utility centers.

Na-S Battery. The sodium-sulfur (Na-S) battery, operating at 300 to 400°C, uses cell sizes close to those being produced currently. The 75-kW system would consist of four batteries each with four 87-kg modules of 70 cells of 65 Ah capacity, delivering about 126 V on discharge. Each module has a variable conductance radiator system on its external surface. The modules are placed on the outside of the utility module.

Energy Wheels. The energy wheel data shown represents a blend of various approaches. This was necessary because of the extremely wide range of characteristics reported for point designs for Space Station flywheels.
A comparison of ESS alternatives are presented in Figure 2. The alkaline H₂-O₂ RFCS is used as the baseline in this comparison.

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>H₂-O₂</th>
<th>Ni-H₂</th>
<th>Ni-H₂</th>
<th>Ni-Cd</th>
<th>Na-S</th>
<th>ENERGY STORAGE</th>
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<td>ROUND-TRIP EFFICIENCY (%)</td>
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<td>82</td>
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<td>95</td>
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<td>DEPTH-OF-DISCHARGE (%)</td>
<td>40</td>
<td>40</td>
<td>40</td>
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<td>6000</td>
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<td>1100</td>
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<td>(270)</td>
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<td>4430</td>
<td>10430</td>
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<td>VOLUME (m³)</td>
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<td>14</td>
<td>11</td>
<td>11</td>
<td>2</td>
<td>9</td>
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<tr>
<td>ECLIPSE HEAT REJECTION (kHz)</td>
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<td>19</td>
<td>19</td>
<td>19</td>
<td>18</td>
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<td>TEMPERATURE (ºC)</td>
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<td>10</td>
<td>10</td>
<td>10</td>
<td>350</td>
<td>35</td>
</tr>
</tbody>
</table>

SS ESS OPTIONS CHARACTERISTICS COMPARISON

**Figure 2**

**PERFORMANCE**

The RFCS has a much lower mass than the other feasible systems, the Ni-Cd, IPV Ni-H₂, and bipolar Ni-H₂ batteries. However, its thermal control equipment is considerably heavier than that of the others, because of the RFCS's relatively low roundtrip efficiency and its resulting high heat rejection rate, albeit at a higher temperature. In the case of the room temperature systems, it is also feasible to use a common thermal control loop for the ESS and PMAD, which is difficult to do with the RFCS. The roundtrip efficiency difference also results in solar array mass 'credit' for the non-RFCS systems. When all the impacts have been included, the RFCS has still the lowest mass, but the other systems become more competitive.

By far, the most attractive is the Na-S battery system; however, this technology has not reached the maturity required for serious consideration for the IOC Space Station. It provides low mass, high efficiency, and minimal thermal support requirements due to the high rejection temperature. With sufficient development, its benefits may be applicable to the growth Station.
1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)
(Continued)

**MATURITY**

The development maturity for the alkaline/alkaline RFCS is split. The fuel cell part has been used on the current Orbiter with success; the electrolyzer has so far been demonstrated only as a laboratory breadboard.

In the case of the IPV Ni-H$_2$ battery a 220-AH cell has been demonstrated by Ford Aerospace and Yardney. Production costs are lowest for the Ni-H$_2$ system due to low complexity, moderate modularity, and replication. The RFCS is intermediate due to greater complexity and lower modularity. Solar array costs and thermal control system costs are somewhat higher for the RFCS because of the greater heat rejection requirement. The RFCS is about 20% lower than the Ni-H$_2$ in total mass. Overall, for the early 1990's time frame, costs appear lowest for the Ni-H$_2$ batteries with the RFCS not far behind. NiCad batteries are not in the running because of cost and weight.

**COSTS**

Operations costs appear lowest for the Ni-H$_2$ batteries because of lower complexity while the RFCS has higher drag related fuel costs because of the larger solar arrays and more extravehicular repair activity.

**ENERGY STORAGE SYSTEMS FOR CURRENT ORBITER**

The development time scale involved for Orbiter block modification consideration roughly coincides with Space Shuttle IOC. Consequently, any major improvement in the fuel cells for the Orbiter could be related to Space Station development.

A significant change in Orbiter mission length could alter the ESS requirements to reconsider the trades for fuel cells, Ni-H$_2$ batteries, and solar cells.

The state-of-the-art for fuel cells is, even today, well advanced over the design used for the Orbiter. Further advancement could be enhanced with more competition, however. Detailed trade studies are recommended which would consider implementation of an improved system with 80% (80 flights) of an Orbiter's life expectancy left.

**ENERGY STORAGE SYSTEMS FOR FUTURE VEHICLES**

Looking ahead to future vehicles past the mid 1990's allows much more latitude in our consideration of alternate energy storage systems.

Specific mission requirements will undoubtedly require up-to-date trade studies with the latest projected state-of-the-art. Today it looks like a run-off between RFCS and Ni-H$_2$ batteries. Looking far ahead, however, there is the developing lithium cell (Li/SO$_2$, Li/Thionyl, Li/Sulfuryl Chloride) technology and the very promising NaS battery.
Future space missions will require much higher power levels than the 5kw needed today. Directed energy weapons, ultrahigh resolution radar, and direct broadcast will boost the maximum requirements several orders of magnitude. Scale-up of present energy storage systems to these high power levels is not practical because of tremendous weight penalties.

The NaS battery is different in that both the anode and cathode are liquids instead of solids (Figure 3). As such, they do not experience the fatigue and degradation problems associated with the continuous cycling of solid electrodes. Conceivably, the sodium and sulphur could continue to cycle forever in an ideal cell. The life limiting factor in this case is not the electrode, but the solid ceramic electrolyte and the cathode container. Shaped in the form of a tube, the electrolyte serves as both an ion conductor and a separator in the cell.
This also results in reduced drag, smaller radar signature, and reduced altitude maintenance propellant requirements -- while each is small, their total is significant.

**NaS Technology Deficiencies**

The cells commonly fail by breakage of the tube resulting from flaws in the ceramic. Corrosion of the cathode container is the other factor presently limiting cell lifetime.

Sufficient lifetime and reliability of the NaS cell for GEO and MAO are questionable. The life goal of ten years is yet to be attained and will not be known for several years. Cell reliability is also unacceptable due to something less than 10% of cell failures still occur within the first 200 cycles.

The NaS battery, at this time, appears to be the best possibility for meeting future requirements. Its current shortcomings are well known and only require further development.

In short, there is immediate need of accelerated materials research for the solid ceramic electrolyte and cathode container.

**1.4.10.7 Conclusions and Recommendations**

The launch processing time required for the PRSD system is not consistent with the requirements for an operational system.

A new technology requirement exists for fuel cells with minimal maintenance -- or replacement of fuel cells with new technology batteries. The latter alternative, batteries, does not appear to be a reachable goal with known technology. However, any R & D goals for fuel cells should place maintainability on equal status with the performance specifications. Even a cursory look at the 3794 pages of OMI's for the current Orbiter PRSD makes it readily apparent that this is not an operational type system.

It is understood that there is an RFP being released by SDIO for development of a fuel cell with 30 times the power density of the current Orbiter cells. Details of this RFP were not available at the release date of this report.
1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E) (Continued)

1.4.10.8 Bibliography

(1) RECON 85N16947
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SPACE SHUTTLE ELECTRICAL POWER GENERATION AND REACTANT SUPPLY SYSTEM

Dueber, R.E.; Aero Propulsion Lab, Wright-Patterson AFB
12 page paper
SODIUM-SULFUR BATTERIES FOR SPACECRAFT ENERGY STORAGE

van Ommering, G.; Ford Aerospace, Palo Alto, CA.
10 page paper
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GALILEO Li/SOCl2 BATTERY MODULES

Halpert, G., et al; JPL
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Hagedorn, N., et al; Lewis Research Center (LeRC), OH.
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Miller, Lee; Eagle-Picher Industries, Inc.
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1.4.10 POWER REACTANT STORAGE & DISTRIBUTION (PRSD) (Tentpole E)
(Continued)

Gonzalez-Sanabria, Olga D., et al; LeRC, OH.
10 page paper
RECENT ADVANCES IN NiH₂ TECHNOLOGY AT NASA LeRC

McDermott, J.K.; Martin Marietta Denver Aerospace
11 page paper
NICKEL-HYDROGEN LOW-EARTH ORBIT TEST PROGRAM

Miller, Lee; Eagle-Picher Industries, Inc.
7 page paper
4.5" DIAMETER NiH₂ CELL DEVELOPMENT PROGRAM

Green, R.S.; RCA Astro-Electronics Div., Princeton, NJ
4 page paper
IMPACT OF SHUTTLE ENVIRONMENT ON PRELAUNCH HANDLING OF NICKEL-HYDROGEN BATTERIES

ORIGINAL PAGE IS OF POOR QUALITY
1.4.11 ORDNANCE OPERATIONS (Tentpole F)

1.4.11.1 Summary

Ordnance devices must be handled with care and have rigid safety restrictions to prevent accidental detonation. All ordnance operations are performed slowly and carefully. "Slowly" often means a task time that is not ideal for an operational type transportation system. In addition to being slow the hazardous nature of ordnance causes other work to be rescheduled or stopped. Forty-four hours of ordnance operations performed in the OPF and at the VAB are serial hours where time is at a premium. Personnel must have special training and equipment and this limits who may perform the work.

The shuttle uses ordnance to perform several different types of operations:

1. Ignition devices
2. Release devices
3. Separation devices
4. Range Safety devices

The release and separation devices appear to be candidates for timeline improvement by substituting non-hazardous and reusable devices. The use of the shape memory metal Nitinol (Nickel-Titanium-Naval Ordnance Laboratory) for release or separation devices is a definite possibility. One of the early uses of Nitinol was a torsion tube use to trigger the rapid and reliable release of satellite instrument booms, replacing an explosive bolt. Contact with the originators of Nitinol about using shape memory devices to replace ordnance was very encouraging.

The ignition devices and the Range Safety devices were excluded from detailed examination because of study time limitations and no readily apparent technology.

It is recommended, for both Shuttle and Future Programs, that concentrated effort be made to eliminate ordnance devices to make ground operations more efficient. Specifically, it is recommended that Nitinol technology be explored as a starting point in replacing ordnance type release and separation devices. Further technology such as lasers should be investigated for ignition devices and a complete assessment be made of Range Safety requirements and ordnance devices.
1.4.11.2 Related Issues

1. Ordnance devices do not lend themselves to quick turnaround operations.

2. Working with ordnance requires clearing the adjacent or pad area thus precluding other work being performed.

3. Personnel who handle ordnance must have special training and certification.

4. Ordnance devices require special logistic handling.

The following are examples from the Preliminary Issues Database:

<table>
<thead>
<tr>
<th>ID:</th>
<th>10.00</th>
<th>Issue(s): TIME/ON-LINE</th>
<th>SAFETY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Issue(s): cont.: PLANNING</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issue Source: F, T</td>
<td>DRAFT DATED 5/96. ANONYM FACT F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Description:**

"HAZARDOUS OPERATIONS AND CONDITIONS IN THE VEHICLE PREPARATION AREA GREATLY AFFECT OPERATIONS TIMES AND INCREASE COSTS. DURING SUCH TIMES, TECHNICIANS ARE PREVENTED FROM DOING USEFUL WORK ON THE VEHICLES, AND ONLY ONE TASK CAN PROCEED AT ANY ONE TIME. TO MINIMIZE THESE DELAYS, ORDNANCE OPERATIONS MUST BE ABSOLUTELY MINIMIZED AND PREFERABLY ELIMINATED FROM THE PROCESSING FLOW. SIMILARLY, THE USE OF TOXIC MATERIALS SHOULD BE ELIMINATED OR STRICTLY CONTROLLED. NECESSARY TOXIC MATERIALS SYSTEMS SHOULD BE MODULARIZED OR CONTAINED SO THAT EQUIPMENT CAN BE CHANGED OUT WITHOUT REQUIRING EVACUATION OF THE SURROUNDING AREA."

<table>
<thead>
<tr>
<th>ID:</th>
<th>70.00</th>
<th>Issue(s): COST/MANEUVERS</th>
<th>SAFETY</th>
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</thead>
<tbody>
<tr>
<td>Issue(s): cont.:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issue Source: COSTS</td>
<td>DRAFT DATED 5/96. TABLE E-1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Description:**

"LOGISTIC SYSTEM OPERATIONAL CONCEPTS | SYSTEM COST DRIVER REQUIREMENTS"

- PYRO DEVICES
  - HAZARDOUS OPERATIONS
  - REFURBISHMENTS
  - INSTALLATION OFF-LINE
    - USE NON ELECTRICAL
    - PYROTECHNICAL INITIATORS
    - CONDUCT ORDNANCE
    - USE MECHANICAL/ELECTRO/PNEUMATIC DEVICES
  - USE LASER INITIATED
  - USE LASER/INITIATED PYRO DEVICES
  - USE LASER INITIATED PYRO DEVICES"
### 1.4.11.3 Related KSC Schedule History

1. The 160-hour schedule had 8 hours for ordnance installation at the Orbiter Processing Facility (OPF).

2. Currently 112 hours of processing time is spent in ordnance operations in the following areas:

<table>
<thead>
<tr>
<th>Location</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPF</td>
<td>8 hours</td>
</tr>
<tr>
<td>External Tank (E/T) CHECKOUT CELL</td>
<td>24 hours</td>
</tr>
<tr>
<td>Vehicle Assembly Building (VAB)</td>
<td>44 hours</td>
</tr>
<tr>
<td>PAD</td>
<td>36 hours</td>
</tr>
<tr>
<td>(20 hours requires complete pad clear)</td>
<td></td>
</tr>
</tbody>
</table>

Total 112 hours
(Total on-line serial time 44 hours)

This schedule is primarily taken from the as-run of 51-L, then modified to simulate a typical STS flow.

The eight hours of scheduled ordnance work in the OPF is considered serial time since clearing is required and restrictions are placed on other activities.

The 68 hours in the VAB (including the E/T checkout cell is parallel work since it is primarily done while the orbiter is in the OPF. It does restrict some other work in the VAB.

The 36 hours at the pad is the most detrimental to the schedule. At least 20 hours requires clearing the whole pad and it would be hard to calculate how many man-hours of other work are lost.
1.4.11 ORDNANCE OPERATIONS (Tentpole F)  
(Continued)

1.4.11.4 Current STS Methods

The descriptions below of the current STS OMI's for the installation of ordnance provide a graphic view of the complications, time on-line, and manhours expended because of the current design:

OMI V5012, Ordnance Installation and Checkout (LPS), is worked in the OPF. The following ordnance items are installed requiring a 10-foot radius to be cleared during hazardous operations. The nose landing gear strut thruster cartridge, the forward separation bolt pressure cartridge, the Remote Manipulator System (RMS) Manipulator Positioning Mechanism (MPM) pyro, the KU-BAND pyro, the fire extinguisher pyro and the fire suppression pyro. Power-off stray voltage checks, shield-to-ground resistance checks and electrical connection of ordnance are performed requiring a 10-foot clear around the affected areas.

OMI B5304, SRB Systems Mate and Closeout, is performed at the VAB. The Linear Shaped Charge (LSC) is installed in the boosters requiring clearing of levels D, B, & E and roped area on ground floor. Installation of the Confined Detonating Fuse (CDF) assemblies requires clearing of platform E-main. Installation of Solid Rocket Booster (SRB) Ignitor Safe and Arm (S&A) device requires clearing extensible platform E-main. A 10-foot radius around the SRB must be cleared for installation of NASA Standard Initiators (NSI's). The E-main, E-roof and AP-100 platforms are cleared for cable installation. The SRB holdown post-ordnance installation requires a 10-foot clear from the SRB aft skirt area. Closeout firing-line continuity checks require the above mentioned areas to be cleared.

OMI T5142, SRSS Ordnance Installation, is also performed in the VAB. The external tank Shuttle Range Safety System (SRSS) LSC is installed in the LO₂ and LH₂ cable trays. The appropriate levels of the E/T checkout cell are cleared during LSC installation.

OMI S5009, Final Ordnance Installation/Connection, and Aft Closeout (LPS), is final ordnance installation, connection and aft closeout at the pad. This procedure is performed in two parts. The first part requires clearing to pad perimeter for SRB ordnance operations, Cargo ordnance operations, Tail Service Mast (TSM) ordnance operations, Orbiter forward Launch Control Amplifier (LCA) and aft Left Hand/Right Hand (LH/RH) separation ordnance operations. The blast danger area is cleared for Pyro Initiator Controller (PIC) resistance testing on the Orbiter, external tank and solid rocket boosters. Part 2 requires clearing to the pad perimeter for stray voltage testing and ordnance electrical connection.
1.4.11.5 New Technology Requirements

Replacement for current Shuttle: ordnance release or separation devices with non-explosive devices. Candidates for replacement are:

- Orbiter main & nose gear strut release
- Orbiter/ET separation bolts
- SRB holddown bolts
- SRB/ET aft separation system
- SRB/ET fwd separation system
- SRB frustum separation
- SRB parachute cutter
- SRB main parachute release
- TSM drop weight release bolts
- E/T H₂ vent arm release

Shape-memory metal (Nitinol) has been used to trigger release of satellite instrument booms replacing an explosive bolt. The shape-memory can be returned to the original configuration so those applications on recoverable portions of the vehicle would not require replacement.

For Future Vehicles:

Eliminate all ordnance devices which require special handling and restrictive safety measures. This will require innovative technology for ignition and Range Safety devices. It also means early coordination with and qualification of devices by the Range Safety Organizations.
1.4.11 Technology Evaluation

The initial 160-hour schedule reflects 8 hours in the OPF to install ordnance. The safety considerations required for handling ordnance preclude ever approaching this amount of time. To reduce the time involved we must consider performing the same functions by other means. First the required operating time must be evaluated for each application to determine actual need. Present Operational Maintenance Requirements and Specifications Document (OMRSD) requirements have 10 or 20 millisecond requirements on many applications. Each application can then be evaluated to see if a non-explosive device can be substituted.

Candidate Devices:

The Orbiter main & nose gear strut release pyros are a back-up system and are initiated if the main hydraulic unlocking mechanism fails to operate. These devices are initiated by pressure cartridges. They are installed at the OPF and the OPF is the last point they can be accessed. See Figure 1 for location of main landing gear pyrotechnic release thruster. Nose gear is similar.

![Emergency Unlock Pyrotechnic Release Thruster](image-url)
The SRB holddown bolts have a load limit of 1,135,000 pounds and a minimum ultimate load of 1,512,000 pounds. They are preloaded to 725,000 to 834,000 pounds. They must operate between 200°F and 150°F. These devices are initiated by detonators. They are installed at the VAB and the PAD is the last point they can be accessed. The frangible nut is shown in Figure 2 and the installation in Figure 3.
The Orbiter/ET forward separation bolts operate similar to the SRB holddown bolts described above. These devices are initiated by pressure cartridges. They are installed at the OPF and the OPF is the last point they can be accessed. See Figure 4.
The SRB/ET aft separation bolts have a flight load limit of 393,000 pounds axial tension and must operate within 10 milliseconds of initiation signal. They must operate between 20°F and 1200°F. These bolts have an installation torque of 1000 foot-pounds. These devices are initiated by NSI pressure cartridges. They are installed at the VAB and the PAD is the last point they can be accessed. See Figure 5.

The SRB/ET forward separation system bolts have a flight load limit of 189,000 pounds axial tension limit load with a 55,344 inch-pound end moment. They must separate within 10 milliseconds of initiation signal and operate within -10°F to 120°F. These devices are initiated by NSI pressure cartridges. They are installed at the VAB and the PAD is the last point they can be accessed. See Figure 5.

SRB SEPARATION SYSTEM ELEMENTS
Figure 5
The SRB frustum separation currently uses a linear shaped charge that runs around the periphery of the frustum. It must operate between 250°F and 1050°F. The ring thickness at the separation line is 0.25 inches thick. This device is initiated by a detonator. It is installed at the VAB and the PAD is the last point it can be accessed. See Figure 6.

The SRB parachute line cutter must be capable of cutting 3 plies of 1 1/8 inch MIL-W-4088, type XX III 12,000 lb. webbing. The operating temperature range must be 20°F to 200°F. This would appear to be the easiest device to replace with a Nitinol device. See Figure 7.
The SRB main parachute release bolt is a 1.25-12 UNJ-3A bolt under a tension load of 135,000 pounds. The bolt is torqued to 775 +/-25 foot-pounds and must operate at 20°F to 200°F. The current release spec is for 20 milliseconds after initiation signal. This device is initiated by a detonator. They are installed at the VAB and the PAD is the last point they can be accessed. See Figure 8.
TSM drop weight release bolts and the E/T H2 vent arm release are of a design similar to the SRB/ET and Orbiter/ET forward separation bolts. All are initiated by NSI pressure cartridges that make the bolt fracture at a predetermined location. They are installed at the PAD; and the PAD is the last point they can be accessed.

Two prime candidates for Nitinol application would seem to be the SRB parachute cutter and main release. The timing is not as sensitive and the type of application lends itself to an electro-mechanical device (solenoid type) or perhaps shape-memory. Either of these cases could be reusable and not sensitive to low level stray voltage actuation.

Candidate Technology - Nitinol

A number of articles and papers indicate potential uses of shape memory are still emerging. The following excerpt from June 1984 Materials Engineering is a sample:

When shape-memory alloys are deformed at one temperature, they remember the previous shape and completely recover it when heated to a higher temperature. The shape recovery produces a displacement or a force, or a combination of the two, as a function of temperature. Shape-memory alloys (SMAs) are used in applications such as pipe and tube couplings and electronic tight seals and connectors.

In addition, improved alloy processing and a better understanding of the shape-memory effect (SME) mechanism has provided alloys that have a precise mechanical response to small and repetitive temperature changes. This characteristic is put to use in mechanical and electromechanically controlled systems.

Although the shape-memory phenomenon occurs in many alloy systems, including austenitic stainless steels, most of these alloys cannot be used because of some inherent limitation, such as low ductility, which causes fracture during shape recovery.

Two alloy systems well suited for commercial application due to the combination of SME and favorable mechanical properties are NiTi alloys and CuZnAl alloys.

Alloys having the shape-memory characteristic need to satisfy certain conditions to obtain shape memory and a number of variables must be controlled to fabricate a useful engineering device.
Foremost, an alloy must undergo an austenite to martensite transformation. Such transformations are crystallographically reversible and typically occur in ordered alloys. The crystal structure can shift into the configuration known as martensite when subjected to a certain temperature or stress and then shift out of it. Those alloys having a thermoelastic martensite transformation also have the shape-memory effect.

For example, a wire of shape-memory alloy can be bent into some configuration at room temperature and then heated until the austenite crystal structure is attained. When the wire is quenched, the atoms rearrange themselves into the crystal form of martensite. If the wire is bent into another configuration and then heated to a temperature above that at which martensite reverts to the austenite or parent phase, an orderly shift of atoms restores the wire to the original configuration. The memory is accomplished at the martensite formation temperature or at a higher temperature - where the alloy reverts to austenite. Transformation temperature is determined by composition for each memory alloy but can also be shifted by applied stress. For many alloys, composition must be controlled within very close tolerances to obtain the required sensitive temperature.

If a shape-memory metal is mechanically deformed at a specific temperature, it will return to its original form when the temperature is raised. The process is known as one-way shape-memory effect - "one-way" because the shape change occurs only in heating. Cooling the material subsequently will not reverse the shape change.

Further research of the shape-memory effect mechanism has provided shape-memory alloys that can be "trained" to remember two configurations. This phenomenon is known as two-way memory effect because the shape changes both on heating and cooling. The metal is trained by appropriate stress and/or thermal cycling below the critical temperature, which limits the number of variants of martensite formed. Stressing the alloy while cooling from the elevated temperature to the critical temperature favors the initial formation of particular variants of martensite. Repeating the sequence of austenitizing, quenching, deforming, and reaustenitizing eventually trains the structure. When this condition is achieved, a specimen will bend spontaneously during the austenite/martensite transformation and unbend to the original shape during the reverse transformation. In both cases, the shape changes with the absence of an external stress.

By restricting the shape-memory transformation, a usable force associated with the shape change is available for doing work or gripping another object. The mechanical stresses produced are limited only by the material. The deformation of a part is limited to an internal strain of between 2 and 9% to achieve 100% shape recovery.
Shape memory alloys also have excellent fatigue properties. For example, the cyclic strain required to cause fracture after a number of cycles is higher by a factor of ten than that required for conventional alloys. Generally, after the first three to five reversals of temperature, the material stabilizes to repeated values. However, if a part, such as an actuator, is overstressed or exposed to temperatures out of the working range of the alloy for long periods, the metal can fail by thermal or mechanical fatigue or the memory can fade.

Although the nickel-titanium (NiTi) intermetallic compound was not the first system that demonstrated the shape-memory effect, as a result of the austenite/martensite transformation, it was the first used for commercial shape-memory applications. Called Nitinol, for Nickel-Titanium Naval Ordnance Laboratory, the alloy provides high yield strength and ductility, high strength-to-weight ratio, and good corrosion resistance. With alterations in the nickel-titanium ratio and additions of small amounts of other elements of small amounts of other elements, the martensite transformation temperatures range of -459 to 212°F.

One of the first applications was the use of a Nitinol torsion tube to trigger the rapid and reliable release of satellite instrument booms, replacing an explosive bolt. Since the phase change from martensite to austenite is diffusionless, the shape-memory effect occurs very rapidly over a narrow temperature range.

Other typical satellite uses include sun seeker/tracker, torsion drives and trigger mechanisms.

Activity in the application of Nitinol Devices is accelerating from 1967 to 1980 there were 90 patents. By 1987 there were 160 patents.

The following chart of physical and mechanical properties of 55-Nitinol was taken from the October 1969 issue of Materials Engineering:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, lb/in.³</td>
<td>0.234</td>
</tr>
<tr>
<td>Melting Point, °F</td>
<td>2390</td>
</tr>
<tr>
<td>Magnetic Permeability</td>
<td>1.002</td>
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<tr>
<td>Ult Tensile Strength, 100 psi</td>
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</tr>
<tr>
<td>Elongation, %</td>
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<tr>
<td>Modulus of elasticity, 10⁶ psi</td>
<td>10.2</td>
</tr>
<tr>
<td>Shear Modulus, 10⁶ psi</td>
<td>3.6</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.33</td>
</tr>
<tr>
<td>Fat. Strength (10⁷ cyc), 1000 psi</td>
<td>70</td>
</tr>
</tbody>
</table>
Although the shape-memory effect was discovered in 1962 most of the effort to develop practical applications has been fairly recent. Design News, 12-1-86, names several active participants and their products:

Beta Phase Inc., Menlo Park, CA, is making shape-memory eyeglass frames.

Innovation Technology International Inc., Beltsville, MD, headed by Fredrick Wang (one of the original researchers) is developing an engine to run on low cost heat sources.

Raychem Corp., Menlo Park, CA., has developed several items including the "Cryotact" ZIF socket and a flexure arm in a hard disc drive that prevents head crashes.

Memory Metals, Inc., Stamford, CT., is working on electrical and optical connectors and a line of safety related devices including an anti-scald shower valve.

Nitinol Investigation:

During the Seattle technical survey trip, robotic applications were demonstrated which further indicated further development of Nitinol or similar alloys have potential for this technology application.

A special technical survey trip was made to the Naval Surface Weapons Center (ex Naval Ordnance Lab) to provide a cursory look at the potential application of Nitinol to substitute ordnance type devices. Discussion of the ten selected devices with David Goldstein of NSWC, a Nitinol Specialist, revealed that the technology should support innovative design of substitute devices. Nitinol is capable of providing 300K PSI as a one-shot operation or 200K+ PSI on a repetitive basis. Reaction time is not a parameter that has been thoroughly researched. Although Nitinol has the approximate resistivity of nichrome wire, there is a need for basic energy versus mass curves. Also, a requirement for innovative design to minimize triggering mass and the required power/energy for triggering.
1.4.11.7 Cost Trades

**SHUTTLE COST TRADES**

**Implementation Description:** Eliminate ordnance devices by making substitute devices using Nitinol.

**Implementation Cost Estimate:**

<table>
<thead>
<tr>
<th>Task</th>
<th>Material</th>
<th>Material</th>
<th>Comment</th>
</tr>
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<tr>
<td>Design &amp; Qual. Tests</td>
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<td></td>
<td>cost for 3 vehicles</td>
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<tr>
<td>Manufacturing</td>
<td></td>
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<tr>
<td>Modification &amp; Installation</td>
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</table>

**TOTALS**

**Ground Ops Cost Savings Per Flight After Implementation:** (N/A = not available)

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<th>Item</th>
<th>Old</th>
<th>DMH</th>
<th>Mat</th>
<th>Other</th>
<th>New</th>
<th>DMH</th>
<th>Mat</th>
<th>Other</th>
</tr>
</thead>
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<tr>
<td>V501C Off</td>
<td>44</td>
<td>316</td>
<td></td>
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<tr>
<td>BDS90 Vac</td>
<td>17</td>
<td>N/A</td>
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<tr>
<td>T-140 ST N/A cell</td>
<td>64</td>
<td>N/A</td>
<td></td>
<td></td>
<td>N/A</td>
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<td></td>
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<td></td>
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</tr>
</tbody>
</table>

**Ground Operations Savings for Future Vehicles:**

The cost savings for future vehicles is approximately equal to cost avoidance of the current STS costs.

**Cost Analysis:** This data is presented in Section 1.6.3, COST TRADE SUMMARY.
1.4.11.8 Conclusions & Recommendations

Due to the criticality of the operations that ordnance devices perform, a high confidence level will be required for any replacement device. Careful analysis should be performed on the OMRSD requirements for each application. A careful study should be performed for other possible substitute devices. Nitinol appears to be a very likely candidate for these devices. Since a number of companies are trying to enter the shape-memory market, the timing for research or study contracts should be ideal. This study therefore recommends that further research into the use of shape-memory devices (for ordnance substitutes) be done as soon as possible.

The ignition devices and the Range Safety devices were excluded from detailed examination because of study time limitations and no readily apparent technology.

It is recommended, for both Shuttle and Future programs, that concentrated effort be made to eliminate ordnance devices to make ground operations more efficient. Specifically, it is recommended that Nitinol technology be explored as a starting point in replacing ordnance type release and separation devices. Further, that other technology, such as lasers, be investigated for ignition devices and a complete assessment be made of range safety requirements and ordnance devices.

In the case of Nitinol technology, it is specifically recommended that NASA KSC fund a small investigation by the Naval Surface Weapon Center to provide the missing basic data on reaction time and energy/power/mass relationships as a basis for a later RFP for substitute ordnance devices.
1.4.11.9 Bibliography - Ordnance Operations

(Each of the references listed below has its own bibliography)

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   55-NITINOL--THE ALLOY WITH A MEMORY: ITS PHYSICAL METALLURGY,
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   Battelle Memorial Institute, 505 King Avenue, Columbus, OH
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   David M. Goldstein; 28 pages; 15 October 1984
   PRODUCTION OF SHAPED PARTS OF NITINOL ALLOYS BY SOLID-STATE
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   Naval Surface Weapons Center, Dahlgren, VA 22448 - Silver
   Spring, MD 20910

3. RECON 82N19033; AD-A108278; NSWC TR 81-129
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1.4.12 PAPERWORK & REQUIREMENTS (ULCE) (Tentpole G)

1.4.12.1 Introduction

Design for performance has been the priority goal for new systems for decades. Consequently, many analytical procedures and data bases have been developed to accomplish these design activities. In contrast, design for support has had much lower priority; consequently, few analytical procedures and databases have been developed which allow the support factors to be included in the design process.

However, the opportunity exists today to significantly, and dramatically, improve the capability to design for supportability. The opportunity exists now because of the convergence of four historical trends.

The first trend is the steadily increasing demand by the Department of Defense to drastically improve the maintenance and support of systems while reducing manpower and costs.

The second trend is the accumulation of evidence from recent research performed by the Human Resources Laboratory at Wright-Patterson Air Force Base which indicates that maintenance and logistics support characteristics must begin with early concept studies. This research indicates, also, that one of best ways to improve design for support is to put the maintenance and logistics data and factors directly into the daily working procedures used by the design engineering personnel. (Reference 1)

The third trend is the "explosive" emergence of computer aided design (CAD) as the daily working procedure within American industry for design of products. One of the main reasons for this rapid growth is that CAD greatly reduces the time and engineering labor hours required to produce a new design. The opportunity, therefore, is to link these trends and develop the technical capability to put maintenance factors, logistics factors and operational requirements directly into the CAD process being used by the aerospace industry. This technical capability does not exist today except in limited scope and then only in isolated cases. The current status of design for support is primarily that of analyses being performed "off-line" from the main performance engineering design activities, and then being performed "after the fact" without input to major design decisions. Development of the technical capability to put maintenance and logistics factors directly into the main CAD process can change this picture. Design for supportability can become an on-line design activity.

The fourth trend is one that will tie together the first three and maximize their combined effect on development of the next generation systems. As costs have risen, the competitive position of aerospace industry in the world market has been further weakened by the inequity of foreign governments subsidizing manufacturing and operating costs. To meet this challenge the Boeing Commercial Airplane Company has developed the Design/Build Team (DBT) concept as a dramatic approach to cost reduction and product improvement.
1.4.12 PAPERWORK & REQUIREMENTS (ULCE) (Tentpole G)
(Continued)

1.4.12.2 Issues

This Study used the STS 51-L (the last Challenger flight) launch operations data and the post 51-L reports as a point of departure. This data was then used to analyze the launch operations characteristics and place documented problems into one or more of several categories called "ISSUES".

A total of 40 different categories were identified, 18 of which will be discussed here. The following list contains those Issues that have a potential for avoidance in the future by incorporation of techniques within ULCE.

ACCESSIBILITY
CHANGE CONTROL
CONSTRAINTS
DESIGN
DESIGN CRITERIA
DISCIPLINE
DRAWING SYSTEM
INTEGRATION
LOGISTICS/SPARES

MAINTAINABILITY
MANAGEMENT
PAPERWORK
PROCEDURE
QA
RELIABILITY
REQUIREMENTS
STANDARDS
TRAINING/CERTIFICATION

1.4.12.3 ULCE Related Issues

Each of the issues described above is listed in the following section with a brief description of the general nature of the problem. Source of these quotes is the Issues Database from this Shuttle Ground Operations Efficiencies/Technologies Study. The number of occurrences of the issue in the database will give the reader a relative feeling of its severity as evidenced by the degree of documentation by numerous committees and organizations.

Accessibility: (104 occurrences) 
"...Contract specifications need to stress LRU maintainability/accessibility...Fund maintainability and accessibility up front to significantly reduce unnecessary support costs in the operational area...include a logistics representative on the design team to continually address the problems of standardization, ease of maintenance, and accessibility..."

Change Control: (30 occurrences) 
"...The qualification of the test article was not in all cases representative of the flight configuration...Work accomplished on Flight 10 was formally approved for Flight 11...This OMI was deviated to change the configuration of the holddown post-blast shields for launch, formal engineering was not available for the operations, verbal agreements were reached and four of the blast shields were modified, post launch inspection revealed that the items incorporated for the mod were blown away at launch..."
Constraints: "...Events associated with the STS 51-L mishap identified SRM flight safety issues not addressed in the FRR process...Manpower limitations due to high workload created scheduling difficulties and contributed to operational problems...MSFC is not part of the formal IFA (Inflight Anomaly) tracking system...Team members identified several problems with the constraint system which hampered effective traceability of open work items...Limited visibility of the constraints status make it difficult to identify and schedule work to support the test flow..."

Design: "...Designers of black boxes should position PCBs so they will be vertical when the black box is installed in the system. Locate electrical feed through connectors on the side or back, not on the bottom...Design specs would require simplicity of design/accessibility to facilitate maintenance; maintainability verification should be conducted to identify & correct maintenance deficiencies before design is "frozen"..."

Design Criteria: "...Perform fit checks of mission equipment hardware on a high fidelity mock-up at the design agency to preclude field problems...Provide a defined maintainability design criteria at the inception of the program and a design review board to monitor adherence to these criteria..."

Discipline "...Five weeks after the 51-L accident, the criticality of the solid rocket motor field joint was still not properly documented in the problem reporting system at Marshall...Work authorization documentation audit, the review has found that the ability of the work control documentation system to guarantee proper real time execution of tasks and their subsequent traceability is inhibited by factors that must be identified and corrected by KSC management..."

Drawing System: "...Incremental delivery of Orbiter/payload mod kits is a problem. A system must be devised to I.D. problems/delays before becoming constraints to the field...Reference designators should be of a constant format across all program elements: Orbiter, External Tank (ET), Solid Rocket Booster (SRBS), develop a uniform system...Enforce a standardized drawing and part number system on all contractor and government furnished equipment..."

Integration: "...Provide a full fidelity model for sub-system maintainability testing, to be used early in the design phase to verify design requirement compliance..."

Logistics: "...Use standard industry hardware rather than unique hardware, unique limits the availability of spares and drives up the cost..."

Maintainability: "...Maintenance requirements should be identified prior to design; Imposed at the sub contractor level, design requirements must address maintenance..."
Management: 
Methods should be developed which assure more direct design contractor involvement in the processing and testing effort at the launch sites...Signature requirements on 'Real Time' work paper (deviations, TPS', IPR'S etc.) are lengthy and required personnel are geographically scattered...

Paperwork: 
The OMRSD system is very difficult to paper track with respect to auditing requirements. The OMP and PSP which are often incorrect in the deviations and revisions are incorporated between the publication of one document and another. The OMP is not a closed loop system and is sufficiently complex such that cognizant systems engineer is the only person who knows the full status of OMRSD requirements..."(ref. to, 'Paperwork Problems' for details)

Procedure: 
Of the 51 work documents generated by the MCR's, 96% were found to have errors of an administrative or format type as defined by the SPI (Standard Practice Instructions)...Task deviation log does not indicate effectiveness of temporary deviations. Therefore, there is no foolproof way to determine if a temporary deviation is effective on a given run..."

QA: 
OMRSD V41BG0.010 which checks the redundancy of individual regulators was not verified under flow conditions...The leak check steps for test port #4 were inadvertently omitted from OMl V1009.04. This is a violation of OMRSD V41AZ0.070...

Reliability: 
Design is a compromise between performance, reliability, maintainability, weight, space restrictions, safety, etc. Management must re-prioritize these factors so maintainability receives it's deserved attention...

Requirements: 
The processing support plan is a KSC document that lists all work that may be performed on a specific STS flow and lists OMRSD requirements and OMl's that will be released. The PSP is published about 50 days prior to OPF roll-in and is continually updated by system engineers. There is NO feedback into the OMP...

Standards: 
Problem reporting requirements are not concise and fail to get critical information to the proper levels of management...

Training/Certif: 
Training must be adequate to ensure that all workers are able to comply with the regulations which govern the paperwork system...The OMRSD requirement of 1 psid in the manifold was violated in that 6 psid were present causing the valve to slam..."

This multiplicity of problems is astonishing! It is imperative that a system be developed to control these interrelated problems. ULCE can provide the core solution!!

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1.4.12 Today's Methods

The problems identified in the previous Issues section all have a common denominator, lack of SUPPORTABILITY. Each of the issues discussed in the previous section are the result of vehicle supportability being de-emphasized early in the design phase. This problem can be seen in almost all vehicle sub-systems as well as ground support systems.

The emphasis on performance has resulted in many tools being developed to support the evaluation of a given design for performance. The evaluation of supportability is primarily performed off-line, after-the-fact and if it is performed at all, too late for initial design influence.

It is clearly defined that the life cycle cost (LCC) of a system can be divided into four primary phases.

1. The Mission Definition phase involves conceptualizing the system; defining the problem to be resolved and considering initial architectures.

2. The Design phase in which the system is designed and the prototype is constructed and tested.

3. The Production phase entails manufacturing the product.

4. The Operations phase involves repair, operations, spares, training, product improvements, maintenance testing etc.

The distribution of the LCC for a DOD or commercial system is given in Figure 1:

<table>
<thead>
<tr>
<th>LCC Phase</th>
<th>LCC %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Definition</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>2. Design</td>
<td>&lt;10 %</td>
</tr>
<tr>
<td>3. Production</td>
<td>30 %</td>
</tr>
<tr>
<td>4. Operations</td>
<td>60 %</td>
</tr>
</tbody>
</table>

DOD LCC Distribution (reference 3)

Figure 1

The current STS LCC has a distribution as shown in Figure 2:

<table>
<thead>
<tr>
<th>LCC Phase</th>
<th>LCC %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Definition</td>
<td>&lt;1 %</td>
</tr>
<tr>
<td>2. Design</td>
<td>6 %</td>
</tr>
<tr>
<td>3. Production</td>
<td>8 %</td>
</tr>
<tr>
<td>4. Operations</td>
<td>86 %</td>
</tr>
</tbody>
</table>

SHUTTLE LCC DISTRIBUTION (reference 4)

Figure 2
In the past, up front costs and performance have been given priority at the expense of reliability and maintainability. The design of future systems will have to consider operational requirements including reliability and maintainability; at the same level as performance, if our designs are to provide life cycle costs competitive in the market place.

The prime reason for this trend has been political economics. If inadequate funds are allocated for the initial design and manufacturing, then proof of concept (initial flight) takes all the allocated funds leaving none for maintainability, and reasonable life cycle costs factors.

1.4.12.5 New Technical Requirements

The previous sections have identified the urgent need for a radical shift in design techniques. The methods used to design systems in the past, although adequate in their time, are no longer suitable for systems of the future where low cost operations are paramount.

There are several CAD (Computer Aided Design) technologies currently available or in development that can alleviate many of the operational problems associated with today's Shuttle.

To define the nature of the work required to provide CAD capability, it is necessary first to understand the relevant characteristics of such a system: (Reference 1)

1. **Quickness of reaction** time is probably the characteristic of CAD that will most affect the future design for supportability. Entire vehicle system design must be established within days or weeks. Support analyses for proposed designs cannot exist off-line. Support analyses will need to respond rapidly or they will be disregarded.

2. Computer-based **automated analysis models** are an essential part of the CAD process. Presently these models are used to assess performance characteristics or weight and balance. These automated analysis models are one of the reasons for quick reaction time of the CAD process. Automated maintenance and logistics analyses models will also be required.

3. The ability to view objects in three dimensions is now resident within many CAD systems. Color representation of objects is now possible. These characteristics will afford opportunities to use CAD to perform mockup maintainability evaluations of equipment during early design.

4. The design and drawing data generated by CAD are being bridged to the databases that operate numerically controlled machines within the manufacturing facility. The data flows from CAD to CAM and eventually to field and service engineering. Unfortunately, the databases that are used in maintenance and logistics analysis models are not linked with the CAD/CAM engineering databases. Design tasks for future systems will have to provide for supportability analysis data interchange with CAD/CAM.
5. Design systems of the future will be required to provide an integrated data path, providing a birth-to-death documentation tracking capability. Data generated during the design and manufacturing phase will have to be compatible with the data structures and processing systems used in the field and vice versa.

6. To achieve the maximum benefit from new computer aided design techniques will require new management techniques that can instill within the project four basic steps (William E. Conway, Conway Quality Inc.):

   A. Desire to change
   B. Belief that change can be accomplished
   C. Wherewithal to change
   D. Doing

1.4.12.6 Technology Evaluation

The Air Force Human Resources Laboratory, Wright-Patterson AFB (AFHRL) is involved in the development of future aerospace systems design techniques to reduce LCC (Life Cycle Costs) and increase supportability; this project is known as ULCE (Unified Life Cycle Engineering).

There are three primary components in ULCE:

1. IDSS (Integrated Design Support System)
2. RAMCAD (Reliability and Maintainability through Computer Aided Design)
   CREW CHIEF and TARS (Turnaround and Reconfiguration Simulation).
3. IMIS (Integrated Maintenance Information System)

IDSS

The integration of dissimilar CAE/CAD/CAM and operational data sources on local and geographically distributed networks is the major problem faced in the development of ULCE. The development of the IDSS by the Air Force will provide a means to accomplish this integration. The goal of IDSS is to develop a computer software methodology for the acquisition, storage, retrieval and coordination of technical information between design engineering efforts and operational activities to support such developments as Operations and Maintenance Instructions (OMI), training programs, and operations problems analyses. The IDSS will provide for the reduction and duplication of data while also providing for rapid distribution and increase in quality of the data. (Figure 3.)
The architecture of the IDSS is comprised of two main areas: the Executive Control System (ECS) and the Data Acquisition System (see Figure 4.)

The ECS will provide for:

1. User interface
2. Application software (e.g., Data query, Data Edit, etc.)
3. Data coordination and distribution
4. Configuration control
5. Project management
6. Data security (i.e., Data access control)

The DAS portion will provide for:

1. Heterogeneous H/W and S/W systems
2. Distributed database management
3. Network communications protocol
4. Data integrity
The modern operational environment is being increasingly inundated with additional information systems. Each new "operational aid" is an operations hindrance because it forces technicians to learn yet another "system". To utilize the valuable information these new systems offer, while eliminating the specialization required for each, AFHRL is developing IMIS.

IMIS will utilize a very small portable computer/display to interface with on-board systems and ground computer systems to provide a single, integrated source of information needed to perform required tasks on-line and in the shop. IMIS will consist of a workstation for use in-shop, a portable computer for flight line use, and a vehicle interface panel. (Figure 5.)

The system will provide the technician with direct access to several information systems and databases compatible with IDSS. IMIS will process, integrate, and display maintenance information to the technician. The system will display graphic and/or technical instructions, provide intelligent diagnostic advice, analyze in-flight performance and failure data, and access and interrogate on-board built-in-test capabilities. It will assure that all of the Operational and Maintenance requirements are satisfied by directly interrogating the requirements database. (see Figure 6.)

It will also provide the technician with easy, efficient methods to receive work orders, report maintenance actions, order parts from supply, and computer-aided training lessons complete with a simulation capability.
RAMCAD

RAMCAD is a joint Air Force in-house and contractor study to develop an analysis model and database structure for assessing the location of line replaceable units (LRUs) within a vehicle with regard to failure rate of the components and accessibility for maintenance actions. The goal is to develop an automated assessment model which will yield a quantitative index of the "goodness" of a given arrangement of LRUs within a housing.

CREW CHIEF and TARS

Crew Chief is a computer-based model of the technician which can be used to assist in the evaluation of equipment designs. The early design was based on the COMBINATION model which was an earlier product of Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base. The Crew Chief model can be used to provide mockup-type evaluations of equipment on 3-D interactive graphic displays.

Crew Chief can be utilized to evaluate such maintenance operations as component testing, component removal and replacement, vehicle servicing and turnaround activities, engine removals, fuel and ordnance loading. The operations may be performed with the model wearing various types of clothing, such as warm weather, cold weather, and chemical defense gear (SCAPE). Exploded view enlargements of hand and arm activities to include manipulation of tools are included. It is also possible to evaluate human strength capabilities for various lifting and pulling tasks. (see Figure 7.)
TARS is a tool similar to Crew Chief except the emphasis is on the interaction of the entire operations team with the vehicle. Provisions are also made for placing the vehicle within a processing facility. This system will provide for the same level of detail as Crew Chief including 3-D interactive graphics while also allowing the designer to evaluate the operations team accessibility to the vehicle, such as the process of engine removal, placement of work stands, positioning and access for robotics, payload bay reconfiguration, and assorted OMG development.
1.4.12 PAPERWORK & REQUIREMENTS (ULCE) (Tentpole G)
(Continued)

1.4.12.7 Management Technology

Without management acceptance, implementation and followup, no successful system can be installed. The discussion of new management technology is a topic deserving of a paper of its own. The topic is so important to the success of any project that it must be mentioned here in an attempt to convey its meaning.

The first two management steps Desire and Belief, of the four basic requirements to install a change, represent about 80% of the effort required to accomplish a change. The aforementioned computer aided techniques are the Wherewithal to accomplish the change and will only be of use if the first two steps are completed. For example the Boeing Commercial Airplane Company is placing new management techniques "on-line" that will provide the means to accomplish the first two steps. Boeing believes this is necessary to survive in tomorrow's marketplace.

Productivity improvement planning requires the same kind of systematic approach as financial planning. Every manager from the highest level (i.e. Presidential and Congressional) down must establish a plan to install the Desire and Belief that change is required and possible. This must be a continuous process requiring frequent follow-up reinforcement.

The manager's greatest responsibility is to work on the system itself; this requires making changes in the ways in which work is performed at all levels of the project. These types of changes are usually highly effective at producing both increased quality and reduced costs. Experts in productivity improvement estimate that 80% or more of the opportunities for change are the result of management's improvement of the system to allow change. The workers accomplish the remaining 20%.

If a problem is shared among several groups, it is important for these groups to share the accountability for it and to work together to solve it. Design Build Teams (DBT) are an effective way to do this. The DBT has members from all of the affected functional areas; design engineering, manufacturing, materials, operations, etc. All team members participate directly in the design process, each assuring that the initial design meets all of the operational and performance requirements.

A quote from W. Edwards Demming (of Japanese industry fame) may be best to close this brief discussion of new management techniques:

"Eliminate targets, slogans, pictures, posters for the work force, urging them to increase productivity, ...what is needed is not exhortations but a road map to improvement, management's obligation."

Pressure to work harder or better does not achieve productivity improvement. Most workers already believe they are doing the best they can in the current environment. Evaluating them by the quality of their work places the entire responsibility for improvement on them alone.
1.4.12 COST TRADE

Improvements in the paperwork processing systems using the IMIS concepts described above can produce a reduction in Life Cycle Cost for the present configuration of the Shuttle of about 5%.

The following figures 8 & 9 present Net Present Value curves showing 5%, 7.5%, & 10% discounts assuming a realistic flight rate of 10 per year. Figure 8 is based on $246M per flight which is actual 1985 expenditures during which 8 STS's were launched. Figure 9 shows the same information based on a per-flight cost of $100M, which is an estimate based on achieving a flight rate of 24 per year or a 300% increase in the flight rate over the rate of 1985.

The best that can be hoped for without major Shuttle block modifications is to improve the launch processing systems to minimize the paperwork and establish this system for future vehicles. If the Shuttle flies an additional 45-55 flights then a payback may be achieved for the current Shuttle configuration. If the current Shuttle does not manage another 55 flights then the system will be on-line and available for the next generation STS configuration.

IMIS IMPLEMENTATION
(10 FLIGHTS PER YEAR - $246 MILLION PER FLIGHT)

Figure 8
1.4.12 Conclusion

Design for Performance has been the priority goal for new systems for decades. The result when supportability takes a back seat to performance is exemplified in the overwhelming Life Cycle Cost and schedule delays evident in the operation of the current Shuttle.

The Shuttle Ground Operations Efficiencies/Technologies Study, using data made available primarily as a result of the 51-L incident, has been able to document a host of problems that are relatable to the lack of supportability considerations in design of the Shuttle.

The current CAD design tools utilized are all related to performance with little or no consideration being given to reliability and maintainability requirements. The USAF has a major effort underway to improve supportability for new systems, by developing design tools to provide on-line analysis of supportability for a proposed design. These tools will include maintenance and reliability factors within CAD.

It is realized that improved design for support is not the only means to an end. Improved training of maintenance personnel, better job performance through new management techniques, and better automated maintenance aids and concepts will also contribute. However, improved design for support will make a significant contribution, and including reliability and maintainability factors in CAD will make a significant contribution to improving the design.

Figure 9

IMIS IMPLEMENTATION
(24 FLIGHTS PER YEAR - $100 MILLION FULL COST PER FLIGHT)
1.4.12 Paperwork & Requirements (ULCE) (Tentpole G)

(Continued)

1.4.12.10 Paperwork Problem References

PAPERWORK PROBLEMS -- SUMMARY

The Presidential Commission Report on the Space Shuttle Challenger Accident noted that of the approximately 5000 documents evaluated, a large percent were found to be incorrectly executed. The discrepancies were generally minor in nature, such as incorrect signatures, missing signatures, lack of Quality Control, incomplete rationale for closure, etc. An in-depth review of all KSC Shuttle Processing paperwork was also conducted by several paperwork review teams. These teams were co-chaired by both NASA and SPC, and team members included representatives from the organizations responsible for Space Shuttle Processing. The information below is taken from these reports.

PAPERWORK PROBLEMS -- CURRENT KSC METHODS

Operation Maintenance Instruction (OMI)

LSOC/NASA quality reviewed 121 OMI's, 47% (57 OMI's) had paper errors, of a relatively minor nature. 13% of the OMI's had some data recording points missing or incorrectly documented (such as calibration dates, voltage, temperature, and pressure readings not recorded).

Work Authorization Documents (WAD)

A total of 479 Orbiter WAD's in the IPR, PR, or TPS category were reviewed, of the 479 70% had the following anomalies:

- 36% - Inadequate/inaccurate level of detail
- 21% - WAD not properly stamped by Shop/QC/QE
- 29% - Correct signatures not obtained
- 20% - Inadequate summary for closure/deferral
- 9% - Task not performed correctly the first time
- 3% - Retest not adequate/satisfactory
- 2% - Inadequate rational to defer WAD

Modification Change Requests (MCR)

A total of 22 MCR's were applicable to the 51-L processing flow. An independent safety review of all MCR's discovered the following errors:

- 20% - Critical skills or wrong numbers for skills
- 20% - No certification annotated
- 80% - Procedure/format problems
- 20% - Missing Safety stamp
- 40% - Quality disposition on a Safety area
These MCR's generated 51 Work Authorization Documents which were reviewed, 96% were found to have the following errors of an administrative or format error as defined by the SPI (Standard Practice Instructions).

- 85% - WAD format incorrect
- 69% - Improperly stamped by Shop/QC
- 35% - Incorrect Signatures
- 35% - Required data not recorded
- 31% - Inaccurate level of detail
- 22% - Proper Engineering not identified
- 10% - Engineering from Design Center not timely
- 10% - Work accomplished did not match Engineering
- 6% - Retest required not identified
- 4% - Inaccurate summary for closure deferral

**Operation Maintenance Plan (OMP)**

KSC maintains an OMP database to track the OMRS requirements and the OMI's and Task Numbers where the requirements will be met. 327 OMI's listed for 51-L the following observations were made:

- 10% - Of the OMI's not applicable to STS-33
- 13% - Of the OMI's were contingency procedures

Also, noted that the OMP is not a closed-loop, therefore as revisions to OMI's are published, page and task numbers are frequently incorrect. The OMP does not reflect the current OMRS implementation. And, the OMP does not contain a "clock" such that when LRU changeouts occur the interval requirement can be updated to indicate the true effective date.

**Processing Support Plan (PSP)**

The Processing Support Plan is a KSC document that lists all work that may be performed on a specific STS flow and lists the OMRS requirements and OMI's that will be released. The PSP is published about 50 days prior to OPF roll-in and is continually updated by system engineers. There is no feedback into the OMP.

**General Findings**

An unacceptable error rate in the work paper was approximately 50% and had these contributing factors:

- Signature requirements on "real time" work paper (deviations, TPS's IPR/PR's, etc.) are lengthy and required personnel are geographically scattered (usually miles, not feet). Rapid response to problems or changing work schedules is precluded; encouraging "short cuts".

- The signature "loop" is manpower intensive, requiring many "processors" as well as full time availability of system engineers.

- The amount of time required to complete any category of documentation from open to close is unacceptably high when compared to the actual time to do the work.
- Many tasks cannot be "bought off" at the location due to Safety or physical restrictions: later transferring stamps provides another failure point.

- Due to its complexity, writers, performers, and "buyers" of tasks have difficulty in understanding the paper system.

- There are many different levels and categories of paper and many inconsistencies in the preparation and disposition of this paper.

- The "tiering" from integrated OMI, to standalone OMI, to RTOMI, to job card (plus all deviations) creates a very complicated control and status trail for Quality Assurance personnel, as well as Operations Management.

- Many tasks, due to the system or poor discipline in the origination process, end up with multiple items of work paper, compounding the buy-off process.

- No single organization has the responsibility for final review for closure.

Conclusions: During the document review, many areas of unclear or inconcise documentation were noted. Instructions in WAD's are frequently not clear or precise. The OMRSD system is very difficult to paper track with respect to auditing requirements. The OMP and PSF, which are the KSC supporting documents to the OMRSD system, are usually incorrect in that the deviations and revisions are invariably incorporated between the publication of one document and the other. Finally, the OMP is not a closed loop system and is sufficiently complex that the cognizant systems engineer is the only person who knows the full status of OMRSD requirements.

Basically, the system is not simplified for the originator, performer, or verifier; and therefore, is not a tool, but an impediment to good work and good records - the only reasons for it's existence.
Recommendations: The solution to this or any problem with a system as complex as the Space Shuttle Processing paperwork system requires a team effort. Most importantly, in this instance, a commitment to compliance with processing procedures and requirements by high level management and the proper training and discipline of personnel responsible for using the paperwork system is required.

To assist management, engineering, and the technicians, in the Space Shuttle processing operation, maximum emphasis on current efforts to develop automated systems to facilitate the planning, tracking and management of processing operations. Many changes being contemplated during this review period will increase the time required to manually process the paperwork. The incorporation of integrated automated systems is imperative in order to ensure proper completion of orbiter turnaround requirements as the launch rate increases.

Paperwork Problem Improvements In-work: All the work performed on Shuttle flight hardware, Shuttle facilities, and Shuttle ground support equipment must be documented for traceability. This results in a large amount of documentation which must be processed each flow. The time spent preparing documentation for each flight can be greatly reduced by the use of computers.

In addition to planned work and scheduled maintenance, the process team must be prepared to react efficiently to real time problems which result in unscheduled maintenance. Problems are documented into three categories. An Interim Problem Report (IPR) is used to describe a problem when troubleshooting is required to determine the cause of the problem. A Problem Report (PR) is used to describe a problem and remedial instructions when the cause of the problem has been determined. A Discrepancy Report (DR) is used to solve minor problems which can easily be returned to normal configuration. In a nominal flow, there are approximately 4000 IPS's, PR's, and DR's written for STS vehicle processing.
1.4.12 PAPERWORK & REQUIREMENTS (ULCE) (Tentpole G)  
(Continued)

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5. 51-L DATA AND DESIGN ANALYSIS TASK FORCE FINDINGS (KSC)  
March 1986.

6. REPORT OF THE PRESIDENTIAL COMMISSION ON THE SPACE SHUTTLE  
CHALLENGER ACCIDENT  

7. HEARINGS BEFORE THE SUBCOMMITTEE ON SCIENCE, TECHNOLOGY, AND  
SPACE OF THE COMMITTEE ON COMMERCE, SCIENCE, AND  
TRANSPORTATION - 99th CONGRESS - FIRST SESSION ON NASA  

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1.5 SPACE STATION TECHNOLOGY APPLICATIONS

Significant technology developments are being funded by the Space Station Program which will be directly applicable to Ground Operations for both Shuttle block changes and future programs. The same is true for SDIO activities.

A minimal look at Space Station development activity was accomplished in the study. This resulted in Figure 1, which illustrates typical Space Station technologies under investigation and their eventual application to space vehicle ground operations.

<table>
<thead>
<tr>
<th>SPACE STATION DEVELOPMENT $55</th>
<th>VEHICLE &amp; GROUND OPERATIONS (SHUTTLE/STAS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXPERT SYSTEM</td>
<td>Elect Pwr</td>
</tr>
<tr>
<td>Fault Diagnosis</td>
<td>X</td>
</tr>
<tr>
<td>Trend Analysis</td>
<td>X</td>
</tr>
<tr>
<td>Power Management</td>
<td>X</td>
</tr>
<tr>
<td>Fault Tolerance</td>
<td>X</td>
</tr>
<tr>
<td>Attitude Control</td>
<td>X</td>
</tr>
<tr>
<td>ROBOTICS</td>
<td></td>
</tr>
<tr>
<td>Teleoperation</td>
<td></td>
</tr>
<tr>
<td>Proximity Touch &amp; Force Sensing</td>
<td></td>
</tr>
<tr>
<td>Range &amp; Image Understanding</td>
<td></td>
</tr>
<tr>
<td>End Effectors</td>
<td></td>
</tr>
<tr>
<td>POWER</td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td>X</td>
</tr>
<tr>
<td>Fuel Cells</td>
<td>X</td>
</tr>
<tr>
<td>OTHER</td>
<td></td>
</tr>
<tr>
<td>Video Probe</td>
<td></td>
</tr>
<tr>
<td>Electron Beam Welding</td>
<td></td>
</tr>
</tbody>
</table>

SPACE STATION TECHNOLOGIES
APPLICABLE TO SHUTTLE AND STAS
Figure 1
1.6 GROUND OPERATIONS EVALUATION SUMMARY

The background and rationale for the future program and Shuttle recommendations presented in this section were described in detail in Section 1.4, "Tentpole and Related Issues Analyses".

1.6.1 Future Program Applications

**FUTURE VEHICLES**

The significant conclusions and recommendations related to the trade studies for future vehicles follows:

1. Major changes in design and management methodology are required.

2. New technology involves management and computer-aided tools.

3. ULCE/CALS (Unified Life Cycle Engineering/Computer Aided Logistics System). This will provide the means to avoid maintenance problems such as accessibility, commonality, change control, interfaces, isolation, procedures, standards, training, QA, integration, spares, etc.

4. DBT/DTC (Design-Build Team/Design to Cost)

5. Without consistent long-term management commitment, 1 through 4 will not work.

6. Future vehicles, beginning with the Design Concept Phase, must put life cycle costs ahead of performance. We are hauling cargo via freighter -- not participating in a yacht race.

7. All engine maintenance should be accomplished off-line with adequate facilities and spares.

8. Cargo should be self-sufficient with minimal power / control / data interfaces. It should be containerized and processed entirely off-line. Weight penalties to provide containerization should be absorbed by system robustness.

9. Design for testability, fault tolerance, transparency to changes, self-improving diagnostics, false alarm discrimination, data compression, optimum man/machine interfaces must all be firm design requirements.
Large, complex, launch control centers must be eliminated by incorporation of BIT, BITE, and concepts such as self-check "automatic test equipment on a chip technology" in the vehicle itself. For manned vehicles, the crew/machine interface should be capable of performing the countdown.

Artificial intelligence and Expert Systems are now in an infantile stage and are not a panacea for the next round of new vehicles. It will be the second round and into the late 1990's before there will be reasonable risk designs available.

Ordnance devices must be eliminated to accomplish efficient processing. It appears practical to eliminate ordnance type release devices at an early date through the use of technology such as Nitinol. SRB ignition and range safety devices are a tougher proposition. Some innovative concepts will be required in these areas. Perhaps something as far out as lasers for ignition and weapon systems (infrared seeker missiles) for range safety.

There are a large number of desirable (required) features for future vehicles which were not investigated because of Study limitations. These include:

1. Eliminate vehicle hydraulic systems with electromechanical devices to simplify ground operations.
2. Eliminate hydrazine systems to simplify ground operations.
3. Minimize facility/GSE/vehicle interfaces to simplify ground operations. Eliminate hardware electrical interfaces and swing arms.
4. Eliminate requirement for ECS GSE to simplify ground operations.
5. Maximize automation of structural inspections to eliminate requirement for off-line periodic inspections.
6. Provide easily maintainable Thermal Protection System.
7. Standardize propellants, fluids, and grades.
8. Incorporate automated servicing in vehicle design.
9. Vehicle/GSE design such that assembly and checkout, intrasite transportation, and landing/recovery are not constrained by weather.
10. Etc., etc. (See Volume 4, Preliminary Issues Database for additional operational needs under topics such as accessibility, commonality, integration, interface, isolation, logistics/spares, maintainability, redundancy, safety, security, and surface transportation).
1.6 GROUND OPERATIONS EVALUATION SUMMARY (Continued)

1.6.2 SHUTTLE RECOMMENDATIONS

1.6.2.1 IMIS (Integrated Maintenance Information System)

Shuttle derived ground operational efficiencies require major block level modifications, and as shown in the cost trade section are not recommended. The single item with the largest payback is a redesign of the SPDMS to conform to IMIS specifications.

The operational environment is being increasingly inundated with additional information systems. Each new "operational aid" is an operations hindrance because it forces technicians to learn yet another "system". To utilize the valuable information that these new systems offer, while eliminating the specialization required for each, the Air Force Human Resources Laboratory (AFHRL) is developing IMIS. IMIS will utilize a very small portable computer/display to interface with on-board systems and ground computer systems to provide a single, integrated source of the information needed to perform required tasks on-the-line and in-shop.

The system will provide the technician with direct access to several information systems and databases. IMIS will process, integrate, and display maintenance information to the technician. The system will display graphic and/or technical instructions, provide intelligent diagnostic advice, analyze in-flight performance and failure data, and access and interrogate on-board built-in-test capabilities. It will assure that all of the operational and maintenance requirements are satisfied by directly interrogating the requirements database.

It will also provide the technician with easy, efficient methods to receive work orders, report maintenance actions, order parts from supply, and computer-aided training lessons complete with a simulation capability.

1.6.2.2 Orbiter Block Change Candidates

NF, the NASA Engineering Development organization at KSC, and NF-PEO, the NASA Shuttle Engineering Project Office at KSC have over 500 specific candidates for vehicle and GSE modifications. These return-to-flight-status mod candidates have been developed at the system engineer level. These candidates are recorded in the Preliminary Issues Database, Volume 4 of this report, with ID's of 1800 to 2900.

Time limitations of the study prohibited an in-depth look at these DE/NE-PEO candidates. However, based on our Operations Analysis and approached from the standpoint of OMI processing, we identified 32 operations which appear to have likely system candidates for design changes that could significantly reduce both processing time and manhours. There is some overlap where these operations overlap the DE/NE-PEO candidates. (Figure 1 lists the OMI's, related systems, the technician manhours, the TIS reference number (from Vol.3 of this Report), and an indication if there are related DE/NE-PEO candidates).
### 1.6 GROUND OPERATIONS EVALUATION SUMMARY (Continued)

<table>
<thead>
<tr>
<th>TIS</th>
<th>OMI</th>
<th>TECH HOURS</th>
<th>M/H</th>
<th>SYSTEM</th>
<th>DE/NE-PEO MODIFICATIONS</th>
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<tbody>
<tr>
<td>3</td>
<td>V1158</td>
<td>56</td>
<td>336</td>
<td>FRCS and CMS pod</td>
<td>Y</td>
</tr>
<tr>
<td>5</td>
<td>V1091</td>
<td>48</td>
<td>192</td>
<td>PRSD LO2 and LH2</td>
<td>Y</td>
</tr>
<tr>
<td>10</td>
<td>V9001VL1-VL4</td>
<td>?</td>
<td>?</td>
<td>power up and power down</td>
<td>N</td>
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<tr>
<td>15</td>
<td>V5043VL1-VL3</td>
<td>96</td>
<td>1632</td>
<td>SSME heat shield removal/inst.</td>
<td>N</td>
</tr>
<tr>
<td>17</td>
<td>V1011.01-.07</td>
<td>252</td>
<td>2064</td>
<td>SSME eng leak and functional</td>
<td>Y</td>
</tr>
<tr>
<td>19</td>
<td>V5006.01-.03</td>
<td>12</td>
<td>96</td>
<td>PLB doors</td>
<td>N</td>
</tr>
<tr>
<td>21</td>
<td>V1009.01-.05</td>
<td>264</td>
<td>2112</td>
<td>MPS leak and functional</td>
<td>N</td>
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<tr>
<td>22</td>
<td>V6018</td>
<td>92</td>
<td>368</td>
<td>cabin air debris screens</td>
<td>N</td>
</tr>
<tr>
<td>23</td>
<td>V5E02</td>
<td>36</td>
<td>360</td>
<td>SSME hp turbopump</td>
<td>N</td>
</tr>
<tr>
<td>24</td>
<td>V5E06</td>
<td>36</td>
<td>324</td>
<td>SSME hp turbopump</td>
<td>N</td>
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<tr>
<td>34</td>
<td>V9002.01-.10</td>
<td>68</td>
<td>212</td>
<td>ground power</td>
<td>N</td>
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<tr>
<td>35</td>
<td>V1131</td>
<td>24</td>
<td>120</td>
<td>hydraulic system GN2</td>
<td>N</td>
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<td>38</td>
<td>V1134</td>
<td>8</td>
<td>48</td>
<td>water drain</td>
<td>N</td>
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<td>39</td>
<td>V1078</td>
<td>48</td>
<td>288</td>
<td>APU lube oil</td>
<td>Y</td>
</tr>
<tr>
<td>41</td>
<td>V1153</td>
<td>8</td>
<td>56</td>
<td>APU water servicing</td>
<td>Y</td>
</tr>
<tr>
<td>47</td>
<td>V1018.02-.04</td>
<td>8</td>
<td>48</td>
<td>APU/water spray boiler</td>
<td>Y</td>
</tr>
<tr>
<td>48</td>
<td>V1055</td>
<td>24</td>
<td>168</td>
<td>potable water</td>
<td>Y</td>
</tr>
<tr>
<td>54</td>
<td>V1196</td>
<td>24</td>
<td>168</td>
<td>APU fuel tank servicing</td>
<td>Y</td>
</tr>
<tr>
<td>56</td>
<td>V1165</td>
<td>72</td>
<td>288</td>
<td>nose landing gear</td>
<td>Y</td>
</tr>
<tr>
<td>57</td>
<td>V1003</td>
<td>12</td>
<td>72</td>
<td>electrical power</td>
<td>N</td>
</tr>
<tr>
<td>68</td>
<td>V1041</td>
<td>12</td>
<td>72</td>
<td>ECLSS</td>
<td>N</td>
</tr>
<tr>
<td>69</td>
<td>V5050</td>
<td>24</td>
<td>96</td>
<td>crew equipment</td>
<td>N</td>
</tr>
<tr>
<td>74</td>
<td>V1037</td>
<td>24</td>
<td>240</td>
<td>ammonia boiler</td>
<td>N</td>
</tr>
<tr>
<td>79</td>
<td>V1007</td>
<td>24</td>
<td>96</td>
<td>PVD structural leakage test</td>
<td>N</td>
</tr>
<tr>
<td>81</td>
<td>V1034</td>
<td>?</td>
<td>?</td>
<td>flight control</td>
<td>N</td>
</tr>
<tr>
<td>82</td>
<td>V5101</td>
<td>12</td>
<td>192</td>
<td>weight and balance (GSE only)</td>
<td>N</td>
</tr>
<tr>
<td>83</td>
<td>N52XX</td>
<td>48</td>
<td>240</td>
<td>cargo/equipment removal</td>
<td>N</td>
</tr>
<tr>
<td>85</td>
<td>N/A</td>
<td>168</td>
<td>336</td>
<td>cargo/equipment reconfiguration</td>
<td>N</td>
</tr>
<tr>
<td>86</td>
<td>N/A</td>
<td>192</td>
<td>1344</td>
<td>payload bay reconfiguration</td>
<td>N</td>
</tr>
<tr>
<td>87</td>
<td>N/A</td>
<td>120</td>
<td>840</td>
<td>PLB radiator</td>
<td>N</td>
</tr>
<tr>
<td>88</td>
<td>N/A</td>
<td>72</td>
<td>288</td>
<td>Orbiter/PLB interface</td>
<td>N</td>
</tr>
<tr>
<td>204</td>
<td>S0024</td>
<td>100</td>
<td>?</td>
<td>hydrazine</td>
<td>N</td>
</tr>
</tbody>
</table>

**VEHICLE BLOCK CHANGE CANDIDATES (TECHNOLOGY IMPROVEMENTS)**

Figure 1

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1.6.3 COST TRADE SUMMARY

Generally, cost trade information is to be found in the appropriate Tentpole and Related Issues Analysis section. This summary section provides an overview and examples. It should be noted that the data required for a rigorous cost trade (manhour data by OHI) was either not available or only partially available since cost data has not been accumulated at this level by the Shuttle Processing Contractor.

Figure 1 provides a brief qualitative summary of each tentpole discussed in detail in Section 1.4, Tentpole and Related Issues Analysis.

The two major cost trades provided in the study are for ANOMALY RESOLUTION and ULCE (Unified Life Cycle Engineering). The prime source of data for these cost trades comes from the Air Force, DoD, and the NASA Congressional Budget Hearings. Improvement factors come from the Air Force and DoD while actual costs and projected costs come from the NASA Congressional Hearings and the Congressional Budget Office.

It should be noted, in examining cost data in this study, that there is a significant difference in cost data from this Study and those in STAS or the NASA budget hearings:

STAS and NASA use a projected figure of 24 total flights per year and an overall life of 100 flights per vehicle. Based on FY-85 actuals for all operations, this gives an approximate operations cost figure of $100 million per flight.

In this study, we have used a more conservative projected figure of 10 total flights per year based on our operations analysis and as an extrapolation of the fact that the best accomplished to date, FY-85, was 8 flights. 100 flights per vehicle was used as an overall life. Based on FY-85 actuals for all operations this gives an approximate operations full cost figure of $246 million per flight.

The following is a quote from Eric Hanushek, Deputy Director, Congressional Budget Office, in hearings before the Senate Subcommittee on Science, Technology, and Space for FY-86:

"The estimated full costs are particularly sensitive to the number of flights, because fixed costs, either operational or capital, must be spread over a smaller base if flights are less than 24 per year estimated by NASA. In table 3 of my full testimony, there is an indication of the sensitivity of the estimates. For example, if there are only 12 flights instead of 24 in 1989, the average full cost increases to $258 million."
## Trade Summary (Continued)

<table>
<thead>
<tr>
<th>TRADE DESCRIPTION</th>
<th>POTENTIAL MAGNITUDE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SSSH PROCESSING</strong></td>
<td>SIGNIFICANT ON-LINE PROCESSING TIME AND MANPOWER SAVINGS</td>
</tr>
<tr>
<td><strong>PLE/APT RECONFIGURATIONS</strong></td>
<td>SIGNIFICANT ON-LINE PROCESSING TIME REDUCTION</td>
</tr>
<tr>
<td><strong>CAEIN AIR</strong></td>
<td>RELATIVELY SMALL IN THAT NO ON-LINE SAVINGS ARE PROJECTED</td>
</tr>
<tr>
<td><strong>WEIGHT &amp; LABOR OPERATIONS</strong></td>
<td>SIGNIFICANT OFF REDUCTION OF ON-LINE TIME</td>
</tr>
<tr>
<td><strong>FUELCELL EMBEDDING</strong></td>
<td>PROBABLY NOT COST EFFECTIVE. FUELCELL REQUIREMENTS SET A SOLUTION FROM OFF VIEWPOINT</td>
</tr>
<tr>
<td><strong>ANYMAL EXECUTION</strong></td>
<td>WELL DOCUMENTED, MAJOR LIFE CYCLE COST SAVINGS IN THE 15 FOR FUTURE VEHICLE. LIMITED POSSIBILITIES FOR SHUTTLE</td>
</tr>
<tr>
<td><strong>WIND PROTECTIVE SHELVES</strong></td>
<td>MODERATE SAVINGS. MAINLY MANHOURLS. PROBABLY NOT COST EFFECTIVE FOR SHUTTLE</td>
</tr>
<tr>
<td><strong>WIND PROTECTIVE SHELVES</strong></td>
<td>NO ON-LINE SAVINGS. SIGNIFICANT DIRECT LABOR SAVINGS</td>
</tr>
<tr>
<td><strong>FRS INSPECTION</strong></td>
<td>MAJOR REDUCTION IN ON-LINE TIME AND OFF-LINE MANHOURLS</td>
</tr>
<tr>
<td><strong>FUEL CELL OPERATIONS</strong></td>
<td>SIGNIFICANT IMPROVEMENT POTENTIAL IN ON-LINE AND OFF-LINE MANHOURLS</td>
</tr>
<tr>
<td><strong>ORDNANCE OPERATIONS</strong></td>
<td>VERY SIGNIFICANT ON-LINE REDUCTION; WOULD SPEED UP ENTIRE SHUTTLE PROCESSING FLOW</td>
</tr>
<tr>
<td><strong>RAREWISE REQUIREMENTS</strong></td>
<td>LIFECYCLE COST REDUCTIONS IN $B FOR FUTURE VEHICLES. LIMITES FOR SHUTTLE EXCEPT ISS IMES</td>
</tr>
</tbody>
</table>

### Figure 1, Trade Studies
1.6.3 COST TRADE SUMMARY
(Continued)

Full Operations Cost Derivation: (From Congressional Budget Office data)

$2189.4M for 8 flights, FY-85 or $273M/flight (total ops cost)

Example: Launch Operations = $347.5M for 8 flights

= $347.5M/$2189.4 = 15.9% of Total Ops

= $347.5M/8 = $43.4M/flight

Note: The $273M/flight was used to verify validity of the $246M derived from other sources and the $246M was used as a more conservative figure determining cost benefits in the cost analysis below.

Life Cycle Cost Derivation:

Operations = $246M/flight x 100 flights/vehicle = 24.6B/vehicle = 86%

R & D = 1.65B/vehicle = 6%

Manufact. = 2.4B/vehicle = 8%

Total LCC = $28.6B/vehicle = 100%

1.6.3.1 Anomaly Resolution and ULCE Cost Trades

The following series of figures, based on AF and DoD references quoted earlier in Section 1.4.6, provide the rationale and Life Cycle Cost savings for the following:

Figure 2, Anomaly Resolution (Future Vehicles)

Figure 3, IMIS (Shuttle)

Figure 4, IMIS Implementation Curves (Shuttle)
(10 flights/yr, $100M/flight)

Figure 5, IMIS Implementation Curves (Shuttle)
(24 flights/yr, $100M/flight)

Figure 6, ULCE (Shuttle)

Figure 7, ULCE (Future Vehicles)
1.6.3 COST TRADE SUMMARY
(Continued)

ORIGINAL PAGE IS OF POOR QUALITY

<table>
<thead>
<tr>
<th>LIFE CYCLE PHASE</th>
<th>% OF SYSTEM LIFE-CYCLE COST</th>
<th>ROUGH ESTIMATE OF ITH COST IMPACT</th>
<th>IMPACT OF ITH ON LIFE-CYCLE COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>R&amp;D Design</td>
<td>10%</td>
<td>Up 10%</td>
<td>Up 1.0%</td>
</tr>
<tr>
<td>Production</td>
<td>30%</td>
<td>Up 5%</td>
<td>Up 1.5%</td>
</tr>
<tr>
<td>Operation &amp; Maintenance (60%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repair Labor Costs</td>
<td>32%</td>
<td>Down 13.1%</td>
<td>Down 4.2%</td>
</tr>
<tr>
<td>Spares &amp; Repair Material</td>
<td>14%</td>
<td>Down 15%</td>
<td>Down 2.1%</td>
</tr>
<tr>
<td>Operation</td>
<td>10%</td>
<td>Down 15%</td>
<td>Down 1.5%</td>
</tr>
<tr>
<td>Initial Logistics Support</td>
<td>4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100%</td>
<td></td>
<td></td>
<td>Down 5.3%</td>
</tr>
</tbody>
</table>

(FOR 100 FLIGHT SHUTTLE THIS WOULD HAVE BEEN (.053 X 28.6B) = $1.5B)

ANOMALY RESOLUTION (FUTURE VEHICLES) (POTENTIAL COST IMPACT)
Figure 2

<table>
<thead>
<tr>
<th>LIFE CYCLE PHASE</th>
<th>% OF SYSTEM LCC</th>
<th>ULCE COST IMPACT</th>
<th>IMPACT OF ULCE ON LCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>R &amp; D DESIGN</td>
<td>6%</td>
<td>0%</td>
<td>N/A</td>
</tr>
<tr>
<td>PRODUCTION</td>
<td>8%</td>
<td>0%</td>
<td>N/A</td>
</tr>
<tr>
<td>O &amp; M</td>
<td>86%</td>
<td>Down 3.4%</td>
<td>Down 3%</td>
</tr>
</tbody>
</table>

NET: DOWN 3%

SHUTTLE LIFE CYCLE COST SAVINGS UTILIZING ONLY IMIS CONCEPTS
IMIS (SHUTTLE) Figure 3

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IMIS IMPLEMENTATION CURVES (SHUTTLE)

(24 flts/yr, $100M/flt)

Figure 5

IMIS IMPLEMENTATION CURVES (SHUTTLE)

(10 flts/yr, $246M/flt)

Figure 4

IMIS IMPLEMENTATION CURVES (SHUTTLE)

(Continued)
1.6.3 COST TRADE SUMMARY
(Continued)

<table>
<thead>
<tr>
<th>LIFE CYCLE PHASE</th>
<th>% OF SYSTEM LCC</th>
<th>ULCE COST IMPACT</th>
<th>IMPACT OF ULCE ON LCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>current</td>
<td>goal</td>
<td></td>
</tr>
<tr>
<td>R &amp; D DESIGN</td>
<td>6%</td>
<td>10%</td>
<td>up 66%</td>
</tr>
<tr>
<td>PRODUCTION</td>
<td>8%</td>
<td>30%</td>
<td>up 375%</td>
</tr>
<tr>
<td>O &amp; M</td>
<td>86%</td>
<td>60%</td>
<td>down 30.2%</td>
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net: up 101%

ULCE (SHUTTLE)
Figure 6

<table>
<thead>
<tr>
<th>LIFE CYCLE PHASE</th>
<th>% OF SYSTEM LCC</th>
<th>ULCE COST IMPACT</th>
<th>IMPACT OF ULCE ON LCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>current</td>
<td>goal</td>
<td></td>
</tr>
<tr>
<td>R &amp; D DESIGN</td>
<td>10%</td>
<td></td>
<td>UP 20%</td>
</tr>
<tr>
<td>PRODUCTION</td>
<td>30%</td>
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<td>UP 10%</td>
</tr>
<tr>
<td>O &amp; M</td>
<td>60%</td>
<td></td>
<td>DOWN 19%</td>
</tr>
</tbody>
</table>

net: DOWN 6.4%

ULCE (FUTURE VEHICLES)
Figure 7
1.6.3 COST TRADE SUMMARY
(Continued)

1.6.3.2 Trade Studies Conclusions and Recommendations

SHUTTLE
The significant conclusions and recommendations for the current Shuttle vehicle are listed below:

* The current Shuttle will always be an R&D vehicle because it was not designed for efficient operations.

* Major block modifications of the Orbiter to make it an operationally efficient vehicle are not cost effective. Besides, the out-of-service time would lose 3 to 6 flights. Cost effectiveness will also be a function of remaining Orbiter life. The launch processing manhour data necessary for credible detailed cost trades is not readily available.

There are two additional considerations, however, for block modifications. (1) If Orbiters are taken out-of-service for mandatory safety mods, then there are efficiency and technology candidates which may be cost effective if packaged with the safety mods, and (2) Shuttle vehicle modifications may be best used as proof-of-concept for future vehicles even though, in themselves, they may not be cost effective.

* Without major block modifications to the Shuttle or the Shuttle Processing Data Management System (SPDMS) only minimal ground operations efficiencies can be achieved. The potential for increasing launch operations efficiency without major block mods or major overhaul of the SPDMS is minimal (in the order of 10%) -- and this potential will be overwhelmed by additional safety requirements for some time to come.

* The Study analysis indicates that very significant improvement in current operations can be gained via redesign of SPDMS to conform to IMIS specifications. Potential savings -- $2.6B plus increase of up to 30% in launch rate (based on FY-85 rate of 8/year).

FUTURE VEHICLES
The significant conclusions and recommendations related to the trade studies for future vehicles follows:

* Major changes in design and management methodology are required.

* New technology involves management and computer-aided tools.

* ULCE/CALS (Unified Life Cycle Engineering/Computer Aided Logistics System)

* DBT/DTC (Design-Build Team/Design to Cost)

* Without consistent long-term management commitment, this will not work.

* Future vehicles, beginning with the Design Concept Phase, must put life cycle costs ahead of performance. We are hauling cargo via freighter -- not participating in a yacht race.
1.7 FOLLOW-ON STUDY RECOMMENDATIONS

The following follow-on study recommendations are provided with the objective of establishing launch operations requirements for probable future vehicle configurations:

* Based on Phase 1 Study results, and using STAS architectures as an input, specific configurations will be recommended to the NASA KSC Study Manager for his approval prior to their analysis.

* Prepare a be conceptual ground operations plan for the vehicles to identified from two selected architectures; e.g., (1) an expendable unmanned cargo vehicle and (2) a manned cargo vehicle.

* Design concepts/requirements for ULCE/CALS will be expanded; coordination between DoD and NASA/KSC will be established, with participation on associated technical advisory groups encouraged and developed.

* Develop operational support requirements and design concepts including a checklist handbook for designers and program managers.

* Launch site facility concepts for the vehicles under study will be developed. These concepts will describe the most efficient processing with respect to time and manhours and will be optimized in conjunction with the operations concepts.

* Highlight new and developing technologies that apply to subjects of the Study.

* Place the Expanded Technology Knowledge Base on line for use by NASA and Air Force personnel.
1.8 APPENDIX -- BIBLIOGRAPHY ABSTRACTS FROM NASA RECON

References which were obtained through NASA RECON have abstracts which make up this appendix. They are listed in numerical order. Some RECON numbers listed are top numbers for Conference documents and contain numerous papers.

72N30468## ISSUE 21 PAGE 2836 CATEGORY 17 RPT#: NASA-SP-5110
LC-74-177266 72/00/00 91 PAGES UNCLASSIFIED DOCUMENT


UNOC: Metallurgy, characteristic properties, and industrial applications of nickel titanium alloy with shape memory

TLSP: Technology Utilization

AUTH: A/JACKSON, C.M. ; B/WAGNER, H.J. ; C/WASILEWSKI, R.J.
CORP: Battelle Memorial Inst., Columbus, Ohio. AVAIL. NTIS
SAP: ; SOD $1.00
CIO: UNITED STATESWashington NASA Sponsored by NASA
MAJS: /*CHEMICAL PROPERTIES /*MECHANICAL PROPERTIES /*METALLURGY /*NITINOL /*PHYSICAL PROPERTIES
MINS: / INDUSTRIES/ METAL WORKING/ NASA PROGRAMS/ STRUCTURAL STABILITY/ TECHNOLOGY UTILIZATION/ THERMAL STABILITY

ABA: Author

ABS: A series of nickel titanium alloys (55-Nitinol), which are unique in that they possess a shape memory, are described. Components made of these materials that are altered in their shapes by deformation under proper conditions return to predetermined shapes when they are heated to the proper temperature range. The shape memory, together with the force exerted and the ability of the material to do mechanical work as it returns to its predetermined shape, suggest a wide variety of industrial applications for the alloy. Also included are discussions of the physical metallurgy and the mechanical, physical, and chemical properties of 55-Nitinol; procedures for melting and processing the material into useful shapes; and a summary of applications.
Progress in Designing for Testability --- of Avionics and Test Equipment

AUTH: A/ALLEN, D. R.; B/FERCH, B. C. PAA: B/(USA, Wright-Patterson AFB, OH)

CIO: UNITED STATES


MAJS: #AVIONICS/#DESIGN ANALYSIS/#ELECTRONIC EQUIPMENT TESTS/#FAILURE ANALYSIS/#RELIABILITY ENGINEERING/#TEST EQUIPMENT/#USER REQUIREMENTS

MINS: /AIRBORNE/SPACEBORNE COMPUTERS/AUTOMATIC TEST EQUIPMENT/CIRCUIT RELIABILITY/NONDESTRUCTIVE TESTS/ONBOARD DATA PROCESSING/TECHNOLOGY ASSESSMENT

ABA: (Author)

ABS: This paper presents an overview of recent developments in testability concepts, testability measures, and testability enforcement in the design of avionics and test equipment. Each of the joint services has efforts recently concluded or underway to better define requirements for testability in the areas of built-in test, the inherent testability of units under test, and the interfaces with test equipment. This paper brings out the significant contributions from the various activities, and provides a critique of proposed solutions.

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Two different interconnect devices for optical fibers have been developed. Each uses the shape memory effect alloy 'NITINOL'. The simpler of the two is of tubular design and accommodates fibers as small as 200 micron diameter. The more complex multi-component design accommodates 125 micron diameter fibers. The complex design is simpler to use, easier to manufacture and lower in cost. It permits less than 1 db loss and is re-matable. A description of NITINOL manufacture is given.
Structural Characteristics of the Shuttle Orbiter Ceramic Thermal Protection System

A/COOPER, P. A.

National Aeronautics and Space Administration. Langley Research Center, Hampton, Va. AVAIL.NTIS


The thermal protection system (TPS) of the Space Shuttle Orbiter is described as well as the results of dynamic response studies conducted in support of the efforts to certify the TPS for flight. The ceramic Thermal Protection System consists of ceramic tiles bonded to felt pads which are in turn bonded to the Orbiter substructure to protect the aluminum substructure from the heat of reentry.
Standard Generic Approach for Spacecraft Intelligence and Automation. Phase 1, volume 2: Technical report TLSP:
Final Report

AUTH: A/BERGER, G.; B/CORNET, J.; C/CELLIER, M.; D/RIOU, L.; E/SOTTA, J.; F/THIBAUT, M.

CORP: MATRA Espace, Paris-Velizy (France). AVAIL.NTIS

SAP: HC A12/MF A01

CIO: FRANCE Paris ESA

MAJS: /*ARTIFICIAL INTELLIGENCE/*AUTONOMY/*ONBOARD PROCESSING/*SATELLITE CONTROL/*SPACECRAFT DESIGN

MINS: / DATA MANAGEMENT/ DECISION MAKING/ GROUND SUPPORT EQUIPMENT/ HIGH LEVEL LANGUAGES/ MICROPROCESSORS/ PATTERN RECOGNITION/ STRESS ANALYSIS

ABA: Author (ESA)

ABS: Applications of onboard autonomy and data processing, and the corresponding spacecraft and ground control organization were identified by analyzing the Viking 75 deep space mission and the ERS-1 (ESA satellite) Earth observation mission. Telecommunication satellites, STS, data relay satellites and large space stations were also studied. An approach to spacecraft intelligence and autonomy based on a hierarchical decentralized system structure, in order to limit failure propagation, simplify interfaces, and improve performance predictability, is proposed. Onboard management is subdivided into routine, crisis, and end product management. Orbit determination and control is autonomous.

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AUTH:  A/ASKREN, W. B.  PAA:  A/(USAF, Human Resources Laboratory, Wright-Patterson AFB, OH)

CIO:  UNITED STATES


MAJS: /*COMPUTER AIDED DESIGN/*DESIGN ANALYSIS/*LOGISTICS/*MAINTENANCE/*PRODUCT DEVELOPMENT/*SYSTEMS ENGINEERING

MINS: /* AEROSPACE INDUSTRY/ BIODYNAMICS/ COMPUTER AIDED MANUFACTURING/ DATA BASES/ MATHEMATICAL MODELS/ RESEARCH AND DEVELOPMENT

ABA: Author

ABS: The concept of including maintenance and logistics factors in computer aided design (CAD) of new systems and equipment is presented. Air Force Human Resources Laboratory's plans for research and development in this area are described. The concept includes the role that CAD could play in improving design for supportability, the characteristics of CAD that are relevant to including maintenance and logistics factors, and the products that are needed to integrate maintenance and logistics factors into CAD. The research and development includes four efforts: the development of a maintenance analysis model for CAD; a biomechanical model of the maintenance technician; demonstrations of maintenance and logistics factors in CAD in the aerospace industry; and integrating a logistics data base with CAD/CAM engineering data bases.

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The development of an ultrasonic technique for determining the strength of the thermal protection tiles used on the Space Shuttle Orbiter is described. The basic test approach was to experimentally relate through transmission pulse velocity readings for 1-inch by 1-inch coupons to ultimate strengths of the same coupons and in turn extrapolate this information to the full size tiles. Factors affecting the pulse velocity such as material thickness variability, sonic coupling, and influences of the higher velocity components of the coating and densified layer were studied. These effects on pulse velocity were integrated in a software correction factor which was applied to the tile data so the strength properties of the basic tile material could be compared with the coupon reference system and the appropriate accept/reject criteria used. Use of the ultrasonic technique to evaluate strength variability within the large blocks of material from which the tiles are machined is also described........
1.8 APPENDIX -- BIBLIOGRAPHY ABSTRACTS FROM NASA RECON

(Continued)

84A26768 ISSUE 11 PAGE 1506 CATEGORY 6 83/00/00 7 PAGES
UNCLASSIFIED DOCUMENT

UTTL: Testing BITE on Boeing 757/767 in a Simulated Operational Environment

AUTH: A/LEE, H. F.; B/CARSON, D. P.
PAA: B/(Boeing Co., Seattle, WA)

CIO: UNITED STATES


MAJS: /*AIRCRAFT CONTROL/*AUTOMATIC TEST EQUIPMENT/*DATA SIMULATION/*FLIGHT CONTROL/*GROUND TESTS/*SYSTEMS MANAGEMENT

MINS: /*BOEING 757 AIRCRAFT/*BOEING 767 AIRCRAFT/*DATA ACQUISITION/*DESIGN ANALYSIS/*ELECTRONIC AIRCRAFT/*FAULT TOLERANCE/*FLIGHT SIMULATION/*FLIGHT TESTS

ABA: Author

ABS: To provide 'on-airplane' data that supports validation of the system-level equipment (BITE), a series of ground tests were conducted with simulated airplane flight and fault conditions. These tests provided qualitative support for establishing BITE credibility, and usage experience prior to airplane service introduction. BITE indications were correlated with the cockpit effects, simulated fault conditions, and simulation limitations to determine proper correlation and utility of indications. Results either indicated proper operation or improvements needed.

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UTTL: Fault, Detection, Isolation, and Recovery Techniques for Fault Tolerant Digital Avionics

AUTH: A/HITT, E. F.; B/ELDREDGE, D. PAA: A/(Battelle Columbus Laboratories, Columbus, OH); B/(FAA, Technical Center, Atlantic City, NJ)

CIO: UNITED STATES


MAJS: /*AIRBORNE/SPACEBORNE COMPUTERS/*AVIONICS/*COMPUTER SYSTEMS PERFORMANCE/ DIGITAL SYSTEMS/*ELECTRONIC EQUIPMENT TESTS/*FAULT TOLERANCE

MINS: / CIRCUIT RELIABILITY/ FAILURE ANALYSIS/ IN-FLIGHT MONITORING/ SYSTEM FAILURES/ RELIABILITY ENGINEERING

ABA: Author

ABS: Fault tolerant design technologies for digital avionics system are described in this paper. The techniques include both hardware and software methods used for detecting faults at three levels. These levels should be implemented to assure (1) the correct operation of each processing unit, (2) valid communication of data between digital subsystems, and (3) data validity, prior to use in subsequent computation and after conversion of digital data. Once a fault is detected, system recovery must take place to assure the continued performance of the function(s) affected by the fault. The methods used to control the system recovery techniques are dependent upon the system's ability to isolate the detected fault to the lowest possible level. The system recovery techniques are also dependent upon system architecture. Fault isolation and system recovery techniques require knowledge of the system status vector and its history in sophisticated systems.

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Processor Monitoring and Self-test In the Boeing 767/757 Flight Control Computer

A/KOVALAN, M. PAA: A/(Rockwell International Corp., Collins Air Transport Div., Cedar Rapids, IA)

UNITED STATES


Based primarily through frequent execution of a comprehensive self-test design is based on functional verification of the processor's ability to properly execute all steps associated with integrated interrupt response. An analysis of the processor algorithms and interrupt response. An analysis of the processor self-test and monitor was performed to assess the coverage of processor functions obtained through the chosen monitoring arrangement. The undetected failure rate for CAPS-6B was predicted to be about 10 to the -7th per hour, corresponding to less than 1 percent of the total processor failure rate.
Mechanical Properties of the Shuttle Orbiter Thermal Protection System Strain Isolator Pad


CORP: National Aeronautics and Space Administration. Langley Research Center, Hampton, Va.

CIO: UNITED STATES

MAJS: /*FATIGUE TESTS/*ISOLATORS/*MECHANICAL PROPERTIES/*SPACE SHUTTLE ORBITER /*SPACECRAFT SHIELDING/*THERMAL PROTECTION

MINS: / COMPRESSION LOADS/ CYCLIC LOADS/ HYSTERESIS/ LOAD TESTS/ SHEAR PROPERTIES/ STATIC LOADS/ STRESS CYCLES/ STRESS-STRAIN DIAGRAMS/ TENSILE STRENGTH/ TILES

ABS: Previously cited in issue 19, p. 2029, Accession no. A82-30079

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**UTTL:** Effect of Simulated Mission Loads On Orbiter Thermal Protection System Undensified Tiles

**AUTH:** A/COOPER, P. A.; B/MISERENTINO, R.; C/SAWYER, J. W.; D/LEATHERWOOD, J. D. PAA: D/(NASA, Langley Research Center, Hampton, VA)

**CORP:** National Aeronautics and Space Administration. Langley Research Center, Hampton, Va.

**CIO:** UNITED STATES

**MAJS:** /*DYNAMIC LOADS/*DYNAMIC STRUCTURAL ANALYSIS/*SPACE SHUTTLE ORBITERS/* SPACECRAFT DESIGN/*THERMAL PROTECTION/*TILES

**MINS:** / CERAMICS/ CLIMBING FLIGHT/ DYNAMIC RESPONSE/ LOAD TESTS/ RANDOM LOADS/ STATIC LOADS/ TENSILE TESTS/ THERMAL SIMULATION

*******************************************************************************
Maintenance of weapon systems is becoming an increasingly important consideration in weapon system development, because the cost of maintenance is a significant portion of the life cycle cost of the system. The objective of the Integrated Testing and Maintenance Technology effort is to define requirements for an onboard test system for the avionic suite planned for tactical fighters in the 1990's. Problems with current onboard test systems were analyzed to determine where improvements could be made. In addition, the anticipated avionic architecture and mission of the 1990's were evaluated to determine the impact on maintenance capability. Requirements for the Integrated Testing and Maintenance System were developed and documented in a system specification. Identified improvements over current systems include better filtering of intermittent failure reports, better isolation of intermittent failures through the use of recorded data, more extensive use of system-level tests of mission operational data and a man-machine interface providing more information to the maintenance technician. In addition, artificially where the intelligence applications were evaluated to determine might be effectively applied to ITM. A design concept for fault classification expert system was developed.
Passive Sun Seeker/tracker and a Thermally Activated Power Module

AUTH: A/SIEBERT, C. J.; B/MORRIS, F. A.

CORP: Martin Marietta Corp., Denver, Colo. AVAIL.NTIS


CIO: UNITED STATES

MAJS: /*HOMING DEVICES/*/NITINOL ALLOYS/*POWER MODULES (STS)/*SOLAR RADIATION

MINS: / ALGORITHMS/ KINEMATICS/ PARABOLIC REFLECTORS/ PHASE TRANSFORMATIONS/ PLASTIC MEMORY/ THERMAL ENERGY

ABA: Author

ABS: Development and testing of two mechanisms using a shape memory alloy metal (NITINOL) as the power source described. The two mech developed are a passive Sun Seeker/Tracker and a generic type power module. These mechanisms use NITINOL wire initially strained in pure torsion which provides the greatest mechanical work capacity upon recovery, as compared to other deformation modes (i.e., tension, helical springs, and bending).

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**UTTL:** Advances in TPS and Structures for Space Transportation Systems

**AUTH:** A/KELLY, H. N.; B/GARDNER, J. E. PAT: A/comp.; B/comp.

**CORP:** National Aeronautics and Space Administration. Langley Research Center, Hampton, Va.

**SAP:** Limited by ITAR

**CIO:** UNITED STATES Symp. held in Hampton, Va., 13-15 Dec. 1983

**MAJS:** /*CONFERENCES/SPACE SHUTTLE ORBITERS/SPACE TRANSPORTATION SYSTEM/SPACECRAFT STRUCTURES/THERMAL PROTECTION

**MINS:** / AEROTHERMODYNAMICS/ CARBON-CARBON COMPOSITES/ CERAMICS/ COMPOSITE STRUCTURES/ METALS/ STRUCTURAL ENGINEERING

**ANN:** Flight experiences with the Space Shuttle orbiter thermal protection system are described and evaluated, and research on new concepts in metallic, ceramic, and advanced carbon-carbon TPS and structures is presented. Advanced and alternate configurations and missions for next-generation space transportation systems and issues and technology needs are discussed.

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This report presents the proceedings of a workshop on artificial intelligence (AI) in maintenance that was sponsored by 7 Department of Defense agencies. The workshop, entitled Joint Services Workshop on Artificial Intelligence in Maintenance, was held October 4-6, 1983 in Boulder, Colorado. The primary objective of the workshop was to provide an exchange of technical information among personnel involved in on-going research and development in artificial intelligence applicable to automatic testing, maintenance aiding, and maintenance training. A second objective was to identify both theoretical and practical applications issues in the use of AI in maintenance. This report is organized into four sections: Overview; The Science; Department of Defense Programs and Projects; and Commercial and Industrial Development Projects. The material in the report includes contributed and, significant papers previously published, and edited transcripts of presentations made at the workshop. For individual titles see N85-11593 through N85-11627.
Advanced methods and tools to support design for avionic maintainability and testability are discussed. Both hardware and software design for maintainability issues and approaches are addressed. For individual titles see N85-16732 through N85-16756.
A Weapon System Design Approach to Diagnostics


CORP:  Naval Electronic Systems Command, Washington, D. C.

SAP:  HC A13/MF A01 in AGARD Design for Tactical Avionics Maintainability 6 p (see N85-16731 08-01)

CIO:  UNITED STATES

MAJS:  /AVIONICS/#GOVERNMENT/INDUSTRY RELATIONS/#MAINTENANCE/#WEAPON SYSTEMS

MINS:  / ARTIFICIAL INTELLIGENCE/ COMPUTER AIDED DESIGN/ COMPUTER AIDED MANUFACTURING/ COSTS/ EDUCATION/ FAULT TOLERANCE/ SYSTEMS ENGINEERING

ABA:  R.S.F.

ABS:  Providing a diagnostics capability for today's weapon systems requires a multifaceted combination of hardware, software, and personnel. The approach to providing this capability is fractionated among a number of different communities (e.g., testing, training, human engineering, publication writers). The result is reflected in the field, where the technician has been furnished a myriad of tools and documentation, which is confusing, complex and often contradictory. The result is lengthy repair times and a waste of manpower and dollars. The basic reason for this diagnostic deficiency is the lack of an integrated design approach providing this capability and the inability to transition technological advancements to weapon systems acquisitions. Recent Department of Defense and U.S. industry efforts to solve this problem are discussed.

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The design philosophy and development experience of fuel cell power generation and cryogenic reactant supply systems are reviewed, beginning with the state of technology at the conclusion of the Apollo Program. Technology advancements span a period of 10 years from initial definition phase to the most recent space transportation system (STS) flights. The development program encompassed prototype verification, and qualification hardware, as well as post-STS-1 design improvements. Focus is on the problems encountered, the scientific and engineering approaches employed to meet the technological challenges, and the results obtained. Major technology barriers are discussed, and the evolving technology development paths are traced to their conceptual beginnings to the fully man-rated systems which are now an integral part of the shuttle vehicle.
Appendix -- Bibliography Abstracts from NASA Recon (Continued)

85N16979** ISSUE 8 PAGE 1104 CATEGORY 16 85/01/00 20 PAGES UNCLASSIFIED DOCUMENT

UTTL: Orbiter Thermal Protection System

AUTH: A/DOTTS, R. L.; B/CURRY, D. M.; C/TILLIAN, D. J.

CORP: National Aeronautics and Space Administration. Lyndon B. Johnson Space Center, Houston, Tex. AVAIL.NTIS

SAP: HC A23/MF A01 In its Space Shuttle Tech. Conf., Pt. 2 p 1062-1081 (SEE N85-16937 08-12)

CIO: UNITED STATES

MAJS: /*AEROTHERMODYNAMICS/*SPACE SHUTTLE ORBITERS/*THERMAL PROTECTION

MINS: / ABLATIVE MATERIALS/ PERFORMANCE TESTS/ REUSABLE HEAT SHIELDING/ SPACECRAFT DESIGN/ TEMPERATURE CONTROL/ THERMAL INSULATION

ABA: E.A.K.

ABS: The major material and design challenges associated with the orbiter thermal protection system (TPS), the various TPS materials that are used, the different design approaches associated with each of the materials, and the performance during the flight test program are described. The first five flights of the Orbiter Columbia and the initial flight of the Orbiter Challenger provided the data necessary to verify the TPS thermal performance, structural integrity, and reusability. The flight performance characteristics of each TPS material are discussed, based on postflight inspections and postflight interpretation of the flight instrumentation data. Flights to date indicate that the thermal and structural design requirements for the orbiter TPS are met and that the overall performance is outstanding.

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-202-
This study provides the foundation for a logical and cost-effective approach for five years. The primary near term applications are design support and maintenance applications. Eight potential applications are developed and evaluated: (1) computer aided preliminary design for testability, (2) Smart Built-in Test, (3) Smart System Integrated Test, (4) Box Level Maintenance Expert, (5) System Level Maintenance Expert, (6) Smart Maintenance Expert, (7) Automatic Test Program Generation, and (8) Smart Bench Tester. All of these application opportunities can be implemented with engineering workstations which are becoming available directly to designers.
Production of Shaped Parts of NITINOL Alloys by Solid-state Sintering

AUTH: A/GOLDSTEIN, D. M.

CORP: Naval Surface Weapons Center, Silver Spring, Md.

SAP: HC A03/MF A01

CIO: UNITED STATES

MAJS: /*METAL WORKING/*NITINOL ALLOYS/*PLASTIC MEMORY/*SINTERING

MINS: / DEFORMATION/ EXTRUDING/ FITTINGS/ LOW TEMPERATURE/ PIPES (TUBES)/ POWDER METEALLURGY/ SHAPES

ABA: GRA

ABS: Nitinol is an alloy of nickel and titanium which exhibits a shape memory effect. The term shape memory effect (SME) is used to describe the ability of certain alloys which, if deformed at a low temperature, will recover their prior shape when heated. A solid state sintering process has been successfully adapted to consolidating Nitinol alloy powders. Nitinol alloys are noted for their shape memory properties. The sintering process is performed at atmospheric pressure upon powders contained in an evacuated glass container. Processing parameters are reported. Tubes and tubular tees were were made as well as solid round bars. Round bar stock was extruded and swaged excellent shape memory properties were obtained.

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This reviews three different expert systems (ATEOPS, ATEFEXPERS, and ATEFATLAS) created to direct automatic test equipment (ATE). Although related, each expert system uses a different knowledge base or inference engine and base their testing on the circuit schematic, test requirements document (TRD), or ATLAS code. Implementing generalized modules allows the expert systems to be used for any unit under test. Because of numerous errors in the ATLAS code and problems with the actual hardware connection, a fully operational system was not developed. These expert systems provide insight into the necessary knowledge bases and inference engines needed by an expert system to direct ATE. Using converted ATLAS to LISP code allows the expert system to direct any ATE using ATLAS. The CP-FRL allows the expert system to expand its control by creating the ATLAS code, checking the code for good software engineering techniques, directing the ATE, and changing the test sequence as needed.
The emphasis on automation and robotics in the augmentation of the human centered systems as it concerns the Space Station is discussed. How automation and robotics can amplify the capabilities of humans is detailed. A detailed developmental program for the space station is outlined.
Verification Tests of Durable Thermal Protection System Concepts

AUTH: A/SHIDELER, J. L.; B/WEBB, G. L.; C/PITTMAN, C. M.
PAA: C/(NASA, Langley Research Center, Hampton, VA)

CORP: National Aeronautics and Space Administration. Langley Research Center, Hampton, Va.


MAJS: /*HEAT RESISTANT ALLOYS*/HONEYCOMB STRUCTURES/*REUSABLE HEAT SHIELDING/* SPACE TRANSPORTATION/*THERMAL PROTECTION

MINS: / ACOUSTIC MEASUREMENT/ AEROTHERMODYNAMICS/ ATMOSPHERIC ELECTRICITY/ CARBON-CARBON COMPOSITES/ ENVIRONMENTAL TESTS/ INCONEL (TRADEMARK)/ TITANIUM/ VACUUM TESTS/ VIBRATION TESTS

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Features of the modern hardware description language for VHSIC devices (VHDL) are described and compared with the features of eight other current languages and to the requirements of a VHDL language. The criteria for flexibility of design-acceptable VHDL are applications, semantics independent of any particular language implementation, user-friendliness, and parts with a programming language orientation. Each requirement is expanded in detail, and comparisons are made with the interactive design language (IDL), the computer design language (CDL), the TI hardware description language (TI-HDL), a hardware programming language (HPL), the ZEUS hardware description language, the consensus language CONLAN, the test generation and simulation language (TEGAS) and the instruction set processor specifications (ISPS). The discussion shows that only VHDL permits user-controlled conversion and alternative interface. Both inertial and transport explicit interface, and no syntactic and semantic extensions to the language.
The traditional approaches to anomaly detection and resolution for modern weapons systems, spacecraft, and complex ground installations are inadequate to meet the requirements incumbent upon future systems. Expert system technology appears to offer a solution, but new types of expert systems will be required. IBM has developed and implemented a concept for such a system. This paper describes that concept, its potential applications, and some of the implications that this general approach has for the design of future spacecraft.
The principle subdisciplines of AI (e.g., expert systems, problem solving, planning and natural language understanding) are presented as well as the larger systems engineering issues. In a chapter devoted to automate systems for managing systems for managing hardware failures, the components of the failure cycle (detection, diagnosis, and repair) are described in tandem with machine approaches and applicable AI methodology. In this report, effective improvement in military maintenance is viewed to be dependent not only on automated systems but also on the development of human resources and the organizational context of maintenance. Evidence and information are provided to support the recommendation that it is possible to build more effective less costly automated diagnostic systems only if these systems exploit human problem-solving capabilities. Four hypothetical examples of advanced systems and a comparison of human vs. machine strengths and weaknesses as problem solvers are outlined. Five research and development recommendations for the use of AI in maintenance conclude that: (1) there is a good match between the need for improved maintenance and the emerging science of AI, (2) AI research should be guided by a policy of integrated diagnostics, (3) field
evaluations of AI applications should focus on organizational impact as well as technical issues, (4) programs should be targeted at both fielded systems and systems under development, and (5) basic research should investigate cooperative human-machine device diagnosis problem solving and the coordination of the specification-and symptom-based approaches.

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86N27356# ISSUE 18 PAGE 2861 CATEGORY 18 85/12/00 5 PAGES UNCLASSIFIED DOCUMENT DCAF E003091

UTTL: Features of the Solar Array Drive Mechanism For the Space Telescope

AUTH: A/HOSTEMKAMP, R. G.

CORP: Dornier-Werke G.m.b.H., Friedrichshafen (West Germany). AVAIL.NTIS

SAP: HC A15/MF A01; ESA, Paris FF 150 or $18 Member States, AU, CN, NO (+20% others) In ESA Second European and Space Mechanisms and Tribology Symposium p 13-17 (SEE N86-27353 18-18)

CIO: GERMANY, FEDERAL REPUBLIC OF

MAJS: /*HUBBLE SPACE TELESCOPE/*MECHANICAL DRIVES/*SOLAR ARRAYS

MINS: / DATA TRANSMISSION/ ELECTRIC POWER TRANSMISSION/ NITINOL ALLOYS/ SYSTEMS ENGINEERING/ TORQUE

ANN: Spacecraft mechanisms; motors and actuators; tribology; space stations; and mechanism analysis and testing were discussed.

ABA: ESA

ABS: The Solar Array Drive Mechanism for the Space Telescope is described. Power and signal transfer is achieved by a flexible wire harness for which the chosen solution, consisting of 168 standard wires, is described. The torque performance data of the harness over its temperature range is presented. The load system which protects the bearings from the launch loads is based by a trigger made from Nitinol, a memory alloy. The benefits of memory alloy and the caveats for the design are discussed.
These additional benefits include items such as: a smaller chance for "human error" through automation, reduced number of people required for operations, smaller number of documentation changes, and an increase in test-to-test consistency. Document these findings and capabilities for use as guidelines for use on STAS and other future programs for both manned and unmanned vehicles.

Using the current STS as a working model: identify existing, or new technologies, changes to flight hardware, or changes to processing methodologies that would reduce the processing time and program manpower costs of space vehicle processing. Document methods of improving efficiency of ground operations and identify technology elements that could reduce cost. Study emphasis is on:
1) Identification of specific technology items.
2) Management approaches required to develop, operate, support and control operationally efficient ground processing activities.

Prime study results are:
1) Identification of existing, or new technology that would make vehicle processing less costly. 2) Recommendations for the use of selected technology items in the current STS program. 3) Recommendations for the research and/or development of specific technology items for use on future programs to make their processing (and operation more efficient. 4) Identification of new management techniques necessary to achieve and control these more efficient operations.

Increased use of automation to provide current and more comprehensive management reports, operational analysis support, evaluation of systems, conduct of operations and other ways to cut costs and provide additional benefits. *see 15