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Spaceport 1-G Human Factors for Optimal Space Transportation System Design

"[i] *A fundamental tenet of human factors is that the human operator lies at the center of system design, the yardstick by which the form, fit, and function of hardware and software must be gauged."*

Acknowledgements

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EXECUTIVE SUMMARY

This paper was written to give a better understanding of 1-G human factors in spacecraft design. Typically when NASA considers human engineering in spacecraft design, the interfaces involving the flight crew and the spacecraft are the focus. Because human errors at the spaceport are directly related to the risk of the flight crew, the interfaces between the ground crew, the spacecraft, and the ground support equipment are equally important.

Throughout the evolution of spacecraft development NASA's involvement and use of human factors for improving human performance has increased. NASA released a document, NASA-STD-3000, that covers crew and spacecraft interactions in detail. The NASA-STD-3000 is a comprehensive document that defines all generic requirements for space facilities and related equipment which directly interfaces with crewmembers. For the 1-G operations NASA currently utilizes documents that can be tailored to aerospace ground processing. One such document is the MIL-STD-1472 Department of Defense Design Criteria Standard for Human Engineering.

Assumptions some designers are currently making for the new exploration vehicles are that they will be built at the factory, sent to Kennedy Space Center (KSC), integrated, fueled and launched. Supposedly very little if any ground processing will be necessary, and for the most part the majority of the spacecraft life will be in space, to and from the Moon, Mars, etc.

There are many cases were, "very little if any ground processing", had been planned but was not the outcome. For example, prior to receiving the first Space Shuttle Main Engines (SSME), at KSC there were no plans for a dedicated engine shop. Reality soon set in, and makeshift SSME shop was put together in the Operations and Checkout

building, and then a real one was built in the VAB, and finally a dedicated SSME shop was constructed.

With more technology available today, very low maintenance is being impressed upon even more, and technology is the great hope as the remedy to eliminate human operations. This again, is another reason why the importance of applying human factors principles may be overlooked early in the design development. Technology may help reduce the human interactions, but in some cases it may increase human interactions. The point is, is that, anywhere a human interacts with the system it is extremely important, and with spacecraft design very critical, that we account and plan for the human activities before the designs have been set in place.

With the lessons learned from previous programs, we have discovered that there has and will be a great need for human factors principles to be applied to spaceport ground processing. In order to accomplish this effectively in future programs, a human factors perspective to consider the human operator, inspector and maintainer as part of the total design must be integrated early in the spacecraft design development process.

1-G Human factors for spaceport ground processing are directly related to the Exploration Systems Enterprise Request for Information (RFI) Focus Area: Design Principles, Objectives and Guidelines. Because the human is such a vital part of system performance, there are several areas within the RFI that are applicable.

- Lessons Learned: Important lessons we have learned from our exploration to the Moon, STS, ISS and OSP.
- Sustainability: Issues related to affordability, reliability (Safety), and effectiveness in achieving mission goals.
- Affordability: Investments in development that reduce operations costs.
- Reusability: Assess the operational concepts, infrastructure needs, and technological advances that are required to enable system reusability.
- Lifecycle Engineering Techniques: How NASA can retain design rationale information about critical design decisions to ensure that this information can be appropriately considered in future enhancements.

INTRODUCTION

For spacecraft operations, there are many aspects where human engineering contributions can be applied to improve the performance and safety of the human. In spacecraft missions there is both ground operations and mission operations. Within spaceport ground operations, improvements can be made in safety, training, logistics, maintenance of facilities, and maintenance of the spacecraft. Because all these areas are influenced by the design of the spacecraft, this paper will primarily look at human factors and maintainability from a spacecraft design perspective and accompanying ground systems.

Within the development of the spacecraft design there are several different engineering disciplines, such as, thermal protective system (TPS), propulsion, electrical power, and more recently, integrated health management. In order for the design to fit the human it is important to apply 1-G human factors improvements to the overall system. More importantly this function needs to be addressed at the beginning of the design process so that human factors contributions can be invoked as part of the total design process. In general this has not been the practice within the previous NASA programs.

With the increase of new technologies and untried methods, and the importance that spacecraft processing operations play in the success of each mission, more emphasis in human factors will be required. The 0-G human factors practices for the flight crew are well in place and will be easily accepted in future programs, but 1-G human factors for the ground personnel will need special attention because there has not been an emphasis for this in previous spacecraft development.

The evolution of manned spacecraft at NASA is mainly through Apollo, Space Shuttle, and International Space Station (ISS), and most recently the short-lived Orbiter Space Plane (OSP) Program. Apollo was a non-reusable spacecraft with little earth spaceport 1-G human factors for maintainability of the spacecraft. The Space Shuttle Orbiter is mostly a 100% reusable spacecraft with very little 1-G human factors in the design for maintainability. And the ISS is considered a spacecraft that remains in space, where the human operations for maintainability are performed in 0-G.

For the upcoming Exploration Program, all three of these programs, (Apollo, Space Shuttle and ISS), and the use of the knowledge of the ELV Program for lift vehicles will play an important role. For example, Apollo and Shuttle could be closely related to the future crew transfer vehicles, and ISS concepts could be used for Moon surfaces bases or for Moon orbiting stations. Because of the plans for the future Exploration Program, we will need to integrate all we have learned from the past programs.

In a sense, the OSP Program did integrate concepts from Station, Space Shuttle, ELV, and Apollo, and in relation to the Exploration Program we could consider the OSP efforts as a trial run in the design development or “prototype” exercises of spacecraft design and development. With the lessons learned and knowledge gained from this trial run in spacecraft design development, and the experience gained by those who were involved with the OSP program, we are now much better equipped to introduce 1-G human factors early in the next program.

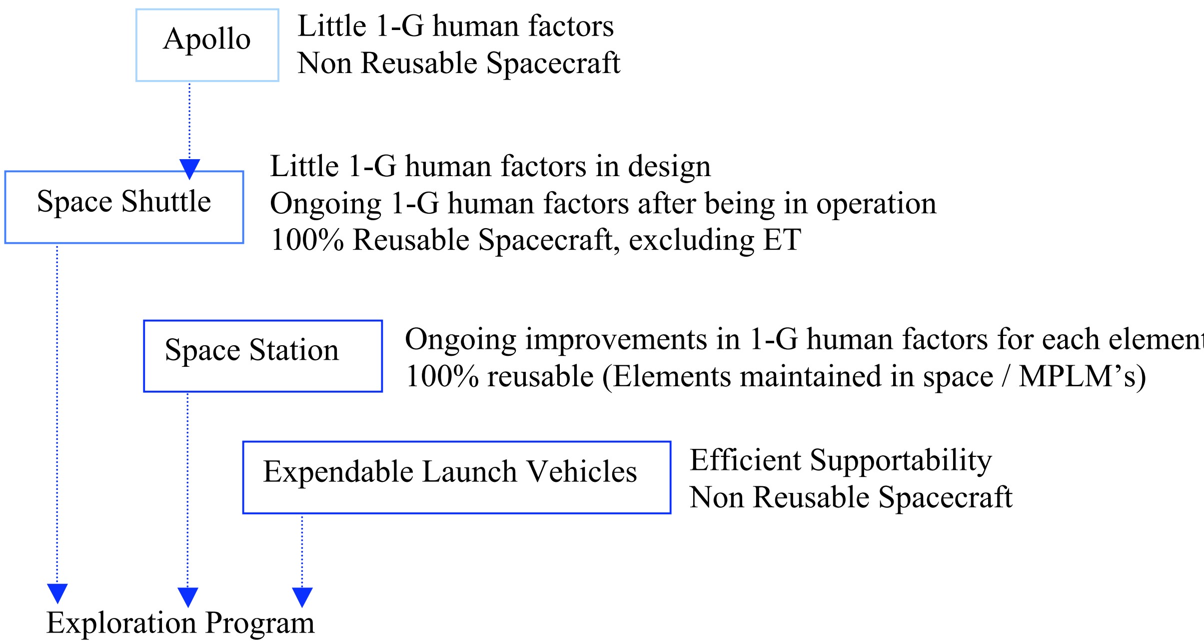

Figure 1: Human factors in NASA programs

CONTENTS

The following section will cover areas found where 1-G human factors improvements to the process were made in previous programs. There are some lessons learned that were found in the Apollo Experience Reports and several examples of the human factors improvements made to the Space Shuttle. Lessons from the ISS and OSP are considered as well. This paper does not attempt to cover all the human factors improvements made in previous programs; it only covers a few examples to give the reader an indication of the importance of human factors in spacecraft design.

Since human factors has an effect on the efficiency and effectiveness of maintainability, within the section on the Space Shuttle, there are two important sections; [ii]Carey McClesky's "Root Cause Analysis" and [iii]Fayssal M. Safie "OSP Supportability Plan." These sections explain how maintainability and supportability are a major portion of operations costs.

Finally the conclusions will give recommendations for future programs.

APOLLO

The zenith of the evolution of capsule space flight lies in Apollo. Although the term human factors was not widely used at that time, the concepts were well defined especially for the displays and controls requirements for the spacecraft. There was a high emphasis on 0-G human factors designing and testing of these interfaces that dealt with the crew, and this led to a well designed interface for the crew. Ground Support Equipment (GSE) safety and other areas dealing with the 1-G operations were important as well but were not maximized through formal human factors principles. To mitigate risk during ground processing, the Space Flight Awareness (SFA) Program originated during the Mercury Program. And since then all U.S. human space projects to date have utilized the concept of the SFA Program as a way to mitigate risk. As stated in the SFA website. [iv]*No matter how well spacecraft are made, safety margins in space travel will always be small. A space vehicle is only as reliable and safe to fly as the human care that goes into its creation. For that reason, each individual associated with human space flight is party to the unwritten contract, "Flight Safety and Mission Success."*

SFA uses a variety of motivational awards and incentives along with active education to remind the government and industry team of their role in achieving flight safety and mission success**.** Training and motivation are important for the human element to perform at their best with any system. But we must first start with the optimal system, then enhance the system with the appropriate training. Ongoing human factors contributions, during the designing of the spacecraft and associated systems, are a key component to how flight safety and mission success can be achieved.

There was not a dedicated human factors section in the Apollo Reference materials. Thus, there were no formal human factors lessons learned as well. The Apollo Experience Reports documents related to human factors are; [v]Crew Station Design and Development, [vi]Crew Station Displays and Controls, [vii]Spacecraft Hand Controller Development, [viii]Stowage and Support Team Concept, [ix]Lighting

Considerations, [x]Ground Support Equipment, [xi]Safety Activities, and [xii]Reliability and Quality Assurance.

The remainder of this section gives examples of lessons learned from Apollo that relate to 1-G human factors. Mainly these are the Ground Support Equipment (GSE), and the Reliability and Quality Assurance (R&QA) reference materials.

R&QA

The Problem Control System was developed by JSC for managing the disposition of problems occurring on hardware during the Apollo program. The system included all participants; contractors, subcontractors, NASA tests sites, and KSC. Some problems had their origin in the design and had to be solved by the designers. Other problems that originated in the manufacturing activities had to be corrected by the department responsible for the problem. Many problems of manufacturing origin were reported.

Analysis of the Apollo spacecraft failure records disclosed that a large percentage for [xiii]failures were caused by workmanship (10.6 %), contamination of equipment (8.2 %) and other manufacturing causes (8.0%). Some of the more significant experiences are discussed in the following paragraphs.

Because of the small size of the crew compartment it was found impractical to try to do the spacecraft wiring; measuring, cutting, and other operations, within the vehicle compartments. Thus a special assembly fixture was developed to assist in the assembly of the crew compartment harness. All fabrication operations were preformed on the fixture.

Initially, the wiring in the crew compartment was exposed and subject to possible damage during ground based operations as well as during flight. To protect the cables from physical damage and to reduce the risk of flame propagation special protective trays were designed. It is important to note that these features to protect wiring during processing were lacking in the Space Shuttle design. This situation indicates that some lessons from Apollo were overlooked during the development of Space Shuttle.

Other problem areas were from crimp failures of wire connectors. To solve this problem crimping operations were controlled rigidly to ensure that the proper calibrated tools were used by personnel. Bent connector pins became so severe that special training was provided for selected personnel. Procedures for straightening pins were prepared, and requirements were established for recording all instances of bent pins.

Again these problems were found after the processes were underway. Further design improvements to reduce bent pins when making connections, was to have a conical entry for the female connector. As the connection is being made, if the male pin were slightly bent, the female conical entry would help guide the male pin into the connector.

The single most important factor leading to the high degree of reliability of the spacecraft was test activity. Testing of the Apollo spacecraft equipment represented a substantial portion of the program resources and consisted of two basic categories, certification testing and acceptance testing. Experience indicated that unless a comprehensive and well integrated test plan is prepared, much unnecessary testing can be performed and some may be missed or testing may be performed at the wrong assembly level. This experience led to the development of special ground rules for testing Apollo spacecraft and equipment.

GSE

In the GSE area there was far less to be found that related to human factors. Some of improvement areas determined were: safety devices such as switch-guards and safety glass on meters and gages should be incorporated into the original design; vehicle cleanliness requirements should be established and thoroughly justified early in the design phase because ground support equipment costs increase geometrically as cleanliness requirements become more stringent; periodic facility technical evaluations should be conducted to ensure that basic requirements (access, lighting, ventilation, air conditioning, and power sources) keep pace with test article and checkout requirement changes; and finally, ground support equipment should be designed for maintainability, troubleshooting and for ease of component replacement. As with most areas, these recommendations should be considered during the early part of design development.

Conclusion Apollo

Although the Apollo program didn't formally call it 1-G human factors, there were concerns for the operator during ground operations. But much of these concerns were learned after the equipment was designed and then adaptation was made to accommodate the human if possible. Even so, it is good to note some of the major results that occurred because of not having formal human factors function within the Apollo Program. These are:

- Because there was no formal human factors function in Apollo there were no formal 1-G human factors representatives in Space Shuttle design development.
- Human factors lessons learned from Apollo were not transferred effectively to the Space Shuttle during the design development.
- For the majority of the work, a task analysis of the equipment was more of a dry run of the designed equipment. This made it difficult to make major changes once the design had gone that far. The system was considered as an interrelated collection of hardware and software that is operated by humans. And most of the time extensive training would be put in place to overcome the risk of safety because of the inefficient design. Today we know that the system must be designed around the human were possible, then training is used where design is not practical.

Since Apollo was not a reusable spacecraft and the Apollo flights were not extensive, the emphasis of 1-G human factors for ground processing was not as profound. Because the extensive maintenance processing of Space Shuttle was not foreseen, and for other reasons, (see Space Shuttle section "Reasons for Lack of Human Factors in Design Development"), there was a lack of emphasis of 1-G human factor contributions for the Space Shuttle during the early design development. It was not until after the Orbiter vehicle was designed and in operation that the full extent of ground processing were realized, as was also the case in Apollo.

The next section will show some of the examples encountered when ground processing is not considered early in the design process. Keep in mind that Space Shuttle processing has been in operation for over 20 years with these outstanding areas of needed improvement.

SPACE SHUTTLE

This section will show the relation that human factors has with maintainability of spacecraft. It will also attempt to show the impact of human error in relation to spacecraft maintenance operations. Figure 1, shows how Space Shuttle processing was planned and how it ended up. As can be seen, by comparing the conception to the actual facility, the involvement of the human in the process was not adequately considered in the conception. Notice the difference in the amount of added GSE and access platforming in the actual processing facility.

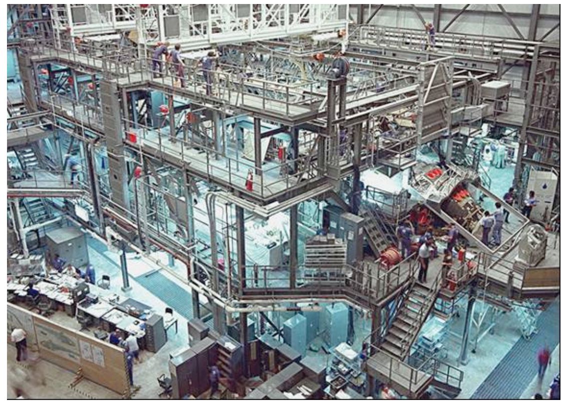

Figure 2: Conceptual and actual processing facilities

Because of the lack of planning for these platforms in the early stages, the results were minimal and awkward human access for maintainability and supportability. Instead of designing a spacecraft that could be easily accessed, operations were inefficiently designed around the existing vehicle. The main cause being that the majority of the human operations were an afterthought.

Root Cause Analysis

Some of the preliminary results of Carey McCleskey's Report on Root Cause Analysis of STS-81 show that there is a high level of activity in 1) Component R&R, Trouble Shooting, Repair, Retest, 2) Vehicle Servicing, and 3) Inspection and Checkout. Figure 2, shows the percentage distribution of Orbiter processing for each of these tasks.

Within these activities, the unproductive tasks times could be eliminated or reduced with the implementation of better human factors practices. For example there are over [xiv]400 ground interfaces to the Orbiter. If this alone can be reduced, servicing time can be reduced, also there are many cases where inspection requires disassembly of good working parts and systems; this is also unnecessary non productive work.

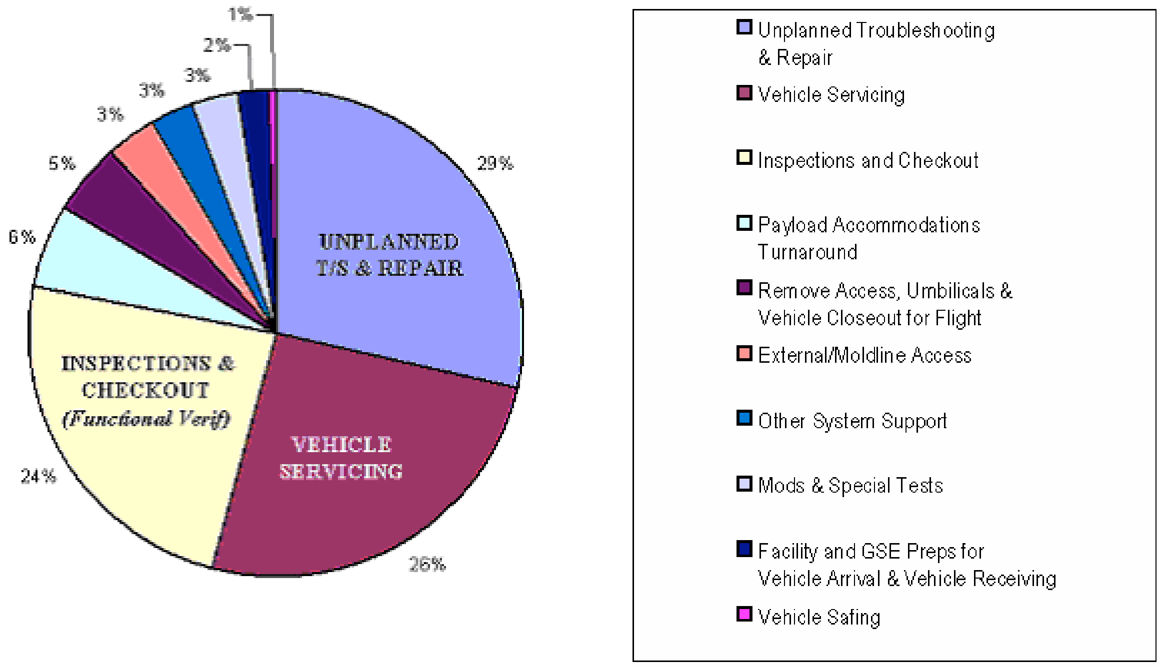

Figure 3: Orbiter processing tasks

One must consider the advantage of foreseeing these tasks and modifying or eliminating them through proper design of the vehicle before the operations began. If these operations were identified early in the design phase, inefficient designs could have been identified, and for many operations 20 years of inefficient processing could have been eliminated.

Now that we have shown the importance of identifying inefficiencies within Space Shuttle processing, it is important to realize the scope of these inefficiencies in terms of costs.

From Fayssal M. Safie OSP Supportability Plan, the largest percentage of System ownership costs are associated with “Operations and Support”. These costs are often overlooked during the development phase, where focus is often on the cost of acquisition only.

Since all of these areas require human intervention, human factors principles can be applied for maximum performance. Therefore, when designing future systems, the areas shown in figure 3, should be taken under consideration. Applying human factors principles at the beginning of the design development will improve the efficiency and effectiveness of maintainability and supportability of the system.

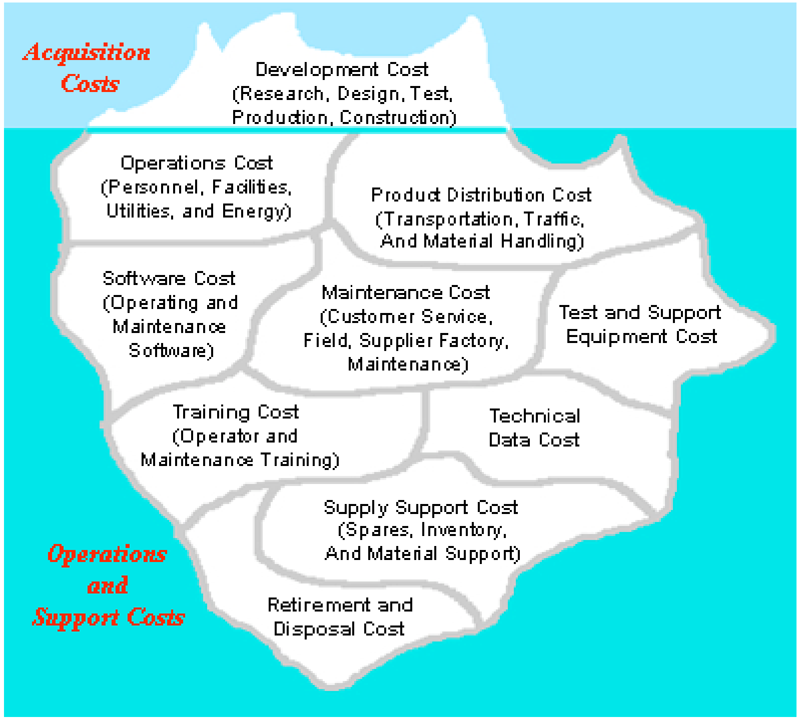

Figure 4: Acquisition, operations, and support costs

Thus, it was shown that operations plays a larger cost role in comparison to the development costs, it was also shown that there is a high level of human activities, most of which is most likely unproductive, and finally it was also shown through the conceptions of the processing facilities that there was a extreme lack of considering the full operations that the human would be involved with in 1-G operations.

If human factors contributions are not made correctly to these maintenance operations there will be more opportunity for human error. [xv]NASA Headquarters directed KSC to "assess the human factor aspects of all incidents." This direction was based on an independent non-KSC review of Space Shuttle ground processing errors. A 28 months analysis of the data revealed that the primary cause category, for 72% of the incidents, was "human error". In addition, several studies of commercial aviation accidents have demonstrated that over 30% of the major causes of flight tragedies are attributable to ground maintenance errors.

To get a feel for the usefulness of human factors for improving the operator's performance, the following example in table 1 is given. The [xvi]US Navy Research

Advisory Committee predicted the following improvements from more effective application of human factors engineering in weapon system development:

System effectiveness and availability (30%)
Productivity increase/personnel reduction (20%)
Job satisfaction and self esteem (20%)
Training improvement (15%)
Survivability (15%)
Cost reduction of personnel (5%)
Reduction in system response time (5%)

Table 1: Predicted improvements through human factors applications

[xvii]The benefits of good human engineering are not always easy to demonstrate, because they are implicit in the design of an effective system. Also it is not easy to anticipate the importance of some human engineering issues except by reference to experience with similar systems. In the space industry for comparisons the Space Shuttle is the premier example where human factors improvements should have been applied in the beginning of the design development.

SPACE SHUTTLE EXAMPLES

The following are some afterthought examples of improvements to Space Shuttle where human factors principles were used. Keep in mind these are just a few examples of improvements that have been documented. There are many human factors improvements that are either documented as another discipline such as safety, or other areas not indicated as human factors. The main goal for this section is to give the reader appreciation of how human factors can improve processing. [xviii]Most of these examples were found in the Industrial Engineering 2003 Annual Report.

Tile waterproofing

[xix]Tile water proofing is a hazardous operation where the operator wears a protective suit, a breathing apparatus, and is required to work in an awkward position. This is not only uncomfortable to the operator it also increases the chance for errors in

the process. Poor vision, uncomfortable position and need for high concentration, do not promote accuracy.

Errors in the waterproofing operation can affect the success of the mission. For example, two tiles on the right hand chime area were lost on Columbia's 2^{nd} flight in 1981. The problem analysis attributed the lost tiles to lack of waterproofing of the tiles. If water enters the tiles upon ascent to orbit, the temperature decreases and the water freezes and expands, thus causing damage to the tiles.

Efforts to improve this process have been the proposed development of a non-toxic waterproofing substance to replace the existing toxic substance. This formulation does not need to be injected and can be sprayed on. This new process is being considered for the FRSI, flexible reusable surface insulation, blankets primarily on the upper surface of the vehicle. There has also been research at Langley Research Center on a robotic device that can automatically do the waterproofing operation for the lower tiles as depicted in figure 4.

Clearly the 1-G Human factors were not considered during the development of this TPS system.

Figure 5: Waterproofing manual process and robot

<u>Auxiliary Power Unit (APU) J.C. Carter Air Half Couplers changed to Fairchild Couplers</u>

The APU J.C. Carter Air Half Couplings are used to service both GN2 and Hydrozine Fuel and have a history of leakage from the internal seal. Removal and replacement requires access to the Aft compartment area and is a SCAPE (Self-Contained Atmospheric Protective Ensemble suit) operation. Due to limited work area there is a high potential for collateral damage to the APU and adjacent subsystems. For example, Main Propulsion System lines were damaged on STS-103 causing a costly launch delay.

The proposed solution is to replace the APU J. C. Carter couplings by 2002 with the Orbital Science (Fairchild) couplings presently certified on OMS/RCS.

Real-time Visual Representation of Orbiter & GSE Configuration

Visual verification is important from a flight hardware damage minimization perspective. There have been numerous examples where the Orbiter and GSE were thought to be in one configuration but were later discovered to be in a different configuration. Due to work load and other tasks, a physical walk-down and visual verification by the operations desk personnel is not always feasible at that moment.

This visual technology strives to help the user keep track of the configuration of the Orbiter by displaying a real-time view of the Orbiters movable surfaces. It is possible to keep track of the platforms as well. In figure 5, the visual representation is on left and the actual configuration is on the right.

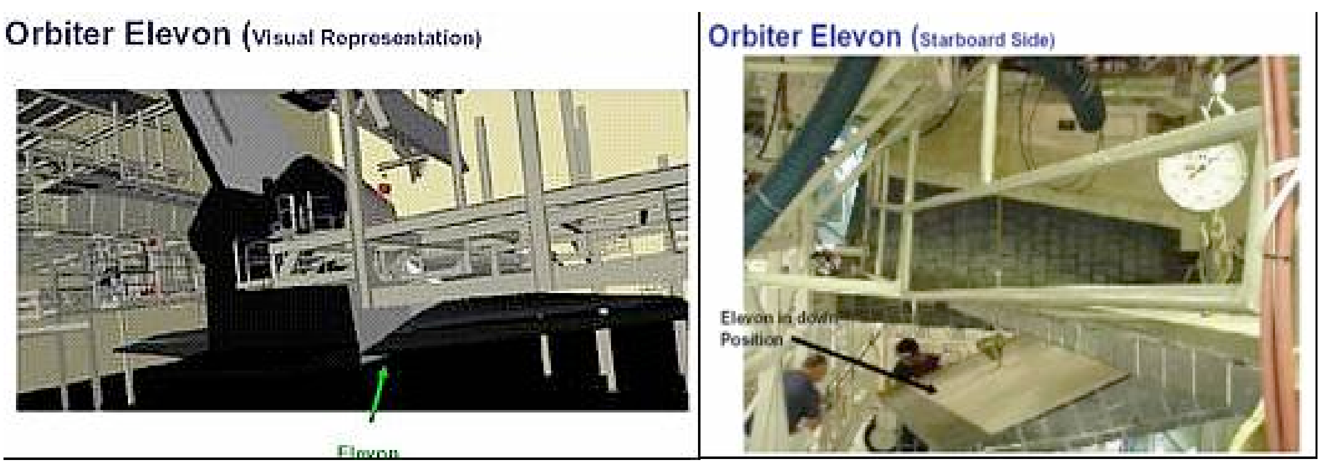

Figure 6: Visual representation and actual elevon

Orbiter Auxiliary Power Unit (APU) U-Tube Installation &Removal Handling Aid

APU located in the Aft of the Orbiter is a heavy component weighing 99-pounds. Handling is cumbersome which promotes the opportunity for personnel injury and flight hardware damage. Off-balance handling can cause back strain and accidental use of Orbiter Aft systems components, such as electrical wiring and tubing, for hand-holds.

An enhanced APU handling solution was needed. Figure 6, shows how the tube "handle" was designed. This temporary handle will help the technician get a better grip on the APU when removing it from the Orbiter.

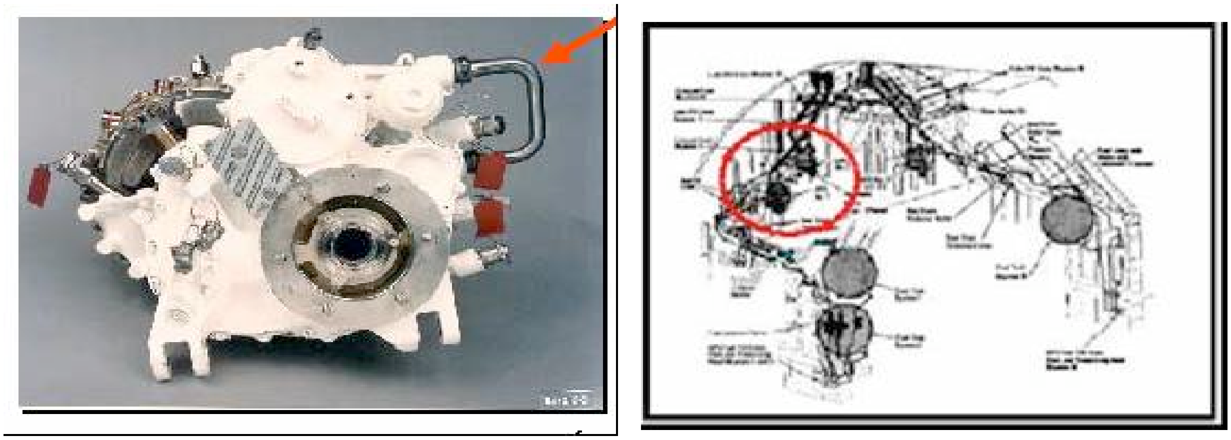

Figure 7: APU handle and location in Aft

<u>Window inspection and polishing</u>

While inspecting the Orbiter windows, the technicians must kneel or lie on platforms to mark the position of defects. They also measure the depth of the defects and make mold impressions of the defects in this position. This is an awkward uncomfortable position that also requires great concentration. See figure 7.

Polishing of the windows is also performed in an even more awkward prone position on these same platforms. A solution to reduce the need for polishing was to redirect the Solid Rocket Booster (SRB) separation thruster exhaust away from the Orbiter windows. This was accomplished by reprogramming the Forward Reaction Control Systems (FRCS) of the Orbiter to fire during SRB separation. The FRCS thrust redirects the SRB separation thrust exhaust and prevents it from coming in contact with the windows.

Figure 8: Window inspection

Removal of Waste Control System (WCS)

Engineers and technicians were seeking improvements to the current process of installation and removal of the large and heavy 186 pounds WCS. The WCS is located in the Orbiter mid-deck and is removed through hatch-C. Technicians would support the WCS weight on their legs as they attempt to align the WCS on to a GSE rail system for removal.

Various 3D simulation models were developed and different processing scenarios were tested. Because it is a 3D model, changes to the design can be made easily. Inserting a virtual human into the simulation models provided the opportunity for analysis of worker ergonomic conditions. This “real to life” 3-D model gave the technicians and engineers a good representation of the hardware in relation to the human, thus making it easier for them to provide pertinent input for improving the process and the required GSE. In figure 8, a 3-D simulation model, and the controls used by the technicians to test the simulated GSE movements are shown.

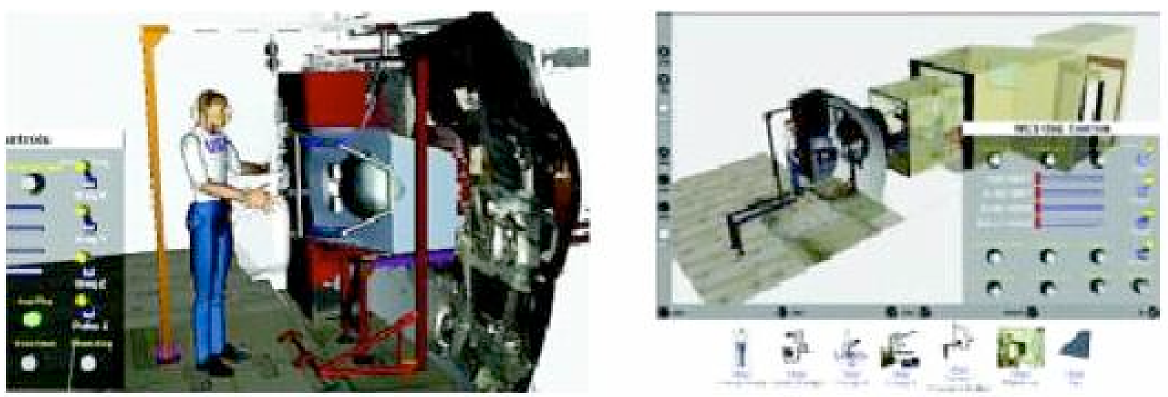

Figure 9: Simulated model and technician controls

Personnel Accountability Tracking Systems (PATS) Study, Phase I

Remote sensing technology provides extremely valuable real-time personnel location information in situations where visibility is reduced or completely impaired. Depicted in figure 9, to the left is the camera view and to the right is a PATS prototype computer readout which if put in operation would be updated with real time location status of personnel while they are changing their physical location at the facility during a hazardous operation.

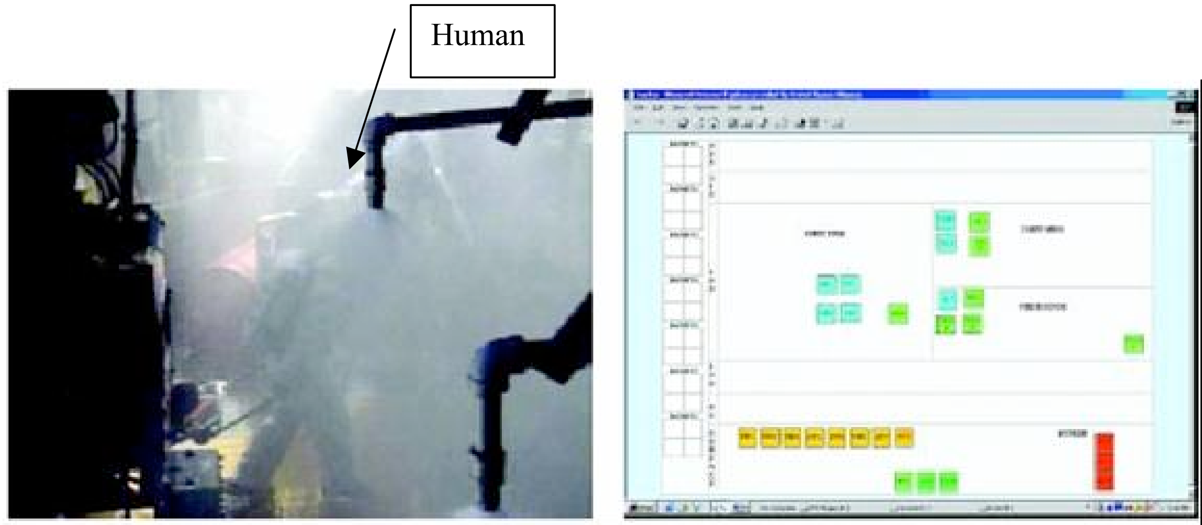

Figure 10: Camera view and program showing the location of the personnel at the facility

<u>HMF OMS Pod Access 35 foot Level Platforms</u>

Personnel at the Hazardous Maintenance Facility required a suitable solution to improved access for servicing the Orbiter Maneuvering System (OMS) pods. In 2002 Industrial Engineering for Safety (IES) funded a virtual reality simulation that modeled the potential platforms, and in 2003 IES, funded the project to build and install the platform hardware. With platform construction completed, access to the OMS pod locations has been significantly improved and resulting safety risks have been mitigated.

In figure 10, shown on the left is the old system of temporary scaffold and pic boards, and on the right is the new platform.

Figure 11: Prior temporary platform configuration and new permanent platform

<u>Orbiter Temporary Access Improvement Project</u>

Temporary platforms are used to gain access to Orbiter and OMS Pods during processing at the Orbiter Processing Facilities (OPF). Currently in use are narrow, aluminum pic boards supported by c-clamps and nylon rope rigging. The ideal improvement is to replace the temporary platforms with permanent / portable platforms. These platforms would be designed to improve safety and access.

Efforts resulted in conceptual designs. Top seven conceptual designs were modeled which is equivalent to a 30% design review. Table 2, shows the locations where the platforms were evaluated.

Platform Locations
OMS Pod: Leading Edge
OMS Pod: Up-Firing Thrusters & Y-web Access
OMS Pod-Access to Flat Side
Engine Cavity #1 (*shown next as an example*)
Forward Electrical Manifold
OMS Pod and Vertical Stabilizer
Eleven Fall Protection

Table 2: Platform locations

Shown in figure 11, is the old method of constructing platforms at Engine Cavity #1

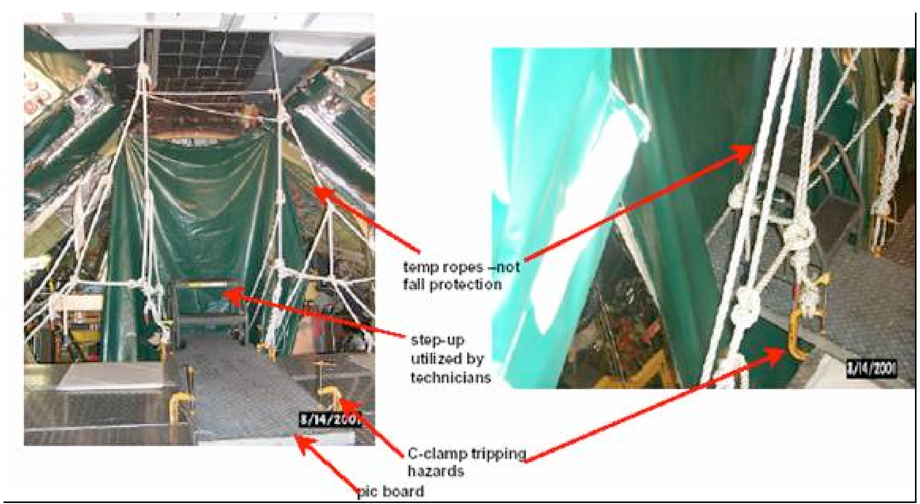

Figure 12: Temporary pic boards and rope

Shown in figure 12, is a 3-D model of the new designed platforms. Technicians were able to evaluate the initial designs and make changes to enhance the performance of these platforms.

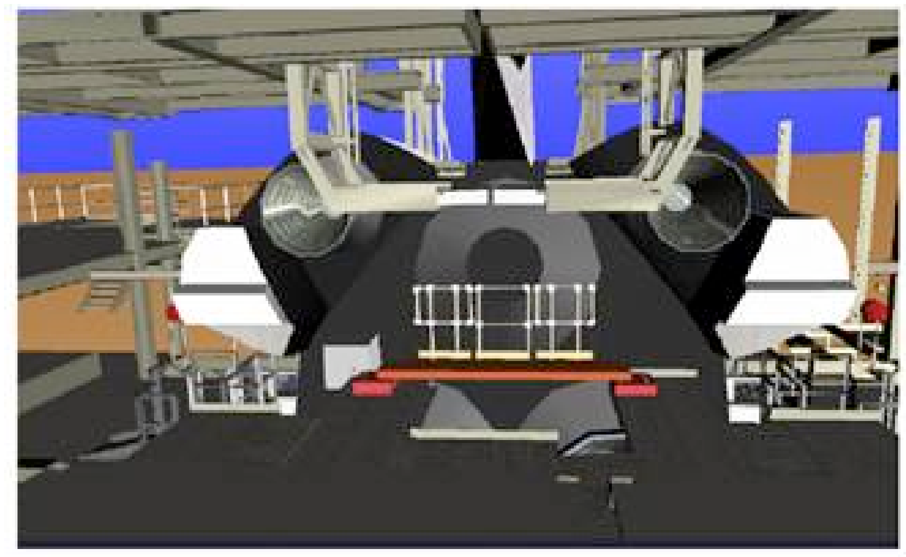

Figure 13: Simulated model of the new platforms

<u>Glass Bead Project</u>

Manual glass beading processes are inherently unsafe for both the workforce and hardware. To improve this process a robotic system was installed to help the Reusable Solid Rocket Motor element performs glass bead operations on case, nozzle, igniter, support equipment, and railcar decks. The automated systems replace six manual abrasive blast stations and one semi-automated station.

By automating the glass beading process, the operator has been removed from the booth and put into the control room, thus eliminating the hazards that include:

- Working directly with high pressure equipment and controlling surging lines
- Poor visibility inside the booth and for surveillance personnel
- Working in high noise levels areas
- Trip, fall, and pinch points
- Awkward positioning in small work areas

Shown in figure 13, are the glass bead booths.

Figure 14: Large and small glass bead booths

KSC Shuttle Landing Facility Training Demonstration

This study modeled Space Shuttle landing scenarios, in conjunction with air control tower simulations. There are plans to use this simulation as a training tool for landing convoy and emergency medical services operations.

Due to the infrequency in shuttle landings, it is important to train and maintain personnel proficiency. Using this high fidelity virtual reality simulations, air traffic controller and support personnel can train and refine operational and emergency procedures more easily, more frequently, and safely. This results in greater flexibility, where trainers can stop, discuss an event, suggest improvements, and replay the training simulation in order to perfect responses. Figure 14, depicts a simulation of the landing facility operations.

Figure 15: Control tower view of simulated convoy vehicle deployment scenarios

OTHER EXAMPLES

Here are a few more key examples where there was a lack of human engineering.

- [xx]Damage to Space Shuttle electrical wiring during maintenance of spacecraft
- [xxi]Improved Quick Disconnect (QD) Interface Through Fail Safe Parts Identification
- TPS repairs (overhead)
- Removal and Replacement of Line Replaceable Units (LRU)
- Access to test ports
- Man loading in crew cabin, Mid-deck, Aft and Mid-body

REASONS FOR LACK OF HUMAN FACTORS IN DESIGN DEVELOPMENT

There are probably many reasons for the lack of implementation of human factors methods during the design development of the Space Shuttle. We are still determining all of these. For example, culture is a big effect from one program to another. Interviews with those that were present during the design development, gave insights to what occurred. From these interviews some areas that had an effect on the implementation of human factors are:

- Flight hardware items were not expected to break, therefore, there were no thoughts on how the human would replace, repair, and test these items. As a result as things broke, it was determined that more testing and replacement were necessary.
- Lack of funds and time. It is not an easy thing to integrate the human element into the system; it takes much effort from all the systems not only to integrate with each system and the environment, but when the human is added a whole dimension of dynamic variability is added to the system. Although it is costly to consider this in the preliminary designs, it is clear that is much more costly and sometimes dangerous not to consider the human as part of the system. A simple example where time and cost came into play; a "Switch Scan & Control" feature was proposed for the Orbiter and never was incorporated due to time and cost. This feature would automatically position/configure the cockpit panel switches in the proper position for certain

tests and for flight. This would have replaced an additional technician in the cockpit to manually position these switches.

- The Space Shuttle designers were so focused on creating a design that would fly, that they had little time to concern themselves with ease of maintenance. Coupled with the inevitable budget pressures caused supportability to fall by the wayside.
- This was in the 70s, when supportability as a practical engineering discipline in the aerospace industry was still in its infancy.
- Finally, the nightmare of Space Shuttle interfaces reflects a lack of integrated systems engineering on the Program.

The results of the lack of emphasis in the human operations led to poor designs. [xxii] Consider these examples of design decisions that have increased the operational and maintenance costs associated with the Space Shuttle and ISS programs.

- Components that must be removed or repositioned to gain access to other components
- Components that must be electrically demated to test
- Components that must be tested through manual human intervention.
- Components that require support equipment to test
- Components with large numbers of interfaces
- Components that require intrusive inspections to test.
- Installation configurations that require human intrusion into areas that house critical hardware

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For the next program, we will have launch vehicles, crew vehicles, and there will be stations on the Moon, Mars, and in between. These stations will require the expertise from what we have learned in the ISS Program. For example, being able to process a spacecraft element on earth and sending it into space to work perfectly with a one shot attempt. In this area alone there are many human factors improvements implemented, such as the task analysis involving the many connections between the different ISS elements. There have been many instances where these interfaces would not have worked in space had they not been first tested and adjusted here on earth. In this area of less than 1-G station assembly, the knowledge of the ISS Program is very proficient and will be a great asset to the new program.

For operations that are more of the 1-G maintainability type such as Multi Purpose Logistics Module (MPLM), meaning going from Earth to space and back, clearly have shown improved processing methods. For example, the robotic rack installer developed for the MPLM lifts and installs the heavy racks. Also, the ISS facility, as compared to the Space Shuttle facilities, has several improvements in lighting, air quality and working temperature, although this is most likely a result of keeping the spacecraft clean. In considering the access outside the vehicles, there are many adjustable platforms employed to provide the required human access.

CONCLUSION

[xxiii]Despite the attention being paid to human engineering in some advanced projects, the integration of human engineering with the systems design process continues to be problematic. A review concluded that it is more likely that the human engineering aspects of system design will be overlooked or neglected than incorporated. Because of this, special attention should be given to the following recommendations in future programs.

RECOMMENDATIONS

1. Consider the “Reasons for Lack of Human Factors in Design Development” in the Space Shuttle section, as well as the conclusion section for Apollo.
2. Use lessons learned derived from the Orbiter Space Plane Program and other NASA programs.
3. Use the lessons learned from the CAIB entire report.
4. Include human engineering under System Engineering and Integration so that more emphasis on human factors effects will be placed on design, development and operation.
5. Ensure data products are in place up front to address human engineering functions at the Systems level.
6. Similar to the NASA-STD-3000 document used for 0-G human factors, NASA should develop its own I-G Human Factors Document that reflects the ground operations and personnel needs.

7. Develop a unified data base for documenting the 1-G human factors developments within NASA, Starting with, but not limited to, Space Shuttle, Station and ELV.
8. Indicate in all the Request for Proposals (RFP) the importance of human factors and have competent and knowledgeable people auditing the contractor's human engineering efforts.
9. Ensure that the contractors produce a Human Engineering Program Plan.

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