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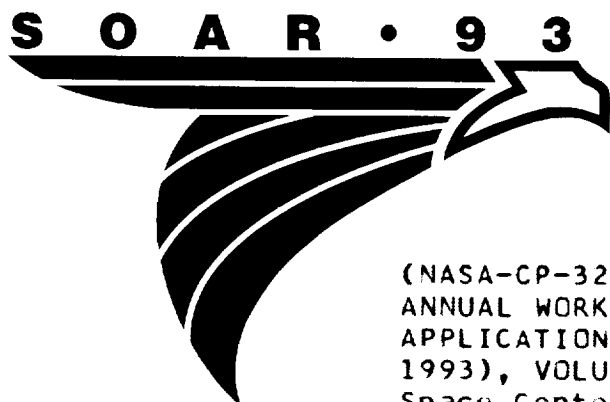


Space Technology Interdependency Group



Seventh Annual Workshop on Space Operations Applications and Research (SOAR '93)

Volume II



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August 3-5, 1993*

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Seventh Annual Workshop on Space Operations Applications and Research (SOAR '93)

Volume II

*Kumar Krishen, Editor
NASA Lyndon B. Johnson Space Center
Houston, Texas*

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August 3-5, 1993



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HUMAN FACTORS

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Session Chair: Dr. Kristin Bruno

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HFE SAFETY REVIEWS OF ADVANCED NUCLEAR POWER PLANT CONTROL ROOMS

N94- 33613

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Advanced control rooms (ACRs) will utilize human-system interface (HSI) technologies that may have significant implications for plant safety in that they will affect the operator's overall role and means of interacting with the system. The Nuclear Regulatory Commission (NRC) reviews the human factors engineering (HFE) aspects of HSIs to ensure that they are designed to good HFE principles and support operator performance and reliability in order to protect public health and safety. However, the only available NRC guidance was developed more than ten years ago, and does not adequately address the human performance issues and technology changes associated with ACRs. Accordingly, a new approach to ACR safety reviews was developed based upon the concept of "convergent validity." This paper describes this approach to ACR safety reviews.

INTRODUCTION

Nuclear Regulatory Commission (NRC) human-system interface (HSI) reviews have typically been directed toward the unique control rooms (CRs) of individual nuclear power plants (NPPs) because these plants and their CRs were already in existence at the time the reviews were performed. Detailed plant designs were evaluated prior to making a safety determination. The NRC and the utility industry have embarked on an effort to standardize future commercial NPP designs. The NRC has issued 10 CFR 52 titled "Early site permits; standard design certifications; and combined licenses for nuclear power plants," in order to achieve these objectives and streamline the licensing process. NPP vendors have begun the design of advanced standard plants, which are being submitted to the NRC for review and certification under Part 52. The General Electric Advanced Boiling Water Reactor, Combustion Engineering System 80+, and Westinghouse AP600 are examples of designs undergoing this type of review.

These designs will employ ACRs which, in comparison to those of conventional plants, utilize increased automation and computer-based HSI technologies that will affect the operators' overall role and their means of interacting with the plant. In addition to technology differences between ACRs and conventional plants, one of the issues to emerge from the initial ACR reviews was that detailed HSI design information was not available. In part because of rapidly changing technology, much of the detailed HSI design will not be completed prior to the issuance of a design certification. Thus the NRC is performing the design certification evaluation based on a process which describes the human factors engineering (HFE) elements that are necessary and sufficient for the development and implementation of an acceptable detailed design.

Since the review of a design process has not been performed in the nuclear industry in the past, and the types of advanced technology employed in ACRs are significantly different from conventional plants, criteria for ACR review are not adequately addressed by current regulations and review guidance.¹⁻² Thus, the criteria for the review of a HFE design *process* and guidelines for the review of the design *product* had to be developed. The HFE Program Review Model (PRM) and Advanced HSI design Guideline, hereafter called the "Guideline," were developed to meet these objectives. In the following sections, the issues that were considered in the development of the review criteria are discussed followed by a discussion of the PRM and Guideline development.

ISSUES IMPACTING REVIEW METHOD DEVELOPMENT

In order to develop an approach to the evaluation of ACRs, it was necessary to consider issues related to trends in advanced NPP design and related human factors issues.

Diversity in Advanced Reactor Technology: The current generation of commercial NPPs operating in the U.S. numbers more than 100; all of those are based upon light water reactor technology. Although the next generation of plants will reflect advances on this technology base, the industry has also developed designs based on different technologies, including heavy water, liquid metal, and gas-cooled reactors. One important design initiative to improve safety and reliability has been the move from "active" safety features (based upon active components such as pumps) toward more "passive" safety features (based upon natural physical processes such as convection flow, radiation cooling, and gravity). This plant diversity and the passive features introduce new and different systems for operators to monitor, control, and test. These will result in different operator roles and tasks that must be understood in performing safety reviews.

HSI Evolution: There are several important trends emerging in advanced HSI design concepts in the nuclear industry, including: (1) increased automation changing the operator's role to system monitor, supervisor, and automated system back-up; (2) centralization of controls and displays into "compact" workstations; (3) use of large display panels visible from anywhere in the ACR to present high-level information and critical parameters; (4) operator's interface with a data management system rather than with components; (5) data integration and graphic displays; and (6) decision-support aids. As these trends are implemented, they will result in a wide range of technological approaches to HSIs.

While the use of advanced technology is generally considered to enhance system performance, advanced HSIs also have the potential to negatively impact human performance, spawn new types of errors, and reduce human reliability.³⁻⁶ Despite its increasing utilization in complex systems such as NPPs and aircraft, there is a consensus that further research is needed to understand the effects of this technology on human performance and system safety.⁷⁻⁸ With the trends in control room design, cognitive issues are emerging as more significant than the physical and ergonomic considerations which dominated the design of conventional HSIs. For example, increases in automation and poor allocation of function decisions that occur early in the design process have been associated with a shift from physical to cognitive workload, loss of operator vigilance, increase in human errors,⁹ difficulty maintaining adequate "situation awareness,"¹⁰ and decay of task performance skills when required because of automated system failure. Thus, the National Academy of Sciences has identified areas such as automation, supervisory control, and human-computer interface as high priority research areas for the human factors community in general and for the commercial nuclear industry in particular.^{7,8} The review process should be sensitive to known and emerging human performance issues and design considerations that give rise to them.

Guidelines to Support Design and Evaluation: For conventional plants, NRC CR reviews rest heavily on an evaluation of the physical aspects of the HSI using HFE guidelines.² In an ACR, the physical layout of the display devices and computer input devices may be less important than the design of the human-software interface. Information in ACRs can be presented in a complex network of hundreds of displays. The difficulty of developing HFE guidelines for the adequate design of human-software interfaces has been well documented.¹¹ Significant to the evaluation of human-software interfaces is that many of the important design features are often hidden to the reviewer (and transparent to the operator). For example, the observed display may be an end product of extensive data processing and integration which results in higher-level, more abstract information than was the case in "single sensor/single display" designs characteristic of conventional CRs). As a result, while hardware guidelines tend to be relatively clear and specific, software guidelines tend to be stated in more general language and have a considerably weaker research/experience base. Thus, an evaluation of ACRs cannot rest on HFE guidelines alone.¹²⁻¹³ Weakness in a guideline-based evaluation will have to be compensated for with other evaluation methods.

The issues discussed above have implications for the development of an approach to the safety review of the HFE aspects of advanced reactor designs. First, an evaluation methodology should provide guidance for reviews to be performed throughout the design process to final design and be sensitive to HFE issues at each point. Second, evaluation methods will have to provide for the review of a broad range of advanced HSI technologies. Third, reviews should extend beyond HFE guideline-based evaluations and include a diversity of evaluation techniques. These factors have led to the technical approach reflected in the PRM and Guideline development described in the following sections.

HFE PROGRAM REVIEW MODEL

PRM Development

The general philosophy underlying the PRM's development is that "safety" is a concept that is not directly observed but must be inferred from available evidence. When reviewing a design to make a safety assessment, different types of information obtained from different assessment methods are weighted towards or against an acceptable finding. Each method has its correlation with safety and each has its own sources of bias and error. The reviewer would like to collect as much information as possible in order to establish "convergent validity"¹⁴; i.e., to establish a coherent finding across different evaluation methods. This approach is similar to a "defense-in-depth" concept applied to HFE/HSI evaluation.

The types of information that can provide assessments of HSI safety include: (1) HFE Planning including an HFE design team, program plans and procedures; (2) design analyses and studies including requirements/function/task analyses, technology assessments, trade-off studies, etc.; (3) design specifications and descriptions; and (4) verification and validation (V&V) analyses of the final design, e.g., compliance with accepted HFE guidelines and operation of the integrated system with operators performing the required tasks under actual (or simulated) conditions). The greatest confidence in a finding that a design is safe can be obtained from one which was: (1) developed by a qualified HFE design team using an acceptable HFE program plan; (2) the result of appropriate HFE studies and analyses which provided accurate and complete inputs to the design process and to V&V assessment criteria; (3) designed using proven technology based upon human performance and task requirements incorporating accepted HFE standards and guidelines; and (4) evaluated with a thorough V&V test program. The PRM was developed around this concept.

There were four specific objectives of the PRM development:

- to develop a model to serve as a technical basis for the review of the development and design of HSIs that is (1) based upon currently accepted practices, (2) well-defined, and (3) validated through experience with the development of complex, high-reliability systems;
- to identify the HFE elements in a system development, design, and evaluation process that are necessary and sufficient requisites to successful integration of the human component in complex systems;
- to identify which aspects of each HFE element are key to a safety review and are required to monitor the process; and
- to identify the types of acceptance criteria by which HFE elements can be evaluated.

To meet these objectives, a technical review of current HFE guidance and practices was conducted along two dimensions: *Technical Basis* (literature providing the theoretical and regulatory basis for evaluating the conduct of HFE); and *Application* (literature reflecting the practice of HFE for development, design and evaluation of complex, high-reliability systems). General systems literature, as well as literature focused specifically on the nuclear industry, was reviewed. From this review a generic system development, design, and evaluation process was defined. Once specified, key HFE elements were identified, and general criteria by which they are assessed (based upon a review of current literature and accepted practices in the field of human factors engineering) were developed.

The PRM was based largely on applied general systems theory¹⁵⁻¹⁶ and the DoD system development process which is rooted in systems theory.¹⁷ Applied general systems theory provides a broad approach to system design and development based on a series of clearly defined developmental steps, each with clearly defined goals and with specific management processes to attain them. System engineering has been defined as "...the management function which controls the total system development effort for the purpose of achieving an optimum balance of all system elements. It is a process which transforms an operational need into a description of system parameters and integrates those parameters to optimize the overall system effectiveness."¹⁷

The effective integration of HFE considerations into the design is accomplished by: (1) providing a structured top-down approach to system development which is iterative, integrative, interdisciplinary and requirements driven, and (2) providing a management structure which details the HFE consider-

ations in each step of the overall process. A structured top-down approach to NPP HFE is consistent with recent nuclear industry standards for advanced control room design¹⁸⁻¹⁹ and with the recognition in the nuclear industry that human factors issues and problems emerge throughout the NPP design and evaluation process. The systems engineering approach was expanded to develop a PRM to be used for the advanced control room design and implementation process review by the incorporation of NRC HFE requirements.

PRM Description

In this section an overview of the PRM is presented to generally describe the HFE elements, the products reviewed for each element, and the acceptance criteria used to evaluate the element.

The PRM is intended as the programmatic approach to achieving a design commitment to HFE. The overall commitment and scope of the HFE effort can be stated as follows: Human-system interfaces (HSI) should be provided for the operation, maintenance, test, and inspection of the NPP that reflect state-of-the-art human factors principles. For the purposes of PRM development "state of the art" human factors principles were defined as those principles currently accepted by human factors practitioners. "Current" is defined with reference to the time at which an HSI is developed. "Accepted" is defined as a practice, method, or guide which is (1) documented in the human factors literature within a standard or guidance document that has undergone a peer-review process, and/or (2) justified through scientific/industry research practices.

The PRM developed to achieve this commitment contains eight elements. Each consists of an overall objective and factors that must be considered in the review process. A very brief description of each element follows. A more complete description along with specific review criteria for each element can be found elsewhere.²⁰

Element 1: Human Factors Engineering Program Management - To assure the integration of HFE into system development, an HFE Design Team and an HFE Program Plan should be established to assure the proper development, execution, oversight, and documentation of the program. As part of the program plan an HFE issues tracking system (to document and track resolution of problems, concerns, issues) should be established.

Element 2: Operating Experience Review - The accident at Three Mile Island in 1979 and other reactor incidents have illustrated significant problems in the actual design and the design philosophy of NPP HSIs. There have been many studies as a result of these incidents and utilities have implemented both NRC mandated changes and additional improvements on their own initiative. Problems and issues encountered in similar systems of previous designs should be identified and analyzed so that they are avoided in the development of the current system or, in the case of positive features, to ensure their retention.

Element 3: System Function Requirements Analysis - System requirements should be analyzed to identify those functions which must be performed to satisfy the objectives of each function area. System function analysis should: (1) determine the objective, performance requirements, and constraints of the design; and (2) establish the functions which must be accomplished to meet the objectives and required performance.

Element 4: Allocation of Function - The allocation of functions should take advantage of human strengths and avoid allocating functions which would be adversely impacted by human limitations. A structured and well-documented methodology of allocating functions to personnel, system elements, and personnel-system combinations should be developed.

Element 5: Task Analysis - Task analysis should provide the systematic study of the behavioral requirements of the tasks that the personnel subsystem is required to perform in order to achieve the functions allocated to them. The task analysis should: (1) form the basis for specifying the requirements for the displays, data processing and controls needed to carry out crew tasks; (2) provide one basis for making design decisions; e.g., determining before hardware fabrication whether system performance requirements can be met by combinations of anticipated equipment,

software, and personnel; (3) assure that human performance requirements do not exceed human capabilities; (4) be used as basic information for developing procedures, and (5) be used as basic information for developing staffing, skill, training, and communications requirements.

Element 6: Human-System Interface Design - Human engineering principles and criteria should be applied along with all other design requirements to identify, select, and design the particular equipment to be operated/maintained/controlled by plant personnel.

Element 7: Plant and Emergency Operating Procedure Development - Plant and Emergency Operating Procedures should be developed to support and guide human interaction with plant systems and to control plant-related events and activities. Human engineering principles and criteria should be applied along with all other design requirements to develop procedures that are technically accurate, comprehensive, explicit, easy to utilize, and validated.

Element 8: Human Factors Verification and Validation (V&V) - V&V evaluations should assure that the performance of the HSI achieves, when all elements are fully integrated into a system, (1) all HFE design goals as established in the program plan; (2) all system functional requirements, and (3) all requirements to support human operations, maintenance, test, and inspection task accomplishments. Four types of evaluations should be performed:

1. Human Factors Issue Resolution Verification - All issues documented in the Human Factors Issue Tracking System of Element 1 should be resolved.

2. HSI Task Support Verification - All controls, displays, alarms, and data processing that are required to accomplish human safety-related tasks and actions should be available.

3. HFE Verification - All controls, displays, alarms, and data processing support provided by the HSI should be appropriate to the crew tasks and designed according to accepted HFE guidelines, standards, and principles.

4. Integrated System Validation - The integration of HSI elements with each other and with personnel should be validated through dynamic task performance evaluation. The evaluations should have as their objectives: (1) demonstrating the adequacy of entire HSI configuration for achievement of safety goals, (2) confirmation of function allocation and the structure of tasks assigned to personnel, (3) adequacy of staffing and the HSI to support the staff in the accomplishment of their tasks, (4) adequacy of procedures, (5) confirmation of the adequacy of the dynamic aspects of all HSIs for task accomplishment, and (6) evaluation and demonstration of tolerance of the design to human error and system failures.

ADVANCED HSI DESIGN REVIEW GUIDELINE

Guideline Development

While the PRM addresses the design process, guidance is needed to support the review of detailed HSI design products of that process (as part of PRM Element 8 described above). The Advanced HSI Design Review Guideline was developed to provide these review criteria and was intended to update the available CR review guideline.² In the discussion below, the term "Guideline" (with a capital "G") refers to the entire document, while the term "guideline" refers to the individual guidelines within the document. A more detailed description of the Guideline development and contents is available elsewhere.²¹

Based upon an evaluation of research and industry experience related to the integration of personnel into advanced systems, a set of High-Level Design Review Principles was developed (see Table 1). These principles provide the generic HSI characteristics necessary to support operator performance and make systems more tolerant to human errors when they occur. Since these principles are stated at a fairly general level, they were further developed to a level of detail sufficient to support HSI review and evaluation. The principles were translated into terms that could be applied to specific applications by developing guidelines for the review of the specific types of technology (e.g., graphic

displays and expert systems).

Table 1. High-Level Design Review Principles

Category	Principle
General	Safety, Cognitive Compatibility, Physiological Compatibility, Simplicity of Design, Consistency
Primary Task Design	Situation Awareness, Task Compatibility, User-Model Compatibility, Organization of HSI Elements, Logical/Explicit Structure, Timeliness, Controls/Displays Compatibility, Feedback
Secondary Task Control	Cognitive Workload, Response Workload
Task Support	Flexibility, User Guidance & Support, Error Tolerance & Control

The effort to develop detailed guidelines began with an identification of existing human factors guidance documents for advanced HSIs. Through a review of the human factors literature, approximately 50 guideline efforts were identified. To identify those that would serve as the "primary sources" for the Guideline, a high priority was given to establishing the validity of the prior guidelines; i.e., assuring that they were based upon empirical research and/or accepted human engineering practice. Validity was defined in terms of two aspects of document development. "Internal" validity was evaluated by the degree to which the individual guidelines within a document were based upon empirical research and provided an audit trail to that research. "External" validity was evaluated as a function of the degree to which the guidelines were subjected to independent peer review. The peer review process was considered a good method of screening guidelines for conformance to accepted human engineering practices. In general, documents which had strong validity were considered primary source documents to serve as a basis for the Guideline.

The guidelines from the primary sources were edited to combine similar guidelines and to transform the material into a standardized format. Where compound guidelines were encountered (several guidelines in a single statement) an effort was made to break them into logical units and represent the units as separate guidelines. Conflict resolution between guidelines was handled on a case-by-case basis.

Guideline Description

The guidelines were organized into seven major sections which are described below. Each of these sections contains a set of general guidelines and more detailed guidelines addressing specific HSI implementations, techniques, and formats.

Information Display - This section deals primarily with the formatting of text and graphic visual displays. Guidance is provided in top-down fashion beginning with display formats (such as topology displays and trend graphs), display format elements (such as labels, icons, symbols, color, coding, etc.), data quality and update rate, and display devices.

User-System Interaction - This section addresses the modes of interaction between the operator and the HSI. Topics include dialog format, navigation, display controls, entering information, system messages, prompts, and system response time. This section also contains guidelines pertaining to methods for ensuring the integrity of data such as inadvertent change or deletion of data, minimization of data loss due to computer failure, and protection of data such as setpoints.

Process Control and Input Devices - This section addresses information entry, operator dialog, display control, information manipulation, and system response time. Considerations of display-control integration are also included here.

Alarms - This section is currently a place holder for the results of another NRC research project to develop review guidance in the area of advanced alarm systems.

Analysis and Decision Aids - This section addresses the use of knowledge-based systems.

Inter-Personnel Communication - This section contains guidelines for activities related to speech and computer-mediated communication between plant personnel, e.g., preparing, addressing, transmitting and receiving messages.

Workplace Design - This section addresses the organization of displays and controls within individual workstations and control room configuration and environment.

In addition to a hard-copy document, the Guideline has been developed as an interactive, computer-based review aid. Each guideline in the database is represented by several primary fields: guideline number, title, guideline statement, additional information, and source (link to primary source document). Other user assistance fields are also available, e.g., to provide location (in the document) information and a note pad for users to append comments related to specific guidelines. The interactive document will facilitate review planning, guideline access and evaluation, data analysis, and report preparation. Guideline maintenance such as editing and the incorporation of new guidelines as they become available is also supported. Availability of the Guideline on a portable computer will also facilitate in-the-field reviews. An Apple Macintosh™ computer and Hypercard™ software were selected for prototyping. The prototype user interface provides for many document functions such as instant table of contents (ToC) access, context index, glossary, and place markers. Users can automatically go to desired sections by clicking on the ToC or index.

CONCLUSIONS

A framework for the review of ACRs has been developed. Safety evaluations are based upon the information from both the design process and its products. The PRM provides criteria for the review of the design process and the Guideline provides criteria for the review of the HSI resulting from the process. This framework is being used to support the NRC reviews of the HFE programs for the current ACR designs being evaluated for design certification.

ACKNOWLEDGEMENT

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USING TASK ANALYSIS TO UNDERSTAND THE DATA SYSTEM
OPERATIONS TEAM

N94- 33614

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ABSTRACT

The Data System Operations Team (DSOT) currently monitors the Multimission Ground Data System (MGDS) at NASA's Jet Propulsion Laboratory. The MGDS currently supports five spacecraft and within the next five years it will support ten spacecraft simultaneously. The ground processing element of the MGDS consists of a distributed UNIX-based system of over 40 nodes and 100 processes. The MGDS system provides operators with little or no information about the system's end-to-end processing status or end-to-end configuration. The lack of system visibility has become a critical issue in the daily operation of the MGDS. A task analysis was conducted to determine what kinds of tools were needed to provide DSOT with useful status information and to prioritize the tool development. The analysis provided the formality and structure needed to get the right information exchange between development and operations. This paper describes how even a small task analysis can improve developer-operator communications and examines the challenges associated with conducting a task analysis in a real-time mission operations environment.

INTRODUCTION

Any human factors engineer would leap at the opportunity to conduct a task analysis for a project. Likewise, project managers would appreciate any opportunity to gain insightful information about their customer's needs and what products will meet those needs. Still task analyses are not typically incorporated into the software development life cycle. This absence is especially odd since system development is a highly interactive process.

The system development process is usually considered a logical, intellectual process, but it often contains many "irrational and nonintellective elements" (Meister, 1971). Even with a good understanding of task analysis methods and their proper application, the analysis may still be subject to other influencing factors like time, budget, and (most importantly) the cooperation of engineers (Meister, 1991). However, even a small task analysis reveals useful

information and insight that would otherwise go unnoticed if no analysis was done at all.

THE SYSTEM

The task analysis described in this paper was conducted to understand the daily activities of the Data System Operations Team (DSOT) who are responsible for running the Multimission Ground Data System (MGDS). The MGDS provides spacecraft telemetry data capture, data processing and display, and system monitor and control capabilities. Data is received into the system from the spacecraft via the Deep Space Network (DSN). The DSN is a network of antennas through which commands are sent to the spacecraft and data is received from the spacecraft and forwarded to the MGDS. The Data System Operations Team monitor the data from the DSN and follow it closely as it is processed through the MGDS and delivered to project scientists, spacecraft teams, NASA centers, principal investigators and other end users (Figure 1).

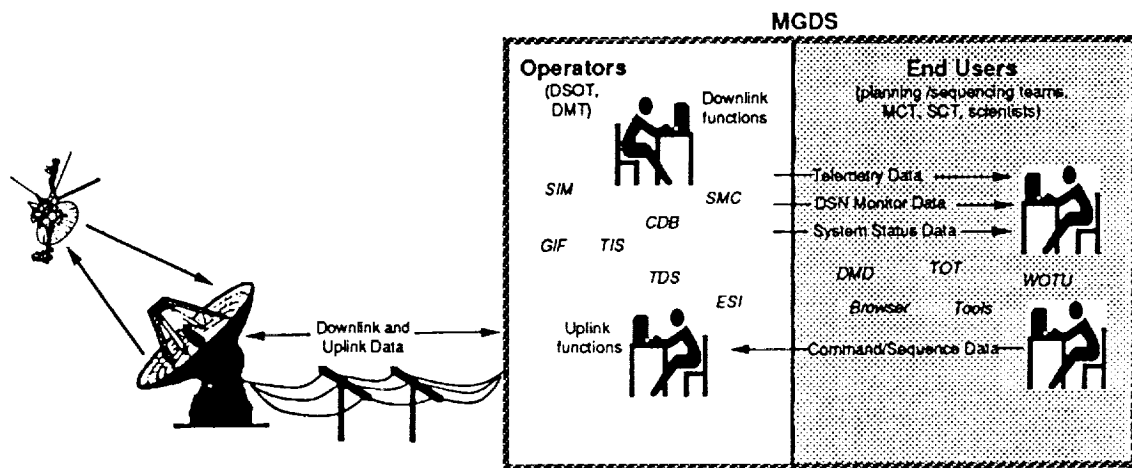


Figure 1. MGDS Operators Keep MGDS Running So End Users May Receive Data and Command the Spacecraft

DSOT primarily focuses on the MGDS itself and how it is functioning, as well as the packaging, routing, and storing of the data, rather than with actual data values and their significance (Miller et al, 1992). Operators rely on experience, teamwork and existing tools to monitor the system and get the data to the system users.

Figure 2 shows a simplified MGDS end-to-end data flow. Running the front-end of the system is labor intensive and difficult. It's labor intensive because the setup for a DSN tracking pass-configuring the processing of the data through the system-is a manual process.

Although some of the setup activities are scripted, they are not automated at startup, and once running there is no mechanism for managing the hierarchy of activities. The process is difficult because there are no tools that provide data accountability or visibility into front-end data processing. For example, DSOT has no tool that estimates the amount of data (by type) a project is expecting from a given track for all the project's data types; nor is there a way to estimate what the output products should be across the front-end subsystems.

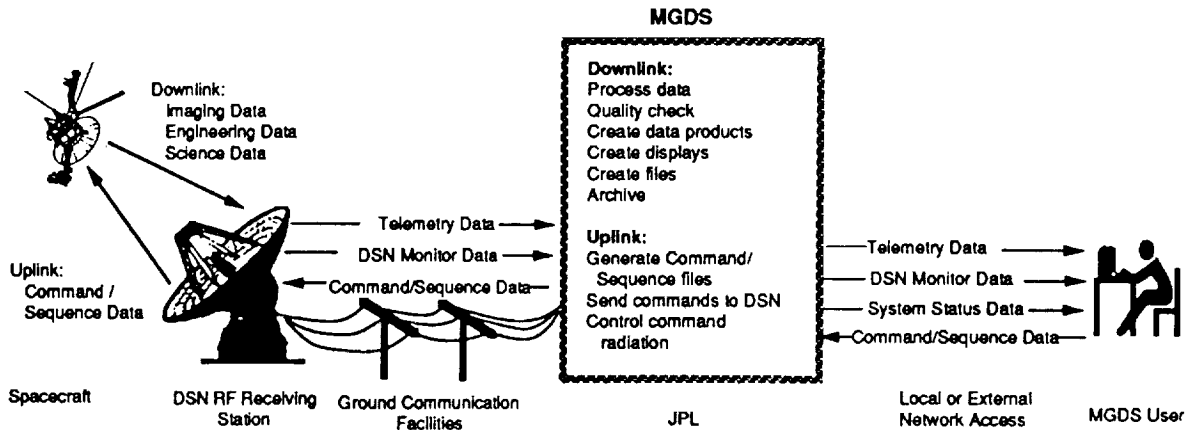


Figure 2. Simplified End-To-End MGDS Data Flow

In order to reduce operations costs through improved efficiency in DSOT, an initiative called DSOT Cockpit was funded to address the special needs of the DSOT operators. The goal of DSOT cockpit was to provide much-needed visibility into the system's front-end processing where DSOT operations are focused. Tools that display information about the current and expected system status are key elements of the DSOT cockpit effort to improve mission operations. The lack of system visibility is critical to mission operations because when a flight project suddenly stops receiving data, DSOT must find the problem and solve it in real-time. The tools needed to *see* what is happening in the system did not exist. The task analysis was conducted to identify what tools were needed and to prioritize development of those tools.

TASK ANALYSIS

Fortunately, management had a good understanding of what a task analysis entailed and what to expect from it. Getting both development and operations management support was not as

difficult as originally anticipated. Before the analysis began, managers were briefed on the purpose of *this* task analysis and what they could realistically expect to find from it. The development side agreed to implement the tools according to the findings in the analysis.

In the interest of time and resources, the task analysis had to be fast, be efficient, and produce reliable results. At a minimum, the results needed to recommend solutions that were as good as or better than those that the developers had come up with on their own. It also needed to accurately reflect the daily tasks of DSOT in terms developers could understand and recommend ways to improve DSOT operations.

One particular challenge was finding a standard task analysis format for real-time mission operations. There isn't one. The closest thing to a standard is the *Handbook for Designers of Instructional Systems*. The goals of this analysis had to be considered and the methods had to be selected, adapted, or developed from the Handbook. At first it seemed overwhelming, but it quickly became clear that for any task analysis, there will be diverse variables that will influence the analysis, design, methods of data collection, and the resulting design recommendations. The process of selecting the task analysis methods and format for DSOT took longer than expected but was worth the effort.

Methods

The primary methods of data collection were individual interviews and observations of work activities. These methods were selected because they were simple, fast, and minimally disruptive during operations. The interviews were conducted at the individual operators' workstations, so the operators were not removed from their work areas. There was only one instance of an interview having to be rescheduled because of a system problem that required immediate attention.

The original task analysis proposal stated that all operators would be interviewed, however because of resource constraints only a random sample of the team could be interviewed. The sample was selected by randomly selecting names from a list of operators. A total of 10 operators were interviewed.

Approximately 20 operators were observed and some of the interviewees were included in the group that was observed.

All the interviews followed a questionnaire of 20 questions regarding DSOT's activities, common problems, frustrations, ways to improve the system and demographics. The last part of the interview was reserved for the operator's questions about the questions or to provide additional information that was not covered. The interviews went smoothly but sometimes turned into gripe sessions about management, the system, or the organization. Some of the operators expressed frustration with their lack of representation in development and design decisions that affect how their tasks are performed or cause changes to the tasks themselves. Comments about the organization, system, or management were noted and forwarded to the appropriate persons, but were not presented in the final findings of the task analysis. At times it was a challenge to keep the interview focused on DSOT tasks as opposed to complaints. Most of the information offered by the operators at the end of the interviews was insightful and honest information that would not have been communicated if the task analysis was not conducted.

Another common problem encountered during the interviews was short answers. Many of the operators had not put much thought into ways to improve the system, but rather had concentrated on making the system work in the current environment. This finding was a surprise because we assumed that the operators would have a lot of immediate suggestions.

The interview method provided good information, but only what little information was offered by (or drawn out of) the operators. The observations were intended to fill this gap, but running the MGDS is complex and simply observing an operator was not as informative as expected. As a result, the observation sessions provided little useful information.

The notes from the interviews and the observation sessions were sorted into a table (similar to Table I) and categorized by task type, difficulty of implementation, and criticality to improving operations efficiency. Each task was categorized into 3 groups (Cushman and Rosenberg, 1991):

- S Sequential: There is a prescribed order in which task elements and sub tasks must be accomplished.

- B Branching: Subsequent task options are based on previous task choices.
- P Process: Continuous monitoring of a process where the user initiates control movements based on feedback from the system.

Table I. Task Categories and Ratings (Example)

<u>Task/Problem</u>	<u>Task Type</u>	<u>Importance</u>	<u>Difficulty</u>
Data gap detection	B	4	3
End-to-end system configuration information	P	5	5
Post-pass data analysis tool	S	3	2
Show data loss between GIF and TIS	P	5	3

Most of the tasks DSOT conducts are process oriented, making them difficult to analyze. The importance rating was given on a scale of 1-5 with 5 being the most important. The rating was based on the data received from the interviews. Some of the importance ratings were subjective, while others were definitive. The difficulty rating was given on the same 1-5 scale as the importance rating; it was based on developers estimates. Surprisingly, the rated importance of a task or problem varied considerably between operators. This variance was attributed to differences in problem-solving styles and experience.

Another surprise was the general displeasure the operators expressed with the usability and stability of the system. Even when specific problems were not identified, each operator said the system was difficult to learn, use, and operate.

CONCLUSION

This task analysis brought new insight and understanding about operations teams and how individuals use the delivered tools, or

adjust to the lack of tools, to run the system. The analysis facilitated constructive communication between development and operations while the analysis was being conducted and has since resulted in more open communications.

The following task analysis tips are based on this experience. They are basic, but they are essential to the use of task analysis as a tool for meeting development and operations goals:

- Define the purpose of the analysis. Task analyses have a variety of purposes; be sure to clearly state which purpose the analysis is aiming to accomplish.
- Be flexible to changes in budget, personnel, or analysis methods. Adaptability is critical to the success of the analysis in a mission operations environment that changes.
- At a minimum, get one person on the development side and one on the operations side to be champions for the analysis. An endorsement will make the analysis run more smoothly and the results will have a better chance of getting implemented.
- Keep everyone informed of the analysis progress or lack of progress. Continuous flow of status information is key to continued support.

Remember, even the simplest analysis can bring more benefit than no analysis brings. It will find hidden problems, highlight strengths, and confirm understandings. It is the key element to making products and systems usable. Task analysis must be included in the development lifecycle (on any scale) in order to develop efficient, usable systems. If you have any doubts, give it a try.

ACKNOWLEDGMENT

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THE VIRTUAL MISSION OPERATIONS CENTER

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N94- 33615

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Abstract

Spacecraft management is becoming more human intensive as spacecraft become more complex and as operators are asked to perform additional functions and interact more with external groups. Operations costs are growing accordingly. Several automation approaches have been proposed to lower these costs. However, most of these approaches are not flexible enough in the operations processes and levels of automation that they support. This paper presents a concept called the *Virtual Mission Operations Center (VMOC)* that provides highly flexible support for dynamic spacecraft management processes and automation. In a VMOC, operations personnel can be shared among missions, the operations team can change personnel and their locations, and automation can be added and removed as appropriate. The VMOC employs a form of *on-demand supervisory control* called *management by exception* to free operators from having to actively monitor their system. The VMOC extends management by exception, however, so that distributed, dynamic teams can work together. The VMOC uses *work-group computing* concepts and *groupware* tools to provide a team infrastructure, and it employs *user agents* to allow operators to define and control system automation.

1 INTRODUCTION

Several trends suggest the need for a new approach to spacecraft management [1]. First, operations complexity is on the rise because the number of telemetry points and spacecraft commands is increasing rapidly and because missions are requiring more real-time, dynamic science processes. It is becoming difficult for operators to actively monitor all telemetry points and issue appropriate low-level commands while trying to respond to dynamic user needs. Second, opportunities for direct spacecraft interaction are decreasing as the ground-spacecraft relationship moves from a master-slave to a peer-to-peer relationship, as more ground system functions are automated, as passes become shorter due to use of ground networks, and as the number of mission events decrease. This decreased interaction combined with increasing complexity suggests that operators will require more information from less interaction. Third, operator work loads are increasing as operations moves from the control center concept to the Mission Operations Center (MOC) concept; previously separated functions are being added to the operators' tasks. Operators therefore must do more under tighter time constraints. And finally, operators are having to interact more with external groups as missions become increasingly linked to each other, as scientists are given more control access, and as the number and distribution of science users increases. Operators will have to spend more time coordinating actions with other groups. All of these trends have tended to drive up the operator skill levels and the number of operations personnel needed. Unfortunately, smaller missions have less money to spend on operations support.

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Any solutions that address these trends must do so without violating several spacecraft management tenets. First, the solution must allow people to take charge of the system. The solution therefore must be semi-autonomous, and it must allow human operators to lower, and possibly remove, any level of autonomy as desired. Spacecraft behavior simply is not sufficiently predictable to allow complete autonomy. Second, the solution must allow operators to move freely from distant, high-level spacecraft interaction to immediate and detailed interaction. Special events, such as launch and maneuvers, require immediate, detailed monitoring and control. The solution also should allow the number of operations personnel to increase and decrease as needed. Special events and problems require engineers and additional operators.

This paper proposes a unified approach to addressing the above trends that does not violate the tenets of spacecraft management. The approach, called the Virtual Mission Operations Center (VMOC), is based on three technologies that are currently being applied in commercial applications: management by exception, work-group computing, and user agents. Figure 1 illustrates how these technologies form an integrated approach to spacecraft management. The *management by exception* model [2] extends the concept of supervisory control [3] to be more asynchronous or on-demand. In the model, the system detects deviations from normal system behavior (i.e., exceptions) and contacts the operator to address the exception before a problem develops. Management by exception frees the operators from having to actively monitor the system and allows them to act more proactively. In this paper, the model has been extended to support teams of operations personnel working together. A team approach is needed because spacecraft complexity requires a specialist for each subsystem. The extended model is called *team-based management by exception*.

Work-group computing [4] is an automated environment in which distributed, dynamic teams perform dynamically defined processes. Work-group computing uses groupware tools and technology to provide the infrastructure needed to support team-based management by exception.

User agents are semi-autonomous programs that act as personal assistants to provide indirect interaction between the user and the system. Such agents provide a user-defined, user-controlled way to gradually introduce automation. The technology also provides a model of how agent authority can develop over time based on proven competence.

The remainder of this paper explores how each of these three technologies can provide a unified approach to the spacecraft management trends identified above. The next three sections discuss each of the technologies in more detail. Section 5 illustrates how the combination of technologies addresses the trends through a series of operations scenarios. The scenarios also show how the approach adheres to the previously identified tenets.

2 MANAGEMENT BY EXCEPTION

In traditional system management, action is taken in response to an existing problem, i.e., when an error has already occurred. The system is constantly monitored and, when an error is detected, problem resolution is typically crisis driven. In the basic *management by exception* model [2], action is taken when there is a deviation from normal behavior, i.e., an exception occurs. Once an exception is detected, there is normally time to address it before a problem develops. Monitoring therefore can be less constant, and response can be less of a crisis. This model currently is used in several enterprise (i.e., distributed computing resource) management systems, for example Hewlett-Packard's PerfView and Operations Center.

What is an Exception? There are several ways to define the conditions under which an exception should be flagged. Most *exception conditions* are of the form: "X must [must not] be the case Y% of the time." For example, the exception "Response times must be less than 10 seconds

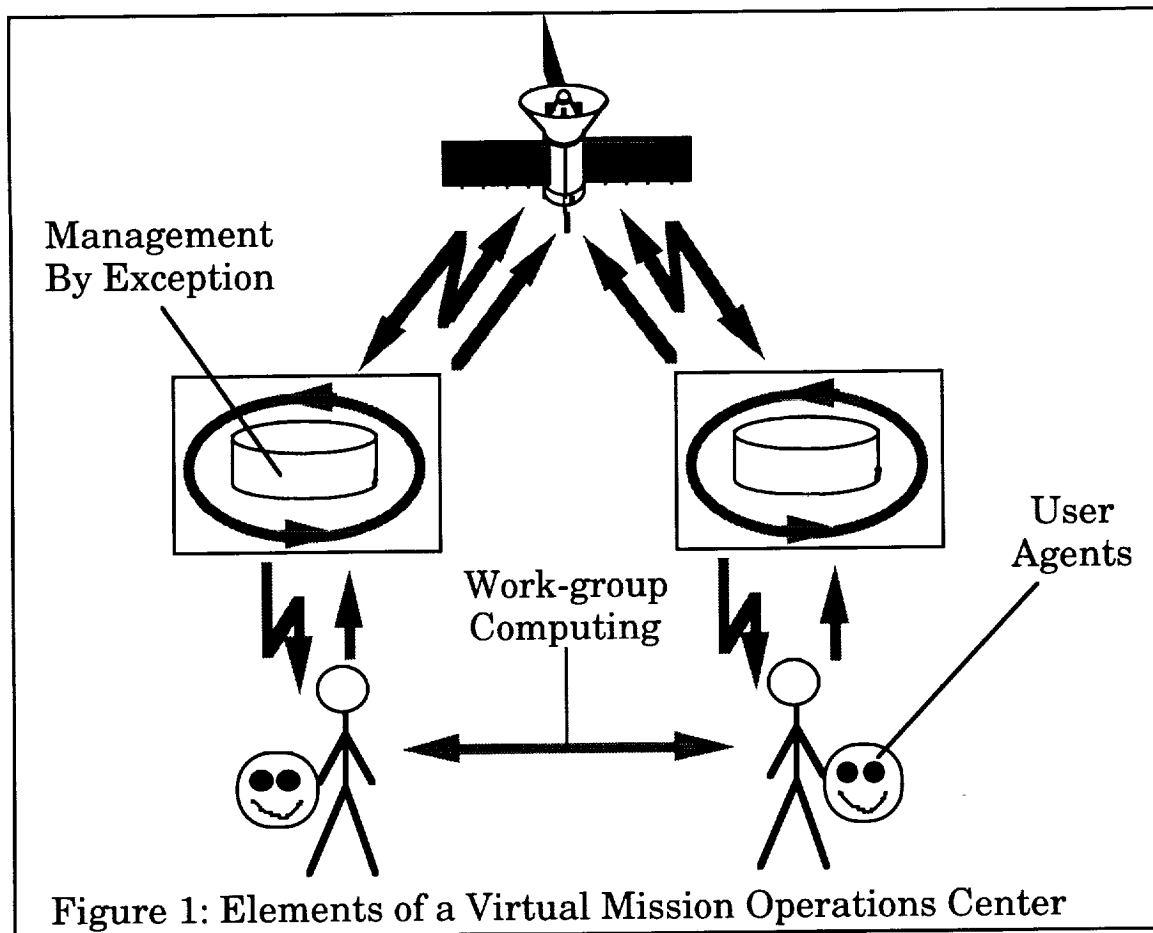


Figure 1: Elements of a Virtual Mission Operations Center

90% of the time" might be used to describe a computing system's normal behavior. The condition (i.e., X) usually contains a system value threshold. Exception conditions also can be defined using trend analysis and knowledge-based techniques. Using these techniques enables more proactive system management but is more difficult to implement.

An exception's definition includes an exception condition, the time interval over which the exception should be checked, and the exception's priority and severity levels. Exception conditions should be tested against a sufficiently long time period to avoid responding to transient behavior. Priorities and severity levels may be assigned to exceptions to assure that bad problems are resolved quickly. Severity may have to be determined dynamically based on the extent of the deviation and the services affected.

The Basic Process. Figure 2a illustrates the basic management by exception model. A centrally located operator defines a set of exceptions for the various system elements and downloads these to the elements. The elements periodically check for exception violations. Data relevant to the exceptions are collected so that they can be included in a possible exception report. While the system is performing its checks, the operator is free to perform other tasks. The operator therefore does not have to actively monitor the system. When an exception occurs, the exception and supporting data are sent to the operator. The operator is notified that an exception has been detected, either directly through the monitoring interface or indirectly through email, FAX, pager, or phone. The operator then may establish a close monitoring or real-time connection to the element.

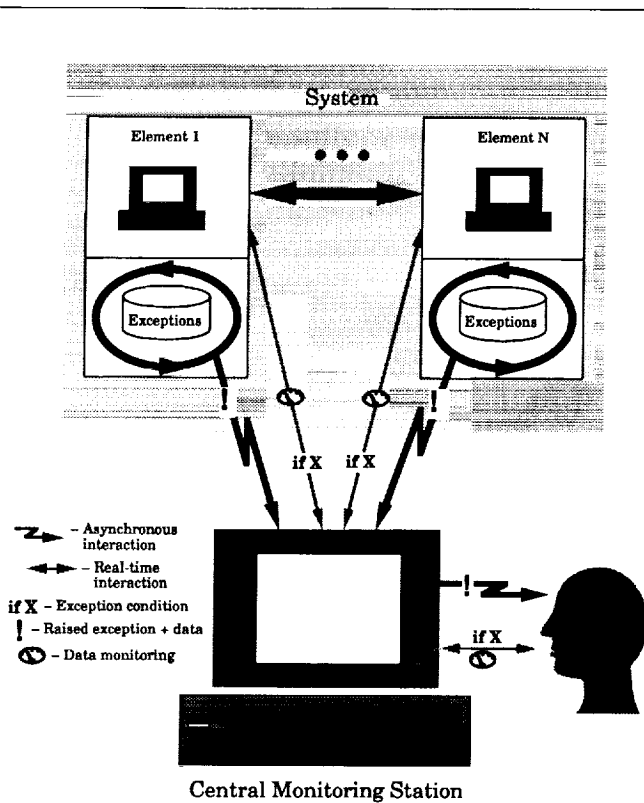


Figure 2a: The Basic Management-By-Exception Model

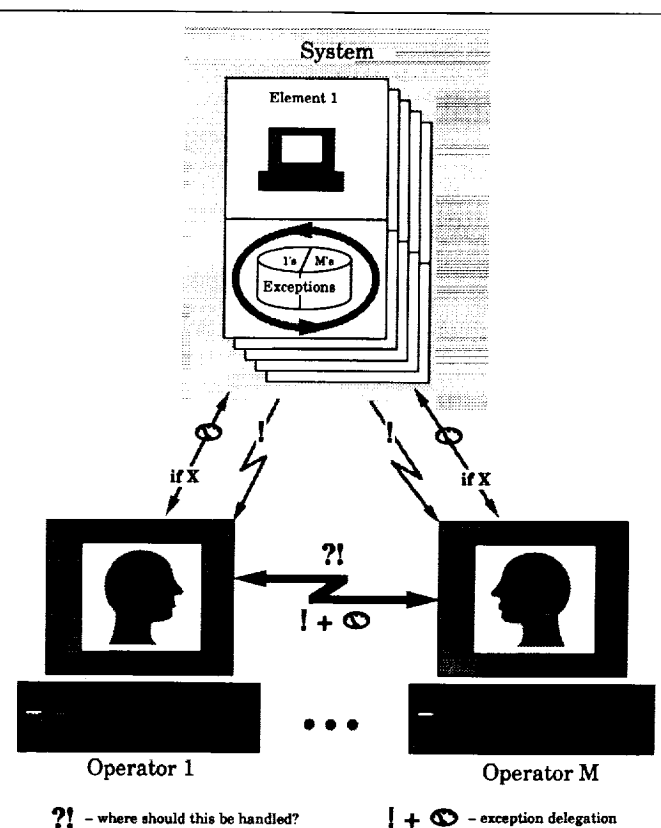


Figure 2b: Distributed Management By Exception

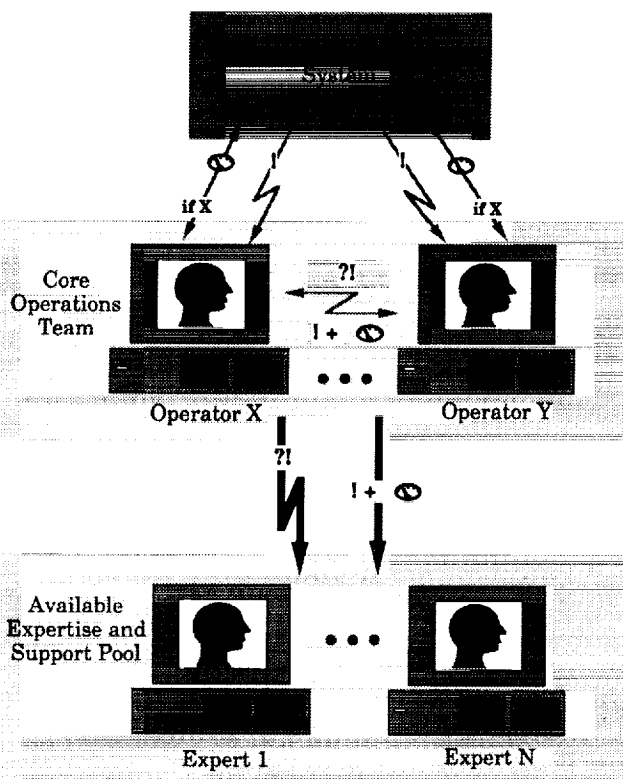


Figure 2c: Management By Exception With Dynamic Groups

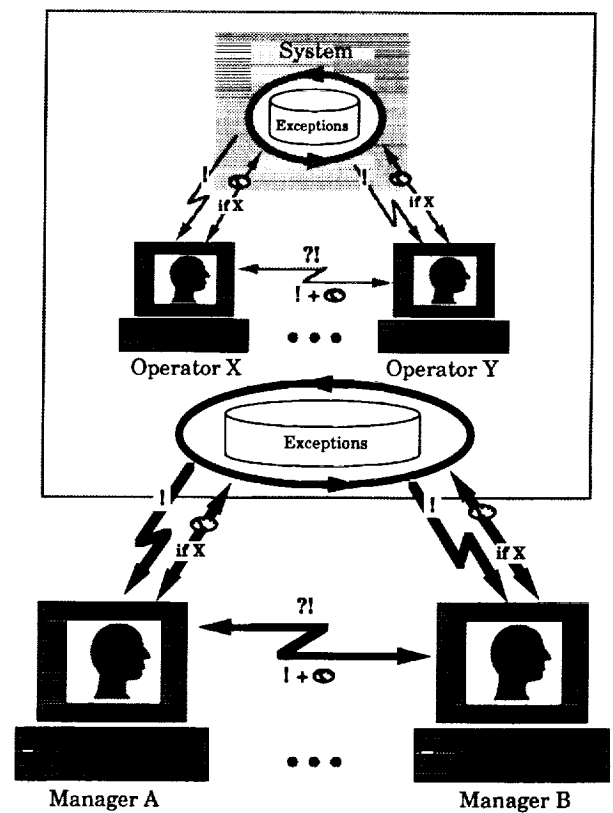


Figure 2d: Hierarchical Management By Exception

Figure 2: Toward Team-based Management By Exception

Team-based Management by Exception. When the system being monitored is sufficiently complex, it may not be possible for a single operator to monitor and resolve all exceptions. Instead, a group of operators may be needed. The basic model can be extended in several ways to support group-based management by exception. Each of these extensions would require specific tools to support the group interactions.

Distributed Management by Exception. First, the model can be extended to *support several monitoring sites and operators* instead of a single central location. This first extension is illustrated in Figure 2b. Operators allocate existing exceptions among themselves. Operators also can define their own exceptions. Data relevant to each exception is collected as in the basic model. When an exception occurs, the exception is sent to the appropriate operator as described in the basic model. However, the receiving operators can decide among themselves who should resolve the exception. Or, they can decide to delegate the exception to another operator. To make this decision, the operators may need to establish close monitoring relationships with the relevant element. These relationships and the exception would be sent to the delegated operator automatically.

Management by Exception with Dynamic Groups. A major assumption of the first extension is that the group of operators assigned to a system is predefined and static. In deciding where to delegate the exception, for example, the available candidates are all assumed to be immediately available. In the second extension to the model, this assumption is removed; the *group of operators managing a system can change dynamically* based on system needs. The second extension is illustrated in Figure 2c. When an exception occurs, the operators may resolve it directly, delegate to another available operator, or they may decide to seek help. The operators then must issue a request for assistance. This request is sent to candidate specialists via a combination of mechanisms. The request includes the exception, data that was collected in determining the exception, and any close monitoring relationships that have been established. If a candidate accepts responsibility for the exception, they notify the appropriate operator. The operator then delegates the exception to the specialist as in the previous extension. The operator must periodically check, however, to make sure that the exception is being resolved.

Hierarchical Management by Exception. In any mission critical environment, it is not enough to simply monitor system elements. There needs to be a way of monitoring the monitoring process to assess its effectiveness. The third extension to the basic model supports the *definition, monitoring, and resolution of exceptions related to the system monitoring process*. For example, a manager might want to be alerted if "The number of unresolved system exceptions is greater than 10 for 20% of the time in any shift." The third extension is illustrated in Figure 2d. It applies the tools of the basic model and extensions to the monitoring process itself.

Benefits of the Extensions. A system that combines the basic model and the three extensions would allow a system to be supervised at several levels of abstraction. It would eliminate the need for active system monitoring during nominal system operations. The operators therefore would be free to perform other functions (e.g., trend analyses and planning for future support) between exception events. The approach would not preclude, however, close monitoring and interaction when needed. The system also would allow managers and senior staff to monitor the monitoring process and system.

A system based on the combined model would be highly flexible. The list of exceptions could be modified easily to reflect changing system behavior and understanding. The number of persons involved in managing the system could be changed quickly and easily.

3 WORK-GROUP COMPUTING

To achieve the benefits of team-based management by exception while ensuring desired system performance, teams employing the model will require tools to help them work together. In this paper, we use the term *work-group computing* [4] for the computational resources needed to support these teams. We use this term because it currently is being used in management science to describe tools that support distributed, dynamic teams performing dynamically-defined processes.

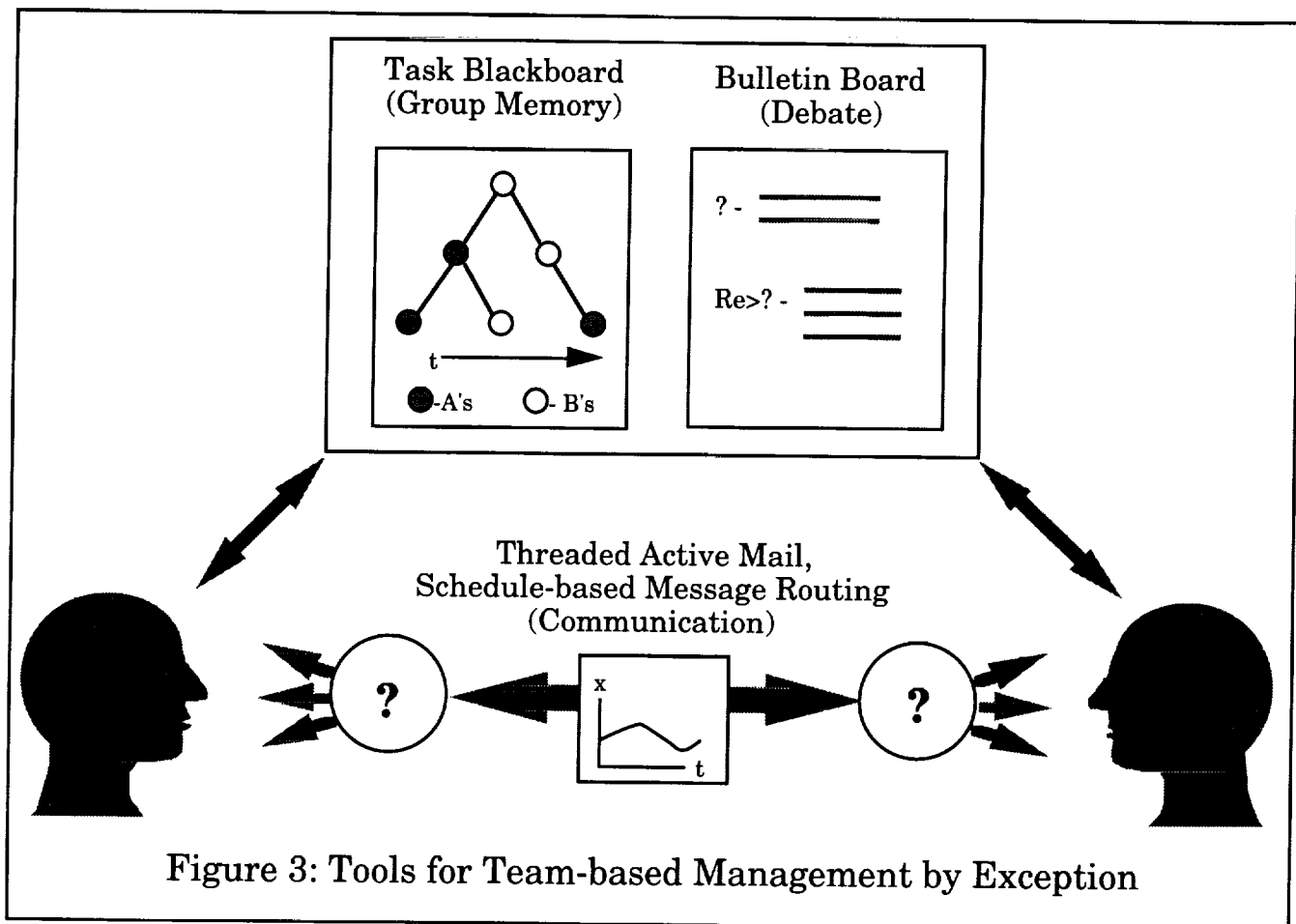
Before we can define tools to support the model, we must understand the nature of interactions implied by the model. Schmidt [5] identifies three *interaction types* that people in teams engage in: augmentation, integration, and debate. We have added two interaction types to describe interactions in dynamic and non-peer relationships: negotiation and direction. *Augmentation* is used when one person cannot do a job alone because of its size. Job size is the main reason for moving to a distributed management-by-exception model. *Integration* is used when specialists are added to the team to support complex problem resolution, which is the motivation for the dynamic group model of management by exception. *Debate* is used for brainstorming and refinement. Operators and specialists will debate among themselves to resolve exceptions in both the distributed and dynamic group models. *Negotiation* is used when one person must locate another person to perform a task, and the parties must reach agreement on the nature of the task, assignment of the task, and task execution constraints. This category describes the process of building a team within the dynamic group model. *Direction* is used when one person tells another person what to do, and social circumstances compel the other person to perform the work. Managers in the hierarchical model will send guiding directions to system operators.

Team-based management by exception supports and encourages fluidity in the system management process. This fluidity extends to the spatial and temporal distance of team members, team member autonomy, directness of interaction between team members, and team composition [5]. Tools that support these dynamics are called *any place/any time* tools. These tools emphasize group communications, memory, and process support [6]. The group memory tools allow team members to share and extend evolving group goals to support cooperation, while the process support tools provide team coordination.

Tool Support. Our search for tools to support team-based management by exception was governed by several principles [7]. First, each tool must allow a single user to address as much of the problem as possible without having to interact with other users. Second, users (however many) deciding to use a tool to interact should receive immediate benefits over those that do not. And finally, the number of tools should be kept to a minimum. This reduces training costs and the user's mental burden.

Figure 3 illustrates the work-group computing tools needed for team-based management by exception. They are explained below.

Tools for Distributed Management by Exception. To support distributed management by exception, operators will need tools that support the augmentation and debate interaction types. Augmentation tools should allow operators to send each other exceptions, associated data, and close monitoring relationships, and allow operators to track exception resolution. A combination of threaded email, conversation-based tools, and Active Mail can provide these capabilities. Threaded email and conversation-based tools [8] provide the necessary group communication and memory capabilities. The Active Mail tool [9] unites email with screen (i.e., real-time connection) sharing capabilities. Another tool that could support augmentation is the shared task blackboard from the ALLY system [10]. The ALLY blackboard appears especially promising as a group coordination and memory tool in situations where operators interact frequently. Each team member can post exceptions and resolutions to the blackboard, and identify who was responsible for each posting.



Debate tools should allow operators to raise questions about exceptions and their resolution and receive answers from team members. Ideally, this knowledge should be recorded for future reference. Bulletin board tools, such as the Internet News services [11], support posting information, requests and responses to a common, hierarchical bulletin board, and tracking relationships between these postings.

Tools for Management by Exception with Dynamic Groups. To support management by exception with dynamic groups, operators and engineers will need tools that support the integration and negotiation interaction types. Integration tools should help identify available expertise and help contact these individuals. One of the key aspects of the dynamic group model is that expertise should be located based on availability. Schedule management tools can help in locating available support. Communications support like that provided in Wang's Freestyle system could contact operations staff using the most appropriate method (e.g., email, FAX, pager, phone) based on their scheduled location and the importance of the problem.

Negotiation tools should help operators and engineers broadcast work to be performed, responses to announced work, and work assignments. This interaction could be achieved through extensions of the augmentation tools described earlier. Conversation tools have already been used to support negotiation in other systems. The shared task blackboard also could be extended to provide some support for negotiation, particularly work announcements. We would expect, however, that most of the work allocation process would take place out of public view (i.e., off of the shared blackboard) via the conversation tools because the process would add too much distracting clutter to the shared view.

Tools for Hierarchical Management by Exception. To support hierarchical management by exception, managers and senior staff will need tools that support the direction interaction type. Direction tools should help managers monitor the spacecraft management process, and they should help managers give direction to the process. Support tools for the other models could be extended to allow managers to raise exceptions to operators and to adjust exception priority.

4 USER AGENTS

Team-based management by exception through work-group computing lowers operator workload by not requiring the operators to actively monitor the system. However, it does require that they issue all commands needed to respond to any exceptions. In this section, *user agents* [12] are discussed as a way of automating the action part of operator activity. *User agents* are semi-autonomous programs that act as personal assistants to provide indirect interaction between the user and the system. Agents are *semi-autonomous* in that they can act in the background without direction from the user. Agent support is called *indirect interaction* [13] because once the user teaches the agent how to do a task the agent performs future task instances automatically.

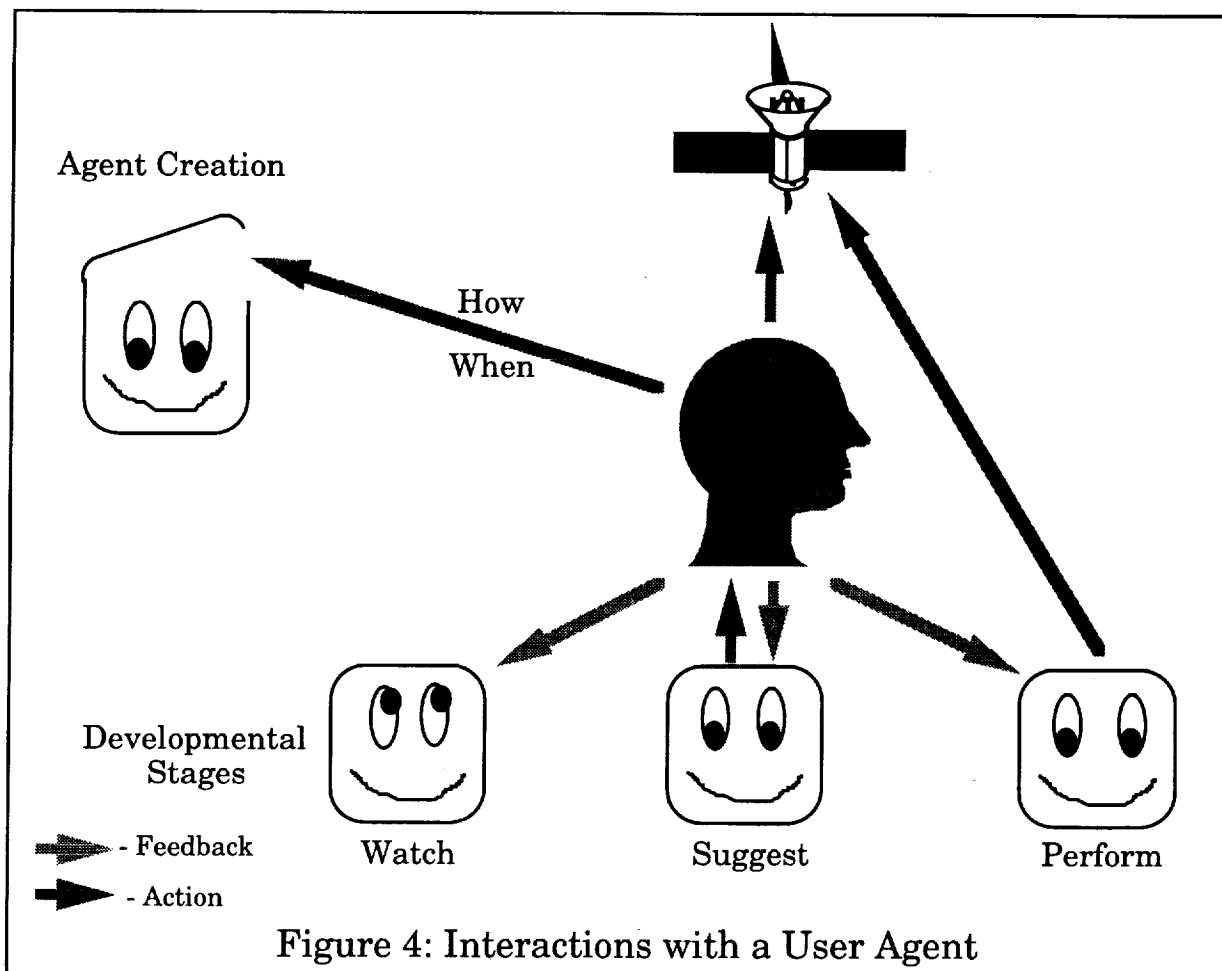
Flexibility is the main advantage user agents have over other automation approaches. User agents can be defined on a per exception basis. Automation therefore can be introduced gradually. Each agent's authority to act can be adjusted by its user. The internal behavior of an agent may be viewed and controlled by the user. And all information, actions, and tools available to the agent are available to the user. In fact, agents can be viewed as a self-invoking macro system. The user can perform all or part of the agent's actions manually.

Figure 4 illustrates the interactions between a user and an agent. Before an agent can perform a task, the agent must learn how and when to perform the task. A user can teach her agent how to perform a task in two ways. The user may instruct the agent to watch her perform the task. The agent then can *imitate* the user's actions. This teaching method has proven powerful in macro systems. Second, the user *can program* the agent to perform the task. It is strictly up to the user what tasks will be taught to her agent and how these tasks will be performed.

Agents can be taught when to perform a task through user feedback, and by generalizing from situations in which they originally learned the task. In the *user feedback* approach, the user reinforces the agent when it tries to perform the task in an appropriate situation and discourages the agent when the situation is inappropriate. The agent uses the feedback to weight features in the situation as indicating an appropriate or inappropriate situation. In the *generalization* approach, the agent uses heuristics to weight features. The user feedback approach is generally preferred since it gives the user more control.

An agent is not allowed to perform a task until it has *demonstrated competence* for the task. When an agent initially learns a task, the agent *watches* the user perform the task to assess if it would have performed the task in the same way and under the same circumstances. The agent asks for corrections when it would have performed the task incorrectly. Once the agent can successfully predict its user's actions, the user may allow the agent to begin *suggesting* when and how to perform the task. This type of interaction can serve as a reminder for the user. After the agent has proven itself in a suggesting role, the user then may allow the agent to *perform* the task.

Users drive all aspects of agents. This addresses some issues that other forms of automation ignore. First, because the progression from watching to performing is controlled by the user and because users teach agents how and when to perform tasks, users tend to trust agents. Second, agents perform tasks in user-specific ways. This makes agents more accepted and understandable. Third, agents easily can adapt to changing operational processes. This helps avoid obsolescence and costly maintenance.



User agents would fit well in a mission operations environment, especially one using team-based management by exception. An agent could be trained to automatically respond to selected exceptions. Exceptions provide a well-defined situation in which a task should be performed. The commands and scripts used in most operations centers easily could be taught to an agent using macro recorder-like capabilities. And the work-group computing tools of a VMOC would make it easy for an agent to act as another team member. For example, agents could post tasks to the shared task blackboard described earlier.

5 PUTTING IT ALL TOGETHER

A VMOC is the combined application of the previously presented technologies to spacecraft management. This section shows, through a series of common operations situations, how the combination addresses the spacecraft management trends and tenets presented in Section 1.

Routine Monitoring. In a VMOC, an operator would no longer have to spend time actively monitoring large numbers of changing data values. The system could monitor these values for her, even if the pass length were dramatically shorter. The operator could perform other tasks, possibly for other missions, until the system alerted her to an exception. If the exception's resolution were simple enough, she could delegate responsibility for responding to her personalized user agent. If the user later wished to respond, she could. If she wished to monitor the system in real-time, she could. The VMOC therefore would allow the operator to adjust her workload as she saw fit.

The Night Shift. When a mission's operations become sufficiently predictable, the use of management by exception could be extended both in the time and distance between the operator and the system. In the night shift, for example, the operator might stay on-call at home. When a sufficiently serious exception is detected, the system would call or page the operator at home. The system might even FAX the operator the data needed to determine if the situation warranted her returning to the operations center. Minor exceptions could be resolved automatically by the operator's user agent.

Expert Assistance. If an operator in a VMOC determines that an exception cannot be resolved without additional expertise, the operator can send a request for assistance to the engineering team. The request could include any data sent with the exception, and any real-time displays. The appropriate engineer would be located automatically using the engineers' schedules. The engineer would be notified using whatever means was appropriate (e.g., a pager). The engineer then could access the same capabilities available to the operator to determine how to respond.

Special Events and Remote Users. The capabilities described in the previous scenarios could be made available to other people associated with the mission to allow them to participate in the monitoring process and to give them a view of the system's behavior. During special events, additional personnel could be added to the monitoring team simply by giving them access to these capabilities, possibly from their offices. Scientists and engineers could use the capabilities to monitor system resources related to their work. They also could use the capabilities to generate personalized reports. This could dramatically lower operator workload, and allow external groups to interact easily with the operations process.

Managing a MOC. In a VMOC, managers or senior operations staff could define, monitor, and respond to exceptions about the process. For example, a manager might request that the system notify her if too many exceptions are occurring in some time period. Managers also could use the exception definition and notification capabilities to introduce exception violations into the process or raise the importance of an exception as a way of guiding the process.

Training a New Person. In a VMOC, new operations team members could be given access only to exception monitoring capabilities for a few subsystems. They also might be given the ability to watch the step-by-step response of other operators. In this way, new operators could learn by watching others, possibly from a remote site. Their access could be increased as they learned the system. The managing capabilities from the previous scenario could be used to monitor and assess a trainee's progress.

These scenarios suggest that a VMOC-based approach to mission operations could reduce staff workloads dramatically, possibly to the point of allowing operations personnel to be shared among missions and possibly reducing staff levels for some shifts. VMOCs would enable external groups to easily join or access the spacecraft management process. The automated nature of the support could allow operators to manage more complex systems with even less access to the system. The fluidity provided by the VMOC approach would achieve these benefits without eliminating existing capabilities. Operators still could perform active spacecraft monitoring and control as needed, including low-level control. Large operations teams still could be co-located in the same room around the clock. In a VMOC, however, these scenarios would no longer be the only options.

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MISSION OPERATIONS AND COMMAND ASSURANCE: FLIGHT OPERATIONS QUALITY IMPROVEMENTS

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Abstract

Mission Operations and Command Assurance (MO&CA) is a Total Quality Management (TQM) task on JPL projects to instill quality in flight mission operations. From a system engineering view, MO&CA facilitates communication and problem-solving among flight teams and provides continuous process improvement to reduce risk in mission operations by addressing human factors. The MO&CA task has evolved from participating as a member of the spacecraft team, to an independent team reporting directly to flight project management and providing system level assurance. JPL flight projects have benefited significantly from MO&CA's effort to contain risk and prevent rather than rework errors. MO&CA's ability to provide direct transfer of knowledge allows new projects to benefit from previous and ongoing flight experience.

Key Words: Mission operations, command assurance, Total Quality Management, defect prevention, error management, system engineering

1. Introduction

A long-term program is in progress at the Jet Propulsion Laboratory (JPL) to reduce cost and risk of flight mission operations through defect prevention and error management. Flight mission operations require systems that place human operators in a demanding, high risk environment. This applies not only to mission controllers working in the "dark room" and Deep Space Network (DSN) operators configuring and monitoring DSN operations, but also to flight teams that plan the mission and develop the command sequences and to engineering teams responsible for analyzing spacecraft performance. The flight operations environment generally requires operators to make rapid, critical decisions and solve problems based on limited information, while closely following standard procedures (Refs. 1-3). This environment is, therefore, inherently risky because each decision made is potentially mission critical.

To contain this risk at JPL, flight mission operations procedures (as described in Refs. 4-5) currently

require intensive human reviews. In addition, when an error does occur, rapid rework is required to ensure mission success. This strategy has worked well to reduce risk and ensure the success of JPL missions. However, the large human labor investment required for review and rework has substantially contributed to the overall cost of flight mission operations and has placed operators in stressful environments. Prevention of errors would greatly reduce both cost and risk of flight projects. Thus, the motivation of the long-term defect prevention/error management program is to contain risk in a more cost effective and human supportive manner by preventing errors rather than reworking them. The goal of this program is the management, reduction and prevention of errors.

A major element of this program is the Mission Operations and Command Assurance (MO&CA) function. MO&CA provides a system level function on flight projects to instill quality in flight mission operations. MO&CA's primary goal is to help improve the operational reliability of projects during flight. MO&CA occupies a unique position in the flight project organization, reporting to both flight project management and the Systems Assurance Division of the JPL Office of Engineering and Review. As a result, MO&CA is able to cross operational boundaries between teams and offices on a flight project enhancing inter-team communication and facilitating problem solving within the project.

This paper describes the development and evolution of the MO&CA function at JPL and the benefits provided to flight projects by MO&CA.

2. Evolution of the MO&CA Task

The MO&CA task began on the Voyager (VGR) project in 1985. In response to an increase in command related problems a study was conducted by the JPL Office of Engineering and Review to analyze the adequacy of procedures, operations and software involved in real-time commanding with the goal of reducing errors. Incident Surprise Anomaly (ISA) reports, problem reports written by flight team members when an anomaly occurs in flight operations, were analyzed from an eight year period

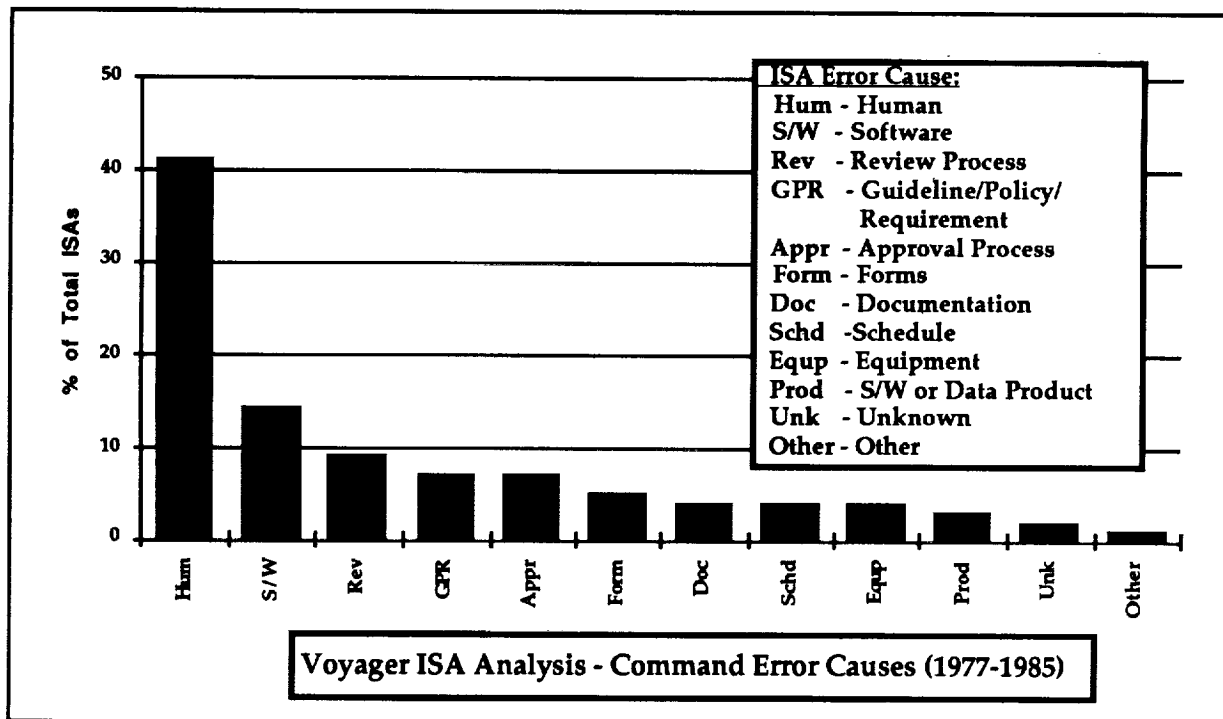


Figure 1
Voyager ISA Analysis

(1977 - 1985) to determine the causes of command errors. This study showed that the major cause for real-time command errors was human error (Figure 1).

Based on this analysis, recommendations were made to the VGR project for improvements including: 1) upgrading the command development software to improve readability of command printouts thereby facilitating command reviews and approvals; 2) providing traceability between command forms and ISAs to facilitate analysis and correction of command incidents; 3) reducing real-time commanding by improving the coordination of real-time and sequence commanding and including as many commands as possible in command sequences; and 4) updating flight team training to include command awareness issues to inform flight team members of potential command problems and how to avoid them. Command development procedures were updated to incorporate these recommendations. Real-time command anomalies decreased from 60 in 1985 to 40 in 1986, and to 24 in both 1987 and 1988.

When an opening occurred in the spacecraft team, the position was filled by a MO&CA engineer who became the Systems Lead for real-time commanding for the VGR Project. This placement allowed

MO&CA to not only recommend changes to command procedures, but also to implement these changes with project management concurrence. MO&CA also continued to analyze ISA reports and make recommendations for continuous improvement to the commanding process. MO&CA provided both a system engineering function for the spacecraft team and a systems assurance function for the VGR Project.

Following VGR, a MO&CA team was activated on the Magellan (MGN) Project in March 1989, just two months prior to launch. The main MO&CA task for MGN was to detect, analyze and correct defects that existed in flight operations and procedures. One of the major efforts of the MGN MO&CA team was assisting the flight project to upgrade the real-time command process and related operational procedures. The initial real-time command process in place at launch included only a handful of steps. Systems coordination and inter-team communication were not included in the procedures.

In the first few months following launch extensive operational workarounds and real-time commanding were required to compensate for the spacecraft hardware problems. Because of the level of commanding and a lack of coordination in the real-time command process, command problems occurred.

MO&CA recommended improvements to the command process which included: 1) review of commands by all subsystems prior to development; 2) system level coordination of all commanding; 3) management approval prior to command development; 4) traceability of commands from initial request to final approval for transmission; 5) development of rigid test requirements for all commands; 6) required representation by all operations teams at command review and approval meetings; 7) spacecraft team support of the command coordination meeting and 8) training for all flight team members with the newly developed command procedures.

By December 1989, an updated real-time command process was in place on MGN. Improved communications enabled the flight team to function well as a unit and respond quickly to anomalies. Real-time command incidents decreased dramatically despite the fact that the flight team continued to face spacecraft anomalies.

In contrast to the VGR project, the MGN team was not integrated directly into an existing team on the flight project, but instead formed an independent unit. While this enabled the MGN MO&CA team to maintain a systems view of flight operations, it did not provide the same ability to implement changes. MGN MO&CA instead provided recommendations for change based on ISA analysis and direct participation in working, review and approval meetings. The flight team, directed by project management, implemented the changes to operations procedures and processes.

Due to the success of the VGR and MGN MO&CA teams, MO&CA teams were placed on the Mars Observer and TOPEX/POSEIDON projects. Both of these new projects experienced immediate benefits through the direct transfer of MO&CA's knowledge and experience from the previous two projects. These MO&CA teams were the first to be in place on the flight project an extended time prior to launch. The teams were therefore able to implement "lessons learned" and process improvements early. This opportunity allowed MO&CA to instill quality into the flight procedures in a pro-active manner, rather than work reactively to update processes and procedures after completion of mission operations development.

Mars Observer MO&CA, like the MGN MO&CA team, was established as an independent unit making recommendations for improvements and updates to command processes and procedures. A prime target for improvement by the Mars Observer MO&CA team was operations communications.

The Mars Observer project had strong real-time and sequence commanding processes in place when MO&CA began working with the project. MO&CA, however, noted problems with inter-team communication and use of ancillary command data. Four separate operations teams, Spacecraft, Planning and Sequencing, Mission Control, and MO&CA, maintained separate command related data files that resulted in redundant and incongruous data. Manual transcription and interpretation errors occurred frequently and unnecessarily increased risk. MO&CA gathered the file structures and reports from each team and identified redundant data usage. MO&CA also initiated and led a working group that analyzed each team's data needs and identified and prioritized requirements for the development of a single command data system. The working group passed recommendations for system implementation to the Uplink Manager. An effort is currently underway to implement an on-line, real-time command data system to be in place by August 1993.

Another communications issue that Mars Observer MO&CA addressed was the result of an unique aspect of the Mars Observer project. The principle investigators have direct control of commanding the science instruments. The remote science teams are situated at several different locations throughout the United States. Therefore, maintaining communications between the science teams and the flight operation team located at JPL is a challenge. Also, the science teams need to have access to real-time spacecraft and instrument status for development of command requests. To facilitate communication, MO&CA recommended that the audio VOCA (Voice Operations Assembly Communications) net be made available to all flight team members, keeping both science and operations teams informed of current spacecraft status.

A third communication problem noted by Mars Observer MO&CA was the definition of the command uplink window, the time period available to transmit commands to the spacecraft. Alignment of the command requester's requirements, the availability of the scheduled commanding windows, and the Mission Control Team's coordination with commanding station hand-overs was complex and prone to errors. MO&CA recommended that a tool be developed to allow the Mission Control Team to interpret, implement and verify the command requester's requirements for uplink windows. This tool was developed by the Mission Control Team and is now being used for flight operations.

Similarly to the Mars Observer Project, the MO&CA task was also well received by the TOPEX/POSEIDON Project. A MO&CA engineer was placed on staff to the TOPEX/POSEIDON Flight Operations System Manager. The

TOPEX/POSEIDON MO&CA task combined elements from the VGR and MGN MO&CA experience. Like the MGN MO&CA team, TOPEX/POSEIDON MO&CA functions as an independent unit, and, like VGR MO&CA, TOPEX/POSEIDON MO&CA has the ability to implement improvements in flight operations procedures.

Once in place on the project in November 1991, MO&CA quickly assessed existing flight operations plans and noted that an additional process for the development and approval of unplanned real-time commands was required. MO&CA worked with the flight team to define inter-team interfaces for the unplanned real-time command process and develop the necessary procedures and process descriptions. While the flight teams were preparing individual team operating procedures, MO&CA was able to provide a system level overview and develop the additional process and procedures that cross team and division boundaries.

As the project planned to use the real-time command process extensively, MO&CA coordinated the development of a Real-time Command Library. This library consisted of all pre-defined real-time command files developed for repeated utilization

throughout the life of the mission. The most beneficial portion of the Real-time Command Library proved to be the Contingency Commands. When spacecraft anomalies occurred early in the mission, the Contingency Commands facilitated recovery operations during a high activity period. The value added by the MO&CA Real-time Command Library is also visible daily during mission operations. The majority of planned real-time commands in the TOPEX/POSEIDON Sequence of Events are pulled "off-the-shelf" from MO&CA's Real-time Command Library.

3. Human Factors Benefits of MO&CA

MO&CA originated in response to a rise in command errors. As was shown in subsequent error analysis (Ref. 6) the largest group of errors was human error (Figure 2). Thus, addressing human factors in flight mission operations has been the overriding benefit of MO&CA. The enumeration of these benefits follows.

The most important of these benefits is a direct transfer of knowledge. Originating from the Systems Assurance Division at JPL, MO&CA is able to transfer knowledge between current missions in addition to providing valuable "lessons learned"

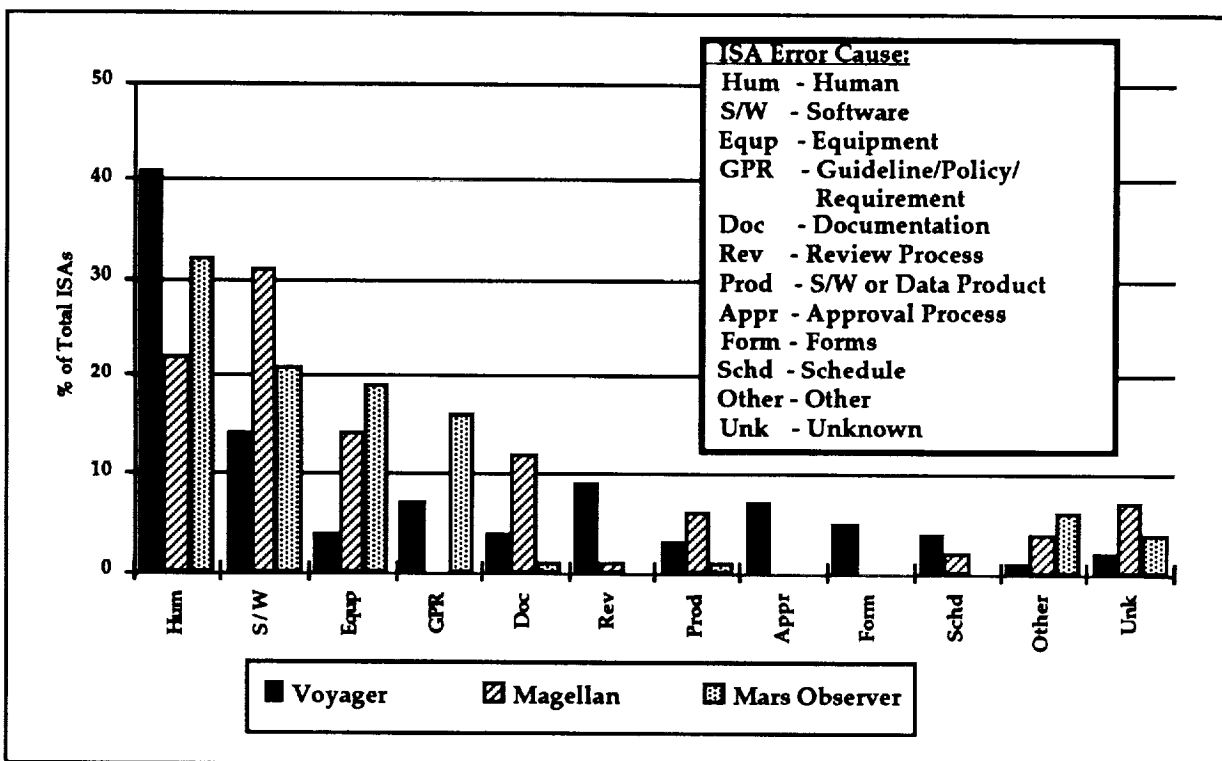


Figure 2
Comparison of ISA Analysis - Voyager, Magellan, Mars Observer

experience to new flight projects. New projects are able to thus benefit directly from both previous and ongoing mission operations experience. Lessons learned can be incorporated early into project requirements, thereby eliminating the amount of necessary rework on flight operations procedures. The real-time command process and library on the TOPEX/POSEIDON project are examples of this direct transfer of knowledge.

Another major benefit is process improvement. Process improvement activities require the ability to measure and evaluate a process. MO&CA teams collect and analyze error data from the ISA reports written by flight teams on operational problems. Many of MO&CA's recommendations for process improvement are based on these reports. This error analysis results in improvements not only to the project that wrote the report, but also to other flight projects via transfer of knowledge. The error analysis information is also used for analysis in the overall defect prevention/error management program that identified human errors as the largest category (Figures 1 and 2).

MO&CA's unique position as an independent unit in the flight project organization provides a third major benefit to flight projects: the ability to facilitate communication and problem solving. Problems that span many teams and offices within a flight project can be effectively addressed by MO&CA. Coordinating real-time command processes is an example of this task. Flight project members who are faced with problems that impact several teams

often bring the issue directly to the MO&CA engineer when they cannot be addressed solely by their team. MO&CA is also able to improve the efficiency of data reporting that crosses team boundaries. On Mars Observer MO&CA worked with the teams to eliminate data duplication and ensure correct data was reported.

4. MO&CA and TQM

The MO&CA function is one example of a Total Quality Management (TQM) process at JPL. Specifically, MO&CA embodies the TQM principle of Continuous Process Improvement (CPI) in which processes are continuously examined and analyzed for opportunities for improvement. Figure 3 shows how MO&CA implements CPI in two ways. First, within ongoing projects, the flight mission operations environment is established and MO&CA participates as a team member. In the course of day-to-day operations, anomalies are documented as ISA reports. The ISAs then serve as data that is analyzed by MO&CA engineers for process improvement opportunities. When these opportunities are identified, MO&CA provides reports and data to support recommendations for improvement to project management. Finally, based on management approval, MO&CA helps the project implement the changes back into the day-to-day mission operations environment. This technique was successfully implemented on the JPL projects.

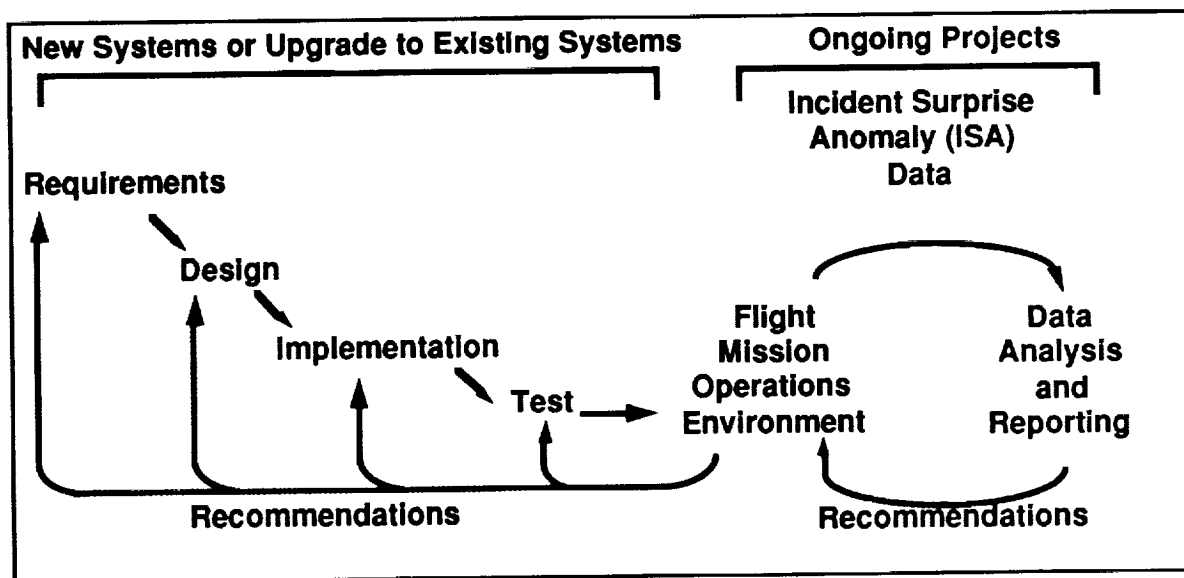


Figure 3
TQM Model of MO&CA

The second way in which MO&CA implements CPI on JPL projects is on new projects or upgrades to existing projects. The recommendations that are developed from the ISA data analysis on ongoing projects are used as input to system requirements on new projects. This allows new projects to benefit from improvements made on past projects as TOPEX/POSEIDON benefited from the experience gained on VGR and MGN.

Using this technique, not only do ongoing projects continuously improve, but each new project starts with a better set of requirements and better processes than the last one. At JPL this continuous improvement feedback loop has improved flight mission operations processes from the Voyager Project, to the Magellan Project, and to the Mars Observer and TOPEX/POSEIDON projects. Additionally, this Continuous Process Improvement reduces both cost and risk of flight mission operations.

5. The Future of MO&CA

Future flight missions at JPL will have smaller spacecraft and flight teams (Refs. 7-8). Development times will be reduced and the teams that design and build the spacecraft will also staff the flight mission operations teams. MO&CA will need to evolve to adapt to this changing flight operations environment. With smaller flight teams the MO&CA engineer will be taking on additional duties such as command procedure development and system lead functions, as did the engineers on VGR and TOPEX/POSEIDON.

MO&CA will also participate during the early phases of the project, enabling MO&CA to implement "lessons learned" and process improvements during development. MO&CA will continue to provide both system assurance and engineering assistance to operations. MO&CA can assist in developing operational procedures and participate in flight team training, especially enhancing flight team communications and problem solving. This participation will streamline procedure development and eliminate late changes and upgrades thus reducing rework and cost.

Automation of ISA data tracking and analysis by MO&CA will help to make operations process monitoring and error analysis more efficient and timely. With automation, MO&CA will be able to address problem areas quickly. Finally, ISA data will be used in a parallel error analysis study. The findings of this study (Ref. 6) will enable prevention of errors through improved requirements development on new projects.

6. Summary

JPL flight projects have benefited significantly from MO&CA's effort to contain risk and prevent rather than rework errors. MO&CA's ability to provide direct transfer of knowledge allows new projects to benefit from previous and ongoing flight experience. The system level view of project operations provided by MO&CA enhances communication to facilitate problem solving within a flight project.

MO&CA will continue to evolve to meet flight project needs. Early involvement with developing projects will ensure that quality is incorporated into mission operations during operations development and training.

The MO&CA function at JPL has built quality into mission operations, enabling flight teams to operate efficiently and effectively in the dynamic flight operations environment. Since error analysis has shown human error to be the largest error category, human factors improvements have, thus far, proved to be the major benefit. MO&CA, as a TQM effort, focusing on continuous process improvement and elimination of rework, will continue to provide benefits to flight projects.

7. Acknowledgment

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Session H2: ENHANCED ENVIRONMENTS

Session Chair: Maj. Gerald Gleason

Call sign intelligibility improvement using a spatial auditory display

N94-33617

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Abstract

A spatial auditory display was designed for separating the multiple communication channels usually heard over one ear to different virtual auditory positions. The single 19" rack mount device utilizes digital filtering algorithms to separate up to four communication channels. The filters use four different binaural transfer functions, synthesized from actual outer ear measurements, to impose localization cues on the incoming sound. Hardware design features include "fail-safe" operation in the case of power loss, and microphone/headset interfaces to the mobile launch communication system in use at NASA Kennedy Space Center. An experiment designed to verify the intelligibility advantage of the display used 130 different call signs taken from the communications protocol used at NASA KSC. A 6 to 7 dB intelligibility advantage was found when multiple channels were spatially displayed, compared to monaural listening. The findings suggest that the use of a spatial auditory display could enhance both occupational and operational safety and efficiency of NASA operations. (Supported by NASA Ames and NASA KSC Director's Discretionary Funding).

1. INTRODUCTION

1.1 Application to NASA communication systems.

During fiscal year 1992, NASA Director's Discretionary Funding was received from Ames Research Center (ARC) and John F. Kennedy Space Center (KSC) by Drs. E. M. Wenzel and D. R. Begault, to develop a four channel spatial auditory display for application to multiple channel speech communication systems in use at KSC. A previously specified design (Begault & Wenzel, 1990; Begault, 1992a) was used to fabricate a prototype device, which was

completed in February, 1993.¹ This prototype places four different communication channels in virtual auditory positions about the listener, by digitally filtering each input channel with binaural head-related transfer function (HRTF) data. Listening over headphones, one has a spatial sense of each channel originating from a unique position outside the head; i.e., as if four people were standing about you, speaking from different directions.

Input channels to the spatial auditory display can be assigned to any position because the design uses four removable EPROMs², with each EPROM corresponding to a particular target position. The EPROMs themselves can contain a binaural HRTF for any given position and measured ear. Hence, an important research question is to determine which four positions would be optimal for speech intelligibility of multiple sound sources. To begin to answer this question, the current investigation focused on what single spatialized azimuth position yielded maximal intelligibility against noise. This was accomplished by measuring intelligibility thresholds at 30° azimuth increments. Intelligibility is defined here as correct identification of a spatialized call sign (signal) against diotic³ speech babble (noise).

The KSC communications handbook (NASA-KSC, 1991) indicates a list of over 3000 call signs, most of which are spoken as four individual letters-- e.g., "NTOC". Communication personnel who monitor multiple radio frequencies must be able to hear these four letters clearly against speech. The use of speech babble as a noise source has been used in several studies investigating binaural hearing for

¹ Tom Erbe (Mills College, Sterling Software) implemented the firmware and hardware design into the prototype.

² EPROM = erasable-programmable-read-only memory chip.

³ "Diotic" playback is defined as a single audio channel presented to both ears.

communication systems contexts (e.g., Pollack, & Pickett 1958). This study concludes with a first approximation of the answer to what HRTF positions are best used in the filter EPROMs within the prototype.

1.2 Binaural advantages and speech intelligibility.

The relationship between binaural hearing and the development of improved communication systems has been understood for over 45 years (Licklider, 1948; see reviews in Blauert, 1983; Zurek, 1993). As opposed to monotic (one ear) listening-- the typical situation in communications operations-- binaural listening allows a listener to use head-shadow and binaural interaction advantages simultaneously (Zurek, 1993). The head-shadow advantage is an acoustical phenomenon, caused by the interaural level differences that occur when a sound moves closer to one ear relative to the other. Because of the diffraction of lower frequencies around the head from the near ear to the far ear, only frequencies above approximately 1.5 kHz are shadowed in this way. The binaural interaction advantage is a psychoacoustic phenomenon due to the auditory system's comparison of binaurally-received signals (Levitt & Rabiner, 1967; Zurek, 1993).

Many studies have focused on binaural advantages for both for detecting a signal against noise (the binaural masking level difference, or BMLD), and for improving speech intelligibility (the binaural intelligibility level difference, or BILD). Studies of BMLDs and BILDs involve manipulation of signal processing variables affecting either signal, noise, or both. The manipulation can involve phase inversion, time delay, and/or filtering.

Recently, speech intelligibility studies by Bronkhorst and Plomp (1988; 1992) have used a mannequin head to impose the filtering effects of the HRTF on both signal and noise sources. The HRTFs were used in either an unaltered condition, or with either time or amplitude components removed. Their results, summarized in Figure 1, show a 6 to 10 dB advantage with the signal at 0° azimuth and speech-spectrum noise moved off axis, compared to the condition where speech and noise originated from the same position. Figure 1 also shows lower BILDs

when either interaural time or amplitude differences are removed from the stimuli. This suggested the inclusion of HRTF filtering within a binaural display for speech communication systems (ref. Begault & Wenzel, 1990; Begault & Wenzel, 1992). According to a model proposed by Zurek (1993), based on averaged HRTFs specified in Shaw & Vaillancourt (1985), the average binaural advantage (speech signal fixed at 0°, noise uniformly distributed across all azimuths, head free to move) is around 5 dB, with head shadowing contributing about 3 dB and binaural-interaction about 2 dB.

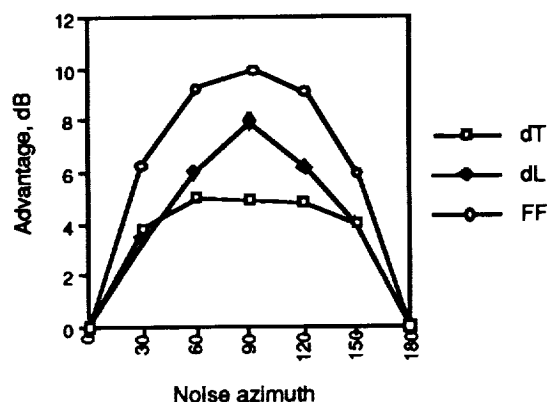


Figure 1. Data from Bronkhorst and Plomp (1988) for speech intelligibility gain. All stimuli were recorded with a mannequin head. Speech signal fixed at 0°; noise moved along azimuth at 0° elevation. FF= data including effects of the HRTF; dT = same data with binaural amplitude differences removed; dL = same data but with binaural time differences removed.

Another advantage for binaural speech reception relates to the ability to switch voluntarily between multiple channels, or "streams", of information (Bregman, 1990; Deutsch, 1983). The improvement in the detection of a desired speech signal against multiple speakers commonly referred to as the "cocktail party effect" (Cherry, 1953; Cherry & Taylor, 1954) is explained by Bregman (1990) as a form of auditory stream segregation. This situation was found to parallel the multiple channel listening requirements of communication personnel, such as test directors (NTDs) at KSC.

2. METHOD

2.1 Stimuli.

The signal portion of the stimulus was drawn from a list of 130 four letter call signs, selected from the KSC communication handbook (NASA-KSC, 1991). The 130 call signs used in the experiment were selected randomly so that groups of five began with a unique letter of the alphabet. A single male voice was used, with each letter of the call sign spoken discontinuously over a duration of about two seconds. Recordings took place in sound-proof booth, using an AKG C451-EB microphone at a distance of 6 inches. Once digitized, each call sign combination was normalized in amplitude, and then scaled to have equal long-term r.m.s. measurement values.

The speech babble used for the noise portion of the stimulus consisted of multiple layers of voices: two layers were from different airport control tower frequencies, containing both female and male voices, with silent intervals of more than .2 seconds deleted; and two recordings of different male voices reading technical repair manuals, one played backwards, the other pitch shifted upwards 4 semitones. The result was a dense speech layer in which words could occasionally be distinguished, but semantic content was lost.

The noise and speech were digitally stored as separate channels of stereo sound files (see Figure 2), using an Apple Macintosh II fx and Digidesign's ProTool hardware and software. The duration of each sound file used in each stimulus presentation was adjusted to 5 seconds, with the noise channel faded in and out over the first and last 0.5 seconds. The signal was always presented 1.5 seconds into the sound file, allowing subjects to predict its onset.

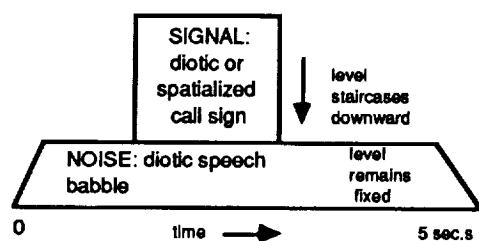


Figure 2. Stimulus soundfile arrangement

Each of the 130 separate noise-signal sound files was played through signal processing software and hardware, using a Crystal River Engineering Convolver that also served as the experimental software host computer (see Wenzel, 1992, for additional information on the hardware). Upon playback, the Convolver passed the speech babble channel unaltered to both ears. Mixed in with this noise was the two-channel signal, after software intensity scaling and HRTF-based spatialization to azimuths at 30 degree increments between 30° - 330° (all at 0° elevation). A diotic control condition was also used for the signal, where the spatialization was bypassed and only intensity scaling was used.

The minimum-phase HRTFs used for the spatialization were reconstructed from actual HRTF measurements as described in Kistler & Wightman (1992). The original measurements used were of one subject (SDO in Wightman & Kistler, 1989), with the headphone frequency response (Sennheiser HD-430) divided out of the HRTF. Although the same model of headphone was used for the subjects in this experiment, nonlinearities in reproducing the HRTF were introduced as a result of the interaction between different pinnae and the headphone chambers. Data on localization error of speech with non-individualized HRTFs can be found in Begault & Wenzel (1991) and Begault (1992b).

2.2 Subjects

Five subjects (4 males, 1 female), were paid \$5.59 an hour to participate in the study over two three hour sessions. This was the "naive subjects" group in that they had no exposure to the call sign list. Another group of 3 lab personnel (3 males) who had previous exposure to the call sign list constituted the "experienced subjects" group; their data is analyzed separately from the naive subject group. This group included a subject whose voice was used in the signal.

All subjects were evaluated for normal hearing from 0.1 - 8 kHz in a pure tone audiometer test. Subjects were given a training session before starting the experiment to familiarize themselves with the computer, the time when to expect the signal in relation to the noise, and the

procedure for entering responses. This training session consisted of a dummy block where the level of the signal was clearly audible against the noise, and was never scaled. The formal blocks were begun after approximately 20 trials.

2.3 Procedure

Software was developed by Phil Stone (Sterling Software) for presenting stimuli and gathering data from subjects using an interleaved, transformed up-down "staircase" method (Levitt, 1970). The software varied the level of the signal against the noise, starting with a maximum stepsize interval of 6 dB, and decreasing to a minimum stepsize of 1 dB. The response sequences were evaluated in such a way as to determine the threshold at a 70.7% probability level (a "2 up, 1 down" procedure).

The decibel level between the diotic stimuli and the spatialized stimuli were considered to be equal with reference to the long-term r.m.s. value of speech-spectrum noise filtered by a left ear 0° HRTF (obtained from the same HRTF set used for the other spatialized positions). The playback level was around 55 dB SPL, when the noise and 0° HRTF-filtered calibration signals were played simultaneously.

Six blocks were administered to each subject over three or four days, with each block containing four staircases randomly chosen from the 11 possible spatial positions or the one diotic signal condition. The four staircases within each block were presented randomly, as were the 130 call sign-speech babble sound files used for a particular stimulus block. The staircases within the blocks were arranged so that ten threshold values were obtained from each subject for each spatial condition, and the diotic condition. No block contained two simultaneous staircases for the same spatial condition of the signal.

Upon hearing the stimulus, the subject typed the four letters they thought they had heard onto a computer keyboard, and then after a short pause the software would present the next trial. The duration to complete each block of four staircases was about 15 - 20 minutes. Testing was administered in a sound-proof booth. No feedback was given as to the correct identification of the call

signs; the subjects were only notified when the 20 staircases within a particular block (4 spatial conditions times 5 staircases) were completed.

3. RESULTS

Figure 3 summarizes the data for the six naive subjects, and Figure 4 summarizes the data for the three experienced subjects. The mean values for each position were obtained before grouping the data by first subtracting each individual subject's threshold for the diotic signal vs. diotic speech babble condition. The results in Figures 3-4 show a greater intelligibility advantage as the signal is moved from to either side of the head; the advantage is maximal between 60° - 90° and 270° - 300°. These are locations where both head-shadowing is maximized, and where the binaural interaction advantage mechanism is given maximal time differences.

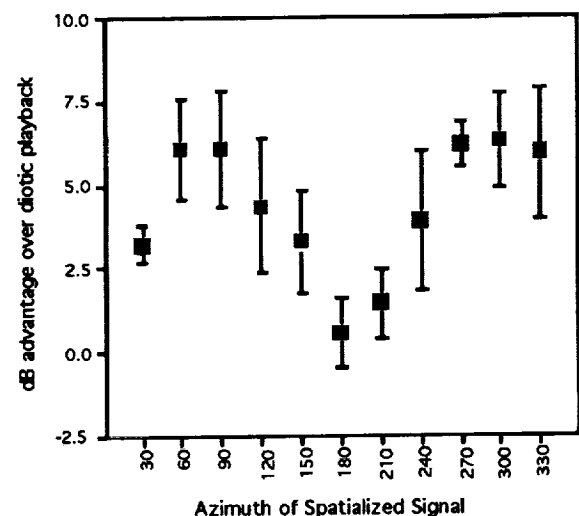


Figure 3. Data for the naive subject group (4 males, 1 female). The mean value for the diotic signal condition were subtracted from each spatialized signal value. Standard deviation bars were based on the 10 staircase solutions obtained for each condition.

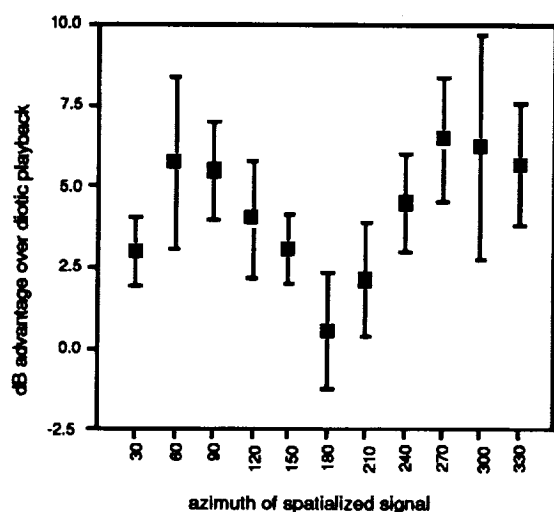


Figure 4. Data for the experienced subject group (see Figure 3).

Figure 5 summarizes Figures 3-4, by showing the mean values for symmetrical left-right positions about the head. This suggests that, without reference to which side a sound is spatialized, the preferred order for HRTF-processing for maximal intelligibility is 60° or 90°, then 120°, then 30°, then 150°, and finally 180°. The latter is hardly better than performance with the diotic stimuli. Figure 5 also shows that the three experienced subjects achieved about a 1 dB additional intelligibility advantage over the five naive subjects. However, an analysis of variance revealed that no significant difference existed between these two subject categories, $F(1,6) = 2.90$, $p = 0.14$.

The mean values for four of the naive subjects had a pattern that followed the symmetrical trend of the overall mean shown in Figure 3; there seemed to be no preferred side to hear the signal. Contrasting this, the responses of one of the naive subjects had an asymmetrical trend, favoring right side positions over left side positions. This trend was similar to a potential subject whose data was excluded from the subject pool and the analysis above due to hearing loss at the left ear (between 20 - 35 dB HL at 4, 6, 8 and 12 kHz).

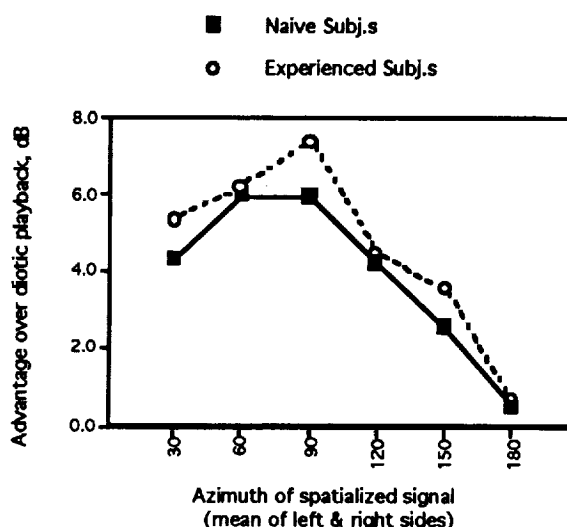


Figure 5. Mean values from Figures 3-4 collapsed about symmetrical left-right positions.

Figure 6 shows the results for these two subjects, along with the overall means from the naive subject group. Except for the 60° azimuth position, both of these subjects had a smaller advantage for left side positions compared to the overall mean, and right side positions show a greater advantage. Additional data would be needed to determine if there was a significant effect due to handedness or other factors (Deutsch, 1983). Nevertheless, a person with asymmetrical hearing loss similar to that experienced by the subject shown in Figure 6 could still benefit from using a 3-D auditory display. Gabriel, Koehnke and Colburn (1991) and Perrott, Sadralodabi, Saberi and Strybel (1991) have pointed out that, excluding severe hearing loss, no apparent relation between audiometric measurements and binaural performance can be established.

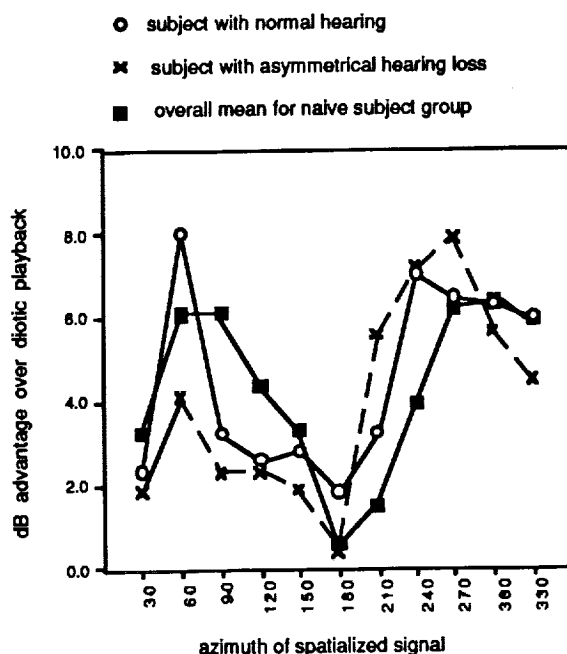


Figure 6. Two subjects (one from the naive group, one subject w/ asymmetrical hearing loss) who tended to favor the right side positions over the left. Overall means (from Figure 3) shown for comparison.

4. DISCUSSION

Overall, a 6-7 dB advantage for left and right 60° and 90° positions was found in the present study, which exceeds the binaural advantage cited in Zurek's model (1993) by 1-2 dB. This means that headphone listening with static spatial positions through the hardware prototype is as least as good as a normal hearing, binaural listener who is free to move their head. Although Bronkhorst and Plomp (1988) found a 10 dB advantage for a signal at 0° azimuth and speech-spectrum noise at 90°, their results are not directly comparable to those found here since both signal and noise were HRTF-filtered by their mannequin head, and in the present study the noise portion of the stimulus was diotic. The additional release from masking they found may have been attained through either HRTF-filtering of both signal and noise, the use of noise rather than speech babble, or both.

The results found here are limited by the fact that only one male speaker was used for the signal portion of the stimulus. In spite of the care taken in preparing the stimulus through

digital editing, there is the potential that extraneous variation was introduced into the results because of the variability of spoken intelligibility (ANSI, 1989). Furthermore, the average spectrum of this particular speaker might have interacted differently with the HRTF filtering than that of another speaker (e.g., a female voice). Finally, the variability in HRTF measurements from different persons or reconstruction techniques could influence the results of any experiment that uses only one set of HRTFs. This is one reason the prototype was designed to allow interchangeable EPROMs- individuals could tailor systems to their best advantage by using a preferred set of HRTFs.

5. CONCLUSION

The advantage of a binaural auditory display for multiple communication channels has been demonstrated, through a case study of a single signal at incremented 30° azimuth positions against a diotic, speech babble noise source. The 6-7 dB advantage for 60° and 90° HRTF-filtered speech represents a halving of the intensity (acoustic power) necessary for correctly identifying a four letter call signs typical of those used in communication systems at KSC. This reduction in the likelihood of misinterpreting call signs over communication systems is an important safety improvement for "high stress", human-machine interface contexts. The binaural advantage could also benefit communications personnel because the overall intensity of communications hardware could be reduced without sacrificing intelligibility. Lower listening levels over headphones could possibly reduce the risk of threshold shifts, the Lombard Reflex (raising the intensity of one's own voice; see Junqua, 1993), and overall fatigue, thereby making additional contributions to safety.

Overall, the findings here suggest that the use of a spatial auditory display could enhance both occupational and operational safety and efficiency of NASA operations. Additional studies are underway at Ames to simulate other applications scenarios within speech intelligibility experiments to determine the additional benefits, if any, of spatial audio communications displays.

6. ACKNOWLEDGMENTS

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This article is available as NASA Technical Memorandum No. 104014. A demonstration tape of virtual acoustic displays is available from the author.

Laboratory and In-flight Experiments to Evaluate
3-D Audio Display Technology

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ABSTRACT

Laboratory and in-flight experiments were conducted to evaluate 3-D audio display technology for cockpit applications. A 3-D audio display generator was developed which digitally encodes naturally occurring direction information onto any audio signal and presents the binaural sound over headphones. The acoustic image is stabilized for head movement by use of an electromagnetic head-tracking device. In the laboratory, a 3-D audio display generator was used to spatially separate competing speech messages to improve the intelligibility of each message. Up to a 25 percent improvement in intelligibility was measured for spatially separated speech at high ambient noise levels (115 dB SPL). During the in-flight experiments, pilots reported that spatial separation of speech communications provided a noticeable improvement in intelligibility. The use of 3-D audio for target acquisition was also investigated. In the laboratory, 3-D audio enabled the acquisition of visual targets in about two seconds average response time at 17 degrees accuracy. During the in-flight experiments, pilots correctly identified ground targets 50, 75, and 100 percent of the time at separation angles of 12, 20, and 35 degrees, respectively. In general, pilot performance in the field with the 3-D audio display generator was as expected, based on data from laboratory experiments.

INTRODUCTION

Virtual audio display generators are being developed for aerospace and non-aerospace applications. Until the mid 1980s, acoustic manikins and loudspeaker arrays were required to simulate 3-D audio environments (Ericson, 1993). Other technological improvements, such as head tracking devices and digital signal processors, have aided in the realization of electronic virtual audio display generators for headphone applications. Many possible applications exist for virtual audio displays. Some aerospace applications include threat warning, collision avoidance, navigation beacons for landing at night and in bad weather, and spatially separated communications. These displays are created by encoding binaural cues onto an audio input signal.

Directional cues are contained in the head related transfer function (HRTF). The HRTF is the difference between the sound field at the entrance to a listener's ear canals and those same points in space in the absence of a listener's body. A more detailed discussion about HRTFs can be found in Blauert (1983) and Genuit (1992). In some applications, especially those in which distance cues are important, the inclusion of auralization or environmental cues becomes critical. Auralization cues include the reflections and reverberation characteristics of a particular listening environment (Lehnert, 1992). However, the experiments presented in this paper only involve directional encoding of audio signals.

All experiments discussed in this paper used virtual audio display generators developed at the US Air Force Armstrong Laboratory (McKinley, 1988, and McKinley, 1993). Two types of applications were explored by measuring human performance with virtual audio displays. One set of experiments explored visual target acquisition using virtual audio over headphones. The other experiments measured the intelligibility of spatially separated speech communications. For each application, experiments were first conducted in the laboratory followed by in-flight tests in a two seat AV-8B Harrier aircraft.

OBJECTIVE/PURPOSE

The objectives and purposes of the four experiments are described below. 1) The objective of the laboratory target acquisition experiment was to measure visual and auditory target acquisition response time and accuracy while performing a secondary compensatory tracking task. The purpose was to determine the effect, if any, of spatially correlated auditory information on visual target acquisition performance. 2) The purpose of the in-flight acquisition experiments was to determine if virtual audio cues could be used to distinguish ground targets in non-maneuvering and maneuvering environments. 3) The objective of the laboratory communication experiment was to measure the intelligibility of diotic, dichotic, and spatially separated speech presentations over headphones. Diotic refers to identical signals at each ear with the perceived location of the sound in the center of the head. In the dichotic presentation, one talker was presented through the left earcup and the other talker through the right earcup. Spatially separated speech was output from the 3-D audio display generator and perceived to come from different directions in the horizontal plane outside the listener's head. The purpose was to determine the relative intelligibility of diotic, dichotic and spatially separated speech messages. 4) The objective of the in-flight communication experiment was to determine if a pilot can better comprehend spatially separated speech messages compared to diotically presented speech messages.

METHODS FOR TARGET ACQUISITION EXPERIMENTS

METHODS FOR THE LABORATORY EXPERIMENT

PROCEDURE - Twenty-four LED displays were placed at fifteen degree separations on a seven foot radius horizontal ring at the level of a subject's head. Directional information was presented either visually on a 3" by 5" monitor directly in front of the subject, binaurally over headphones, or with a simultaneous presentation of visual and auditory binaural information. While waiting for the random targets to appear, the subjects performed a compensatory tracking task using a game joystick and a 14" diameter VGA monitor. The subjects were instructed to find the number zero on the horizontal ring that surrounded them. Once the LED target was presented, the subject turned his/her head towards the "zero" target on the ring and pressed a button switch on the joystick. Random false alarm targets were intermixed with the real targets 2% - 8% of the time to help ensure an honest response. Response time, the interval between presentation of the LED target and pressing of the joystick button, was the primary performance measure. Head pointing accuracy and tracking accuracy were secondary performance measures.

EXPERIMENTAL DESIGN - A balanced, repeated measures design was used in which each subject participated in all test conditions. Zero targets from each of the 24 directions were presented twice to each subject for each condition. Each subject participated in the auditory only, visual only, and combined visual and auditory conditions. Presentation orders of the three conditions were randomized across subjects to reduce order effects. Eight subjects participated in the experiment.

SUBJECTS - Eight volunteer, paid subjects participated in the experiment. Four males and four females ranged from 18 to 25 years in age with a mean age of 20. All had normal hearing sensitivity and function. All had normal (or corrected to normal) vision.

METHODS FOR THE IN-FLIGHT EXPERIMENT

During the in-flight tests, the forward pilot performed a series of passes, some straight and level and some maneuvering, on a path towards 3 ground targets: a bullseye, a tower, and an F-4 bunker. At a distance of 0.3 nautical mile (nmi) from the target, corresponding to 20 degrees of angular separation between the targets, the forward pilot randomly selected one of three targets which produced a 3-D audio beacon for five seconds. The task for the aft aviator was

to report which of the three targets had produced the sound. If the response at 20 degrees was correct, then on the next pass, the audio beacon was presented at 0.1 nmi, corresponding to twelve degrees of angular separation between targets. If the response at 20 degrees was incorrect, then on pass two the beacon was presented at 1.0 nmi, corresponding to 35 degrees of angular separation between targets. All non-maneuvering passes were made before all maneuvering passes. The performance measure for this test was accuracy in identifying the correct target by the aft aviator. While there were a total of eleven 3-D audio flights, not all tests were completed for every flight. In the maneuvering condition, six tests were completed at 20 degrees, five runs at twelve degrees, and four runs at 35 degrees. In the maneuvering condition, five runs were made at 20 degrees, four at twelve degrees, and none at 35 degrees.

RESULTS FOR TARGET ACQUISITION EXPERIMENTS

LABORATORY EXPERIMENT

Results from the laboratory experiment are plotted in Figure 1. Response times in the audio, visual, and combined conditions were very similar across presentation angle, with the audio being slightly longer. In the audio condition, response times ranged from 1.6 to 2.4 seconds. Response times for the visual and combined conditions ranged from 1.5 to 2.2 seconds. There were no significant differences at $p=.01$ for response times. Head pointing accuracy was also very similar across conditions. There was no significant differences at $p=.05$. For the audio condition, there were individual differences in the amount of difficulty with which one could use the directional audio to determine the target direction.

IN-FLIGHT

Pilots reported that directional audio information enabled faster acquisition of the visual targets, with an approximate accuracy of fifteen degrees. On the completed tests, accuracy and the number of runs were sometimes given as approximations by the pilots. Thus, results are given as estimates of accuracy and not as precise figures. In the non-maneuvering passes, approximately 85% were accurate at 20 degrees of separation between targets, 50% at twelve degrees, and 85% at 35 degrees. For maneuvering approaches, there were fewer passes, and estimates of accuracy were 100% correct at 20 degrees and 40 % at 12 degrees. Pilots reported that at all angles of separation they were able to eliminate one of the three targets, but they had more difficulty in determining with confidence which one of the two remaining targets had produced the audio cue. They felt that in general 3-D audio complemented the visual displays and reduced target acquisition times.

METHODS FOR COMMUNICATION EXPERIMENTS

METHODS FOR THE LABORATORY EXPERIMENT

PROCEDURE - The competing messages experiment was conducted in the voice communications research and evaluation system (VOCRES) (McKinley, 1986) facility. Each of two talkers was prompted to simultaneously read messages of similar structure and content. Each message consisted of a call sign (ringo or baron), a color (red, white, blue, or grey), and an integer (one through eight). The message choices were randomized, however the order of call sign, color, and number were kept constant. Two listeners heard the messages presented diotically over headphones and two listeners heard the messages presented spatially at various angles of separation. Each listener was assigned a call sign, either ringo or baron. The listeners were to respond to the color and number spoken after their call sign. There were two diotic listeners and two spatial listeners, with a baron and a ringo listener in each group. A correct response required reporting all the information correctly about the call sign, color, and number. Scoring was measured automatically by computer, and no correction for guessing was employed.

EXPERIMENTAL DESIGN - This experiment used a balanced, within subjects design. Four ambient noise levels (75, 95, 105, and 115 dB SPL) were generated to simulate typical cockpit listening environments. The coordinate response measure

was used to measure the speech intelligibility for one of two competing messages in noise. Three talker pairs participated in the experiment. Each pair consisted of either a two males, two females, or a male and a female. Two groups of four listeners each participated in all the conditions. The spatially separated speech was presented at five angular separations (0, 45, 90, 135, and 180 degrees). Dichotically presented speech was realized by presenting one talker in the left ear and the other talker in the right ear.

SUBJECTS - A total of twelve subjects, 6 male and 6 female, were paid to participate in the experiment. Two of the male talkers doubled as listeners. The subjects ranged from 18 to 43 years of age with a mean age of 23. All subjects had normal hearing sensitivity and function.

METHODS FOR THE IN-FLIGHT EXPERIMENT

The communication separation feature of the 3-D audio display generator was evaluated on the return trip from the target acquisition experiments. For this test, the communication (COMM) switch position was selected on the 3-D cuer control panel (Figure 3). Presentation levels of COMM-1 and COMM-2 were adjusted according to user preference. The aft pilot listened to two competing messages, which sounded as if they were coming from 315 degrees and 45 degrees bearing, and at 45 degrees elevation. Two persons on the ground using separate radio frequencies read separate messages; a nine-line brief and an emergency check procedure. The messages were received over two radios, COMM-1 and COMM-2. The aft pilot's task was to determine whether he could better distinguish these dual messages using the 3-D audio display generator than he could under the normal COMM-1 and COMM-2 modes. A total of seven pilots participated in communications separation experiment.

RESULTS FOR COMMUNICATION EXPERIMENTS

LABORATORY

Data from the laboratory experiments are plotted in Figure 4. Separations as small as 45 degrees provided a large improvement (over 25%) in speech intelligibility. Above 80% intelligibility is considered acceptable by flying personnel. Between 70 and 80% is marginal performance, and below 70% is considered unacceptable. The female talker pair tended to mask each other more than the other talker pairs. Dichotic (left/right) presentation provided the greatest intelligibility.

IN-FLIGHT

The communication separation feature of the 3-D audio display generator worked well. Most pilots felt that the spatial separation of speech communications improved the mutual intelligibility of each message. One pilot commented that spatial separation seemed to help a lot. However, the task of listening to one communication while two were broadcast simultaneously was still difficult.

DISCUSSION

Several differences between the laboratory and in-flight testing conditions may explain the relatively better performance with the 3-D audio system while in-flight than in the laboratory. There were only three targets to attend to in-flight, whereas there were 24 targets in the laboratory experiments. Pilots typically flew below 500 feet of altitude at 400 knots equivalent air speed while surrounded by mountains. The in-flight task was more stressful than the laboratory task and required a higher level of attention. In this situation, the 3-D audio display tended to complement the visual display since the pilot was often busy looking out of the cockpit for the targets and not looking down at the visual display. The 3-D audio display reduced workload by making the target acquisition task easier for the pilot to accomplish.

The 3-D audio display could be used for several other visual target acquisition applications. An auditory beacon could be used to help a pilot navigate towards a runway, especially at night or in bad weather. Auditory buoys

could warn pilots of possible collisions with either other airborne objects or with the ground, and thereby help the pilot to avoid collision. Possible military applications include threat warning with radar warning receivers, off-boresight missile targeting, and aerial refueling. An audio beacon could be used to find and track one's wingman in air to air combat. 3-D audio could improve many target acquisition and communication tasks.

3-D audio displays may be a better modality for alerting a pilot as to the location/direction of a threat. 3-D audio encompasses all space around the person in azimuth and elevation, where visual displays are mostly limited to a person's line of gaze (fovea vision). Current threat warning visual displays are two dimensional and do not map 1 for 1 with the 3-D environment around the person. However, the 3-D audio display was spatially correlated to the ground targets, which provided a much more natural man-machine interface.

Laboratory and in-flight experiments showed spatially separated speech communications to be more intelligible than diotically presented speech. Two factors contributed to the relative success of spatially separated communications. These were the HRTF encoding and the head motion cues. The HRTF consists of magnitude and phase cues. The magnitude portion of the HRTF provided spectral filtering and the phase portion provided time of arrival differences between the two ears (Bronkhorst, 1992). People use these cues to unmask speech from noise. Head motion cues helped to space stabilize the direction of speech presentation. HRTF and head motion cues caused the speech communications to be spatially separated and easier to understand.

The success of the spatially separated speech communication experiments suggests that communication systems have room for improvement. Most of all, a pilot's safety would be improved if he/she could better understand multiple communications from on board radios. Critical messages would probably not be misunderstood or have to be repeated as often. If the speech were spatially correlated with the source locations, then a pilot's situational awareness would be greatly improved. Spatially correlated communications would benefit pilots in formation flying situations. The laboratory and in-flight data support the inclusion of 3-D audio technology in airborne communication systems.

Many airborne applications for spatially separating speech communications exist. Any person that receives more than one speech communication at one time could benefit from the spatial separation of speech messages. Any command-control-communication post could benefit from this technology. Armored personnel carriers and submarines are visually blocked from their environments and their operators would probably have better situational awareness with 3-D audio displays.

CONCLUSIONS

Several conclusions can be drawn from the laboratory and in-flight experiments with target acquisition and spatially separated speech communications. They are listed below without any particular rank ordering.

- 1) 3-D audio cues were equally effective as visual cues for finding targets in the laboratory.
- 2) 3-D audio improved target acquisition tasks in-flight by reducing acquisition times.
- 3) 3-D audio improved multiple speech listening tasks up to 25% intelligibility in the laboratory and also worked well in-flight.
- 4) 3-D audio was reported to improve situational awareness in target acquisition and speech communications tasks without increasing workload.

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TARGET ACQUISITION PERFORMANCE WITH PART TASK SIMULATION

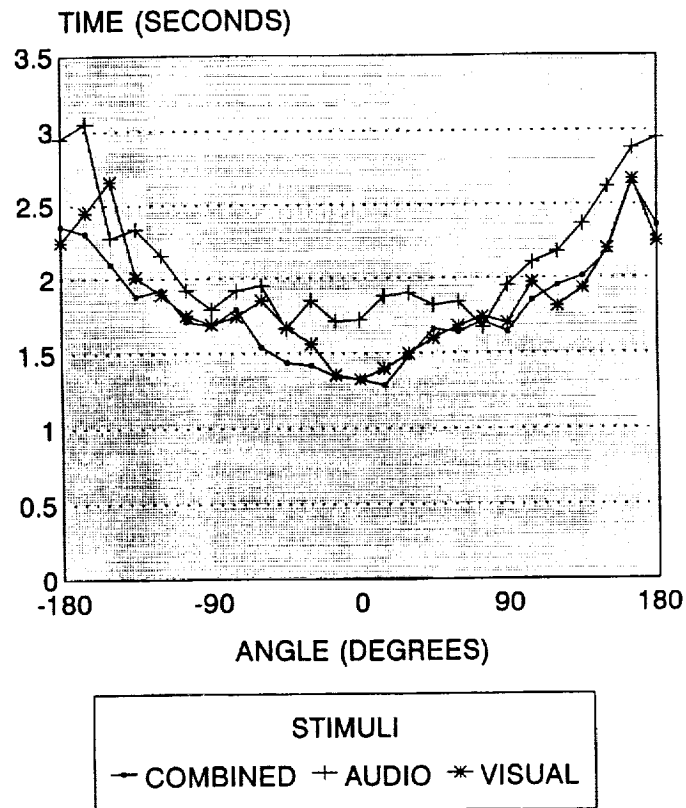


Figure 1
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get Acquisition Accuracy VS Angular Separation

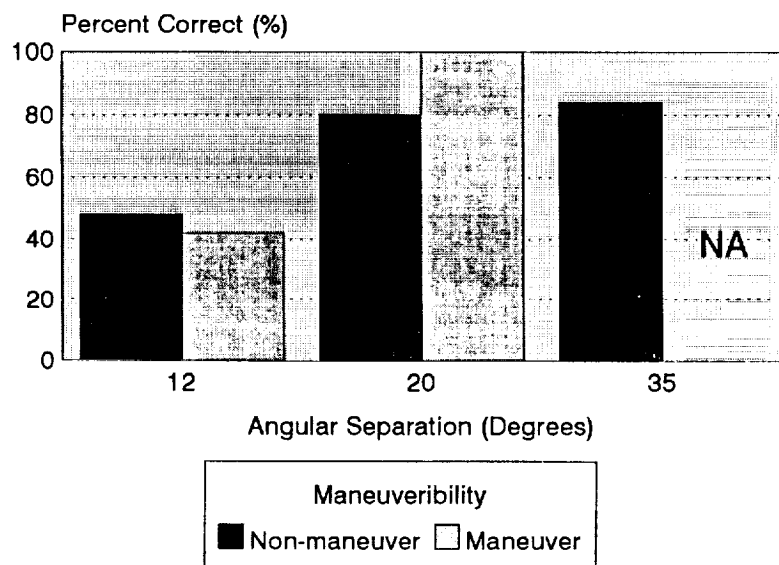


Figure 2

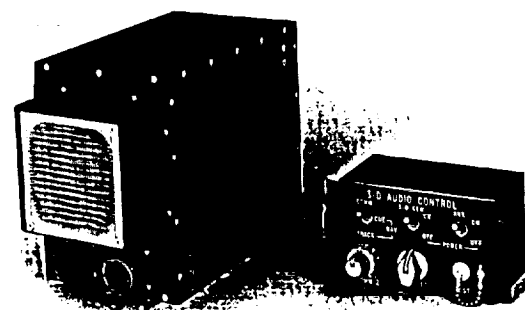


Figure 3

COMPETING MESSAGES SPATIALLY SEPARATED VS DIOTIC

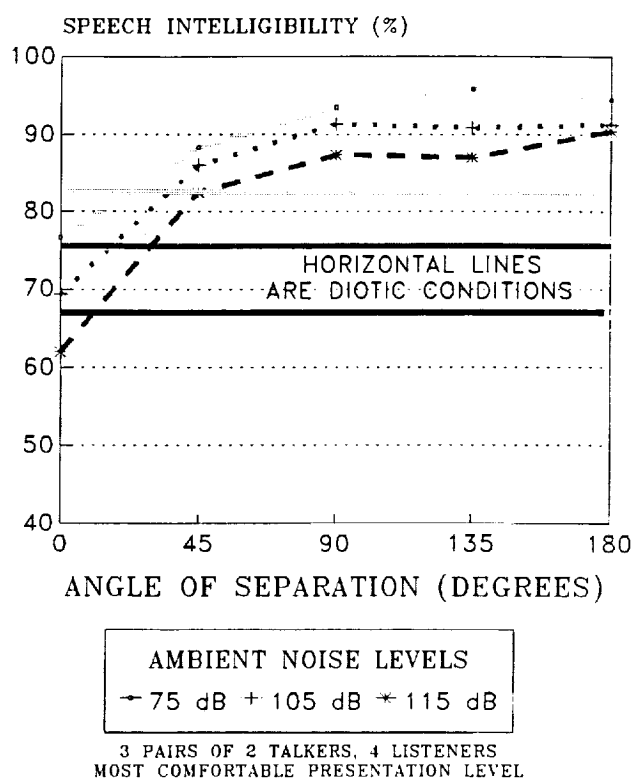


Figure 4a

COMPETING MESSAGES LEFT/RIGHT VS DIOTIC 115 DB OF NOISE

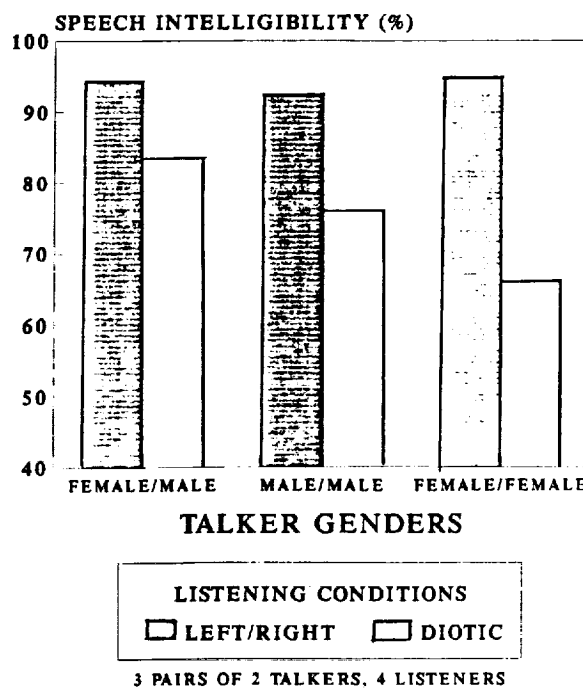


Figure 4b

Fusion Interfaces for Tactical Environments: An Application of Virtual Reality Technology

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Abstract

The term Fusion Interface is defined as a class of interface which integrally incorporates both virtual and non-virtual concepts and devices across the visual, auditory and haptic sensory modalities. A fusion interface is a multi-sensory virtually-augmented synthetic environment. A new facility has been developed within the Human Engineering Division of the Armstrong Laboratory dedicated to exploratory development of fusion interface concepts. This new facility, the Fusion Interfaces for Tactical Environments facility, or FITE, is a specialized flight simulator enabling efficient concept development through rapid prototyping and direct experience of new fusion concepts. The FITE facility also supports evaluation of fusion concepts by operational fighter pilots in an air combat environment. The facility is utilized by a multi-disciplinary design team composed of human factors engineers, electronics engineers, computer scientists, experimental psychologists, and operational pilots. The FITE computational architecture is composed of 25 80486-based micro-computers operating in real-time. The micro-computers generate out-the-window visuals, in-cockpit and head-mounted visuals, localized auditory presentations, haptic displays on the stick and rudder pedals, as well as executing weapons models, aerodynamic models, and threat models.

1 Introduction

Future tactical aircraft will be operating in a much more demanding environment than they do today. The lethality of weapons systems continues to increase. The proliferation of advanced weapon technologies such as directed energy weapons, reduced target detectability, and increasing use of passive sensor methods will create increased air combat dynamics as well as requiring additional time critical decisions to be made by the pilots of future tactical aircraft. This will place the tactical aircraft pilot in a more difficult mission environment

than he currently experiences. To counter the increasingly complex tactical environment, advanced pilot-vehicle interface (PVI) techniques, which enable a more efficient use of the pilot's abilities, are required to be developed and employed, thus providing greater situation awareness, enhanced controllability of the overall weapon system, increased lethality, and increased survivability. These factors, in turn, combine to enhance weapon system effectiveness.

The cockpit is not the only environment in which advanced interfaces may increase the performance of a total system. The link, or interface, between man and intelligent machine, may be limiting the productivity and efficiency obtainable through automation and machine intelligence [3]. The challenges involved in linking humans and intelligent machines are increasing due to increased computational power, increased availability, increased machine-to-machine communication capability, increased functional capability through higher level languages, and increased memory capacity.

The PVI can be viewed as a type of human-machine interface, with the machine representing the advanced avionics system. This generalization highlights an opportunity, that being the opportunity to transition military-sector advanced PVI concepts and devices to the commercial-sector, as human-machine interface concepts and devices. This paper describes ongoing research and exploratory development of multi-sensory virtual interfaces, an advanced PVI technology within the Human Engineering Division of the Armstrong Laboratory.

2 Multi-sensory virtual interfaces

A melding, through the interface, between user and system can couple the inductive capability of the system with the enormous deductive power of the human user. Advanced multi-sensory interface concepts and technologies can aid this melding process by providing a flexible and adaptive interface medium.

Multi-sensory virtual-interfaces may enhance weapon system performance during tactical engagements by contemporaneously and coherently providing display of multiple-sensory channels of information to the fighter pilot and enabling novel control methodologies to be employed through the use of virtual devices. In the same way, multi-sensory virtual-interface concepts may provide enhancements in other human-machine links by capitalizing on the human's innate ability to integrate, assimilate, and fuse multiple sensory experiences simultaneously. Multi-sensory interfaces may better support the interactions necessary to fully realize and direct the capability of increasingly powerful avionics and weapon systems.

The application of advanced, multi-sensory interface concepts may best be accomplished using a combination of non-virtual (or conventional) and virtual control and display devices. The use of a combination of virtual and non-virtual devices can create a novel experience for the user, such as in high-

fidelity embedded in-flight training, wide field-of-view multi-sensory imagery portrayal, or in cockpit portrayals adaptive to the tactical situation and the pilot's condition. This type of experience, in the general sense, has been termed in the current literature as virtual reality [10]. The perceptual space created by this experience has been termed the virtual environment and more recently, the synthetic environment.

3 Enabling Devices for Virtual Interfaces

Three sense modalities lend themselves for use as virtual interfaces within tactical environments. These are vision, audition, and touch. Touch may be more clearly defined, in this context, as haptic, involving both cutaneous and kinesthetic stimulation. Several technologies are currently being utilized to create virtual interfaces within these modalities. Some of these technologies are very mature while others are in their infancy.

The technology to totally emulate naturally occurring environments within a virtual environment does not exist at this time. However, devices enabling the creation of a limited virtual experience do exist [3]. Helmet mounted displays, helmet mounted head, hand, and eye line-of-sight trackers, three dimensional auditory displays, and tactile stimulation devices have been developed and evaluated by several academic, industrial, and military institutions in a non-integrated fashion or, context independently, since the mid 1960s [4], [5], [12], [14], [13], [11]. Perceptual research which may impact the design, development and application of virtual environment technology in the areas of vision, audition, and proprioception is continuing internationally.

3.1 Virtual Visual Devices

The virtual visual interface is composed of a visual image generator and a visual image portrayal system. The visual image generator can be a computer graphics system, an imaging camera, or other similar sensor. Of the three modalities, the technology for visual virtual interface application is the most mature. Computer graphics, sensor technology, and image portrayal mechanisms are important technologies for the creation of robust and high-fidelity virtual environments. Image portrayal technologies involved in the transformation of electronic-formatted imagery to a visual format include miniature cathode-ray tubes, liquid crystal displays, optics, interface electronics. Many of these technologies are being considered for incorporation, or are already integrated, into aircraft cockpits. These include HUDs, and helmet mounted displays (HMD), as well as three-dimensional panel mounted displays. Virtual visual controls include helmet mounted head position/attitude trackers and eye line-of-sight trackers. A discussion of helmet mounted display technologies can be found in a paper by Kocian [6].

3.2 Virtual Auditory Devices

Virtual auditory displays have been developed which utilize three-dimensional auditory localizers combined with audio image sources and stereo headsets. The three-dimensional auditory localizer samples the auditory image created by an audio image source such as an intercom or computer generated tone source, digitally filters the signal based on a head-related transfer function that is a function of sound location in azimuth, elevation, and range, and results in a stereo audio pair. The stereo pair is converted to an analog form and displayed over a stereo headset. A discussion of current technology and perceptual research issues concerning auditory localization is found in papers by McKinley [7], Wenzel [15] and Durlach [2].

3.3 Virtual Haptic Devices and Virtual Control

Haptic displays, which enable the portrayal of virtual cutaneous and kinesthetic information, and other virtual control methods, are less developed technologies than the visual and auditory technologies, but may be made available for use as currently ongoing research makes advances. These include tactile/haptic stimulation devices, hand and body flexure measurement devices, direct vestibular stimulators, direct retinal displays, and directly-coupled brain-actuated control. Control loaders, typically utilized in flight simulation to accurately model the stick feel of a particular aircraft, also fall into this category but are a mature technology. Some of these technologies are discussed by Rheingold [10], Meyer [8], and Monkman [9].

4 Fusion interfaces

The term Fusion Interface is utilized within this context as a class of interface which utilizes both virtual and non-virtual concepts and devices integrally across the visual, auditory and haptic modalities. A fusion interface is a multi-sensory virtually-augmented interface.

Although much is known about human perception and performance [1], the creation and evaluation of multi-sensory virtually-augmented interfaces presents a design problem in that it is difficult to design or evaluate these interface attributes without experiencing them within the application context. In many cases, what seems to be a valid display or control concept breaks down when it is experienced. For this reason, multi-sensory virtual-interface creation, integration, and evaluation can best be accomplished within a rapid prototyping environment capable of generating the virtually-augmented environment for the pilot. The Fusion Interfaces for Tactical Environments (FITE) laboratory, a facility within the Crew Systems Directorate of the Armstrong Laboratory, has this capability and is currently supporting the exploratory development of multi-sensory virtual-interface technologies for tactical cockpits by a multi-disciplinary

team composed of operational pilots, human factors engineers, electronics engineers, computer scientists, and experimental psychologists.

4.1 Development Process within the FITE

The products of the FITE laboratory are the multi-sensory virtual-interface concepts themselves, the evaluations of the interface concepts, and the identification of basic research topics to be pursued in more controlled experimental settings. The FITE laboratory operates in three main cycles. These cycles, and the resultant products, are depicted in Figure 1. The three cycles are the rapid prototyping loop, enabling the rapid creation and initial evaluation of concepts, the basic research loop, outputting basic research topics to other facilities and inputting results back into the interface design process, and the evaluation loop, which is the traditional simulation evaluation loop.

4.2 FITE Hardware Architecture

The central component of the FITE laboratory is a F-16 cockpit shell which is the focus of the multi-sensory virtual-interface concept development and evaluation. The other components of interest in the FITE are its computational structure, its virtual and non-virtual visual displays, its virtual auditory display, and its haptic display. A block diagram of the hardware architecture is shown in Figure 2.

4.2.1 Computational Structure

The computational structure consists of a distributed collection of 80486-33 MHz computers configured with 4 Mbytes of memory and a single high-density floppy drive. This computer configuration provides real-time performance inexpensively. The computers interface in real-time through an off-the-shelf 128 Byte shared-memory unit manufactured by Bit-3. The computer communications through the shared-memory is transparent to the software executing within the computers enabling software protocols to be eliminated. Software development is performed on two 80486-33 MHz machines configured with hard-drives and off-the-shelf compilers and linkers. Software development and run-time execution is performed under the DOS operating system. High-C and Absoft FORTRAN are the software languages used and are linked with the Phar-Lap DOS extender enabling utilization of extended memory.

All of the visual displays are generated using Irisvision boards, which are an off-the-shelf two-board graphics card set fabricated by Silicon Graphics and Pelucid. The Irisvision boards are physically located inside the 80486-33 MHz systems. The graphics systems provide several video formats ranging from standard television formats (NTSC or PAL) to 1280 by 1024 pixels, non-interlaced, at 60 Hz. The FITE facility has standardized on a 1024 by 768 pixel format,

interlaced, at 30 Hz . Independent of video format, the Irisvision graphics systems provide double-buffering, anti-aliasing, 24-bit z-buffering, Gouraud shading. 90,000 triangles/second, and over 14,000 shaded triangles/second. This capability supports symbology-only, imagery- only, and symbology-over-imagery graphical depictions. Data acquisition, digital-to-analog, and analog-to- digital conversion is performed by off-the-shelf data acquisition cards, manufactured by Computer Boards Inc, which are incorporated into the 80486-33 MHz computers.

The tactical environment, including aerodynamic modeling, weapons modeling, avionics modeling, as well as digital and manned threat modeling, are computed on distributed 80486-33 MHz systems. The processors within the FITE cycle in real-time at integer multiples of the visual imagery update rate of 30 Hz due to synchronization considerations. While most of the processors operate at 30 Hz, , the manned threat stations, the out-the-window scene generation, and the complex aerodynamic models operate at 15 Hz.

4.2.2 FITE Visual Displays

The FITE laboratory incorporates several non-virtual and virtual visual displays. The front panel of the F-16 cockpit shell is filled with 6 off-the-shelf color LCDs forming a composite large area head-down display. The head-down display is virtually-augmented with a see-through HMD, the Tactical All-Aspect Helmet Mounted Display (TAAHMD). The TAAHMD provides an instantaneous monocular 20° field-of-view wherever the pilot aims his head. The TAAHMD is used not only for displaying information, but also for aiming weapons and pointing avionics. A head-tracker is incorporated into the TAAHMD and allows displays to be stabilized to the outside world, to other aircraft, or to the cockpit, allowing augmentation of head-down displays. Out-the-window visuals are portrayed using 6 off-the-shelf monochrome-white projectors focused onto flat screens forming a cube around the F-16 cockpit shell. The cube is approximately 3.7m on each edge and the out-the-window projections cover an area slightly greater than the frontal hemisphere relative to the pilot. A single monochrome-green projector is used to portray HUD imagery. Each of the LCDs, the projectors, and the HMD is driven by a graphics card-set incorporated into a computer system for a total of 14 systems utilized for visual display.

Three Kaiser Sim-Eye HMDs, which are binocular, monochrome, and incorporate a 60° by 40° field of view, are integrated into flight stations which support other participants during real-time simulation. These helmet mounted displays are used to portray the out-the-window scene as well as a totally virtual visual cockpit for the other participants.

4.2.3 FITE Audio Displays

Audio signals from tone generators, intercoms, and speech synthesizers are driven through an auditory localizer which provides spatially-linked auditory displays. Tone generation and speech synthesis are performed by Sound Blaster Pro cards, manufactured by Creative Labs Inc. The auditory localizer, a Convotron, is also off-the-shelf and is manufactured by Crystal River Engineering. The auditory localizer can input four audio signals and localize in azimuth, elevation, and range. Because the azimuth, elevation, and range provided to the localizer is computed within the flight simulation, various localization algorithms can be employed, ranging from radar warning receiver tones emanating from the aircraft producing the radar energy, to using localization to enhance non-position derived information, such as tail aspect angle of an attacking aircraft. The intercom allows voice communications between individuals within the flight environment with individual stations being localized in real-time.

4.2.4 FITE Haptic Displays

A McFadden hydraulic control-loader provides real-time-modifiable stick and rudder feel to the cockpit as well as providing flight control inputs from the pilot to the simulation. In real-time, several characteristics of the stick and rudder pedals can be manipulated, such as position, force reflection, friction, damping, dead-band, velocity limits. Break points for non-linear position-based characteristics can also be manipulated. This capability provides the ability to modify stick feel as a function of any combination of variables within the flight simulation. The resultant algorithms could modify stick feel as a function of aircraft energy state or even tactical situation.

5 Summary

The human is a complex and adaptive receiver whose perceptual performance within a virtual environment is tied to the quality of the visual, auditory, and haptic stimulus generated within the multi-sensory virtual-interface. Many questions remain unanswered regarding virtual techniques, which, when answered, may increase the potential usefulness of virtual interfaces. In-context rapid prototyping is required to support creation and evaluation of multi-sensory virtual-interface concepts. Facilities can be developed utilizing off-the-shelf technology which provide high-fidelity flight simulation capability for in-context development of multi-sensory virtual-interfaces concepts for tactical aircraft. The Armstrong Laboratory has developed the FITE laboratory as part of an exploratory development program investigating multi-sensory virtual interfaces for tactical aircraft and is currently utilizing the facility to develop the initial multi-sensory virtually-augmented cockpit for air-to-air combat.

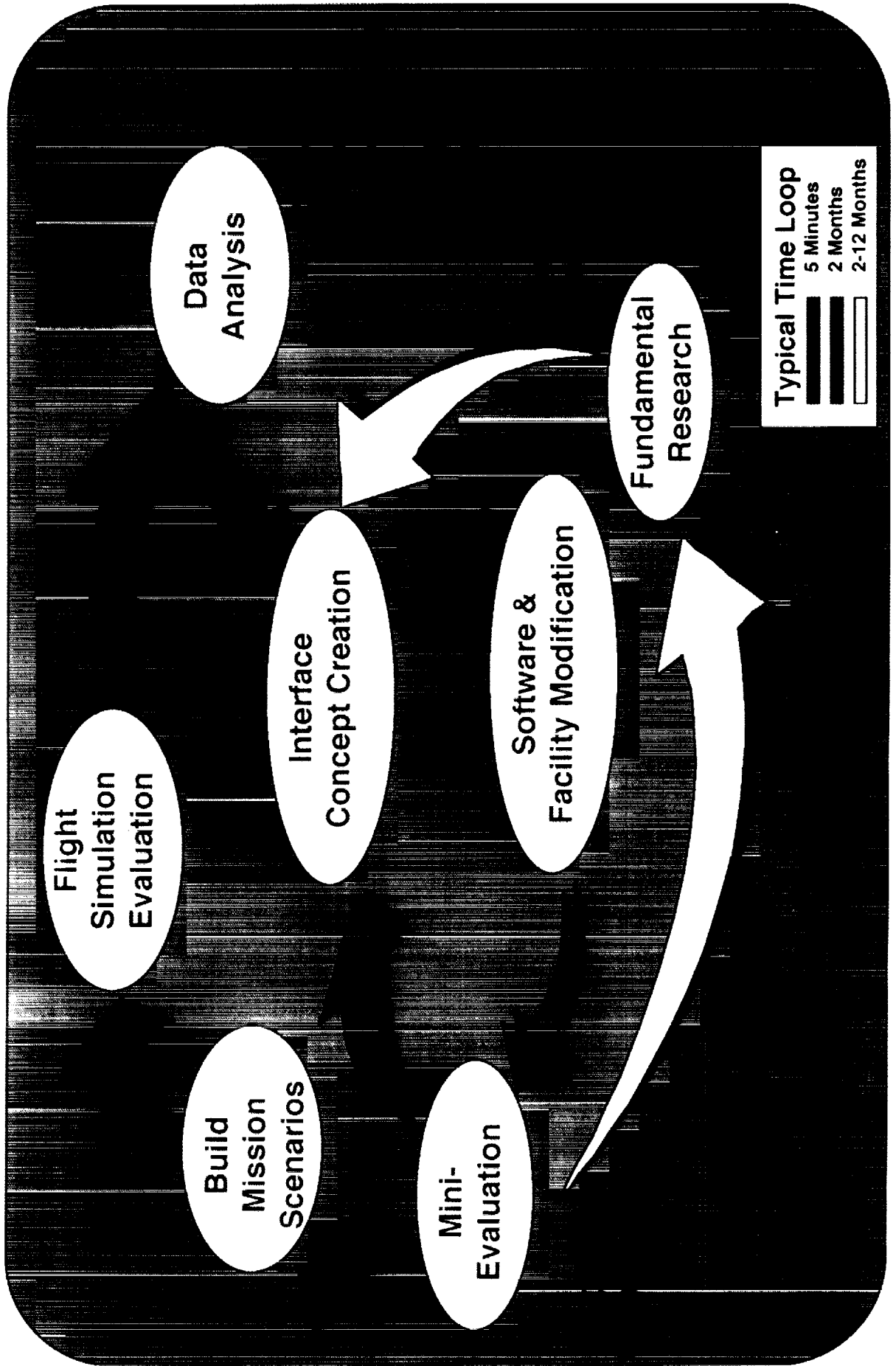
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Multi-Sensory Development Process

A Near-Term Vision



**Virtual Reality as a Human Factors Design Analysis Tool:
Macro-Ergonomic Application Validation and Assessment
of the Space Station Freedom Payload Control Area**

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A Virtual Reality (VR) Applications Program has been under development at the Marshall Space Flight Center since 1989. Its objectives are to develop, assess, validate, and utilize VR in hardware development, operations development and support, mission operations training, and science training. A variety of activities are under way within many of these areas. One ongoing macro-ergonomic application of VR relates to the design of the Space Station Freedom Payload Control Area (PCA), the control room from which onboard payload operations are managed. Several preliminary conceptual PCA layouts have been developed and modeled in VR. Various managers and potential end users have virtually "entered" these rooms and provided valuable feedback. Before VR can be used with confidence in a particular application, it must be validated, or calibrated, for that class of applications. Two associated validation studies for macro-ergonomic applications are under way to help characterize possible distortions or filtering of relevant perceptions in a virtual world. In both studies, existing control rooms and their "virtual" counterparts will be empirically compared using distance and heading estimations to objects and subjective assessments. Approaches and findings of the PCA activities and details of the studies will be presented

A RAPID ALGORITHM FOR REALISTIC HUMAN REACHING
AND ITS USE IN A VIRTUAL REALITY SYSTEM

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ABSTRACT

The Graphics Analysis Facility (GRAF) at NASA/JSC has developed a rapid algorithm for computing realistic human reaching. The algorithm was applied to GRAF's anthropometrically correct human model and used in a 3D computer graphics system and a Virtual Reality system. The nature of the algorithm and its uses are discussed.

INTRODUCTION

The Graphics Analysis Facility (GRAF) at NASA/JSC provides tools and methods for visualization of space vehicles, structures, designs and procedures. A detailed 3-dimensional geometric database of the Space Shuttle, its payloads, and various Space Station designs in different stages of construction is maintained and continuously updated by GRAF. This information can be visualized by GRAF's customers with color printouts, transparencies, video tape animations, or within a Virtual Reality system. GRAF also maintains an accurate anthropometrically correct human computer model.

The aim at GRAF is to incorporate this accurate human computer model into a Virtual Reality (VR) system. A VR system allows the person who wears the helmet to visualize the simulated environment. The motion of the helmet is monitored to determine head motion of the person and to update the images displayed in his helmet. When this person is doing more than viewing his environment, and begins to perform tasks such as reaching and lifting objects, then it is necessary to track the motion of

his arms. Usually, a magnetic tracking device is attached to the hand to record position and orientation of the palm. Some systems use this information to draw a non-jointed hand/arm model with the position and orientation as measured by the tracking system. This is fast and simple, but has limited use. When VR systems are being used with multiple people in the same environment, one user looking at another needs to see correctly positioned arms, not hands dangling in space. In order to display the person's jointed arm in his computer environment, it is necessary to calculate the actual joint angles necessary to position each limb of the arm to obtain the position and orientation (posture) of the end effector (palm).

Inverse kinematics was an early and popular method of determining the joint angles in the arm. The arm is, at a minimum, a 7 degree of freedom (DOF) device with 6 constraints. Inverse kinematics solutions for such a system need not be unique, with solutions often looking very unrealistic. Also, often the solutions get trapped in local minima, and the calculations can be slow.

The method of determining joint angles from posture of the hand used in GRAF is a simple look-up table approach. This approach always gives a solution (if a solution exists) and is extremely fast. The sections below describe this look-up table approach, its advantages and disadvantages, along with possible extensions and refinements to this approach.

REACHING

Reaching is a complicated task. Usually the entire body and not just the arm is involved in this task. The challenge is to monitor and reproduce an accurate reaching motion with a minimum of magnetic trackers on the person. Attaching magnetic trackers to each limb segment of a person would allow capture of the actual reach motions, but this method requires many trackers. We have developed a method of simulating realistic reaching motions using a limited number of trackers to determine basic body posture. Look-up tables give solutions for the joint angles needed to obtain this posture.

Consider a virtual environment with an EVA person attached to a portable foot restraint (PFR). The person wearing a VR helmet and magnetic trackers must move in this environment as if his feet were attached to the PRF. In our system the motion of the subject would be monitored using 3 magnetic trackers; one tracker on the back to

determine motions of the torso, one tracker on the palm to determine posture of the hand, and a third tracker on the head to monitor head motion for viewing purposes (Figure 1). (Note: This configuration of 3 trackers monitors only one arm. Four trackers would be needed to monitor both arms.)

The tracker on the back is processed first. Translation motions of the tracker are used to move the figure's waist position forward/backwards. A look-up table determines the joint angles necessary to keep the feet attached to the PFR (Figure 2). Orientation of the tracker is used to rotate the waist until the computer figure has the correct back orientation. With this new body orientation, the tracker on the head is processed to determine neck motion necessary to give the correct viewing direction. The tracker on the hand is used to get a position and orientation in space relative to the shoulder of the computer figure. A look-up table then determines the joint angles needed to position the arm. This requires 7 joint angles for our EVA figure. An unsuited figure would need 9 joint angles to allowing positioning of the clavicle to give a correct arm posture.

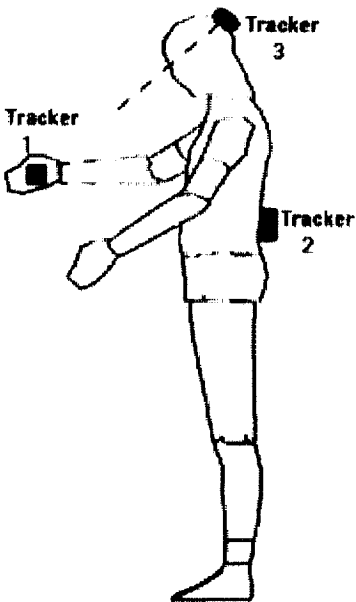


Figure 1. Location of magnetic trackers

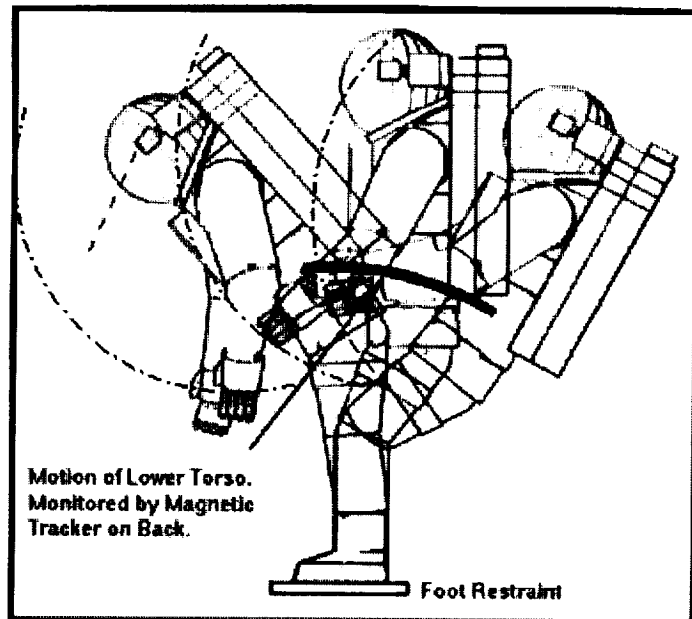


Figure 2. Motion of Torso and arms determined by trackers.

Look-up Table Generation

In order to generate our look-up table, all the arm joints of the computer figure were exercised through their range of motion. This generated vast amounts of data relating position and orientation of the palm to the joint angles necessary to achieve these postures. This data was organized into a grid of points, with a grid of orientations for each point. This table initially contains redundant data. Various methods to prune the data could be used. A strength criterion was used initially to prune the solution set. This criterion assumes that the human body uses maximum strength[1] as the preferred position for the joint chain. Isokinetic strength data was previously collected on 14 subjects for all degrees of freedom of rotation of the arm[2]. The redundant joint chain solution in the reach table at a particular position and orientation were compared in terms of their available strength at those joint angles. The table was then purged to maximize strength. This scheme is still under research. For EVA motion, we are also considering looking at joint postures closest to neutral body posture for pruning the table.

The advantages of the look-up table are that a solution is always obtained (if one exists), many criteria (such as strength, posture, or task dependencies) may be applied to select the correct set of solutions, and it is very fast (three orders of magnitude faster than the inverse kinematics routine[3] used in our lab). The disadvantage is that the resolution of the solution is dependent on the table size, and even with moderate resolution, the table size may be enormous (e.g., a 2 inch resolution requires 1.2 million data points).

USE OF THE REACH LOOK-UP TABLE

The reach look-up table was installed in the 3D interactive graphics system used in the GRAF Lab. The user can "fly" the end effector using keyboard commands, and the reach algorithm fills in the joint angles to produce a realistic reach. The end effector may be the hand or the waist; a separate look-up table is used for each. This application allows computer animations to be generated with greater realism and speed. Formerly, human motion for animations was guided by providing commands to control each joint individually. It was a tedious procedure and often produced unnatural motion.

The reach algorithm was also installed in a Virtual Reality system. The system's hardware consists of two Silicon Graphics Reality Engines, a Virtual Research head-mounted display (HMD), two Ascension Technology Bird magnetic trackers, and one Polhemus Isotrak magnetic tracker. The magnetic tracking information is used to update the computer human model motions. For a description of the Virtual Reality System implementation see [4]. Work is now in progress on recording animation scripts from the motion of VR users immersed in the environment of the animation.

The suitability of the VR system, equipped with the reach algorithm, as a planning and analysis tool for reaching tasks is also being studied.

CONCLUSIONS

A very rapid algorithm for producing approximate solutions to human reach problems was described. The method uses a look-up table, and the accuracy of the solution increases with the table size.

The algorithm has been integrated into a 3D interactive graphics system and a VR system. It has proved useful for generating animation and promises to be useful for planning and analysis of reaching tasks.

FUTURE WORK

Ways of using the look-up table data in methods that can represent the data in a more compact form will be explored. Work has begun on looking at using the look-up table data to train neural networks. We are also looking at ways of interpolating between data points to improve resolution.

In the hope of further increasing the realism of the solutions, a look-up table will be constructed using data collected by tracking the actual movements of human subjects instead of arbitrarily exercising joints in the computer figure.

We have noted that accurate judgment of distance is often difficult in VR systems. We intend to investigate the causes of this difficulty and to look for ways to improve distance judgments. The use of artificial depth cues will be considered.

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**Session H3: PSYCHOPHYSIOLOGY, PERFORMANCE,
AND TRAINING TOOLS**

Session Chair: Dr. James Whitely

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Autogenic-Feedback Training Improves Pilot Performance During Emergency Flying Conditions

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Summary

Studies have shown that autonomous mode behavior is one cause of aircraft fatalities due to pilot error. In such cases, the pilot is in a high state of psychological and physiological arousal and tends to focus on one problem, while ignoring more critical information. This study examined the effect of training in physiological self-recognition and regulation, as a means of improving crew cockpit performance. Seventeen pilots were assigned to the treatment and control groups matched for accumulated flight hours. The treatment group comprised four pilots of HC-130 Hercules aircraft and four HH-65 Dolphin helicopter pilots; the control group comprised three pilots of HC-130s and six Dolphin helicopter pilots. During an initial flight, physiological data were recorded for each crewmember and individual crew performance was rated by an instructor pilot. Eight crewmembers were then taught to regulate their own physiological response levels using Autogenic-Feedback Training (AFT). The remaining subjects received no training. During a second flight, treatment subjects showed significant improvement in performance, while controls did not improve. The results indicate that AFT management of high states of physiological arousal may improve pilot performance during emergency flying conditions.

Introduction

Human error is the largest single cause of accidental mortality among aviators (ref. 1). It is not surprising then, that increased attention has been placed on the human factors associated with aircraft accidents. The Aviation Safety Research Act of 1988, for example, directed the Federal Aviation Administration (FAA) to expand research efforts examining the relationships between human factors and aviation safety (ref. 2). A central human factors problem, human error (HE) has been identified as the leading cause of aviation mishaps in

aircraft (ref. 3). Recent FAA reports reveal that HE is a causal factor in 66% of air carrier incidents and accidents, 79% of commuter and 88% of general aviation accidents (ref. 2). HEs account for a substantial number of military aviation accidents as well. It has been estimated that in excess of 50 to 70% aviation mishaps across all branches of the armed forces are attributed to HE (refs. 4 and 5).

The Aviation Safety Commission (refs. 6 and 8) narrowly defines the cause of accidents as pilot error only in those instances where the error appears "undeniable." This definition and the figures cited above can be misleading, however, as a result of the simplistic approach generally taken in the identification of HE as contributory or causal in aircraft incidents. These classifications do not adequately address the fact that HEs are the result of very complex processes. The term "pilot error" carries with it the implication that an aircraft commander was solely responsible for a given accident as a result of some discrete act of omission or commission. In point of fact, errors are only rarely attributable to a single cause (ref. 7) and culpability for accidents lies within the interaction between human and other factors. These factors typically include mission demand characteristics, environmental considerations and equipment design. Another factor often involved is the abrupt onset of emergency conditions, where the impact on task performance has been demonstrated (ref. 9).

Historically, attempts to decrease HEs in aviation have focused on the automation of tasks leading increasingly to the pilot as a backup to the automated systems (ref. 2). This approach, however, does not adequately address the full spectrum of human factors problems. As automation and complexity increase, so does the potential for HE (ref. 10). Within automated systems there is the expectation that humans will remain alert during boring periods and deftly assume control of the aircraft in the event of a critical situation. However, the complacency that accompanies prolonged reliance on automated systems may reduce one's ability to respond effectively in emergency situations (ref. 11). It is becoming increasingly recognized that efforts to reduce HE must be aimed more directly at the human element.

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Cockpit Resource Management (CRM) is a relatively recent attempt to reduce HES in the multi-crew cockpit (ref. 12). CRM attempts to address the HE issue through enhanced communication and workload distribution and appears to have been a fairly successful strategy. A primary assumption of CRM training is that crew coordination will become overlearned, thereby increasing the probability that it will be utilized during stressful situations. This assumption may be unrealistic as these crew coordination and communication skills may become peripheral tasks during an inflight emergency, as the pilots' central focus may well be with stick and rudder activities. Perhaps the primary value of CRM is as a preventive measure. That is, this training may produce enhanced crew effectiveness, thereby reducing the likelihood of those errors caused by crew coordination degradation.

But the problem of HE incidents are not addressed sufficiently by CRM training alone. Reasonable evidence exists to conclude that pilots may lose control of their aircraft as a direct result of reactive stress (refs. 13–17). The condition in which a high state of physiological arousal is accompanied by a narrowing of the focus of attention can be referred to as autonomous mode behavior (AMB). This study examined the efficacy of physiological self-regulation training as a means of improving pilot performance during emergency flying conditions. A number of studies have produced evidence that this type of training effectively reduces physiological arousal with a resultant efficacious effect on operational efficiency in student pilots (refs. 16 and 18). The specific method used in the present study was Autogenic-Feedback Training (AFT), which was developed by Cowings et al as a potential treatment for space motion sickness of astronauts aboard the space shuttle (refs. 19–21). This method has also been used successfully by the U.S. Air Force to control airsickness in military flight crews (refs. 22 and 23).

AFT has advantages over other methods for this particular application because it enables training individuals to regulate the levels of multiple physiological responses simultaneously, thus enabling a more system-wide reduction in reactivity to stressors. AFT was designed to be administered in a relatively short period of time (6 hrs total), can reliably produce sufficient autonomic control necessary to reduce responses to severe environmental stressors (i.e., motion sickness stimuli); and has been demonstrated to be effective in a wide population of subjects under a variety of stimulus conditions (ref. 19).

Materials and Methods

Subjects

All subjects were active-duty Coast Guard personnel, and received no additional compensation for their participation. Their informed consent was obtained prior to the initiation of the study. The research protocol was approved by the Clinical Investigation/Human Use Committee of Tripler Army Medical Center. The 17 pilots who served as subjects were volunteers from the Coast Guard Air Station, Barbers Point, Hawaii. These crewmembers consisted of 7 men from fixed-wing aircraft (HC-130), and 9 men and one woman from rotary wing aircraft (HH-65). Following an initial flight, subjects were assigned to one of two groups (treatment or control), matched for accumulated flight hours. The treatment group comprised four pilots from fixed-wing aircraft and four helicopter pilots; the control group comprised three fixed-wing pilots and six helicopter pilots. No attempt was made to match groups for sex or type of aircraft.

Apparatus

Physiological responses monitored were: respiration rate, with a pneumograph (PNG) placed around the subject's chest; heart rate (HR), with electrodes located at precordial sites; skin conductance level (SCL) electrodes placed on the underside of the right wrist; skin temperature using a thermistor placed on the lateral side of the right small finger, and muscle activity (EMG) with surface electrode placement bilaterally on the upper trapezius.

Electrode/transducer wires were secured to each subject and exited the flight suit at the collar opening and connected to J&J I-330 data acquisition system mounted behind the subject's headrest. Cables connecting the modules to a laptop computer were taped to the deck of the aircraft. Neither motor movements or sensations of the subject or other crewmembers were inhibited by the instruments. In both aircraft and ground-based training sessions, these data were digitized and stored as 0.75-second averages on a lap-top computer.

Procedures

Initially, all subjects participated in an intense emergency flying condition "check ride." Physiological monitoring and evaluation of performance commenced with the pre-flight checklist and continued throughout the flight scenario, terminating with the aircraft's return to the ramp. Allowing for the differences in flight parameters of the two types of aircraft flown and given the inherent

limitations of conducting a field study, each flight scenario was essentially the same.

The airborne portion of this study took place on U.S. Coast Guard HC-130 and HH-65 aircraft. Actual aircraft (in contrast to simulators) were utilized for this study primarily because it is methodologically desirable to study, as much as possible, real-life situations with their inherent uncertainties. No modifications to the aircraft were made and each flight carried its routine crew complement. These crew members performed their usual duties aboard the HH-65 and HC-130, with one exception on the HC-130 flights: the navigator, while on the aircraft, was not stationed at his table on the flight deck. As the scenario did not require his presence in the cockpit, his table was utilized as a work station for the physiologic data acquisition.

HC-130 emergency flight scenario— Subsequent to the pre-flight and taxi and take off, subjects climbed to a cruising altitude as designated by the air traffic controller (ATC). As a peak performance exercise, the subject was instructed to return to the traffic pattern and execute a series of touch and go maneuvers (one systems-normal, one simulated number one engine fire, and one automatic direction finder instrument approach). Upon completion of these tasks the subject departed the pattern at an altitude assigned by the ATC for a search and rescue (SAR) case in which there was ostensibly a downed A-4 pilot approximately 20 miles off shore. In order to assess the subject's performance and physiologic response while experiencing a considerable stressor, a compounding emergency condition was simulated. Once the search pattern had been established, the cargo door opened and secured, and the aircraft had descended to 200 feet above ground level (AGL), a turbine overheat of the number two engine followed by an uncontained turbine failure of that engine was simulated. The subject was then notified by a confederate of simulated airframe damage, a minor fuel leak from the number two engine, and that a crew member had sustained injuries resulting presumably from shrapnel. This announcement was followed by left hand and Essential AC bus failure indicators. Moments later, the instructor pilot communicated to the subject that there was simulated smoke (without fire) emanating from under the flightdeck, there was charring in the vicinity of the number one generator on the nacelle paint, and the master fire light, T-handle, and a visible confirmation revealed that the number one engine was on fire. Upon stabilizing the aircraft, the subject was directed to maintain a cruising altitude as instructed by the ATC, return to base and make a two engine full stop landing. This was further complicated by a simulated landing gear malfunction which required a simulated manual extension of the landing gear.

HH-65 emergency flight scenario— Following pre-flight and taxi to a hover-take off, the subject climbed to the ATC designated altitude. The subject was then instructed to execute a series of touch and go maneuvers (one standard no hover, one standard engine stall at takeoff, and one simulated number one engine stall to a running landing). Upon completion of these tasks the subject departed the pattern at an altitude assigned by the ATC for a SAR case in which there was ostensibly a distressed boat that would likely require removal of a crew member with unknown injuries. While proceeding to the vessel's position, the aircraft experienced an AC bus malfunction with a resulting loss of the gyro and pitch and roll controls. Upon stabilizing the aircraft and returning to systems-normal flight, the subject was directed to the position of the simulated craft and instructed to prepare to hoist the injured party aboard. While in a hover at approximately 50 feet AGL, the subject was given a servo-jam warning followed by a secondary hydraulic failure indicator which resulted in the rudder pedals being fixed. The subject was then requested to enter a holding pattern and return to base and land the "impaired" aircraft as instructed by the ATC. The subject was then directed to fly from the runway to the outer ramp (helo-pad). As the subject was on short-final approach, the instructor pilot simulated a stall of the number one engine from which the subject was to recover and land the aircraft as instructed.

Performance evaluation— Pilot performance measures involved subjective assessments of two instructor pilots who served as observers, with roughly equal numbers of treatment and control subjects assigned to each. The observers were not told the group assignments of individual pilots, and they graded the same individuals on both flights. Two types of observer ratings were obtained, both adapted from performance scales developed by Foushee et al. (ref. 24). The first type involved performance judgments made routinely by supervisory check pilots and were grouped by specific phases of the flight (i.e., checklist execution, taxi/takeoff, cruise, touch and go, cruise/SAR, emergency initiation, emergency return to base, and emergency approach and landing). Performance dimensions examined by this study were: stress management; crew coordination and communication; aircraft handling; and planning and situational awareness. Each performance dimension was scored on a five-point Likert scale with the following anchors: 1 = below average performance; 2 = slightly below average; 3 = average; 4 = slightly above average; and 5 = above average. The observer was instructed to circle N/A (not applicable) should a dimension not apply for some reason.

The second type of rating was designed to assess the observer's overall impression of performance throughout the flight (ref. 24), and was done upon completion of each

flight. All subjects were instructed not to discuss the specific aspects of their participation in the study with other crewmembers.

Autogenic-feedback training– The treatment condition consisted of twelve 45 minute sessions utilizing a regimen of AFT training based upon the protocol developed by Cowings (ref. 19). This protocol included directed biofeedback, discrimination training and stress challenge training with and without feedback designed to increase subject efficiency in maintaining appropriate psychophysiological control. With respect to the stress challenge condition, subjects were required to maintain physiologic control within identified parameters while actively involved in a video game challenge. The treatment group also utilized daily progressive relaxation exercises via audio tape. The control group received no treatment. This design was deemed appropriate because previous research by Toscano and Cowings (ref. 25), demonstrated that control group subjects given “sham training,” with the same number of exposures to experimenters as treatment group subjects had no advantage over a “no treatment” control group in improving their tolerance to environmental stress.

Following completion of the treatment condition, each pilot again flew the simulated emergency scenario at the same approximate time of day, and with the same rater as in their initial flight.

Results

Figure 1 shows the average overall scores obtained from each group on the first and second emergency flights. Treatment group subjects show an improvement in all nine performance dimensions while Control subjects show higher post-test scores on only two of the nine dimensions measured and actually decreased performance scores for five of these dimensions.

Performance data were analyzed with nonparametric statistics: Mann-Whitney -U tests and Wilcoxon Sign-Ranks tests. Tables 1a and b show the results of analyses which compared performance scores between and within groups during specific phases of the flights. There was no significant difference between groups on the first test, with the exception that Control subjects scored significantly higher on Aircraft Handling during Cruise Search and Rescue (table 1b). Treatment group subjects had improved their performance after training and the two groups were no longer significantly different during the Cruise Search and Rescue phase of the second flight. Following training, the performance of AFT subjects during specific phases of flight were significantly better than that of the controls for stress management, crew coordination and communication, as well as planning and situational awareness.

There was no significant difference between groups in Aircraft handling during any phases of the second flight.

Comparisons within groups revealed that AFT subjects showed significant improvements in specific phases of the flight for all performance categories, while Control subjects showed no improvement. In fact, Control subjects showed a significant decrease in crew coordination and communication during the touch and go phase of flight.

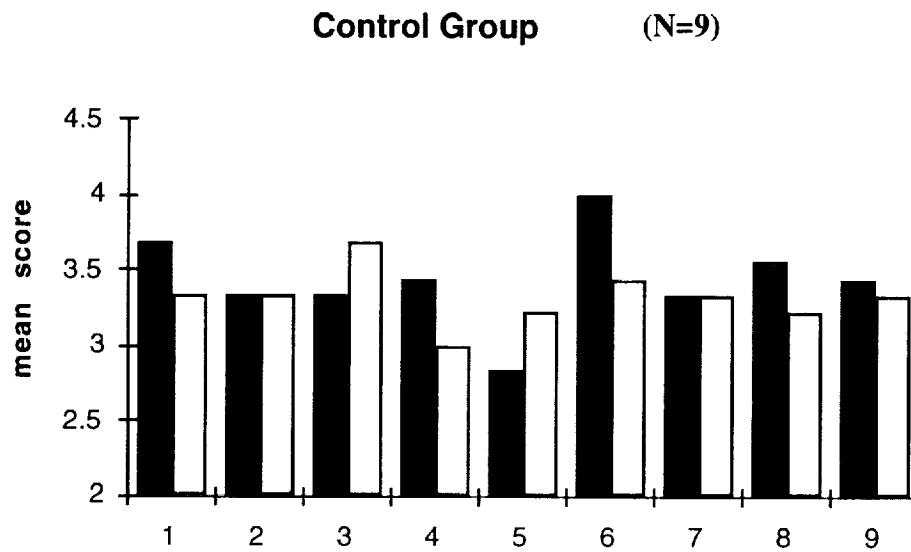
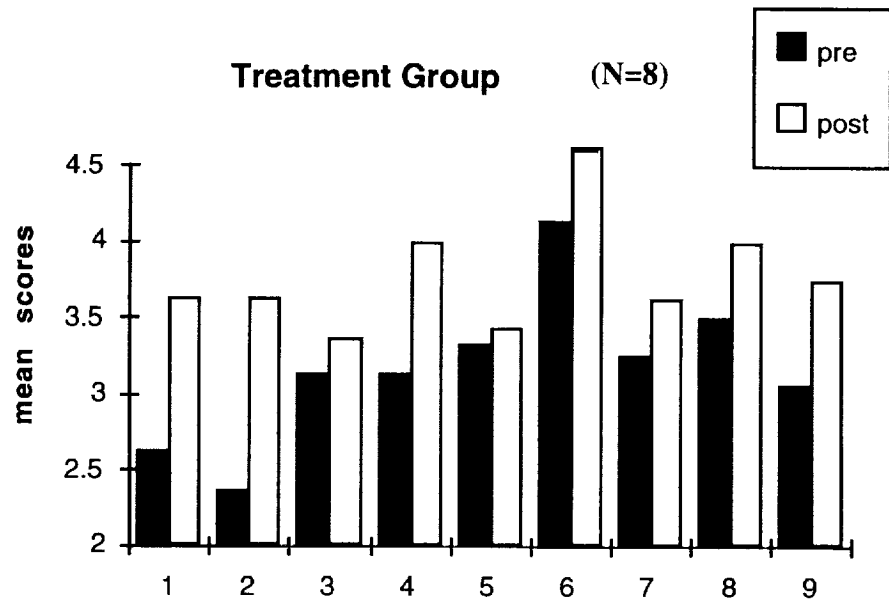
Physiological data obtained during flight and training sessions were not analyzed and will be presented in another paper.

Table 2 shows the results of Wilcoxon Signs-Ranks tests which was performed to examine the performance category, Crew Coordination and Communication, in detail. AFT subjects performed significantly better than Controls in 10 of the 13 specific dimensions of this category.

Discussion

The results support the proposition that AFT improves pilot performance during emergency flying conditions. Specifically, the data reveal that those pilots trained in AFT demonstrated improved overall knowledge of the aircraft and procedures, technical proficiency, and performance through the flight scenario. Of particular importance is a demonstrated improvement in overall performance and execution of duties as well as crew coordination and communication during that segment of the flight where multiple compounding emergencies were experienced. This suggests that AFT may be effective as a countermeasure for pilot stress-related performance decrements.

The improved crew coordination and communication performance found in the AFT subjects is particularly noteworthy, as these factors are emphasized in CRM approaches to the management of human error. AFT treatment effects were demonstrated in those dimensions involving communications with crew members, crew briefings, workload delegation, planning, and overall technical proficiency. As all of the subjects of this study have had some form of CRM training, as well as comparable previous experience in emergency flying conditions, the demonstrated improvement of these measures by the treatment group suggests that AFT may aid in the successful utilization and expansion of these skills. It is hypothesized that this improvement occurred because AFT reduced individuals' physiologic reactivity during stress. As a result, crew coordination and communication factors were not reduced to the pilot's periphery. Given



1 = knowledge of aircraft/procedures; 2 = technical proficiency; 3 = smoothness; 4 = crew coordination and communication; 5 = external communication; 6 = motivation; 7 = command ability; 8 = vigilance; 9 = overall performance and execution

Figure 1. Changes in overall performance during emergency flight scenarios.

Table 1a. Group performance dimensions by phase of flight: Mann-Whitney U-Test

Crew Coordination and Communication	Between Groups AFT vs Controls		Within Groups pre- vs post-tests	
	pre-test	post-test	AFT	Controls
Checklist Execution	—	$p < 0.05$	$p < 0.05$	—
Taxi/takeoff	—	$p < 0.05$	—	—
Initial Cruise	—	—	—	—
Touch & Go	—	—	—	$p < 0.05^*$
Cruise Search and Rescue	—	—	$p < 0.05$	—
Emergency Initiation	—	$p < 0.005$	$p < 0.01$	—
Emergency Return to Base	—	—	—	—
Emergency Approach and Landing	—	—	—	—
Planing and Situational Awareness	Between Groups AFT vs Controls		Within Groups pre- vs post-tests	
	pre-test	post-test	AFT	Controls
Checklist Execution	—	—	—	—
Taxi/takeoff	—	$p < 0.05$	—	—
Initial Cruise	—	—	—	—
Touch & Go	—	$p < 0.05$	—	—
Cruise Search and Rescue	—	—	—	—
Emergency Initiation	—	—	—	—
Emergency Return to Base	—	—	$p < 0.05$	—
Emergency Approach and Landing	—	—	$p < 0.05$	—

* Control subjects scored significantly lower during the second flight.

Table 1b. Group performance dimensions by phase of flight: Mann-Whitney U-Test

Stress Management	Between Groups AFT vs Controls		Within Groups pre- vs post-tests	
	pre-test	post-test	AFT	Controls
Checklist Execution	—	—	—	—
Taxi/takeoff	—	—	—	—
Initial Cruise	—	—	—	—
Touch & Go	—	$p < 0.05$	$p < 0.05$	—
Cruise Search and Rescue	—	—	—	—
Emergency Initiation	—	$p < 0.05$	$p < 0.05$	—
Emergency Return to Base	—	$p < 0.05$	$p < 0.05$	—
Emergency Approach and Landing	—	$p < 0.05$	$p < 0.05$	—
Aircraft Handling				
	Between Groups AFT vs Controls		Within Groups pre- vs post-tests	
	pre-test	post-test	AFT	Controls
Checklist Execution	—	—	—	—
Taxi/takeoff	—	—	—	—
Initial Cruise	—	—	—	—
Touch & Go	—	—	$p < 0.05$	—
Cruise Search and Rescue	$p < 0.05^*$	—	$p < 0.05$	—
Emergency Initiation	—	—	$p < 0.05$	—
Emergency Return to Base	—	—	—	—
Emergency Approach and Landing	—	—	$p < 0.05$	—

* Control subjects scored significantly higher than AFT subjects during their first flight.

Table 2. Improvement in specific dimensions of crew coordination and communications during the second flight scenario: Wilcoxon Sign-ranks test

Dimension	AFT vs. Control		
	N	z	p<
Briefing thorough, establishes open communication, addresses coordination, planning, team creation, and anticipates problems	8	2.20	0.05
Communications timely, relevant, complete and verified	8	2.20	0.05
Inquiry/Questions practiced	8	1.69	0.05
Assertion/Advocacy practiced	8	1.82	0.05
Decisions communicated and acknowledged	8	1.57	—
Crew self-critique of decisions and actions	7	1.82	0.05
Concern for accomplishment of tasks at hand	8	0.91	—
Interpersonnel relationships/group climate	8	1.82	0.05
Overall vigilance	8	1.09	—
Preparation and planning for in-flight activities	8	2.20	0.05
Distractions avoided or prioritized	8	1.34	—
Workload distributed and communicated	8	2.20	0.05
Overall workload	8	0.91	—
Overall technical proficiency	8	2.02	0.05
Overall crew effectiveness	8	2.02	0.05

the current emphasis on crew coordination and communication skills in the reduction of human error in flight, identification and control of the physiologic mechanisms that enhance or inhibit these activities warrant further study.

The problems associated with AMB are manifest when the pilot becomes saturated with tasks requiring increased complex decision-making skills. When a major ingredient of this saturation includes the pilot's own physiology, the recognition of internal cues that precede this hypersympathetic arousal and initiation of appropriate corrective action become increasingly important. Utilizing one's physiology as an asset rather than as an undesirable event to be ignored, the available resources to deal with an external problem are increased. It is suggested that, by expanding the pool of available resources for dealing with in-flight emergencies, the pilot is better able to manage the endogenous and exogenous stressors being experienced.

While the small subject population in this study precluded fixed vs. rotary wing comparisons, air frame and related mission requirement influences are areas that necessitate further study. Future studies will determine if performance improvements are related to type of aircraft and if those pilots of multiple crew aircraft gain more value

from training than those flying tactical (single or dual crew) aircraft. Use of ambulatory monitoring equipment for recording physiological responses in flight would be less obtrusive than the instrumentation used in the present study and will provide objective indices of the effects of training on treatment group subjects. More comprehensive examinations of AFT and its effect on pilot performance may reveal that training in recognition and regulation of one's own physiological reactions to environmental stress should become a portion of the standard curriculum of aerospace crews.

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**Implementing Bright Light Treatment for MSFC Payload
Operations Shiftworkers**

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Intense light can phase-shift circadian rhythms and improve performance, sleep, and wellbeing during shiftwork simulations, but to date there have been very few attempts to administer light treatment to real shiftworkers. We have developed procedures for implementing light treatment and have conducted controlled trials of light treatment for Marshall Space Flight Center's Payload Operations staff during the USML-1 mission. We found that treatment had beneficial effects on fatigue, alertness, self-rated job performance, sleep, mood, and work attendance.

Although there are portable bright light boxes commercially available, there is no testing protocol and little performance information available. We measured the illuminance of two candidate boxes for use in this study and found that levels were consistently lower than those advertised by manufacturers. A device was developed to enhance the illuminance output of such units. This device increased the illuminance by at least 60% and provided additional improvements in visual comfort and overall exposure. Both the design of this device and some suggested procedures for evaluating light devices will be presented.

FLIGHT CONTROLLER ALERTNESS AND PERFORMANCE DURING MOD SHIFTWORK OPERATIONS

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ABSTRACT

Decreased alertness and performance associated with fatigue, sleep loss, and circadian disruption are issues faced by a diverse range of shiftwork operations. During STS operations MOD personnel provide 24 hr. coverage of critical tasks. A joint NASA Johnson Space Center and NASA Ames Research Center project was undertaken to examine these issues in flight controllers during MOD shiftwork operations. An initial operational test of procedures and measures was conducted during STS-53 in December, 1992. The study measures included a Background Questionnaire, a subjective daily logbook completed on a 24 hr. basis (to report sleep patterns, work periods, etc.), and an 8 minute performance and mood test battery administered at the beginning, middle, and end of each shift period. Seventeen flight controllers representing the 3 Orbit shifts participated. The initial results clearly support further data collection during other STS missions to document baseline levels of alertness and performance during MOD shiftwork operations. Countermeasure strategies specific to the MOD environment are being developed to minimize the adverse effects of fatigue, sleep loss, and circadian disruption engendered by shiftwork operations. These issues are especially pertinent for the night shift operations and the acute phase advance required for the transition of day shift personnel into the night for shuttle launch. Implementation and evaluation of the countermeasure strategies to maximize alertness and performance is planned. As STS missions extend to further EDO (extended duration orbiters) timelines and planning for 24 hour Space Station operations continues, alertness and performance issues related to sleep and circadian disruption will remain highly relevant in the MOD environment.

INTRODUCTION

The Mission Operations Directorate (MOD) at the Johnson Space Center (JSC) in Houston, Texas has been responsible for manned space operations since 1965. The center for operations at Houston is the Mission Control Center (MCC), and the operators are designated as Flight Controllers. All flight operations are handed over to the Mission Control Center (MCC) immediately after launch occurs. Prior to that point, the Kennedy Space Center in Florida has control authority from their Launch Control Center (LCC).

Early human space operations required limited 24 hour support from Flight Controllers, due to both the simplicity of the space vehicles, and the very limited duration of the missions. The overwhelming drive of the early programs was to establish a U.S. human presence in space, and to extend the capabilities of that presence to a length that would support a lunar landing and return.

The first U.S. space station, the Skylab program, posed significant challenges to the agency. The majority of space vehicle hardware did not prove to be a significant technical challenge. However, the operations community was significantly challenged, as once the vehicle was launched, 24 hour monitoring would be required for the life of the program. These challenges included maintainability issues for a control center designed for short flights, and budget limitations that prohibited increased hiring of Flight Controllers to staff the MCC. Since 24 hour operations were not prevalent at that time in industry, the management of the Mission Operations Directorate did not have experience bases to draw upon.

Significant anecdotal reports exist on the effects of 24 hour operations on the Skylab Flight Controller population. High turnover and divorce rates are still commonly cited, almost twenty years after the program. One primary concern to management was morale among the Flight Controllers, since historically this has been a highly motivated and extremely dedicated group.

Current shuttle flights are relatively short in duration, but the trend is quickly moving toward longer duration missions. The intent is to increase both the science return from a given flight and the operations experience for long duration missions in preparation for an orbiting space station.

Another factor has been the large demographic changes that have occurred since the early programs. The original Flight Controller population, similar to the original astronauts, were almost exclusively white males, and highly educated in a focused area of expertise. The current Flight Controller population is male and female, with very diverse educational and experience backgrounds.

PROBLEM IDENTIFICATION

Shuttle shiftwork support is dictated by both the mission objectives and the standards and policies of the Mission Operations Directorate. Since the mission objectives are used to decide a launch date, as well as time of day, these are directly reflected in the support schedule designed by the Lead Flight Director for the given flight.

For flights scheduled shorter than 10 days, three Flight Control Teams (FCTs) are used to provide 24 hour operations support. For the orbit phase of flight, the teams are typically designated Orbit 1, Orbit 2 and Orbit 3. Shift lengths vary, but require a hand-over both at the beginning of a shift and the end of a shift. Daily shift lengths of 10 hours are not uncommon. For flights of 10 days and longer, a fourth Flight Control Team (FCT) is added for the purpose of relief. The fourth team is rotated into the flight support schedule to allow each of the other three FCTs time off. The number of days off, and the specifics of the fourth team rotation are driven by the goals and length of the mission.

The Flight Controllers are responsible for a wide range of cognitive tasks, from sustained trend analysis to rapid response emergency actions. Multiple voice channels must be monitored concurrently by each controller for effects by other activities to their system. The demanding nature of the task requires that cognitive processing levels and vigilance remain high, as even small mistakes can be operationally significant.

The Lead Flight Director must consider a diverse number of other constraints when developing the shift work schedule for a given flight. For example, the launch time, landing time, mission goals, in-flight crew schedule, and training for a given FCT are all considerations. The clock hour difference between the launch and landing times determines if the FCTs must phase advance or phase delay their schedule. The launch time of day is dependent on the day of the year the launch is to occur, requiring the schedule to be flexible and dynamic. Since all FCTs are not trained to support all activities, when a launch slips the FCTs must also slip an appropriate period of time. Each FCT is essentially tied to flight activities that occur at a specific Mission Elapsed Time (MET).

The Mission Operations Directorate became proactively interested in assessing cognitive performance levels, as well as potential countermeasures, as part of continuing efforts to assure safe flight operations. MOD management became aware of NASA supported activities to address sleep and circadian issues with the astronaut flight crews, and subsequently initiated efforts directed at the Flight Controller population.

MOD PROJECT DEVELOPMENT

MOD management was aware of a workshop sponsored by the Johnson Space Center Space and Life Sciences Directorate held in Houston in 1991. The workshop involved Flight Surgeons, Flight Directors, Astronauts and circadian rhythm and sleep researchers from academia and within NASA. The focus of the workshop was to address some of the shiftwork issues raised as part of the Roger's Commission report on the Challenger accident, specifically, the hours of service required of Launch and Flight Controllers. At this workshop MOD operations personnel provided background on both crew and Flight Controller flight support requirements for the pre- and during flight time frames. Initial efforts focused on flight crew support, as the Health Stabilization Program provided greater control over the astronaut preflight schedules than over Flight Controller schedules.

However, the Flight Controllers shiftwork issues continued unsupported. The concerns of MOD management were heightened by the increase in flight durations and the subsequent increase in comments received by management from Flight Controllers regarding shiftwork issues. To address these concerns, an effort was initiated within MOD by forming an MOD lead project to include the appropriate institutional personnel from MOD, the Space and Life Sciences Directorate, and Ames Research Center/Fatigue Countermeasures Program.

MOD intent was to capitalize on the expertise of each organization, by recognizing each had a role in supporting the project from a study phase through to a fully operational support program. Various meetings were held between MOD and the other participants to delineate areas of responsibility and expertise. These efforts resulted in the initial operational test described here, the first to document Flight Controller performance levels during actual operations support. The final group of Principal Investigators included MOD personnel, Fatigue Countermeasures Program personnel from Ames Research Center, and Ames' collaborators from the University of Pennsylvania.

PROJECT PLAN

The complete project is composed of three distinct phases: Phase I Operational Test, Phase II Assessment, and Phase III Intervention. Since the project represents the first time an investigation of the human element is occurring in the Mission Control Center during operations, a conservative but progressive approach was planned.

The Phase I Operational Test was designed to identify the constraints and practicality of conducting a study in the unique environment of the MCC. The leading concern of both the investigative team and the Flight Director's Office was to assure that the study did not interfere with usual operations, and "safety valves" were provided to ensure that interference did not occur.

These issues were addressed at all levels of participation. The Flight Controllers were instructed to withdraw from participation at any point if operations support was in jeopardy. Each member of the Data Collection Team had the authority to suspend data collection at anytime, either temporarily or permanently, if operations support was in jeopardy. The Data Collection Team during the Operational Test was composed of experienced MOD personnel. The Flight Director on each of the three shifts also had the authority to suspend the project at any time.

The Phase II Assessment, which has not yet been conducted, is designed to provide more detailed and refined measures of the most significant factors identified during the Phase I Operational Test. More specific performance evaluation and refined subjective measures will be incorporated. Performance evaluation methods will be enhanced to allow near-real-time analysis of the data. Phase II is designed to be conducted during several future flights, to assure a representative sample of the Flight Controller population under a number of operational conditions.

The Phase III Intervention is designed to provide the most promising and operationally relevant interventions tailored to the requirements of MOD operations and currently available for implementation. Preference will be given to strategies implemented and demonstrated effective in a field setting. Evaluation of the Phase III Intervention will be conducted using the same data collection methods and measures obtained during the Phase II Assessment. Efforts will be made to differentiate the effectiveness of distinct strategies employed during the Phase III Intervention.

PHASE I OPERATIONAL TEST: METHODS

The Phase I Operational Test was conducted during STS-53 flight operations in December, 1992. The specific measures obtained and data collection procedures are described below.

Measures

The operational test utilized measures modified from previous field studies conducted by the Ames Fatigue Countermeasures Group (Rosekind et al., 1993, Gander et al., in press, Rosekind et al., in press). The measures used included a background questionnaire, MOD Controller Daily Logbook, and a MOD Shiftwork Evaluation packet. Measures were modified to collect information on the unique features posed by MOD Flight Controller operations during a shuttle mission. Some modifications were required due to the limited time available from Flight Controllers pre-, during and post-flight, as well as time constraints agreed upon with the Flight Director's Office. Data was collected at all phases of flight operations except the launch and landing time frames.

The selection of the specific measures was guided by subject availability and operational constraints. Extensive baseline data collection was not practical in part due to preflight training and other preflight responsibilities. During the mission, evaluation time was limited to minimize interference with flight support operations.

Background Questionnaire: The background questionnaire was originally designed for use in short- and long-haul flight operations studies (Gander et al., in press). The MOD Flight Controller Background Questionnaire for this study consisted of 192 questions in a variety of formats and took approximately 45 minutes to complete. It examined factors associated with fatigue, including sleep/wake cycles, nutrition, life-style, attitudes toward work and certain personality profiles. Sections of the inventory assessed basic demographics, including MOD and shiftwork experience, general health, home sleep quality, quantity and timing, and self-ratings of personality characteristics.

MOD Controller Daily Logbook: The MOD Controller Daily Logbook was modified from a "Pilot's Daily Logbook," used extensively by the NASA Ames Fatigue Countermeasures Program (Gander et al., in press, Rosekind et al., in press). Consistent parameters were obtained for later comparisons between the Flight Controller data and the existing NASA Ames Fatigue

Countermeasures Program Pilot database. The total number of questions was reduced, though sampling rate was increased.

The MOD Controller Daily Logbook was used to obtain information on bed and wake-up times, sleep patterns (quantity and quality), exercise, shift information (i.e., duty time), naps, meals and beverages, smoking behavior, medication use, and physical symptoms. The logbook also contained questions and analog scales for rating workload and fatigue factors that were completed during the shift period.

MOD Shiftwork Evaluation of Performance and Mood Packet: The MOD Shiftwork Evaluation of Performance and Mood Packet included measures of performance and alertness selected according to three criteria: (1) their sensitivity to sleep loss, circadian variation and fatigue from shiftwork; (2) the extent to which they reflected fundamental elements in the cognitive work demands of Flight Controllers; and (3) their brevity and unobtrusiveness for use as probes during flight operations. Objective performance measures included a probed-recall memory (PRM) test (Dinges et al., 1993), a two-digit serial addition (SA) test, and a word fluency (WF) test. Subjective measures included traditional psychometrics with different constructions (e.g., Likert-type, adjective checklist, analog), as well as tailored ratings of performance and effort required to perform during shift, and ratings of factors that interfered with performance during shift. Examples included 100-mm visual analog ratings of eight subjective dimensions; the Stanford Sleepiness Scale (SSS; Hoddes et al., 1973); the activation-deactivation adjective checklist (AD-ACL; Thayer, 1978); and ratings of performance and effort required to perform during performance bouts (Dinges et al., 1992).

Procedures

Data obtained preflight included the 45 minute MOD Flight Controller Background Questionnaire and the MOD Controller Daily Logbook. Also in the preflight time frame, administrative requirements, such as performance packet practice sessions and informed consent were obtained. Most information and performance practice sessions were conducted in groups, however, due to preflight workload some individual sessions were required.

The subjects were requested to initiate entries into the MOD Controller Daily Logbook one week prior to flight. The flight slipped, therefore, the actual period documented preflight was greater than planned. One period of interest was the transition from pre-flight to during flight shift support. All subjects completed the entries for this period.

During the flight, the Flight Controllers continued completing the MOD Controller Daily Logbook, including sections that were completed in the first and second halves of shifts. The shift sections provided a second independent source of data that was used to examine any unusual finding in the MOD Shiftwork Evaluations.

Data collection personnel were assigned to each of the three shifts. Since the STS-53 flight represented the last Department of Defense classified flight, and was also the proof of concept operational test, it was decided to use MOD personnel with MCC experience for data collection.

Actual data collection started on the first shift after launch and was terminated on the shift scheduled to monitor the deorbit burn. No efforts were made to obtain data during the entry and landing phases of flight. Though clearly of interest, it was determined that data collection would have adversely affected operations during these phases.

During each shift, an MOD Shiftwork Evaluation Packet was completed by each volunteer Flight Controller at the beginning, middle and end of a shift. The evaluations were centered around 1.5 hours into the shift, the mid-point of the shift, and 1.5 hours from the scheduled end of the shift. The Performance Evaluations initially took about 9 minutes to complete, and as the subjects became more familiar with the procedures evaluation time decreased to approximately 7 minutes. The specific timed components of the Evaluation Packet were carefully timed by stopwatch and logged by data collection personnel.

The volunteer Flight Controllers completed the Daily Logbook for a minimum of three days post-flight. Many of the volunteers completed the logbooks beyond this period and therefore provided data on the readaptation process.

Due to scheduling constraints, for most volunteers the process of baseline performance and alertness evaluations was also done in the post-flight time frame and paralleled the methodology used during the flight.

Data Analyses

Background Questionnaire data were analyzed descriptively for overall variable means, including population demographics and sleep/wake reports. The Daily Logbook was also analyzed descriptively for duty parameters, subjective ratings of sleepiness and boredom, and sleep/wake parameters during the mission.

Performance and alertness data were analyzed descriptively. Graphic displays were made of each shift's mean value on each variable for all three time points within each of six days of the mission. Analysis of variance and t-tests were used to compare performance and mood variables among shifts, although sample sizes were considered too small to yield statistically reliable outcomes for the Phase I Operational Test. Positive results at this Phase do serve, however, a hypothesis-generating function for the Phase II Assessment.

PHASE I OPERATIONAL TEST: RESULTS

Subjects

Seventeen volunteer Flight Controllers participated in the Phase I Operational Test. They included 5 Flight Controllers on Orbit 1, 7 Flight Controllers on Orbit 2, and 5 Flight Controllers on Orbit 3. During STS-53, Orbit 1 corresponded to a day shift, Orbit 2 corresponded to an evening shift, and Orbit 3 corresponded to the night shift.

MOD Flight Controller Background Questionnaire Results

Demographic Data: Demographic data describing the 10 male and 7 female volunteer Flight Controllers are portrayed in Table 1. Table 1 provides data for the overall group and by Orbit. The average age for all volunteers was 28.6 years with an average of 4.1 years at Johnson Space Center.

<i>Table 1. Background Questionnaire: Demographic Data (10 M, 7 F)</i>				
	Overall	Orbit 1	Orbit 2	Orbit 3
Age (mean yr.)	28.6	28.0	30.0	27.2
Yr. at JSC	4.1	4.9	3.4	4.4
Yr. on console	2.7	3.8	1.6	3.1
Yr. at status	2.2	2.0	1.8	3.2
Height (in.)	68.8	70.8	66.7	69.8
Weight (lb.)	156.7	172.6	148.7	151.8

Subjects: Orbit 1 = 5; Orbit 2 = 7; Orbit 3 = 5.

These data demonstrated that the Flight Controller population was a relatively young group with experience at JSC ranging from 3.4 to 4.9 years. There was a greater range of years experience on console with the Orbit 2 individuals at roughly half (ave. 1.6 yr.) the other 2 Orbits.

Sleep/Wake Parameters. On the Background Questionnaire, the volunteer Flight Controllers reported their usual sleep/wake patterns at home. This included information about time-in-bed, time-out-of-bed (for both weekdays and weekends), average time to fall asleep (i.e., sleep latency), average total sleep time (hr.), and number of awakenings per night. These retrospective, subjective data portrayed the average sleep/wake patterns in the Flight Controllers usual home environment. These results are portrayed in Table 2.

<i>Table 2. Background Questionnaire: Sleep/Wake Parameters</i>				
	Overall	Orbit 1	Orbit 2	Orbit 3
InBed: weekdays (24-hr. clock)	23.2	22.9	23.1	23.5
OutBed: weekdays (24-hr. clock)	6.5	6.6	6.3	6.7
InBed: weekends (24-hr. clock)	24.0	23.8	24.2	23.9
OutBed: weekends (24-hr. clock)	8.6	8.3	8.3	9.4
Sleep latency (min.)	22.1	19.0	20.7	27.0
Total sleep time (hr.)	7.3	7.8	7.1	7.2
Number awakenings	1.0	0.4	1.3	1.2

The Sleep/Wake data showed a classic weekday vs. weekend pattern. Overall, the group reported getting into bed earlier and awakening earlier during the work week (ave. 7.3 hr.) compared to weekend nights when getting into bed later and sleeping later (ave. 8.6 hr.). This pattern also suggested a compensatory lengthening of weekend sleep to offset a probable cumulative sleep debt that accrued during the work week.

MOD Controller Daily Logbook Results

Duty parameters. The MOD Controller Daily Logbook included data on shift duration and breaks during the duty period. The results are portrayed in Table 3.

<i>Table 3. Daily Logbook: Duty Parameters</i>				
	Overall	Orbit 1	Orbit 2	Orbit 3
Shift duration (hr.)	9.5	10.0	8.7	9.8
Duty breaks (#)	0.5	0.9	0.5	0.1

The data revealed that while the overall average shift duration was 9.5 hr., there was a considerable range across Orbits. Orbit 3 night shift at 9.8 hr. was very close to the average daytime shift duration (10 hr.), while the Orbit 2 evening shift averaged 8.7 hr. The data regarding breaks during a shift revealed that the Orbit 1 day shift took an average of 1 break per shift, while during the Orbit 3 night shift (of approximately equal duration to Orbit 1) Flight Controllers averaged 0.1 breaks per shift.

Sleep/Wake Parameters. In the MOD Controller Daily Logbook Flight Controllers reported data about their daily sleep/wake patterns, including the time it took to fall asleep (sleep latency), total sleep time, number of awakenings during sleep, and other sleep episodes (e.g., naps). The Sleep/Wake parameter results from the Daily Logbook are portrayed in Table 4.

<i>Table 4. Daily Logbook: Sleep/Wake Parameters</i>							
	Overall	Orbit 1	Orbit 2	Orbit 3	Pre	Duty	Post
Sleep latency (min.)	22.1	26.5	24.4	14.8	25.6	21.9	18.8
Total sleep time (hr.)	6.5	6.6	6.7	6.1	6.4	6.3	6.8
Number awakenings	1.2	0.9	1.2	1.4	1.2	1.3	1.0
Sleep Efficiency (%)	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Total daily sleep (hr.)	7.6	7.8	7.2	7.8	7.7	7.3	7.7

Overall, the group reported obtaining an average of 6.5 hr. of sleep with a distinct range between Orbits. The Orbit 3 night shift Flight Controllers averaged 6.1 hr., while the other two Orbits averaged 6.6 to 6.7 hr. As a group, the lowest average total sleep occurred during the mission (6.3 hr.) with an apparent compensatory rebound to 6.8 hr. post-mission. This reflects the average sleep obtained in Flight Controllers' primary sleep period. However, overall the group obtained about 1 hr. more sleep per day by taking sleep episodes (e.g., naps) at other times of the day. This suggests that the Flight Controllers acknowledged the decreased sleep obtained in the primary sleep period and sought other sleep opportunities to supplement their total daily sleep. With the "extra" sleep, the group averaged a total daily sleep of 7.6 hr., though this decreased to 7.3 hr. during the mission.

MOD Shiftwork Evaluation of Performance and Mood Results

Effects of acute phase advance on day 1 of mission. Subjective measures of sleepiness, alertness, and fatigue showed similar trends on day 1 of mission, regardless of the type of psychometric used. On the first day of mission, Orbit 1 tended to average higher ratings of sleepiness relative to Orbits 2 and 3. This was especially evident for ratings made midway in shift, as shown in Table 5. The elevated sleepiness appeared to be a direct result of the 3-hr. acute phase advance of the start time for the Orbit 1 shift on day 1 of mission. This was confirmed by the fact that the median time of evaluation of Orbit 1 midway through their day 1 shift was 0715 hr. (range 0640-0734 hr.), compared to a median mid-shift time of 1537 hr. (range 1510-1610 hr.) for Orbit 2 and 2240 hr. (range 2222-2254 hr.) for Orbit 3.

<i>Table 5. Mean sleepiness/fatigue ratings midway in shift on mission day 1</i>					
Psychometric	Orbit 1	Orbit 2	Orbit 3	F2.14	p value
Stanford Sleepiness Scale	3.20	2.02	2.20	1.95	.178
AD-ACL deact-sleepiness	13.20	8.10	9.60	2.62	.107
Analog alert/sleepy	5.84	2.68	4.08	4.33	.034
Sleepy/fatigue on shift	1.00	0.33	0.20	3.18	.072

The results of the objective performance measures revealed trends similar to those for subjective sleepiness on day 1 of mission, but there were no significant differences among shifts on day 1.

Effects of shift for days 2-6 of Mission. Subjective measures of sleepiness, alertness, and fatigue showed similar trends between shifts across mission days 2-6, regardless of the type of psychometric used. Conspicuous in all metrics was the marked elevation of sleepiness and fatigue (and diminution of alertness and energy) on Orbit 3 at the midway and final phase of shift time points, especially on days 2 and 3 of mission. Table 6 displays ratings taken near the end of shift on day 2. The elevated sleepiness near the end of shift for Orbit 3 appeared to occur at a time of increased circadian propensity for sleepiness. This was confirmed by the fact that the average time of evaluation of Orbit 3 near end of the day 2 shift was 0330 hr. (range 0303-0349 hr.), compared to the average time of 2030 hr. (range 2007-2126 hr.) for Orbit 2 and 1108 hr. (range 1048-1140 hr.) for Orbit 1.

<i>Table 6. Mean sleepiness/fatigue ratings near end of shift on mission day 2</i>					
Psychometric	Orbit 1	Orbit 2	Orbit 3	F2.14	p value
Stanford Sleepiness Scale	2.40	2.34	3.80	2.93	.086
AD-ACL deact-sleepiness	12.20	10.70	16.40	2.73	.099
Analog alert/sleepy	4.30	4.02	5.88	1.12	.353
Sleepy/fatigue on shift	0.20	0.78	1.20	2.69	.102

Ratings of motivation level and performance during the evaluation bouts showed a differential pattern near the end of shift assessment on day 2 for Orbit 3, indicating that Orbit 3 subjects were less motivated and that they felt they did less well on the performance probes. These data are shown in Table 7.

<i>Table 7. Performance-related ratings near end of shift on mission day 2</i>					
Psychometric	Orbit 1	Orbit 2	Orbit 3	F2.14	p value
Analog motivation level	5.58	7.46	4.20	3.50	.058
Performance self-evaluate	7.40	7.33	5.80	6.44	.010

Consistent with subjective assessments of sleepiness and fatigue, objective performance of cognitive (arithmetic) speed, memory, and word fluency, also showed some evidence of trends toward lower performance efficiency in Orbit 3 subjects (relative to Orbits 1 and 2) near the end of shift on mission days 2 and 3. These results are contained in Tables 8 and 9.

<i>Table 8. Mean performance near end of shift on mission day 2</i>					
Performance	Orbit 1	Orbit 2	Orbit 3	F2,14	p value
SA test (# completed)	16.20	15.37	11.80	2.89	.089
PRM test (# correct)	3.60	3.44	2.60	1.73	.213
WF test (# completed)	40.00	42.87	34.80	2.14	.154

<i>Table 9. Mean performance near end of shift on mission day 3</i>					
Performance	Orbit 1	Orbit 2	Orbit 3	F2,14	p value
SA test (# completed)	16.80	15.57	13.60	0.64	.541
PRM test (# correct)	3.20	3.71	2.60	2.22	.145
WF test (# completed)	40.00	40.00	29.00	3.35	.064

Two factors appeared to contribute to the variability in cognitive performance. The first was substantial inter-individual variability. This information will be important in calculating the sample sizes required for the Phase II Assessment, and possibly in helping to develop assessments that identify Flight Controllers who are more resilient to night work. The second factor was intra-subject variability learning, which resulted in systematic improvements in performance across days of mission, especially on the serial addition and word fluency tests. To reduce this source of variance in Phase II, pre-mission training would need to be completed on tasks. Even in this case, however, some learning would likely occur across missions days. Since even the simplest tests of cognitive speed tend to have prolonged learning curves (Dinges & Kribbs, 1991), a better solution would be to utilize probes that have been demonstrated to be devoid of learning effects. A more difficult version of the probed-recall memory test (Dinges et al., 1993) and the psychomotor vigilance task (Dinges & Powell, 1985, 1988; Rosekind et al., in press), both of which have been well validated to be sensitive to sleep loss and circadian variation, appear to be reasonable solutions to the problem of learning curves.

Finally, many non-fatigue related factors showed no differences among shifts. These include ratings of workload, work equipment problems, stress, boredom, anxiety, personal worries, co-worker problem, happiness, hunger and thirst. Thus, we do not have reason to believe that these factors contributed to the trends we observed in fatigue-related variables. When differences did emerge among shifts they tended to cluster in the domain of sleepiness/fatigue/alertness, on both subjective and objective measures, and they appeared to be associated, as expected, with night shift operations. The fact that both Orbit 1 and Orbit 3 experienced fatigue when engaged in night work suggests that the trends observed were not idiosyncratic to one shift of Flight Controllers. On the other hand, the differences observed among Orbits appeared to diminish across the 6 days of mission, suggesting the possibility that some adaptation is occurring to the night shift. We conclude that Flight Controllers working night shift either acutely or chronically may be at increased risk of lowered alertness and reduced performance capacity, especially during the first few days of mission. The Phase II Assessment is aimed at providing a detailed documentation of this

hypothesis, and of pointing to practical countermeasures to performance degradation for testing in Phase III. The Phase I Operational Test demonstrated clearly that it is possible to safely and efficiently acquire objective data through periodic probes of performance and alertness in Flight Controllers, during shifts and across mission days, without interfering with mission goals or operations. This makes it possible to mount and sustain a program of self-evaluation aimed at promoting the highest levels of performance in Flight Controllers.

DISCUSSION

Overall, the results of the Phase I Operational Test support several observations. During the STS-53 shuttle mission, the volunteer Flight Controllers reported an average of 6.5 hr. sleep during their primary sleep period. The lowest reported average was 6.1 hr. of sleep for Orbit 3 Flight Controllers. This sleep was supplemented with an average of 1.1 hr. of "other" sleep (e.g., naps) obtained at other times of the day. The average total sleep obtained during the mission was less than pre and post-mission levels. The Orbit 3 night shift duration equalled Orbit 1 (i.e., about 10 hr.), though Orbit 3 personnel averaged 0.1 breaks per shift compared to the 1 break per shift obtained on the Orbit 1 day shift. The subjective measures demonstrated an increase in reported sleepiness on Orbit 3 compared to Orbits 1 and 2. Performance evaluation measures suggested decreased cognitive performance on Orbit 3 compared to Orbits 1 and 2. The data also suggested specific periods of vulnerability during transition from pre-launch status to mission operations.

All objectives of the Phase I Operational Test were met during STS-53 in December, 1992. The investigation was viewed as a success by Flight Controllers for its minimal intrusion in usual MOD operations. The results clearly established the feasibility of conducting the Phase II Assessment and the subsequent Phase III Intervention. This demonstration also solidified an effective and coordinated Johnson Space Center/Ames Research Center collaboration. The investigation team was able to utilize the combined group expertise to identify specific issues, develop a project plan, implement and complete data capture, and follow through with data analysis, reporting, and further recommendations. The results of the Phase I Operational Test support the planning and implementation of the Phase II Assessment and the subsequent Phase III Intervention.

Recommendations for the Phase II Assessment include an appropriate broader baseline training period, larger N per Orbit, implement a refined performance battery (with attention to issues of sensitivity and learning curves), and consideration of inter-individual variability. The Phase III Intervention should target areas specifically identified in the more complete Phase II Assessment. Intervention recommendations might include shiftwork education and training, the development of preventive strategies prior to and during mission, and the development of operational countermeasures to maintain alertness and performance during missions (Rosekind et al., 1991). Finally, it would be critical to develop a core for future program development and implementation during STS short and long duration flights and Space Station operations.

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AUTOMATING THE TRAINING DEVELOPMENT PROCESS FOR MISSION FLIGHT OPERATIONS

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ABSTRACT

Traditional methods of developing training do not effectively support the changing needs of operational users in a multimission environment. The Automated Training Development System (ATDS) Copyright © 1993, California Institute of Technology, provides advantages over conventional methods in quality, quantity, turnaround, database maintenance, and focus on individualized instruction. The Operations System Training Group at the Jet Propulsion Laboratory performed a six-month study to assess the potential of ATDS to automate curriculum development and to generate and maintain course materials. To begin the study, the group acquired readily available hardware and participated in a two-week training session to introduce the process.

ATDS is a building activity that combines training's traditional information-gathering with a hierarchical method for interleaving the elements. The program can be described fairly simply. A comprehensive list of candidate tasks determines the content of the database; from that database, selected critical tasks dictate which competencies of skill and knowledge to include in course material for the target audience. The training developer adds pertinent planning information about each task to the database, then ATDS generates a tailored set of instructional material, based on the specific set of selection criteria. Course material consistently leads students to a prescribed level of competency.

INTRODUCTION

The term "training" is open to interpretation. In its strictest sense, training (as opposed to education) can be described as a process enabling an individual to consistently produce a desired result. Individuals are trained to follow an established pattern of behaviors; they do not necessarily need to know what they are doing, why they are doing it, or what the result of their actions means in terms of an end product. In industry, a management goal is to get a product of consistent quality out the door in a timely manner. Computers are now widely used to automate labor-intensive operations. As complex software tools evolve to shave seconds off production time, training requirements become more intuitive in nature.

However, as commercial software has evolved, so has competition. To be successful in the marketplace, a program must be reliable and easy to learn. A significant investment in market research has produced software products with imbedded training tools for easier learning. In fact, learning ease has prompted the development of graphical user interfaces and other imbedded tools that nearly eliminate the need for formal training altogether. Complex processing mechanisms are nearly invisible to users of most commercial software, and command line entry has been virtually replaced with option selection via a mouse click. Users don't have to understand the process in order to work effectively with today's off-the-shelf programs.

A different production strategy is used in the development of custom, in-house software. With no marketing concerns and no competition, development time, effort, and funds are concentrated on functional design, enhancements as new ideas surface, and fixes as problems arise. At the Jet Propulsion Laboratory (JPL), custom mission operation software is developed, tested, and delivered to coincide with specific events. Many single-purpose programs are created to enable a limited number of users to support whatever unmanned spacecraft missions are currently active. Flexibility has a much higher priority than learning ease in mission operations software, so users are required to have great insight into the nature of the task in order to make effective on-line decisions while using the software.

As the name implies, multimission ground data systems software is being used by multiple spacecraft projects in differing stages of their mission life cycle. For example, the Voyager and Galileo projects are converting from their original systems to the Multimission Ground Data System, while Mars Observer launched using it; Magellan began life with an early version of the multimission system and decided to stick with that early version, rather than to evolve with the system as new versions were released. Cassini has not yet launched, but is planning its operational activities around the multimission system. Each project is made up of teams that focus on one or more functional activities; each team includes members that handle one or more elements of team concern. Each individual member has a unique perspective on software functionality and looks to training for guidance in meeting readiness goals.

Spacecraft operations personnel are often responsible for one-shot science opportunities that must be identified and pursued by dedicated, knowledgeable people working together as a well-rehearsed unit. A team may have some experienced "old-timers" from previous missions, but will always include new recruits who must begin training with the basics. Each team relies on its members to react intuitively to anomalous conditions, as well as on-going activities, so team members must understand the process, as well as the procedure.

JPL's Operations System Training Group designs and implements workstation training for mission operations personnel. Our resources for workstation training include a dedicated classroom, two real-time-access workstations running the current Multimission Ground Data System software, on-going system and configuration support (graphical user interfaces are beginning to appear for some tools and mature subsystems), two dedicated training developer/instructors, and outside consultation support from subject matter experts.

Since traditional training development methods generally rely on functional requirements to provide the impetus for generating courses and since procedural training is sequential in nature, it is often assumed that there exists one correct method, and that the procedures for that method can be performed by individuals with little or no related knowledge or experience. In fact, some commercial training seminars have concluded that even the trainer need not know anything about a subject to design an effective course. NOT SO for our training group! In fact, we must give the term "training" the broadest of definitions.

ROOM FOR PROCESS IMPROVEMENT

As training developers, we are aware of training deficiencies, but lack personnel and resources to redesign our methods. Training is based on Instructional System Development (ISD) methods, but courses often lack consistency and structure. Our workstation training weaknesses have included a throughput bottleneck, cut-and-paste course maintenance, inefficient tracking and reporting methods, insufficient planning for future course development, and an on-going seat-of-the-pants approach to meeting customer needs on a "best efforts" basis. Requirements are difficult to define, especially during mission build-up when staffing deadlines are being met while job definitions are still fuzzy. Training materials are often based on software capability, rather than customer need.

A demonstration of the Automated Training Development System (ATDS) attracted our curiosity. Initial interest was monetarily based; ATDS was in-house technology that might be inexpensive to adapt for our implementation. The system was already in use for procedural training on a tactical military program, with documented success, and it seemed to have potential for our use in developing effective, maintainable training materials. ATDS, however, had not been tested for use with highly intuitive, computer-dependent data-analysis subject matter, but we were able to get funding for a six-month pilot study to assess the system's potential for use in our dynamic operational environment.

ATDS was originally developed to aid in the production of training materials for the JPL-managed All Source Analysis System project. System functionality is based on MIL-STD-1379D training specifications and conforms to current ISD training philosophies. We used ATDS on a Macintosh IIcx with a 19-inch monitor, 20-MB of RAM, an 80-MB hard disk, a 9600-baud modem, and an additional external storage device with removable 90-MB disks.

LEARNING ATDS

Two weeks of training were held at the developer's site in Killeen, Texas. An existing beginning-workstation course in need of updating was used as a working project in learning the system, and an instructional task flow was developed prior to the training in order to get a head start on the course design process.

ATDS training was divided into two parts: design logic and hands-on practice. The program developer and database manager provided logical details about program design and functionality. The goal for the week was to gain a general understanding of the process. This understanding included traditional training development concepts, logical sequencing techniques for nesting competencies (individual skills and/or knowledge) within each task, and suggestions on how to determine the depth of detail necessary.

ATDS Learning Process	
<u>Logical Steps</u>	<u>ATDS Steps</u>
• list candidate tasks	• create tasks
• determine prerequisites	• enter prerequisite skills and knowledge
• determine enabling competencies	• develop skill and knowledge hierarchy
• describe each competency	• enter narratives
• determine user need	• survey analysis
• determine course content	• select critical tasks

Figure 1. Automated Training Development System (ATDS) Learning Process.

Figure 1 summarizes the ATDS learning process. For any given learning situation, there is a finite set of tasks that could be performed. This list of tasks will be referred to as "candidate tasks." The first step in creating a subject database is to define each task from the list of candidate tasks using ATDS. In order to perform each individual task, prerequisite skills or knowledge may be required prior to learning the task. These prerequisites may be entered once the task has been defined. Each task is made up of a set of competencies (skills and/or knowledge) that must be acquired during the learning process in order to complete the task. A Skill and Knowledge Hierarchy is subordinated to each task and may be nested up to six indenture levels. (Skills are usually supported by at least one knowledge and sometimes dependent upon lesser skills. See Figure 2.) Narratives describing each skill and knowledge in detail are then added to the database, along with other pertinent information about each task.

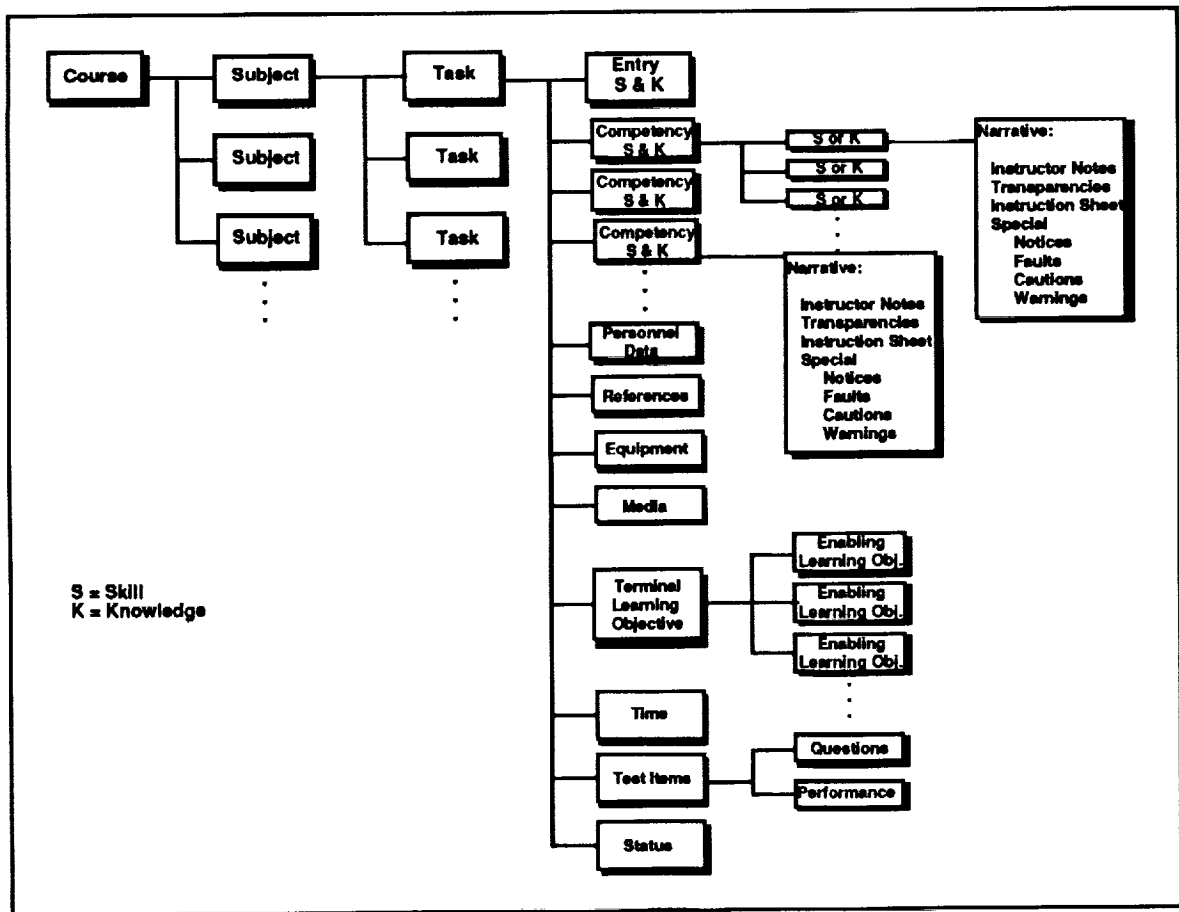


Figure 2. Database Hierarchy of the Automated Training Development System (ATDS).

Once the subject is thoroughly described within the database, the process of determining user requirements begins. A survey is taken to determine the task needs of the target audience. The results of the survey are fed into ATDS and a modeling process weighs the results to determine general criticality for training each task, based on survey consensus. The tasks that are selected for inclusion in the course material are called "critical tasks," since they are required by the target audience in order to complete a job.

During ATDS training, we recognized significant potential for supporting our current training development efforts. Drawbacks such as slow response time and numerous task changes were accepted as temporary in order to remain focused on the possibilities of ATDS. Many of our ideas for improving performance were incorporated into the program, and several more are being considered for future implementation.

IMPLEMENTING ATDS

During the learning process, several issues surfaced as important goals needing closer attention in future training efforts:

- (1) Establish structured subject baselines. Instead of starting from scratch each time a new set of course material is needed, maintain and draw from a single-source all the material for a given subject, start to finish.
- (2) Build a solid foundation of skills and knowledge to the level of detail required to guarantee that complete mastery of a given subject is not lost with time and/or attrition.

- (3) Track development activities for future planning purposes. As new or enhanced subject matter is developed, estimates of development time for creating and populating databases and subsequently generating course materials should become predictable, based on growing experience.
- (4) Develop reporting mechanisms for relaying statistical training information to management.

In reviewing the contents of the database for the first time, something was missing from the overall task and competency subordination scheme; the sequences didn't flow correctly. The level of detail was then examined in the original course material and found to be inconsistent.

Meanwhile, a survey was prepared in order to exercise the critical task selection model for determining individual course content. The original basic workstation course was analyzed using the ATDS selection model to verify critical task selection activity with real survey results in order to fairly assess its value.

Figure 3 describes the content of the survey. The survey process had not yet been automated, so many hours were spent creating survey forms, writing introductory memos to participants and their managers, then distributing, and finally collecting the surveys. Our initial survey form was cumbersome and lengthy, and it missed the point about identifying tasks. Instead, it asked detailed questions about subordinate skills that were basically irrelevant to achieving the goal of task selection.

Difficulty, Importance, and Frequency (DIF) Survey

Task (Identify the task)

Question #1: Is the task Difficult?

Select one of the following answers:

- a. Very difficult
- b. Somewhat difficult
- c. Not difficult

Question #2: Is the task Important?

Select one of the following answers:

- a. Important
- b. Not important

Question #3: Is the task performed Frequently?

Select one of the following answers:

- a. Very frequently
- b. Somewhat frequently
- c. Not frequently

Figure 3. Critical Task Selection Survey.

Analyzing the results seemed impossible without computer assistance. At least forty responses were recommended for adequate analysis, but in its existing state, there was no way to increment values within the model, and there were 27 possible values to consider. (See Figure 4.) The response to each question was weighted according to the response to the previous question. Questions with incomplete responses were thrown out altogether. The analysis process seemed endless, and the first five tasks all revealed the same thing--training was not required.

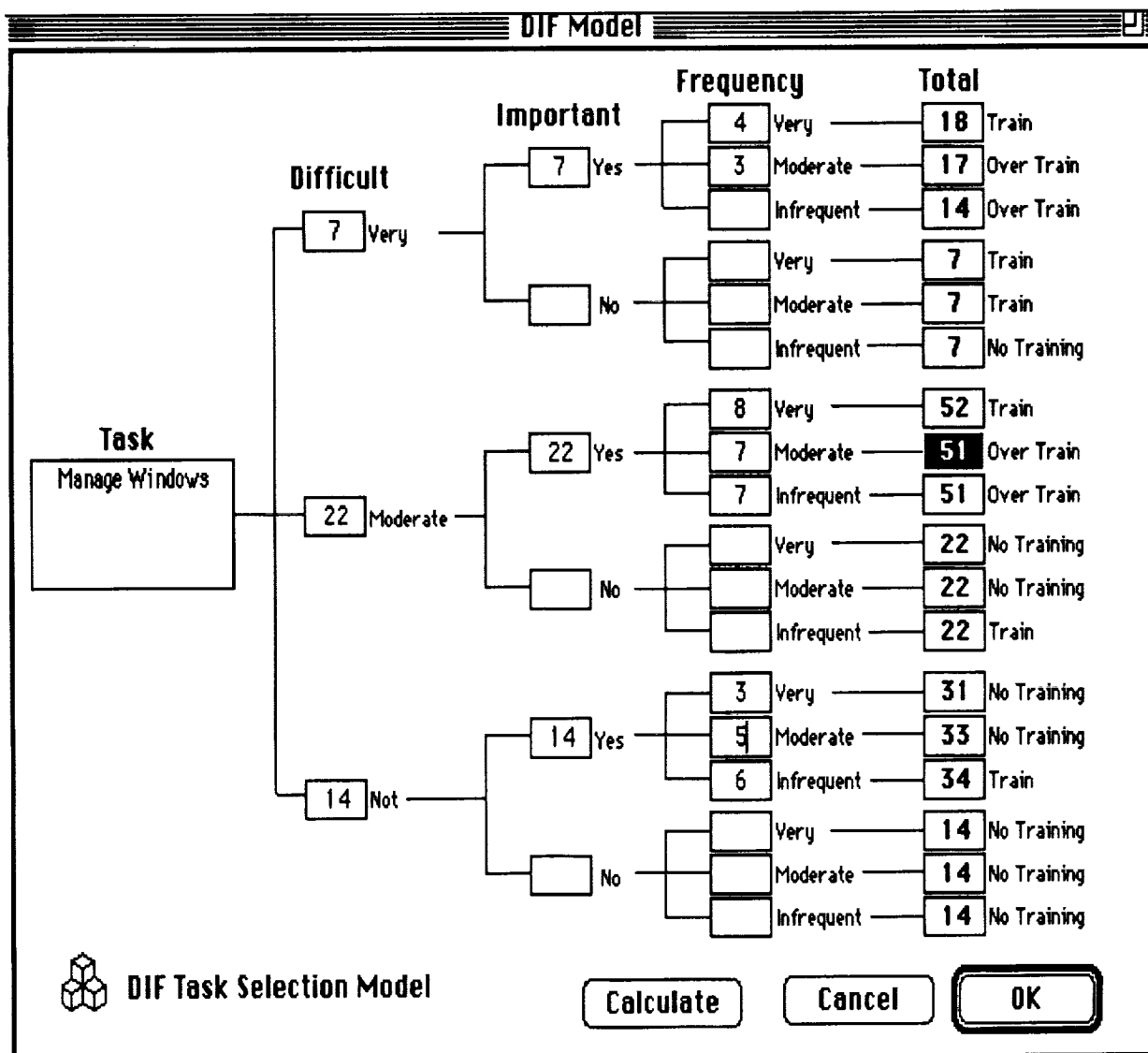


Figure 4. ATDS Difficulty, Importance, and Frequency Selection Model.

It took only a few calculations to realize that the original course content did not adequately meet student needs. A random sampling of task results revealed that the selected tasks were not critical tasks at all; instead, the original course was presumed to contain only critical tasks, and the ATDS development effort simply forced the expected results, rather than using ATDS as a vehicle to redesign the content of the course.

The importance of the survey became very clear. The training task list included an incomplete set of candidate tasks. It was the intent of the survey to filter out the unnecessary tasks and provide the training developer with a list of critical tasks. It became apparent that very little of the actual course content was included in the original course materials. Instead, a lot of "off-the-cuff" information had been directed at individuals in response to their questions, but had not been written down anywhere. The survey analysis provided solid insight into a potential single-point-of-failure in training.

ATDS could now provide us with a repository for narrative descriptions of each skill and knowledge (see Figure 5) that had previously gone undocumented.

Competency List Competency Attributes

Domain: [|||||]

Line	Domain	Class	Indenture	Verb	Noun
7	K	(U)			Login to your workstation user environment
8	K	(U)			Enter your User ID
9	K	(U)			Enter your Password
10	K	(U)			How does the operating system identify a user?
11	K	(U)			How is your processing environment defined?
12	K	(U)			.cshrc file

Line 10 Details:

Domain	Class	Indenture	Verb	Noun
K	U	2		How does the operating system identify a user?

Comp Attributes: ☒ CTUG ☒ COJT ☒ CTUH ☐ CCTQ ☒ CLPN ☒ CPTI ☒ CJSH ☐ ✓

Text Editor Enabling Objective Conditions Standards RL

You of authorized user IDs contained in field one of each record in the workstation-resident password file. If there is a match, then the system compares the entered password to the coded password previously provided to the system by the account owner. If it also matches, then the user is allowed into the system; if not, the user is given another chance at the entire process. Once the user is validated, the system uses field six of the password file entry (absolute path to the home directory) to determine where the user fits into the directory structure. Field five identifies the owner of the account and

Notes and Resources G

- Instructor Notes
- Instruction Sheets
- Cognitive Test
- Item
- Cautions
- Notices
- Warnings

Resource Attributes: ☐ RTUG ☐ ROJT ☐ RTP ☐ RTG

Competencies Cancel OK

Figure 5. ATDS Skill and Knowledge Hierarchy Data Input Screen.

FINDINGS

ATDS has limitations, but its potential for grasping the global nature of subject matter has had great impact on our perspective of the knowledge gathering activity.

The program is tedious to learn. It is not as easy to grasp as it appears. One of the problems with structured course development is that new information relevant to the subject matter floods the mind faster than it can be incorporated into the database, and constant juggling between competency levels is required. The reload delay between competencies causes frustration when thoughts dissolve before they can be captured.

Once all the tasks and their competencies are entered, along with their narratives and other supporting information, database maintenance and course generation are fairly simple. Developers can generate a course for a given set of users based on their needs, and can also generate any number of tailored courses that provide training by way of classroom instruction or self-guided workbooks for on-the-job training.

In its final form, the material is organized and easy to use. We found that ATDS product formats are consistent in quality and quantity, based upon database contents, so serious attention to input detail is essential.

During a dry-run session with partially completed materials, the problems encountered were the result of inexperience in dealing with such structured materials. Once "ad-libbing" is eliminated and explicit instructions followed, the materials were easy to use. In an emergency, substitute trainers should be able to implement course materials with very little notice.

Potential

Considering the many aspects of our operations training development, ATDS has potential for improving the way we gather and maintain course material by preserving the global perspective of the subject. ATDS is a springboard for creative ideas. It is an effective organizing and building tool for thoughts and processes, and its basic functionality could be adapted to other uses, such as building and maintaining requirements.

ATDS requires a significant commitment of time and effort on the part of training developers to collect all the pieces of information and design learning sequences to best use each piece. The reward is a smoothly choreographed training presentation.

Not for Everyone

ATDS can be a tedious learning experience and those who have never agonized over the design of a training module may have difficulty sticking with the process.

Those who have never designed a learning sequence, and probably never will again, need to have someone design the training for them. They could probably learn to maintain the material, once a baseline is established, but for a small training task it might not be worth the time.

Those who have no training background, but need to design training materials (for instance, to teach a new subordinate how to perform the job), will probably want to work with a consultant. Again, a solid subject baseline is the goal, although the training developer might feel comfortable with routine material maintenance once the baseline is created.

For those whose training requirements change significantly and frequently, possibly never to be repeated, ATDS is probably not a solution. The value of ATDS lies in its consistency and maintainability over time.

Who Will Benefit?

ATDS will be most cost effective over time. Initial training database development activity will probably be a lengthy process; its value will be realized in quality, flexibility, and maintainability. However, the basics of design are not limited to trainers, and with some labeling changes within the program, this development process could take on many design formats.

Long-range planners take a goal or an idea and break it down into basic milestones or components that build upon each other to form a whole. Like training developers, they start with a basic set of tasks or criteria that drives their design process and defines its boundaries. ATDS helps maintain focus and records the entire process to whatever depth of detail is desired.

Unlike planners, strategists work in the realm of possibilities. Many options may be available, and their job is to trace each to its end and determine which strategy will work best. Again, they are building something, only in multiples. ATDS may be helpful here because it allows all the details to be recorded to any desired level of detail. In this case, the mathematical model might be useful in gathering opinions and assessing political or financial support.

Anyone who has ever had to maintain documentation, presentations, or procedures over time will appreciate the capabilities of ATDS. Of course training developers must maintain all three simultaneously.

CONCLUSION

ATDS is not an authoring system, nor does it interface directly with the student at this point in time. It has, however, ignited a new interest in course development that focuses on a single-source information retention system, individualized course tailoring, and easy maintenance. The program is still under development, but our preliminary study supports its continued use.

Many of our Operations System Training Group development activities will benefit from conversion to ATDS. It would enhance our ability to quickly respond to our customers' needs. In fact, our products that support new or modified software programs should be developed and maintained for release to coincide with the software deliveries. Updated training material could be a part of any software delivery, provided good communication existed between software development, training development, test, documentation, and configuration control personnel. (A significant motivator to enhance communication between these groups would be to tie project acceptance of the software to the availability of training and documentation.)

Another area that should benefit from ATDS is training throughput. Trainer/mentors might evolve from the training automation process. Once a course has been tailored to the needs of a team or group, it may be possible to enlist a representative member of that team, at the project's request, to oversee self-guided learning within the operational environment. Full training support and on-going training material maintenance and development would, of course, be required. Resident trainer/mentors might address a concern commonly voiced from operations management that their people can't be away from their jobs, and certainly not in groups, for training activities.

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**Session H4: MODELING IN SUPPORT OF OPERATIONS
AND ANTHROPOMETRY**

Session Chair: Ms. Barbara Woolford

**APPLICATION OF STATISTICAL PROCESS CONTROL AND
PROCESS CAPABILITY ANALYSIS PROCEDURES IN ORBITER PROCESSING ACTIVITIES AT
THE KENNEDY SPACE CENTER**

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Abstract

Successful ground processing at the Kennedy Space Center (KSC) requires that flight hardware and ground support equipment conform to specifications at tens of thousands of checkpoints. Knowledge of conformance is an essential requirement for launch. That knowledge of conformance at every requisite point does not, however, enable identification of past problems with equipment, or potential problem areas. This paper describes how the introduction of Statistical Process Control and Process Capability Analysis identification procedures into existing shuttle processing procedures can enable identification of potential problem areas and candidates for improvements to increase processing performance measures. Results of a case study describing application of the analysis procedures to Thermal Protection System processing are used to illustrate the benefits of the approaches described in the paper.

Introduction

In his keynote address, at the 1992 S.O.A.R. Conference, Mr. Geoff Giffin, Deputy Director, Operations Thrust NASA/OAST stated: "We live in an era of flat or shrinking budgets. The days of constant growth in NASA and defense budgets appears to be behind us. If we want to do new things, we must reduce the costs of doing existing things - that means operations." In the context of this paper, the term "quality" refers to the areas of productivity and efficiency

as well as the more traditional areas of safety and reliability. KSC shuttle operations has established an industrial engineering function in the Operations Analysis Office to facilitate the systematic institution of shuttle processing operation quality improvements as a way of reducing the costs of processing operations. Research personnel from the Department of Industrial Engineering and Management Systems at the University of Central Florida participate in project activities conducted through the Operations Analysis Office.

Shuttle Processing Operations: Process Performance Measure Data

Conformance to specification (being within acceptable tolerance limits) is essential to Space Shuttle processing. However, to the individual needing to identify processes for improvement or desiring to quantify the potential for improvement in a process, knowledge of the fact that specifications were conformed to and requirements were met, is not sufficient information. The statistical process control procedures necessary for continuous improvement of processes require that actual variables data values of Process Performance Measures (PPMs) be available for analysis. Space Shuttle ground processing at Kennedy Space Center (KSC) involves the execution of thousands of written work instructions. In addition to "buying off" steps in the work instructions after they are properly completed, "variable" data elements are frequently collected during the execution of the work step. Examples of variable data elements are:

- Torque readings
- Leak rates from mass spectrometer probe operations
- Ambient temperature readings
- Results of visual inspection for damage and debris
- Calibration numbers and due dates for tools and ground support equipment (GSE)

The variable data elements are currently recorded when engineers and technicians fill in blanks in the paper work instructions. The variables data is mainly used for real-time control of work steps (to ensure functional conformance to specifications). However, the only way to retrieve past variables data is through a labor-intensive paper or microfilm search of the completed work instructions.

Ready availability of these PPM variables data values would enable relatively easy determination of:

- Control charts for delineation of common and special causes
- Process capability analysis

- Continuous process performance monitoring procedures
- Other useful statistical process control tools

Variables data consist of measurement values, usually defined on a continuum (e.g. length, time, pressure, pull weight, etc.). Variables data complement attribute data which classify the output of a process as conforming or non-conforming to requirements. Variables data combined with the information that defines requirements for performance enables the determination of process capability and the qualification of processes for use in operations targeting high levels of quality performance.

As organizations grow in their awareness to improve processes (and, thus, reduce cost and raise productivity), increased usage of attribute data to control and stabilize factors affecting end product quality is required. As relatively high levels of quality and accompanying low levels of non-conformance or defective product is realized, continued process improvement demands variables data. This is particularly true in "low volume" operations desiring to certify processes for high levels of quality (e.g. satisfaction of criteria for flight requiring one in a million or less probability of non-conformance.)

Statistical Process Control and Capability Analysis

Total Quality Management (TQM)/Continuous Improvement Process (CIP) is based on statistical process control (SPC). SPC is the foundation for measurement based process improvement activity. An important aspect of SPC used for process improvement is capability analysis.

Process "capability" is a measure of the natural behavior of a process after the process has been stabilized by the removal of all special or assignable causes. Special or assignable causes affect the process performance measures but are not considered to be causes that

are part of the process. A process must be stabilized and have an established process capability before process improvement can be measured.

Process capability analyses associated with process performance measures described by variables data express the process capability in terms of the probability distributions of the statistics characterizing the PPMs.

In the absence of specification limits for a process performance measure, the process capability is expressed in terms of the "spread" of probability distributions of the PPM around its center. The width of the interval encompassing plus or minus three standard deviations around the mean of the distribution is usually chosen as an expression of the process capability. When specification limits for the Process Performance Measures are given a process capability index based on the ratio of the spread of the distribution to the width of the interval defined by the specification limits.

Capability index values can be related to probabilities that measures will exceed specification limits as indicated in Table I below.

Capability Index	Probability that Measure will <i>Exceed</i> Specification Limit
.5	.0668
1.0	.0013
1.5	1.515×10^{-5}
2.0	1×10^{-9}

Table I - Capability Index

Thermal Protection System Analysis

A structured analysis was conducted of Thermal Protection System (TPS) processing activities at the Kennedy Space Center to identify candidates for processing improvement and to evaluate statistical tools in the operational environment supporting Space Shuttle process-

ing. As part of this activity, the primary customers of any methods improvement activities were considered to be the technicians who were performing the work on the floor of the Orbiter Processing Facilities (OPFs). As such, they were queried about the processing activities which could benefit most from a detailed analysis. A survey was distributed to the TPS Engineering Team, the TPS Quality Team and the TPS Technicians responsible for maintenance of the flight critical Thermal Protection System on the Orbiters. These surveys were collected and analyzed to identify potential sources of methods improvements. Attention was then focused on the top 20 candidates for improvement. A procedure was identified which cuts across several of the top ranked processes. This procedure was a temperature measurement task to compare the OPF ambient temperature with the Orbiter Vehicle substrate temperature in an attempt to identify conditions which would increase the probability of moisture formation at the vehicle substrate surface. The temperature/dew point differential criteria used was an ambient temperature reading three degrees (or more) higher than the substrate temperature. Conditions outside this tolerance would favor moisture formation under certain humidity conditions, thus preventing proper bonding of the TPS components. Discussions with several technicians and engineers indicated the temperature measurement process was unnecessary in the controlled conditions of the OPFs and should be eliminated. The major issue was the requirement to perform a Process 217 (P-217) Temperature/Dew point stabilization procedure for any out-of-tolerance conditions identified by the temperature measurements. P-217 is a time consuming and complex procedure to stabilize the temperature of the substrate prior to bonding TPS components. Therefore, it is well suited to an analytical review, based on the capability analysis procedure cited herein. Although P-217 is seldom called out in the OPF as a result of an out-of-tolerance temperature condition, the requirement to continuously check for the temperature differential consumes significant manpower resources and creates unnecessary expenses centered

Orbiter Vehicle	Flow	Capability	# of σ
OV 104	11	1.12	3.36
OV 104	10	1.11	3.33
OV 105	2	1.11	3.33
OV 104	8	.69	2.07
OV 102	11	1.67	5.01
OV 105	1	1.03	3.09
OV 103	8	1.48	4.44
OV 102	8	1.19	3.57
OV 104	6	1.07	3.21

Table II - Capability Analysis Summary Matrix

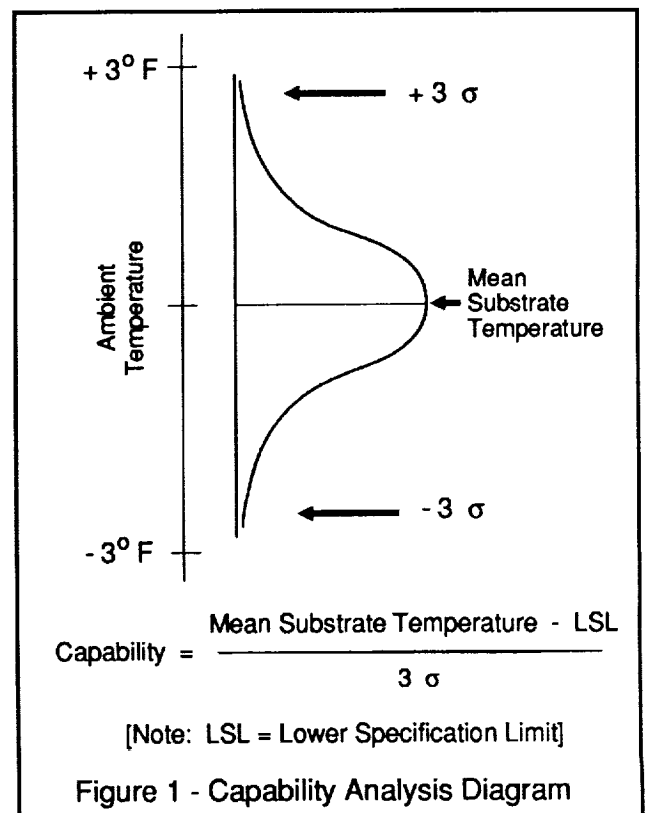
around training, re-training, as well as the purchase, calibration and maintenance of the temperature measurement pyrometers.

An Application of Capability Analysis

As part of this research activity, a capability analysis of the Environmental Control Systems for all three OPFs was performed. This analysis was conducted to insure the OPFs could be consistently maintained at the proper atmospheric conditions to insure proper bonding criteria for TPS components. A procedure is now in place which requires the measurement of ambient OPF temperatures and the orbiter substrate temperatures to minimize the possibility of moisture formation on the substrate surface of the Orbiter which could adversely affect proper TPS bonding criteria. The capability analysis was done in support of an analysis to validate the need to perform this temperature measurement procedure in the controlled environment of the OPFs. Over 119 temperature measurements were analyzed based on a random selection process covering all four Orbiter Vehicles, all three OPF bays and all four seasonal conditions in Central Florida. The results of the capability analysis, computed for each set of sample data are shown in Table II above. This analysis quantifies the capability of the OPF Environmental Control System to provide the necessary stabilized temperature conditions which would preclude P-217 from being called out. Numbers support the contention of the TPS technicians and engineers that the temperature measurement is not required. Formal review procedures are

being initiated to consider deletion of the temperature measurement requirement.

A capability value of 1.0 indicates a 3 sigma (3σ) or $\approx 99.8\%$ probability that temperatures will be within specified limits. It should also be noted that the variability inherent in the temperature readings for ambient and substrate temperatures *includes* variability for the temperature itself (the variable of interest), the equipment tolerances, and the measurement processes. The measurement process includes variability due to operator techniques,



**TASK NETWORK MODELS IN THE PREDICTION OF WORKLOAD IMPOSED BY
EXTRAVEHICULAR ACTIVITIES DURING THE HUBBLE SPACE TELESCOPE
SERVICING MISSION**

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ABSTRACT

In a joint effort with Brooks A.F.B, Texas, the Flight Crew Support Division at Johnson Space Center has begun a computer simulation and performance modeling program directed at establishing the predictive validity of software tools for modeling human performance during spaceflight. This paper addresses the utility of task network modeling for predicting the workload that astronauts are likely to encounter in extravehicular activities during the Hubble Space Telescope (HST) repair mission. The intent of the study was to determine whether two EVA crewmembers and one intravehicular activity (IVA) crewmember could reasonably be expected to complete HST Wide Field/Planetary Camera (WFPC) replacement in the allotted time.

Ultimately, examination of the points during HST servicing that may result in excessive workload will lead to recommendations to the HST Flight Systems and Servicing Project concerning (1) expectation of degraded performance, (2) the need to change task allocation across crewmembers, (3) the need to expand the timeline, or (4) the need to increase the number of EVA's.

INTRODUCTION

Future manned space missions will represent unprecedented expansion of civilization into the solar system. Space Station Freedom will permit crews to live and work in Earth orbit 90-day intervals, and perhaps longer. Lunar outposts will demand that crews work routinely in a harsh extraterrestrial environment, conducting scientific experiments and eventually supervising complex operations such as resource utilization. The proposed mission to Mars will involve outbound and return flights of a combined duration of one to three years, including time spent working on the planetary surface (Stocklosa, 1985). Clearly, as

spaceflight becomes increasingly complex and of longer duration astronauts are likely to encounter greater workload. However, human performance under various workload conditions, critical to the success of spaceflight, has only recently begun to be studied systematically (Stocklosa, 1985).

The need to assess workload becomes even more critical in a shuttle mission such as STS-61 which is scheduled to repair and service the Hubble Space Telescope in December, 1993. A committee review states that the mission is achievable but risky because of the growing workload, tight schedule and management complexity. The independent panel noted that the timeline for EVA is "very tight, having grown 25% in the period of our review, and continues to grow". Indeed, any additional component failures may require additional tasks to be added between now and the mission. The list of repairs has grown to fill an 11-day flight, with at least consecutive days of EVA's by alternative pairs of astronauts, making it by far the most ambitious shuttle EVA plan.

To date no attempts have been made to assess the workload imposed by tasks during intravehicular or extravehicular activities, and yet of all activities performed by humans in micro-gravity, those performed outside the pressurized modules are the most dangerous. Clearly, there is a requirement to develop methodologies for workload measurement and a need to identify points during a mission that may result in excessive workload.

This paper describes the current status of a program of investigation for assessing whether two EVA crewmembers and one IVA crewmember can reasonably be expected to complete WFPC replacement in the allotted time. Specifically, task network modeling and workload component scaling are discussed in detail as the suggested methodologies for predicting the amount of workload likely to be encountered when replacing the WFPC during the HST servicing mission. Ultimately, results will lead to the

parallax error, environmental influences and other cumulative errors. These cumulative errors, when removed from consideration would combine to further reduce the variability of the temperature and thus increase the probability of conformance. Figure 1 (see previous page) provides a pictorial representation of the capability analysis procedure, including the formula used to derive the capability analysis values in this application.

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formulation of recommendations to the HST Flight Systems and Servicing Project concerning EVA/IVA mission functions for which task re-allocation, expansion of the timeline, or increases in the number of EVA's, could be used as strategies for reducing mental and physical workload.

Task Network Modeling

Task network modeling is a methodology for investigating human performance in systems. It involves the breaking down of an operation or process into a series of subtasks, where relations among tasks are represented by the networks that connect them. Each node of the network represents a discrete subtask performed by the human and has associated parameters selected for their relevance to the analysis. Node parameters may include performance time, resources consumed, or potential errors. The network structure defines the order in which the operator performs the subtasks and can include branching pathways to denote decisions or alternatives. Loops are used to represent repetitions, the consequences of errors or the impact of environmental conditions (Laughery, 1985). Task network modeling permits in-depth analyses and quantification of human performance variability and is used primarily during initial system design where direct measures of crew performance are not available or are impractical. The overall process of task network modeling is depicted in Figure 1.

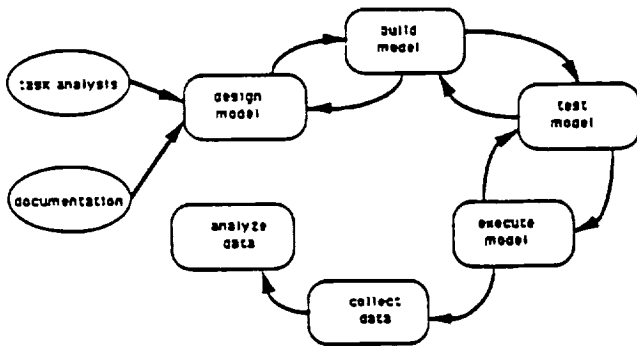


Figure 1. Task Network Modeling Process (from Laughery, 1989)

Figure 2 depicts a proposed task network for dialing a telephone. As can be seen, one picks up the receiver, determines whether a long distance call is to be made, and dials the number. Such a task network would easily permit exploration of the effect of using a touch tone or rotary telephone on error and call completion time. A parametric experiment testing the effect of telephone type could than easily be conducted (see Naylor, 1969).

Workload Component Scaling

Task network modeling is not designed specifically as a workload assessment tool. The only output provided is time required to accomplish the task and the sequence

in which tasks are performed (Laughery, 1989). Task network modeling was made more usable for the assessment of workload in the current study by augmenting it with a set of workload constructs. The approach was a modification of the procedure developed by Aldridge and Szabo (1984) and implemented by Laughery (1989), where each operator activity in a task network is characterized by the workload demand in each of four channels: auditory, visual, mediational and motor.

METHOD

The methodology was developed in a three-phase program of investigation that included development of a workload component scale used to produce computer-generated estimates of workload during Extravehicular activity (EVA) mission segments.

Phase I -- Task Network Modeling

It is important to note that the HST servicing mission was comprised of five major tasks, including the replacement of the (1) two Solar Arrays, (2) High Speed Photometer with the Correcting Optics Space Telescope Axial Replacement, (3) WFPC (4) two Rate Sensor Units and (5) Electronics Control Unit. Replacement of the WFPC was selected for this analysis because it was believed that it represented an EVA timeline estimate too optimistic.

During this phase, a complete, descriptive task listing of the wide field/planetary camera replacement task was compiled. The task listing was developed as a static series of flow diagrams that portray the HST servicing mission as a paper flowchart, illustrating the steps that crewmembers must accomplish to complete the task. The first step in the static model development involved examination of flight data files in order to decompose the task into its component behaviors. The task was decomposed into a consistent sequence of sub-tasks which supported performance of the task. A subtask was defined as a statement of activity, work, or action to be performed in support of the task.

During this phase, the static flow diagram developed previously was translated into a dynamic task network model depicting the flow of decisions and actions performed in support of WFPC replacement as a computer simulation.

Apparatus. Two simulators were employed to gather the required data. The Systems Engineering Simulator provides a high fidelity dynamic simulation of the shuttle AFT flight deck. It is a standard trainer for RMS tasks. The Air-Bearing Floor Facility provides a two-dimensional simulation of microgravity. In addition, the Weightless Environment Test Facility (WEFT) provides a three-dimensional simulation of microgravity through the attainment neutral buoyancy.

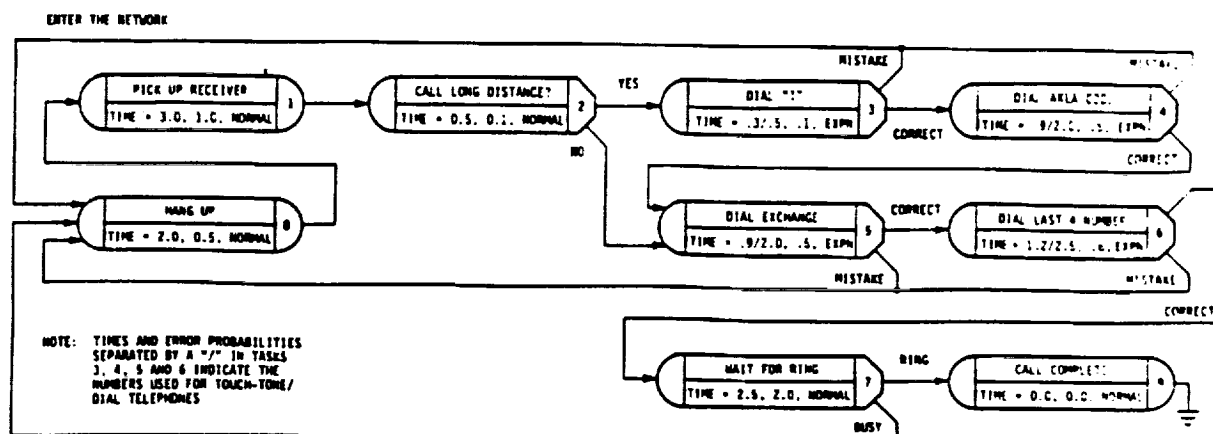


Figure 2. Task Network for Dialing a Phone

Procedures. Analysis of the WFPC replacement was based informally on the Structured Analysis and Design Technique (SADT). SADT provides a structured discipline for the task analyst to use in decomposing a system into a hierarchy of functions. Decomposition of the WFPC replacement task using the IDEF concept involved in-depth examination of the task in terms of the following types of functions: control, resources, input, and output. Control functions determine the constraints under which a particular subtask operates. For the WFPC replacement task, the only control function identified was the flight data file timeline. Resource functions denote the mechanisms that are the major contributors essential to the transformation of input functions to output functions. Analysis of the WFPC replacement task resulted in the identification of the following resource functions: Pilot, Mission Specialist 1, and the STS-61 Flight Data File checklist. Input functions represent the entities that are to be transformed into output, such as hand controller inputs which result in the movement of the Remote Manipulator System.

The static model representation of WFPC replacement was further analyzed during the Systems Engineering Simulator, WETF and Air-Bearing Floor Facility training sessions. A total of 4 STS-61 WETF training sessions were monitored. These sessions provided information concerning the nature of crew coordination, subtask performance times and the use of direct views, camera views, and checklists. They served to identify additional subtasks not readily apparent from the flight data files or from subject matter experts.

Phase II -- Workload Component Scaling

Identification of EVA/IVA Tasks. Scaling of workload components required identification of tasks specific to EVA/IVA activities. Each of these tasks was classified according to one of four workload channels: motor, visual, auditory, cognitive and psychomotor.

Content Validation. A total of four astronauts participated in the content validation effort. Two had prior EVA experience. Content validation sought to assess the degree to which the EVA/IVA tasks identified previously accurately reflected those activities performed during a mission.

Scale Development. Aldridge and Szabo (1984) developed an ordinal scale for determining the demand required in each of the four channels noted above. In the current study, several methods were considered for generating interval scales. An interval scale was selected because there was a desire to reflect equal magnitude differences in workload between corresponding tasks. Magnitude estimation was the method of choice. O'Donnel and Eggemeier (1986) found that magnitude estimation more closely achieved interval scale measures than did ranking. Further, magnitude estimation also appears to be less subject to fatigue effects than pair comparisons, especially when a large number of stimuli must be judged. It also has high convergent validity (O'Donnel et al. 1986). More importantly, magnitude estimation tends to be more reliable than other scaling methods because there is no need to resort to theory (e.g., distributions of discriminial dispersions) to generate them. In addition, O'Donnel et al. (1986) indicated that magnitude estimation provided a sensitive measure of perceive task difficulty and effort.

A total of 10 subjects from the aerospace community were presented each with a description of an EVA/IVA task twice in random order for each of the four workload channels. For each task, subjects assigned a numerical estimate that reflected the amount of workload likely to be imposed by the task. Similar estimates were than made for subsequent tasks. Workload was defined in terms of the mental and/or physical effort required to complete the task. Subjects were asked to assign numbers so the they were proportional to the amount of workload imposed by each tasks. Thus, ratios assigned to the different tasks were intended to correspond with the ratios between the workload imposed by the different tasks.

Mean logarithms were used as the scale values once inter-individual sources of variability were removed from the data in accordance with the procedures developed by Lane, Catania and Stevens (1961). According to these authors, use of magnitude estimation results in a source of variation attributed to the fact that different observers may prefer to work in different number ranges. According to Lane, et al. (1961), a transformation is needed which leaves invariant the individual slopes and intercepts, while partialing out variability due to individual differences. The resulting workload scales are presented in Table 1.

Ideally, the derived scale would have been further evaluated to determine whether it conformed to a power function to assess whether the response magnitudes provided by the subjects were proportional to the stimulus intensity raised to power. However, because in the current study the nature of the stimuli (i.e., EVA/IVA tasks) precluded quantification in terms of intensity, degree of conformance to a power function could not be determined.

Phase -- III Tabulation of Workload Demands

As of this writing Phases I and II have been completed. Current work on the tabulation of workload demands has begun. Execution of the model will permit estimation of total attentional demands across all tasks during any part of the simulation. It will also permit characterization of the crewmember's attentional requirements graphically.

All tasks comprising WFPC replacement have been organized into five major segments (1) removal WFPC I from HST, (2) installation of WFPC I into temporary parking fixture, (3) removal of WFPC II FROM SIPE, (4) installation of WFPC II into HST, (5) removal of WFPC I from temporary parking fixture, and (6) installation of WFPC II into SIPE. The time estimates for subtasks comprising each segment have been used to construct timelines with 30-second intervals. Total demand placed on each astronaut has been estimated by summing across concurrent entries for each modality.

Summation of all concurrent entries within each modality (i.e., visual, mediational, motor and auditory) for each astronaut will provide an estimate of workload.

RESULTS

Although the preliminary results of Phase III were quite rudimentary in nature, it is believed that the methodology described provides an objective approach for evaluating the workload that astronauts are likely to encounter in extravehicular activities. It also provided a first-iteration estimate of the amount imposed within each information processing channel across each of the six HST repair activities.

Table 1. Workload Component Scales

Scale Value	Task
<u>Motor Processes</u>	
0.18	Discrete activation
0.49	Translation without equipment
0.52	Ingress/Egress
0.60	Restrained Manipulation of ORU's
0.65	Compensatory Tracking
0.69	Translation with equipment
1.10	Unrestrained Manipulation of ORU's
<u>Visual Processes</u>	
0.28	Confirmation
0.30	Discrimination/Identification
0.47	Comprehension
0.49	Status Monitoring
0.61	Alignment and Orientation
<u>Mediation Processes</u>	
0.24	Alternative Selection
0.49	Estimation/calculation
0.65	Plan Formulation
0.78	Problem solving
<u>Auditory Processes</u>	
0.53	Comprehension
0.58	Discrimination

Initial execution of the preliminary model suggested that installation of WFPC II may be particularly demanding due to the frequency and duration of activities requiring manipulation of WFPC II.

A detailed description of the results will be presented in a report to be released to the HST Flight Systems and Servicing Project in December, 1993.

FUTURE STUDIES

Ultimately, the methodology developed during this program of investigation will lead to a number of products that will be applied to future task network simulations of the workload likely to be experienced during future EVA activities, including:

- task analyses that provide indications estimates of workload components.

- validated workload component scales for rating the visual, auditory, motor and mediation components of workload.
- methods for evaluation of the workload imposed by concurrent EVA tasks.
- measures for identifying overload conditions.
- strategies for reducing workload during EVA.

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A HUMAN FACTORS EVALUATION USING TOOLS FOR AUTOMATED KNOWLEDGE ENGINEERING

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INTRODUCTION

The purpose of this paper is to describe a human factors evaluation of the MH-53J helicopter cockpit. This evaluation was an application and further development of Tools for Automated Knowledge Engineering (TAKE). TAKE is used to acquire and analyze knowledge from domain experts (aircrew members, system designers, maintenance personnel, human factors engineers, or others). TAKE was successfully utilized for the purpose of recommending improvements for the man-machine interfaces (MMI) in the MH-53J cockpit.

METHODOLOGY

One of the most difficult tasks facing designers, programmers, and engineers is creating the knowledge base to define system requirements. Once the tedious and perplexing task of eliciting the knowledge from experts is complete, the resultant mountain of data and the analysis and distillation of this data often becomes a major choke point in the design process. TAKE alleviates these problems by applying a formalized methodology to acquire knowledge from experts, and providing tools to facilitate the analysis of that knowledge.

TAKE utilizes concept mapping to capture information collected from domain experts (DEs). Concept mapping was proven to be a superb knowledge acquisition technique for design during the development of the Advanced Knowledge and Design Acquisition Methodology (AKADAM) (McNeese, Zaff, Peio, Snyder, Duncan, McFarren, 1990). TAKE was created from the ideas generated and the knowledge gained while utilizing AKADAM. TAKE applies concept mapping to create integrated knowledge bases that are then analyzed with computer assistance to distill and extract information that allows the human factors engineer to develop a sound man-machine interface.

Concept Mapping

Concept maps are verbal-graphical knowledge representations created during an interactive interview process in which the domain expert and the interviewer share a common information construct. While the DE is expounding on the topic of interest, the interviewer creates the concept map on a drawing

board representing his or her interpretation of the relayed information. The DE can actually see how the interviewer is interpreting his or her comments and descriptions, and can alter and correct the concept map as it is constructed. Iterative interviews and reviews of the map further enhance the information content of the structure and ensure its accuracy. A unique characteristic of the concept map is that it is virtually unbounded in the types of relationships that it can convey. In addition, concept maps can be created from notes, or text.

Computer Analysis

TAKE software transforms the information content of the maps into a data base that can be categorized and formatted to facilitate analysis. Two of the software tools that were utilized extensively for this evaluation are an Outline function and an Analysis function.

The Outline tool does just what the label implies -- it organizes the map content into a hierarchical outline format that improves readability and groups information into logical clusters. This function has proven extremely useful in generating functional decompositions and in organizing large scale data bases. In addition, the outline can be edited and the changes will be reflected in the concept map. The outline feature is very powerful because it produces a universally recognized format that can be utilized by multiple disciplines. This universality makes it possible for users, engineers, designers, and programmers to fully understand the domain of interest.

The Analysis tool allows categorical information to be selectively extracted from the maps using a "graphical spreadsheet" interface. Several categories of key terms can be defined with this function and are typically grouped in functional and descriptive classes. Verbal constructs within the concept map that contain any of the defined key terms can be identified, extracted, and examined along with related concepts. With this function, information can be easily categorized for problem identification, task assignments, or other characterization. Categories can be color coded and displayed on the concept map to provide a visual representation of the data.

Another very important feature of TAKE is the Drawing tool. The Drawing tool significantly improves the speed of entering concept maps into the computer format. A unique feature of the drawing tool enables the user to embed information within a concept map. Submaps, text, and graphics can be embedded in nodes to provide additional information on particular concepts of the map. Small icons are depicted in the nodes that contain this embedded information. Clicking on these icons opens windows that display the embedded information. Consequently, a map can be extremely rich with data and contain a great amount of detail but still maintain an uncluttered overall view of the domain. In addition, the drawing tool provides the user with the ability to move, delete, or zoom portions of the map, and highlight nodes of interest by size, shape, or bold lines.

Other functions TAKE include a combining feature that allows the integration of data bases from multiple maps and an alphabetical sorting function for listing all the verbal constructs within the maps.

RESULTS

A request for a human factors evaluation of the MH-53J PAVE LOW helicopter provided an excellent opportunity to test the TAKE process.

To conduct the evaluation, several methods were used to gain an understanding of the cockpit, the mission, and how the design of the cockpit impacted the safe and successful performance of that mission. The methods used included reviewing Technical Orders, Operators Manuals and checklists. In addition, traditional techniques such as interviews, questionnaires, and observations made during actual flights were used to determine mission requirements and cockpit configuration.

Interviews

During the interview process, traditional interviews and concept maps were utilized to elicit knowledge from the domain experts. This allowed comparison of the two approaches. The anchor used during both sessions was a generic mission profile that was developed with experts on our initial visit. During both techniques, the DEs were asked to explain the things that they did during each segment of the mission profile. They were asked to be very specific and describe the tasks that they performed, whether they were focusing inside or outside the cockpit, what cues they were looking for, etc.

The interviews and checklists were the basis of the task analysis. Constructing the task analysis from the traditional interviews, was a tedious process. First, audio tapes were reviewed to fill in the notes taken during the interviews. Then the information needed for the task analysis was extracted from each interview. These steps were performed for each individual interview. Constructing the task analysis with the concept maps was a much simpler process. First the maps were entered into TAKE and a database of the information was created. Outlines were then produced from the maps using the Outline feature previously described. The maps were then combined according to crew position. Pilot maps, copilot maps, and flight engineer maps were combined so that only one document per crew position had to be analyzed. This streamlined the process because one map was used instead of paging through several to obtain the same information. The outline format quickened the process of building a task analysis because it was easy to extract the functions, procedures and tasks from the indentations of the outlines. It is estimated that it took half the time to construct the task analysis utilizing TAKE versus the more traditional techniques.

Questionnaires

Questionnaires were distributed to aircrew members who were asked to rate a number of instruments, panels, or controls with respect to lighting, legibility, visibility, functional grouping, access, location, and utility. In addition, a section was provided for the crew members to make any additional comments that were not addressed in the questionnaire or that needed further explanation. Statistical Analysis Software (SAS) was used to analyze the numeric ratings and the TAKE was used to evaluate the users written comments.

The Analysis tool was used to sort the data into five categories. The five categories used are listed below along with an example of some of the keywords used to identify that category:

- Spatial - reference to location, e.g. "near," "overhead"

- Temporal - anything that referenced time, e.g. "day," "night"

- Resources - requirements, e.g. "need," "require"

- Differences - negatives, e.g. "couldn't," "didn't"

- Visual - anything that dealt with the visual processing of information, e.g. "see," "look," "NVG"

A color coded map was produced which coded the five categories to provide a visual representation of the data. Based on this color coded map, it became very obvious that the bulk of the problems were first visual, then spatial. This was extremely useful because it focused the analysis process. Until this point, a definite approach had not been decided because of the volume of information that was involved. This categorization of the data focused the evaluation and led the human factors engineers to find ways to improve visual information processing and access to various instruments in the cockpit. It was also interesting to note that the bulk of the spatial problems were identified by the flight engineer. This was not surprising because the observations and task analysis revealed that the flight engineer was required to access panels and instruments located all over the cockpit.

Observations

Observations included visits to the aircraft and actual flights. These observations provided a means to further identify problem areas and visualize what the operators were saying in the interviews and on the questionnaires. Also, cockpit measurements were taken for instances where crew members remarked that a certain instrument was hard to reach or hard to see. These measures were documented and compared with visual angle and anthropometric requirements. A concept map was created from the notes and measurements taken during the observations. Analysis was performed and again problem areas were identified as being mainly visual and spatial.

An engineering drawing of a proposed cockpit modification was shown to operators after each interview session. They were asked to comment on what they liked and disliked about the design. They were also given the opportunity to re-configure the design using hard copy cut outs of the controls and displays. This allowed the operators to design their own cockpit and explain why they wanted certain controls and displays located in the various positions.

SUMMARY

The MH-53J helicopter evaluation has verified concept mapping to be a superb knowledge acquisition technique and has proven the TAKE process to be very effective in organizing and analyzing the acquired information.

Concept maps collected during interviews proved to be an effective means of eliciting knowledge from DEs. They were also very useful in organizing user comments on the questionnaires and notes taken during observations.

The Outline and Combine functions streamlined the process of building a task analysis from information organized in the form of concept maps. The Analysis tool made it very easy to extract the information needed from the observations to document in the report. In addition, the categorization of visual and spatial problem areas allowed the human factors engineers to focus on ways to improve visual information processing and access to various instruments in the cockpit. Based on the results of this evaluation using these methods, an optimal cockpit configuration was recommended for the MH-53J.

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An Overview of Space Shuttle Anthropometry and Biomechanics Research with Emphasis on STS/Mir Recumbent Seat System Design

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ABSTRACT

The Anthropometry and Biomechanics Laboratory (ABL) at the Johnson Space Center conducts multi-disciplinary research focusing on maximizing astronaut intravehicular (IVA) and extravehicular (EVA) capabilities to provide the most effective work conditions for manned space flight and exploration missions. Biomechanics involves the measurement and modeling of the strength characteristics of the human body. Current research for the Space Shuttle Program includes the measurement of torque wrench capability during weightlessness, optimization of foot restraint and hand hold placement, measurement of the strength and dexterity of the pressure gloved hand to improve glove design, quantification of the ability to move and manipulate heavy masses (6672 N or 1500 lb) in weightlessness, and verification of the capability of EVA crewmembers to perform Hubble Space Telescope repair tasks.

Anthropometry is the measurement and modeling of the dimensions of the human body. Current research for the Space Shuttle Program includes the measurement of 14 anthropometric parameters of every astronaut candidate, identification of EVA finger entrapment hazards by measuring the dimensions of the gloved hand, definition of flight deck reach envelopes during launch and landing accelerations, and measurement of anthropometric design parameters for the recumbent seat system required for the Shuttle/Mir mission (STS-71, Spacelab M) scheduled for June 1995.

INTRODUCTION

The Anthropometry and Biomechanics Laboratory (ABL) at the Johnson Space Center conducts multi-disciplinary research focusing on maximizing astronaut intravehicular activities (IVA) and extravehicular activities (EVA) capabilities. This research is conducted to provide the most effective work conditions for manned space flight and exploration missions. The ABL performs research in two areas: anthropometry and biomechanics. Biomechanics is the measurement and modeling of the strength characteristics of the human body, while anthropometry is the measurement and modeling of the dimensions of the human body. An overview of the current research directions will be presented along with an example (Shuttle/Mir recumbent seat system design) of the how the human factors product is used in practice.

BIOMECHANICS

In altered-gravity environments, such as the "weightlessness" of low earth orbit, crew capabilities are dramatically different from what they are in the one-gravity environment on Earth. The ABL performs tests to measure and model human strength capabilities in weightlessness. In addition to the laboratory itself, several different simulation facilities are used to conduct investigations. These facilities include the Precision Air Bearing Floor and the Weightless Environment Training Facility at the Johnson Space Center, as well as the KC-135 zero-gravity research aircraft based at Ellington Field, Houston, TX.

A recent test was conducted on the KC-135 to measure torque wrench capabilities of subjects while in prototype intravehicular activity (IVA) foot restraints¹. The KC-135 provides brief

periods of zero-gravity (25 to 30 seconds) while flying parabolic profiles. The test set-up utilized a prototype foot restraint with an adjustable pitch angle. The test subject, wearing socks, was allowed to adjust a 3.8 cm (1.5 in) wide foot loop to a comfortable tension. The subject was then directed to apply torques to an instrumented task board with a torque wrench. Instead of torque, the applied forces were reported, allowing the designer or mission planner to select the appropriate tool length required to generate the necessary torque to complete the task. The forces measured were highly dependent on the direction of effort. When applying force in an up or down direction, the subject was able to position his/her body to use the large muscle masses in the legs to generate large forces. These forces were on the order of 467 N (105 lb) in the down direction and approximately 663 N (140 lb) in the up direction. Forces to the left and right of the subject averaged about 356 N (80 lb) to the left and 400 N (90 lb) to the right, while forces toward (such as pulling an object) and away (such as pushing an object) were about 289 N (65 lb) towards and 356 N (80 lb) away, respectively.

In addition to tasks requiring strength inside the crew compartment of the Shuttle, crewmembers must perform numerous physical tasks while EVA. Occasionally, portable foot restraints are not available to react applied forces and torques. In this situation, crewmembers must use only one hand to counteract the forces and torques of the tool hand. During another study carried out on the KC-135 in which EVA suited subjects applied torques with a 25 cm (10 in) tool handle and used only a single hand restraint, the torques measured were on the order of 70 to 80 N-m (52 to 59 ft-lb) in zero-gravity².

One of the keys to a successful EVA is adequate hand function. The hand serves as a multi-purpose end effector required to perform a variety of tasks ranging from holding on to free floating satellites to using EVA tools. Measurements of grasp breakaway forces, which simulate holding a satellite by hand with an EVA handrail, found crewmembers capable of exerting grasp forces in excess of 1000 N (225 lb)³. Results from the hand grasp breakaway test indicated that the right hand is generally stronger than the left, and female grip strength is typically 50 percent of male grip strength. Further tests, evaluating barehanded versus gloved hand performance, found the following results: wearing an EVA glove reduces grip capability by 50 percent regardless of gender, performance decreases with increasing pressure, and pinch strength is unaffected by wearing an EVA glove⁴.

Manipulation of large masses is another task often required of the crewmember. This task is required in the IVA environment due to the need to move instrumentation racks about the crew compartment on Space Station Freedom. To measure the forces and torques required when manipulating a Space Station IVA rack, a test was conducted on the Precision Air Bearing Floor at Johnson Space Center⁵. This test used a heavy rack mock-up weighing 6672 N (1500 lb) with an instrumented handrail. The results indicated forces of less than 11 N (8 lb) and torques of less than 3.4 N-m (2.5 ft-lb) were required to manipulate the rack.

Manipulating large masses is also required in the EVA environment. Manual handling of the Intelsat satellite (STS-49, June 1992) was required to successfully capture the satellite. Large mass handling will also be required on the Hubble Space Telescope Service Mission 01 (STS-61, December 1993). Significant operational concerns are inherent with EVA mass handling tasks. Of critical importance to insure safety of the crewmember as well as the integrity of the payload, is to verify that the tasks required are within the crewmember's capability. A mass handling test, which used a mock-up of one of the Hubble's instruments scheduled for replacement, with correct mass and inertia properties, was conducted on the Precision Air Bearing Floor⁶. This test measured the forces and torques required to maintain stable control of the orbital replacement unit (ORU) while performing insertion tasks and operations with the remote manipulator system (RMS). The results found that the amount of force that can be expected during ORU insertion tasks varied from about 18 N to 62 N (4 lb to 14 lb) while the

torques varied from 11 N-m to 20 N-m (8 ft-lb to 15 ft-lb). During the RMS operations, the worst case force at the handrail was approximately 222 N (50 lb) during a sudden stop of the RMS when translating at 0.5 m/s (1.5 ft/sec). This test verified that the forces and torques required to perform the task were well within the crewmember's capabilities.

ANTHROPOMETRY

Anthropometry is the measurement and modeling of the dimensions of the human body and includes both static and dynamic measurements. Anthropometric data can be used to size pressure garments, EVA gloves, and flight clothing so appropriate tariffs can be developed to accommodate all crewmembers. Other uses include developing hardware such as exercise equipment, EVA and IVA tools, crew seats, and flight control systems.

The ABL maintains a database of anthropometric measurements from astronauts and astronaut applicants. As part of the astronaut selection process, the ABL measures 14 anthropometric variables from each astronaut applicant. Recently, statistical analyses were performed on the database created over the data collection period from 1985 to 1991⁷. This period includes 473 individuals, 82 of which were selected as astronauts.

An operational concern involving anthropometry during EVA includes the risk of finger entrapment. The potential for such a situation would be a serious safety problem. The ABL conducted a glove box test with series 3000 gloves at 0.624 kPa (4.3 psi) to determine the range of hole sizes that could result in finger entrapment⁸. Based on experimental results, the smallest diameter should be less than 13 mm (0.50 in) and the largest diameter should be greater than 35 mm (1.38 in) in order to eliminate the possibility of finger entrapment during EVA.

Anthropometry is typically static, that is there is no motion. However, certain conditions can require the measurement of anthropometry under dynamic conditions. An example of this is a crewmember's reach envelope and how it changes under various gravitational conditions⁹. Launch profiles create accelerations on the order of three times that of Earth's gravity (3 g's). Certainly, the reach envelope of a crewmember on the flight deck during launch will be different than that experienced in 1 g. Measurement of reach envelopes under various acceleration environments provide designers with the information needed to properly design flight systems which are accessible under flight conditions.

SHUTTLE/MIR RECUMBENT SEAT SYSTEM

Anthropometry is used frequently to design equipment and flight hardware. An example of this process is the anthropometric data required to design the seating system for the Shuttle/Mir mission.

In June of 1995, the Space Shuttle (STS-71, Spacelab-M mission) will rendezvous and dock with the Russian space station Mir¹⁰. The Space Shuttle will return to a landing site in the U. S. with three crewmembers: a Russian trained U.S. astronaut and two cosmonauts. The primary U. S. scientific goals are to investigate the effects of long-duration space flight on the human body. One of the operational concerns is the level to which the returning Mir crewmembers will be able to withstand the g conditions during the return flight. Because the long stay aboard Mir will cause cardiovascular deconditioning and muscle atrophy, it was proposed that the crew return to Earth in a recumbent position to minimize the effects of these physiological changes.

Returning the crewmembers in a recumbent position requires the design of a new seating system. However, the existing anthropometric data for seat systems is based on measurements taken

while the subjects were unsuited and sitting¹¹. To insure accuracy, the anthropometric data must be collected when the subjects are wearing a pressurized Launch and Entry Suit (LES) and are lying in a recumbent position.

Additionally, the design of the recumbent seating system must meet the requirements of both 5th percentile Japanese female and 95th percentile American male crewmembers. To accommodate this requirement, a test was conducted where the subjects were measured in the shirtsleeve condition, and then again after donning and pressuring the LES¹². To account for the spinal elongation which occurs due to the absence of gravity, an additional three percent was added to the spinal measurements¹¹. The difference between shirtsleeve and suited measurements, which is representative of the change due to the suit, posture, and pressure can then be added to the existing Man-Systems Integration Standards (MSIS) (NASA-STD-3000) anthropometric data to project the measurements for 5th percentile Japanese female and 95th percentile American male crewmembers¹¹.

CONCLUSION

Anthropometry and biomechanics research makes up an important component of a successful manned space flight program. The environment of space, so unlike that here on Earth, often requires performance tests in simulation facilities to measure crewmember capabilities. Interaction with mission planners, hardware designers, astronauts, and others is essential in creating a useful human factors product.

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ABSTRACT

Over the past three years a new set of methodologies has been developed to specify and evaluate anthropometric accommodation in USAF crewstation designs. These techniques are used to improve the ability of the pilot to reach controls, to safely escape the aircraft, to achieve adequate mobility and comfort, and to assure full access to the visual field both inside and outside the aircraft.

This paper summarizes commonly encountered aircraft accommodation problems, explains the failure of the traditional "percentile man" design concept to resolve these difficulties, and suggests an alternative approach for improving cockpit design to better accommodate today's more heterogeneous flying population.

INTRODUCTION

There is a considerable body of evidence detailing body size accommodation design problems encountered by USAF pilots in a variety of cockpits. Most commonly these difficulties are: the inability to reach both hand and foot operated controls; limitations on control authority due to stick interference with the legs; inadequate clearance for ejection; limitations on external visibility; difficulty seeing instruments or labels inside the cockpit; inadequate overhead clearance which prevents the pilot from sitting erect in the correct ejection posture; and finally a generalized lack of mobility due to overall cramped accommodation.

Specifications

The goal of the procurement process for USAF aircraft has been to write specifications which ensure that the body size of a very large portion of the USAF population will be accommodated in the design. Traditionally this has been attempted by using percentiles to specify how much of the USAF population is to be accommodated. Typical specifications have read: "The system shall be designed to allow safe operation by the fifth percentile pilot through the ninety-fifth percentile pilot". But how is a 5th or 95th percentile pilot defined? And once defined, how is the design evaluated to determine if the required level of accommodation has been achieved?

There are a number of errors inherent in the "percentile man" approach which have resulted in marked difficulties for a number of pilots operating or escaping from their aircraft. To correct these deficiencies a multivariate alternative to the percentile approach has been developed to more accurately describe body size

variability of the USAF flying population. A number of body size categories called "representative cases" are calculated, which, when used in specification, design, and testing of new aircraft can greatly improve the desired level of accommodation. These "representative cases" not only describe the typical "small" and "large" pilot (as the percentile approach attempted to do), but, expand these categories to include individuals with variable body proportions such as people with short torsos and long limbs. Two technical reports are in preparation which describe this new approach in detail (Zehner 1992, Meindl 1993).

Evaluations

It is not enough to write specifications whose desired end is to accommodate a more variable population. An additional step in meeting this goal is a thorough evaluation of the cockpit design to verify if it will in fact accommodate ALL of the intended user population. While cursory evaluations of new designs have always been performed, these efforts have never been given the level of support they require. A third USAF technical report (Kennedy 1993) currently in preparation, describes evaluation techniques for ensuring optimum body size accommodation. The technique goes beyond merely verifying that the specifications have been met; it attempts to define the body size limits of persons who can safely operate a particular aircraft.

The Changing Pilot Population

This issue is critical in today's Air Force because the demographics of the pilot population are beginning to change. In the 1950s and 1960s (when most of our current aircraft were being designed), the USAF pilot population was almost exclusively a white male domain. Anthropometric databases reflected these demographics and, as a result, body size descriptions in aircraft specifications did too. The current mix of males and females of many races greatly changes the anthropometric profile of the population. The body size restrictions for entry into undergraduate flight training in AFR 160-43 have also changed. Larger pilots than ever before are being admitted, and discussions currently taking place may well result in lowering restrictions to allow smaller people into pilot training as well. Changes such as these should only be made after serious consideration of the effect and consequences of allowing individuals to fly aircraft which were not designed to accommodate their particular body size. Any rational consideration of changing body size criteria for aviators must include data that describes the limits the aircraft imposes on the pilot. If there is a high probability that the long legged pilot will strike the canopy bow during ejection, or that short legged pilot will not be able to get full rudder throw, then these individuals should not be allowed to fly that particular aircraft.

PROBLEMS WITH PERCENTILES

A percentile is a very simple statistic. It shows the relative ranking of an individual point in a given distribution. For example, in the distribution for the body dimension, Stature (1967 USAF pilot sample), the fifth percentile value is 65.8". This means simply that five percent of a population is shorter than 65.8", and ninety-five percent of the same population is taller than 65.8". This example points up two problems with the percentile approach. First, percentiles are only relevant for one dimension at a time (univariate), and second, they are specific to the population they were calculated upon.

The Univariate Problem

Previously, USAF policy has been to ignore the smallest 5% of the pilot population in design specifications. The 5th percentile was the starting point. But, in attempting to describe or categorize an individual as a 5th percentile person, a single value (such as stature) tells us essentially nothing about the variability in remaining measurements on that individual's body. Consider Weight, for example. Individuals of 65.8" in stature in the 1967 anthropometric survey of pilots (Kennedy 1986) ranged from 125 lbs. (less than 1st percentile) to 186 lbs. (74th percentile). So, what weight should be assigned to the 5th percentile pilot? A logical conclusion is to consider the 5th percentile for BOTH measures. However, using 5th percentile in weight (140 lbs.) and 5th percentile stature (65.8") simultaneously to classify an individual as a 5th percentile pilot, presents a new problem. Only 1.3% of the 1967 survey were smaller on both measures, while 9% were smaller for one or the other of those criteria. This problem becomes much worse with each additional measurement that must be used in the design. It is not difficult to see that the use of percentiles to specify a complex design will lead to uncertainty as to exactly what body size values should be used and what percentage of the population will be accommodated (or excluded) after production.

The Exclusion Problem

A few body dimensions are critical to laying out the crewstation: Sitting Height (for clearance with the canopy), Eye height Sitting (for adequate vision), Buttock-Knee Length and Knee Height Sitting (for escape clearance with instrument panel and canopy bow), Shoulder Breadth (for side clearances), and Functional Reaches (to operate controls and rudders). Generally a group of measures such as this is listed in a specification or standard along with 5th and 95th percentile values for EACH. This gives the misleading impression that if these values are used as design criteria, 90% of the population will be accommodated. This is not the case as can be seen in Figure 1. Since an individual need only be disaccommodated for any one of these measures to invite potential problems in operating or escaping the aircraft, these measures must be looked at SIMULTANEOUSLY to determine the percentage of the population described by the measurements.

In figure 1, the pilot population is represented by the shaded bar. It is a simple matter to screen the population with 5th and

95th percentile values for Sitting Height and retain the desired 90% of the population. However, when those same individuals are also screened for 5th to 95th percentile values for Buttock-Knee Length, their numbers drop again. With the application of each additional cockpit relevant dimension, the group diminishes until, finally, only 67% of the original pilot population remains. In other words, as many as 33% of the pilot population could experience difficulty operating an aircraft that fully met specifications. Historically, such large numbers of USAF pilots have not in fact experienced body size related problems with their aircraft. But, this is due only to the design philosophy of USAF contractors, not the government specifications.

THE MULTIVARIATE ACCOMMODATION METHOD

What follows is a brief description of an alternative to the use of percentiles that corrects the deficiencies described above, while retaining the original intent of using percentiles in specification and design. That is, the recommended technique uses anthropometric data to develop and purchase equipment that accommodates a specific range of body sizes in the user population. Two examples of the approach are given below: a very simple two-measurement scenario, and a more complex cockpit layout which makes use of more measurements.

A Bivariate Example

A bivariate frequency table (Fig. 2) is very similar to the univariate distribution for which percentiles are suitable. The difference is that two measurements are considered simultaneously. In this example, the distribution of Stature in the 1967 USAF flyers survey is plotted on the horizontal axis, while Weight is plotted on the vertical axis. Each individual pilot is plotted on the graph at the point where his (in 1967 the pilot population was all male) stature and weight intersect. Using the mean value for both stature and weight as a starting point, an ellipse can be statistically imposed on the graph which includes any desired percentage of the population inside of it. A 90% ellipse is shown in the figure. Also shown on this figure are the intersection points for the mean (point X), and points similar to the 5th and 95th percentile concept (points 1 and 2) in that they persons who are small or large on both measures.

The Two Point Assumption

Another erroneous assumption that has been made over the years is that if the 5th and 95th percentiles of a distribution are used as design points, all individuals between these two points will be accommodated in the design. However, selecting only those individuals who are small or large for both Stature and Weight does not describe all the variability in body size that must be considered in a design. That is because an individual located at point 3 (a short heavy person) is just as likely to occur in the population as any other individual along the perimeter of the ellipse. There are many short heavy people as well as tall thin

ones (point 4). A multivariate approach would pick, at the very least, four points (subsequently called "representative cases") from along the perimeter of a circle and use them to describe size variability. In this case the representative cases would describe people who are: short and light (1), short and heavy (3), tall and light (4), and tall and heavy (2). The rationale for the multivariate approach is that several individuals spread along the edge of a circle better represent the extreme body types within the circle (not only in size - but in proportions), than does the use of two points in the distribution.

In designing a cockpit, of course, more than two variables are needed to ensure the proper fit of an individual and his or her equipment. Obviously, the bivariate approach will be inadequate as soon as a third body size variable such as leg length is considered. The two-dimensional problem now becomes a three dimensional one and the circle becomes a sphere. More than four representative cases would be necessary to describe the various combinations of these measures. It would now be necessary to describe tall heavy pilots with long legs, tall heavy pilots with relatively short legs, and so on. As each additional measurement is added to the design, an additional dimension or level of complexity is added to the analysis with the accompanying geometrical expansion of the number of representative cases which would have to be considered in the design. Clearly the problem becomes unworkable very quickly.

Principal Component Analysis

Principal Component analysis is a statistical approach which helps get around this problem. It is a data reduction procedure which reduces the number of measurements needed to describe body size variability by combining a large number of measurements into a small set of eigenvectors (a group or combination of related measures) based upon their correlation or co-variance. A set of these eigenvectors and a reduced set of representative cases can be used to describe (in multivariate terms) the body size variability in a population. Indeed, most cockpits and workstations can be accomplished with two or three eigenvectors. This means that a bivariate circle or tri-variate sphere can be used to define population limits. Representative cases are selected from the perimeter of the bivariate or surface of the sphere to encompass those individuals within. The results can be graphically demonstrated.

Another feature of the principal component technique is that each individual is ranked multivariately using standardized Z scores on each measurement of interest. This permits alteration of the size of the circle or sphere with scale adjustment only, making it possible to easily change or adjust the percentage of the population to be accommodated. Principle component analysis also can be used to eliminate redundant measurements, by determining the proportion of body size variability each eigenvector explains, so that only the most relevant representative cases are considered as design points. The current specification philosophy in the USAF is to use six cockpit

related variables to define six to eight "representative test cases". Designing a cockpit on the basis of these cases should make it possible to consider a design that will accommodate as many as 99% of current pilots. Six USAF representative cases which have been used in several aircraft procurement programs are shown in Table 1. Traditionally used 5th and 95th percentile values from MIL. STD. 1472 are given in Table II for comparison purposes.

While there are many measurements that could be included to describe the representative cases, most are simple clearance dimensions such as Shoulder Breadth, which can be dealt with as minimum and maximum expected values. In most cases it does not matter if the widest shoulders are found on an individual with a tall sitting height or a short one. Both sets of shoulders must clear the sides of the cockpit. Based on that reasoning, a number of minimum and maximum expected values for other measurements are included in the specifications when they are not dependent on seat or rudder pedal position. These are shown at the end of Table I.

The six so-called cockpit measurements however MUST be considered as COMBINATIONS because it is very important to consider problems of an individual who has, for example, a very short sitting height and long legs. This pilot would adjust the ejection seat all the way up to attain proper over-the-nose vision, and adjust the rudder carriage full forward to accommodate the long legs. In this seat position the knee/shin may be much closer to the bottom edge of the instrument panel where it represents an ejection injury potential. In the case of non-ejection seat aircraft with a yoke or wheel, the vertical distance between the seat and the bottom edge of the wheel becomes reduced causing the possibility of interference problems with the leg (particularly during cross-control maneuvers). Similarly, the position of the shoulder during reach to controls is a matter of some importance. Imagine two individuals with short arms reaching down to a control on a side panel. If the shoulders of one are several inches higher than the shoulders of the other, their ability to reach that control will differ considerably. Now imagine the same two individuals reaching to an overhead control. These examples are but a few of many which suggest why, for some measurements, COMBINATIONS of body proportions are more useful than minimum and maximum values or percentile lists.

When all of the representative cases in a given distribution can function safely, efficiently, and comfortably in a cockpit, individuals in between these extremes should be similarly well accommodated.

EVALUATION METHODS

Currently, all aircraft designed for the USAF are evaluated during the proposal stage (on paper, CAD, or mock-up) and revisited several times during development to ensure that anthropometric requirements are being met. Using accommodation of

the representative cases described above as a contract requirement, test subjects representing those sizes are selected and fit tested in the crewstation. Small test subjects are used to determine if pilots of similar size will have: adequate internal and external vision; the ability to reach all controls; the ability to reach all CRITICAL controls with locked inertial reels; have full control authority with the seat full up; and the ability to achieve full rudder throw and brake. Large test are used to determine: overhead clearance; operational clearances; ejection clearance with cockpit structures such as the canopy bow, glareshield, instrument panel, and canopy sill; and full control authority with the seat in various adjustment positions. It is usually necessary to test at least a dozen subjects in order to account for variations in body posture and shape. Subjects of exactly the same size as the representative cases are nearly impossible to find. Therefore, miss distances (or excess) are added to subjects' anthropometric dimensions where necessary to arrive at appropriate values, or, several subjects each having a few of the required characteristics, are used to simulate each of the "representative cases".

CONCLUSION

Multivariate accommodation techniques for describing body size variability in the user population will remove the ambiguity currently associated with government anthropometric requirements. Once proper specifications for cockpits or other workstations have been documented, thorough evaluations must take place to ensure the design meets those specifications. This approach has been used by the USAF in a number of recent aircraft procurements and has significantly enhanced the resulting product. Approximately 30 aircraft competing for various contracts have been evaluated to date. Problems for large pilots problems such as potential canopy bow strikes, limited control authority, inadvertent control activation, and inadequate clearance overhead have been revealed during these hands-on evaluations. For small pilots problems involving inadequate external vision, problems reaching critical controls, difficulties in turning the aircraft because of inadequate space between the seat and bottom of the yoke, and inability to reach the rudders have all been found.

A major benefit of this technique is that it is used throughout the procurement and design cycle. In this way accommodation problems can be discovered and corrected early in the design phase, or the aircraft can be prevented from entering the inventory until such defects are taken care of.

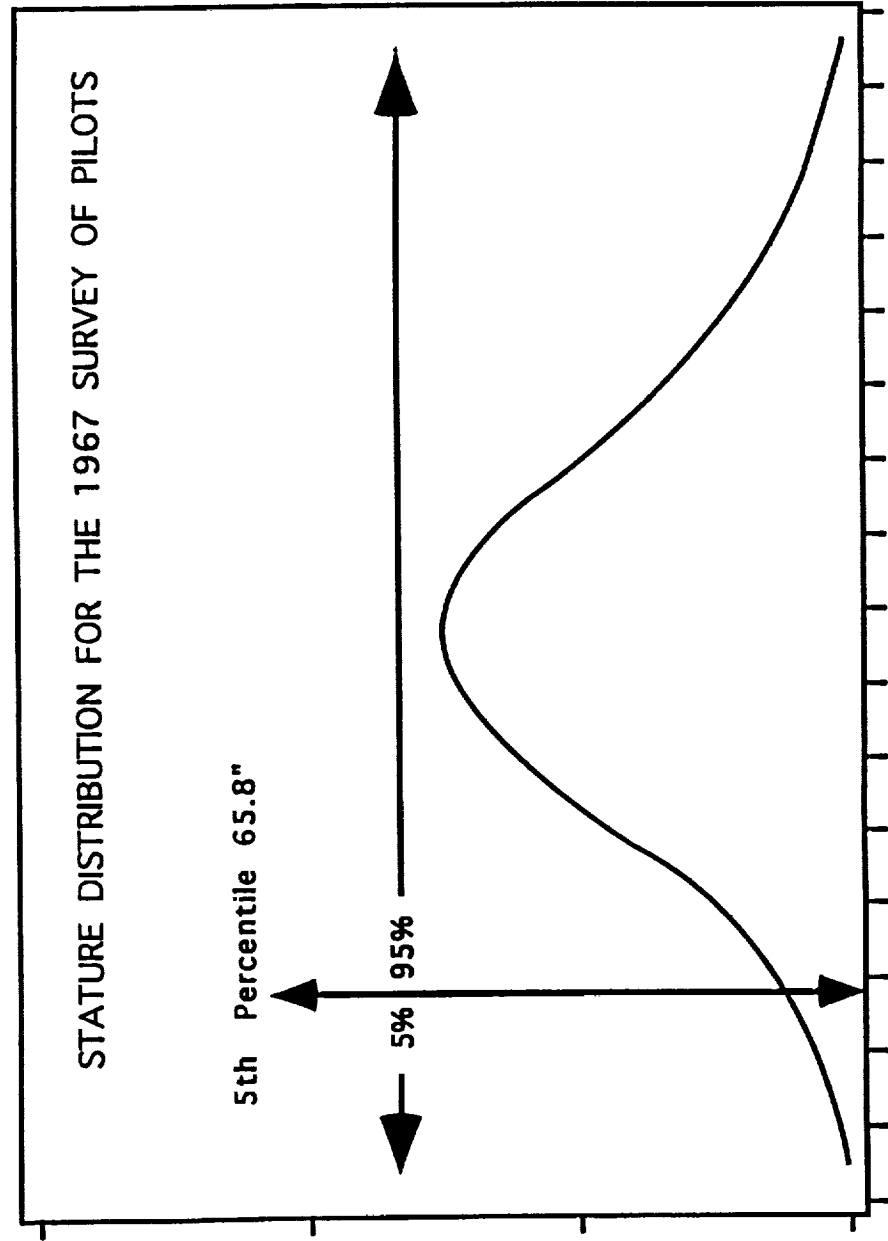


FIGURE 1

Normal Distribution For Stature: 1967 USAF Survey

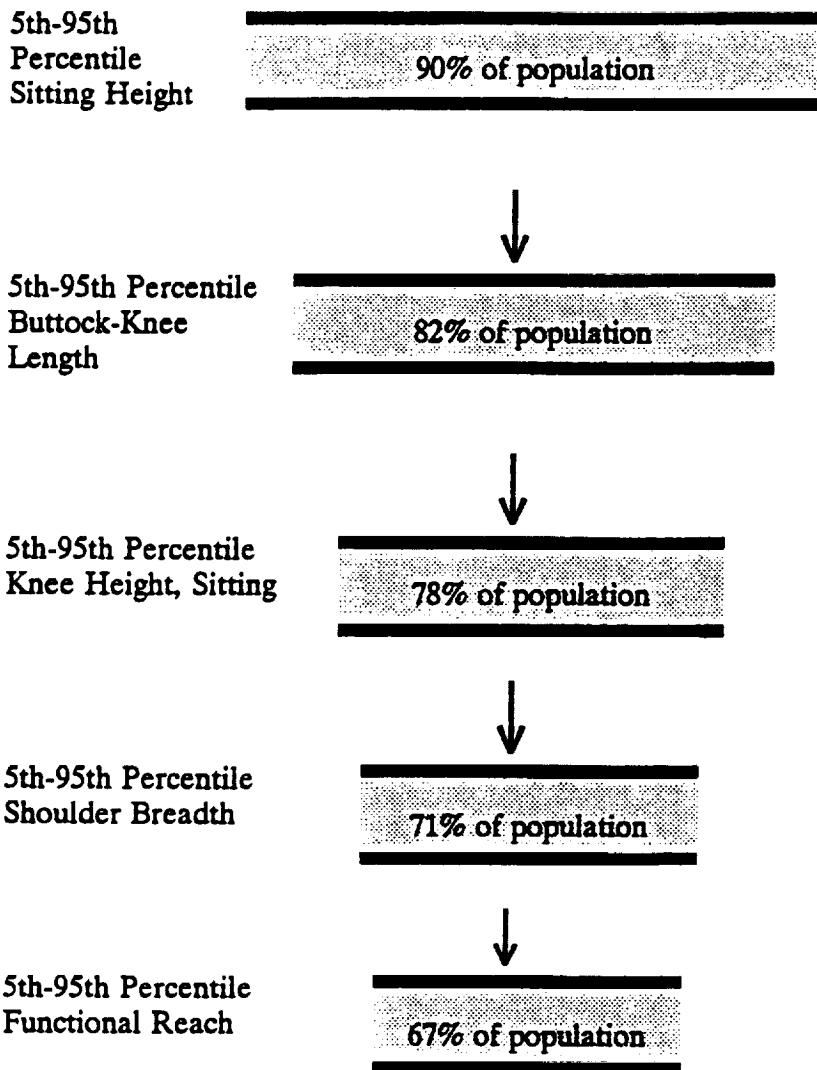


FIGURE 2

**Diminution of Population Coverage with Successive
Screening for 5th-95th Percentile Values of
Selected Dimensions: 1967 USAF Survey Data**

SMALL PILOTS

Case 1 Generalized Small Pilot

Thumb-Tip Reach	28.3
Buttock-Knee Length	22.1
Knee-Ht. Sitting	19.5
Sitting Ht.	34.0
Eye Ht. Sitting	28.9
Shoulder Ht. Sitting	21.3

Case 2 Shorter reach with higher shoulders

Thumb-Tip Reach	27.6
Buttock-Knee Length	21.3
Knee-Ht. Sitting	19.1
Sitting Ht.	35.5
Eye Ht. Sitting	30.7
Shoulder Ht. Sitting	22.7

Case 3 Shortest Torso

Thumb-Tip Reach	30.4
Buttock-Knee Length	23.9
Knee-Ht. Sitting	20.8
Sitting Ht.	32.4
Eye Ht. Sitting	27.9
Shoulder Ht. Sitting	20.5

PILOTS WITH CONTRASTING PROPORTIONS

Case 4 Short Sitting Ht. with very long limbs

Thumb-Tip Reach	33.9
Buttock-Knee Length	26.5
Knee-Ht. Sitting	23.3
Sitting Ht.	34.9
Eye Ht. Sitting	30.2
Shoulder Ht. Sitting	22.6

Case 5 Short Limbs with very large Sitting Ht.

Thumb-Tip Reach	29.7
Buttock-Knee Length	22.7
Knee-Ht. Sitting	20.6
Sitting Ht.	38.5
Eye Ht. Sitting	33.4
Shoulder Ht. Sitting	25.2

Table I. Multivariate "Representative Cases" (values in inches)

LARGE PILOTS

Case 6 Generalized Large Pilot

Thumb-Tip Reach	35.6
Buttock-Knee Length	27.4
Knee-Ht. Sitting	24.7
Sitting Ht.	40.0
Eye Ht. Sitting	35.0
Shoulder Ht. Sitting	26.9

Case 7 Longest Limbs

Thumb-Tip Reach	36.0
Buttock-Knee Length	27.9
Knee-Ht. Sitting	24.8
Sitting Ht.	38.0
Eye Ht. Sitting	32.9
Shoulder Ht. Sitting	25.0

Case 8 Largest Torso

Thumb-Tip Reach	33.3
Buttock-Knee Length	25.4
Knee-Ht. Sitting	23.2
Sitting Ht.	41.4
Eye Ht. Sitting	35.9
Shoulder Ht. Sitting	27.6

For additional measures of importance, the simple clearance values listed below represent the largest and smallest values for any one dimension that can be expected for pilots. The small values do not necessarily accompany the small flyers listed above, nor do the large. These values could occur at any seat position and should be considered in that light.

Shoulder Breadth	14.1	-	21.6
Forearm to Forearm Breadth (seated)	14.5	-	25.5
Hip Breadth (seated)	11.7	-	18.1
Shoulder to Elbow Length (arm flexed)	12.5	-	16.6
Elbow to Fingertip Length (arm flexed)	16.2	-	23.2
Buttock to Popliteal Fossa Length (leg flexed)	16.5	-	23.2
Popliteal Height Sitting	15.0	-	21.2
Boot Size	6	-	13
Thigh Clearance (sitting thickness)	3.8	-	8.0
Chest Depth	6.6	-	12.2
Chest Circ.	30.0	-	48.0
Waist Circ.	26.0	-	44.0
Thigh Circ.	18.0	-	30.0
Weight	103.0	-	245.0
Interpupillary Distance	2.0	-	3.0

Table I. Continued (values in inches)

Sitting Height	34.7"	38.8"
Eye Height Sitting	30.0"	33.9"
Shoulder Height	22.2"	25.9"
Buttock-Knee Length	22.1"	25.6"
Knee Height Sitting	20.4"	23.6"
Thumb Tip Reach	29.1"	34.3"

Table II. 5th and 95th Percentile Values (from MIL-STD 1472)

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**Session H5: BEING THERE: PROTOTYPE AND SIMULATION
FOR DESIGN**

Session Chair: Dr. Jane Malin

END EFFECTOR MONITORING SYSTEM: AN ILLUSTRATED CASE OF OPERATIONAL PROTOTYPING

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ABSTRACT. This paper introduces operational prototyping, to help developers apply software innovations to real-world problems, to help users articulate requirements, and to help develop more usable software. Operational prototyping has been applied to an expert system development project. The expert system supports fault detection and management during grappling operations of the Space Shuttle payload bay arm. The dynamic exchanges among operational prototyping team members are illustrated in a specific prototyping session. We discuss the requirements for operational prototyping technology, types of projects for which operational prototyping is best suited and when it should be applied to those projects.

1. INTRODUCTION

We developed the concept of operational prototyping during a case study of NASA intelligent systems [3], which was conducted to identify useful types of human-intelligent system interaction. During that case study, we observed that developers supporting a large flight controller group were using highly successful methods, although (or perhaps because) they were not following standard software engineering practices. Though their methods were informal, they developed fieldable software rapidly, satisfied their user customers, and avoided the pitfalls of wandering development, lack of documentation and excessive nonstandard custom software. Their methods interested us, not only because of their success, but because they seemed to also address problems that human-computer interaction designers have in common with users. That is, usability evaluation and human factors concerns often have too little effect on delivered software. These methods emphasized the user and usability, and achieved success at lower development cost, by using rapid prototyping methods and by exploiting the advanced graphics technology and automated object-oriented programming capabilities available in expert system development environments.

Traditional software engineering has weaknesses in the areas of helping users to articulate system requirements, assisting technology insertion, and providing innovative task support to users. Consequences of these weaknesses include slow and late deliveries, and products that require costly rework to satisfy customers. The practices we observed were strong where traditional software engineering was weak. Since we could expect that advanced software development tools would become more widely available to software developers in the future, we analyzed these methods and began to describe and codify them. We refined them to integrate with software engineering concepts and human-computer interaction concerns [1].

We call these methods operational prototyping. Operational prototyping is an approach to aid the development of innovative software applications for complex tasks, such as those found in aerospace operations. Innovative applications are those for which important aspects are not well understood by software developers. For instance, the operational prototyping approach introduced in this paper is based on applications of artificial intelligence technology to real-time fault management problems.

Operational prototypes are called "operational" because they can be used in an operational setting to demonstrate how a new approach solves a specific problem and supports user task performance. Since the prototyping is user-driven, these systems are more likely to be operations-scenario-driven than systems from many traditional, requirements-driven projects. They are called "prototypes" because of their informal, iterative development. Although the development schedule is informal, the addressing of system requirements is rigorous. This must be so, since the stakes are high: these prototypes are fielded for side-by-side use and evaluation in the operational setting. They are intended to stand in until the "software engineered" versions are developed, and can be used to validate them.

2. EXAMPLE APPLICATION

Recently, we have had the opportunity to further evaluate and refine these methods by doing our own operational prototyping. We have been using these methods while developing a monitoring and fault detection expert system for flight controllers, the DEcision Support SYstem (DESSY) End Effector application. DESSY is an object-oriented, rule-based, decision support system to assist ground-based flight-controllers in monitoring and managing faults in the Shuttle payload bay arm. It is being developed incrementally: the end effector module is the second of several modules being developed for arm subsystems. The End Effector module helps to monitor the grappling device at the end of the arm, which makes a secure connection with the payload so that it can be manipulated by the arm.

On the one hand, the DESSY End Effector development approach resembles traditional software development because there are similar development activities, which are initiated in about the same order as a traditional waterfall development approach. A requirements analysis drove some initial designs for displays, object hierarchies and structures, rule organizations, and testing scenarios.

On the other hand, our operational prototyping methods differ in important ways from traditional development methods. First, the development activities are being addressed iteratively. No attempt has been made to state all the requirements in detail before exploring the implications of those requirements by design, implementation, and evaluation of a prototype. Since DESSY is an innovative application, it is not possible to understand the requirements fully before beginning the design. The second major difference is use of the prototype in operational scenarios as a means for involving the customer in analysis, design, implementation, and evaluation. Our flight controller representative offers suggestions for solving development problems rather than just passing judgment on the decisions we have already made. Finally, we refine the requirements and design based on our experience with the prototype. This is where the magic of operational prototyping happens.

2.1. Example Operational Prototyping Session

To convey the sense of operational prototyping in a concrete fashion, we present an example of a specific operational prototyping session early in the development of the DESSY End Effector module. In this session, we made improvements in the screen layout and discovered new requirements for the intelligent system.

Figure 1 shows an original screen layout sketched on the Macintosh before the prototype was developed. The end effector consists of two mechanisms: a snare and a rigidizer. The snare has wires which wrap around a pin protruding from the payload, thereby capturing the payload. The rigidizer pulls the snare into the interior of the end effector until

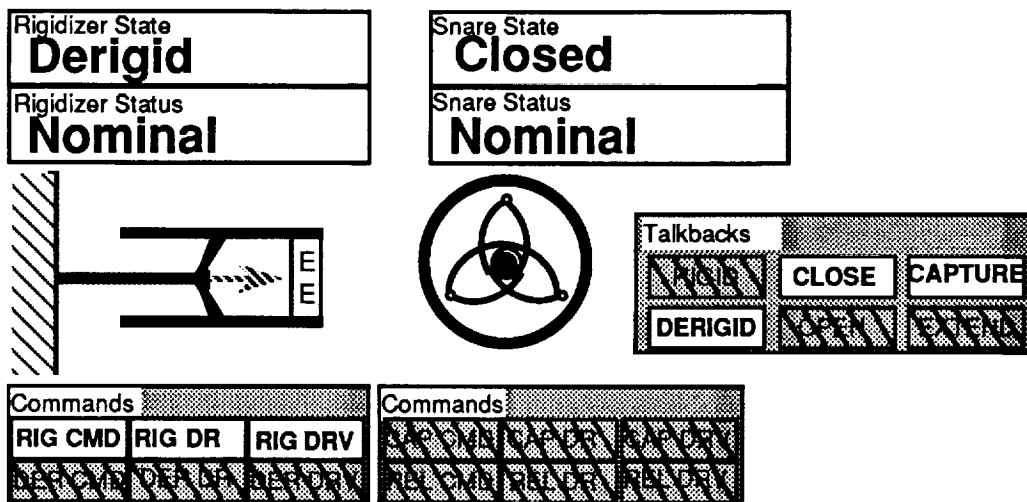


Figure 1. Before Operational Prototyping Session

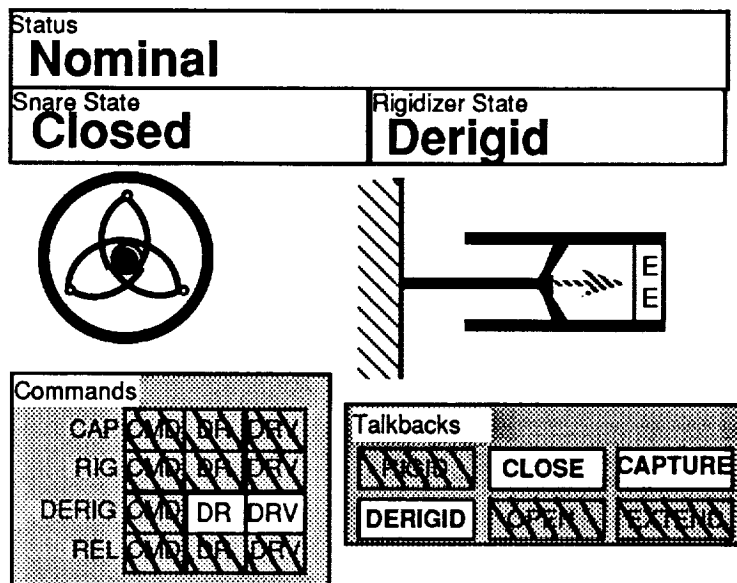


Figure 2. After Operational Prototyping Session

the end effector and the wall of the payload press against one another, making rigid the connection between the arm and the payload. These two mechanisms are represented iconically in the central portion of the screen, and these icons move to portray the current state of the each mechanism. Most of the remainder of the screen is organized around the icons, with rigidizer information on the left and snare information on the right. Because this design is neat, orderly, and logical, all the team members, including the user, were initially satisfied before the prototyping began.

During the first prototyping session, however, it became apparent that with the original screen layout, events in nominal capture and release sequences were difficult to follow in real time. Some end effector events last only a second and can be accompanied by seven display changes. With the design in Figure 1, none of us (not even our expert flight

controller) could adequately monitor a nominal sequence of events in real time. As a group, we arrived at the solution depicted in Figure 2.

The layout in Figure 2 is more compact, and the commands have been re-organized according to the direction of movement rather than mechanism. For example, the capture and rigidize commands are represented contiguously because both commands are used when capturing a payload. By the same token, the derigidize and release commands are represented contiguously because they are both used when releasing a payload. With this new display layout, we can verify that critical events take place for nominal capture and release sequences. We discovered the need for improvement by interacting with the prototype, and we arrived at an acceptable solution by interacting with one another and experimenting with the prototype.

Operational prototyping is not just for improving user interfaces. Another result of this prototyping session was correction of the logic for inferring end effector states from telemetry data. While interacting with the prototype, the flight controller identified an error in our understanding of the sequence of command telemetry. This, in turn, affected the application logic for inferring end effector states. We had all looked at this information before, but its inaccuracies were evident only when the experienced flight controller was observing the events unfolding before him.

Improvements from this session occurred in the screen layout, and in understanding of operational sequences and their implications for the logic in the application. Because this session occurred early in DESSY End Effector development, the primary improvements were in our understanding of system requirements. Improvements in later sessions have also emphasized design and implementation. It is hard to imagine how these improvements could have been achieved in such a timely way by text-based requirements analysis or by human factors evaluation later in the development process.

2.2. Analysis of Operational Prototyping Benefits

What makes the magic of operational prototyping happen? One contributor to the magic is the critical expertise included in the development team. On the DESSY End Effector development team are (1) a flight controller, (2) a computer scientist, specializing in intelligent systems, and (3) a human factors engineer, specializing in systems analysis, software engineering and intelligent systems. The flight controller contributes subject matter expertise based on his engineering background and years of experience in monitoring, detecting failures, and managing failures in the end effector. This expertise helps to ensure the quality of our intelligent system application. The flight controller contributes equally valuable expertise as a user. This user member of the team knows the most about the tasks to be supported by the new software application, and its context. This is critical if the new application is to successfully improve productivity, reliability and safety of operations tasks.

Another major contributor to operational prototyping magic is that the whole team interacts with the prototype and experiments with ideas to improve the design. Because we interact with a prototype in an operational scenario and change the screen designs during the session, each person is able to see the implications of design decisions. What You See Is What You Get, or WYSIWYG, is a descriptor for applications which immediately show the full implications of user input. Prototyping is the WYSIWYG of analysis and design.

Because we all interact with the prototype, we are able to consider different design concerns and viewpoints simultaneously. The implications of a proposed change can be evaluated from engineering, intelligent systems, users, and human factors perspectives

because the team has expertise in all these areas. Because we can consider these viewpoints simultaneously, we are able to make dynamic tradeoffs. For example, if a new change seems ideal except for implementation feasibility (e.g., a performance or a development time impact), the expert in that area can voice an objection along with the reason for it. At that point, a brainstorming session can ensue, in which all participants can propose potential alternatives. In this situation, with all experts present to help solve the problem, a solution that satisfies the concerns of each is more likely to be developed. In fact, this is the motivation behind the concurrent engineering impetus in systems development [2]. Finally, operational prototyping magic happens when the team focus is on generating improvement options, rather than on evaluating the prototype for acceptance or rejection.

What is the magic? Quite simply, the magic of operational prototyping is a quickly improved design. The application design is improved by concurrent and cooperative design changes, and thus meets requirements and design constraints better than could have been achieved by team members working separately. It is achieved more quickly because team members with each type of critical expertise meet around the prototype, exploring the implications of design decisions from each perspective.

3. INTEGRATING SYSTEM DESIGN WITH OPERATIONAL PROTOTYPING

3.1. What Projects are Best for Operational Prototyping?

The strengths of operational prototyping appear to be complementary with traditional software engineering. Traditional software engineering practices are reasonably adequate for projects with stable requirements; whereas operational prototyping is well-suited to projects whose requirements are initially unstable, or where continuous improvement is a goal.

Two types of development projects have initially unstable requirements: those for innovative applications of new technology and those for innovative support of user tasks. Innovative applications of technology to specific problems, by their innovative nature, are unproven and unfamiliar. Unproven designs make managers of project resources uneasy. Prototypes can demonstrate the feasibility of an innovative application to ease the concerns of those managers. Because of the abbreviated development cycle, prototypes allow the evaluation of multiple innovative alternatives so that the best one can be selected. Thus, innovative applications of technology to specific problems are good candidates for operational prototyping.

Another type of project whose requirements are inherently unstable are those which provide innovative support of user tasks. The first contribution of operational prototyping is to give users a proper medium in which to express their requirements. Operational prototyping allows users to explore the implications of their expressed requirements before expending considerable resources for a definitive requirements document. Operational prototypes can help to clarify hidden tasks and requirements. For example, user requirements for support for supervising, overriding and updating intelligent systems have not been immediately evident in most expert systems projects. Another contribution is to allow initial requirements to change *early* in project development, when those changes are the least costly. The requirements for a software application change when the application is introduced into the workplace. An operational prototype can help to drive out many of those changes earlier, before the first delivery, when the design can be changed more easily and cheaply. The operational prototype can also remain available to support further design for continuous improvement by the customer after the system is delivered.

In summary, the best projects for operational prototyping are those whose requirements are unstable. Development projects which fit this description are those which involve innovative applications of new technology, those which involve innovative support of user tasks, and those where continuous improvement is a customer goal.

3.2. When Is the Best Time to Apply Operational Prototyping?

The best time for operational prototyping is at early stages of projects. Operational prototyping is a requirements articulation process which accepts pre-requirement inputs and produces a working prototype and a set of stabilized requirements to support full-scale development. From that point, the full-scale development and integration of the new system can proceed according to traditional software engineering approaches. Since operational prototyping will have stabilized the system requirements, the traditional approaches should be even more efficient and less susceptible to unexpected delays. Thus, operational prototyping can bring initially risky projects to a sufficient level of maturity for traditional development.

The operational prototype can provide additional benefits. If measures are taken to overcome potential safety and reliability concerns, the operational prototype can be used to provide interim user task support during full-scale development. It can also be maintained to help users articulate the inevitable changes which will occur in the future as tasks change and experience is gained with new systems.

These roles for operational prototyping imply sophisticated software support, both for prototyping and for side-by-side operation in control centers. Current commercial technology appears to be prepared for this challenge.

3.3. Roles for Human Factors Personnel in Operational Prototyping

Operational prototyping also implies changes in the roles of system developers. Human factors personnel have much to gain from concurrent engineering methods such as this. There is hope that their roles can change from ones of frustrated guidelines enforcers and evaluators on the sidelines, to positive active developers. Human factors personnel can become valuable team members, helping with development of operational test scenarios, and facilitating prototyping sessions while they represent usability and human factors style concerns.

We are currently developing a feasibility prototype that includes reusable and modifiable software library elements in the prototyping system. These library elements can enforce the concerns of several types of system developers, including human factors personnel. For example, library elements can embody human factors guidelines in designs that will be the first things the prototyping teams use. Instead of refining guidelines documents and style guides that are difficult to use, human factors personnel can participate in design of application elements that conform to their concerns, and that can be used immediately in prototyping.

4. RELATED WORK AND CONCLUSION

A useful source for refining the concept of operational prototyping has been Boehm's spiral model [4]. The spiral model shows how to place operational prototyping and traditional software engineering in the same project development life cycle. It shows how to accommodate iterative development while maintaining a sense of direction for the project. It also shows how to accommodate changing risk priorities through periodic evaluations, giving the early project development a risk-driven, rather than a document-driven source of

direction. Finally, it helps to identify what risks to address within each prototyping iteration as the project matures.

Operational prototyping has two primary objectives: (1) to demonstrate the feasibility of new application, (2) provide interim operation during full-scale development. It is intended to be complementary to traditional software engineering approaches rather than a replacement for them. It complements them by addressing the risk which is most disruptive to traditional approaches: unstable requirements. Software engineering organizations can complete full-scale development for successful operational prototypes, while the operational prototype provides interim task support to its user. After full-scale development is completed, the operational prototype can serve as a test-bed for future enhancements. Because operational prototyping is a requirements articulation process, the primary emphasis is on analysis, though the quality of that analysis is evaluated by designing, building, implementing and using the prototype.

Operational prototyping helps developers to apply new technology to real-world problems by helping software developers, subject-matter experts, and human factors experts and users to quickly explore the implications of requirements, design, and implementation decisions. Operational prototyping helps users to articulate their requirements for systems that use new technology, and it helps developers to manage the risks associated with new technologies. Consequently, it can help reduce the costs of both development and operations, while improving the quality of both.

ACKNOWLEDGEMENT

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The PLAID Graphics Analysis Impact on The Space Program

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Abstract. An ongoing project design often requires visual verification at various stages. These requirements are critically important because the subsequent phases of that project might depend on the complete verification of a particular stage. Currently, there are several software packages at the Johnson Space Center (JSC) that provide such simulation capabilities. In this paper, we present the simulation capabilities of the PLAID modeling system used in the Flight Crew Support Division for human factors analyses. We will summarize some ongoing studies in kinematics, lighting, EVA activities and briefly discuss various applications in the mission planning of the current Space Shuttle flights and the assembly sequence of the Space Station Freedom with emphasis on the redesign effort.

1. Introduction

A complex engineering project is often divided into several stages. For economic purposes, management must have the capability to exercise options at the end of each of the stages [1], which often includes such decisions as: continue or abandon a project, the modification of design, the re-planning the remaining stages, etc. In order to be able to select these options, two major assessments must be provided: (i) financial assessment, and (ii) technical assessment. *Financial assessment* is the calculation of cash flows for the projects [2]. *Technical assessment* is the proof of correctness or demonstration of workability [3]. The scope of this paper is concentrated on the technical assessment capability via software simulations, with emphasis on the ongoing projects at NASA Johnson Space Center.

There are several techniques used to verify the technical merit of a design, and since many of the *advanced* projects at JSC are in the designing stages, test bedding is often augmented, prefixed or substituted by computer simulations. The type of simulation testing most often used is the scenario analysis, which is the testing of a few special cases. The system discussed here is most often used for scenario analysis in order to perform a quick look verification of well-known cases, to test and review new ideas or designs [1,2] or to analyze contingency cases.

There are several software packages that provide simulation capabilities [4,6,7]. In this paper, we present the simulation capabilities of the PLAID system [4] used in the Flight Crew Support Division.

Since 1978, the PLAID system has been used to serve many groups at the NASA Johnson Space Center. These groups include Space and Life Sciences, Mission Operations, Engineering, Space Station Project Office, Astronaut Office, etc. In addition, other NASA centers such as Marshall Space Flight Center, Goddard Space Flight Center, and Ames Research Center have also made use of the system.

These groups have primarily used the system for engineering analyses, visualization of designs, and, on

occasion, public relations pictures of NASA high-tech projects. The PLAID system has successfully fulfilled these objectives by serving as a computer aided engineering tool to provide rapid, economical mission support; to develop and apply unique, state of the art, computerized Human Modeling; and to perform system engineering analyses to optimize crew station design, development, and operation.

2. Facilities Description

The PLAID system is a three dimensional computer modeling system, which enables the creation of the geometry and kinematics of humans, as well as their environments.

Figure 2.1 depicts basic components of PLAID.

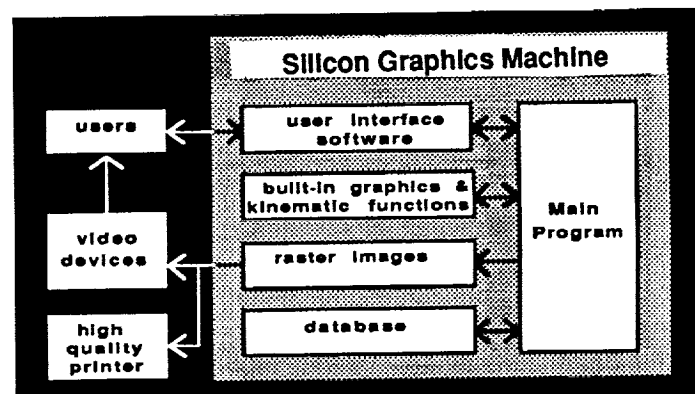


Figure 2.1. Basic Components of PLAID

2.1 Hardware Components. The system currently uses a local area network (Ethernet) of Silicon Graphics Iris workstations (IRIS)TM and personal computers, with connectivity to a network of DEC VAX computers. The workstations are high performance machines with hardware graphics rendering capabilities such as smooth shading, Z buffering and texture mapping. The other machines support image conversions for documentation purposes, as well as geometry and bitmap conversions for building, exporting and importing of models and images.

Hardcopy and video devices are used to produce imaging products. Full color prints and transparencies can be generated on Kodak XL7700 continuous tone color printer, Tektronix Phaser III color printer, and Tektronix 4693DX Digital printer. Computer generated animations are also created using Sony 3/4 inch tape recorders and 1/2 inch VHS recorders.

Use of remote video lines and the JSC site-wide computer network enable the PLAID system to support camera viewing simulations at the Space Station Mockup and Training Facility.

2.2 Software Components. Figure 2.1 shows some of the basic groups of software components of the PLAID system: user interface functions, database management functions, and graphics and kinematics functions.

The user provides the PLAID software with model information such as decomposed solid shapes, dimensions, color, degrees of freedom (rotational and translational capabilities), and interconnection relations. User commands can be stored as scripts and executed in a batch mode for complex and/or redundant operations and unattended operations.

The database management functions provide controlled access to the various projects and categories. The access control allows multiple users to share models at various stages of development with minimum conflict. The databases used in the PLAID system are: (i) the payload components database for both shuttle mission and space station projects, (ii) anthropometry database for human astronaut models, (iii) general space station and space shuttle components database and (iv) individualized databases used for special projects and research applications.

Graphical functions are varied. The user can generate wireframe views, hidden line views, false color solid model views, true color solid model views or a variety of all the views on a model by model basis. Models can also be made transparent for enhanced visualization capability. The graphical functions make use of the specialized graphical capability of the hardware.

Kinematic functions are used to control motion in the models. To simulate the SRMS, the inverse kinematics algorithm for the SRMS is integrated into the system so that the motion is accurately modeled. A general purpose inverse kinematics algorithm is used for other kinematic systems (for systems greater than 6 degrees of freedom) such as the human arm. All the kinematic systems can have their components, such as joint limits, selectively constrained by the user.

Other functions available in the system provide analyses for clearance, collision detection, quantitative lighting, human vision and human reach envelopes.

3. Capabilities

Currently PLAID provides for four basic capabilities: (i) simulation, (ii) lighting illumination, (iii) visualization, and

(iv) evaluation. These capabilities help provide a realistic testbed for testing, validation, and verification.

Simulation, in scientific applications of computer graphics, is the process of interpreting the performance of an action-related task into a sequence of visual images representing an approximation of the activity. The current PLAID database enables the creation of specific viewing scenarios and animation sequences, which provide simulation visuals for mission planners to develop task procedures, and engineering designers to verify ideas and develop configuration design.

Lighting illumination is the simulation of light sources as an additional feature of the simulation capability. A light source can be characterized by its intensity, location, degree of dispersion, and the medium it travels in. These physical properties are transformed into numerical parameters that PLAID software uses to create shadows, reflection, and backlight.

Visualization is the process of arranging images in such a way that a human can see and understand the scenario. For a single view, what is in the scene is what a human would see. For an animation, a sequence of images is displayed sequentially at a frequency between 30 and 60 frames per second. This manner of display creates a perception that images in the scenario have motion. A person who views the sequence of images thinks that he/she is seeing a scenario in real motion as in a movie.

Evaluation is the final step of confirming the validity of a task. For kinematic validity, this is the confirmation of an existing solution free of collision. For lighting validation, the extent of visibility relative to light sources is evaluated.

4. Current Projects and Specific Examples

The PLAID system is currently utilized to support several engineering space projects. Some examples are: the verification of mission planning for the shuttle flight STS-51, the evaluation of reach envelopes for the SSRMS situated at different locations during the assembly sequence of the new redesigned options, and a lighting study of the space shuttle cargo bay from the Aft Flight Deck window view.

4.1 Shuttle Flight STS-51. Various mission plans have been examined for STS-51 utilizing PLAID, particularly for the Advanced Communications Technology Satellite/Transfer Orbit Stage (ACTS/TOS) spacecraft. An animation was produced of the ACTS/TOS satellite deployment from the payload bay, as well as the ultimate deployment of its solar arrays and antennas; it was to be used primarily for public relations purposes as requested by Lewis Research Center. The animation sequence depicted approximately eleven definitive stages of the spacecraft deployment, resulting in its fully operational stage, all of which is represented in a 5-minute video.

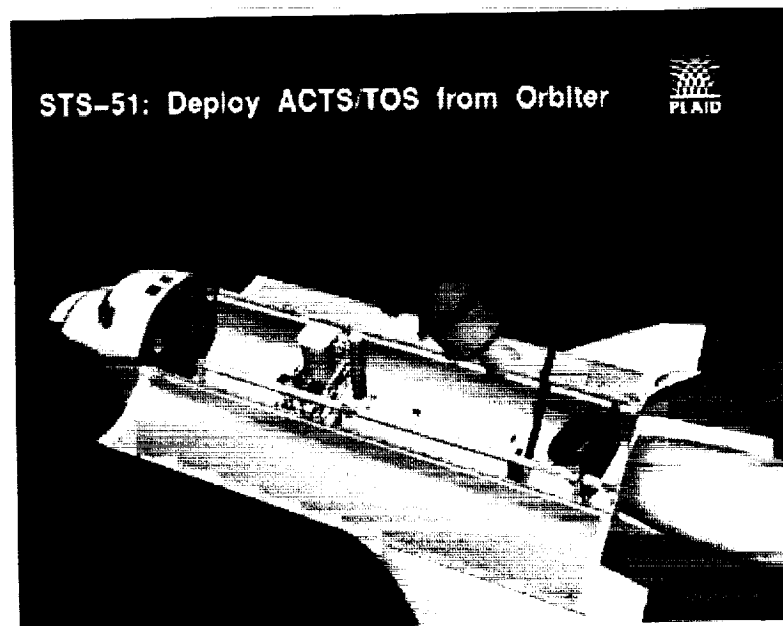


Figure 4.1

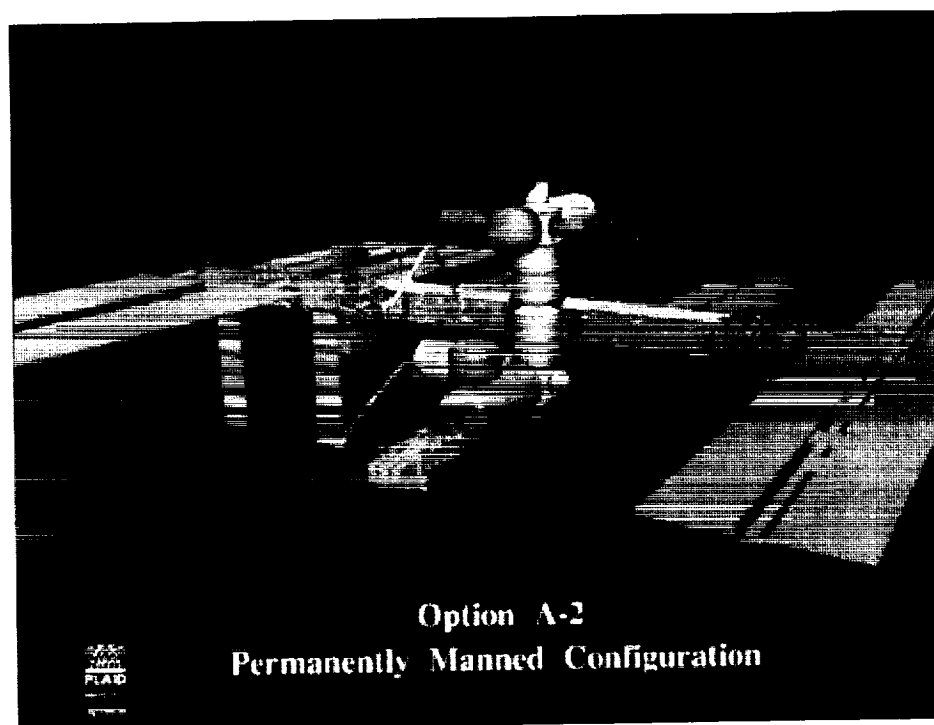


Figure 4.2



Figure 4.3

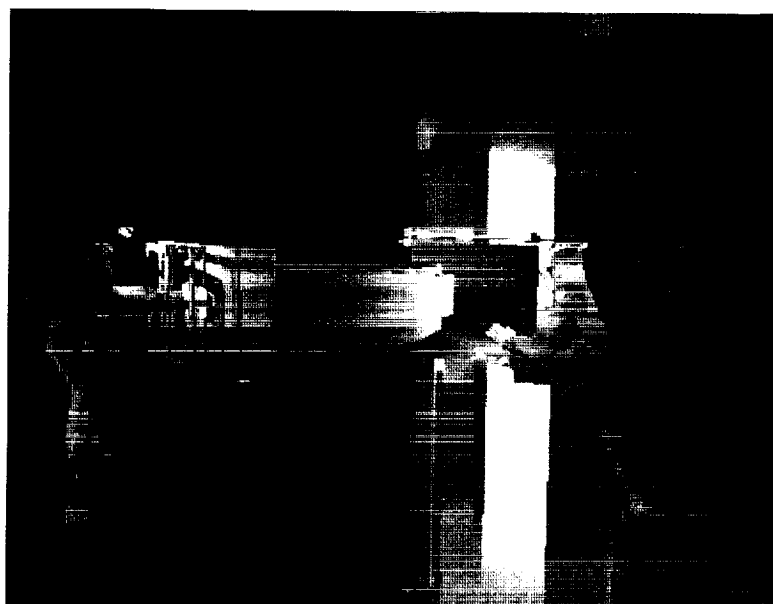


Figure 4.4

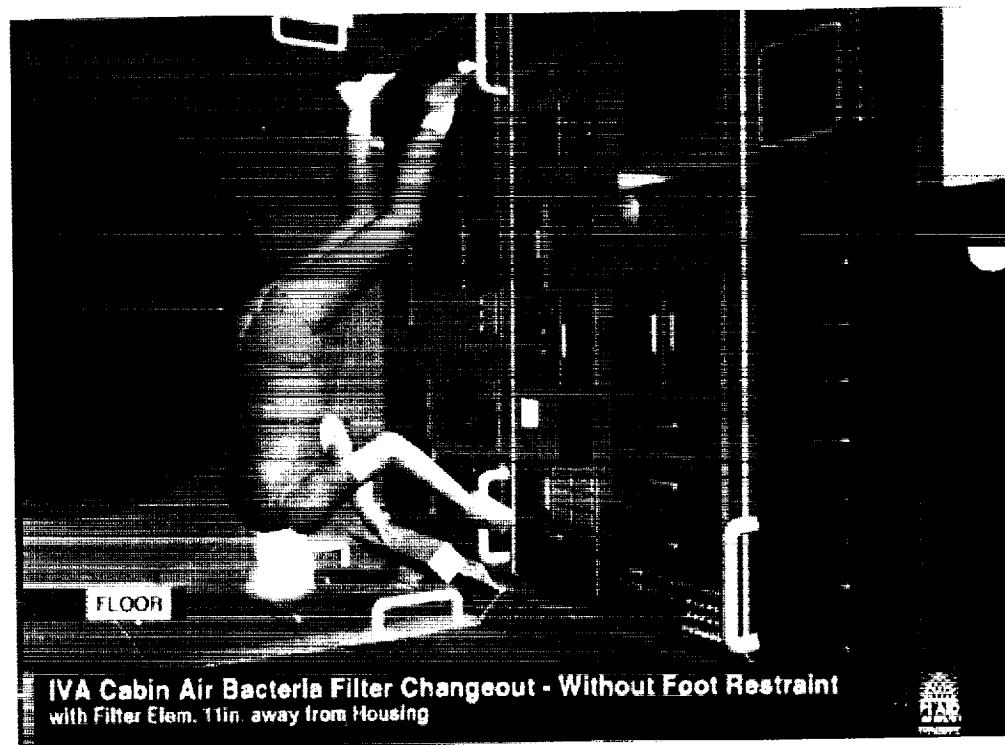


Figure 4.5

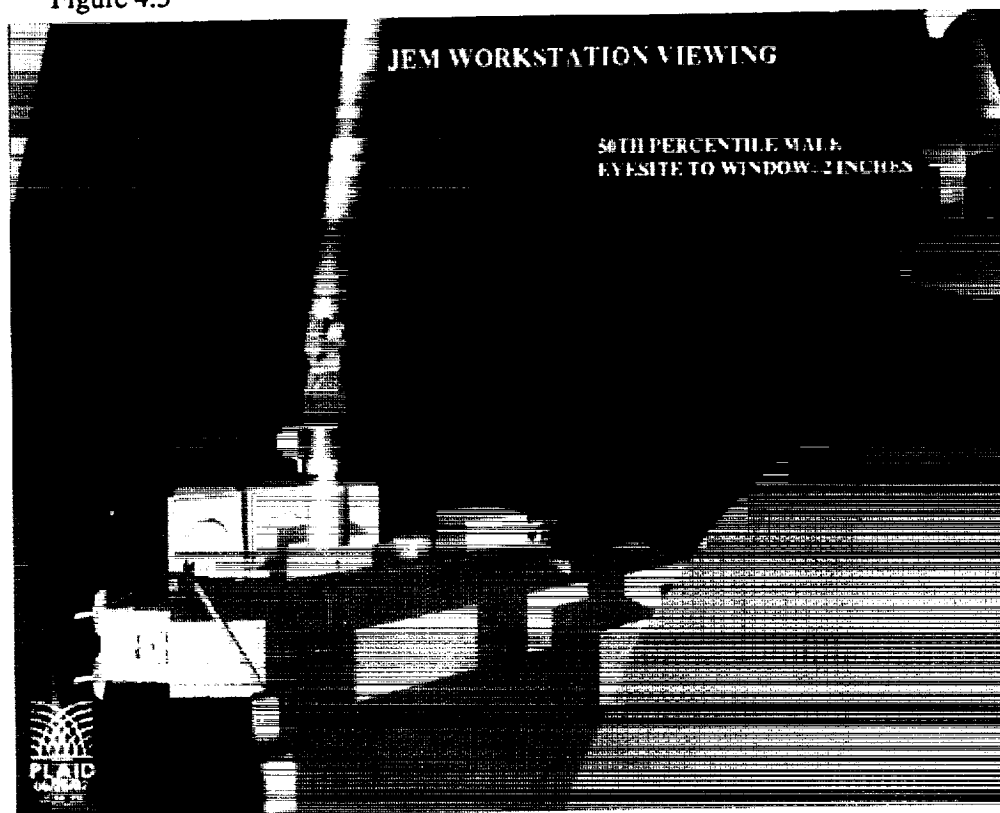


Figure 4.6

The view in Figure 4.1 illustrates a snapshot of the ACTS/TOS spacecraft being deployed from the orbiter bay.

4.2. Assembly Sequence of Space Station Redesign During the redesign phases, the space station assembly designs require almost continuous modifications. As a result, different sequences and concepts, both internally and externally, have to be evaluated in the effort to provide cost effective plans for various proposed configurations. The capabilities of PLAID to examine the designs from the payload manifest to the actual assembly construction stages, to simulate window and camera views to study visibility issues, and to provide virtual reality walk-throughs of the design enhance the overall planning and development of these redesign efforts.

The option A-2 station configuration displayed in Figure 4.2 illustrates one of the latest proposals being evaluated.

4.3. Lighting Study for EVA mission. A lighting analysis was conducted for the Hubble Space Telescope (HST) servicing mission, Space Shuttle Flight STS-61, to support pre-flight planning. Lighting is a crucial concern since the EVA astronauts must rely on the available lighting in order to conduct the changeout of the WF/PC and HSP/COSTAR components of HST. The components are of such size that they block the astronaut's field of view considerably, and the payload bay and forward bulkhead lights are all the lighting that exists when sunlight is unavailable. Various combinations of the bay and bulkhead lights were evaluated in the simulation of the changeout procedure. The results revealed that the forward and mid bay lights rendered no assistance with the present cargo configuration.

Figures 4.3 and 4.4 illustrate the difference in the shaded rendering with and without the lighting capability. This analysis exposes the more realistic representation of the lighting attributes at this proposed worksite. The results of this lighting analysis exemplified the use of the lighting models with respect to complex visibility issues, and in the optimum selection of lights and payload arrangement.

4.4 Human Modeling Analysis. PLAID provides the ability to integrate an anthropometric scale-modeled human in the modeled geometric environments created on the system, in order to examine human performance issues. The anthropometric data is collected from astronaut candidates in the JSC Anthropometrics and Biomechanics Laboratory, and is used to generate human models with realistic joint limits and user-specified size characteristics. The models are utilized in EVA suit, as well as unsuited, to evaluate human-system interactions and reach envelope considerations.

The viewing analysis of the feasibility/clearance assessment of the IVA crewmember changing out the cabin air bacteria filter in the U.S. Laboratory module is depicted in Figure 4.5

4.5 Viewing Analysis. Viewing requirements are prime considerations for all aspects of space exploration. Both direct viewing via windows, orthogonal and isometric viewpoints, and indirect viewing via cameras constitute the majority of the analysis performed.

The maximum visibility of a 50th percentile male viewing through the Japanese Experiment Module (JEM) window is represented in Figure 4.6.

5. Research Activities

5.1 Virtual Reality. Virtual reality gives the user the illusion of immersion in a computer-generated environment. The illusion is created by generating three-dimensional stereo images from a viewpoint controlled by the user's actual head position.

Virtual reality has been added to the PLAID facilities [9], on both hardware and software levels. Three dimensional visual immersion forms a natural extension of the PLAID graphics facility's visualization capabilities. An investigation is being made of the advantages and limitations of virtual environments for planning and analysis of prescribed EVA/IVA tasks.

5.2 Human Modeling. The goal of research activities at the GRAF is to create a realistic human computer model. Present work is directed mainly towards developing a human strength model and controlling motion of the computed figure to produce realistic motion, especially the arm reach motion.

Research work at the GRAF lab is a cooperative effort between various NASA facilities and universities. Current and past cooperative efforts include: (i) human modeling research with the University of Pennsylvania, (ii) muscle research with the University of Texas at Austin, (iii) strength measurements with Texas Womens University, (iv) realistic human reach envelopes with NASA/JSC Work Station Design Group, and (v) lighting model validation studies with NASA Lighting Lab.

A dynamic strength model for the arm based on empirical data has been developed [10]. Maximum isolated torque data for the shoulder, elbow and wrist joints were collected using a LIDO dynamometer. These data were reduced into a tables of polynomial coefficients and organized for convenient storage and retrieval. Strength prediction equations between a person's lean body mass and the maximum torque that can be exerted have been developed. In addition maximum isolated torque measurements for the waist, hip, and knee are currently being collected. This strength model could be used to determine if an individual has the amount of strength needed for a task. Future work will extend this model to allow estimations of the amount of work done and possible fatigue during a task.

Essential to accurate reaching with the arm is a comprehensive model of the shoulder. The PLAID model of the shoulder simplifies the complex motion into two

joints, a clavicle joint and a humerus joint. Equations determine the interdependent motion of the clavicle and humerus, allowing them to move together. Measurements of reach sweeps for 14 subjects compared to within, on average, 1cm of the computed reach [5].

To simulate realistic human reaching, a rapid algorithm has been developed for computing joint angles of the computer human figure. This algorithm can be used with magnetic trackers on an actual person in a virtual reality environment to allow rapid and accurate motion of a human computer model. The research work serves two purposes: (i) making the process of creating an animation less time consuming and (ii) producing a more realistic motion of the EVA astronauts.

6. Conclusion

It has been demonstrated that PLAID software is a valuable computer aided engineering tool for the NASA community. The wide range of support provided by the graphics facility has further illustrated favorable acceptance from engineers working in various space projects. The ongoing research efforts and extensions to the PLAID capabilities in the future will insure that the PLAID users are provided state-of-the-art tools.

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HUMAN FACTORS INVOLVEMENT IN BRINGING THE POWER OF AI TO A HETEROGENEOUS USER POPULATION

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ABSTRACT

This paper describes the Human Factors involvement in developing COMPAQ QuickSolve, an electronic problem-solving and information system for Compaq's line of networked printers. Empowering customers with expert system technology so they could solve advanced network printer problems on their own was a major goal in designing this system. This process would minimize customer down-time, reduce the number of phone calls to the Compaq Customer Support Center, improve customer satisfaction and, most importantly, differentiate Compaq printers in the marketplace by providing the best, and most technologically advanced, customer support.

This represents a re-engineering of Compaq's customer support strategy and implementation. In its first generation system, SMART, the objective was to provide expert knowledge to Compaq's help desk operation to more quickly and correctly answer customer questions and problems. QuickSolve is a second generation system in that customer support is put directly in the hands of the consumers (an example of "knowledge publishing"). As a result, the design of QuickSolve presented a number of challenging issues. Because the product would be used by a diverse and heterogeneous set of users, a significant amount of human factors research and analysis was required while designing and implementing the system. Research that shaped the organization and design of the expert system component as well.

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1.0 INTRODUCTION

Human Factors involvement and the iterative usability test and design process were key to the development of a utility called QuickSolve - an electronic problem-solving and information system for Compaq's line of networked printers. QuickSolve includes a case-based reasoning module that helps troubleshoot network printer problems and is a second-generation customer support system based on Compaq's SMART system (Acorn & Walden, 1992).

SMART was developed for Compaq's help desk operation. It used case-based reasoning to provide expert-level knowledge and experience to Compaq's Customer Support Center to help representatives answer customer calls via the 1-800 hotline number. With the success of SMART, Compaq looked for additional ways to use case-based reasoning technology to improve customer service. This analysis resulted in a re-engineering of Compaq's customer support strategy. The decision was made to package and deliver the troubleshooting knowledge and expertise directly with the product, allowing consumers to solve most issues on their own and to use Compaq's help desk as a backup facility.

1.2 Background

Compaq Customer Support representatives must provide technical support on a wide range of topics, from simple product information requests to complex questions about networked environments. Catalogued questions pertain not only to Compaq hardware, but to third-party hardware and software compatibility as well. With an expanding product line, 24-hour technical support, and a three-year product warranty, the need for support tools was high. For these, and many other reasons, the SMART system was designed.

A key point is that SMART was designed only for use in Compaq's Customer Support department. The case base for SMART was intended to cover all Compaq personal computers, Compaq servers, and third-party software and peripherals. QuickSolve, which has a new case base specific to networked printer products, was also envisioned to be used by our Customer Support Center, but Compaq recognized an opportunity to provide QuickSource to dealers, service providers, and end users as well. Therefore, the target audience for QuickSolve was dramatically more heterogeneous than that for SMART². This was a challenge for the knowledge engineers and developers working on the system, as designing expert systems for heterogeneous user populations is known to be a difficult problem (Gordon, 1991).

Based on Compaq's experience with SMART, case-based reasoning (CBR) was known to be an effective technology for our Customer Support Center, and it was decided that the same expert system technology could be used successfully by a wider audience. One of the nice features of CBR is that it can be fine-tuned to work with user groups of different levels of expertise. CBR was also used because the stimulus environment (networked printers) was continuously changing, and because both novices and experts would need explanations of proposed printer solutions, which can be easily provided using CBR (Gordon, 1991).

2.0 QUICKSOLVE DESCRIPTION

QuickSolve was developed as a Microsoft Windows^{®3} application with an intelligent search engine that targets three groups of users: printer customers, service providers, and the Compaq Customer Support Center. SMART, the tool on which QuickSolve was based, was developed with Inference's CBR Express^{®4}. SMART and QuickSolve recently switched to another Inference tool called CasePoint⁵ for their run-

²SMART was designed to be used by several hundred trained customer support representatives, whereas QuickSource needed to be designed for thousands of general printer customers.

³Microsoft Windows is a product of Microsoft Corporation, Redmond, WA

⁴CBR Express is a product of Inference Corporation, El Segundo, CA

time search engines. CasePoint was selected primarily because of its memory requirements (less than 40KB). Other reasons included its ability to invoke other Windows applications via Dynamic Data Exchange (DDE), performance, natural language capability, and fuzzy search capability.

2.1 QuickSolve Architecture

The QuickSolve case base was developed by two printer specialists and one knowledge engineer. This development team designed cases and stored them in Raima⁶ database format, located on the corporate Banyan Vines⁷ network. The structure for entering cases was leveraged from earlier work on the SMART system (Acorn & Walden, 1992). This structure divided the case base into several partitions: hardware problems, software problems, networking problems, and general information. Using this structure allowed the team to define a limited set of questions that needed to be answered for a unique solution to be retrieved from the case base. The team also used the case entry structure to design the front-end QuickSolve panel that allowed users to select answers to questions about their problem from a list.

QuickSolve's interface has a description field which allows the user to describe the printer problem encountered. This description field is accompanied by a weight used to indicate the field's importance in determining the closeness of a match by the system. Similarly, a weight is assigned to each "honoring" question presented to the user by the system, to specify the importance of the answer. The overall matching score is defined by the combination of these weights during the search process.

One problem observed during Human Factors testing with this weighting scheme was that if an important question or description was input incorrectly by users, it could dominate, and the correct matching solution might not be found. Therefore, the case base was fine-tuned for fault tolerance by dropping the weight assigned to the description field and the first few questions that the end user answers to disallow any input error from dominating the overall matching score.

During the design process, the Human Factors Engineer worked with the knowledge engineers to develop a simpler case structure for software and network cases. This was necessary because the information obtained from our printer experts was highly unstructured. Thus, more information content was anticipated in the description field than from answers to questions. Therefore, the number of questions for network and software cases was reduced resulting in "shallow" cases.

Users begin a search for a problem solution by invoking the QuickSolve panel. This allows them to answer a set of predefined questions and to access the underlying search engine (CasePoint). In testing, users found this search engine to perform extremely well, resulting in a list of potential solutions within one second (based on a 386 microprocessor). (Our field research has shown that electronic documentation users judge the value of the documentation by the power of its search engine). Misspellings when entering problem symptoms are handled gracefully by the search engine, and confirmation questions step users toward the solution.

Solutions were developed in both text and graphical formats in a highly inter-related Microsoft Windows Help[®] environment. Complicated printer fault isolation techniques often required referencing many printer repair and replacement procedures. To meet our ease of use goal, these textual and graphical solutions were developed with an emphasis on the hypertext capability of Windows Help. This enabled the development team to support end users with varying degrees of network printer experience. The user interface was developed on end user task and needs analysis (interviews with users of the SMART system, as well as printer specialists in the field), and iterative usability testing.

⁵CasePoint is a product of Inference Corporation, El Segundo, CA

⁶Raima Data Manager is a product of Raima Corporation, Bellview, WA

⁷Vines is a product of Banyan Inc., Westboro, MA

The screenshot shows the QuickSolve panel with the following sections and callouts:

- File Search Help** (Menu bar)
- Search Switch To Clear Profile Defaults Exit** (Buttons)
- Instructions:** "Select the terms corresponding to your problem, or describe the problem in your own words in the problem description area. Then click on the Search button."
- Problem Type:**
 - Category:** Hardware, Software, Network, General Information
 - Subcategory:** Power On Self Test, PDT Diagnostic, Print Quality, Paper Transportation, Printer Operation
- Problem Detail:** "What print quality problem are you having?" with a dropdown menu showing "Blurs / Smears".
- Problem Description:** A text box containing "my paper is smearing".
- Preanswered Questions in Search Panel Based on Profile Information:**
 - ☒ Printer
 - ☐ Host Computer
 - ☐ Network

Callouts:

- "Click on the category that best describes your problem."
- "Next click on the closest matching subcategory."
- "Pull down a list or type in problem details."
- "Type the problem description in your own words (optional)"
- "Check a box to guide search toward relevant problem environment."
- "Click on Search button at the top left of screen to begin search."

Figure 1. Screen Example from QuickSolve panel

2.2 Example Using QuickSolve

To understand the use of QuickSolve, consider the following: A common printer print quality problem - "Blurs/Smears" - has been detected and the user is asked to correct the problem. When QuickSolve is invoked the first time the user is presented with a QuickSolve menu screen. This initial panel allows users to select symptoms from pre-designated sets of questions, which are presented in a logical and dynamic structure similar to the previously defined case base structure. For this example, the user should answer that this is a hardware problem, a problem of print quality and that the symptom is blurs/smears. The user can also type more specific symptom information in the problem description box (see Figure 1).

QuickSolve has the added capability over the predecessor SMART system of providing answers to some questions based on information previously stored in the printer profile file. Usability testing demonstrated this added functionality to be key if users were to accept and use the system. The printer profile information is saved during the installation process and includes printer configuration, host computer configuration, and network environment information. Users may keep multiple printer environment profile files.

Figure 2 shows an example search panel where six questions have been answered by the system. The first three questions were answered from the profile, while the next three questions were answered from the initial QuickSolve panel (Figure 1).

Rule-based reasoning pre-answers as many questions as possible based on the user's problem description. Rules also can answer questions based on previously answered questions. This ability to pre-answer questions, coupled with the CBR search engine, resolved another major usability challenge observed during earlier Human Factors testing.

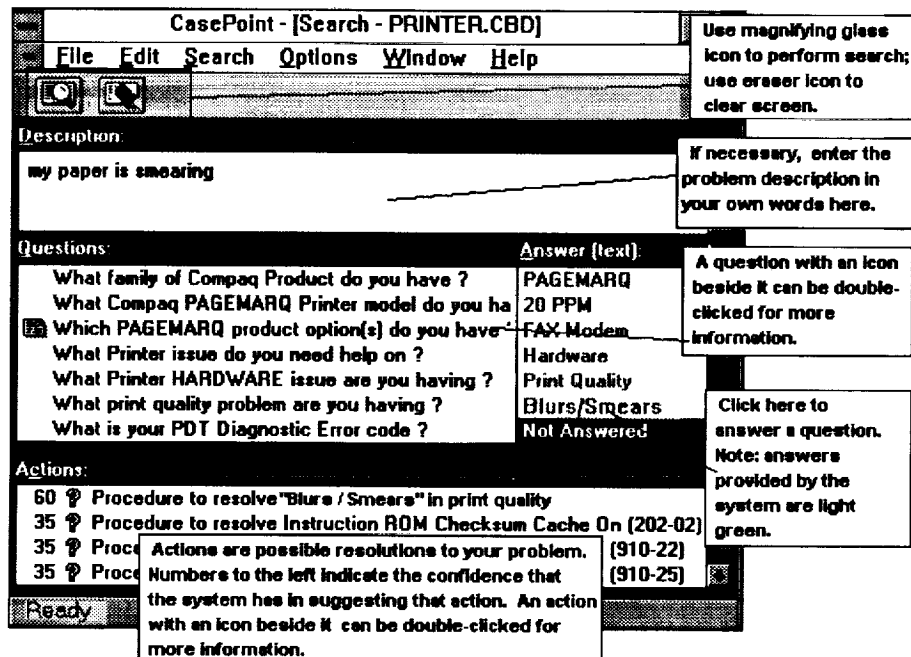


Figure 2. Example of Search Panel with Pre-Answered Questions

Once QuickSolve finds an appropriate solution, the user may double-click on the solution topic in the Actions area of the search panel and a detailed solution appears. Figure 3 shows a detailed solution retrieved from the QuickHelp module. To further explore this solution, users can access related procedures/glossary information through hypertext links.

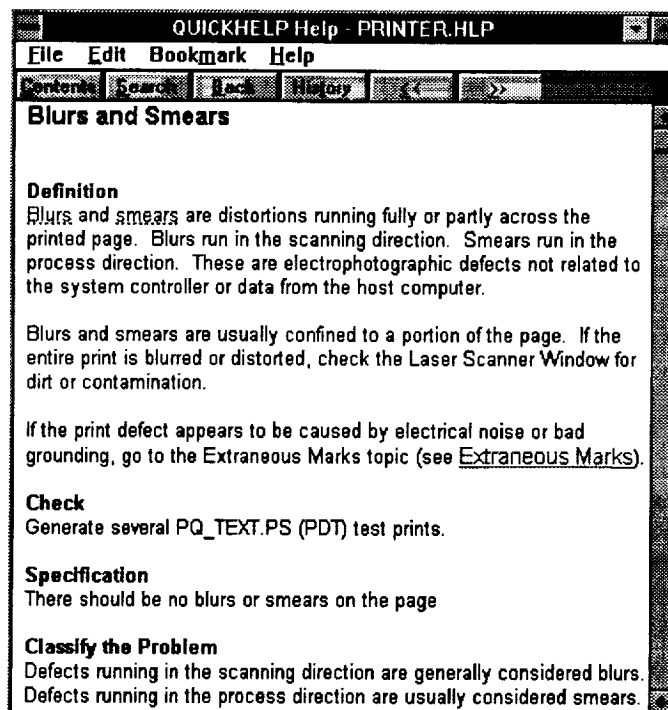


Figure 3. Example of Blurs/Smears Solution Available in QuickHelp

2.3 Designing QuickSolve Based on Human Factors Research

QuickSolve and its complementary problem-solving modules have gone through nine iterations of usability testing by Compaq's Human Factors Department during all phases of the development cycle. This section discusses the Human Factors research that helped us overcome usability issues.

The Human Factors analysis started with prototype testing of the SMART system with Customer Support representatives. Usability issues were noted and passed on to developers via reports and videotapes of users performing tasks with the system. Later, Human Factors professionals analyzed Customer Support representatives performing the same tasks without the SMART system, in order to compare solution times and error rates. Finally, after the SMART system was fully implemented and on the network, Human Factors performed interviews with Customer Support representatives (both novice and experienced) to determine if they were, or were not, using SMART and why. Problems and issues with SMART were presented in a report for management. At that time, QuickSolve was in the conceptual stage of design and the developers called on Human Factors to begin testing prototypes of the QuickSolve system, especially the QuickSolve module.

We had noted that with the SMART system, users were often frustrated with the flow of questions and answers. Specifically, users were frustrated when forced to answer questions that were redundant or to which they had already input into the description field. This problem was attacked from two perspectives: internally through the use of rules and profiles, and externally through a new user interface panel. Rules were built in to pre-answer redundant, confirmation questions. Also, a profile was built for each user's environment during installation of QuickSolve that pre-answered several basic questions that the system needed to guide its search. Multiple profiles could be stored, so different questions would be pre-answered by the system, depending on the user's chosen environment (e.g., networked or not).

Novice users were provided with a front-end panel that allowed them to answer relevant questions in a flexible manner. This panel (shown in Figure 1), uses drop-down lists based on particular selections to provide the user with information about a problem area. In essence, the drop-down lists give novice users information about a problem domain prior to their committing to that problem space. Usability testing showed this technique to be very effective in determining a problem category with these users. Novice users could also use the natural language capability of the front panel to describe their problem. The problem description field of the panel allows for typographical errors and common naming conventions (e.g., "winword" for Microsoft Word for Windows) and essentially performs a fuzzy search based on the entries in that field. A tutorial was developed to instruct the end user on panel use.

Case Base Issues. With the SMART system, there were usability issues with respect to the case base. For the design of the QuickSolve system, it was decided that in order to build a consistent structure for entering and retrieving cases, the case base had to become uniform. To institute this uniformity, the knowledge base was divided into four separate problem domains: hardware, software, networking, and general information. For each domain, a distinct structure for asking questions about the problem was devised. For the hardware and general information domains, this structure was gleaned from existing documentation. For the software and networking domains, this structure was engineered by interviewing technical support experts for networked printers.

When entering cases, the knowledge engineer followed this structure strictly in building the case using a pre-designated pool of questions with which to query the user about problem symptoms. To further promote system usability, the knowledge engineer has been vigilant in reusing questions from this pool whenever possible (as opposed to making up new questions). In doing so, the system retrieves cases that match a user's symptoms more cleanly. Whenever possible, QuickSolve prompts the user with a list question (i.e., a question that the user can answer by choosing from a list). This more often insures that the user provides the system with the correct symptomatic input.

Tuning the Casebase. It was determined during Customer Support interviews that questions coming back from the SMART system were sometimes not well-tuned or clearly relevant to the problem description. To address this usability issue, weights indicating a question's importance were adjusted to achieve fault-tolerant system behavior. A user could answer one or more questions incorrectly, and still find the appropriate answer to the problem.

Rule Based Implementation. To further enhance performance of the expert system's problem-solving abilities, a decision was made to add in rule-based reasoning. With this implementation, a user types in a problem description using natural language and the character strings are used to pre-answer some of the questions used for searching the case base. Rules are also used to pre-answer certain focusing questions based on previous answers. This was once again in response to a Human Factors issue observed during usability testing.

2.3 Future Enhancements

Further enhancements to QuickSolve have been, and will continue to be, identified through usability testing. These enhancements are already being tested in the Human Factors laboratory. Specifically, the rule-based reasoning component is being further optimized to pre-answer even more of the focusing questions. Also underway are performance enhancements to the integration of the QuickSolve initial search panel and the search engine. Finally, various knowledge elicitation techniques, such as concept mapping (Gowin & Novak, 1984; McFarren, 1987) and repertory grid analysis (Boose, 1986) are being investigated to better understand and differentiate the problem solving techniques of expert and novice users. The objective is for QuickSolve to further exploit an expert user's problem solving capabilities and tailor the system's operation to the knowledge level of the user.

3.0 CONCLUSION

QuickSolve represents Compaq's first use of "knowledge publishing". Compaq intends to further develop this technology, and Human Factors involvement is crucial to its success. Unless the power of artificial intelligence is presented to the end user in an easy to use, non-intimidating user interface, it will never afford the benefits so often espoused by its proponents. For this reason, Human Factors continues to follow our users into the field, watching how they use intelligent tools and asking how they can be better designed to support problem-solving styles and information needs.

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A COMPARISON OF PAPER AND COMPUTER PROCEDURES IN A SHUTTLE FLIGHT ENVIRONMENT

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ABSTRACT

The Electronic Procedures Experiment (EPROC) was flown as part of the Human Factors Assessment (HFA) experiment aboard the SpaceHab-1/STS-57 mission. EPROC is concerned with future, longer-duration missions which will increasingly rely on electronic procedures since they are more easily launched, updated inflight, and offer automatic or on-request capabilities not available with paper.

A computer-based task simulating a Space Station Propulsion System task was completed by one crewmember. The crewmember performed the task once using paper and once using computer procedures. A soldering and desoldering task was performed by another crewmember. Soldering was completed with paper procedures and desoldering was completed using computer procedures.

Objective data was collected during each task session from the computer programs, videotapes, and crew notations in the paper and computer procedures. After each task session, subjective data was collected through the use of a computer-based questionnaire program. Resultant recommendations will be made available to future designers of electronic procedures systems for manned-space missions and other related uses.

INTRODUCTION

Experiment Description

The primary concerns of Human Factors engineers at NASA's Human-Computer Interaction Laboratory (HCIL) are the investigation and evaluation of human-machine interfaces unique to spaceflight which affect crew productivity and ultimately mission success. The Human Factors

Assessment (HFA) was an experiment conducted aboard SpaceHab 1/STS-57 by the HCIL. During this mission, HFA personnel evaluated the design and use of electronic procedures (EPROC).

All Shuttle onboard tasks are currently performed using written paper procedures. This represents a large amount of launch weight and valuable stowage space. There are also particular problems with using paper procedures with hands-on tasks. For example, it is cumbersome for crewmembers working in a glovebox to take their hands off the task to turn a page of the procedures or to make an annotation. There are also limitations on the amount of information that can be presented in onboard paper procedures. Electronic, computerized procedures have none of these problems. The amount of information that can be made available and the capabilities that can be provided via computers to improve crewmembers' performance make electronic procedures worthy of investigation.

The goal of the HFA-EPROC experiment was to determine Human Factors requirements for electronic procedures systems in flight environments. Performance measures were taken for the same task using both computer and paper procedures. Advantages and disadvantages of each procedure type were noted. In addition, several automated procedures capabilities were provided to the crewmembers for evaluation. Thus, the investigation could identify the benefits of paper and the potential benefits of computer presentation; rather than solely making a comparison between the two.

The HFA-EPROC experiment consisted of two types of tasks: a computer task and a non-computer task. The computer task consisted of a simulated Space Station Propulsion System task which involved interacting with a graphical interface to configure the system. The

task was performed once with computer procedures and once with paper procedures. This type of task was included because future missions will be commanded entirely via graphical software interfaces where crewmembers read on-screen procedures and then configure systems by clicking on icons and soft buttons.

The non-computer task portion of the investigation consisted of a solder/desolder experiment. This portion was performed in conjunction with the SpaceHab Tools and Diagnostic Systems - Solder Equipment (TDS-SE) experiment. The solder portion was completed using paper Flight Data File (FDF) procedures, and the desolder portion was completed using computer procedures. This non-computer task was included to collect information on the use of electronic procedures with a hands-on glovebox task. Because of the hands-intensive nature of the glovebox task, voice input was one of the computer capabilities investigated.

Previous research into paper and computer procedures has been performed in the HCIL at the NASA Johnson Space Center (O'Neal 1992; O'Neal and Manahan 1990; Desaulniers, Gillan, and Rudisill 1989). Results from this research and reviews of relevant literature (Johns 1988; Kelly 1988) provided the basis for the design of the HFA-EPROC experiment.

METHOD

Subjects

Two crewmembers were recruited for the computer task and one crewmember was recruited for the soldering task. Additional subjects and trials were not possible due to mission timeline constraints. During the STS-57 mission, one crewmember was unable to participate due to unexpected mission difficulties; therefore only one crewmember participated in the

computer task, plus the crewmember in the soldering task for a total of two subjects.

Apparatus and Materials

A Macintosh Powerbook 170 was used to run the custom-built electronic procedures software. The electronic procedures and the computer task display were created with Supercard. The cursor control device used was a slightly modified version of the standard PowerBook trackball.

The electronic procedures software was custom-built to investigate the usability of the interface. The display was split into halves vertically. The procedures were presented on the left-hand side; the crewmember scrolled through to complete the task. The task was completed on the right side of the display, where a simulation of the Space Station Freedom (SSF) core system Propulsion display was presented. The display was a direct manipulation interface where the user could click on icons representing system objects such as valves or heaters and change the parameters associated with those objects (see Figure 1). The software kept track of task times (between each step in the procedure), the sequence of window openings and closings, and the sequence of button presses.

The non-computer task included the use of a voice input system (Voice Navigator software by Articulate Systems). The system was used solely to move from step to step in the procedure.

Design

The experiment used a simple within-subjects design. The independent variable was Procedure Type (Paper vs. Computer). Dependent variables were: total time on task, time on subsets of

tasks, error rate, and subjective ratings.

This basic design was repeated for each task type: Computer and Non-Computer (see Table 1).

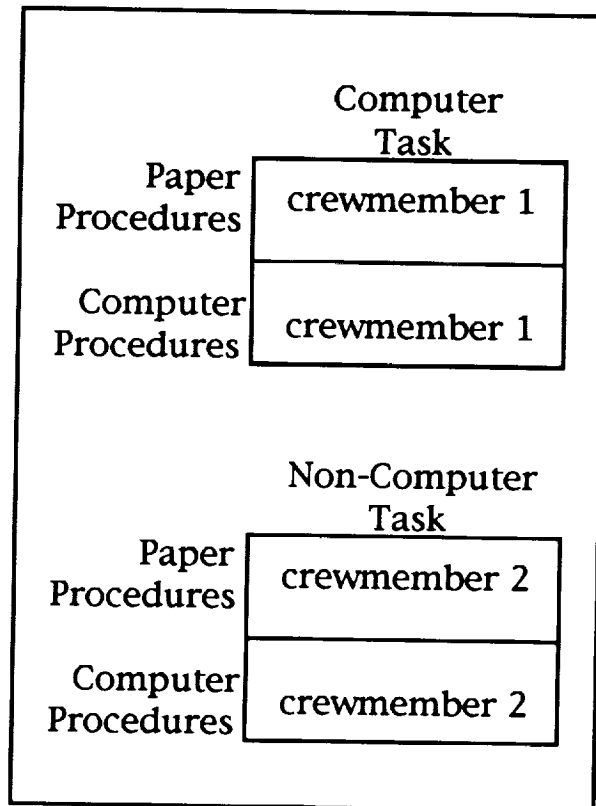


Table 1. The experimental design

Subjective ratings were collected via a computerized questionnaire that was presented after the completion of each task. The questionnaire ratings were anchored by using 7 point Likert scales.

Procedure

The crewmembers were trained on their respective tasks during formal familiarization, hands-on, and timeline training sessions. Crewmember 1 also

requested and completed several task review sessions prior to the mission.

For both the computer and non-computer tasks, the procedural information available to the crewmember was identical in the paper and computer versions of the procedures. What differed were capabilities to access the information. Table 2 summarizes these differences.

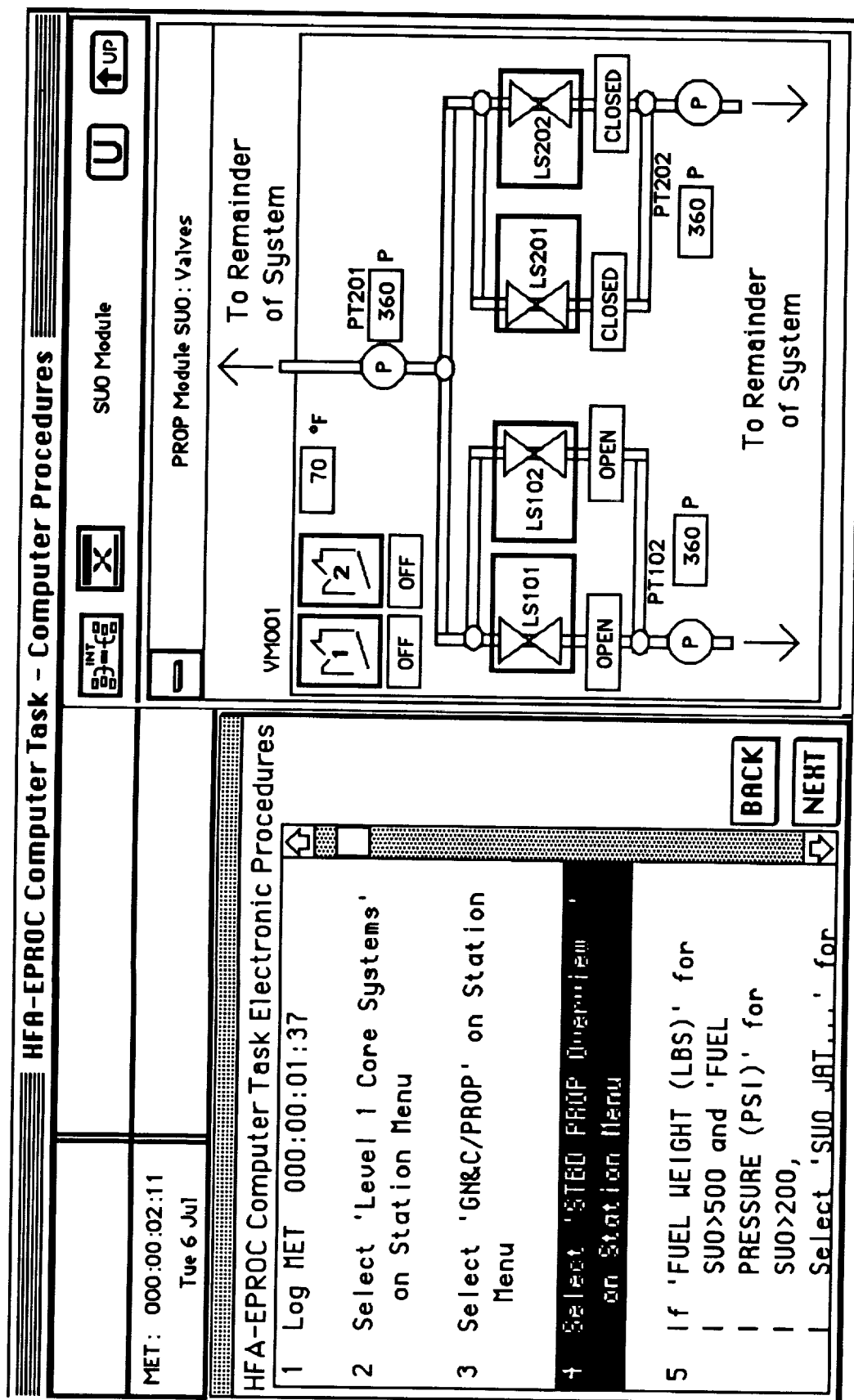


Figure 1. Sample Screen Display for Computer Task, Computer Procedures

Computer Procedures	Paper Procedures
<ul style="list-style-type: none"> • Immediate access to diagrams, schematics, and malfunction procedures • Immediate access to step details • Notes, Cautions, and Warnings automatically displayed only when relevant • Current step highlighted to assist in placekeeping • Placekeeping input through use of onscreen buttons • Timing information tracked automatically through initial input and use of onscreen buttons • Annotations and comments accepted through available notepad • Scrolling provided through onscreen buttons and manual use of scroll bars • Voice input available for increased hands-free procedure operation (non-computer task only) 	<ul style="list-style-type: none"> • Diagrams, schematics, and malfunction procedures in an appendix • Step detail information in a separate table • Notes, Cautions, and Warnings printed along with procedure steps • Current step not highlighted • Placekeeping possible only through manual mark-up of procedures • All timing information tracked manually • Annotations and comments available through pre-defined blank lines or other markings • No scrolling facilities provided • No voice input facility provided

Table 2. Comparison of features provided with each procedure type

Computer Task

Crewmember 1 began each computer task session by setting up the computer in the SpaceHab compartment on either the workbench or a computer table. Setup included plugging the computer in, opening it up, and turning it on. The computer was attached to the surface of the table with Velcro. The crewmember stayed in place by using foot restraints.

Crewmember 1 first completed the computer task session while using paper procedures and then completed another computer task session while using computer procedures. Figure 1 shows the display used with computer procedures. Note that for paper procedures the left side of the display remained blank. The right side of the display remained the same for both tasks.

Non-Computer Task

Crewmember 2 began the soldering sessions with the setup of the glovebox apparatus. While performing the computer procedures session, the Powerbook was set up and attached with Velcro to a locker to the crewmember's left in a flat upright position. The Voice Navigator headset was plugged in and the headset was donned.

Crewmember 2 then performed a soldering task session while using the paper procedures. The soldering task consisted of soldering some pre-selected sites on an electronics board while following the procedures. Next, the crewmember completed a desoldering task session on a different electronics board while using the computer procedures. The computer procedures allowed the crewmember to advance to the next step in the procedures via a voice command for "hands-free" operation.

Objective data was gathered for both computer and non-computer task sessions via the computer programs, videotapes, and FDF procedure annotations. This provided baseline data on migrating from paper to computers in space. After each task session, subjective data was gathered through the use of a computer-based questionnaire program, providing data on what to include and what to avoid in the design of future electronic procedures systems.

RESULTS AND DISCUSSION

Computer Task

Due to a late return of flight data, a full data analysis has not yet been completed. Computer data and videotape data have not yet been analyzed; thus the results below include only the completion times and

subjective comments. Data from the non-computer task in particular are insufficient for presentation at this time. Thus, only preliminary data from the computer task are presented.

In addition to overall task completion times, task times were broken down into subsets (thirds) in order to get a more granular look at the crewmember's ability to complete the task. The overall task completion time, as well as all of the individual subset completion times were faster for the computer procedures (see Table 3). Formal statistical tests are not appropriate here since the data represent only a few data points from one subject. However, the consistency in trends among each of the sets of completion times indicates that there probably is a real time advantage for the computer procedures.

	Paper	Computer
Overall	17.42	14.83
Subset 1	5.02	3.87
Subset 2	2.98	2.02
Subset 3	9.43	8.23

Table 3. Overall and task subset completion times in minutes.

A full error analysis has not yet been completed. However, a preliminary look at the data indicates no significant errors.

Overall, the computer procedures were rated very favorably in the questionnaire. Regarding the ease of use of the computer procedures interface, the crewmember's comment was "The format of the procedures was very user friendly and resulted in the task being easily performed."

The primary advantage of computer procedures over paper procedures, as identified by the crewmember, was that the current step was highlighted automatically. This released the crewmember from the burden of keeping their place in the procedures. Another comment regarding highlighting was "The procedures were very easy to read. The highlighting assisted tremendously in keeping your place in the procedures. This method assures a 'check and balance' approach to following through required procedures."

One significant improvement that was identified and should be included in any future procedures interface was the capability for the astronauts to be able to move on to the next step via the keyboard or by trackball. The addition of keyboard redundancy allowed the crew to move on to the next step in the procedures while keeping the cursor in the working portion of the display (the task display).

Ultimately, when asked which procedures the crewmember would prefer to use if they were given the choice between paper and computer, the crewmember responded with "I definitely preferred the computer procedures."

The questionnaire data suggested some possible reasons for the quicker task times while using computer procedures. One comment made about using the paper procedures was "The necessity to use paper and pencil to follow through the procedures causes some overhead in zero g. The extra time necessary to clip or tether procedures in the vicinity of the work area and to ensure procedures and writing utensils are not free floating extends the time required to complete the task." Another possible reason for the time difference between computer and paper procedures could be the order of completion. The paper procedures were completed first,

therefore the task would have been fresh in the mind of the crewmember as they completed the computer task. However, this effect should have been significantly diminished since the task had been rehearsed many times before the actual mission. Order and practice effects should have been minimal.

CONCLUSIONS

Because Shuttle missions currently use paper procedures, one objective was to establish the paper procedures usability data as a minimum baseline for performance while using computer procedures. Data reviewed thus far would indicate that computer procedures can be used in the future, in place of paper procedures, with no significant loss in productivity.

After the full data analysis has been completed, Human Factors design guidelines will be created, helping designers create more powerful, usable electronic procedures systems. In the future, longer-duration missions will rely increasingly on electronic procedures since they are more easily launched, updated inflight, and offer automatic or on-request capabilities not available with paper.

To facilitate future migration to electronic procedures, performance must at least be equal to performance achieved with paper procedures. This investigation has begun to confirm that electronic procedures are a feasible alternative and can offer many benefits over paper presentation.

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SECTION IV

LIFE SUPPORT

Session L1: SPACE PHYSIOLOGY

Session Chair: Ms. Susan Fortney

Gravity, the Third Dimension of Life Support in Space

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The ascent of the human into high altitudes required a two-dimensional life support system that supplied: (1) oxygen, and (2) heat. At lower altitudes, increased oxygen concentration in the inhaled gases was useful, but at higher altitudes for longer durations, this "clever" life support approach was no longer adequate – physiologic requirements had to provide a natural pressure-based environment. In space, the life support system requires a third dimension – gravity. Although substituting for gravity (e.g., LBNP, exercise, elastic restraints, etc.) has been successful on a limited number of physiologic functions for short-duration stays in space, long durations will require the effects of the real thing for critical physiologic functions. It has been known for over a hundred years that the forces of acceleration (G) and gravity are equivalent. Therefore, gravitational stimulation in space can be achieved with centrifugation. However for this stimulation to be effective, the dosage of G (intensity and duration) required to maintain normal physiologic function must be determined. An approximation of this dosage of G for the human can be determined with 3-day bed-rest studies including periodic centrifuge exposure. Recent research on this topic will be reviewed.

The U.S. Navy/Canadian DCIEM Research Initiative on Pressure Breathing Physiology

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Development of improve positive pressure breathing garments for altitude and acceleration protection has occurred without collection of sufficient physiological data to understand the mechanism of the improvement. Furthermore, modeling of the predicted response of future enhanced garments is greatly hampered by this lack of information. A joint, international effort is under way between Canada's Defense and Civil Institute for Environmental Medicine (DCIEM) and the United States Navy's Naval Air Warfare Center Aircraft Division, Warminster (NAWCACDIVWAR). Using a Canadian subject pool, experiments at both the DCIEM altitude facility and the NAWCACDIVWAR Dynamic Flight Simulator have been conducted to determine the cardiovascular and respiratory consequences of high levels of positive pressure breathing for altitude and positive pressure breathing for acceleration protection. Various improved pressure breathing garments were used to collect comparative physiological and performance data. New pressure breathing level and durahon capabilities have been encountered. Future studies will address further improvements in pressure suit design and correlation of altitude and acceleration data.

Response to Graded Lower Body Negative Pressure (LBNP) After Space Flight

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To study the effects of space flight on orthostatic function. LBNP tests (0 to -60 mmHg) were administered to 7 crew members preflight and 2 to 6 hrs after 6 to 9 day Shuttle missions. Cardiac stroke volumes were obtained each minute by Echo Doppler. Orthostatic responses are shown below:

PREFLIGHT POSTFLIGHT

Measure	Rate	+ %Change	Rest	%Change
Heart Rate (bpm)	56 (3)	33 (3)	61 (4)	*79 (9)
Stroke Volume	94 (4)	- 34 (3)	92 (6)	* - 50 (9)
Cardiac Output (liters/min)	5.4 (0.2)	- 15 (5)	5.7 (0.5)	- 27 (10)
Total Periph. Res. (31) (mmHg/l./min)	15.3 (1.1)	20 (7)	16.2 (1)	50
Leg Circumference (0.3) (mm.)	392 (14)	2.0 (0.4)	*382 (15)	1.7

*Postflight value differs ($P < 0.01$) from preflight, mean (SE). + % change preflight to -60 mmHg or final LBNP level tolerated.

The data suggest a decline in postflight orthostatic function, as assessed by LBNP, due to reduced cardiac filling despite potentiated heart rate and vasoconstrictor reflex responses in most crew members.

Dual-cycle Ergometry as an Exercise Modality During Prebreathe with 100% Oxygen

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In an effort to reduce prebreathe time requirements prior to extravehicular activities and high-altitude flights, a combined arm and leg exercise task (dual-cycle ergometry) has been integrated into a shortened prebreathe period. This exercise task proposes to enhance denitrogenation by incorporation of both upper and lower body musculature at a moderately high work intensity during prebreathe with 100% oxygen. Preliminary findings indicated peak oxygen consumption ($\text{VO}_{2\text{peak}}$) levels attained on the dual-cycle ergometer do not differ significantly from those levels attained on the treadmill. Eight male subjects were exercised to $\text{VO}_{2\text{peak}}$ using leg-only cycle ergometry and dual-cycle ergometry on separate days. Preliminary data during dual-cycle ergometry showed arm work equaling 30% of the leg workrate at each stage of the incremental test resulted in arm fatigue in several subjects and a reduced $\text{VO}_{2\text{peak}}$ compared to dual-cycle ergometry with arm work at 20%. Thus, the 20% workrate was used during the dual-cycle $\text{VO}_{2\text{peak}}$ trial. On a third experimental day, subjects performed a 10 min exercise test at a workrate required to elicit 75% of $\text{VO}_{2\text{peak}}$ for each subject on the dual-cycle ergometer. Blood lactate response to the exercise was monitored as an objective measure of fatigue. Peak VO_2 levels attained on the leg-only and the dual-cycle ergometry tasks were not significantly different. Blood lactate levels were significantly elevated following the dual-cycle ergometry at 75% $\text{VO}_{2\text{peak}}$. However, lactate levels show the expected rate of decline during recovery and, as demonstrated in the literature, should return to baseline levels within 30 min following exercise cessation. Thus, dual-cycle ergometry at 75% $\text{VO}_{2\text{peak}}$ appears to be a valid exercise for use during prebreathe and should not contribute to fatigue during subsequent EVAs.

EXERCISE WITH PREBREATHE APPEARS TO INCREASE PROTECTION FROM DECOMPRESSION SICKNESS

Preliminary Findings [as of 1 August 1993]

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ABSTRACT

Extravehicular activity (EVA) from the space shuttle involves one hour of prebreathe with 100% oxygen, decompression of the entire Shuttle to 10.2 psia for at least 12 hours, and another prebreathe for 40 min before decompression to the 4.3 psia suit pressure. We are investigating the use of a one-hour prebreathe with 100% oxygen beginning with a ten-minute strenuous exercise period as an alternative for the staged decompression schedule described above. The 10-min exercise consists of dual-cycle ergometry performed at 75% of the subject's peak oxygen uptake to increase denitrogenation efficiency by increasing ventilation and perfusion. The control exposures were preceded by a one-hour prebreathe with 100% oxygen while resting in a supine position. The twenty-two male subjects were exposed to 4.3 psia for 4 hours while performing light to moderate exercise. Preliminary results from 22 of the planned 26 subjects indicate 76% DCS following supine, resting prebreathe and 38% following prebreathe with exercise. The staged decompression schedule has been shown to result in 23% DCS which is not significantly different from the exercise-enhanced prebreathe results. Prebreathe including exercise appears to be comparable to the protection afforded by the more lengthy staged decompression schedule. Completion of the study later this year will enable planned statistical analysis of the results.

INTRODUCTION

To avoid the serious threat of DCS symptoms developing during EVA from the Space Shuttle in a 4.3 psia pressure suit, some form of denitrogenation is required. Denitrogenation prior to direct decompression from 14.7 psia requires at least 3.5 hours of resting prebreathe to achieve DCS protection comparable to that provided by the current staged decompression method of denitrogenation (Waligora et al., 1984). The staged decompression schedule involves decompression of the entire Shuttle to 10.2 psia for at least 12 hours, requires a total of 1.67 hours of 100% oxygen prebreathing, and results in problems such as reduced instrument cooling capacity at 10.2 psia. The staged decompression is preferable because it requires less prebreathing time immediately prior to EVA. Development of less time-consuming prebreathe procedures which provide comparable protection from severe venous gas emboli (VGE; precordial Doppler grades 3 and 4) and DCS while allowing decompression directly from 14.7 psia to 4.3 psia would improve efficiency of EVA operations.

Efficiency of denitrogenation and protection from DCS can be increased by including negative pressure breathing (Balldin and Borgstrom, 1977), warm environmental conditions (Balldin, 1973), warm water immersion (Balldin and Lundgren, 1972), or various forms of exercise (Vann, 1989; Balke, 1954; Webb et al., 1943) during the prebreathe period. We are investigating the use of a ten-minute strenuous exercise period at the beginning of a one-hour, 100% oxygen prebreathe as a means of enhancing denitrogenation by increasing ventilation and perfusion while avoiding exercise-induced fatigue (Webb et al., 1989, 1993).

METHODS

Twenty-two male subjects were exposed to a pressure of 4.3 psia for 4 hours while performing moderate exercise. The prebreathe conditions consisted of 60 min of prebreathing 100% oxygen, beginning with (or without, as a control) 10 min of dual-cycle ergometry performed at 75% of the subject's peak oxygen uptake (Heaps et al., 1993). The resting portion of each prebreathe was accomplished in the supine position. Subjects were monitored for VGE using a Hewlett-Packard SONOS 1000 Echo Imaging System and observed for DCS symptoms. The endpoints were completion of the 4-hour exposure or development of Grade 2 DCS joint pain or any other DCS symptoms. The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFR 169-3.

RESULTS

The experiment is currently 85% completed, and final statistical evaluation awaits completion of control and test exposures on all 26 subjects. To date, the incidence of any DCS following exercise-enhanced prebreathe with 100% oxygen is 36% versus 77% after resting prebreathe (N = 22). DCS symptoms disappeared during repressurization to ground level in all eight subjects experiencing DCS following exercise-enhanced prebreathe. Symptoms included joint pain, headache, paresthesia, and hot/cold flashes. During the exposures following a one-hour resting prebreathe, two incidents of respiratory DCS (chokes) occurred, one of which continued to be evident at ground level. That subject was treated with hyperbaric oxygen therapy resulting in complete resolution of symptoms.

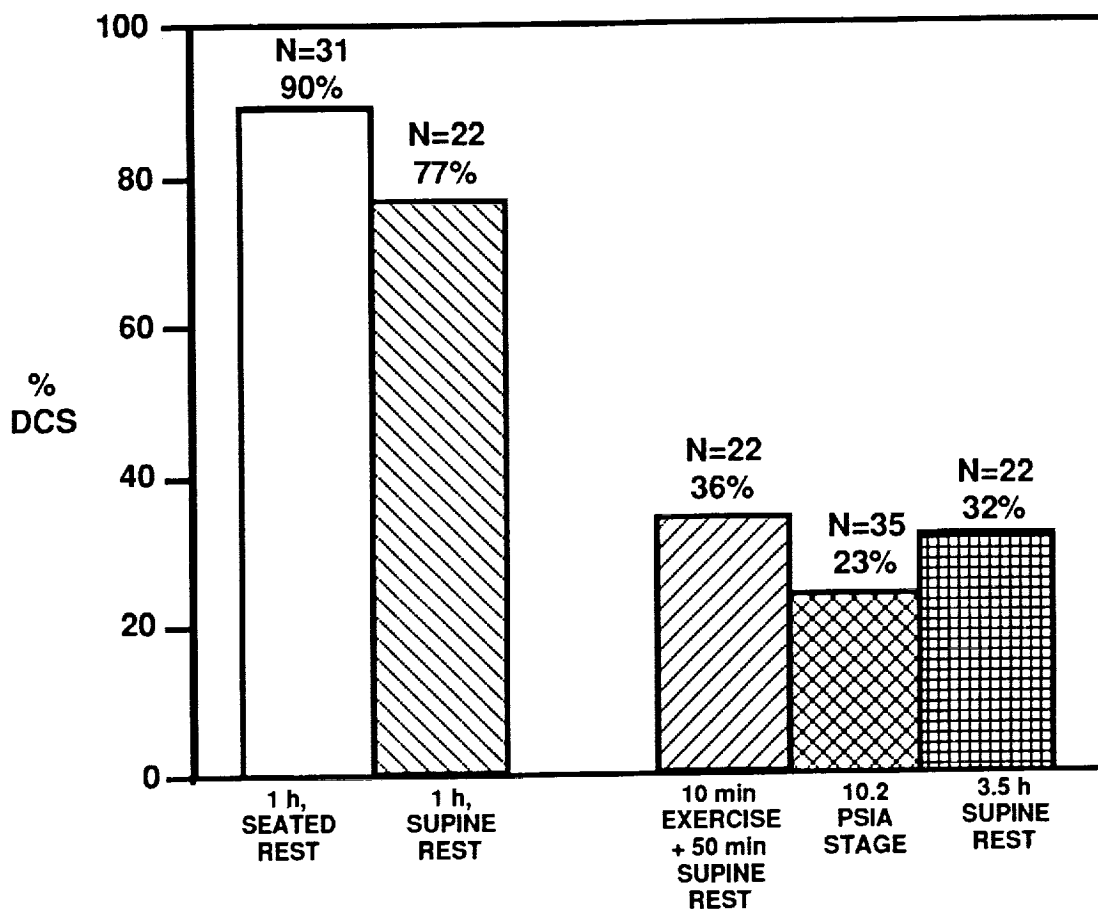


Figure 1: COMPARISON OF DCS INCIDENCE

DISCUSSION

We compared the incidence of DCS during the test (exercise-enhanced prebreathe) and control (resting prebreathe) exposures to data from previous experiments where length of 100% oxygen prebreathe and pressure of exposure were identical and where exercise during exposure was similar. A study accomplished at the USAF School of Aerospace Medicine in the 1980s used a seated one-hour prebreathe and less energetic exercises at altitude. As seen in Figure 1, the incidence of any DCS symptoms following 1 h of resting prebreathe, seated or supine, was not different. The subjects in the current study therefore appear to be equivalent in DCS susceptibility with subjects who participated in the earlier study.

When the incidence of DCS symptoms in the current study test exposures, exercise-enhanced one-hour prebreathe, is compared with the incidence of symptoms in a study examining past and current Shuttle EVA prebreathe procedures (Waligora et al., 1984), the difference is not significant. We caution that these data are preliminary and that completion of the remaining subjects could negate the findings reported here.

The method of obtaining data on VGE occurrence during the study by Waligora et al. (1984) did not involve the more sensitive capabilities of echo-imaging in addition to Doppler ultrasound used during the current study. Comparison of VGE incidence and levels could be affected by the differences in these methods.

Some indicators of exposure severity based on VGE (time to development of any VGE, time to development of severe VGE [Grade 3 or 4; Spencer Scale], and time to development of either severe VGE or DCS) indicated that exercise-enhanced prebreathe offered better protection than resting prebreathe under the conditions tested here. If the one-hour prebreathe with exercise continues to result in levels of DCS symptoms which are not significantly different from the 10.2 psia staged decompression, further research will be recommended with the goal of possibly substituting an exercise-enhanced prebreathe for the 10.2 psia staged decompression procedure. As shown in Figure 2, this substitution could reduce total prebreathe time and alleviate the need for decompression of the entire Shuttle.

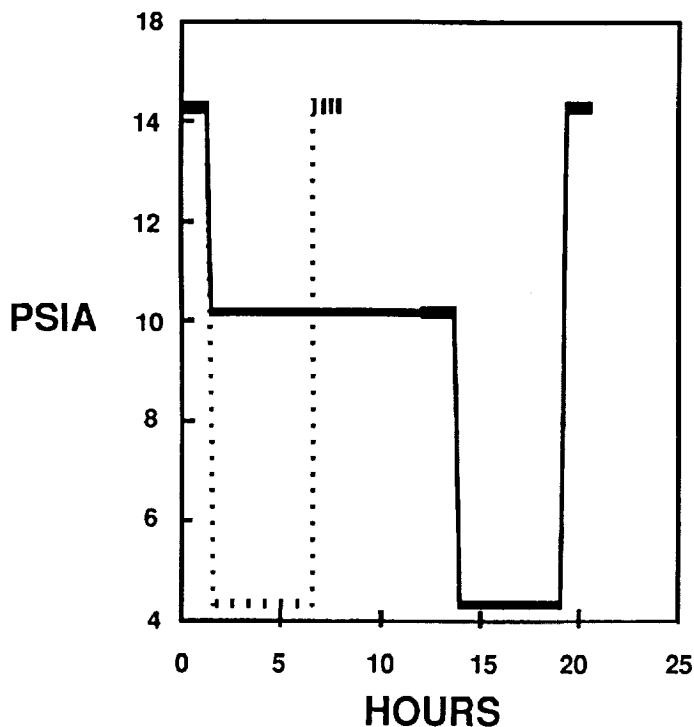


Figure 2: PREPARATION FOR A 6-HOUR EVA

CONCLUSION

A one-hour prebreathe beginning with 10 minutes of dual-cycle ergometry may offer protection from development of DCS symptoms which is comparable to either the current 10.2 psia staged decompression schedule or to 3.5 hours of resting prebreathe. Continued testing to complete the full complement of 26 subjects is underway to allow planned statistical comparisons.

ACKNOWLEDGMENTS

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**ORTHOSTATIC RESPONSES TO DIETARY SODIUM RESTRICTION
DURING HEAT ACCLIMATION**

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ABSTRACT

Several studies have shown that individuals consuming low-salt diets and working in the heat have an increased risk or incidence of heat injury, suggestive of inadequate cardiovascular adjustment. Furthermore, others have shown that prolonged work in hot climates can precipitate orthostatic hypotension and syncope. This study was designed to evaluate the effects of moderate-salt (MS) and low-salt (LS) diets on the circulatory responses and incidence of presyncopal symptoms to an orthostatic test (OT) during successive days of heat acclimation (HA). Seventeen unacclimatized male soldiers (mean \pm SE: age, 20 ± 1 yrs) participated in this two-phase study. The first phase consisted of a seven day dietary stabilization period during which all subjects consumed similar diets of about 4000 kcal/day containing 8g NaCl and lived in a dormitory setting (21°C , 30% RH). The second phase commenced on day eight and consisted of dietary NaCl restriction and 10 days HA (days 8-17). Volunteers were randomly assigned to either the MS diet ($n=9$) providing 8g NaCl/day or the LS diet ($n=8$) furnishing just 4g NaCl/day. The acquisition of HA was manifested in both groups by reductions in exercising rectal temperature and heart rate (HR); these characteristics were similar in the MS and LS diets. The OT was performed at 21°C on day seven of the stabilization phase and on days 9, 11, 13, 15, and 17 of the HA phase, before and after 8.5 hr of intermittent treadmill walking (30 min/hr, 5.6 km/hr, 5% grade) in a hot environment (41°C , 21% RH, 1.2 m/sec windspeed). Blood pressure (BP) and HR responses at 1, 2 and 4 min and any presyncopal symptoms were recorded after assuming an upright position from recumbency. All subjects completed the OT before and after prolonged exercise in the heat without incidence of either hypotension or presyncopal symptoms irrespective of dietary-salt intake and day of HA. There were no between-diet or between-day differences in supine systolic (Psys, 117 ± 1 mmHg), diastolic (52 ± 1 mmHg), and mean (74 ± 1 mmHg) BP or HR (66 ± 1 bpm) during the pre-exercise OT. Furthermore, the pre-exercise BP and HR responses to standing were not different between MS and LS diets or between HA days, and these OTT responses reflected typical increments in HR (17 ± 1 bpm), Psys (4 ± 1 mmHg), Pdias (18 ± 1 mmHg), and mean BP (13 ± 1 mmHg). The post-exercise OT responses were qualitatively similar to those observed pre-exercise. However, during the post-exercise OT on day 11, significant between-diet differences occurred; smaller increases were observed in the LS group in Pdias (LS: 4 ± 2 mmHg; MS: 22 ± 2 mmHg) and mean BP (LS: 6 ± 4 mmHg; MS: 18 ± 1 mmHg) at 2 and 4 min standing. The plasma volume expansion (% Δ PV) associated with HA was also significantly attenuated in the LS diet (+2%, day 11; +7%, day 15) compared to the MS diet (+11.5%, day 11; +13%, day 15), although all sweat losses incurred during HA were replaced hourly with equal volumes of pure water. These results indicate that the prolonged work in the heat can be performed without orthostatic hypotension or syncope while consuming 4g NaCl/day with adequate fluid replacement. Furthermore, the circulatory responses to OT showed no improvement with successive days of HA irrespective of dietary-salt intake.

INTRODUCTION

During rapid deployment from garrison to either jungle or desert conditions, both caloric and salt intakes of soldiers are typically reduced. Concomitant with these reductions in consumption are the elevated sweat NaCl losses, particularly during the first few days of heat exposure. Although the salt requirements for extended living and working in a hot environment have been previously studied, the results are of limited value because requirements range from 2g per day to as high as 20g per day (1,2,3,9,13,14,15,16). As reported by Hubbard et al. (9), the lack of agreement between studies most probably is due to inadequate fluid replacement (dehydration), uncontrolled exercise level, unknown heat acclimation status, unknown initial salt and water status, and lack of a dietary stabilization period.

Orthostatic hypotension and/or presyncopal symptoms have been reported following numerous stressors including water deprivation, heat exposure and dehydration due to exercise (4,7,8). In addition, both prolonged work in hot climates or acute exhaustive exercise can precipitate orthostatic hypotension and syncope (5). Furthermore, several studies have shown that individuals consuming low-salt diets and working under hot conditions may have an increased risk of heat injury (1,3) or incidence of orthostatic hypotension (14,15) and syncope (3,14,15), suggestive of inadequate circulatory adjustment.

It is generally agreed that heat acclimation is manifested by improved cardiovascular and thermoregulatory responses to work in a hot environment. In contrast, the effects of heat acclimation on orthostatic responses are inconsistent with both positive (11,12) and negative benefits (4,7) reported. Mild orthostatic increases in heart rate and decreases in blood pressure are typical clinical signs of acute moderate NaCl losses (16). However, the effects of a reduction in salt intake on orthostatic responses during repeated days of working in the heat are largely unknown, but are important to the military planner particularly during the first few days of heat exposure when both the incidence of syncope and the salt loss in sweat are high.

The current study, which incorporated seven days of dietary stabilization followed by 10 days of heat acclimation while consuming a low-salt (4g NaCl/day) diet, afforded the unique opportunity to assess the impact of reduced NaCl intake on orthostasis during subsequent days of heat exposure. In addition, the effect of heat acclimation on orthostatic responses was evaluated.

METHODS

Seventeen (17) healthy, physically fit, unacclimatized male soldiers (mean \pm SE: age, 20 ± 1 yrs; height, 179 ± 2 cm; weight, 78.4 ± 2.4 kg; surface area, 1.97 ± 0.03 m²) were briefed on the experimental design, procedures, medical risks, and freedom to withdraw at any time without retribution. Prior to participation, a medical history and physical examination were performed, and the volunteers provided their written consent.

This study consisted of two phases. The first phase comprised a seven day dietary stabilization period during which all subjects consumed diets of about 4000 kcal/day containing 8g NaCl and lived in a dormitory setting (21°C, 30% relative humidity). The second phase commenced on day eight and consisted of dietary NaCl restriction and 10 days of heat acclimation (days 8-17). Subjects were randomly assigned to either the moderate-salt (MS) diet (n=9) and continued to consume 8g NaCl/day or to a low-salt (LS) diet (n=8) and consumed 4g NaCl/day. During the 17 days, dietary intake and activity level were supervised 24 hrs/day.

Heat acclimation to a simulated desert climate was acquired via exercise in the heat for 10 consecutive days (days 8-17). On each day, subjects performed eight repetitions of intermittent treadmill walking (30 min/hr, 5.6 km/hr, 5% grade) and rest (30 min/hr) in a hot environment (41°C, 21% RH, 1.2 m/sec wind). Subjects unable to complete all work/rest cycles remained in the hot environment. After

completion of the 8.5 hr exercise-heat exposure, subjects returned to their dormitory setting (21°C) until resuming the heat exposure the next morning.

During the heat acclimation trials, ad libitum fluid intake and body weight were measured every 30 min. Sweat loss (SL) was calculated as the difference between the pre- and post-exercise nude body weights, adjusted for fluid and food intake, urination, blood sampling, and respiratory water loss. Changes in plasma volume (PV) were calculated using venous hematocrit and hemoglobin samples drawn before the first treadmill iteration and immediately upon completing the final walk.

An orthostatic test (OT) was performed in a secluded room at 21°C on day seven of the stabilization phase, and on days 9, 11, 13, 15, and 17 of the heat acclimation phase, both before and after the 8.5 hr exercise-heat exposure. The purpose of the OT was to measure the circulatory responses to a sudden change in position from horizontal to upright. Specifically, each subject lay supine for 4-10 min, and then quickly stood from the lying to erect (90°) position by his own effort. Blood pressure (systolic, diastolic and mean) and heart rate were measured just prior to standing and at 1, 2 and 4 min after assuming an upright position. While erect, body weight was supported by the legs. Appearance of presyncopal symptoms (lightheadedness, dizziness, nausea, vomiting, or pallor) constituted orthostatic intolerance.

Data were analyzed using analysis of variance with repeated measures (ANOVA) with Scheffe's post hoc analysis. The null hypotheses were rejected at $p < 0.05$. Data are expressed as mean \pm standard error (1SE).

RESULTS

The acquisition of heat acclimation (HA) was manifested in both groups by reductions in exercising heart rate (HR, 154 ± 6 bpm to 125 ± 3 bpm, $p < 0.005$) and rectal temperature (T_{re} , $38.3 \pm 0.1^\circ\text{C}$ to $37.8 \pm 0.1^\circ\text{C}$, $p < 0.02$) from day 8 to day 17. These changes were similar in the moderate-salt (MS) and low-salt (LS) diets. Exercising mean blood pressures (BP, 73 ± 1 mmHg) and daily sweat losses (5.2 ± 0.1 L) incurred by HA were not different between diets or days. These daily fluid losses were replaced hourly during the exercise-heat regimen by having each subject consume a volume of pure water that matched the deficit in body weight; thus, negligible body weight losses (0.03 ± 0.006 kg/hr) were observed. Nonetheless, the plasma volume expansion ($\%\Delta PV$) typically associated with HA was significantly ($p < 0.04$) attenuated on days 11 and 15 in the LS diet compared to the MS diet, although the $\%\Delta PV$ incurred during the eight hours of exercise was similar ($+6.5 \pm 0.6\%$) for both diets on all days (TABLE 1). No heat injuries occurred in either diet group although the daily eight hrs of walking resulted in several cases of overuse injury (blisters, shin splints, skin chafing) and completion of only 66 ± 4 and 60 ± 7 out of a possible 80 walks for the MS and LS diets, respectively.

Neither diet nor day of HA had an effect on the values for supine HR and systolic (P_{sys}), diastolic (P_{dias}), or mean blood (BP) pressures during the pre-exercise OT. All subjects completed the pre-exercise OT without any presyncopal symptoms or orthostatic hypotension. In addition, the pre-exercise OT responses from supine to 1, 2 and 4 min standing were not different between the MS and LS diets or between the 10 days of HA (TABLE 2), and reflected typical average increments in HR (17 ± 1 bpm), P_{sys} (4 ± 1 mmHg), P_{dias} (18 ± 1 mmHg), and mean BP (13 ± 1 mmHg).

Irrespective of dietary-salt intake or day of HA, all subjects completed the post exercise-heat exposure OT without displaying signs or symptoms of intolerance. No significant differences in the post-exercise supine values for HR, P_{sys} , P_{dias} and BP were seen between either diets or days of HA. While

TABLE 1. Responses to Heat Acclimation

		<u>Day 8</u>	<u>Day 11</u>	<u>Day 15</u>	<u>Day 17</u>
Final walk	4g	147±8	130±7	122±5 (4)	121±5
HR (bpm)	8g	161±8	135±4 [‡]	126±4 [‡] (8)	128±3 [‡]
Pre-exercise	4g	37.3±0.1	37.1±0.1	36.9±0.2 [‡] (4)	37.0±0.1
Tre (°C)	8g	37.4±0.1	37.1±0.1	37.0±0.1 [‡] (8)	37.2±0.1 [‡]
Final walk	4g	38.3±0.2	38.1±0.1	37.7±0.1 [‡] (4)	37.8±0.1 [‡]
Tre (°C)	8g	38.3±0.1	38.0±0.1	37.8±0.1 [‡] (8)	37.9±0.1
Daily Sweat	4g	6.36±0.25	5.45±0.39	4.49±0.36 [‡]	5.53±0.32
Loss (L)	8g	5.26±0.48 [*]	5.87±0.25	5.24±0.41	5.61±0.24
Final walk	4g	77±3	74±4 (6)	70±6 (4)	69±4
BP (mmHg)	8g	77±3 (8)	72±4 (5)	75±2 (8)	68±2
% ΔPV ¹	4g	-----	2.0±1.8	6.6±2.0	12.5±1.6 [‡]
	8g	-----	11.5±2.8 [*]	12.8±2.2 [*]	12.4±1.7
Daily % ΔPV ²	4g	8.0±1.3	4.8±1.2	7.8±4.5	5.7±1.7
	8g	8.4±2.2	6.2±1.8	4.8±1.1	6.2±0.6

HR, heart rate; Tre, rectal temperature; BP, blood pressure

Values are mean ± SE. Unless indicated, LS (4g) diet, n=8; MS (8g) diet, n=9.

1 Percent change in plasma volume from day 8 pre-exercise to pre-exercise that day.

2 Percent change in plasma volume from pre-exercise that day.

* Significantly different (p<0.05) from LS (4g) diet; † from day 11; ‡ from day 8.

TABLE 2. The Effects of Exercise and Heat-Acclimation on Orthostatic Responses

			Change upon standing (4min) from the supine position				
<u>Supine</u>			<u>Day 9</u>	<u>Day 11</u>	<u>Day 13</u>	<u>Day 15</u>	<u>Day 17</u>
<u>Heart Rate (bpm)</u>							
Pre-exercise	4g	66±2	17±2	17±4	24±3	16±2	19±2
	8g	66±1	19±7	14±7	15±7	11±5	18±4
Post-exercise	4g	70±1	19±4	20±3	16±2	16±3	11±3
	8g	71±2	16±3	13±2	18±4	14±6	14±5
<u>Psys (mmHg)</u>							
Pre-exercise	4g	113±1	3±4	-3±5	1±4	11±4	3±3
	8g	122±1	7±5	8±5	6±3	4±2	6±3
Post-exercise	4g	111±1	1±1	8±8	0±6	7±6	-1±3
	8g	113±1	9±6	11±3	5±3	6±3	2±3
<u>Pdias (mmHg)</u>							
Pre-exercise	4g	52±1	21±7	18±3	13±3	21±3	20±3
	8g	51±1	18±4	18±6	18±3	18±3	12±5
Post-exercise	4g	58±1	17±6	4±5	18±4	13±5	20±4
	8g	57±1	17±4	22±2*	17±2	24±5	10±4
<u>BP (mmHg)</u>							
Pre-exercise	4g	72±1	15±6	11±2	9±3	18±3	14±3
	8g	75±1	15±3	15±6	14±3	13±3	10±3
Post-exercise	4g	76±1	12±4	6±5	12±3	11±4	13±3
	8g	76±1	14±2	19±1*	13±1	18±3	8±3

* Significantly different (p<0.05) from LS (4g) diet.

increases in HR and blood pressures at 1, 2 and 4 min standing were generally not different between diets or HA days, the OT response was significantly attenuated in the LS diet on day 11 (day four of exercise-heat exposure). During the post-exercise OT on day 11, subjects on the LS diet manifested significantly smaller increases in P_{dias} (LS: 4 ± 2 mmHg; MS: 22 ± 2 mmHg, $p < 0.02$) and mean BP (LS: 6 ± 4 mmHg; MS: 18 ± 1 mmHg, $p < 0.007$) concurrent with larger increments in HR (LS: 20 ± 3 bpm; MS: 13 ± 2 bpm) at 2 and 4 min standing.

The OT responses following the 8.5 hr exercise-heat exposure were qualitatively similar to those seen pre-exercise. Significantly ($p < 0.03$) higher post-exercise supine values for P_{dias} and mean BP were seen in the LS diet on days 11 and 15 and for HR, P_{sys} and P_{dias} in the MS diet on day 17. A further important finding was the smaller ($p < 0.02$) increase in both P_{dias} and mean BP in the LS diet following the exercise-heat exposure on day 11 compared to the pre-exercise OT response.

DISCUSSION

The work of Taylor et al. (14,15) has shaped our opinions and much doctrine regarding salt requirements for preventing performance decrements and heat injury in hot climates. This classical study demonstrated that acclimation to heat is impaired by a low-salt diet (6g NaCl/day), and compared to moderate-salt (15g NaCl/day) intake, significantly higher work heart rates, rectal temperatures and incidence of heat injury were noted. In addition, subjects consuming the 6g NaCl/day elicited poorer circulatory responses to postural change and failed to show any improvement in their orthostatic responses during the first few days of heat acclimation (14,15). Taylor and colleagues (14,15) concluded that 15g NaCl/day was required to work under hot conditions where sweat losses would be 5-8 L/day. They further concluded that the 6g NaCl/day or their low-salt diet contributed to a salt deficit and subsequent cardiovascular strain and heat injury. Several others have concurred with the findings that low-salt diets contribute to salt deficits during work in the heat (3,9), salt deficiencies elicit poor circulatory responses to work and postural change (3,16) and the highest incidence of salt depletion and postural hypotension and syncope occur in the first few days of heat acclimation (3,9,16). However, others (3,9,13) have reported optimal salt requirements ranging from 2 to 20g NaCl/day for both acclimatized and unacclimatized men.

Based on these studies, we anticipated a negative sodium balance and a higher incidence of heat injury and postural syncope during the first 3 to 5 days of exercise-heat exposure in subjects consuming the low-salt (4g NaCl/day) diet compared to the moderate-salt (8g NaCl/day) diet. However, after completing 8.5 hrs of intermittent treadmill exercise under hot simulated desert conditions on each of 10 days, all of our subjects completed the orthostatic test without incidence of hypotension or syncopal symptoms. In addition, the pre-exercise heart rate and blood pressure responses to standing were not different between the low- and moderate-salt diets or between heat acclimation days. Our results indicate that prolonged work in the heat can be performed for successive days with consumption of 4g NaCl/day and adequate fluid replacement without increasing the incidence of heat injury or circulatory incompetence.

In spite of the absence of orthostatic hypotension and presyncopal symptoms during the 10 day heat acclimation period, during the post-exercise orthostatic test on day 11 (fourth day of acclimation) significantly smaller increases in diastolic and mean blood pressures at 2 and 4 min standing were observed in the low-salt diet. Concurrent with this poorer orthostatic response was a delay in plasma volume expansion in the low-salt diet during the initial days of heat acclimation (day 11). It is generally agreed that much of the cardiovascular improvements with heat acclimation occur within the first four days of exercise-heat exposure and are due to an increase in plasma volume (2,14). With the increase in plasma volume (days 15 and 17) in the low-salt diet, the post-exercise responses to postural change were

not different between diets. This result is in agreement with several studies that have observed orthostatic hypotension following dehydration and decrements in plasma volume (7,8) but not after rehydration (8).

Pitts and colleagues (10) reported that replacement of sweat losses with water resulted in sustained effective work performance in the heat, and that replacement of salt alone showed no benefit. Furthermore, several studies (10,13,14,15) have noted that the higher the dietary-salt intake, the more fluid consumed. In the earlier studies in which low dietary-salt intake elicited orthostatic hypotension or syncope (3,14,15,16) or increased the risk of heat injury (1,3,9,14,15), fluid replacement of sweat losses was inadequate and significant body weight deficits usually occurred. Salt-depletion heat injury develops over several days and occurs when large volumes of sweat are replaced by adequate fluid intake but not salt (9,13,16). Furthermore, sodium depletion is rarely elicited by dietary restriction of NaCl alone in healthy men in normal climates (16). Thus, it is probable that dehydration significantly contributed to the high incidence of heat illness and syncope observed in the earlier studies (1,3,9,14,15) particularly since circulatory incompetence and orthostatic hypotension are more marked when dehydration accompanies salt deficiencies (16). In the current study, the replacement of all sweat losses incurred during each exercise-heat exposure by an equal volume of pure water on an hourly basis resulted in negligible body weight losses which may have prevented heat injury during exercise and postural hypotension and syncope during the post-exercise orthostatic tests.

Sohar and Adar (13) conjectured that the majority of salt-depletion heat injuries reported in the literature most probably were not actual salt deficiencies but rather represented the inability of unacclimatized individuals to conserve salt and replace water losses during the first few days of heat acclimation. It is generally accepted that salt losses in the urine and sweat are dramatically reduced by heat acclimation (1,2) and maximal conservation occurs by 5 and 10 days, respectively. In the current study, sodium conservation was evident in both the 4 and 8g NaCl diets; urine and sweat sodium losses were significantly reduced during the first four days of acclimation in the moderate-salt diet and during the entire acclimation period in the low-salt diet (Moore et al., unpublished data). Francesconi et al. (6) demonstrated that endocrinological adaptations, especially in the low-salt diet reflected renal and sweat gland NaCl conservation contributing to a positive sodium balance throughout most of the acclimation period.

Acclimation to heat has been reported to both enhance (5,11,12) or have no effect (4,7) on orthostatic tolerance in either warm or hot climates. Our results suggest that heat acclimation had no effect on blood pressure and heart rate responses while either supine or standing, irrespective of dietary NaCl intake. Although one of the important effects of acclimation on orthostatic responses may be a reduced incidence in syncope following work in the heat (5,7,11,12,14), the absence of syncopal symptoms in the current study did not enable us to address this hypothesis.

Our results indicate that while consuming 4g NaCl/day with adequate fluid replacement, prolonged work in the heat can be performed on successive days without orthostatic hypotension or syncope. We further conclude that the blood pressure and heart rate responses to postural changes showed no improvement with heat acclimation irrespective of dietary-salt intake. Future research should evaluate the effects of combined NaCl restriction and ad libitum water consumption on orthostatic responses after prolonged work in the heat.

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Session L2: MEDICAL OPERATIONS

Session Chair: Lt. Col. Roger Bisson

Telemedicine, Virtual Reality, and Surgery

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In terms of Systems Space, Causality is one dimension. Causality distinguishes between:

Teleoperation in which the operator's actions affect the real world. *Virtual Environments* in which the operator's action affects a 3D computer-generated simulated world.

Other dimensions include:

Sensory Modalities used by the System.

Nature of the Models of Environment surrounding the user.

Displacements or scaling in time or space between the user's true position and the environment he or she interacts with. There are many systems – for example, the Head Mounted Display (HMD) – with the common theme of Technologically Medicated Experience, or Synthetic Experience.

Examples of Synthetic Experience include:

Virtual Reality – which uses a stereoscopic wide angle HMD to create the illusion of a SD surrounding fantasy world.

Teleoperation – which uses devices such as an HMD and force – feedback handgrip electronically linked to a distant robot. The robot head turns to mimic the operator's head motions and the robot arms mimic hand motion, so that the operator's eyes and hands are effectively projected into the remote environment and the operator can look around and do things via the robot. The remote environment may be a human body.

Other examples include: Microteleoperation, Sensory Prostheses, Telecommunication, and Synthetic sense.

In this paper, I will deal with two types of Synthetic Experience – both in the medical sphere: Telemedicine, Virtual Reality, and Surgery.

Telemedicine, Virtual Reality, and Surgery

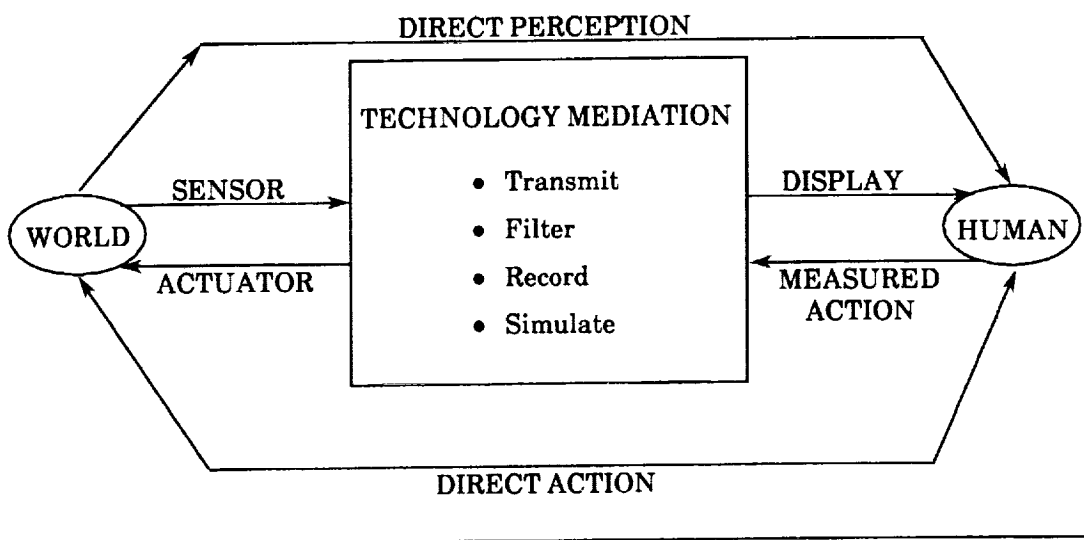
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- › *Teleoperation* – Operator's actions affect the real world
- › *Virtual Environments* – Operator's actions affect only a simulated (computer) world
- › *Technologically Mediated Experience (TMD)*
- › *General Model*



► ***Examples of Time (Synthetic Experience)***

- ***VR***
 - Uses a stereo wide-angle HMD
 - Creates illusion of a 3D surrounding fantasy world
- ***Flight Simulation***
 - Accurately models the behavior of a real a/c
- ***Teleoperation***
 - Uses devices such as HMD and force-feedback handgrip
 - Linked to a distant robot body with robot arm + video cameras
 - Robot head mimics operator's head motions
 - Robot arm mimics hand motions

► ***Microteleoperation***

- Uses a microscope and micromanipulator
- Gives operator a sense of presence
- Gives operator ability to act in a microscopic environment
- **Examples:**
 - Retinal surgery / neurosurgery
 - Telecommunications
 - Sensory prostheses
 - Augmented reality

In This Paper

- Two Types of Synthetic Experience dealt with
 - Virtual Reality and Surgery
 - Telemedicine

► *V.R. Systems*

- Allows user to enter a computer-generated 3D environment
- Education, communication, military, entertainment, and medicine
- *Basic Components*
 - Computer + Software
 - Head-coupled display
 - Input devices (handgrip)

► *Software*

- Description of structure, appearance, and behavior of virtual world
- System monitors input device (from user) and reforms model of the world
- Systems sends f.b. to user – sound, tactile, force → new state of virtual world

▶ ***Geometric Models***

- 3D structures represented by
 - Surface Geometry (polygon patchwork)
 - Volumetric Data (CT or MRI data)
 - Finite Elements

▶ ***Force Feedback***

- Tactile – cutaneous or force to hand or whole body
- Multiple Joint Reaction Forces

▶ ***Physiological Sensors***

- Pneumatic mouth-actuated controllers
- Eye trackers
- Dispersed switches

▶ ***HMDs***

- User wears an HMD to experience *sights* and sounds of the virtual world

▶ ***Input Devices***

- Joysticks, keyboards, buttons, and knobs
- Allows user to manipulate virtual objects
- Dataglove measures finger flexion
- Magnetic tracking sensor transmits whole hand motion → virtual hand

► ***Surgical Applications***

- VR used in teaching, planning, training, and prediction of outcomes

► ***VR Surgical Training***

- Allows student to enter and tour the body; e.g., can see how a synapse works
- Allows two or more surgeons to interact with a virtual cadaver
- 3D surgical simulator requires a detailed model of the body
- Zettger's kinematic model of the human skeleton

► ***Virtual Cadaver***

- Central component of a VR anatomy trainer
- 3D model of the anatomy plus sim. of biomechanics, physiology, and pathology
- Stored library of congenital anomalies
- Student can "see through" the skin to underlying structures

► ***VR Surgical Simulation***

- VIRTUAL abdomen has been developed
- Student can move from esophagus to rectum (cf. endoscopy)
- Touching the mucosa could produce
 - A histologic view of mucosa
 - A videotape of gastric motility etc.

► ***VR Surgical Simulation (cont'd)***

- Can rotate organs to show hidden nerves, arteries, etc.
- Techniques of ligation, isolation, etc., can be detailed

► ***Present VR Simulation***

- Torso + stomach, duodenum, liver, bile ducts, gall bladder, pancreas, and colon
- Instruments (scalpels, clamps, etc.) are provided

► ***Five Requirements for Realistic Sim.***

- Fidelity
- Object properties
- Reality
- Interactivity
- Sensory input (force feedback, tactile, and pressure felt by surgeon)

► ***VR Surgical Simulation (cont'd)***

- Present simulators use the HMD and Dataglove
- Surgeons do *not* use a helmet or glove
- Will need a telepresence surgery system with a 3D monitor in place of the HMD
- Will need handles of *actual* instruments in place of Dataglove

► ***Telesurgery***

- NASA Space Station
- Problems with time delay in data transmission
- Problems with telepresence errors
- *Simulation and Training* will be the main applications of VR

► ***VR Surgical Trainer***

- *Three Basic Components*
 - Physical model
 - The interface
 - The computer
- *Physical Model*
 - Math. representation of patient + surgeon's tools
- *Interface*
 - Dataglove
 - Allows user to manipulate tools and patient model
- *Computer*
 - Software + hardware
 - Runs model in real time
 - Surgeon practices surgery in the VE

► ***Abdominal Surgery Pilot Study***

- Dr. Joe Rosen, Dartmouth College
- *GOAL* – Substitute for animals or cadavers
- Includes a 3D model of bowel and surrounds
- Bowel modeled as a linked set of rigid objects
- Object deformation modeled by relative segment motion
- Structures modeled – Surgeon's L. and R. Hands
 - Bowel Segments
 - Suturing Clamp
 - Needle / Sutures
 - Surgical Table, etc.
- Audio feedback as analog to touch

► ***Advanced Abdominal Simulator***

- Wider range of organs
 - Gall Bladder
 - Stomach
 - Bowel
- "Fly Through" and "See Through" capability
- Example: Placement of purse-string sutures within the four layers of bowel

► ***Knowledge Gained to Date***

- Audio feedback not a good substitute for touch
- Realism limited in bowel model
 - Interactivity of the tools
 - Surgeon / virtual op. room interface
 - Need to sim. physical reactions of bowel; e.g., bleeding
 - Lack of force f.b. in Dataglove

► ***Future Developments in Surgical Simulation Hybrids***

- Combination of VR simulator with real apparatus
- Trainee holds and manipulates real devices
- High-accuracy tactile f.b.
- Good finite model of soft tissues in abdomen

► ***Conclusions***

- VR provides a unique advantage for
 - Teaching
 - Training
 - Planning
 - Performance evaluation
 - Prediction of surgical outcomes
- Realism limited in bowel model
 - Virtual patient
 - Surgeon's tools
 - Operating room

► ***Examples of Telemedicine***

- NASA / Armenian (Yerevan) Satellite Link-1990
- Post-Armenian earthquake disaster
- Two satellites used – Intel and Comsat
- Network
 - Yerevan General Hospital
 - Moscow
 - Satellites
 - Roaring Bend, Pennsylvania
 - NASA HQ
 - Baltimore Training Center
 - USUHS, Bethesda
 - L.D.S. Trauma Center, Salt Lake City
 - Houston Trauma Center

▶ ***Total Earthquake Casualties***

- Fatalities – 25,000
- Injured – 25,000

▶ ***Public Health Problems***

- Lack of disposable needles – population inoculation slow
 - Needles shipped in from Europe and U.S.
- Lack of dialysis units*
 - Only eight old units in whole Republic
 - Modern units shipped in from Europe and U.S.

*Many cases of renal failure from crush injuries.

Telemedicine Spacebridge – *Communication Capabilities*

- Telecommunications equipment installed at four U.S. medical centers
- Ground station at Republic Diagnostic Center, Yerevan, A.S.S.R.
- Capabilities

Real Time

- Audiovisual
- Fax
- Broadcast Monday—Friday, 0900—1300 EDT (1800—2200) Armenian time
- Slow Scan Video

Non Real Time

- Two portable field camcorders

Telemedicine Spacebridge – *Communication Capabilities (cont'd)*

- U.S.S.R. accepts this offer and the satellite capability becomes operational July 5, 1989
- Spacebridge operations terminated July 28, 1989

Telemedicine Spacebridge – *Operations*

- Daily agenda of topics established with one medical center taking the lead
- On Fridays, Armenia faxes to the U.S. medical centers information on patients to be presented the following week
- On Mondays, U.S. medical centers fax professional material to Armenia
- Cases are presented by Armenian physicians (2/3 patients directly related to earthquake; 1/3 miscellaneous difficult management problems)
 - Patient sometimes present
 - X rays, CT, imaging presented
 - General discussion
- U.S. physicians discuss cases with Armenian physicians and offer recommendations
- Spacebridge extended through July 28, 1989, to accommodate consultations for burn victims of the Ufa train accident

Telemedicine Spacebridge – Results

- Excellent results with communication equipment
- Medical consultants developed efficient medical data acquisition and transmission procedures
- Patient care/problems discussed
 - Public health
 - Post-traumatic stress
 - Infectious diseases
 - Epidemiology
 - Dialysis
 - Orthopedics
 - Prosthetics and rehabilitation
 - Imaging/lab
 - Burn management
 - Spinal cord injury
 - Plastic surgery
 - Vascular surgery
 - Eye injury
 - Aggravation of preexisting disease

▶ ***Performance***

- Via consultations and advice of U.S. experts
- Diagnosis and/or therapy in case of 250 American casualties was significantly changed
- Over period of 3 months

▶ ***UFA Train Disaster (near Moscow)***

- 400 severe burn cases
- Link extended to deal with this disaster
- Link extended to burn center in Galveston

▶ ***Post-link Follow-up***

- Several conferences – in U.S., Russia, and Armenia have been held
- Improvements in data transmission capabilities planned

Total Hydrocarbon Analysis by Ion Mobility Spectrometry

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NASA/Johnson Space Center
Houston, TX**

Astronauts must be alerted quickly to chemical leaks that compromise their health and the success of their missions. An ideal leak detector would be equally sensitive to all compounds that might constitute a hazard and insensitive to nontoxic compounds. No ideal sensor exists; thus, selection of a methodology is a series of compromises. The commonly used methods are either insensitive at the low exposure levels set by OSHA, NASA, and other organizations or are selectively insensitive to important classes of chemicals such as Freons. After extensive study and experience, the Toxicology Group at Johnson Space Center has selected ion mobility spectrometry (IMS) for development into a broad range, sensitive detector. In addition to the sensing method, signal processing is important in leak detection because a background signal can be expected at all times. The leak-detecting instrument must be programmed to discriminate between authentic leaks and background fluctuations caused by routine operations. A prototype leak detector, called a total hydrocarbon analyzer (THA), based on IMS, has been built to detect many types of compounds known to occur in spacecraft atmospheres. The prototype THA includes four signal-processing algorithms that display the signal as a single value representative of the total hydrocarbon concentration in the air.

The authors of this paper will present the results of an evaluation of the prototype THA in terms related to spacecraft operations. The evaluation included determination of instrumental parameters such as stability and response times. We also included responses to some common components of spacecraft atmospheres in pure form and in binary and ternary mixtures. The output of the four algorithms to the mixtures was found to be noticeably different. These responses will be compared on the basis of their utility for signaling a chemical leak. As a means of evaluating its resistance to a falsely positive response, the THA was challenged with carbon dioxide and methane, compounds whose concentrations normally increase in spacecraft air during human habitation. The instrument showed virtually no response to these interferences. Although the prototype THA is designed for space flight, this detector is expected to be useful for field screening at chemical waste dumps and other environmentally sensitive locations.

Total Hydrocarbon Analysis By Ion Mobility Spectrometry

**John H. Cross, Ph.D., Thomas F. Limero, Ph.D.
and John T. James, Ph.D.***

***NASA Johnson Space Center
KRUG Life Sciences**

Organization

- **Background**
- **Design Requirements**
- **Instrument Selection**
- **IMS Design**
- **Experiment Discussion**
 - **IMS stability**
 - **Responses to typical contaminants**
 - **Algorithms**
- **Conclusions**

Design Requirements

Functional

- ▶ Detect Leaks and Spills
- ▶ Broad Spectrum Response (ppm)
- ▶ Track Decontamination
- ▶ No Responses from Major Atmosphere Components (O₂, N₂, CO₂, CH₄, H₂)

Design Requirements (cont'd)

Constraints

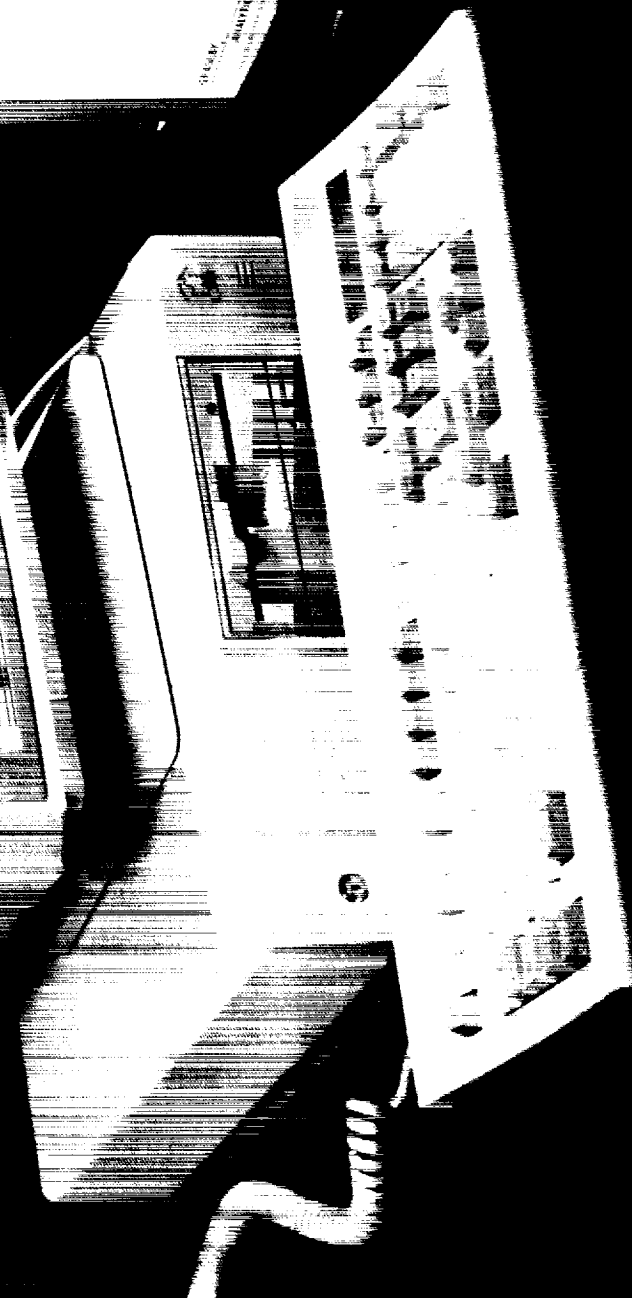
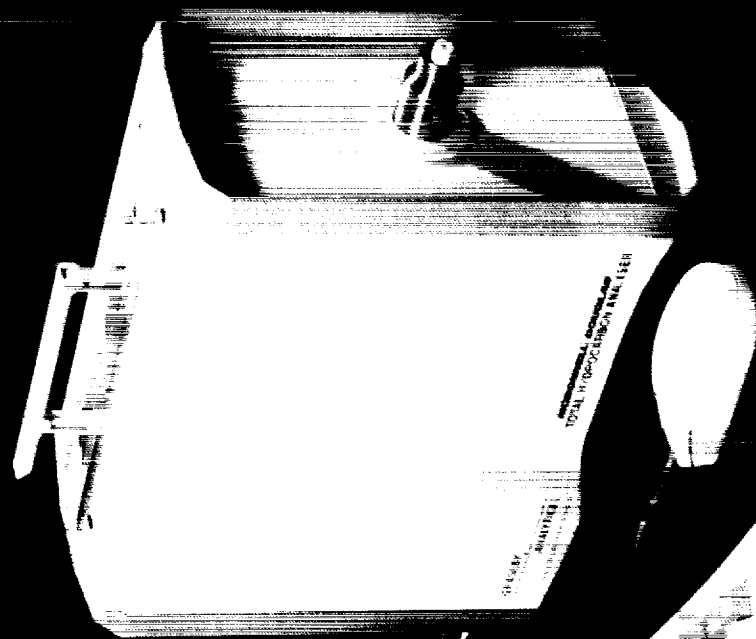
- ▶ Simple, Fast Operation
- ▶ Low Power, Mass, and Size
- ▶ Low Maintenance
- ▶ Reliable
- ▶ Microgravity Compatible
- ▶ Withstand Shock and Vibration of Liftoff

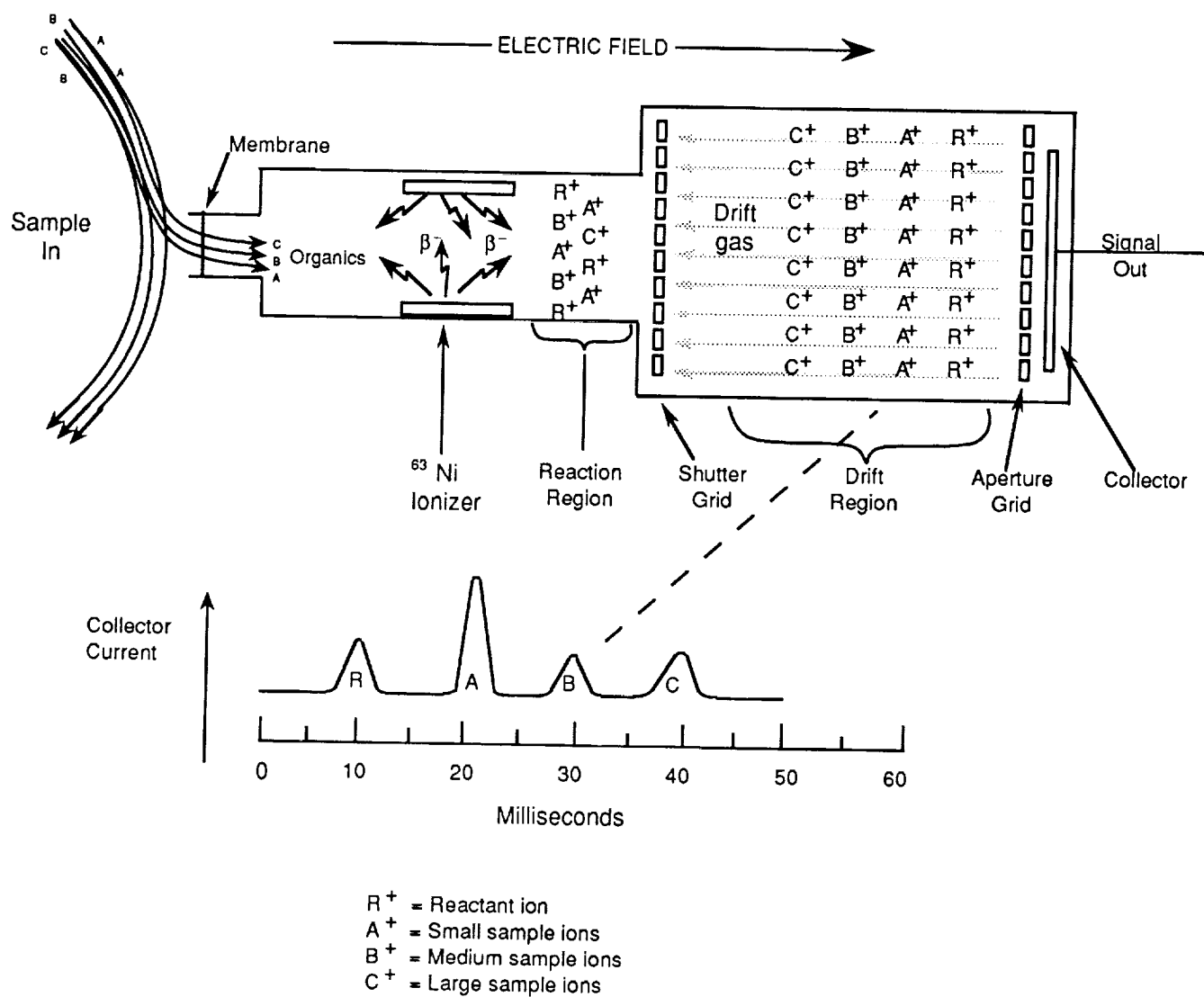
Methodologies

- ▶ **Catalytic Bead**
- ▶ **Tin Oxide Ceramic**
- ▶ **Photoionization**
- ▶ **Ion Mobility Spectrometry (IMS)**

Conclusions

- ▶ **Stable Output**
- ▶ **High Sensitivity and Precision**
(No response to methane)
- ▶ **Fast Response and Recovery**
- ▶ **Complicated Response to Mixtures**
- ▶ **Algorithms Trend with Concentration**





OPERATING PRINCIPLE OF ION MOBILITY SPECTROMETER

Configuration Operation Algorithm Quit

JN040IR0.ACQ 00:55:02 15/12/1992 THA Evaluation: Humidified zero air, Jan 4

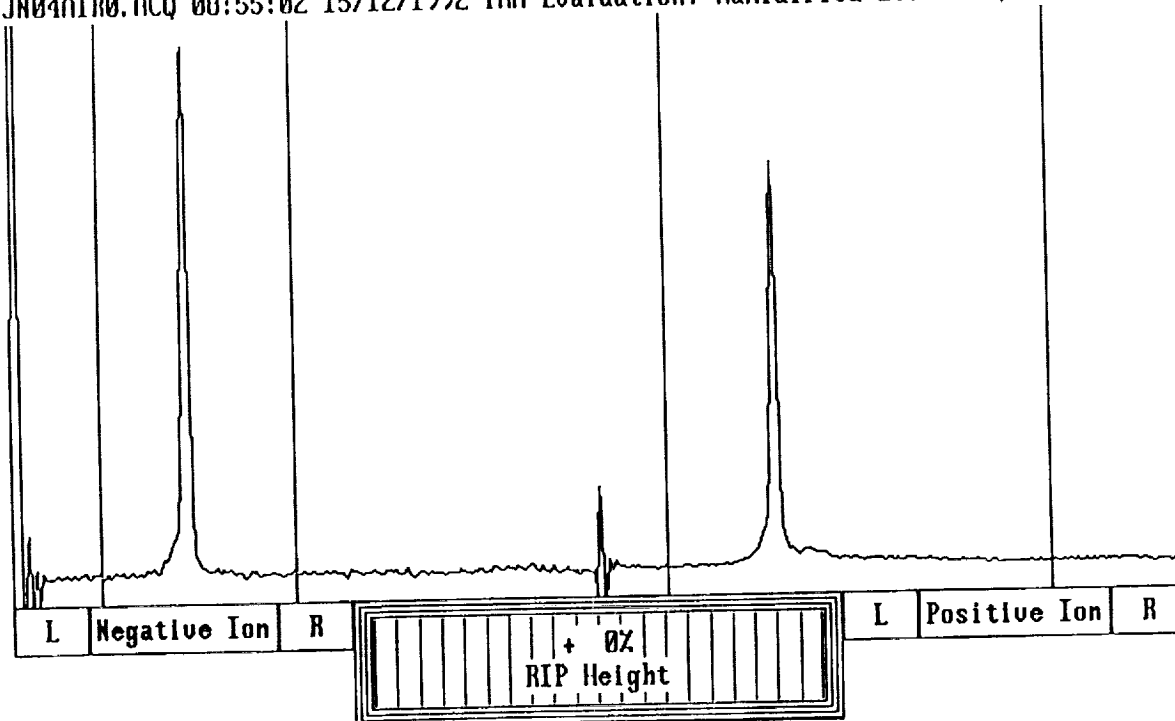


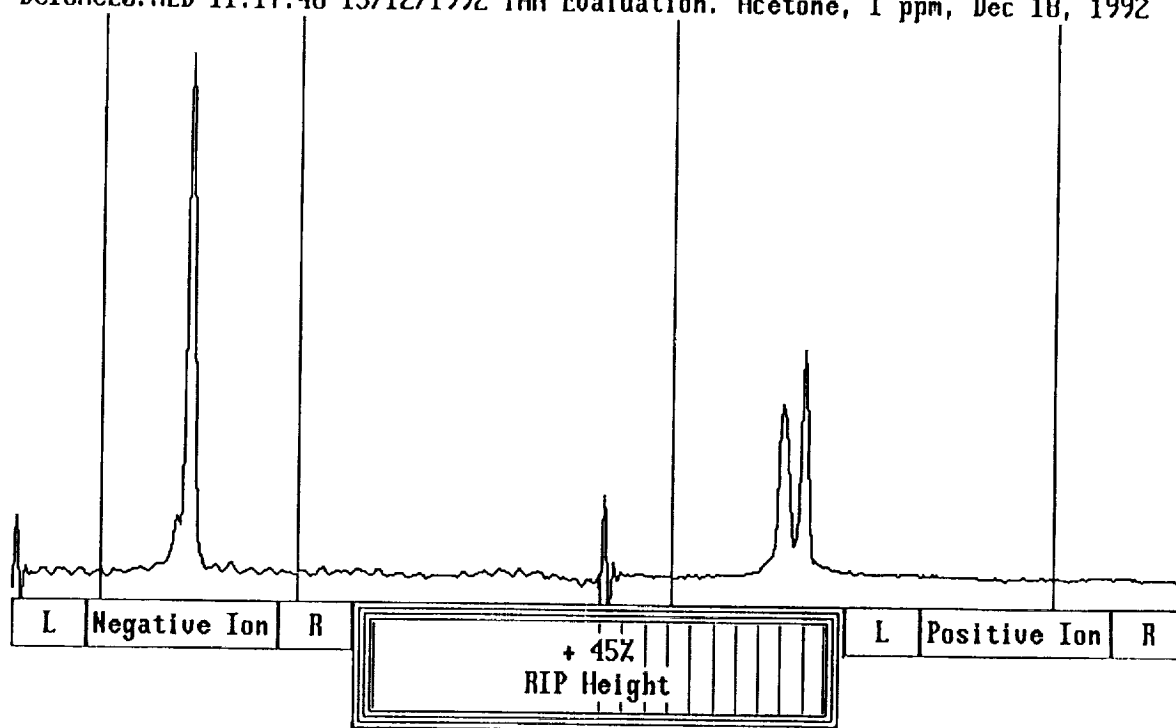
Table 1: Instrument stability measurements with humidified air.^(a)

Data Set	Positive Mode			Negative Mode		
	Baseline (mV)	RIP Height (mV)	RIP Drift time (ms)	Baseline (mV)	RIP Height (mV)	RIP Drift time (ms)
1-5-93	355 ± 4 ± 1	2414 ± 8 ± 0.3	6.40 ± 0 ± 0	354 ± 16 ± 5	3158 ± 16 ± 0.5	6.22 ± 0 ± 0
Average of 10 data sets	359 ± 3 ± .8	2419 ± 39 ± 1.6	6.36 ± .03 ± .5	357 ± 4 ± 1.0	3086 ± 121 ± 3.9	6.19 ± .02 ± 0.3

(a) Average ± Standard Deviation ± Relative Deviation (%).

Configuration Operation Algorithm Quit

DC18ACE0.MED 11:17:46 15/12/1992 THA Evaluation. Acetone, 1 ppm, Dec 18, 1992



Compound and Concentration	Peak Height (Average \pm SD \pm Relative Deviation)	
	1st Peak	2nd Peak
Acetone 0.4 ppm 1 1.8	644 \pm 40mV \pm 6.3% 1300 \pm 40 \pm 3 1701 \pm 51 \pm 3	-- (a) -- --
MEK 0.1 ppm 0.3 0.9	581 \pm 20 \pm 6 683 \pm 10 \pm 1 501 \pm 14 \pm 3	296 \pm 17mV \pm 6% 816 \pm 19 \pm 2 1467 \pm 21 \pm 1
HCTS 1 ppm 3 ppm 10 ppm	344 \pm 49 \pm 14 (b), (c) 581 \pm 18 \pm 3 734 \pm 39 \pm 5	-- (a) -- --

- (a) The acetone spectrum had only one peak.
 (b) The larger relative variability was probably partially the result of the method of preparing the sample.
 (c) Largest peak in spectrum.

Configuration Operation Algorithm Quit

RESPNS59.MEK 10:48:08 08/01/1993 TIA Evaluation. Response and recovery

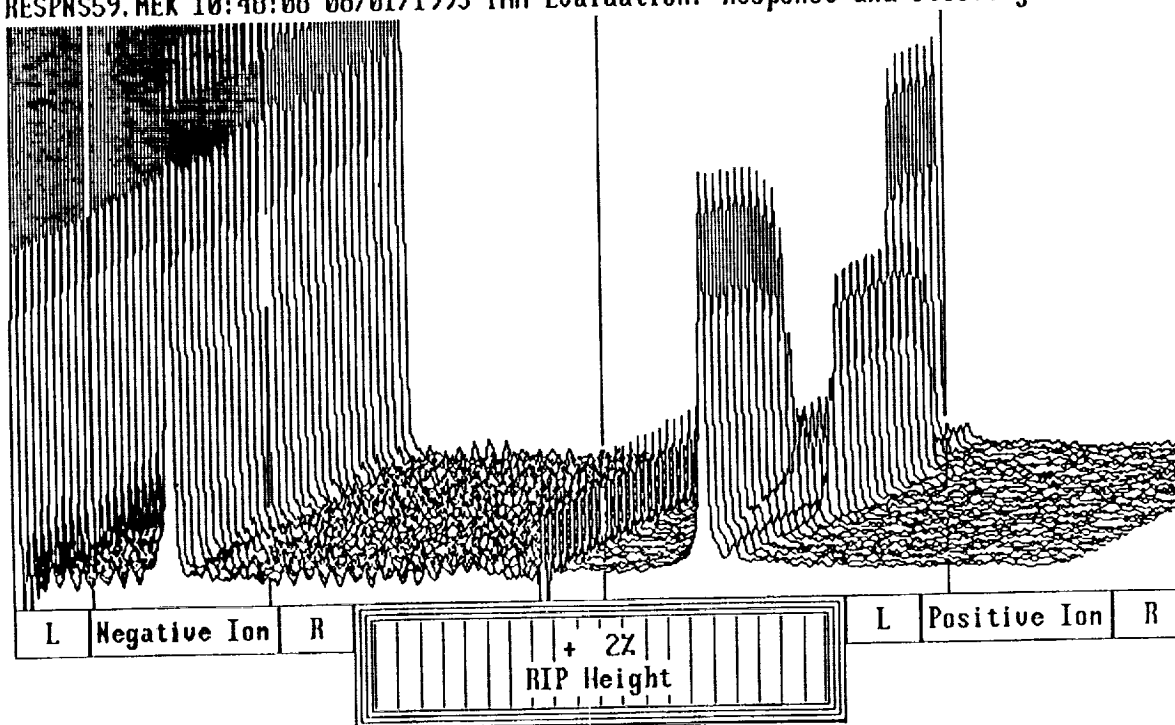
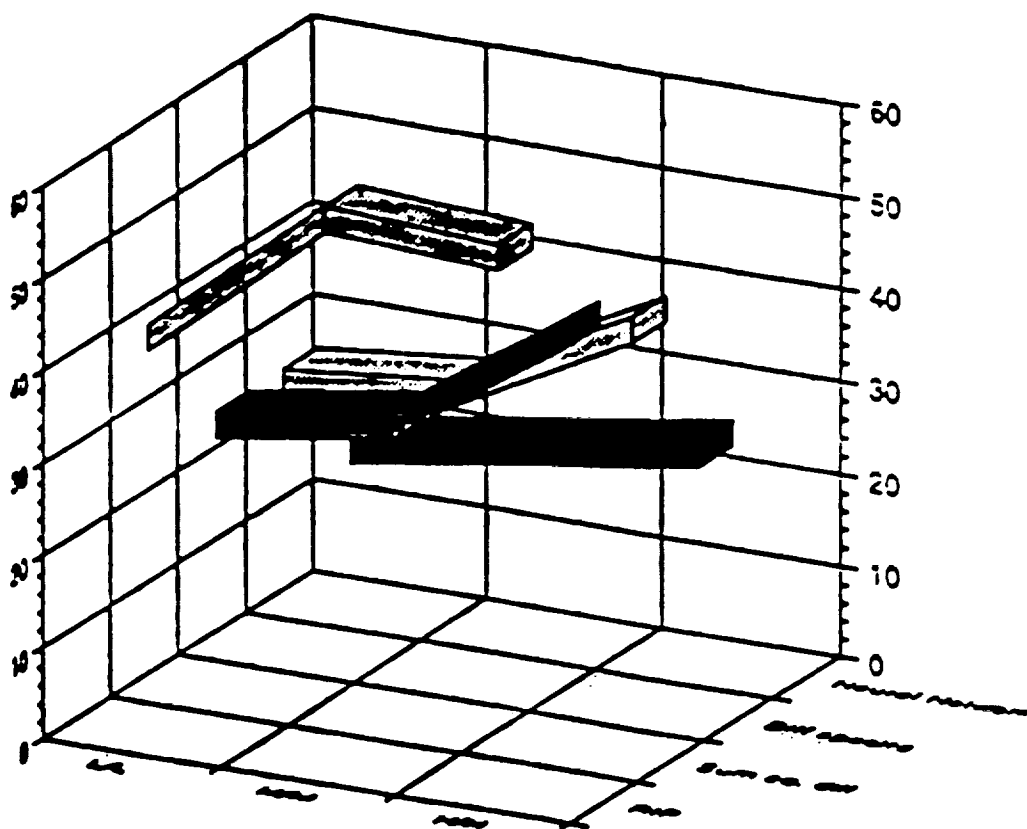


Table 3: Response and recovery times.

Compound	90% Response	90% Recovery
Acetone	3 ± 0 sec	5 ± 1 sec
MEK	3 ± 1	5 ± 1
HCTS	4 ± 1	5 ± 1



The response of the four algorithms to low, medium, and high concentrations of acetone and MEK.

**THE EFFECTIVENESS OF GROUND LEVEL
POST-FLIGHT 100% OXYGEN BREATHING AS THERAPY FOR
PAIN-ONLY ALTITUDE DECOMPRESSION SICKNESS (DCS)**

John T. Demboski* and Andrew A. Pilmanis
Armstrong Laboratory/CFTS
Brooks AFB, TX

ABSTRACT

In both the aviation and space environments, DCS is an operational limitation. Hyperbaric recompression is the most efficacious treatment for altitude DCS. However, the inherent recompression of descent to ground level while breathing oxygen is in itself therapy for altitude DCS. If pain-only DCS occurs during a hypobaric exposure, and the symptoms resolve during descent, ground level post-flight breathing of 100% O₂ for 2 hours (GLO2) is considered sufficient treatment by USAF Regulation 161-21. The purpose of this study was to define the effectiveness of the GLO2 treatment protocol.

Between 1983 and 1993, 1163 experimental hypobaric exposures were conducted at the Armstrong Laboratory altitude simulators at Brooks AFB, Texas. Constant pain or development of more severe signs or symptoms of DCS were designated as the endpoints of exposures and occurred in 309 (26.6%) of the chamber flights. Pain-only symptoms were present in 265 (85.8%) of these exposures. Of those, 261 (98.5%) met the criteria for GLO2 of onset of pain-only DCS at altitude with resolution during descent. Treatment was successful in 259 (98.5%) cases. Post treatment sequelae were not present after any of these treatments, and recurrence of symptoms was noted 2 times. No permanent injury is believed to have resulted from any of these exposures.

These data supports utilization of the GLO2 protocol for treating pain-only altitude DCS which resolves during descent in space operations. Although extravehicular activity (EVA) from the shuttle to date has yielded no reported cases of DCS, the DCS risk will rise with increased EVA associated with space station construction and operations. The availability of such a simple but effective protocol may provide an alternative to aborting a mission or depleting precious oxygen stores for a hyperbaric recompression. It is emphasized that the most effective treatment for DCS cases with signs and symptoms more severe than pain-only is hyperbaric recompression.



**HIGH ALTITUDE
PROTECTION FUNCTION**

Capt John T. Demboski, USAF

**SYSTEMS RESEARCH BRANCH
CREW TECHNOLOGY DIVISION
ARMSTRONG LABORATORY**

**The Effectiveness of Ground Level
Post-flight 100% Oxygen Breathing
as Therapy for Pain-only
Altitude Decompression Sickness**

John T. Demboski and Andrew A. Pilmanis

**ARMSTRONG LABORATORY
Brooks AFB, TX**

Purpose

Using data from the Armstrong Laboratory Hypobaric Decompression Sickness Research Database, assess the effectiveness of ground level post-flight 100% oxygen breathing (GLO2) in treating pain-only altitude DCS which resolved during descent.

PAIN-ONLY ALTITUDE DCS

- **Results from exposure to reduced atmospheric pressure**
Tissue gases reach supersaturation
Bubbles form exerting pressure on pain receptors
Characterized by constant pain, usually in the joints
- **May induce mission abort or manifest in more severe symptoms unless treated**
- **Treatment: recompression and bubble resolution**

Air Force Pamphlet 161-27

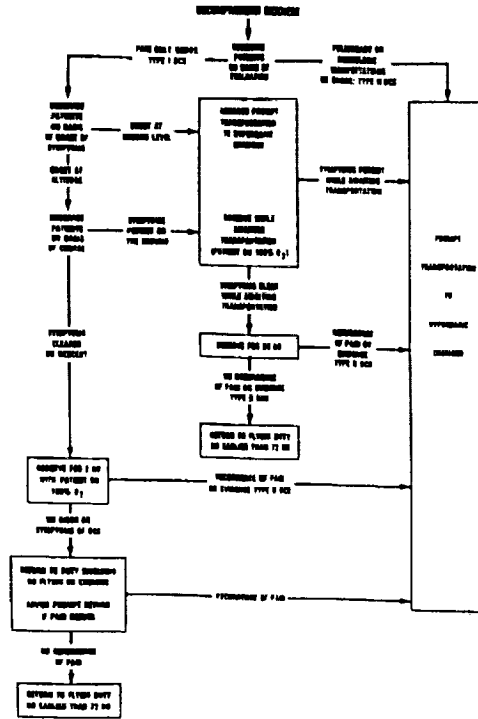
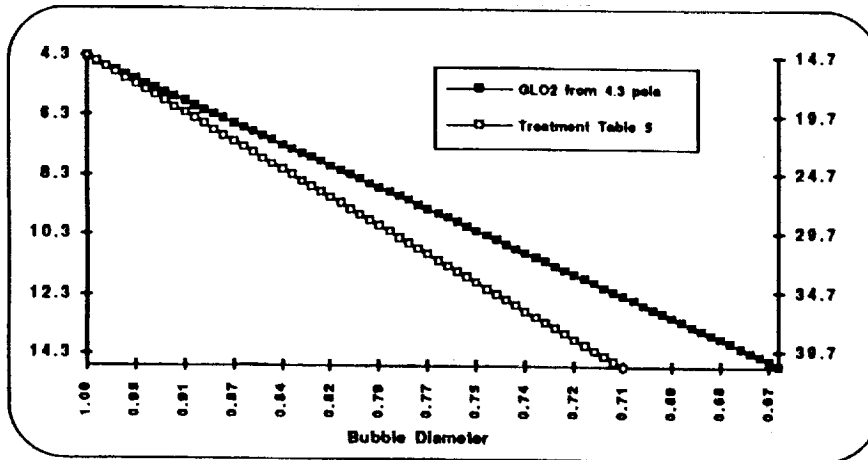


Figure 6-1. Diagram of Decision Points in Evaluating Decompression Sickness for Hyperbaric Treatment

BUBBLE RESOLUTION

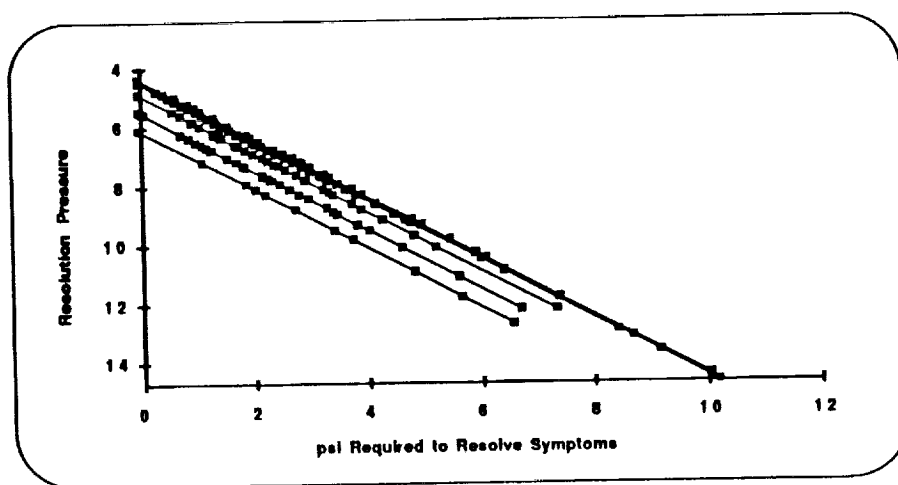


Exposure Pressure (psia)	4.4	4.5	4.9	5.5	6.1	7.8	TT5
Compression Ratio	3.4	3.3	3.0	2.7	2.4	1.9	2.8

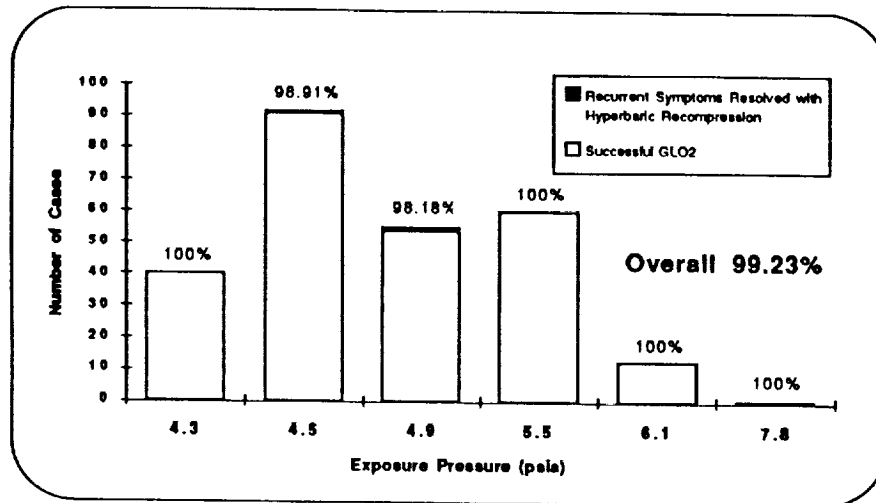
Distribution of DCS Cases

	Raw Data	Percent
Total Exposures	1163	
All DCS Cases	309	26.6%
Pain-only DCS	265	85.8%
Met GLO2 Criteria	261	98.5%

RESOLUTION OF CASES STUDIED



TREATMENT EFFECTIVENESS OF GLO2



CONCLUSION

GLO2 has proven 99.2% effective in treating pain-only altitude DCS which resolved during descent.

These data support the utilization of GLO2 therapy in space operations.

Emergency Medical Services

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Mr. Michael Chandler
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When NASA was established in 1958 it was known that space flight would require efforts beyond those of NASA to ensure the health and safety of our astronauts. On August 10, 1958, a Secretary of Defense memorandum was signed that assigned the first Department of Defense (DOD) Manager to provide support to NASA for Project Mercury. This established a chain of command through the Joint Chiefs of Staff to the Secretary of Defense. The current charter is dated March 19, 1986, and assigns the DOD Manager responsibilities to the Commander in Chief, United States Space Command. The DOD Managers charter has many support areas and among them are recovery of astronauts and medical support.

Today these efforts support the Space Shuttle and Space Station Programs. Briefly, the program works with each organization tasking the other through a requirements document. Level of care, communications, and recovery requirements are established; NASA and the DOD provide the capability to meet them. NASA is also responsible for the specialized training and equipment needed to meet these requirements.

A Shuttle launch at Kennedy Space Center (KSC) requires an Emergency Medical Services (EMS) coordinator on console to facilitate communications, ensure proper coverage, and coordinate with area hospitals. A contingent of NASA medical personnel are assembled to provide triage and medical support capabilities. The DOD provides medical evacuation (MEDEVAC) helicopters with surgeons and pararescue specialists (PJs) or emergency medical technicians (EMTs). Each helicopter is equipped with at least one doctor and one PJ/EMT per astronaut crew member. Transoceanic abort landing (TAL) sites and end of mission (EOM) sites have similar structures, with TAL sites utilizing fixed wing aircraft for MEDEVAC. The DOD also supports contingency planning for the support and return of crew members from the Space Station Freedom. Much of this support has been directed at the recovery of crew members following the landing of an Assured Crew Return Vehicle.

The EMS programs are expensive and would have been difficult for NASA to implement without DOD support. The DOD has gained valuable experience with deployments to areas such as Ben Guerir, Morocco, and Banjul, The Gambia. They have used this experience to improve their own military operations. This has also been the case with the operations at the Continental United States (CONUS) landing sites. Shuttle contingency exercises provide DOD personnel opportunities to participate in decontamination, triage, field medical care, and MEDEVAC simulations. This is often used to fulfill military training requirements and to provide the surgeons the opportunities to perform medical procedures in rotary and fixed wing aircraft.

The unique hazards associated with space flight and the Shuttle have also led to improvements in the capabilities of some DOD units. Support to the Shuttle Program requires that the surgeons be Advanced Cardiac Life Support (ACLS) and Advanced Trauma Life Support (ATLS) qualified, with refresher training every 4 years. A NASA Flight Surgeon Training Course is also required and taught at JSC. This course is taught to approximately 50 surgeons each year and provides the participants insight into the Shuttle operations and hazards, the JSC medical operations branch astronaut care program, and the NASA and DOD EMS system that is in place to support space flight. Both the military and NASA have benefited from this relationship.

Preliminary Health Survey Results from Over 250 High Flyer Pilots with Occupational Exposures to Altitudes Over 60,000 Feet

**Lt. Col. Roger U. Bisson
Maj. Michael Ainscough
Armstrong Laboratory
Brooks AFB, TX**

High Flyer Health Survey

Decompression Sickness Workshop - 1990

- ▶ **Review Pathophysiology Of DCS**
- ▶ **Evaluate Existing Options for Predicting DCS**
- ▶ **Defining Problems of DCS in Space**
- ▶ **Documenting Current Incidence of DCS in Aviation**
- ▶ **Discussing "Acceptable Risk" of Altitude DCS**
- ▶ **Listing Areas of Needed DCS Research**

**An Accurate Accounting Operational
Incidence of DCS Does Not Exist**

High Flyer Health Survey

DCS Survey - Beale AFB 1991

- ▶ 40 AD U-2/TR-1 Pilots (Anonymous)
- ▶ One or More Episodes Self-Diagnosed DCS
 - 57.5 - 65%
- ▶ Rates:
 - 4-5 % per mission
 - 8-9 % per 1000 hours exposure
- ▶ Reluctance to Report - Fear
 - Aeromedical Response
- ▶ Number 1 Occupational Health Concern
 - Exposure to Ionizing Radiation (75%)

High Flyer Health Survey

Occupational Health of U-2/TR-1 Pilots

- ▶ Decompression Sickness
 - Long Term Sequela Unknown
 - Musculoskeletal
 - CNS
- ▶ Ionizing Radiation
 - Long latency
 - Exposure Levels Unknown
 - Somatic (Cataracts)
 - Genetic (Neoplastic)
 - Teratogenic (Reproductive)

High Flyer Health Survey

Biological Effects of Radiation

- ▶ **Enzymatic Alterations**
- ▶ **DNA Strand Breaks**
- ▶ **Chromosomal Aberrations**

- ▶ **Technologically Enhanced Radiation**
 - ▶ **Linear Energy Transfer**
 - ▶ **Dose Rate**
 - ▶ **Environmental Factors**

High Flyer Health Survey

Cosmic Radiation

- ▶ **Galactic**
 - **Protons, Alpha particles, Heavy Nuclei**
 - **Secondary Ionizing Particles - 65,000 ft**
- ▶ **Solar**
 - **Protons, Alpha, Gamma**
 - **11-Year Cycle**
- ▶ **OSHA Standards (500 mrem/yr)**

High Flyer Health Survey

Regulation and Monitoring

- ▶ **High Flyer TLD/TED Dosimetry**
 - **SR-71 (1983): 1.04 mrem/hr**
 - **WB-57(1982): 0.9-1.5 mrem/hr**
 - **U-2 (1987): 1.48 mrem/hr**
 - **U-2 (1990): 0.5-0.6 mrem/hr**
- ▶ **Increasing Public Health Concern**
- ▶ **ICRP, NCRP, EPA, OSHA, FAA, USAF**

High Flyer Health Survey

Hammer - 1984

- 1. Formal designation of high flyers as occupationally exposed**
- 2. Monitoring of Cockpit Dose Rates**
- 3. Early Warning of Solar Flare Events**
- 4. Occupational Monitoring**
- 5. Personal Lifetime Dose Monitoring**
- 6. Life Long Surveillance**

High Flyer Health Survey

Study Design

- ▶ 16 Page Survey
 - General Health Demographic Data
 - Health Status Review
 - DCS Survey
- ▶ Cohort: 503 U-2/TR-1 Pilots
- ▶ Addresses: 416
- ▶ Response: 269 Returned/36 Deceased
 - ▶ 73 Percent Response rate

High Flyer Health Survey Preliminary Results

Demographic Data

- ▶ Mean Age: 50 yrs
 - 27% over age 60
 - 72% Retired; 28% Active Duty
 - 7.7% Medically Retired/Partial Disability
- ▶ AF Flight Time: 4390 hrs
- ▶ High Fly (U-2/TR-1): 1028 hrs
- ▶ Missions: 144 (59% > 100)
- ▶ FL250 Exposure: 701 hrs

High Flyer Health Survey Preliminary Results

Demographic Data

- ▶ **General Health**
 - Good to Excellent: 94%
 - Retirees: Fair (3.7%) Poor (1.5%)
- ▶ **Diet**
 - Low Cholesterol: 30%
- ▶ **Tobacco:** 10-12% continue (50%users)
- ▶ **Alcohol:** 84% (4.6 beers/5.3 mixed/wk)

High Flyer Health Survey Preliminary Results

Medical History

- ▶ **Regular/Continuing Doctor's Care**
 - 23%
- ▶ **Medications**
 - 27% (Regularly take 1 or more meds)
 - 7% (3 or more medications daily)
- ▶ **Surgeries**
 - 55.4% (One or more surgeries)
- ▶ **History of malignancy - 28.5%**

High Flyer Health Survey Preliminary Results

Problems with Eyes or Vision N = 267

Hx Eye Probs	Cataracts	Glaucoma
10.9%	2.6%	4.1%

Problems with Ears or Hearing

Hx Ear Probs	HFHL	Disequilib
31.1%	26.6%	3 - 5%

Sinuses, Mouth, Throat

Hx of ENT	Sinusitis	Oral CA
25.1%	9.4%	1.5%

High Flyer Health Survey Preliminary Results

Heart and Circulatory System N = 267

Any Heart	42.7%	114
Hypercholesterolemia	31.8%	85
Hypertension	12.4%	33
Coronary Bypass	3.4%	9
Stroke/CVA	1.5%	4
Myocardial Infarction	1.5%	4
Valvular Disease	0.7%	2
Congestive Failure	0.4%	1
Other Heart	3.4%	9

High Flyer Health Survey Preliminary Results

N = 267

Pulmonary/Lung

Any Lung Probs	7.5%	20
COPD	4.5%	12
Lung Cancer	1.1%	3
Tuberculosis	0.7%	2
Freq Pneumonia	0.4%	1
Other Lung	1.1%	3

High Flyer Health Survey Preliminary Results

N = 267

Gastrointestinal

Any GI Probs	18.4%	49
Gastritis/Heartburn	6.0%	16
Ulcer Disease	3.7%	10
Gallbladder Dz	2.6%	7
Hepatitis	2.6%	7
Polyposis	1.9%	5
Colon/Rectal CA	1.5%	4
Liver CA	0.4%	1
Other GI	4.1%	11

High Flyer Health Survey Preliminary Results

N = 267

Renal/Kidney Problems

Any Hx of Kidney Dz	9.7%	26
Kidney Stones	6.7%	18
Hematuria	3.4%	9
Renal Tumor	0.4%	1
Glomerulonephritis	0.4%	1
Other Kidney	0%	0

High Flyer Health Survey Preliminary Results

N = 267

Hematopoietic/Metabolic

Tumor of Lymph Nodes or Glands	1.1%	3
Leukemia	0.4%	1
Thyroid CA	0.4%	1
Hodgkin's	0.0%	0

High Flyer Health Survey Preliminary Results

N = 267

Bones, Joints, Muscles

Any Musculoskeletal	44.2%	118
Back/Disk Problems	26.6%	71
Arthritis	19.5%	52
Pain/Tremors of Hands	4.9%	13
Progressive Weakness	3.4%	9
Other M-S Problems	7.5%	20

High Flyer Health Survey Preliminary Results

Neurologic/Psychologic

N = 267

Any Hx Neuropsych	10.9%	29
Numbness/Tingling	3.7%	10
Memory Loss	1.5%	4
Paralytic Symptoms	1.5%	4
Fainting Spells	1.1%	3
Slurred Speech	1.1%	3
Seizures	0.7%	2
Depression/Anxiety	0.7%	2
Other N-P Probs	1.1%	3

High Flyer Health Survey Preliminary Results

Skin

N = 267

Any Skin Problems	28.8%	77
Basal Cell Carcinoma	8.6%	23
Eczema/Psoriasis	5.6%	15
Frequent Rashes	5.2%	14
Melanoma	3.7%	10
Squamous Cell CA	2.2%	6
Other Skin	9.4%	25

High Flyer Health Survey Preliminary Results

DCS

N = 232

	Percent	Pilots	Events
Limb/Joint Pain	64.7%	150	1520
Headaches	29.4%	68	73
Skin Manifestation	19.4%	45	278
Inappropriate Fatigue	17.0%	39	424
Cognitive Problems	10.4%	24	123
CNS Sensory/Motor	3.0%	7	8

High Flyer Health Survey

Discussion

- ▶ **Sample Size**
 - **False Reassurance**
- ▶ **Incomplete Exposure Data**
 - **Dosimetry, Latitudes, Solar Flare Activity**
- ▶ **Duration of Exposure**
- ▶ **Multiple End Points**
- ▶ **Long latency**
- ▶ **Recall Bias, Incomplete recall, non-response**

High Flyer Health Survey

Forecast??

Conclusion

Session L3: TELEMEDICINE

Session Chair: Dr. Gerald Taylor

Quantitative 3-D Imaging Topogrammetry for Telemedicine Applications

Col. (Dr.) Bruce R. Altschuler, USAF
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Meade, MD 20755

The technology to reliably transmit high-resolution visual imagery over short to medium distances in real time has led to the serious consideration of the use of telemedicine, telepresence, and telerobotics in the delivery of health care. These concepts may involve, and evolve toward: consultation from remote expert teaching centers; diagnosis; triage; real-time remote advice to the surgeon; and real-time remote surgical instrument manipulation (telerobotics with virtual reality). Further extrapolation leads to teledesign and telereplication of spare surgical parts through quantitative teleimaging of 3-D surfaces tied to CAD/CAM devices and an artificially intelligent archival data base of "normal" shapes. The ability to generate "topograms" or 3-D surface numerical tables of coordinate values capable of creating computer-generated virtual holographic-like displays, machine part replication, and statistical diagnostic shape assessment is critical to the progression of telemedicine. Any virtual reality simulation will remain in "video-game" realm until realistic dimensional and spatial relational inputs from real measurements *in vivo* during surgeries are added to an ever-growing statistical data archive. The challenges of managing and interpreting this 3-D data base, which would include radiographic and surface quantitative data, are considerable. As technology drives toward dynamic and continuous 3-D surface measurements, presenting millions of X,Y,Z data points per second of flexing, stretching, moving human organs, the knowledge base and interpretive capabilities of "brilliant robots" to work as a surgeon's tireless assistants becomes imaginable. The brilliant robot would "see" what the surgeon sees – and more, for the robot could quantify (measure) its 3-D sensing and would "see" in a wider spectral range than humans, and could zoom its "eyes" from the macro world to long-distance microscopy. Unerring robot hands could rapidly perform machine-aided suturing with precision micro-sewing machines, splice neural connections with laser welds, micro-bore through constricted vessels, and computer combine ultrasound, microradiography, and 3-D mini-borescopes to quickly assess and trace vascular problems *in situ*. The spatial relationships between organs, robotic arms, and end-effector diagnostic, manipulative, and surgical instruments would be constantly monitored by the robot "brain" using inputs from its multiple 3-D quantitative "eyes" remote sensing, as well as by contact and proximity force measuring devices. Methods to create accurate and quantitative 3-D topograms at continuous video data rates are described.

IMIS - An Intelligence Microscope Imaging System

**Michael Caputo
Norwood Hunter**
KRUG Life Sciences Inc.
Houston, TX

Gerald Taylor
NASA Johnson Space Center
Houston, TX

Until recently, microscope users in space relied on traditional microscopy techniques that required manual operation of the microscope and recording of observations in the form of written notes, drawings, or photographs. This method was time consuming and required the return of film and drawings from space for analysis. No real-time data analysis was possible.

Advances in digital and video technologies along with recent developments in article intelligence will allow future space microscopists to have a choice of three additional modes of microscopy: remote coaching, remote control, and automation. Remote coaching requires manual operation of the microscope with instructions given by two-way audio/video transmission during critical phases of the experiment. When using the remote mode of microscopy, the Principal Investigator controls the microscope from the ground. The automated mode employs artificial intelligence to control microscope functions and is the only mode that can be operated in the other three modes as well.

The purpose of this presentation is to discuss the advantages and disadvantages of the four modes of microscopy and how the IMIS, a proposed intelligent microscope imaging system, can be used as a model for developing and testing the concepts, operating procedures, and equipment design of specifications required to provide a comprehensive microscopy/imaging capability onboard Space Station Freedom.

**The Portable Dynamic Fundus Instrument:
Uses in Telemedicine and Research**

**Norwood Hunter
Michael Caputo**
KRUG Life Sciences Inc.
Houston, TX

**Roger Billica
Gerald Taylor**
NASA Johnson Space Center
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**C. Robert Gibson
F. Keith Manuel**
St. John Eye Associates
Nassau Bay, TX

Thomas Mader
Madigan Army Medical Center
Tacoma, WA

Richard Meehan
University of Colorado
Denver, CO

For years ophthalmic photographs have been used to track the progression of many ocular diseases such as macular degeneration and glaucoma as well as the ocular manifestations of diabetes, hypertension, and hypoxia. In 1987 a project was initiated at the Johnson Space Center (JSC) to develop a means of monitoring retinal vascular caliber and intracranial pressure during space flight.

To conduct telemedicine during space flight operations, retinal images would require real-time transmission from space. Film-based images would not be useful during in-flight operations. Video technology is beneficial in flight because the images may be acquired, recorded, and transmitted to the ground for rapid computer digital image processing and analysis. The computer analysis techniques developed for this project detected vessel caliber changes as small as 3%.

In the field of telemedicine, the Portable Dynamic Fundus Instrument demonstrates the concept and utility of a small, self-contained video funduscope. It was used to record retinal images during the Gulf War and to transmit retinal images from the Space Shuttle Columbia during STS-50. There are plans to utilize this device to provide a mobile ophthalmic screening service in rural Texas. In the fall of 1993 a medical team in Boulder, Colorado, will transmit real-time images of the retina during a normal ocular examination and during fluorescein angiography to a medical team at JSC for remote consultation and diagnosis.

The research applications of this device include the capability of operating in remote locations or small, confined test areas. There has been interest shown in utilizing retinal imaging during high-G centrifuge tests, high-altitude chamber tests, and aircraft flight tests. A new design plan has been developed to incorporate the video instrumentation into a face-mounted goggle. This design would eliminate head restraint devices, thus allowing full maneuverability to the subjects. Further development of software programs will broaden the application of the Portable Dynamic Fundus Instrument in telemedicine and medical research.

Technical Parameters for Specifying Imagery Requirements

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Providing visual information acquired from remote events to various operators, researchers, and practitioners has become progressively more important as the application of special skills in alien or hazardous situations increases. The impracticability of providing expert care or procedure is overcome by bringing appropriate visual information to a specialist who is then able to effect the required resolution either through a surrogate executor or through a remote control system. In either case, the visual information feedback is critically important to a successful outcome. Tele-imaging systems provide this visual information.

Certain imaging systems also provide visual imagery for general information purposes and for entertainment. Too often image requirements for these two types of imaging systems (technical and nontechnical) are discussed within the same forum without considering the specific application. Confusion or, at best, compromises in specifying image requirements often result. This situation is particularly significant because the same groups and often the same systems used to produce the esthetic category of imagery are also used to produce what is believed to be scientific or technical data. To ensure accurate, meaningful visual data, the image user must identify the pertinent characteristics of the information required for the application. All subsystems and technical operations personnel along the signal transmission and reproduction channel must be informed of the required characteristics, and all variables must be carefully controlled.

To provide an understanding of the technical parameters required to specify imagery, we have identified, defined, and discussed seven salient characteristics of images: spatial resolution, linearity, luminance resolution, spectral discrimination, and temporal discrimination, edge definition, and signal-to-noise ratio.

We then described a generalizing imaging system and identified how various parts of the system affect the image data. To emphasize the different applications of imagery, we have contrasted the common television system with the significant parameters of a televisual imaging system for technical applications.

Finally, we have established a method by which the required visual information can be specified by describing certain technical parameters which are directly related to the information content of the imagery. This method requires the user to complete a form listing all pertinent data requirements for the imagery.

Session L4: THERMAL STRESS

Session Chair: Col. Gerald Krueger

PERSONAL COOLING SYSTEMS: POSSIBILITIES AND LIMITATIONS

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Personal thermal control by means of gas- or liquid-conditioned garments was developed during the 1960s and has been applied in a variety of aerospace and industrial settings. Both USAF fighter pilots and astronauts are required to wear heavy protective clothing which insulates them from the environment and thus creates stress through storage of metabolic heat. The problem is particularly severe in astronauts who perform heavy physical work during EVA; without artificial cooling they could reach incapacitating hyperthermia in a matter of minutes.

This paper reviews the factors which influence the design of personal cooling systems. An important early step is determination of acceptable heat stress level, taking into account possible interactions of heat stress with other physiological problems such as motion sickness, diminished plasma volume, decompression sickness and acceleration tolerance. Other factors which require consideration include the work schedule, the area to be covered by the cooling garment, and the practicalities of a fixed or body-mounted heat sink and its power source. Nearly every imaginable heat sink has been proposed or tried over the past 30 years, including direct gas systems, phase-change systems with open or closed loops and thermoelectric heat sinks. The latter are now the system of choice for aircraft.

It appears that personal conditioning requirements for the space station may vary widely. Astronauts performing physical work inside the station may benefit from ventilated garments over the torso or the entire body, thus providing comfort and evaporating sweat without the need to cool and ventilate the entire compartment. On the other hand, a heated suit may be useful aboard the station to improve denitrogenation and thus prevent decompression sickness. With the advent of prolonged, complex extravehicular activity, the liquid cooled garments worn under the space suit may require automated control systems, segmental control and a capability to provide heating, especially to the hands and feet. Many of these options have already been explored in work done during the 1970s, making it possible to develop new applications from an existing base of experience.

MODELING HEAT EXCHANGE CHARACTERISTICS OF LONG TERM SPACE OPERATIONS: ROLE OF SKIN WETTEDNESS AND EXERCISE

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ABSTRACT

The problems of heat exchange during rest and exercise during long term space operations are covered in this report. Particular attention is given to the modeling and description of the consequences of requirements to exercise in a zero-g atmosphere during Space Shuttle flights, especially long term ones. In space environments, there exists no free convection therefore only forced convection occurring by movement, such as pedalling on a cycle ergometer, augments required heat dissipation necessary to regulate body temperature. The requirement to exercise at discrete periods of the day is a good practice in order to resist the deleterious consequences of zero-gravity problems and improve distribution of body fluids. However, during exercise (ca. 180 to 250W), in zero-g environments, the mass of eccrine sweating rests as sheets on the skin surface and the sweat cannot evaporate readily. The use of exercise suits with fabrics that have hydrophobic or outwicking properties somewhat distributes the mass of sweat to a larger surface from which to evaporate. However, with no free convection, increased skin wettedness throughout the body surface induces increasing thermal discomfort, particularly during continuous exercise. This report presents several alternatives to aid in this problem: use of intermittent exercise, methods to quantify local skin wettedness, and introduction of a new effective temperature that integrates thermal stress and heat exchange avenues in a zero-g atmosphere.

INTRODUCTION

The general heat balance equation (in $W \cdot m^{-2}$) associated with physiological responses to any thermal environment, including Space Shuttle astronauts and those exercising in zero gravity, can be expressed by

$$S = M - W - E - (R + C) \quad (1)$$

where:

S = the time rate of change of body heat

M = the rate on metabolic heat production

W = the rate of accomplished mechanical work

E = the rate of evaporative heat loss via sweating from eccrine sweat glands, diffusion, and respiration

C = the rate of convective heat loss from the total body surface and respiration

R = the rate of radiant heat loss (or gain from) the surrounding surfaces

Radiation Exchange:

In any space environment, a linear radiation transfer coefficient may be derived (6, 9) by

$$h_r = 4 \cdot (0.72) \cdot (5.67 \times 10^{-8}) \left[(T_o + T_{surf}) / 2 + 273.15 \right]^3, \text{W} \cdot \text{m}^{-2} \cdot \text{C}^{-1} \quad (2)$$

where the factor 0.72 represents the ratio of the effective radiating area of the human body to the total body surface area, as measured by the Dubois surface area formula. The interior environmental temperature is composed of an average of the operative temperature + all the surface temperatures (T_{surf}); the constant (5.67×10^{-8} , in $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$) is the Stefan-Boltzmann constant.

Convective exchange:

Under zero gravity, as present in a Space Shuttle flight, there is no free convection and the only means of generating a forced convection is by increased metabolic activity or increased room air movement artificially (1, 11). Two equations for estimating the convective heat transfer coefficient have been formulated based on a composite of free and forced convection (9). For still room air in which the convective heat exchange is generated mainly by increased metabolic activity

$$h_c = 1.2 \left[(M - 50) (P_B/760) \right]^{0.39}, \text{W} \cdot \text{m}^{-2} \cdot \text{C}^{-1} \quad (3)$$

where M is the metabolic activity in watts/sq. m and P_B is the barometric pressure in Torr. Alternatively, h_c for fan generated forced convection, in which ambient air movement (V , $\text{m} \cdot \text{s}^{-1}$) is the main factor affecting convective heat exchange can be expressed by either (h_c in $\text{W} \cdot \text{m}^{-2} \cdot \text{C}^{-1}$)

$$h_c = 8.6 \left[V \cdot P_B/760 \right]^{0.53} \quad (4)$$

when persons are dressed in shorts and T-shirts or by

$$h_c = 12.7 \left[V \cdot P_B/760 \right]^{0.50} \quad (4')$$

when persons are clothed in general purpose work clothing (9).

THERMAL ENVIRONMENT OF A SPACE SHUTTLE

The heat balance in a Space Shuttle may be described in a graphical format in terms of two independent gradients : Operative temperature (T_o) in the interior space and ambient water vapor pressure (P_a) requiring only an adequate calculation of convective, radiative (h') and evaporative heat transfer coefficients (h'_e) affected by clothing factors, the Lewis relation, and knowledge of net heat flux (H_{sk}) through the skin surface (3,6,8,9). H_{sk} may be determined from metabolism (M), less work level (Wk), less respired, evaporative (E_{res}) and convective (C_{res}) heat losses, and any incurred heat storage (S) (all in $\text{W} \cdot \text{m}^{-2}$).

This relationship is shown in eq (1) for thermal equilibrium conditions in exercising persons as:

$$(P_a - P_{s,sk}) = -h'/(wh'_e) \cdot [T_o - (\bar{T}_{sk} - H_{sk}/h')] \quad [\text{Torr}] \quad (5)$$

The ratio h'/h'_e or Ψ is the effective combined physical heat transfer characteristic of the Space Shuttle environment that incorporates all sensible and insensible heat exchange coefficients (9,11). $P_{s,sk}$ is the skin saturation vapor pressure (Torr) and w is the skin wettedness, the fraction of the skin surface that is enveloped by a layer of thermoregulatory sweat. Skin wettedness has been classically described by Gagge (5) as being equivalent to the ratio of evaporative heat loss (E_{sk}) to maximum evaporation possible (E_{max}).

CHALLENGE TO THE HEAT BALANCE EQUATION

The theoretical bases of the above heat balance can be characterized on a psychrometric chart in which ambient water vapor pressure is depicted on the y-axis and dry bulb temperature is on the x-axis. The use of a graphical description allows facile assessment of thermal limits for a given work level that a astronaut might employ during his/her daily exercise within the interior of a shuttle craft. Any of the dependent physiological variables affected by or governing heat exchange such as skin temperature (\bar{T}_{sk}), skin wettedness (w) due to regulatory sweating, internal body temperature or skin blood flow (SkBF) can be displayed (3,8).

The critical parameter, $(\bar{T}_{sk} - H_{sk}/h')$, present in eq (5) can be further described in terms of a transient factor, T_{act} , ($^{\circ}\text{C}$) which accounts for the magnitude and level of rate of heat storage as sweat glands are impeded by continual level of hypo-hydration. Equation 5 could also be expressed by

$$-\frac{\Psi}{w} = \frac{\Phi_a P_t - P_{ssk}}{T_o - T_{act}} \quad (5')$$

where $\Phi_a P_t$ is the ambient relative humidity (as a fraction) times the saturation pressure of the ambient temperature.

Figure 1 illustrates these concepts further. In this figure, a given environmental condition (e.g. the operating point, OP) is composed of a distinct dry bulb temperature and relative humidity (Φ_a) or ambient water vapor pressure (P_a). A common point, CP is always formulated by a distinct locus on the x-axis composed of T_{act} and the y-axis, composed of $P_{s,sk}$. The slope of the line connecting OP and CP has the value of the ratio $-h'/(wh'e_c$ or $-\Psi/w$ (in $^{\circ}\text{C}/\text{Torr}$) which represents a unique parameter of the sensible to evaporative heat exchange coefficients of the Space Shuttle environment. T_{act} is a derived, theoretical temperature at which all heat dissipation would occur by dry (sensible) heat exchange alone. The term, H_{sk} , is that component of the final sensible and insensible heat flux arriving at the skin surface that must be dissipated to the environment.

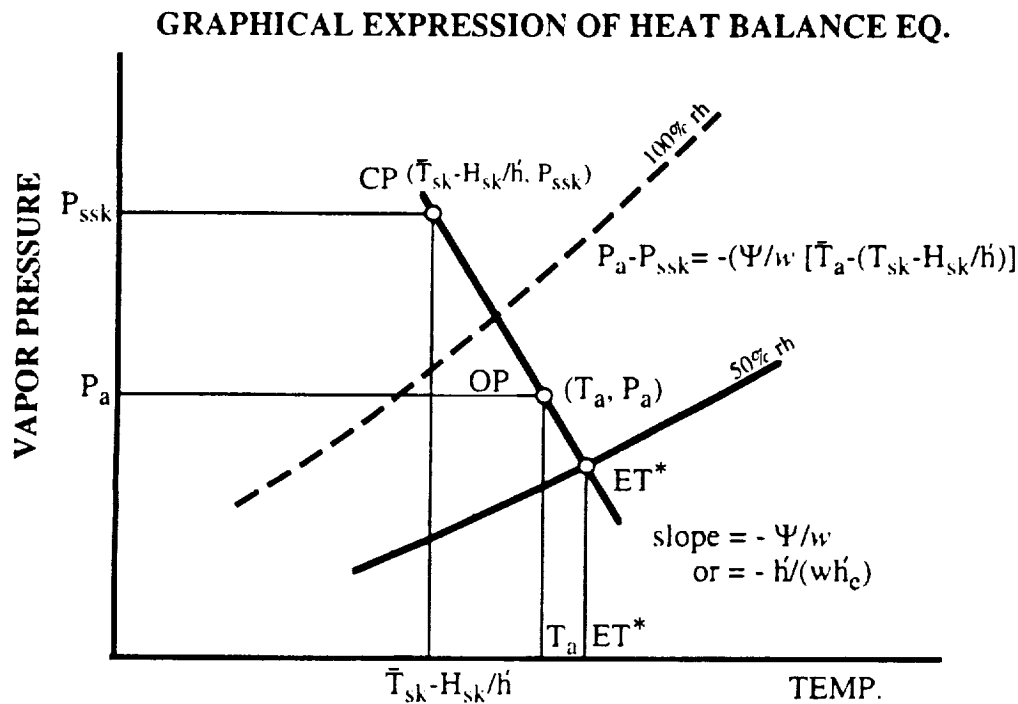


Figure 1. Graphical description of heat balance equation and ET* in a Space Shuttle environment.

The intersection of the CP-OP lines along the 100% saturation line (100% rh) of the psychrometric chart represents the humid operative temperature (T_{oh}).

Since humans recognize the effect of a humidity on perceived thermal discomfort, a new Effective Temperature (ET*) described by dry bulb temperature in which the intersection of the CP-OP line intersects the 50 % rh line (Figure 1) has better meaning by which to integrate heat stress of the environment to physiological responses. This ET* ($^{\circ}\text{C}$) may be determined analytically by

$$ET^* = T_o - \frac{(P_a - 0.5P_{ET^*})}{(-\Psi/w)} \quad (6)$$

This displacement of heat balance can readily be expressed graphically on a psychrometric chart or illustrated graphically in real time (e.g. on a PC-VDT of a shuttle craft) in which P_a is placed on the y-axis and operative temperature (e.g. $T_o \approx T_a = T_{wall}$ of the shuttle) is shown on the x-axis. Towards the right x-axis of operative temperature, level of heat storage, if any, is expressed by Gain = $(T_{act} + \Delta T_{stor})$ and may be also quantified by

$$\Delta T_{stor} = (\Delta \bar{T}_b / \Delta t) \cdot [(0.97 \cdot m_b) / A_D] / h', \quad ^\circ\text{C} \quad (7)$$

where $(\Delta \bar{T}_b / \Delta t)$ is the rate of change of core and skin temperatures (weighted as a mean body temperature, \bar{T}_b per time in hours), 0.97 is the body specific heat constant ($\text{W} \cdot \text{h} \cdot \text{kg}^{-1} \cdot ^\circ\text{C}^{-1}$) and m_b is sea-level body weight (kg), and A_D is Dubois surface area (m^2). This Gain concept has been used adequately before to express effects of atropine treatment during exercise in warm environments by Kolka et.al. (8).

EXERCISE IN A SPACE SHUTTLE

Table I is a simulation of the probable heat balance in an environment of 27°C and $P_a = 21$ Torr (80 F/ 70 % rh) that would be the anticipated maximum for any Space Shuttle environment (1, 11). In this simulation a typical 60 min bout of exercise at 180 watts ($\dot{V}_{O_2} \approx 2.6$ L/min) was considered.

Table I. Typical Space Shuttle Exercise Bout.

Exercise	% VO2 Max	M (1)	Wk (2)	T_a ($^\circ\text{C}$)	P_a (Torr)	T_{es}	\bar{T}_{sk}	\dot{m}_{sw} (3)	skin wetted- ness (%)	ET^* ($^\circ\text{C}$)
A	65	480	96.4	27	21	38.0	32	15.45	>100	42
B	32	240	40.0	27	21	37.3	33	8.12	88	36

Simulation assumes an Astronaut has a $\dot{V}_{O_2} \text{ max} = 4.0$ L/min; $A_D = 1.9$ m^2 ; shorts + T shirt; forced convection with $h_c = 5.5$ $\text{W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$ using equation 4. Units for : 1) & 2) in $\text{W} \cdot \text{m}^{-2}$; 3) in g/min.

As shown in Table I (A), assuming that this astronaut exhibits a maximum aerobic power of 4.0 L/min and a 1.9 m^2 surface area, the intensity is about 65 % $\dot{V}_{O_2} \text{ max}$ or around 8 met (1 met = 100 watts). Table I assumes that the rate of heat storage S at most is no greater than 10% of M. The essential part of the simulation is that the rate of body weight loss due to thermoregulatory sweating of some 15.45 g/min would be developed in this

environment in the which the maximum evaporative capacity of the Space Shuttle is $174 \text{ W}\cdot\text{m}^{-2}$. In these circumstances, the predicted skin wettedness would become greater than 100%. Under zero-g at the ambient water vapor pressure given above, such an amount of sweating will likely create a sheeting layer appearing on the skin surface as documented by many astronauts (Dr James Bagian, personal communication 1992).

Alternatively, a simulation based on one-half the work intensity as shown in Table I (B), or roughly 32 % \dot{V}_{O_2} max indicates that the rate of body weight loss due to sweating would be about 8 g/min with a likely skin wettedness of some 80%. In the zero-g of the Shuttle, this amount of sweat would probably create a thinner sheeting layer appearing on the skin surface and would be more acceptable to crewmembers. Based on the formulation of ET^* described in this report, the simulation also predicts that the ET^* during exercise bout (A) would be about 42°C whereas during exercise (B), the ET^* would be about 36°C , or result in a 6°C downward shift in overall thermal strain.

Obviously, any relief in zero-g atmospheres when there exists anterior fluid displacements and congestion of the head during various sojourns in Space Shuttle flights can be facilitated by exercise which has been documented repeatedly (11). However, there should be an optimum exercise intensity to prevent salt and fluid imbalance leading to hypo-hydration (see paper by Sawka et. al. in this symposium). Perhaps intermittent work at 3 min of 65 % \dot{V}_{O_2} max coupled with 3 min of free pedalling would be a more suitable option instead of continuous exercise for 60 minutes.

LOCAL SKIN WETTEDNESS IN SPACE SHUTTLE

One parameter that has never been fully experimented upon is the actual measurement of local skin wettedness during space flight. The above simulation only covered effects due to total body skin wettedness. However, it is known that the level of skin evaporation often remains constant as ambient water vapor rises (3). Local skin wettedness, alternatively, at various skin sites undoubtedly increases in a less regular manner since the skin dew point temperature and convective heat transfer are variable throughout the human body sites (2). The result is that the skin surface wetted area may become increasingly larger than predicted from estimates of whole body $E_{\text{sk}}/E_{\text{max}}$ to facilitate evaporation of water. The development of a small resistance type dew point sensor (7) allows the direct measurement of skin relative humidity. This has permitted the combining of theoretical concepts by which calculation of local regional water loss (\dot{m}_{sw} , $\text{mg}\cdot\text{cm}^{-2}\cdot\text{min}^{-1}$) from specific skin areas may be quantified. There is evidence that local skin wettedness is physiologically adjusted as an efferent drive from the central nervous system to provide the required rate of evaporation (6, 8). How all these physiological and physical factors inter-relate in the absence of gravity environments is not known at present and should prove a fruitful source of research.

CONCLUSION

An effective temperature index (ET^*), which assesses both dry heat stress and humid heat stress in terms of observed heat exchange may be derived for any given exercise intensity. This ET^* is defined as the dry bulb temperature (T_a) at 50% rh in which total heat exchange from the skin surface is the same as in the actual indoor Space Shuttle environment, described by T_a and P_a and movement by the individual. A means to characterize the thermal environment in a Space Shuttle by use of a rational effective temperature (ET^*) may therefore allow a better integration of human heat balance, rate of heat storage, and local and total skin

wettedness during exercise at zero-g environments.

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HYDRATION AND BLOOD VOLUME EFFECTS ON HUMAN
THERMOREGULATION IN THE HEAT: SPACE APPLICATIONS

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ABSTRACT

Astronauts exposed to prolonged weightlessness will experience deconditioning, dehydration and hypovolemia which all adversely affect thermoregulation. These thermoregulatory problems can be minimized by several countermeasures that manipulate body water and vascular volumes. USARIEM scientists have extensively studied dehydration effects and several possible countermeasures including hyperhydration, plasma and erythrocyte volume expansion. This paper reviews USARIEM research into these areas.

INTRODUCTION

Space physiologists have an interest in thermoregulation because astronauts must perform strenuous exercise (~250 watts during space shuttle extravehicular activities (EVA) and probably higher during space station construction) that could be limited by thermal strain (5). This may be a particular problem during space station construction and habitation, because prolonged weightlessness will cause deconditioning, reduced blood volume and dehydration. All of these factors will adversely affect the astronaut's ability to thermoregulate during exercise-heat stress. In addition, EVA missions during space station construction might require astronauts to exercise at barometric pressures reduced to equivalent altitudes of 914 to 1524 meters. These lowered barometric pressures could also adversely influence thermoregulation.

This paper reviews USARIEM (and other selected) research concerning hydration and blood volume effects on human thermoregulation. This review has direct application for development of approaches to maintain thermoregulatory and exercise capabilities during prolonged human presence in space.

TEMPERATURE REGULATION

Physical exercise will routinely increase body metabolism by 3-10 times the resting rate to provide energy for skeletal muscle contraction, and most (70% and 100%) of the metabolic rate results in heat which must be dissipated to restore body heat balance. Depending on environmental temperature, the relative contributions of evaporative and dry (radiative and conductive) heat exchange to the total heat loss vary. The hotter the environment the greater the dependence on evaporative heat loss, and thus on sweating. Therefore, in hot environments, a considerable amount of body water can be lost through

sweat gland secretion to enable evaporative cooling of the body.

During exercise in the heat, thermoregulatory responses are primarily influenced by a person's heat acclimation state, aerobic fitness and hydration level. Heat acclimated persons, who are aerobically fit and fully hydrated, will have less heat storage and optimal performance. Hydration level is particularly important during exercise in the heat because a body water deficit will neutralize the thermoregulatory advantages of heat acclimation and high aerobic fitness (1,28).

DEHYDRATION

During physical exercise in the heat, it is a problem to closely match the volume of fluid intake to the volume of sweat output. This is a difficult problem to solve because thirst does not provide a good index of body water requirements (4,13). It is not uncommon for individuals to "voluntarily" dehydrate by 2-8% of their body weight during exercise-heat stress, despite the availability of adequate amounts of fluid to rehydrate.

Sweat loss results in a reduction of total body water if an adequate amount of fluid is not consumed. As a consequence of free-fluid exchange, dehydration will affect each fluid space within the body. At low volumes of body water loss, the water deficit primarily comes from the extracellular space; however, as the body water loss increases, a proportionately greater percentage of the water deficit comes from the intracellular space (3). Regardless, dehydration from sweat loss will result in an increased plasma osmolality with a decreased blood volume (22).

Generally, loss of body water impairs aerobic exercise performance in the heat; and the warmer the environment, the greater the adverse effect of dehydration (22). In comparison to euhydration, a water deficit of as little as 1% of body weight increases core temperature during exercise in both comfortable and hot environments, and the greater the water deficit, the greater is the elevation of core temperature during exercise (15,30). Dehydration impairs both dry and evaporative heat loss (22). In addition, dehydration causes exhaustion from heat strain to occur at lower core temperatures during exercise-heat stress (31).

Dehydration may be associated with either reduced or unchanged sweating rates at a given metabolic rate in the heat. However, even when dehydration is associated with no change in sweating rate, core temperature is usually elevated, so that sweating rate for a given core temperature during dehydration is still lower. The physiological mechanisms mediating the reduced sweating rate during dehydration are not clearly defined, but both the separate and combined effects of plasma hyperosmolality and hypovolemia play a part (7,8,25).

Dehydration affects cardiovascular responses to exercise-heat stress. During submaximal exercise with moderate to severe thermal strain (15,18), dehydration increases

heart rate and decreases stroke volume and cardiac output relative to euhydration. Dehydration also reduces cutaneous blood flow for a given core temperature (6,7,18), and therefore the potential for dry heat exchange. Likewise, hyperosmolality, in the absence of hypovolemia, can also reduce the cutaneous blood flow response during exercise-heat stress.

In addition to the effects of dehydration on thermoregulatory responses, USARIEM scientists have examined the effects of dehydration on hormonal (9,10), muscle glycogen (19), immunological (29), gastric emptying (20) and vascular volume (24) responses during exercise-heat exposure. USARIEM scientists continue to have an active program studying dehydration effects in hot environments.

HYPERHYDRATION / HYPERVOLEMIA

If dehydration reduces performance during exercise-heat stress, can excess body fluids improve performance beyond the levels achieved when euhydrated? Moroff and Bass (17) examined the influence of excessive fluid ingestion on thermoregulatory responses during exercise in the heat. They reported that hyperhydration decreases core temperature, while increasing sweating rates above control levels. During the control experiments, however, their subjects were slightly (greater than 1%) dehydrated. Therefore, these results may demonstrate the effects of dehydration rather than hyperhydration. In addition, Nielsen and colleagues (21) reported lower core temperatures during exercise in subjects who were hyperhydrated with 1.5 liters of water; however, they did not employ a euhydration control experiment. In contrast, Grucza and colleagues (12) reported that water hyperhydration will reduce core temperature responses during exercise in a temperate environment.

Several well controlled studies have not observed any thermoregulatory benefits from water hyperhydration. Greenleaf and Castle (11) reported that excessive water ingestion did not alter core temperature or sweating rate from control levels during exercise in the heat. Nadel et al. (18) hyperhydrated subjects by administering antidiuretic hormone and water. They did not find any significant improvements in thermoregulation from hyperhydration.

Recently, Lyons et al. (14) reported that glycerol-induced hyperhydration had a marked thermoregulatory advantage during an exercise-heat stress. They reported increases in sweating rate and substantial reductions in core temperature during the glycerol-induced hyperhydration compared to hyperhydration with water. Subsequent studies from their laboratory have reported no thermoregulatory improvements with glycerol hyperhydration (16). USARIEM has recently initiated a comprehensive research program on glycerol hyperhydration and temperature regulation.

If hyperhydration does improve performance during exercise-heat stress, these improvements will most likely be mediated by hypervolemia. Several studies on the

effects of artificially expanded plasma volume have indicated no differences in core temperature (6,27) in comparison with normovolemic control levels during exercise-heat stress. Generally, these studies found that plasma volume expansion lowered heart rate responses during exercise in the heat. In contrast, both Fortney et al. (8) and Deschamps et al. (2) reported that artificially expanded plasma volume lowered core temperature below control levels during exercise, despite no difference in the sweating rate response.

BLOOD INFUSION

Two studies examined the effects of acute polycythemia (via erythrocyte infusion) on thermoregulation during exercise in the heat (23,26). In the first study (23) nine male soldiers, who were not heat acclimated, were infused with either 600 ml of a saline solution containing a ~50% hematocrit (n=6, infusion) or 600 ml of saline only (n=3, control). Subjects attempted a heat-stress test while euhydrated at approximately 2 wk pre- and 48 h post-infusion. The heat stress test consisted of a 120-min exposure (two repeats of 15 min rest and 45 min treadmill walking) in a hot (35°C, 45% rh) environment. The erythrocyte infusion subjects tended to store less body heat during the post-infusion heat-stress test. For the control group, a tendency for a greater body heat storage was evident during the post-infusion heat-stress test (compared to pre-infusion).

The avenues of heat exchange responsible for the reduced body heat storage after erythrocyte infusion were inconclusive. For the erythrocyte infusion group, steady-state values for evaporative as well as radiative and convective heat exchange were not altered from pre- to post-infusion. However, the sweating onset time was reduced (50%) and sweating sensitivity was increased (78%) post-infusion (25). These thermoregulatory advantages occurred despite the fact that erythrocyte infusion reduced plasma volume so that total blood volume was the same as during the pre-infusion measurements.

This initial study (23) raised questions concerning the use of acute polycythemia as an ergogenic aid during exercise in the heat. First, would the small thermoregulatory advantage conferred by acute polycythemia still be present in heat acclimated subjects? Heat acclimation enables an individual to perform exercise in the heat with reduced heat storage, and may elicit optimal thermoregulatory adaptations that acute polycythemia cannot improve upon. Second, would acute polycythemia provide a thermoregulatory advantage or disadvantage in dehydrated subjects during exercise in the heat? Dehydration reduces plasma volume (22), and this reduction may be accentuated by the decreased plasma volume in response to acute polycythemia which could provide a thermoregulatory disadvantage during subsequent exercise in the heat. Therefore, acute polycythemia could potentially reduce exercise performance (below pre-infusion levels) for hypohydrated subjects.

In the second study (26), five heat-acclimated men attempted four heat-stress tests; two pre- and two post-infusion with autologous erythrocytes (product of two blood units) in saline solution (~50% hematocrit). Both pre- and post-infusion subjects attempted one

heat-stress test while euhydrated, and one heat-stress test while hypohydrated (-5% of body weight). The protocol for the heat-stress tests was the same as in the previous investigation. During exercise, the subjects stored less body heat after erythrocyte infusion during both euhydration and hypohydration heat-stress tests. In addition, the subjects demonstrated an improved sweating response to exercise-heat stress after erythrocyte infusion. Both total body sweating and steady-state local sweating were greater post-infusion, and onset time for sweating tended to be more rapid. The sweating sensitivity was increased (~68%) after infusion (25). Unlike the previous study, erythrocyte infusion resulted in a slightly expanded plasma volume during rest and exercise in the heat-acclimated subjects. The slightly expanded plasma volume combined with the additional erythrocytes to increase total blood volume during both rest and exercise. Finally, the investigators found a reduced plasma hyperosmolality during the post-infusion hypohydration experiments. Future research projects will examine the potential for erythropoietin administration to induce polycythemia and modify exercise-heat performance.

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**PREDICTION MODELING OF PHYSIOLOGICAL RESPONSES AND HUMAN
PERFORMANCE IN THE HEAT WITH APPLICATION TO SPACE OPERATIONS**

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ABSTRACT

This Institute has developed a comprehensive USARIEM Heat Strain Model for predicting physiological responses and soldier performance in the heat which has been programmed for use by hand-held calculators, personal computers, and incorporated into the development of a heat strain decision aid. This model deals directly with five major inputs: (a) the clothing worn, (b) the physical work intensity, (c) the state of heat acclimation, (d) the ambient environment (air temperature, relative humidity, wind speed, and solar load), and (e) the accepted heat casualty level. In addition to predicting rectal temperature, heart rate and sweat loss given the above inputs, our model predicts the expected physical work/rest cycle, the maximum safe physical work time, the estimated recovery time from maximal physical work, and the drinking water requirements associated with each of these situations. This model provides heat injury risk management guidance based on thermal strain predictions from the user specified environmental conditions, soldier characteristics, clothing worn, and the physical work intensity. If heat transfer values for space operations' clothing are known, NASA can use this prediction model to help avoid undue heat strain in astronauts during space flight.

INTRODUCTION

Since the early 1970s, our Institute has established the data base and developed a series of predictive equations for deep body temperature, heart rate and sweat loss responses of clothed soldiers performing physical work in the heat. Individual predictive equations for rectal temperature (4), heart rate (5), and sweat loss (16) as a function of the physical work intensity, environmental conditions and particular clothing ensemble have been published in the open literature. In addition, important modifying factors such as metabolic rate (2,11), state of heat acclimation (6), state of hydration (14,15), and solar load (1) have been studied and appropriate predictive equations developed.

Currently, we have developed a comprehensive USARIEM Heat Strain Model which has been programmed for use by hand-held calculators, personal computers, and incorporated into the development of a heat strain decision aid. The mathematical basis employed in the development of the various individual predictive equations and the predictive capabilities of our heat strain model have been published previously (12,13). Our model deals directly with five major assessment factors and associated inputs: (a) U.S. Army clothing systems as selected from a clothing menu; (b) physical work intensity entered at three fixed values (i.e., light, moderate, or heavy), or directly entered if a value

for metabolic rate is known (i.e., watt, kcal/hr, or MET), or computed from march speed, soldier body weight, external load carried, terrain type and grade; (c) functional state entered as either non-heat acclimated or fully-heat acclimated; (d) the ambient environment entered as the air temperature ($^{\circ}\text{C}$ or $^{\circ}\text{F}$), humidity (% relative humidity, vapor pressure or dew point), wind speed in three categories (calm, breezy or windy) or entered in user friendly units, and solar load/sky conditions as an index of cloud cover; and, (e) accepted heat casualty level inputted as light (<5%), moderate (20%), or heavy (>50%). In addition to predicting rectal temperature, heart rate and sweat loss given the above inputs, this model predicts the expected physical work/rest cycle, the maximum safe physical work time, estimated recovery time (shade or sun) from maximum physical work, as well as the drinking water requirements associated with each of these situations.

The USARIEM Heat Strain Model provides heat injury risk management guidance based on thermal strain predictions from the menus selected or the user specified environmental conditions, soldier characteristics, clothing, and physical work intensity. The military user can employ this heat strain prediction model to help avoid unnecessary casualties associated with exposure to the environmental heat extremes, and for prediction of appropriate physical work/rest cycles and water requirements to facilitate achievement of military mission objectives. If heat transfer values for space operations clothing are known, NASA can use this prediction model to help avoid unnecessary heat strain and develop better heat injury risk management guidance for astronauts during space flight.

The potential for astronauts experiencing significant thermal stress exists in several NASA space flight scenarios (3,8,9,18,19). During extravehicular activity (EVA) while wearing the shuttle Extravehicular Mobility Unit (EMU), the liquid cooling garment worn with the EMU has been shown to provide adequate cooling capacity for most EVAs conducted at an average metabolic rate of 200 kcal/hr and thought to provide adequate cooling at metabolic rates up to 400 kcal/hr (3,8). Astronauts are reported to become less heat acclimated, dehydrated, and maintain a state of hypohydration during sustained space flight which alters their ability to effectively thermoregulate (3,7). Therefore, EVAs conducted by astronauts at sustained high metabolic rates while in a state of hypohydration and less heat acclimated may provide a potential thermal challenge and possible adverse consequences on crew member performance. Under certain EVA scenarios such as above, Fortney (3) suggests that "proper work/rest cycles to prevent large rises in body temperature, and adequate fluid replacement" are desirable. During launch, re-entry and emergency egress, astronauts wear a Launch and Entry Suit (LES) which has a ventilation system that circulates cabin air through the suit (3,9). Kaufman et al. (9) have evaluated the LES (ventilated and unventilated) during simulated pre-launch conditions for up to eight hours at an ambient temperature of 27.2°C and reported insignificant levels of thermal strain. The potential for excessive heat strain exists while wearing the LES at higher ambient temperatures which could occur during re-entry, higher metabolic rates which could happen during emergency egress and/or crew members who are in a state of hypohydration and less heat acclimated during re-entry or emergency egress.

This paper briefly presents the capabilities of our heat strain model to predict physiological responses as depicted by rectal temperature as well as the expected physical work/rest cycle, maximum single physical work time, and associated water requirements for different military scenarios. In addition, our model evaluates certain NASA scenarios where thermal stress and the potential for heat strain could be present.

USARIEM HEAT STRAIN PREDICTION MODEL CAPABILITIES

Foreign and U.S. Military Scenarios

Figure I presents a comparison of observed and predicted rectal temperature responses for 12 soldiers while wearing three different military clothing ensembles (US NBC closed, UK NBC closed and jungle uniform) under two different climatic conditions ($\sim 30^{\circ}\text{C}$, 62% rh, shade; $\sim 32^{\circ}\text{C}$, 41% rh, sun) during a field study in Australia. These data which were collected by a group independent of our Institute are in quite good agreement with the predicted values, and in all but two instances, the observed responses are within ± 1 standard deviation of the predicted responses using the USARIEM Heat Strain Model.

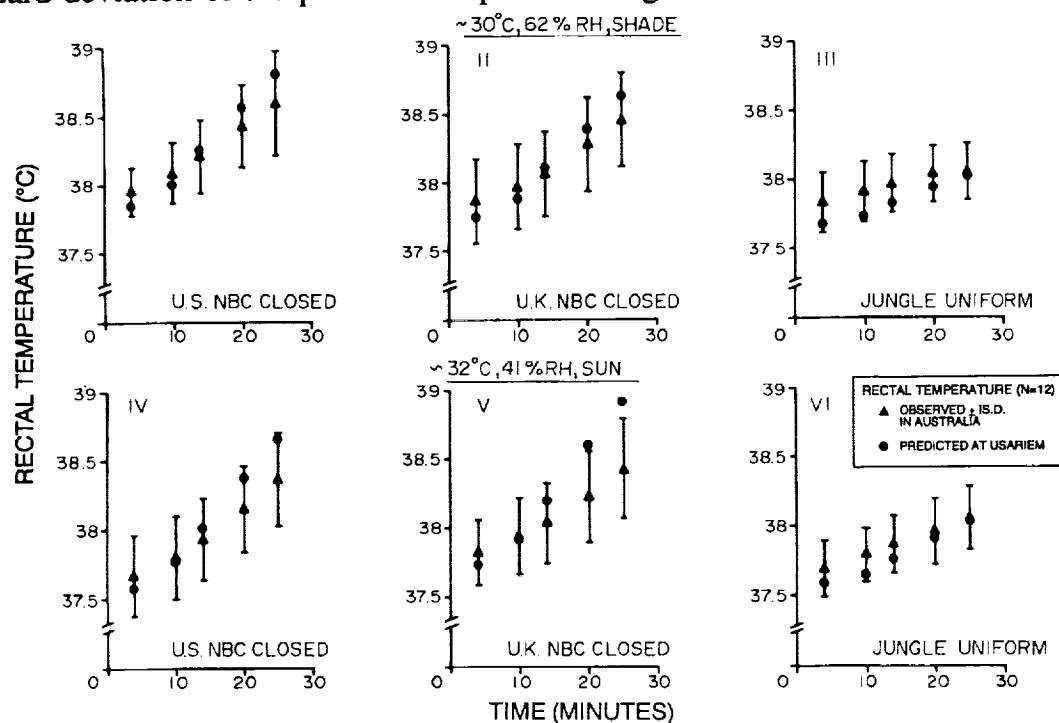


FIGURE I. COMPARISON OF PREDICTED AND OBSERVED RECTAL TEMPERATURE RESPONSES OF 12 SOLDIERS WHILE WEARING THREE DIFFERENT MILITARY CLOTHING SYSTEMS EACH UNDER TWO DIFFERENT CLIMATIC CONDITIONS.

Table I shows a comparison of observed and predicted final rectal temperatures while wearing Canadian Forces NBC protective clothing (10). Twenty-three unacclimated male soldiers performed light or heavy exercise in either a cool (18°C , 50% rh) or warm (30°C , 50% rh) environment for an attempted 300 minute exposure in protective clothing (TOPP High). As illustrated in Table I, the USARIEM Heat Strain Model predicted final rectal temperature responses of these soldiers at their respective tolerance times within ± 1 standard error of measurement from the observed mean rectal temperature responses in three of the four test conditions with the exception being light exercise in the warm

environment. These authors concluded: "Thus, US Army Guidelines for maximum allowable work times with minimal heat casualties, based on the Pandolf et al. model, can be considered to be applicable to our CF Infantry NBC protective clothing." (10).

TABLE I. COMPARISON OF OBSERVED AND PREDICTED FINAL RECTAL TEMPERATURES WHILE WEARING CANADIAN FORCES NBC PROTECTIVE CLOTHING*

Condition	Tolerance Time (min)**	Observed T_{re} (°C)	Predicted T_{re} (°C)
Light Exercise @ 18°C, 50% rh	242 (±33)	38.3 (±0.2)	38.2
Light Exercise @ 30°C, 50% rh	83 (±4)	38.9 (±0.1)	38.4
Heavy Exercise @ 18°C, 50% rh	57 (±7)	38.5 (±0.1)	38.5
Heavy Exercise @ 30°C, 50% rh	34 (±4)	38.3 (±0.2)	38.4

* Canadian Forces NBC Protective Clothing = TOPP High. ** Attempted 300 min exposure. Values are means ±SEM.

CONCLUSION: "Thus, US Army guidelines for maximum allowable work times with minimum heat casualties, based on the Pandolf et al. model (16), can be considered to be applicable to our CF infantry NBC protective clothing."

FROM: McLellan, T.M. et al. Influence of Temperature and Metabolic Rate on Work Performance with Canadian Forces NBC Clothing. Aviation, Space and Environmental Medicine 64:587-594, 1993.

Table II illustrates the predicted physical work/rest cycles, maximum work times and associated water requirements for four different military scenarios as determined by the USARIEM Heat Strain Model. The required inputs for these four scenarios are the clothing worn (MOPP 1 or MOPP 4), physical work intensity (HVY. WRK. or MOD. WRK.), casualty level (HVY. CASLT.), acclimation state (ACCL.), environmental conditions (HOT DRY), wind speed (WINDY) and solar heat load (CLOUDY or CLEAR SKY). The expected outputs are the physical work/rest cycle (minutes), one-time only maximum work period (minutes), and the associated water requirements (canteens per hour). Compared to Scenario 1, the results of Scenario 2 depict the importance of the solar load in reducing both the physical work/rest cycle and one-time only maximum work period while increasing the associated water requirements. Results from Scenario 3 show the dramatic reduction in the work component of the physical work/rest cycle and the associated reduction in the one-time only maximum work period while wearing MOPP 4. The results from Scenario 4 display the benefits of reducing the metabolic work rate from heavy to moderate in terms of improvement in the work component of the physical work/rest cycle and enhancement of the one-time only maximum work period. Hopefully, the military user can employ the USARIEM Heat Strain Model to help avoid unnecessary casualties associated with exposure to the environmental heat extremes, and by predicting appropriate physical work/rest cycles and water requirements facilitate the achievement of mission objectives.

**TABLE II. PREDICTED PHYSICAL WORK-REST CYCLES AND WATER REQUIREMENTS
ASSOCIATED WITH FOUR DIFFERENT MILITARY SCENARIOS**

Scenario 1	Scenario 2	Scenario 3	Scenario 4
INPUTS: MOPP 1 HVY.WRK. HVY.CASLT. ACCL. HOT DRY WINDY CLOUDY	MOPP 1 HVY.WRK. HVY.CASLT. ACCL. HOT DRY WINDY CLEAR SKY	MOPP 4 HVY.WRK. HVY.CASLT. ACCL. HOT DRY WINDY CLEAR SKY	MOPP 4 MOD.WRK. HVY.CASLT. ACCL. HOT DRY WINDY CLEAR SKY
RESULTS: Time W:R:M=33*27*84 Water W:R:C=2.3*0.9*1.7	Time W:R:M=28*32*74 Water W:R:C=2.4*1.1*1.7	Time W:R:M=14*46*52 Water W:R:C=2.4*1.1*1.4	Time W:R:M=24*36*87 Water W:R:C=2.2*1.1*1.6

W:R:M= work:rest:maximum work (time periods (minutes))

W:R:C= work:rest:combined (water requirements (canteens per hour))

NASA Scenarios

After evaluating available clothing heat transfer values (EMU (17) and LES (personal communication, C.M. Chang)) and the potential for experiencing excessive heat strain while wearing these clothing ensembles during space flight (3), we decided to model three NASA scenarios involving the LES primarily because the potential for excessive heat strain appeared greater than that for the EMU. The three scenarios involved pre-launch/launch, re-entry and landing, and emergency egress after re-entry and landing. The pre-launch/launch scenario (9) was an eight hour exposure to 27°C (50% rh) at a metabolic rate of 100 kcal/hr. The re-entry and landing scenario (18) was a five and one-half hour exposure to 24°C (50% rh) at a metabolic rate of 100 kcal/hr followed by a one and one-half hour exposure to 35°C (70% rh) at this same metabolic rate. The emergency egress scenario (personal communication, J.P.Bagian, M.D.) was the same as the re-entry and landing scenario except for an additional 10 minute attempted exposure (35°C, 70% rh) at a metabolic rate of 430 kcal/hr.

For each of the above three scenarios, the USARIEM Heat Strain Model was used to predict final rectal temperature, required cooling (air or liquid) to maintain minimal levels of heat storage, and if applicable the tolerance time (minutes) to reach a rectal temperature of 39.0°C. Prediction modeling was conducted with an unventilated or ventilated LES at clo values of 1.47 (unventilated), 1.29 (ventilated), and 1.20 (metabolic rate = 430 kcal/hr). During these scenarios, individuals were assumed to be either heat acclimated or unacclimated, and either euhydrated or 3% dehydrated.

TABLE III. PREDICTED FINAL RECTAL TEMPERATURES, REQUIRED COOLING AND TOLERANCE TIMES WHILE WEARING THE NASA LAUNCH AND ENTRY SUIT (LES) DURING SCENARIOS (UNVENTILATED OR VENTILATED) CONSIDERING HEAT ACCLIMATION AND HYDRATION STATE

SCENARIO *	UNVENTILATED				VENTILATED			
	ACCLIMATED		UNACCLIMATED		ACCLIMATED		UNACCLIMATED	
	Euhydrated	Dehydrated	Euhydrated	Dehydrated	Euhydrated	Dehydrated	Euhydrated	Dehydrated
Pre-Launch/Launch Final T_{re} (°C) Cooling (W)	37.8 80	38.1 80	38.4 80	38.7 220	37.7 50	38.0 50	38.3 60	38.6 200
Re-Entry Final T_{re} (°C) Cooling (W)	38.2 140	38.5 170	38.8 190	39.1 360	38.1 130	38.5 130	38.8 190	39.1 360
Emergency Egress Final T_{re} (°C) Tolerance Time (min)	38.4 18	38.8 13	39.1 9	39.4 6	38.4 18	38.7 14	39.0 10	39.3 6

* Scenario: Pre-Launch/Launch = 27°C, 50% relative humidity for 480 min at a metabolic rate of 100 kcal/hr.
Re-Entry = 24°C, 50% relative humidity for 330 min (metabolic rate, 100 kcal/hr), 35°C, 70% relative humidity for 90 min (metabolic rate, 100 kcal/hr).
Emergency Egress = 24°C, 50% relative humidity for 330 min (metabolic rate, 100 kcal/hr), 35°C, 70% relative humidity for 90 min (metabolic rate, 100 kcal/hr), 35°C, 70% relative humidity for 10 min (metabolic rate, 430 kcal/hr).
LES clo values: 1.47 (unventilated); 1.29 (ventilated); 1.20 (metabolic rate = 430 kcal/hr).
Final T_{re} (°C) = final rectal temperature; Cooling (W) = air or liquid cooling; Tolerance Time (min) = time to reach T_{re} of 39.0°C; Euhydrated = 0% dehydration; Dehydrated = 3% dehydration.

Table III shows the predicted final rectal temperatures, required cooling and tolerance times while wearing the unventilated or ventilated LES, and considers the effects of heat acclimation and hydration state. For the pre-launch/launch scenario (unventilated or ventilated), the predicted mean final T_{re} for euhydrated-acclimated and euhydrated-unacclimated individuals is in close agreement with the observed final T_{re} values (~38.0°C) for this same scenario reported by Kaufman et al. (9) indicating minimal heat strain. For this scenario, dehydrated-unacclimated individuals, a state thought to occur during space flight (3,7), demonstrate moderate heat strain as depicted by final T_{re} values. For the re-entry and landing scenario (unventilated or ventilated), the predicted final T_{re} for euhydrated-acclimated individuals are indicative of minimal heat strain; however, moderate to excessive heat strain is exhibited for all of the other situations (dehydrated-acclimated, euhydrated-unacclimated, or dehydrated-unacclimated individuals). The required cooling (air or liquid) depicted in Table III for the above two scenarios demonstrates the required heat extraction from the body using a vest-cooling system and does not consider the efficiency factor of the particular vest-cooling system. For the emergency egress scenario (unventilated or ventilated), moderate to severe levels of heat strain are shown for all situations. In addition, tolerance time would be limited to approximately six minutes for emergency egress if individuals were dehydrated and unacclimated.

CONCLUSIONS

The USARIEM Heat Strain Model has been shown to accurately predict rectal temperature responses for soldiers wearing different military clothing ensembles in the

heat during both foreign and U.S. military scenarios. This model can be used to predict the expected physical work/rest cycle, the maximum safe physical work time, the estimated recovery time from maximal physical work, and the drinking water requirements given the clothing worn, the physical work intensity, the state of heat acclimation, the ambient environment, and the accepted heat casualty level. The utility of this same model has been demonstrated presently for three NASA scenarios involving the Launch and Entry Suit (LES). The LES (unventilated and ventilated) was modeled during pre-launch/launch, re-entry and landing, and emergency egress after re-entry and landing scenarios to primarily evaluate the effects of heat acclimation and hydration state. During the pre-launch/launch scenario, predicted final rectal temperatures were in close agreement with observed values indicating minimal heat strain; however, dehydrated-unacclimated individuals exhibited moderate levels of heat strain for this same scenario. During the re-entry and landing and emergency egress scenarios, the separate and combined effects of dehydration and lack of heat acclimation were even more pronounced in producing excessive heat strain. Crew member performance should be predicted for other NASA scenarios and space operations clothing ensembles to assess the potential for heat strain and further consider heat acclimation and hydration state.

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DISCLAIMER

The views, opinions and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other official documentation. Approved for public release; distribution is unlimited.

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Session L5: BIOMEDICAL RESEARCH AND DEVELOPMENT

Session Chair: Capt. Terrell Scoggins

**Evaluation of a Liquid Cooling Garment as a Component of
the Launch and Entry Suit (LES)****J. Waligora****J. Charles****I. Fritsch****S. Fortney****S. Siconolfi****L. Pepper****L. Bagian****V. Kumar****NASA Johnson Space Center
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The LES is a partial pressure suit and a component of the Shuttle life support system used during launch and reentry. The LES relies on gas ventilation with cabin air to provide cooling. There are conditions during nominal launch and reentry, landing, and post-landing phases when cabin temperature is elevated. Under these conditions, gas cooling may result in some discomfort and some decrement in orthostatic tolerance. There are emergency conditions involving loss of cabin ECS capability that would challenge crew thermal tolerance.

The results of a series of tests are presented. These tests were conducted to assess the effectiveness of a liquid-cooled garment in alleviating thermal discomfort, orthostatic intolerance, and thermal intolerance during simulated mission phases.

La Chalupa-30: Lessons Learned from a 30-day Subsea Mission Analogue

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The Behavior and Performance Laboratory (BPL) utilizes space mission analogues to study issues such as the psychological health and wellbeing, team characteristics, and task performance of crew members on long-duration missions. The analogue used in this investigation was an underwater habitat named *La Chalupa*, which was selected for its similar features to a space station environment. The primary objectives of the *La Chalupa*-30 investigation were to (1) evaluate the efficiency of several methods for collecting data in remote environments, and (2) assess aspects of living and working under isolated and confined conditions.

A primary data collection technique tested was the Individualized Field Recording System (IFRS) software installed on a portable computer. This customized, Microsoft Windows-based software permits questionnaires to be administered to crew members and stores responses in individual, confidential databases. Other methods of data collection tested included Question Cards and microcassette recorders, two-way video and audio link, and actigraphy. The BPL evaluated the quality of information obtained with each method and assessed crew member's preference for the methods.

Evaluation of data collection procedures and equipment indicated: (1) the IFRS software proved effective for collecting self-report, repeated-measures data; (2) since each crew member may prefer to respond in different ways (e.g., spoken versus typed responses), multiple methods of data collection are helpful for eliciting pertinent information; and (3) two-way audio and video link was perceived as a significant means of promoting the sense of tight coordination between crew and controllers.

Preliminary analysis of the data collected indicates: (1) overall, the crew experienced very little difficulty in the areas measured during the 30-day mission and felt that a 60-day mission would be no different. However, the crew members felt that significant countermeasures would be necessary for a 90-day + mission: (2) crew members reported that it was critical to have personal space to express individuality in the isolated and confined environment: and, (3) two 30-minute opportunities per week provided for communication with family members was perceived as too frequent.

La Chalupa-30: Lessons Learned from a 30-day Subsea Mission Analogue

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Background

Behavior and Performance Lab investigates issues related to individual and team psychological health, wellbeing, and performance as crews live and work in isolated and confined environments for extended periods.

Analogues provide the platform to collect this information.

Must be able to remotely track these variables during L/D missions:

- ▶ Collecting repeated measures data from remote crews has been problematic: compliance, storage
- ▶ Methods study was necessary

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Objectives

- ▶ Assess equipment for improving data collection in remote environments:
 - Repeated Measures
 - Maximum storage/security
- ▶ Evaluate software, hardware, and procedures for collecting data in L/D analogues and space flights.
- ▶ Evaluate the subsea environment as a platform for future L/D space analogue investigations.
- ▶ Gather information for establishing guidelines for 30-day space missions.

3

Approach

Marine Resources Development Foundation (MRDF)

- ▶ "Piggyback" onto their planned 30-day mission.

Crew Composition:

- ▶ 4 Males: Marine Biologist (CDR), Diver (Deputy), Hyperbaric EMT (CMO), Cell Biologist.
- ▶ One crew member exited mission day 3 due to flu-like symptoms.

30-day mission preceded by 2-day "Sea Trial."

4

Facilities

La Chalupa (Habitat):

- ▶ Lagoon depth 9 m, hatch depth 7 m, pressure 1.69 atm.
- ▶ Habitable Volume = 55.63 cubic meters.
 - 3 main chambers: Wetroom, Commons, and Sleeping Quarters (2 suites / 4 bunks)
 - Head and shower facilities.
- ▶ Life Support Systems from topside (umbilicals):
 - Habitat/diving air supply, potable water, waste water disposal, electrical.

Control Van: Comm. and system monitoring/control.

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Study Components

Data Collection Methods

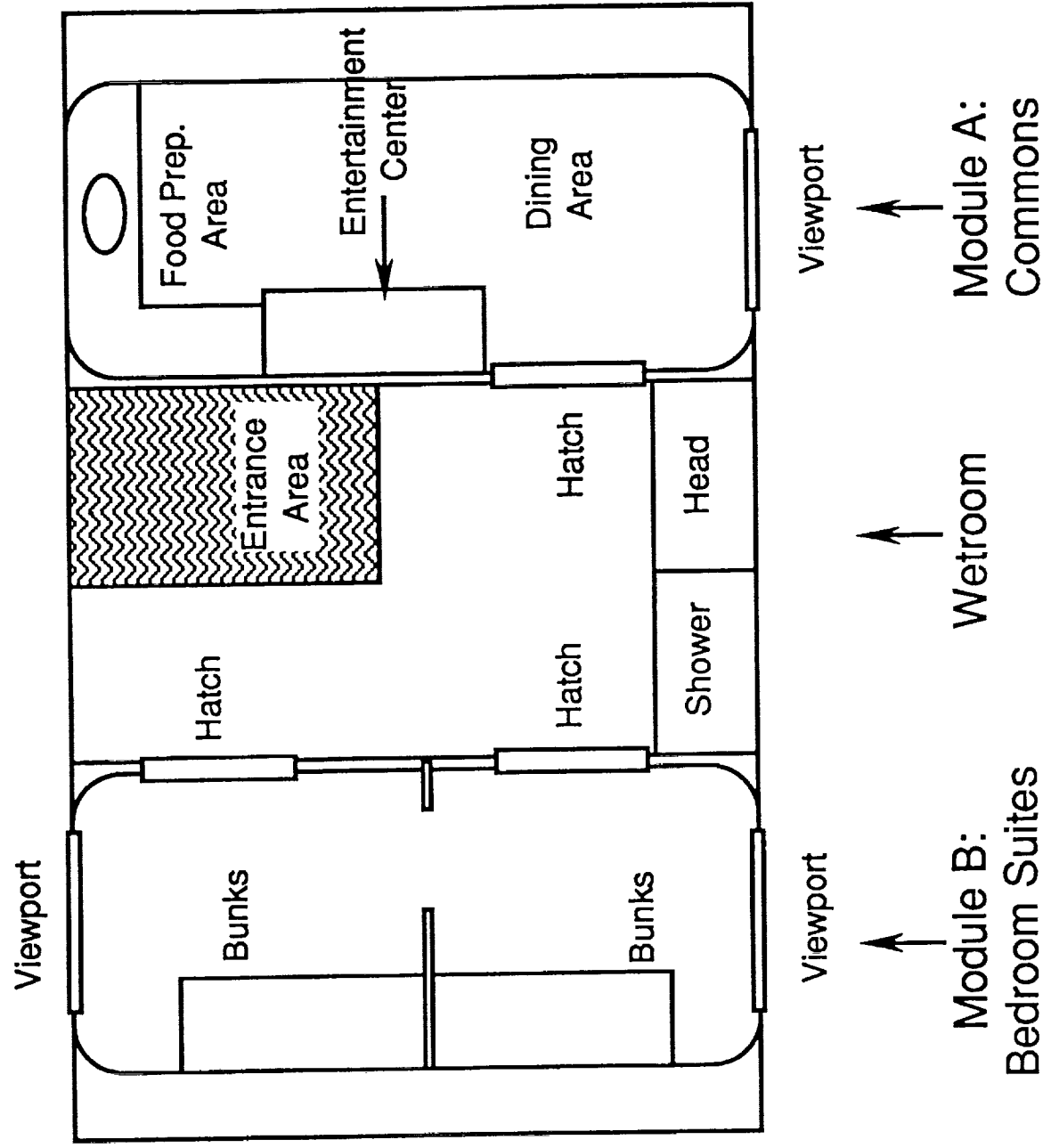
Pre-mission: abbreviated version of battery used in astronaut selection research, including psychological tests and interview.

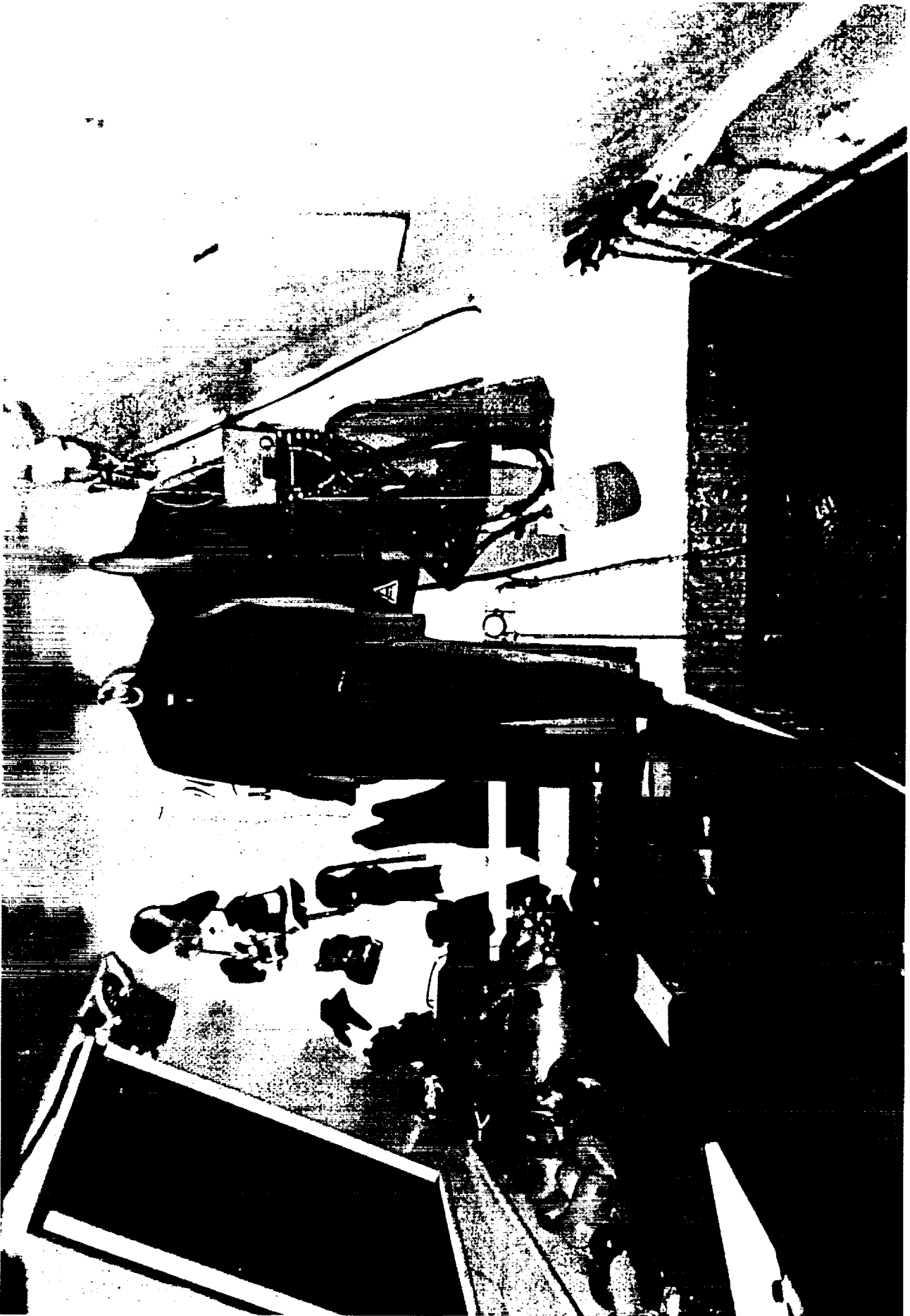
During mission:

- ▶ Individualized Field Recording System (IFRS)
 - Computer-based questionnaire pres. system.
 - Incorporates A/V "postcards."
- ▶ Automated Neurological Assessment Metrics (ANAM)
 - Computer-based cognitive assessment.

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Schematic of Underwater Habitat used in *La Chalupa-30*





Wetroom



Bedroom Suite



Crewmember Completing IFRS in Commons

Study Components (cont'd)

Data Collection Methods, continued

- ▶ **Micro-recorders and Question Cards**
 - Oral responses given to questions.
- ▶ **Audio/Video**
 - 2-way A/V team debriefs.
 - Taped meal prep. and schedule planning (evenings).
- ▶ **Sleep Quality/Quantity**
 - Sleep diaries.
 - Actigraph Activity Monitors.

Post-mission: conducted 1-hour debriefs.

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Lessons Learned

Crew members completed all IFRS questionnaires and judged it to be effective for collecting self-report, repeated measures data.

Field environment taught important lessons for software upgrades to IFRS system and procedures:

- ▶ Lengthen narrative response buffer.
- ▶ Make s/w operation as simple as possible.
- ▶ Training to observe and report psych. events.

Extremely positive response to the A/V "postcards" and gaming that was incorporated. Generated ideas for future field investigations.

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Lessons Learned (cont'd)

Multi-method approach is desirable to obtain data:

- Information from one source helped to explain the information collected from another source.
- Each crew member had a preferred method for reporting.
- Some methods could be combined (Q-card narratives with IFRS).

Over time, bright people will tinker with equipment:

- Perusing our computer files.

Remote up- and downloading of data was touchy but workable. Will improve with better software.

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Lessons Learned (cont'd)

Actigraphs were reliable, but limited battery and storage would be problematic in field settings.

Significant changes in the data occurred during specific mission events, such as:

- 4th crew member exiting mission.
- Press-day.
- Personal experiments going well.
- End-of-mission activity scheduling.

Crew desired more space to store personal effects and a place to "get away" from rest of crew (used bottom time).

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Lessons Learned (cont'd)

Certain food/snack items took on great importance:

- Disappointment when resupply excluded M&M's.
- Crew members began hoarding Kudos.

Family communication 2x/week was too frequency:

- Interfered with crew's focus on mission and work.
- Suggested 1x/week.

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Lessons Learned (cont'd)

Moral/Cohesion:

- Removal of 4th crew member had significant effect on remaining crew members' morale:
 - Bounced back within 3 days
 - A focal point for generating cohesiveness.
- High morale and cohesion were maintained – Affected positively by off-time projects (e.g., spa construction).
- Relationship with topside was good – Occasional conflicts with topside, generally over schedule constraints and coordination of resupply.

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Lessons Learned (cont'd)

2-way video team debriefs were well received:

- ▶ Simple but powerful means of creating greater level of cohesion between controllers and crew.

Overall no mission-stopping psychological issues over the 30 days.

Subsea habitat proved to be useful analogue for on-orbit space operations.

Comparative Performance of a Modified Space Shuttle Reentry Anti-G Suit (REAGS) With and Without Pressure Socks

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INTRODUCTION. In a prior study, the Armstrong Laboratory (AL) demonstrated that +G_z protection during simulated Shuttle reentry could be improved with an extended coverage anti-G suit with pressure socks but no abdominal bladder (REAGS). In a subsequent study conducted at the NASA Johnson Space Center it was shown that REAGS had a down side which included restricted mobility (during simulated Shuttle egress) and a larger boot size needed for the pressure socks. **METHODS.** The present study was conducted using a modified REAGS to increase mobility during egress. The size of the crotch opening was increased, and the fabric covering the buttocks was replaced with more elastic material. Six healthy male members of the AL centrifuge panel served as subjects for the study. As in the earlier study, subjects received 20 to 35 mg of IV Lasix approximately 6 hours before being exposed to a simulated Space Shuttle reentry +G_z profile on the AL centrifuge, which induced a mean weight loss of 2.8%, range 2.1% to 3.7%. The REAGS was inflated to 1.0 psig 10 minutes prior to G onset. The G-profile was identical to that used in the previous REAGS study (ending with a gradual onset run (GOR) to peripheral light loss (PLL)). Physiologic parameters monitored were also the same; i.e., eye-level systolic blood pressure (ELBP) using the Finapres digital cuff technique and heart rate and rhythm. Subjective comments were obtained from questionnaires administered after the increased G exposure. Systolic ELBP was maintained at 60 mmHg or above by pressurizing the anti-G suit in 0.5 psig increments up to a maximum pressure of 2.5 psig. **RESULTS.** There were no significant differences in mean G-suit pressure required to maintain systolic ELBP at 60 mmHg or above between the REAGS worn with and without pressure socks. Maximum mean G-levels achieved during the GOR were also the same under both experimental conditions; i.e., 4.7 G with socks and 4.6 G without socks. These G-levels were essentially the same as recorded earlier with the unmodified REAGS. There were no significant differences in comfort rating during the G exposure assigned by subjects when they wore the modified REAGS with or without the pressure socks. **CONCLUSIONS.** The REAGS modified increased mobility, with or without pressure socks, and inflated to 1.0 psig 10 minutes prior to acceleration onset offered the same degree of protection as the unmodified REAGS with pressure socks.

Current and Future Issues in USAF Full Pressure Suit Research and Development

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In accordance with Air Force Regulations, full pressure suits must be worn by aircrew for sustained flight at altitudes above 50,000 ft. This requirement is based on the physiological need to provide protection from both hypoxia and ebullism (vaporization of body fluids and tissue due to exposure to extremely low pressures). Currently, USAF full pressure suit operations are used almost exclusively for high-altitude reconnaissance missions in the U-2 aircraft. Full pressure suits are also used on a limited basis for high-altitude test and evaluation flights in a variety of aircraft. NASA uses the same kind of suits for high-altitude research flights in the SR71 and ER-2 aircraft. Also, NASA/JSC is developing a full pressure suit to replace the current partial-pressure launch escape suit for Shuttle operations. Although the full pressure suits currently in the USAF operational inventory provide acceptable performance and crew protection for these missions, there is considerable room for improvement, especially in the areas of comfort, mobility, glove and helmet performance, and maintenance/supportability. As future aircraft push the envelop towards operations at higher and higher altitudes and transatmospheric flight, advances in full pressure suit technology will be needed. Also, enhanced pressure suit technology will be required to meet NASA's need for protection during future EVA operations for both on-orbit and planetary surface missions. This presentation will review the results of efforts at the Armstrong Laboratory to develop and demonstrate advanced full pressure suit technology for use in future high-altitude reconnaissance aircraft and transatmospheric vehicle operations. For those readers who may not be familiar with this area of life support equipment, a brief review of the important physiological and operational requirements for full pressure suits used in these applications will be addressed first, followed by a summary of the current state-of-the-art in USAF pressure suit technology. Ongoing and recently completed work on enhanced mobility pressure suit joints and improved pressure suit gloves will then be reviewed. The presentation will conclude with discussion of the technical challenges for successful development of an advanced full pressure suit for aerospace operations in the 21st century.

Advanced Integrated Life Support System Update

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The Advanced Integrated Life Support System Program (AILSS) is an advanced development effort to integrate the life support and protection requirements using the U.S. Navy's fighter/attack mission as a starting point. The goal of AILSS is to optimally mate protection from altitude, acceleration, chemical/biological agent, thermal environment (hot, cold, and cold water immersion) stress as well as mission enhancement through improved restraint, night vision, and head-mounted reticules and displays to ensure mission capability. The primary emphasis to date has been to establish garment design requirements and tradeoffs for protection. Here the garment and the human interface are treated as a system. Twelve state-of-the-art concepts from Government and industry (primarily) were evaluated for design versus performance. On the basis of a combination of centrifuge, thermal manikin data (c_{lo} and i_m), thermal modeling, and mobility studies, some key design parameters have been determined. Future efforts will concentrate on the integration of protection through garment design and the use of a single layer, multiple function concept to streamline the garment system.

Session L6: TOXICOLOGY AND MICROBIOLOGY

Session Chair: Mr. Richard Sauer

Continuous Monitoring of Bacterial Attachment

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A major concern with the Space Station Freedom (SSF) water supply system is the control of long-term microbial contamination and biofilm development in the water storage and distribution systems. These biofilms have the potential for harboring pathogens as well as microbial strains containing resistance factors that could negatively influence crew health.

The proposed means for disinfecting the water system on SSF (iodine) may encourage the selection of resistant strains. In fact, biofilm bacteria have been observed in water lines from the Space Shuttle Columbia (OV-102); therefore, an alternative remediation method is required to disinfect spacecraft water lines. A thorough understanding of colonization events and the physiological parameters that will influence bacterial adhesion is required. The limiting factor for development of this technology is the ability to continuously monitor adhesion events and the effect of biocides on sessile bacteria.

Methods have been developed to allow bacterial adhesion and subsequent biocidal treatment to be monitored continuously. This technique couples automated image analysis with a continuous flow of a bacterial suspension through an optical flow cell. A strain of *Pseudomonas cepacia* isolated from the water supply of the Space Shuttle Discovery (OV-103) during STS-39 was grown in a nitrogen-limited continuous culture. This culture was challenged continuously with iodine during growth and the adhesion characteristics of this strain was measured with regard to flow rate. Various biocides (ozone, hypochlorite, and iodine) were added to the flow stream to evaluate how well each chemical removed the bacteria. After biocide treatment, a fresh bacterial suspension was introduced into the flow cell and the attachment rate was evaluated on the previously treated surface. This secondary fouling was again treated with biocide to determine the efficacy of multiple batch chemical treatments in removing biofilm.

Characterization of Spacecraft Humidity Condensate

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When construction of Space Station Freedom reaches the Permanent Manned Capability (PMC) stage, the Water Recovery and Management Subsystem will be fully operational such that (distilled) urine, spent hygiene water, and humidity condensate will be reclaimed to provide water of potable quality. The reclamation technologies currently baselined to process these waste waters include adsorption, ion exchange, catalytic oxidation, and disinfection. To ensure that the baselined technologies will be able to effectively remove those compounds presenting a health risk to the crew, the National Research Council has recommended that additional information be gathered on specific contaminants in waste waters representative of those to be encountered on Space Station. With the application of new analytical methods and the analysis of waste water samples more representative of the Space Station environment, advances in the identification of the specific contaminants continue to be made.

Efforts by the Water and Food Analytical Laboratory at the Johnson Space Center have been successful in enlarging the database of contaminants in humidity condensate. These efforts have not only included the chemical characterization of condensate generated during ground-based studies, but most significantly the characterization of cabin and Spacelab condensate generated during Shuttle missions. The analytical results presented in this paper will be used to show how the composition of condensate varies amongst enclosed environments and thus the importance of collecting condensate from an environment close to that of the proposed Space Station. Although advances have been made in the characterization of space condensate, complete characterization, particularly of the organics, requires further development of analytical methods.

Computation of Iodine Species Concentrations in Water

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During an evaluation of the use of iodine as a water disinfectant and the development of methods for measuring various iodine species in water onboard Space Station Freedom, it became necessary to compute the concentration of the various species based on equilibrium principles alone. Of particular concern was the case when various amounts of iodine, iodide, strong acid, and strong base are added to water. Such solutions can be used to evaluate the performance of various monitoring methods being considered. The authors of this paper present an overview of aqueous iodine chemistry, a set of nonlinear equations which can be used to model the above case, and a computer program for solving this system of equations using the Newton-Raphson method. The program was validated by comparing results over a range of concentrations and pH values with those previously presented by Gottardi for a given pH. Use of this program indicated that there are multiple roots to many cases and selecting an appropriate initial guess is important.

Comparison of program results with laboratory results for the case when only iodine is added to water indicates the program gives high pH values for the iodine concentrations normally used for water disinfection. Extending the model to include the effects of iodate formation results in the computed pH values being closer to those observed, but the model with iodate does not agree well for the case in which base is added in addition to iodine to raise the pH. Potential explanations include failure to obtain equilibrium conditions in the lab, inaccuracies in published values for the equilibrium constants, and inadequate model of iodine chemistry and/or the lack of adequate analytical methods for measuring the various iodine species in water.

A Volatile Organic Analyzer for Space Station: Description and Evaluation of a Gas Chromatography/Ion Mobility Spectrometer

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A Volatile Organic Analyzer (VOA) is being developed as an essential component of the Space Station's Environmental Health System (EHS) air quality monitoring strategy to provide warning to the crew and ground personnel if volatile organic compounds exceed established exposure limits.

The short duration of most Shuttle flights and the relative simplicity of the contaminant removal mechanism have lessened the concern about crew exposure to air contaminants on Shuttle. However, the longer missions associated with the Space Station, the complex air revitalization system, and the proposed number of experiments have led to a desire for real-time monitoring of the contaminants in the Space Station atmosphere.

Contingency air samples, prompted by crew discomfort (e.g., foul odor, eye/nasal irritation), have been collected during half the missions since the Challenger accident. Analyses of contaminants in air samples collected on board Shuttle have shown that over 60 different compounds are present in the Shuttle atmosphere, albeit at concentrations generally far below the Spacecraft Maximum Allowable Concentrations (SMACs). The sources of these air contaminants are similar to those expected on Space Station and may include: materials offgassing, utility and payload chemicals, hygiene products, food, and human metabolic processes. The prospect of extended, chronic exposure to such a matrix on board Space Station has resulted in the concept of a VOA for near real-time monitoring of volatile organic compounds.

Achieving the performance requirements established for the VOA within the Space Station resource (e.g., power, weight) allocations led to a novel approach that joined a gas chromatograph (GC) to an ion mobility spectrometer (IMS). The authors of this paper will discuss the rationale for selecting the GC/IMS technology as opposed to the more established gas chromatography/mass spectrometry (GC/MS) for the foundation of the VOA. The data presented from preliminary evaluations will demonstrate the versatile capability of the GC/IMS to analyze the major contaminants expected in the Space Station atmosphere. The favorable GC/IMS characteristics illustrated in this paper include excellent sensitivity, dual-mode operation for selective detection, and mobility drift times to distinguish coeluting GC peaks. Preliminary studies have shown that the GC/IMS technology can meet and surpass the performance requirements of the Space Station VOA.

Safety Concerns for First Entry Operations of Orbiting Spacecraft

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The Space Station Freedom crew will face operational problems unique to the spacecraft environment due to the absence of convection currents and the confined atmosphere within the habitable modules. Airborne contaminants from materials offgassing or contingency incidents like thermodegradation may accumulate until they reach hazardous concentrations. Flow modeling and experiences from previous space flight missions confirm that caution must be exercised during first-entry operations. A review of the first-entry procedures performed during the Skylab Program will be presented to highlight the necessity for carefully planned operations.

Many of the environmental conditions that can be expected on the Space Station are analogous to those which exist in confined storage or work spaces in the industrial setting. Experiences with closed-loop environmental operations (e.g., atmospheric control of submarines) have also demonstrated that the buildup of trace contaminant gases could result in conditions that lead to mission termination or loss of crew. Consequently, some first-entry issues for Station can be addressed by comparing them to familiar techniques developed on Earth. The instruments of the Environmental Health System (EHS) will provide the necessary monitoring capability to protect crew health and safety during the planned first-entry procedures of the MTC phase of the SSF Program. The authors of this paper will describe those procedures and will cite an example of the consequences when proper first-entry procedures are not followed.

SECTION V

SPACE MAINTENANCE AND SERVICING

Session S1: SPACE STATION MAINTENANCE

Session Chair: Mr. Kevin Watson

UNIQUE METHODS FOR ON-ORBIT STRUCTURAL REPAIR, MAINTENANCE, AND ASSEMBLY

Ray Anderson
Phil Fuson

INTRODUCTION

Current and future missions by NASA to establish a permanent presence in space include establishing a permanent space station in low Earth orbit for conducting scientific research, and in the long term establishing an outpost on the moon and landing of personnel on Mars. The currently planned NASA Space Station Freedom will be constructed and joined on Earth, with final assembly being performed on orbit by astronauts and telerobotics. Tools and procedures that are both extravehicular activity (EVA) and telerobotically compatible will be required for maintenance and repair for this most ambitious NASA effort.

Reliability and continued operational performance become major factors for future manned space vehicles with long-duration life expectancies. On-orbit systems such as life support fluid and gas lines, habitation module walls, and structural support components will require repair and maintenance during their continued exposure to the hostile environment of space. Such operations will be performed in both EVA and intravehicular activity (IVA) using astronauts or a combination of astronauts and telerobotics. The NASA space shuttle has an extensive inventory of tools compatible with both EVA and IVA use to perform temporary repairs in space, but these tools do not possess the required capability of long-term performance or telerobotic capability.

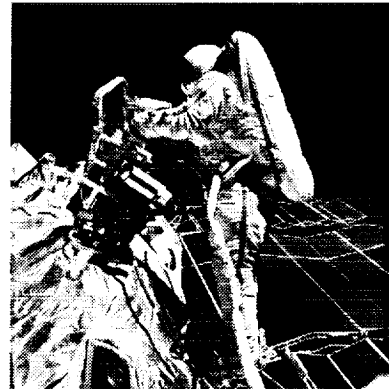
Welding would be a highly effective and reliable method by which repairs could be performed on orbit for damaged fluid lines, truss assemblies, pressurized habitation modules, and critical structural supports. The United States has been slow in developing an on-orbit welding capability, although NASA did perform a self-contained electron beam welding experiment aboard Skylab in 1973 (Reference 1) and has proposed development of a space welding capability through its IN-STEP programs (References 2 and 3).

The former Soviet Union, on the other hand, has continued to develop welding in space since 1965. This resulted in a weld repair being successfully performed in space in 1986 aboard Soyuz T12 using Universal Hand Tool (UHT) electron beam space welder, shown in Figure 1, developed by the Paton Welding Institute (Reference 4). A 1.5-kW version of the UHT currently resides as a permanent repair tool on the Mir Space Station.

Mechanical tube fittings offer an established option to welding for the near-term on-orbit repair of tubular compo-

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**Figure 1. Soviet Union Cosmonaut Successfully
Performing Welding in Space on Soyuz T12**

nents such as fluid lines or structural components. One-piece mechanical fittings have been evaluated extensively by the Air Force as reliable hardware for in-place repair of tubes and tube components on aircraft. Such repairs are defined as depot maintenance and involve the use of special installation tools and procedures. Tools and hardware demonstrations for on-orbit line repair are required for mechanical repair procedures to be acceptable for use by NASA on near-term structures such as the Space Station.

McDonnell Douglas Aerospace (MDA) has been investigating both welding and mechanical tube fittings since 1986 as viable methods for on-orbit tube repair. Emphasis was initially placed on mechanical tube fittings as this technology had progressed to a higher degree in the United States, thereby minimizing risks for use in near-term space applications. Since 1990, MDA, through the Paton Welding Institute in Kiev, Ukraine, has placed increased emphasis on welding in space, evaluating the Paton space welding and metal processing capabilities and their potential application to NASA's near-term requirements as defined for Space Station Freedom.

This paper reviews the MDA independent research and development (IRAD) efforts since 1986 in the development of two distinctly different approaches to on-orbit tube repair: (1) one-piece mechanical tube fittings that are forced, under pressure, onto the tube outer surface to effect the repair and (2) electron beam welding as demonstrated with the Paton-developed UHT space welding system for the repair of fluid lines and tubular components. Other areas of potential

on-orbit repair using the UHT include damage to the flat or curved surfaces of habitation modules and truss assemblies. This paper will also address MDA evaluation of the Paton UHT system for on-orbit coating, cleaning, brazing, and cutting of metals. MDA development of an on-orbit compatible NDE system for the inspection of tube welds is an important part of this complete space welding capability and will be discussed in a separate paper.

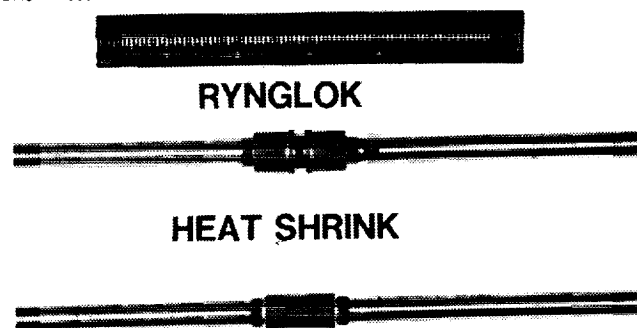
ON-ORBIT REPAIR DEVELOPMENT

Repair Scenario Definitions

A single scenario was established for the MDA development of procedures and tools for the on-orbit repair of tubes. This scenario includes (1) removal of the defective tube section, (2) use of the precut tube length to replace defective sections, and (3) installation of the precut length using either mechanical fittings or welding. Defects in either curved or flat metal places would be repaired by welding a metal patch over the defective area.

Mechanical Tube Fittings

Preliminary Studies. Based on past experience in aircraft, commercial, and space usage, 10 fitting types were evaluated for use in the MDA on-orbit repair development program. These fittings, along with their ability to meet certain functional requirements, are described in Table 1. The MDA program concentrated its effort on fittings that were simple in design and nonseparable in operation and that required minimum EVA involvement for installation and removal. MDA selected the Raychem heat shrink fitting and the Aeroquip Rynglok fitting as best meeting these requirements. Both fittings are designed for one-piece installation and, once installed, cannot be disassembled. Seals for each fitting are formed by high pressure exerted between the tube outer diameter and fitting inner diameter. The two fittings selected for evaluation are shown in Figure 2.



PERMANENT FITTINGS

Figure 2. Nonseparable Tube Fittings Selected for On-Orbit Repair Development

Tool Development. Two types of tools are required for use of any mechanical fitting for on-orbit tube repair: (1) a tube cutter and (2) a fitting installation tool. The selected fittings must also have a fool-proof method, readily visible to astronauts, that indicates an acceptable installation.

Tube Cutter. MDA developed an EVA-compatible modular power tool (MPT) fitted with a tube cutter head capable of cutting metal tubes in minimum clearance openings while producing a cut that is externally free of burrs and minimizing contamination (Figure 3). The MPT is modular in design and capable of operating a variety of different heads in addition to the tube cutter. The cutter head has the capability of capture, alignment, and hard docking to the tube prior to cutting. The cutter wheel feeds at a preselected rate until the tube cut is completed. At that time, the MPT will automatically shut off. The MPT is automated and is capable of hands-off operation after hard docking is complete. The cutter will produce an external burr-free tube surface cut and minimal internal burr formation, which will eliminate the need for additional fluid line repair preparation.

Table 1. Mechanical Tube Requirements for Use in Space Fitting Requirements

No.	Fitting type	Zero leak at 10^{-9} cc/sec	Metal-to-metal seal	Simple to		Complete installation in space	Simple design	Go/no-go indicator	High reliability	Cost (tools and fitting)	Installed with small tools	Qualified for high-pressure service up to 6000 psi
				Install	Repair							
1	Rynglok	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Moderate	Yes	Yes
2	Swagelok	No	Yes	Moderate	No	Yes	No	Yes	Yes	Low	Yes	No
3	Dynatube	Yes	Yes	No	No	No	No	Yes	Yes	High	Yes	Yes
4	Cryofit	Yes	Yes	Yes	No	Yes ¹	Yes	Yes	Yes	Moderate	(1)	Yes
5	Permaswage	No	No	No	No	No	No	Yes	No	High	No	No
6	37-deg flare	No	No	No	No	No	Yes	No	No	Low	Yes	No
7	Flareless	No	Yes	No	No	No	No	Yes	No	Low	Yes	No
8	Wiggins	No	No	No	No	No	No	Yes	No	Moderate	Yes	No
9	Gamah	Yes	Yes	Moderate	No	No	No	Yes	Yes	Moderate	Yes	Yes
10	Heat shrink	Yes	Yes	Yes	No	Yes ²	Yes	Yes	Yes	Moderate	Yes ²	Yes

Notes: 1. Requires portable storage in liquid nitrogen
2. Requires heat source

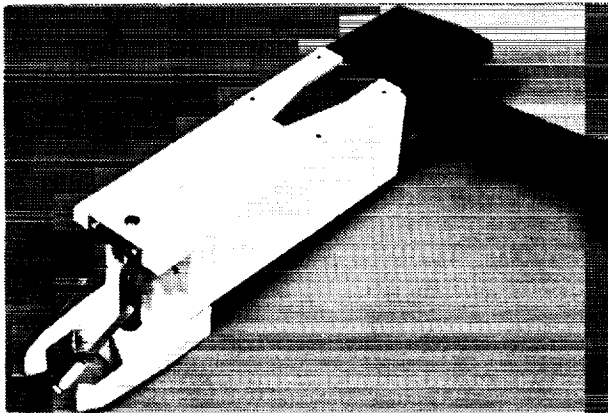


Figure 3. Modular Power Tool

Fitting Swage Tool. The Rynglok nonseparable tube fitting is installed by sliding two sleeves forward until they contact a center flange. Upon contact, the sleeves have exerted sufficient pressure between mating tube and fitting surfaces to effect a seal. This swaging action of the fitting sleeve is performed by an EVA-compatible swage tool developed under the program (Figure 4). The tool is hydraulically operated through a pneumatic intensifier pump. The swaging action is controlled by an EVA-compatible switch. This switch, shown in Figure 4, is separate from the swaging head. Total time to effect a swage is approximately 5 to 10 sec per sleeve. Once the two sleeves have been moved forward against the center flange, the fitting is successfully swaged to the fluid line.

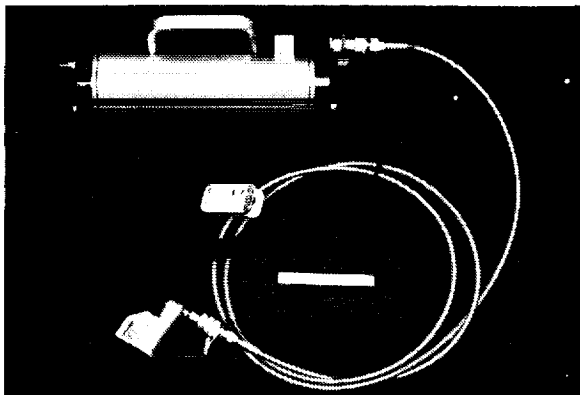


Figure 4. Rynglok Fitting Swage Tool

Torobonder. The Raychem heat shrink fitting is a one-piece nonseparable unit fabricated from a titanium-nickel "memory" alloy that shrinks a predetermined amount when heat is externally applied. NASA has developed an EVA-compatible source for this heat application, which was evaluated on this program (Figure 5). This heat source, known as an Inductron Torobonder, is supplied with a number of different heat source configuration heads. Each fitting half is heated separately with the Inductron Torobonder until it has shrunk onto the tube outer diameter. This

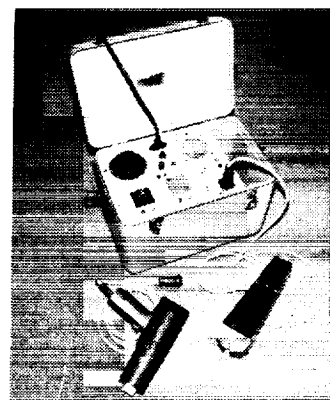


Figure 5. Inductron Torobonder for Installation of Heat Shrink Fittings

operation is complete when the color indicating pads on each fitting turns from light green to black (approximately 300°F). It takes approximately 5 sec for each side of the fitting to shrink onto the tube surface.

Hardware Demonstrations. The MPT and tube cutter head have been successfully demonstrated by both NASA and MDA in various environments. Stainless steel tubing representative of sizes proposed for SSF were cut in the underwater test facility at MDA at tube clearances typical of those for space fluid systems (Figure 6). A precut tube length was manually placed in the space where the section had been removed. Rynglok fittings were then manually slid over the cut joints to hold the precut length in place. The fitting swage tool (Figure 4) was operated by extravehicular mobility unit (EMU) suited subjects to successfully install the Rynglok fittings.



Figure 6. MPT Demonstration in Neutral Buoyancy Environment

The MDT cutter was successfully operated and Rynglok fittings installed in the 0-g environment of the NASA KC-135 (Figure 7). The tools were operated and fittings installed by members of the NASA astronaut crew. Tube sizes representative of fluid lines on SSF were used in the demonstration. Tube samples containing the swaged fittings were leak-tested to determine conformance to selected

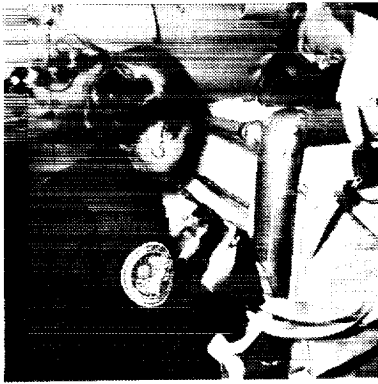


Figure 7. Swaging of Rynglok Fitting on KC-135

leakage requirements (10^{-6} scc/sec He at room temperature). Leak rates of all prepared tube samples were between 5×10^{-5} and 8×10^{-5} scc/He at room temperature.

The heat shrink fittings were successfully installed on both stainless steel and titanium tube samples using the Inductron Torobonder. All fittings were installed in a laboratory 1-g environment. Leak testing of the prepared samples indicated acceptable leak rates on all tube samples at 3000 psi and temperature cycles between room temperature and 160°F. Heat shrink fittings installed on stainless steel tubes leaked excessively at temperatures between -50° and -100°F. Differences in coefficient of thermal expansion between the Ti-Ni fitting material ($3.67 \times 10^{-6}/^{\circ}\text{F}$) and the stainless steel tubing material ($9.6 \times 10^{-6}/^{\circ}\text{F}$) resulted in contraction of the tube away from the fitting resulting in excessive leakage ($> 10^{-3}$ sec/sec He). Because the heat shrink fitting is developed around the metallurgy of a "memory" Ti-Ni composition, it cannot be fabricated from any other metal alloy composition. The Rynglok fitting can be fabricated from a variety of materials (titanium, stainless steel, aluminum) and can be compatible with a variety of line materials.

Welding

Preliminary Studies. Several studies by both NASA and industry have proposed various welding processes and demonstrations of welding in space. Explosive welding has been proposed by NASA-Langley (Reference 5). Electron beam, laser, plasma arc, and gas tungsten arc welding were proposed for a shuttle flight demonstration through the initial NASA IN-STEP program (Reference 2). NASA also flew an electron beam experiment as a part of its Skylab program. However, none of these activities has led to any further welding-in-space development activities.

The former Soviet Union has been studying welding in space since 1965 and selected electron beam welding as the single process that met all of its requirements and was suitable for the space environment. Paton Welding Institute of the Ukraine developed an operational space welding and metals processing system based on electron beam technology. The system is shown in Figure 8. This space-qualified

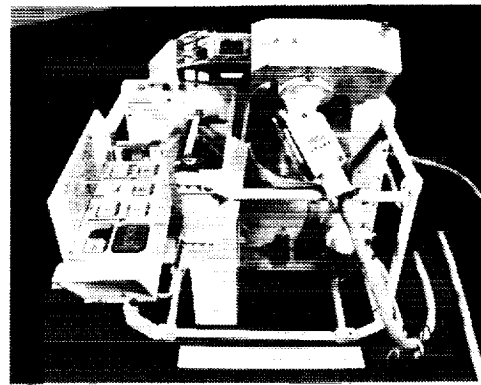


Figure 8. Paton-Developed Universal Hand Tool Space Welding and Metal Processing System

system, the Universal Hand Tool (UHT), can weld, braze, cut, clean, and coat metals in space. As shown in Figure 1, the welding unit was used successfully in 1986 to repair a damaged line segment on Soyuz T12. No data were available on the resultant weld quality except that it met operational requirements.

MDA Approach. The MDA approach to space welding is to develop a complete on-orbit capability to prepare weld joints, perform the welding operation, and inspect the completed welds. To this end, MDA has developed and demonstrated tools and procedures that will provide a capability to weld in space. MDA has concentrated its effort in understanding and demonstrating the space-qualified Paton UHT because it is the single system most applicable to near-term NASA space vehicle repair. To complement the UHT system, MDA has developed the MPT tube cutter, investigated joint preparation procedures, and developed an on-orbit tube weld inspection tool.

Tool Development. The MPT tube cutter (Figure 3), developed as part of the mechanical tube fitting repair procedure, is compatible with on-orbit weld joint preparation procedures. The MPT tube cutter produces a burr-free external tube cut and is capable of being both soft- and hard-docked to the tube, providing for crew freedom and safety, reaching into areas of minimal fluid line clearance, and cutting all weldable metal tubes proposed for space structure fluid line assemblies.

The Paton-developed UHT (Figure 8) is currently designed to weld flat plate and sheet materials. MDA, as a part of its 1993 joint IRAD program with MSFC, is developing a fixed tube welding head that is compatible with the UHT system. The tube weld head is stationary and provides electron beam orifices through which the tube weld is prepared. This fixed tube weld head will be demonstrated in 1993 as a part of the MSFC-MDA joint IRAD program. The Paton-developed UHT weighs approximately 65 lb and contains a manually operated, EVA-compatible hand-held weld gun that weighs approximately 5 lb (Figure 8). Safety

devices built into the system protect the EVA operator and provide for complete crew control. MDA is evaluating the 1.5-kW UHT in its 1993 joint MSFC-MDA IRAD program. Our program will prepare various joint designs in plate, sheet, and tubes using the tools and procedures developed in previous and current IRAD programs.

The 1993 IRAD program will also evaluate other metal processing capabilities of the UHT. Metal cleaning, brazing, cutting, and coating capabilities will be demonstrated. The 1993 IRAD program will also evaluate the on-orbit compatible tube weld nondestructive evaluation (NDE) system being developed for MDA by Oceaneering Space Systems.

MDA is also investigating variations in joint preparation procedures and their effects on weld quality. Such weld joint parameters as squareness, bevel, burr retention, and gap can vary as a result of the space environment in which a weld joint is prepared. Harvey Mudd College has completed a subcontract under the MDA 1993 IRAD program, and the data are currently being analyzed. Leak tests of tube samples prepared with controlled weld parameters have indicated that acceptable electron beam welds can be prepared with significant variations in these joint preparation parameters.

Tool Demonstrations. Our demonstrations to date have involved human interfaces with a high-fidelity model of the UHT; however, no actual welding has been performed until this year. Welding using an operational UHT will begin in 1993 under the MSFC-MDA joint IRAD program. Welding and UHT demonstrations will be performed in a vacuum chamber containing gloves or other provisions for hand-controlled remote UHT operation. Welds will be performed on both flat material and tubes. Tube welds will be inspected using the MDA-developed NDE system. Weld joint designs will be designed and prepared by MSFC. Joint preparation variations developed by Harvey Mudd College will be incorporated as a part of the weld joint designs. UHT performance, MDA-developed tool operation, and weld joint designs will also be evaluated in 1993 through a series of KC-135 flight demonstrations. Participants in the evaluations will include both NASA astronaut crew and MSFC personnel.

MDA has demonstrated the MPT tube cutter extensively through a series of neutral buoyancy and KC-135 evaluations. This modular system has successfully cut various tube materials, sizes, and clearances typical of those proposed for SSF (Figure 6).

MDA has also performed extensive crew interface evaluations with the UHT in both neutral buoyancy (Figure 9) and KC-135 0-g environments. The demonstrations concentrated on crew interfaces, operational scenarios, workstation performance, and safety issues. Crew feedback was vital and has been utilized extensively by Paton scientists to upgrade the UHT system design.

The telerobotic compatibility of the UHT system has been demonstrated by MDA (Figure 10). Using a supervised

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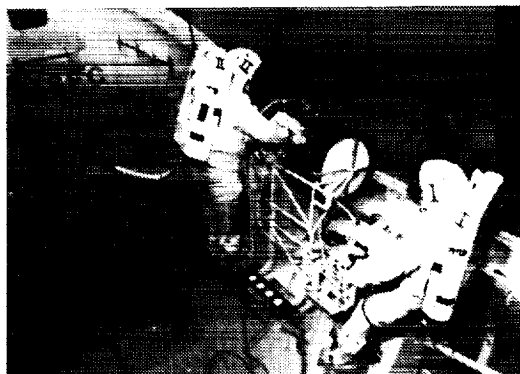


Figure 9. NASA-MDA Space Welding Activity

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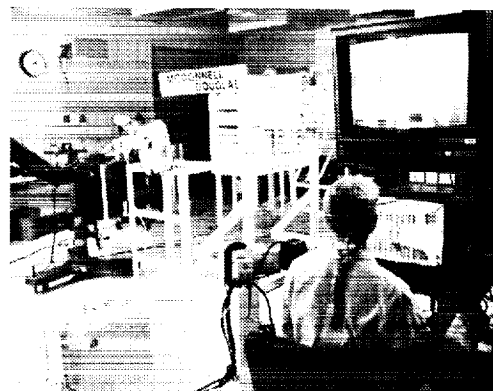


Figure 10. Telerobotic Manipulation of the UHT Space Welding System

programmed Kraft telerobotic arm and a specially designed robotic interface, the task scenarios included UHT removal from its storage basket, controlled movement of the UHT along a series of weld joint seams, and return of the UHT to its storage basket. Telerobotic demonstrations utilized both computer- and personnel-monitored tasks. This was a milestone first evaluation of a telerobotic interface with the Paton-developed UHT.

CONCLUSIONS

Both welding and mechanical fitting technology are compatible with future on-orbit repair and maintenance tasks for long-duration space vehicles. On-orbit repair by welding will require further study and development for selecting the weld system most appropriate for NASA future applications. The following specific conclusions apply to these two space repair technologies.

Mechanical Tube Fittings

Technology is well developed and adaptable to on-orbit repair scenarios of fluid lines and tube components. Further tool refinements are required to simplify the process and make it more EVA-compatible.

MDA-developed EVA-compatible tools and procedures, when qualified for flight, will have direct application to NASA's near-term space vehicles.

Technology developed on this IRAD program with the Rynglok nonseparable mechanical tube fittings forms the basis upon which MDA Space Station Division WP-2 has developed its on-orbit fluid line repair capability for SSF.

Welding

The Paton-developed electron beam space welder and metal processing system is space-qualified but requires further evaluation and demonstration to understand its full operational potential and performance safety.

MDA-developed tools will complement the UHT and any other selected space welding system to provide a complete on-orbit weld capability for space structure repair and maintenance.

A Space Shuttle EVA flight experiment in 1996 has been jointly proposed to NASA Headquarters by MSFC, JSC, and MDA to demonstrate an on-orbit welding capability using the UHT system and MDA Space Station Division developed tools and procedures.

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ACRONYMS

EB	electron beam
EMU	extravehicular mobility unit
EVA	extravehicular activity
He	helium
ID	inner diameter
IN STEP	In Space Technology Experiments Program
IRAD	internal research and development
IVA	intravehicular activity
JSC	(NASA) Johnson Space Center
KC-135	NASA aircraft for 0-g research
MDA	McDonnell Douglas Aerospace
MPT	Modular Power Tool
MSFC	(NASA) Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NDE	nondestructive evaluation
Ni	nickel
OD	outer diameter
scc	standard cubic centimeters
SSD	Space Station Division
SSF	Space Station Freedom
Ti	titanium
UHT	Universal Hand Tool
WP-2	Work Package 2

ON-ORBIT NDE—A NOVEL APPROACH TO TUBE WELD INSPECTION

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ABSTRACT

The challenge of fabrication and repair of structures in space must be met if we are to utilize and maintain long-duration space facilities. Welding techniques have been demonstrated to provide the most reliable means to accomplish this task. Over the past few years, methods have been developed to perform orbital tube welding employing space-based welding technology pioneered by the former Soviet Union. Welding can result in the formation of defects, which threaten the structural integrity of the welded joint. Implementation of welding on-orbit, therefore, must also include methods to evaluate the quality and integrity of the welded joints. To achieve this goal, the development of an on-orbit tube weld inspection system, utilizing alternating current field measurement (ACFM) technology, has been undertaken.

This paper describes the development of the ACFM on-orbit tube weld inspection tool. Topics discussed include: requirements for on-orbit NDE, basic theory of ACFM, its advantages over other NDE methods for on-orbit applications, and the ACFM NDE system design. System operation and trial inspection results are also discussed. Future work with this technology is also considered.

INTRODUCTION

To successfully utilize long-duration space facilities, adequate consideration must be given to maintenance and repair. In low Earth orbit, space structures are subject to significant risk of damage from debris impact, thermal cycling, and radiation exposure in addition to degradation from normal operational stresses and wear. Because of this adverse operating environment and the expense of replacing large structures, performing repair operations in space is the best approach to ensure long-term utilization.

For pressurized systems, welding offers the most reliable method for permanent repair of metal joints in space. McDonnell Douglas Aerospace (MDA) has advanced this technology since 1986 using tools and procedures developed by MDA as well as incorporating state-of-the-art electron

beam space welding hardware developed by the Paton Welding Institute located in Kiev, Ukraine. Welding is a critical process involving many variables to produce acceptable quality hardware. Even under controlled conditions on Earth, weld quality is not guaranteed and nondestructive evaluation (NDE) methods are commonly used to ensure weld quality. Verification of weld quality through NDE becomes even more significant in the remoteness of space, where the absence of process controls and the effects of a single flaw in a critical structure could prove catastrophic.

One of the most likely and challenging maintenance problems to be encountered on a complex structure such as Space Station Freedom is the repair of pressurized tubing. For this reason, the initial development of space welding capabilities at MDA has focused primarily on tube welds. With the help of the Paton Welding Institute, an automated electron beam device for welding small metallic tubes (0.5 in. OD, 0.035-in. to 0.063-in. wall thickness) is being developed and evaluated for use in a zero-gravity vacuum environment as part of a MDA Independent Research and Development (IRAD) task during 1993.

On-Orbit NDE of Tube Welds

In conjunction with this welding effort, an IRAD task to develop an on-orbit NDE system to inspect tube welds has been undertaken by MDA and Oceaneering Space Systems (OSS). The first step in the system development was to select the NDE method most suitable for this application. To objectively evaluate candidate NDE methods, the Kepner Tregoe analysis method was employed. This technique is a formal methodology for objectively selecting among numerous technical solutions by organizing requirements into MUST and WANT categories. Each candidate NDE method must first satisfy all of the MUST criteria. The successful methods are then evaluated against the WANT criteria through a weighted comparative process. Design requirements used for this analysis consist of the following MUST and WANT criteria:

1. **MUST Criteria**—The capability to detect welding flaws in the size range of interest without consideration for flaw position comprise the MUST criteria. Maximum allowable defect sizes derived from MDA tube welding specifications were used to develop these criteria. The specific flaw types and sizes selected are shown in Table I.

Table I. MUST Design Criteria

Sharp Flaws	Value	Notes
Maximum length	1.57 in.	The circumference of the tube
Minimum length	0.035 in.	The tube wall thickness
Maximum depth	0.035 in.	The tube wall thickness
Minimum depth	0.0175 in.	50% of tube wall thickness
Blunt Flaws	Value	Notes
Burn through	ALL	
Minimum diameter of single pore	0.0123 in.	35% of tube wall thickness
Minimum area of scattered porosity	0.011 in. ²	20% of weld area per inch of weld

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2. **WANT Criteria**—The following criteria and desired features, listed in Table II, were used to provide a weighted comparison between candidate NDE methods.

Table II. WANT Design Criteria

Criteria	Desired Feature
Safety	Low radiation hazard
	No sharp edges
	Low thermal output
	Low electrical discharge risk
Simplicity	No moving parts
	Loose positioning tolerances
	No system calibration
	Little operator training
	Easy data interpretation
Size	Probe head less than 2.0 in. in diameter
	Single hand manipulation
Power	28 VDC or less for use in Shuttle bay
	120 VDC or less for use on Shuttle flight deck

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Of 15 initial candidate NDE methods, only radiographic, ultrasonic (shear wave, surface wave, and plate wave), eddy current, alternating current potential drop (ACPD), and alternating current field measurement (ACFM) offered the potential to meet all of the MUST criteria. Further comparisons utilizing the weighted WANT criteria resulted in the selection of ACFM as the best NDE method for on-orbit inspection of tube welds.

ACFM technology was first pioneered in 1988 by mechanical engineers at University College, London. Inspection systems utilizing this method have been developed for underwater inspections of offshore structural welds since 1990 by Technical Software Consultants, Ltd. (TSC). Currently, ACFM arrays are being developed for remote operated vehicles (ROVs) and have been tested in the North Sea.

ACFM offers many advantages over other NDE methods for remote on-orbit operations. ACFM technology allows complete mathematical modeling of the signal response, thereby rendering repeated system calibration unnecessary. ACFM coils can be multiplexed in array configurations to provide fast inspection times and eliminate the need for scanning and moving parts. Furthermore, ACFM is relatively insensitive to liftoff variations and direct contact with the part surface is not required. These features allow for simple operation by just placing the probe over the area to be inspected and energizing the coils. Data analysis is accomplished by computer with permanent storage of results. Packaging of the electronics allows the ACFM NDE tool to be contained in a hand-held, lightweight device.

Basic Theory of ACFM

ACFM is an electromagnetic technique which induces or injects a uniform electrical field into a conductive material and measures the magnetic field above the specimen surface (Reference 1). The current is confined to a thin layer of the material at the surface, known as skin depth, similar to eddy current fields. These surface currents produce alternating current (AC) surface magnetic fields which decay with distance from the surface. Uniform fields used with ACFM, however, decay more slowly than the non-uniform eddy current fields, making ACFM much less sensitive to liftoff and probe misorientation. A non-contacting probe coil is used to record the magnetic field strengths. Size and shape of the probe coil can be selected to provide optimum sensitivity to suspect defects.

When the uniform field current encounters a defect in the conductor, it is forced to flow around the defect, diverting some of the current away from the defect center and concentrating it near the ends. When the probe crosses the defect, perturbations in the primary components of the magnetic field result. An illustration of the uniform field at a crack and the resulting magnetic field components is shown in Figure 1.

The uniform AC field can be injected or induced by separate field injectors unlike eddy current methods which use the same coil to induce a non-uniform field and measure the material response. Because the field in ACFM is uniform, theoretical predictions for the magnetic perturbations are possible, eliminating the need for system calibration during use. Topp and Dover (Reference 2) have shown that Laplace and Born type approximations can be used to model the response from cracks in conductive materials. Figure 2 shows the comparison of experimental and theoretical distributions of magnetic field components over a grid in the x-y plane above surface breaking defects in mild steel (Reference 3). Changes in the B_x component of the magnetic field (Figure 2a) reflect the changes in current density so that B_x is below its background level over most of the crack length but rises above that level near the crack ends. The component B_y (Figure 2b) is determined by the current flow parallel to the crack edges and thus peaks

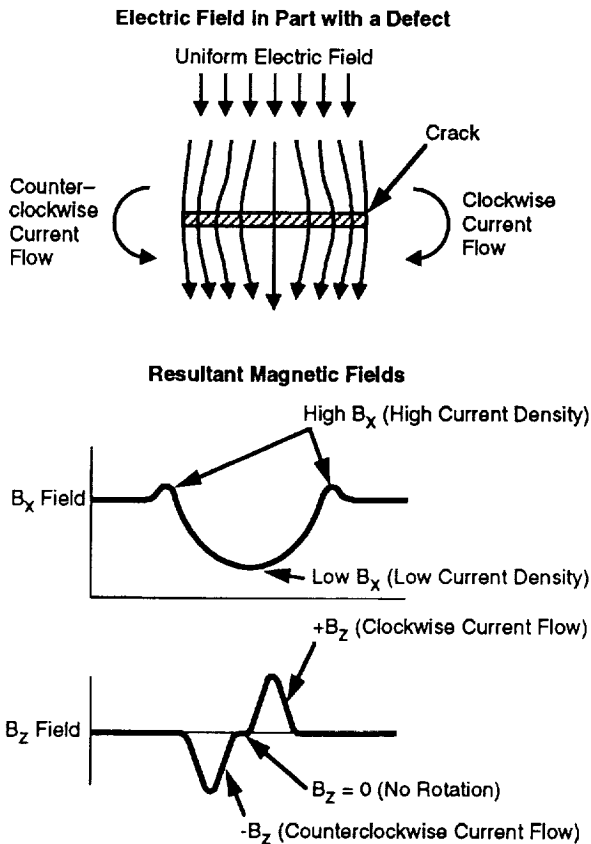


Fig. 1. ACFM electric and magnetic fields

toward the crack ends and is of opposite sign on each side of the crack. The vertical component B_z (Figure 2c) is determined by the circulation of the current around the crack ends. Since this circulation is clockwise at one end but counterclockwise at the other, the B_z signal consists of a peak at one end and a trough at the opposite end of a crack. This characteristic response of the B_z field in the presence of a flaw is the most identifiable of the three components and offers the greatest sensitivity for the detection of surface breaking flaws.

Quantitative predictions of the magnetic field response have been produced for various crack shapes and sizes in a variety of metals. These predictions can then be used to determine not only the presence of a crack but also its length and depth. Utilization of uniform fields also makes the implementation of sensor arrays easier, eliminating the need for scanning. The following sections detail how this innovative technique has been applied to the development of a proof of concept (POC) NDE system for the inspection of tube welds.

ACFM ON-ORBIT NDE SYSTEM DEVELOPMENT

System Design

The POC ACFM NDE system is made up of three major components, all interconnected by umbilicals. The first of these is the extravehicular activity (EVA) tube inspection hand tool which is connected by a tool umbilical to the

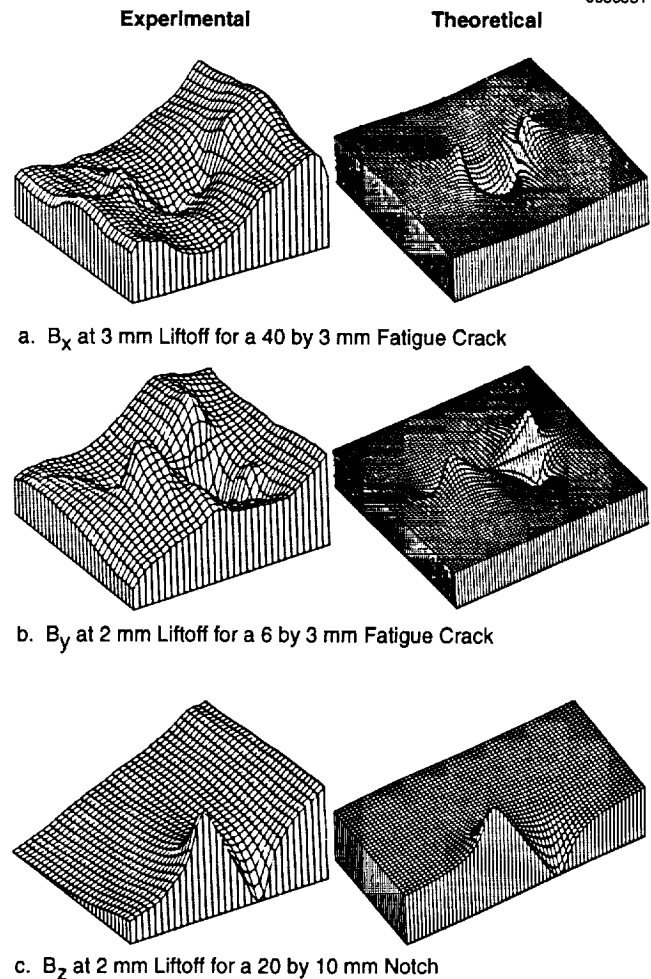


Fig. 2. Comparison of experimental and theoretical distributions of magnetic field components

second component, the U10 data acquisition unit. The third unit is a standard 486 33-MHz personal computer (PC) which communicates with the U10 by a serial line. Separation of the POC system into these three individual components allows maximum use of currently available equipment and provides easy development into a subsequent flight system. Configurations for both the POC system and a proposed flight system are shown in Figure 3.

Hardware Description

1. ACFM NDE Tube Weld Inspection EVA Hand Tool—The EVA tube inspection hand tool is shown in Figure 4. Its function is to place the ACFM array around the tube weld and to inject a uniform AC field into the weld area. Multiplexing in the tool head switches through the array coils, sending the voltages they are experiencing to the U10 data acquisition unit. The control computer makes the decisions based on the data collected by the hand tool and relays these decisions to the hand tool where appropriate light emitting diodes (LEDs) are illuminated to inform the EVA operator of the status of the inspection. LEDs also

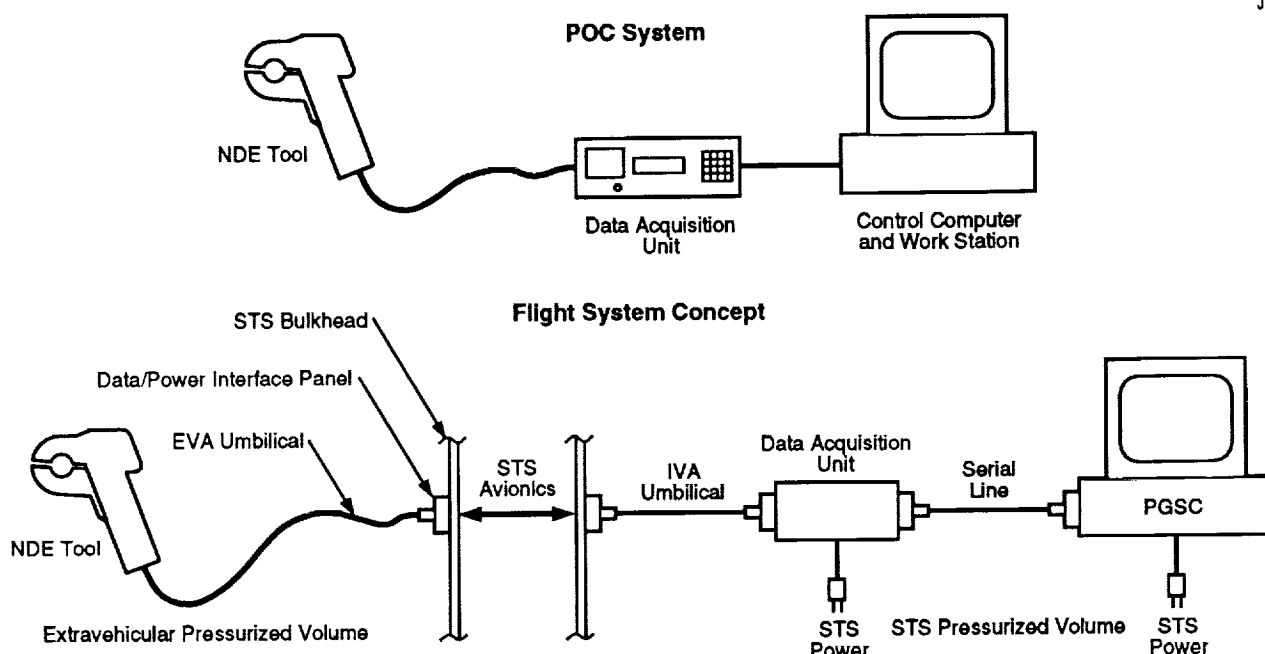


Fig. 3. Proof of concept and flight system configurations

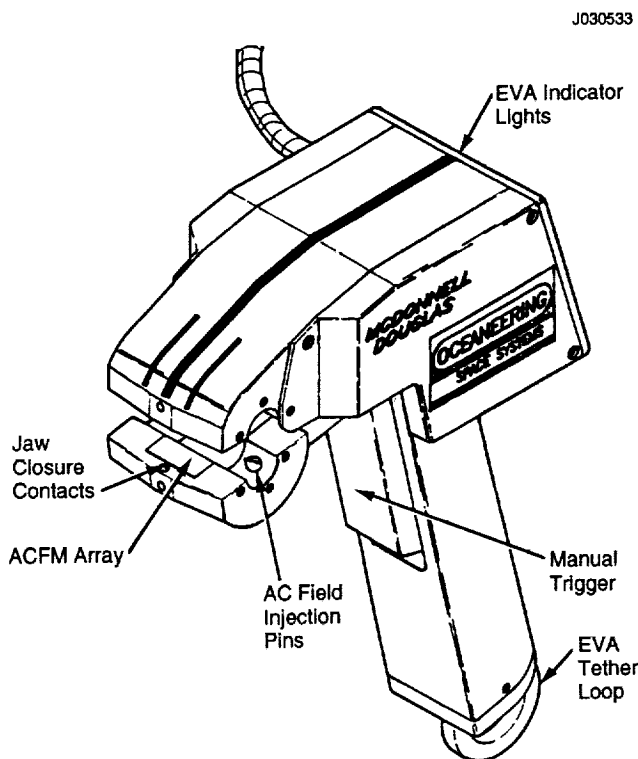


Fig. 4. EVA tube inspection hand tool

reflect whether the hand tool jaw is properly closed and whether the AC field has been successfully injected.

Jaw opening and closure is manually controlled by a squeeze trigger. The jaw opening is designed to accommodate a tube with a maximum diameter of 0.5 in., thus reducing the

EVA pinch risk. The jaw closure is sensed by contacts in the mouth of the jaws and an LED is illuminated. The hand tool grasp interface is designed to conform to Manned Systems Integration Specification (MSIS) EVA gloved hand requirements. A jaw opening actuation force of approximately 5 lb has been selected to provide easy but deliberate activation. Injection of the AC field occurs through eight contact pins; these are designed to ensure a uniform input field. Four LEDs are mounted on the back plate of the hand tool with clearly marked labels.

The ACFM 96-coil array is housed in two semicircular blocks designed to accept 0.5-in. diameter metal tubes. The total array is made up of 3 rows of 32 rectangular coils each measuring 0.197 in. long by 0.039 in. wide and inspects the entire tube circumference for a length of 0.5 in. Each coil is oriented perpendicularly to the tube surface to provide optimized measurement of the resultant B_z magnetic field. The rectangular coil arrangement provides maximum resolution in the circumferential direction (coil width direction) while maintaining the total number of coils at a manageable level. Fast multiplexing electronics built into the tool head reduces the amount of cabling required to transmit data back to the U10. A sketch of the ACFM probe head depicting the coil arrangement and field injector locations is shown in Figure 5.

2. U10 Data Acquisition Unit—The POC system will use a modified TSC U10 data acquisition unit. The U10 contains a 68000 series microprocessor and communicates with a PC by an RS232 serial line. The function of this data acquisition unit is to control sensor readings from the ACFM array, provide the AC field for injection into the test piece, and to distribute the inspection data to the control computer. The

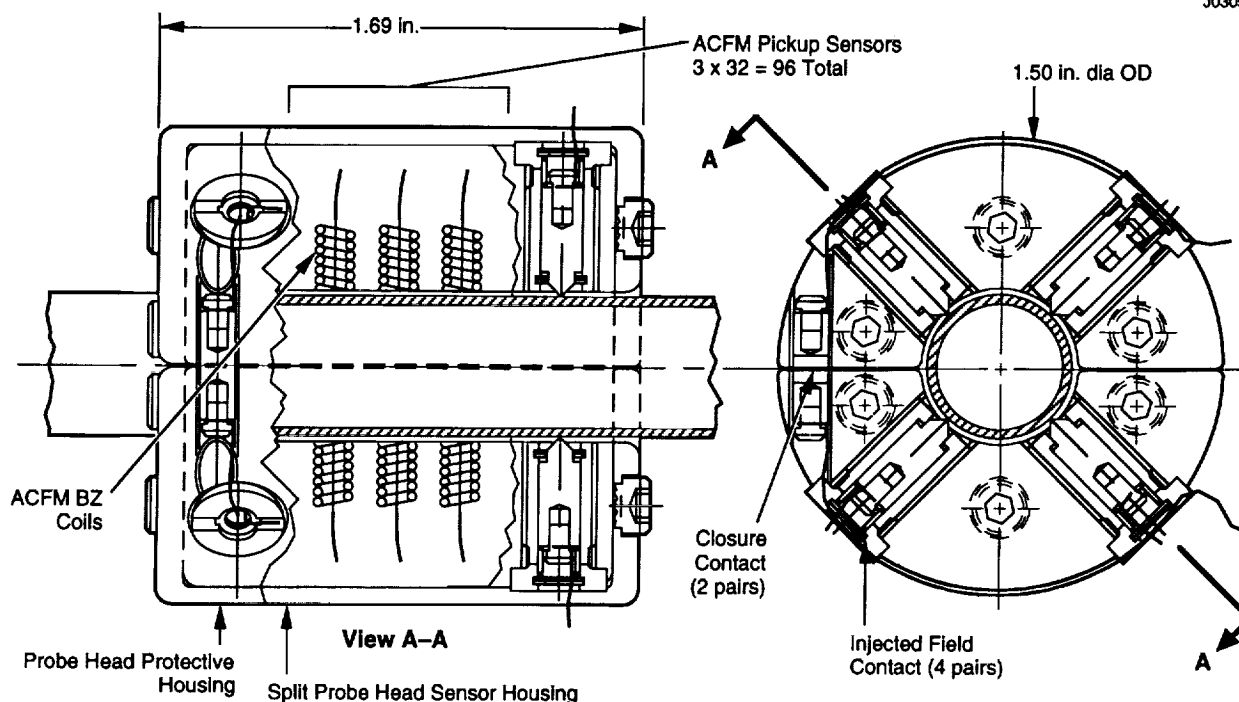


Fig. 5. ACFM probe head

U10 is the standard laboratory ACFM data acquisition unit manufactured by TSC.

3. PC Control Computer—Computation and data storage are performed by the 486 PC. The PC also controls the U10, collects inspection data from the U10, analyzes the data through the use of algorithms derived from the experimental results, and displays the results through a customized graphical user interface. The inspection data will take the form of a two-dimensional false color map of the inspected area and three Bz amplitude representations. A pictorial representation of the anticipated operator display is shown in Figure 6. All data will be capable of being labeled and stored to hard or floppy disk.

Control and Interface Software Description

The control system is split between software on the PC, firmware on the U10 instrument, and local logic on the NDE tool. A schematic of the system architecture is shown in Figure 7.

The PC software is written in C++ with Visual Basic graphics at the front end for easy customization. This software controls initiation and override of scan sequence and provides the user with an interface for data display and storage. PC software also analyzes the data through comparisons to programmed acceptance criteria models and determines the defect accept/reject status.

The U10 firmware is written in assembler and installed on electronically programmed read only memory (EPROM) chips. It sets up the instrument parameters and checks for field high/low resistance by A/D channels. The firmware

also controls LEDs for field contact and defect accept/reject status as well as the hand tool multiplexer for data collection.

ACFM ON-ORBIT NDE SYSTEM OPERATION

Inspection Procedure

The ACFM on-orbit NDE system is designed for simple reliable operation. In an on-orbit scenario, the system will utilize two operators—one crew member at the PC computer on the shuttle flight deck (PC operator) and another crew member in the Shuttle cargo bay with the umbilically linked ACFM hand tool performing the EVA weld inspection (EVA operator). The following steps outline a typical weld inspection procedure:

1. Using the graphics interface on the PC, the PC operator selects one of the three inspection control modes (single shot scan, continuous scan, or diagnostic). The continuous mode is assumed in this scenario.
2. The EVA operator squeezes the tool trigger and opens the jaws. He then moves the tool over the weld and releases the trigger which closes the tool around the tube weld.
3. The computer confirms that the injected AC field is present and that the jaws are closed, lighting two LEDs on the hand tool, then initiates a scan.
4. The computer decides if a significant defect has been located, displays the result on the PC screen, and lights the appropriate LED on the hand tool.

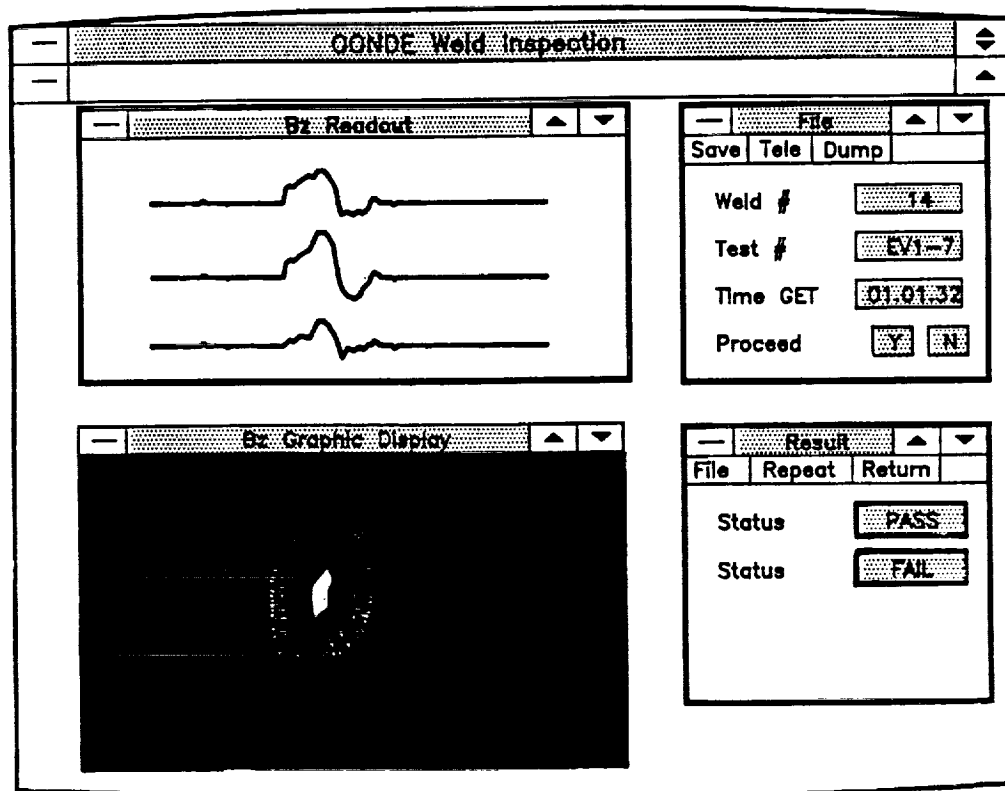


Fig. 6. Operator display screen

5. If the EVA operator does not open the jaws to move on to the next inspection another scan is initiated.
6. The PC operator now has the option to permanently store the inspection results on floppy or hard disk.

Preliminary Test Results

Although integration of the entire system is not yet complete, initial tests have been conducted by TSC using a partial ring array on man-made defects in a sample of 0.5-in.-diameter stainless steel tubing. The partial ring array is a semicircular block of 16 coils (one-sixth of the total POC array). Data was collected with this array using the completed POC electronics and control software. In each of the reported tests the partial ring array was clamped over the inspection area and the uniform AC field was injected via crocodile clips at either end of the tube. Using the PC interface, the array was sampled by the U10 and the results of the inspection displayed on the PC screen. Because only 16 coils were used, representing one-half of a complete ring, only one line of data appears on the screen rather than three.

The results of these inspections are shown in Figure 8.

Figure 8a illustrates the inspection results from a 0.2-in.-long, 0.018-in.-deep saw cut in a stainless steel tube. This large defect is clearly seen in the line plot of the Bz amplitude. The dashed lines on the Bz display indicate the

thresholds for defect detection. Figure 8b illustrates the response of a smaller defect, in this case a 0.02-in.-diameter through hole. Again, the defect signal response exceeds the threshold and the inspection is successful. Figure 8c illustrates the response of a defect-free area of the tube with the instrument sensitivity identical to the previous tests.

CONCLUSIONS/FUTURE WORK

The on-orbit NDE tube weld inspection system, utilizing ACFM technology offers a viable approach to tube weld inspections. The preliminary results indicate that the sensitivity of the system should allow the detection of the minimum defects while providing a clear and automatic indication to the operator of the inspection status. Once integration of the entire system has been completed, comprehensive testing will be performed throughout the remainder of 1993 to more fully establish the performance capabilities of the system.

As previously mentioned, this POC system has been designed to facilitate development to a flight ready system. Future plans include the development of a flight system for demonstration onboard the Space Shuttle as a part of the proposed Welding In Space Experiment. The NDE flight system will utilize the same major components as the POC system and will be its functional equivalent. The major difference between the two systems is the design of the

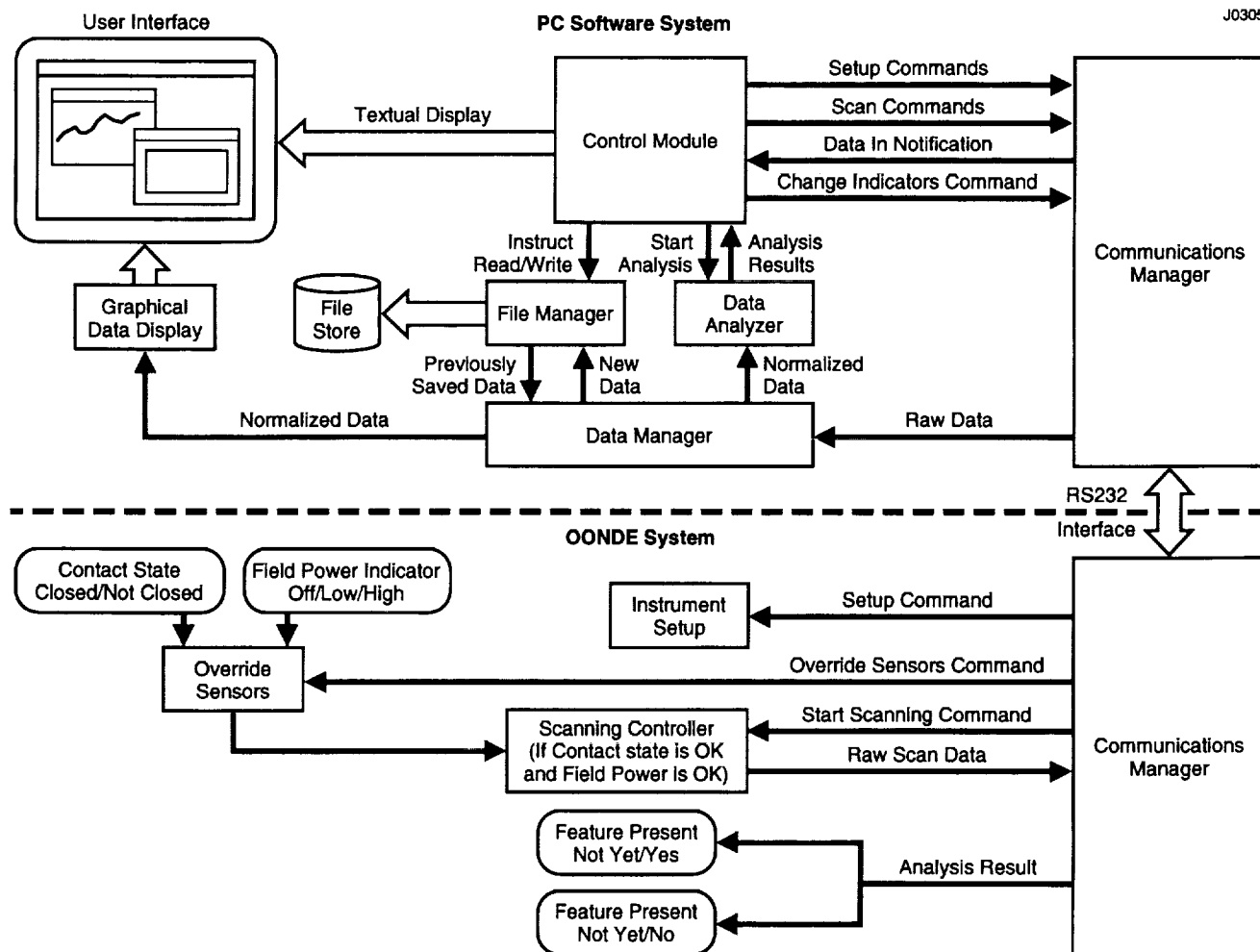


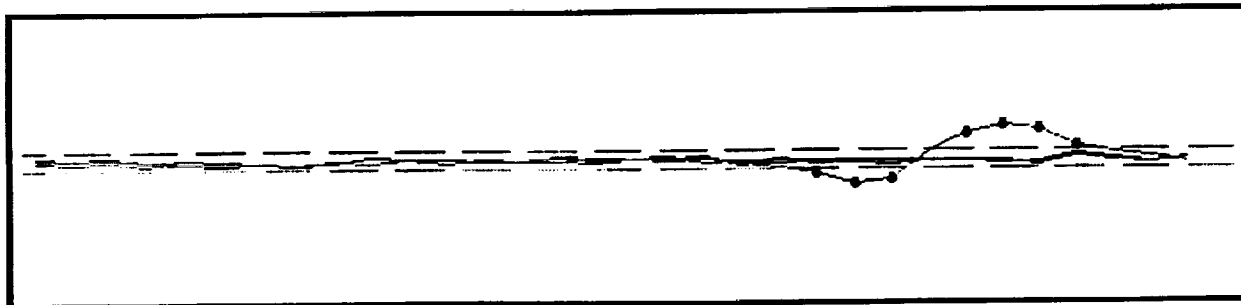
Fig. 7. ACFM on-orbit NDE system architecture

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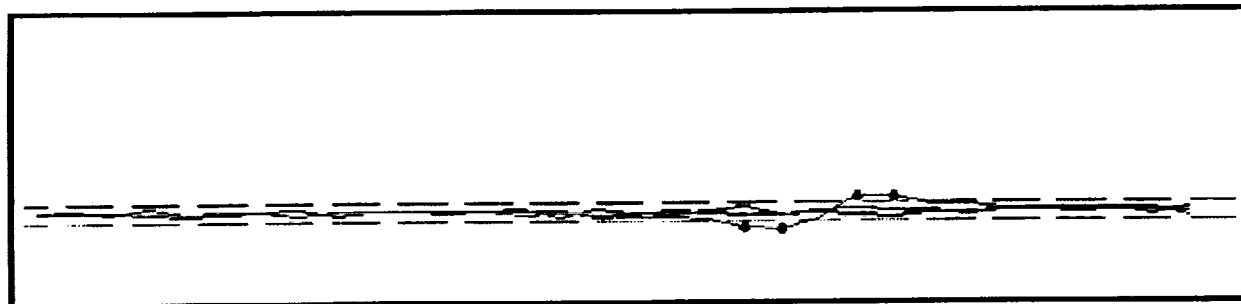
individual components and their interconnection with each other and with the Space Shuttle intravehicular and extravehicular systems.

ACFM array technology may also offer a competitive alternative to conventional NDE for Earth applications as well, considering the obvious advantages of operational simplicity, speed of inspection, small size, and data retention capabilities over conventional NDE techniques. Furthermore, ACFM arrays offer the flexibility to design specialized inspection tools for specific geometries, configurations, and defect types with remarkable sensitivity.

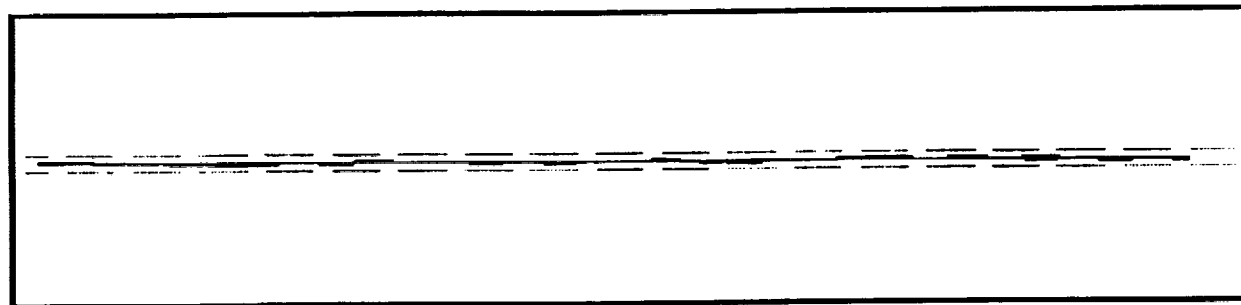
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a. Response From 0.2 x 0.018-in. Saw Cut



b. Response From a 0.02-in.-Diameter Through Hole



c. Response From Defect Free Area

Fig. 8. Preliminary test results

Force Override Rate Control For Robotic Manipulators

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1 Abstract

The work reported deals with the problem of operating a robot manipulator under a rate control mode while the end effector is not in contact with the external environment, and then switching to a force control mode when contact is made. The paper details how the modal changeover may be accomplished in a manner transparent to the operator, and will allow operator applied forces to be reflected at the robot end effector. A one degree of freedom demonstration system is used to illustrate the concept, which is then applied to a PUMA manipulator. Sample code for the implementation of the control is provided, experimental results show that the optimum setting for the gain is a function of the compliance of the end effector, and the compliance of the external constraint.

2 Introduction

Many conventional robot manipulators operate either in rate, or in positional control modes. That is to say that a command issued by the operator causes the end effector of the manipulator to move with a particular velocity in a certain direction, or to move in a specified direction a given distance. Intuitively, this is the most useful form of motion required of a manipulator, since it can be used to accomplish a wide variety of tasks involving the positioning of objects for assembly tasks, or the performance of speed related tasks such as welding, or grinding.

Another class of motions for which manipulators may be used may be classified as force control problems. In these cases, it is required to develop forces and perhaps moments between the manipulator and an external environment, in order to perform the required task. Examples of application of force control would include removing a module from a satellite in the cargo bay, or assembling components of the space station structure. Clearly, more than simple motion of the end effector is required, and some knowledge, and subsequent control of the interactive forces and moments developed between the manipulator and the environment in which it works, has to be established.

3 Background

Force control of robotic manipulators is an established subject with an extensive literature [1], [2], [3], [4], [5], [6]. Much of the existing work is focussed on how to transform force and moment requirements expressed in the world or task frame, to torques exerted by the individual joints of the manipulator. An example of this might be where a manipulator is attempting to insert a screw. The problem to solve is: what robot joint torques provide a torque about the screw axis, and a downward force on the screwdriver to accomplish insertion. This problem, and many like it, are solved by using the manipulator Jacobian to relate forces and moments expressed in terms of joint and world coordinate frames. Since the Jacobian relates differential displacements in these two frames, we may write

$$\delta \mathbf{x} = \mathbf{J} \delta \mathbf{q} \quad (1)$$

where the differential displacement in the world frame is $\delta \mathbf{x}$, while the differential displacement in the tool frame is $\delta \mathbf{q}$. The principle of virtual work may be used to derive

$$\boldsymbol{\tau} = \mathbf{J}^T \mathbf{F} \quad (2)$$

where $\boldsymbol{\tau}$ is the vector of joint torques and \mathbf{F} is the vector of forces and moments expressed with respect to the world frame. Although most manipulators implement equation 1 to relate world and joint motions, few if any implement equation 2, enabling engineers to control world space forces by controlling individual joint torques. Even if this were available, the task of accurately controlling joint torques¹ is very difficult.

In the majority of tasks in which we are interested, man in the loop, rather than computer control, is the normal mode of operation. In such operations, the forces needed to accomplish a particular task are not specified analytically, rather, they are generated by the operator in a natural manner. Inserting a screw is a good example of this. All that is required is to feed back to the operator a measure of the forces generated by the manipulator as it performs the task, enabling a reduction or increase in force as appropriate. This scenario is usually described as bi-lateral teleoperation.

In the work described here, we use a simple adaptation of conventional position and speed controlled manipulation tasks to achieve force control in a natural and operator transparent manner. In addition, the system is not strictly bi-lateral in nature, although the operator does experience the forces being applied to the remote manipulator. The overall system provides a simple means to implement force control strategies on existing manipulation systems in order to accomplish assembly-type tasks.

4 Single Degree of Freedom Force Control System

The system is meant to simulate a one degree of freedom actuation system operating in rate and force mode, i.e. on a commanded signal, the output of the system achieves a velocity proportional to the input. The system schematic is shown in figure 1.

¹usually by controlling motor current

A simple center-off toggle switch represents the rate input signal, and may be either zero, positive or negative. The switch output drives an electro-hydraulic servo valve which is connected to a hydraulic cylinder. Using this arrangement, the piston rod may be driven in either direction at a constant speed, or held stationary when the switch is in the center position. The end-effector attached to the cylinder rod now has to interact with an external, compliant constraint, and has to exert operator applied forces to it.

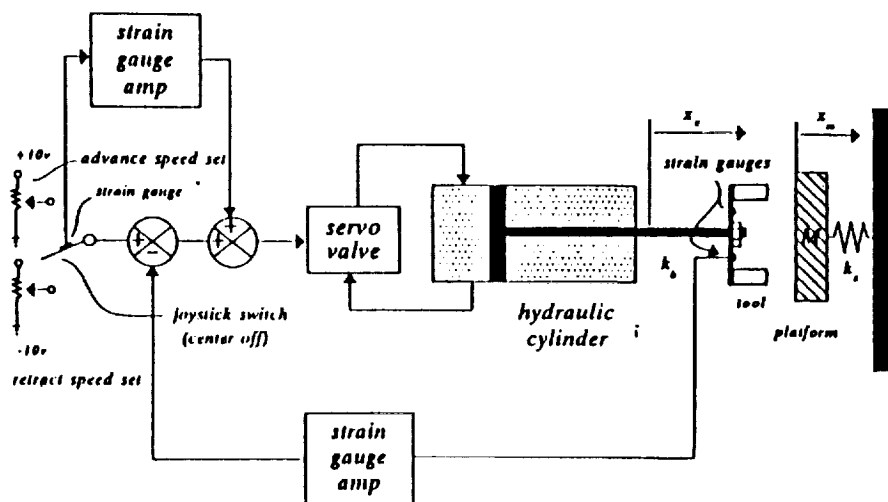


Figure 1: Force Override Control System

A strain gauge is attached to the extended handle of the toggle switch, and another strain gauge fixed to the stiff, but compliant part of the end effector, as shown in figure 2.

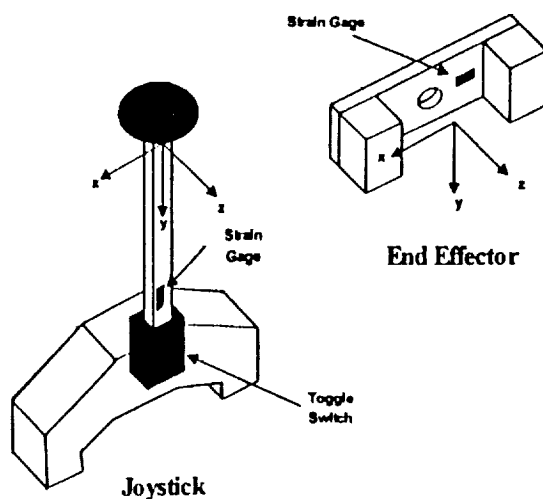


Figure 2: Strain Gauge Placement on Joystick and End Effector

The strain gauge on the end effector now acts as a mechanism to prevent large forces being

applied to the spring loaded plate, representing the external environment, by feeding back its signal to a summing junction following the toggle switch. By moving the toggle switch off the center position, the ram will advance at a constant speed until contact with the plate occurs. Further motion of the ram increases the feedback signal, reducing the ram speed until equilibrium is achieved with the ram stationary, and a finite deflection of the plate. This deflection may be adjusted by the feedback strain gauge amplifier gain,

At this point, the operator may press forward on the toggle switch handle, generating a signal from the strain gauge attached to it. This signal is added to the forward path signal causing further advancement of the ram. Pulling back on the lever will reduce the contact force. Returning the toggle switch to the off position will cause the ram to retract until the end effector is just touching the plate, theoretically with no interactive force between them.

In this manner, the forces applied by the operator to the control handle are reflected to the end effector. Although no force signal is fed back to the operator, because he/she is applying the demanded force to a compliant member, some knowledge of the magnitude of the applied force is sensed. The ratio of demanded and actually exerted forces may be scaled up or down using the forward path gain.

If the dynamics of the servo valve are considered to be faster than the rest of the system, the block diagram of the force override rate control system appears as shown in figure 3.

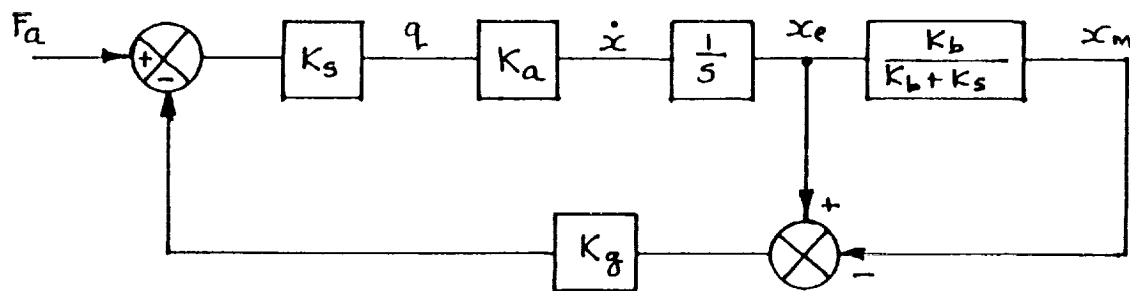


Figure 3: System Block Diagram

In the figure, we define: K_g = strain gauge amplifier gain, K_s = servo valve constant, K_a = actuator gain, K_b = end effector stiffness, and K_s = constraint stiffness. Since the open loop transfer function may be written as

$$GH(s) = \frac{K_s K_a K_g A}{s} \quad (3)$$

where

$$A = 1 - \frac{K_b}{K_b + K_s} \quad (4)$$

and is clearly a positive constant, it appears that the system is first order. The step response may be expected to be exponential, with a time constant selectable by the forward path gain. Experimental results, though not presented here, confirmed the result.

4.1 Robot Manipulator Based System - One Degree of Freedom

In this phase of the work, the preceeding concept was applied to an industrial manipulator, a PUMA 560, in order to determine the functional requirements of a commercial controller which could accommodate the force control system. Figure 4 shows a schematic of the system, and indicates how the toggle switch controller and end effector from the electro-hydraulic test facility were simple changed to the robot facility.

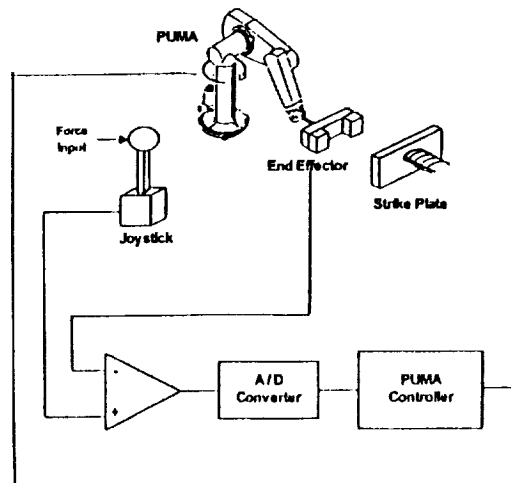


Figure 4: Force Override Using Manipulator

The force error is determined by analog equipment, so the problem is to firstly communicate the magnitude of this error to the PUMA controller, and then to drive the manipulator in an appropriate manner in response to the error. The first problem was solved by simple A-D conversion, at about 200 Hz, and connecting the resultant eight bit number to the PUMA controller parallel port.

Moving the manipulator in response to the resultant force error is somewhat machine specific, but results for the PUMA are presented in detail since most manipulators offer a similar programming environment, and so the algorithms should be easily transportable to other platforms. The resultant code is as follows, written in the VAL II language.

```
20  prompt 'Calibrate (1) or run (2)';c
    if c=2 goto 10
    rate=25
    signal 1,2,3,4,-5,-6,-7,-8
    cv=bits(1001,8)
    type 'Calibrated value=';cv
    goto 20
```

```

10  x=bits(1001,8)
    z=(cv-x)/rate
    if(abs(z))<2 goto 10
    type x,z
    departs z
    goto 10

```

The first half of the program, between lines 20 and 10, reads the A-D converter to obtain a current value. This allows for drift in the analog part of the system. At line 10, the A-D converter is read into x , and a target displacement z calculated. This value actually corresponds to a speed, since the program executes the loop recursively, hence the motion of the tool is observed as a constant speed. The actual speed may be varied to a convenient value by the experimentally determined variable $rate$. The motion command `departs z` causes the end effector to move in a straight line z centimeters in the direction of the positive z axis. Because the loop is executed about every 50 msecs, new force errors from the A-D converter are read in each time. In addition, a dead space of 2 reduces spurious motion of the end effector due to noise and vibration causing the A-D converter output to vary in a random manner. This program exhibits both rate control of the PUMA, and force control when driven by the joystick.

The selection of the variable $rate$ will affect the operation of the system. If the manipulator is in contact with a very stiff spring, and the force error commands the tool to advance, say 10 mm, large forces will be developed before the control loop next examines the force error, and retracts the tool. The effect of changing $rate$ is the same as changing the forward path gain in an inverse sense, i.e. increasing $rate$ decreases the forward path gain. In this experiment, and the one described next, the forward path gain has to be determined by considering the external stiffness with which the manipulator interacts, so as to prevent the development of large forces.

4.2 Robot Manipulator Based System - Multi-Degrees of Freedom

To implement this phase of the work, it was decided to try to make the end effector of the PUMA apply three dimensional forces exerted by the operator on a compliant joystick. Figure 5 shows the design of both the joystick and end effector attached to the PUMA.

In this design the forces applied in the x , y and z directions of the joystick frame are decoupled by means of the placement of strain gauges. Gauges are placed in identical locations on the end effector. In designing these units, the stiffness in each of the three directions was made the same. Commercial force/torque sensor units could be used instead.

Force errors in each of the three directions were generated in analog mode with the use of three differencing junctions. These force errors were then fed to a multi-input A-D converter which the PUMA could address. The software for acquiring the analog signals and moving the PUMA in response to them is very similar to that written for the one degree of freedom discussed earlier.

Test were performed on the system by observing the step response of the force applied by the robot tool to a demanded force applied at the joystick. The applied force was generated by applying a static load in the required direction on the joystick. Force outputs in the x , y and z directions at the tool were recorded, for various settings of the servo-system forward path gain β . Experimental

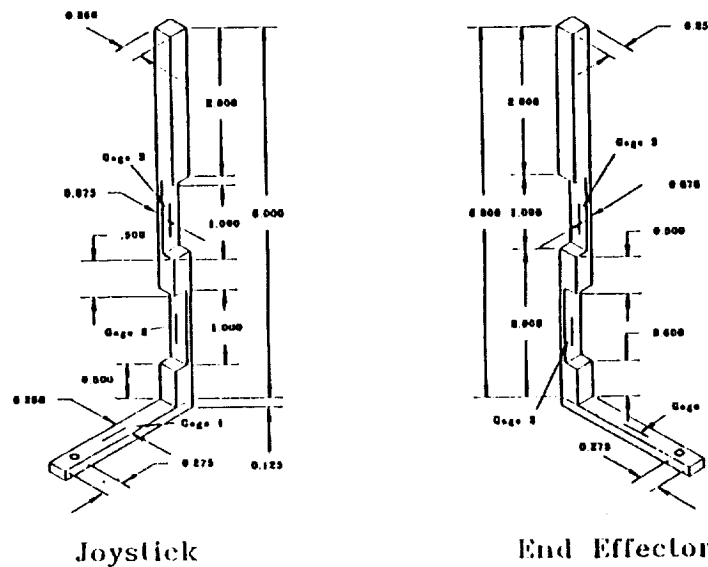


Figure 5: Force Sensing Joystick and End Effector

data, for increasing β , are shown in figures 6, and 7. In these tests, the tool interacted with the same spring loaded plate constraint described earlier.

5 Discussion of Results and Conclusions

Although developed in a heuristic manner, the concept of a force control system overriding a rate control system appears to perform as expected. Operator applied forces and moments may be reflected at the end effector, with the operator experiencing some measure of the forces being applied. In the purely analog implementation using a one degree of freedom electrohydraulic actuator, the response time may be freely adjusted by means of the forward path control system gain.

In applications in which sampling of the force, or force error is used to drive the actuator, the response is a function of the forward path gain, the compliance of the end effector and the compliance of the constraint against which the end effector reacts. The external stiffness has to be known before the limiting gain, consistent with stability, may be determined. Examples of such unstable response corresponding to increased gain may be seen in figures 6 and 7.

Since prior knowledge of the environmental compliance is needed to set the system gain to obtain acceptable response, a system with fixed gains cannot provide optimum response for all tasks it has to perform. If the external stiffness is unknown, the manipulator needs to carefully probe the environment in order to determine the nature of the constraint it is dealing with. Once this has been determined, the system gains may be adaptively set to deal with the task. It will be expected that different responses will be obtained from objects constrained by springs (of varying stiffnesses), and objects subject to purely inertial forces, such as a freely floating satellite. Current work is being directed to this area.

The implementation of the force override system has been implemented on a particular robotic platform, but the concept is general enough to be transferred to most manipulation systems. One advantage of the system is its ability to be overlaid onto an existing manipulator and controller

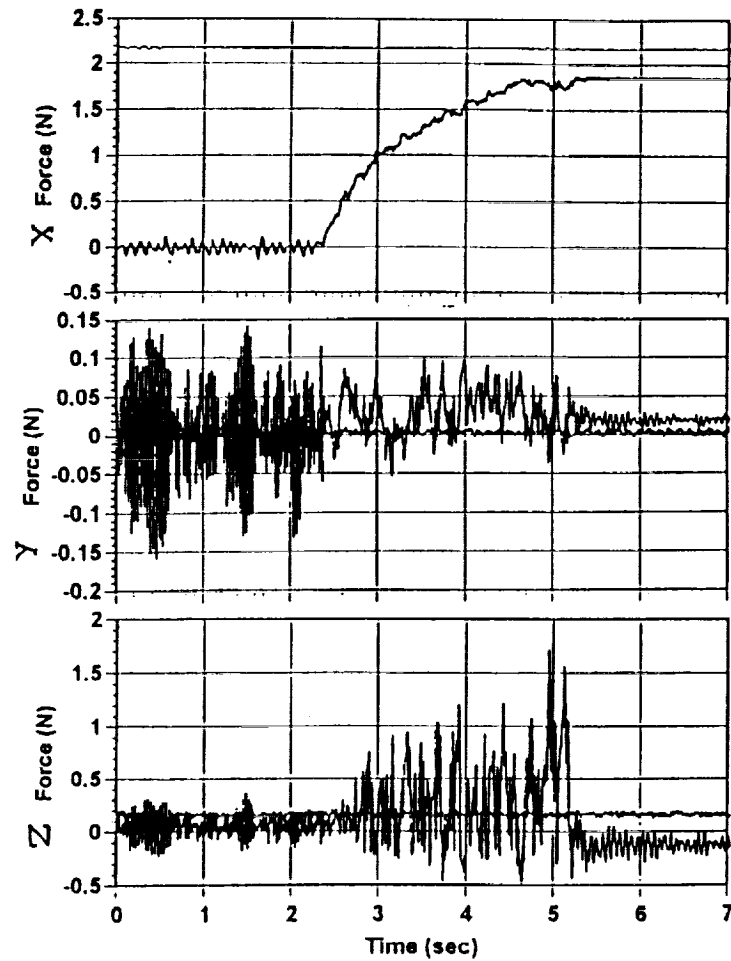


Figure 6: Step Response in x Direction for $\beta = 0.5$

combination.

6 Acknowledgement

The author wishes to acknowledge NASA Johnson Space Center, and the Naval Postgraduate School for their support of the research work reported.

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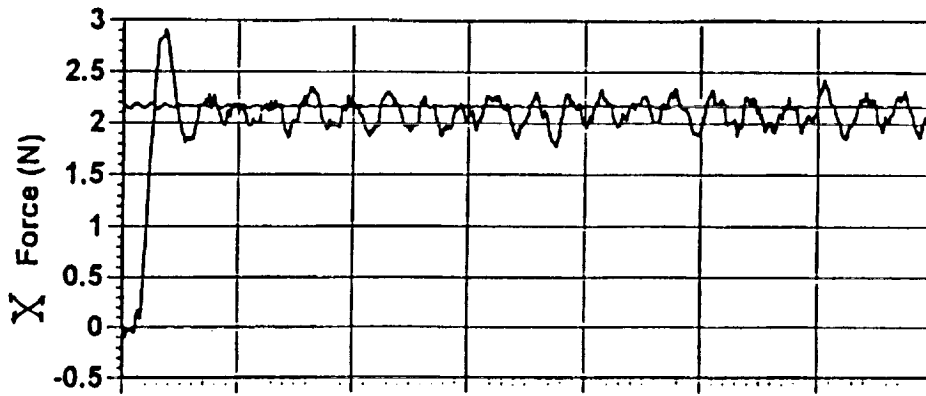


Figure 7: Step Response in x Direction for $\beta = 4.0$

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NASA Shuttle Logistics Depot Support to Space Station Logistics

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Over the past 25 years, Space Logistics has undergone a great evolution in thought and practice. We have progressed from a "Fire and Forget" posture to providing complete integrated logistics support for a reusable spacecraft with a multimission role. This shift in the framework of Logistics has influenced the various design communities in their endeavor to support the changing requirements for the types of hardware necessary to meet the space flight mission challenges.

We are about to embark on the next evolutionary step from the reusable spacecraft to a permanent on-orbit facility. This facility will have the capability of supporting human life over a 30-year period. Many new challenges to our Logistics systems must be met with the same emphasis on innovation as has led us in the past. We must be careful to take full advantage of the lessons learned on the Shuttle Program, as well as to develop new approaches and techniques to solve the many challenges that confront us with the Space Station Program.

Session S2: SPACE MAINTENANCE AND SERVICING

Session Chair: Mr. Charles Woolley

GRAPHICAL PROGRAMMING: A SYSTEMS APPROACH FOR TELEROBOTIC SERVICING OF SPACE ASSETS

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ABSTRACT

Satellite servicing is in many ways analogous to subsea robotic servicing in the late 1970's. A cost effective, reliable, telerobotic capability had to be demonstrated before the oil companies invested money in deep water robot serviceable production facilities. In the same sense, aeronautic engineers will not design satellites for telerobotic servicing until such a quantifiable capability has been demonstrated.

New space servicing systems will be markedly different than existing space robot systems. Past space manipulator systems, including the Space Shuttle's robot arm, have used master/slave technologies with poor fidelity, slow operating speeds and most importantly, in-orbit human operators. In contrast, new systems will be capable of precision operations, conducted at higher rates of speed, and be commanded via ground-control communication links. Challenges presented by this environment include achieving a mandated level of robustness and dependability, radiation hardening, minimum weight and power consumption, and a system which accommodates the inherent communication delay between the ground station and the satellite. There is also a need for a user interface which is easy to use, ensures collision free motions, and is capable of adjusting to an unknown workcell (for repair operations the condition of the satellite may not be known in advance). This paper describes the novel technologies required to deliver such a capability.

INTRODUCTION

Graphical Programming uses 3-D animated graphics models as intuitive operator interfaces for the programming and control of complex robotic systems. This paper reviews several example robotic systems that use Graphical Programming as practical operational systems. The general approach to implementing Graphical Programming systems at SNL is then examined together with a description of the software environment used to implement general Graphical Programming concepts. Lessons learned from applying Graphical Programming to prototypical waste cleanup robotic system control

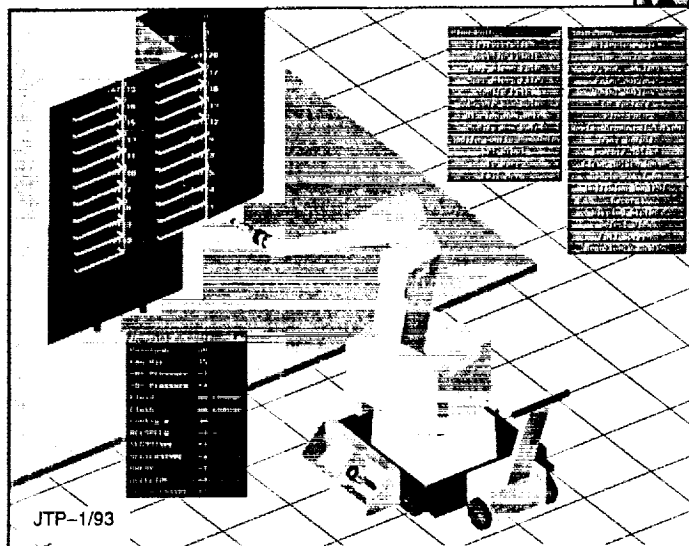
are then reviewed with suggestions for new directions for future technology development.

The US Department of Energy Office of Technology Development (DOE OTD) has sponsored the Robotics Technology Development Program (RTDP). Development of innovative technologies for programming and controlling advanced robotic systems for application to the clean up of hazardous radioactive waste has been a focus of the RTDP. Of particular concern has been the development of generalized control approaches which automate clean up operations to reduce the time and cost of waste clean up while providing very high safety. Many of

*This work was performed at Sandia National Laboratories supported by the US Department of Energy under contract number DE-AC04-76DP00789.

Operation of Sandia's Graphical Programming-Based Coating System.

The robot is automatically following the contour of the surface being painted.



JTP-1/93



Graphical Programming Interface to System. Pop-up menus and 3-D graphics provide a powerful yet easy-to-use robot control system.

Figure 1: A Graphical Programming System for Applying Hazardous Coatings

the technologies developed in this program are directly applicable to the telerobotic servicing of space assets. The operational issues of space applications are in many ways similar to hazardous waste applications. For example, redundant safety, operator involvement, and robust operation are key issues in both environments. Therefore, technologies developed for hazardous waste environments, such as model based motion preview, modular sensor integration, and remote intelligence are appropriate for telerobotic operation in space. Model-based control approaches have proven to be very effective in allowing non-experts to easily program robot systems. This approach, coupled with animated graphics operator interfaces which employ advanced visualization software technologies both to communicate information to the operator and to facilitate operator communication to the robot system, reduces the robot operator training requirements while decreasing the programming time for even complex operations.

OVERVIEW

Figure 1 shows a prototype robot system with a Graphical Programming interface. The graphic rep-

resentation of the robot allows an operator who is not an expert robot programmer to easily interact with the robot's supervisory system control software and command robot motions. The photograph shows the actual robot and its graphical model. In a typical prototype robot system, as shown in Figure 1, the robot's supervisory control software:

- Translates commanded tasks into graphical robot motions.
- Simulates and analyzes robot motions to check for safety.
- Commands the robot to execute motions that have been determined to be safe.
- Monitors the robot's motions to verify task compliance.
- Updates the graphics model as tasks are performed by the robot.

The Graphical Programming paradigm, as developed by Sandia for application to robot system control, broke new ground by integrating sophisticated 3-D graphics modeling technology into the real-time control of robot systems. The real-time updating of the graphics model to allow continual validation of robot motions distinguishes Graphical Programming from conventional off-line program-

ming. Off-line programming requires complete knowledge of the robot's workspace while Graphical Programming, with the key attributes of environmental sensing and dynamic model updating, allows operation with incomplete knowledge (see next section). Thus, conventional off-line programming is a tool to verify robot programs before execution while the graphics model of a Graphical Programming system is an integral part of the high-level system control environment.

The next section, *The Graphical Programming Approach*, describes Graphical Programming as a general approach to designing robot supervisor systems. The following section, *Graphical Programming System Examples*, describes several robot control systems that use Graphical Programming or significant concepts from Graphical Programming. The *Sandia's Graphical Programming Systems* section describes Sandia's particular approach to implementing Graphical Programming systems, several tools that Sandia uses in designing those systems, and important features that Sandia has implemented in various Graphical Programming systems. Finally, the paper concludes with *Future Work* and *Conclusions* sections to briefly describe Sandia's current plans and directions.

THE GRAPHICAL PROGRAMMING APPROACH

Graphical Programming systems use graphic-based, robot simulation systems in the operator interface for programming, controlling, and monitoring complex robot systems. The Graphical Programming Supervisor software module commands, controls, and monitors robots and sensors in the task, or high-level control loop while the robots and sensors use local controllers to control the low-level aspects of the robot including servoing and autonomous operations. The Supervisor monitors the sensors used for low-level tasks (including encoders and force sensors) and other sensors (including laser range finding sensors) to maintain the world model's accuracy.

Simulation and monitoring are integral functions of the Supervisor software. Robot tasks are simulated before they are performed and the simulation system's safety validation functions determine whether the task can be performed safely. System operators who have proper access control can override safety systems if they determine that the safety analyses are too conservative for a particular task. While the tasks are being performed, the Supervisor slaves the simulation system to the robot's motion

sensors and monitors the robot to verify that the task was performed as simulated, or, as with sensor-controlled tasks, to track the real-world effects of the sensors. The Supervisor can also interrupt robot motions that excessively deviate from predicted motions or result in entry into hazardous regions. Force compliant motions are performed at the Subsystem level, making the system tolerant of long network delays between the Subsystem and Supervisor while still providing stable motion. This also minimizes data bandwidth requirements.

With the real-time tracking inherent in Graphical Programming, the Supervisor can command sensors to locate new or moved objects (i.e., fixtures and workpieces) in the environment and instantly display those sensed objects in the graphic environment. Engineers can also use these up-to-date models as an accurate base to design workcell modifications when requirements change. If the Supervisor is space-based, the effect of emergency stops and other unplanned events are immediately represented in the world model and can be quickly and effectively acted on by the system operator.

The real-time tracking also provides a continual quality audit function from development to retirement. In any development effort, the robot is commanded to move many times to test robot functions. By using Graphical Programming, the Supervisor simulates the robot before each motion and monitors the motions when they are performed. This cycle closes the loop on simulation and experimentation by allowing the system to verify its own simulation accuracy each time the robot moves. In effect, each robot motion is an experiment that verifies the Supervisor's safety systems. This lets the developer identify and eliminate simulation model inaccuracies in the early phases of system integration, and allows operators to verify the model throughout the life of the system.

Graphical Programming systems are largely data driven. Supervisors can be rapidly modified for new robot systems by modifying the system's world model. Tasks can be redefined within the model without changing the Supervisor program. Only code that reflects fundamental requirement changes needs to be written to extend a Supervisor for a new robot system. For example, a Graphical Programming Supervisor that was designed for remote retrieval of orbital replacement units could be rapidly modified to control a space-based maintenance operation by changing the geometric (graphic) and motion (kinematic) models and by modifying a few very task-specific command menus.

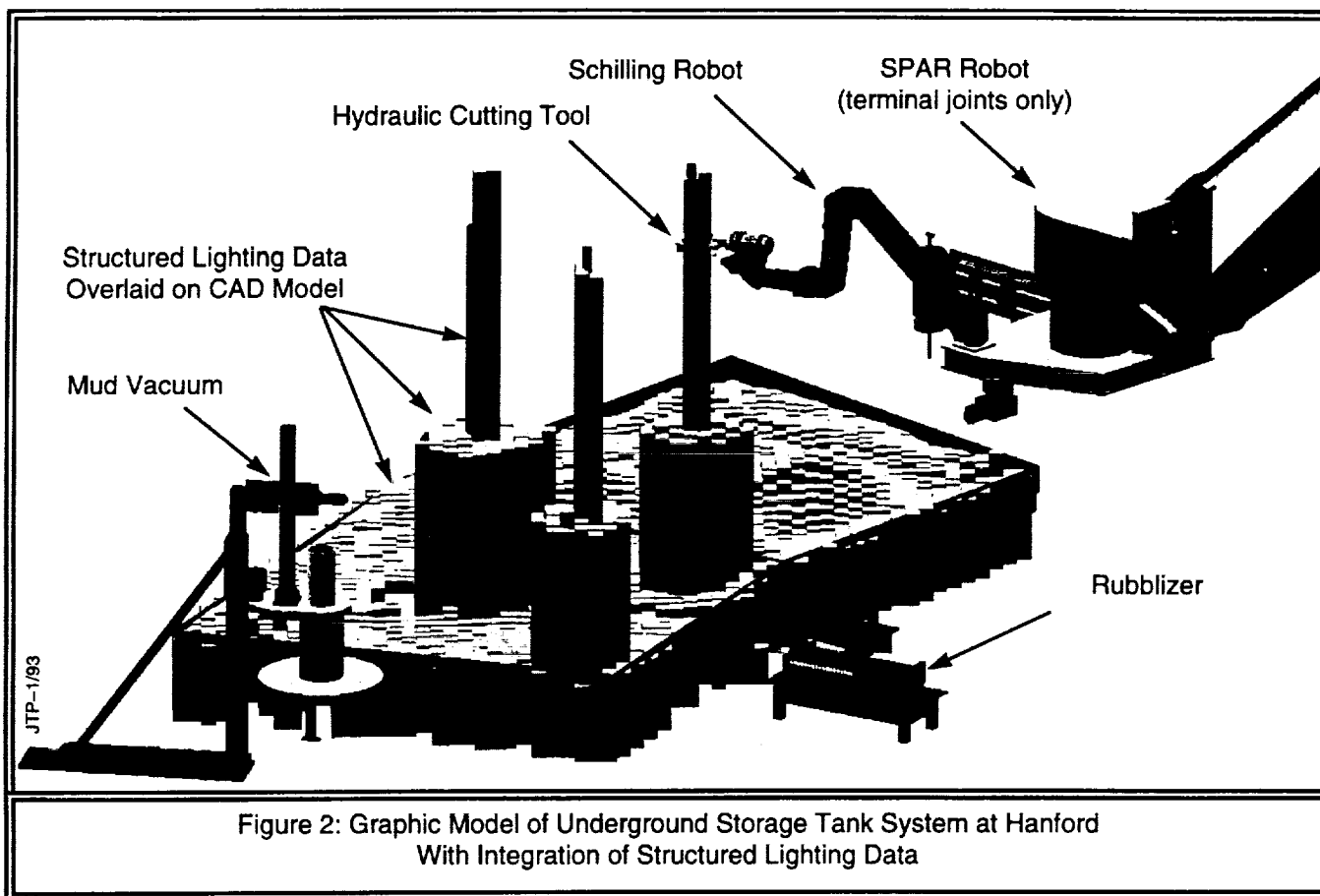


Figure 2: Graphic Model of Underground Storage Tank System at Hanford
With Integration of Structured Lighting Data

Graphical Programming systems bring advanced technology to the robot operator. With Graphical Programming, the operator can visualize and understand the result of complex commands before moving any machinery. Advanced planning and sensor-based control systems are integrated into Supervisors without taking control away from the operator. The operator can see intended robot motions from any angle, position, or magnification and can modify the motions to accommodate for conditions that the automation and planning subsystems did not resolve. The operator can analyze motions by using standard simulation system analysis tools (including collision and near-miss detection) and optimize the motions by using sophisticated input devices (including spaceballs, dial boxes, and robot teach pendants).

Graphical Programming systems improve system safety over competing systems in several important ways.

- Hazards are predicted through simulation and locked out through program control.
- The operator is warned of motions that would cause near-collisions (with the near-miss distance set by the operator).

- Motions that could cause collisions cannot be commanded to the robot unless the operator has specific override permission.
- The quality audit function of linking simulation to monitoring is a thorough method for verifying that safety calculations are correct.
- The Supervisor world model is consistent with the real world and, therefore, safety checks remain accurate even when the robot's operating environment changes.
- Software reuse allows Supervisory software to be quality-verified in many situations.
- Advanced technologies can be integrated to improve operator efficiency without reducing safety.

GRAPHICAL PROGRAMMING SYSTEM EXAMPLES

In 1990, Sandia demonstrated that Graphical Programming provides a dramatic improvement in ease of operation and operational safety when compared to teleoperation [1, 2, 3]. The Graphical Programming Supervisory system used a real-time computer subsystem to control a gantry robot, several sensor systems (including structured lighting,

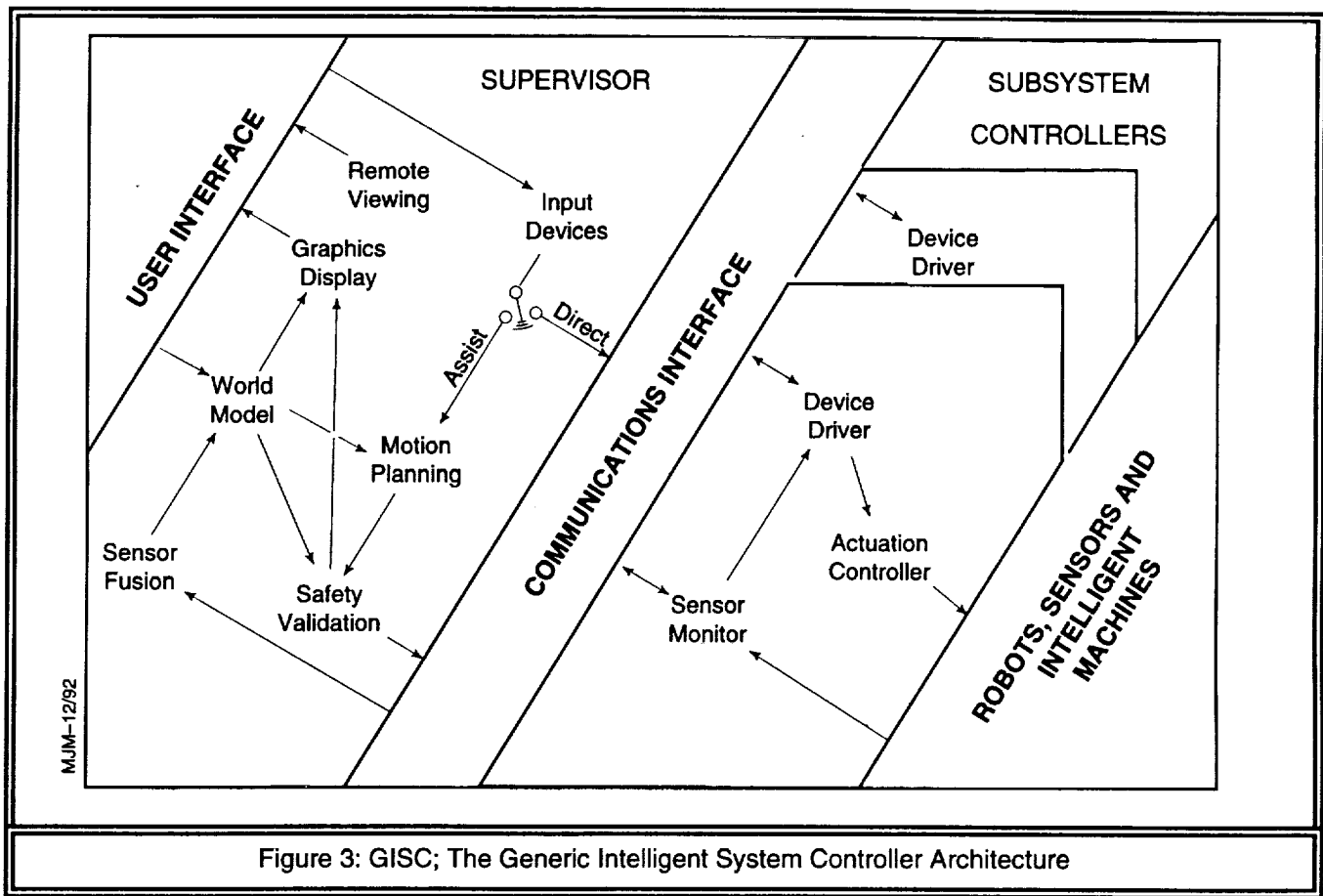


Figure 3: GISC; The Generic Intelligent System Controller Architecture

ultrasonic and magnetometer), and special tools. The Supervisor imported a contour model of a surface that had been measured with a structured lighting system into the simulation model of the robot workspace. Operators could graphically program robot motions in the workspace with menus and a spaceball input device. The Supervisor then used motion preview, collision detection, and joint travel checking routines to verify the safety of programmed motions before giving the operator an option to execute the motions on the robot. Visitors to the lab were trained in minutes to safely command and safely control the powerful gantry robot.

In 1991, the RTDP sponsored development of a multi-robot demonstration system for underground storage tank operations at the Hanford site near Richland, Washington [4]. The Supervisor here simultaneously controlled SPAR, Redzone, and Schilling robots, and monitored several sensor systems. The effort demonstrated that diverse intelligent subsystems, developed at different and distant laboratories, and each with unique control systems, could be rapidly and effectively integrated into a single system and controlled with a Graphical Programming-based Supervisor.

In 1992, Sandia developed four new Graphical Programming supervisory systems. These systems were a CIMCORP survey gantry robot, a GMF painting robot for applying hazardous coatings (Figure 1), a Schilling ESM long-reach painting robot, and an enhancement to the underground storage tank system developed in 1990 (Figure 2). In addition, Savannah River Technical Center (SRTC), in consultation with Sandia, implemented a Graphical Programming Supervisor for a gantry telerobot that had an added ability to take control away from an operator who commanded unsafe motions through the direct control master/slave input devices. All these diverse systems shared significant portions of their Supervisor application software and differed mainly by the unique tasks that each system needed to perform.

Sandia recently showed that a Graphical Programming Supervisor could control a robot Subsystem over the Internet using minimal bandwidth. The Supervisor was located at Hanford, Washington, and the gantry robot subsystem was located at Sandia in Albuquerque, New Mexico. The communications link included many hops and shared a 56 KB link with the rest of our group. The distance was transparent to the user because of local

previewing of operations and a clean division between the Supervisor and Subsystem.

Besides Sandia, other institutions are using significant concepts or techniques related to Graphical Programming. In 1990, the Jet Propulsion Laboratory (JPL) described a system that used computer graphics techniques to enable the human operator to both visualize and predict detailed 3-D trajectories of teleoperated manipulators in real time [5]. In 1991, MITRE Corp. reported on a virtual image concept that allowed software-based graphical monitoring to monitor teleoperation tasks in real time [6]. These efforts foreshadow the wide use of Graphical Programming as a telerobotic interface.

SANDIA'S GRAPHICAL PROGRAMMING SYSTEMS

Sandia constructs Graphical Programming systems in unique ways to facilitate rapid prototyping and to reduce development costs. The following points outline the major differences that the remainder of the section describes in greater detail:

- Sandia uses the Generic Intelligent System Control (GISC) approach, an RTDP approved method for robot system integration.
- Our Supervisors use high-performance, Unix-based graphic workstations.
- We use dedicated real-time computers for high speed and low-level robot control.
- We link the real-time computers to the Supervisor's computer with standard communication interfaces.
- We use a Sandia-developed generic communications message protocol to command robot motions.
- We rely on our extensive library for robot system development.
- We use commercial three-dimensional simulation and visualization systems in our Supervisors.

Sandia develops Graphical Programming systems by using the GISC approach [7, 8, 9, 10, 11]. GISC is a general approach to constructing robot systems that was developed by the RTDP. Figure 3 is a diagram of the GISC approach to designing complex robot systems. Sandia's Graphical Programming Supervisors are examples of Supervisors (Figure 3) designed using the GISC approach. GISC Subsystem Controllers (Figure 3) control the low-level aspects of the robots and sensors through Device Drivers.

This low-level control includes servoing, direct teleoperation, and autonomous task execution.

The GISC system (Figure 3) starts with a World Model that is generated by the user from *a priori* engineering data. As shown in Figure 3, the GISC Supervisor:

- Interprets user commands made with menus and other Input Devices into tasks that are planned with the Motion Planner.
- Tests tasks for safety with the Safety Validation module and displays test results through a Graphic Display.
- Commands the robot subsystems to perform tasks that are verified as safe.
- Updates the World Model from sensor data generated by the subsystems.

Sandia's approach to Graphical Programming uses GISC to define the overall control algorithm and to set feature requirements for the supervisors and subsystems. Our Graphical Programming Supervisors perform all the functions of the GISC supervisor and interface with GISC Device Drivers. In this way, our Supervisors are plug-compatible with other GISC Supervisors and can be developed in parallel to Supervisors that do not need the advanced features of Graphical Programming.

Supervisors and robot Device Drivers are separate programs and normally run on different computers. Supervisors communicate with the Device Drivers by using conventional communication media including TCP/IP and RS232. These standard communication systems are enhanced for the application programmer with Sandia's Intelligent System Operating Environment (ISOE) and GENeralized Interface for Supervisor and Subsystems (GENISAS) [10] communications libraries. The ISOE library multiplexes synchronous and asynchronous commands, status queries, and data exchanges over a single synchronous communications link. The GENISAS library links ISOE to user functions and data from application programmer defined tables of functions and data. Together, these libraries free the application programmer from writing code that links commands and queries made through the communications link to robot control functions and data transfers.

We design our subsystems to respond to generically-defined commands that are broadly applicable to robot control. These generic commands are based on the Robot Independent Programming Environment and Language (RIPE/RIPL) developed

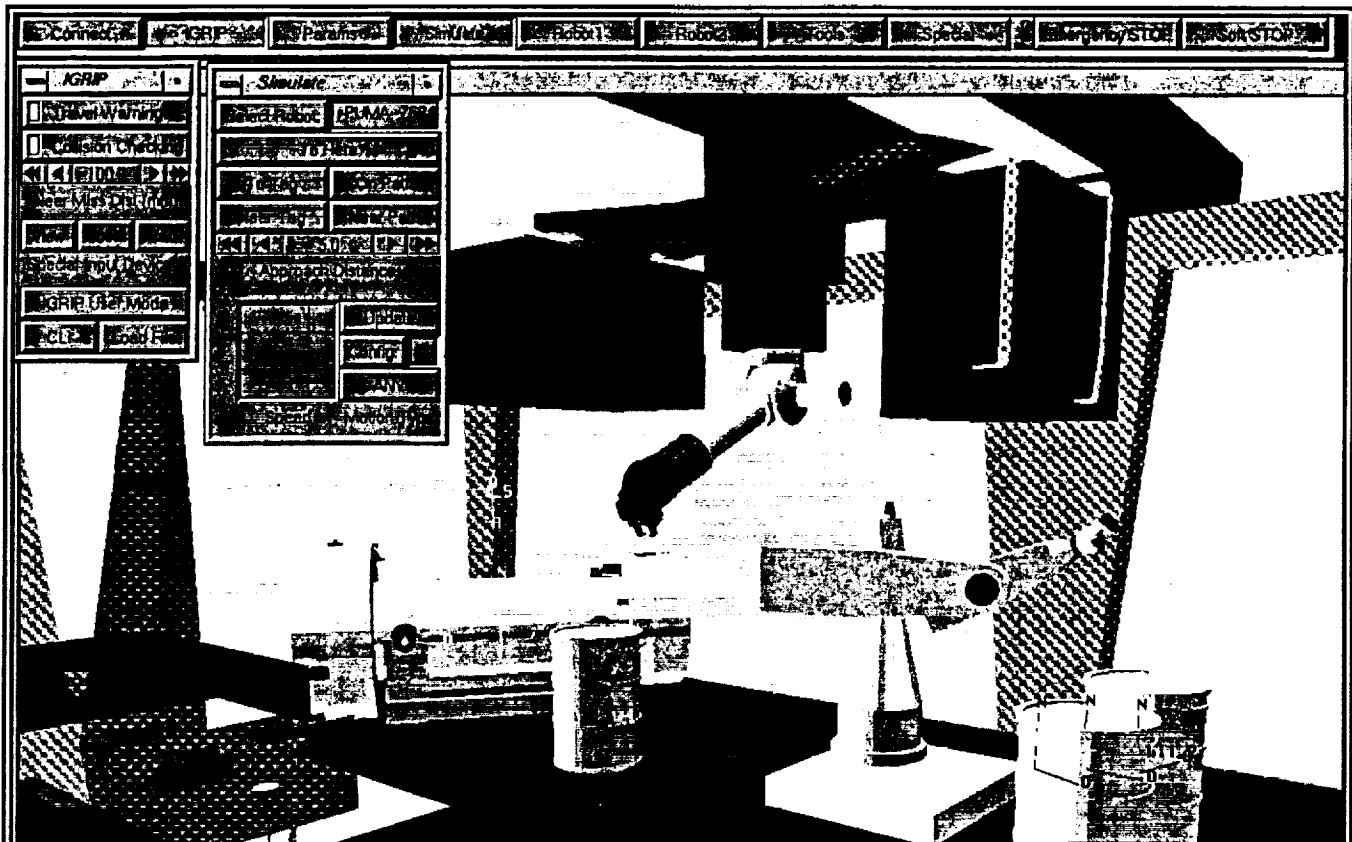


Figure 4: A Prototypical Graphical Programming System Written with the External Control Feature of IGRIP

at Sandia for autonomous systems [12]. Commands range from point-to-point and path moves to force-controlled and other sensor-based motions. Our GISC-designed Device Drivers that are written with RIPE/RIPL take full advantage of the GENISAS and ISOE libraries.

The generic command set and standardized communications libraries are the enabling technologies that allow the Supervisor programs to be data driven. Because dissimilar robots respond to the same command sets, the Supervisor only needs to be programmed to generate one command set to communicate with a wide variety of robots. In this way, only the portion of the World Model that describes how the robots will behave when given these generic commands and the portion that contains the geometry of the specific objects in the workspaces need to be changed to allow a Supervisor designed for one system to control a new and different system.

Our Supervisors use commercially-supplied robot simulation systems to simulate and graphically display robot motions and to perform routine analysis checks. This approach to developing Supervisors leverages from the commercially available simulation systems and frees Sandia from devel-

oping simulation and visualization subsystems. The approach also makes the Graphical Programming technologies easier to transfer to industry as the bulk of the system programs are already in the commercial arena. Finally, Sandia's product surveys indicate that any of several simulation systems could be used for Graphical Programming systems. This means that while our systems might be developed with one simulation system, the final application can use a different system.

Until recently, the Sandia-written application program for the Supervisors was contained inside the simulation system by using application programming languages. For example, the menus and high-level functions for the painting robot shown in Figure 1 were written with Deneb Inc.'s IGRIP [13, 14] using its Graphical Simulation Language (GSL) application programming language. While developing the application programs inside the simulation environment allowed Sandia to rapidly develop its initial Graphical Programming Supervisors and test various Supervisor system algorithms, ultimately, it limited the scope of the Supervisory program to only include functionality supported by GSL. For example, a translator was required to access ISOE- and GENISAS-driven subsystems. This

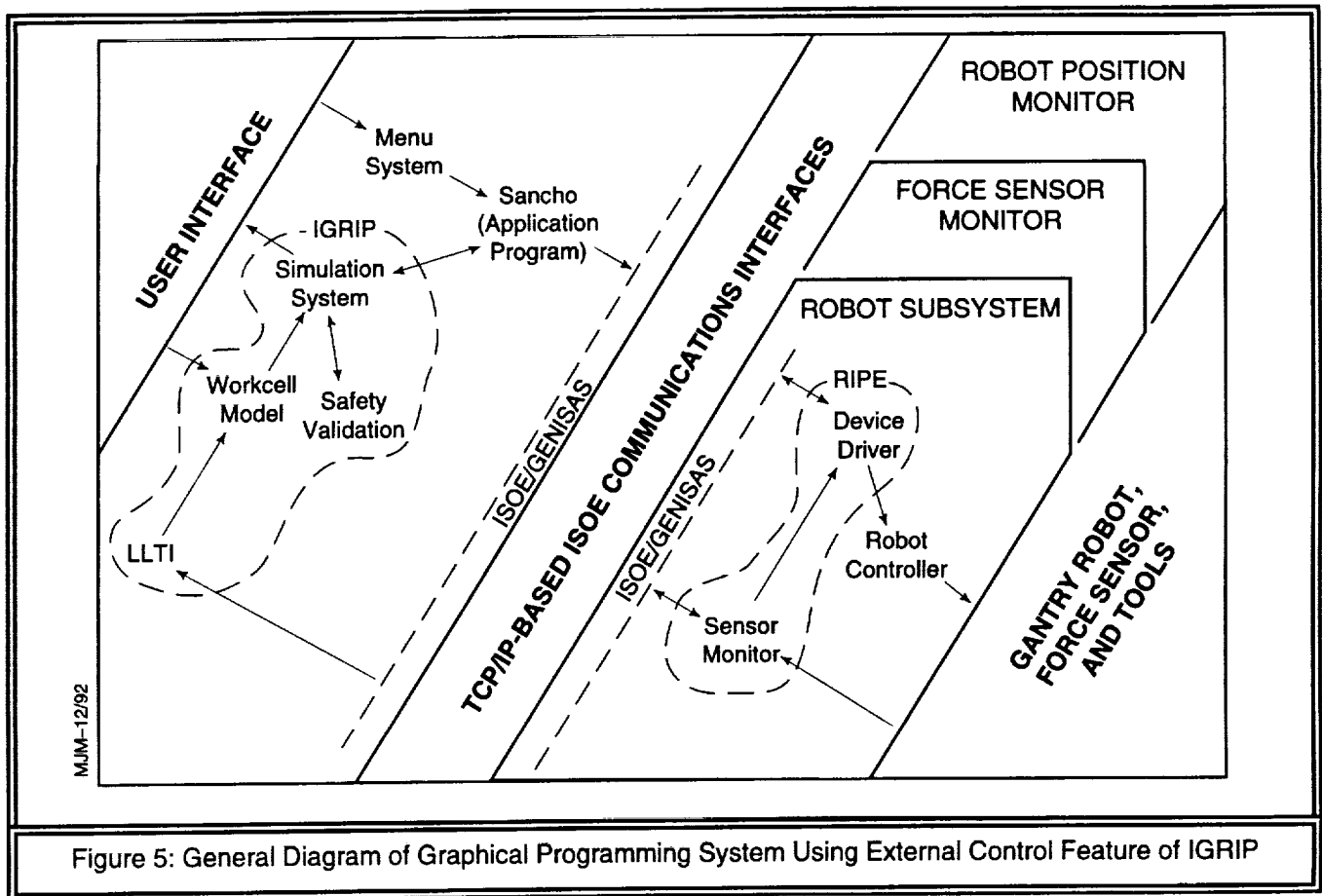


Figure 5: General Diagram of Graphical Programming System Using External Control Feature of IGRIP

approach also limited Sandia's ability to convert Supervisors to use other simulation systems.

Recently, we have leveraged features of IGRIP that allow us to write the application portion of our Graphical Programming Supervisory systems external to IGRIP while retaining IGRIP as the simulation system. The feature that allows this external control of IGRIP is called Socket-mode in IGRIP and uses a standard TCP/IP communications interface to form the link. We have surveyed several available robot simulation systems and have found that they also contain the ability to be controlled from external programs in similar ways.

We are currently writing a Supervisor Application Program called Sancho and an interface library which accesses IGRIP through socket mode. We are designing Sancho and the library to allow it to be rewritten to access other simulation systems. This will allow Sandia and other system developers to rapidly reuse supervisor software on multiple simulation packages and robotic systems.

Sancho uses Unix-based menu systems, operating system services, and communications systems and is directly compatible with ISOE and GENISAS. We

are constructing our interface library between IGRIP and Sancho to allow us to use other simulation systems by changing the interface library. We are exploring methods to integrate other advanced technology including path planning and advanced sensor fusion by developing communications-based interfaces to the new subsystems.

Figure 4 shows a prototypical example of a Graphical Programming system that was written with Sancho. The robot in the figure is the gantry robot (see *Graphical Programming System Examples*) used for radiation surveys and the lines coming from the robot's tool show a path that the robot followed. The menus in this system use an X-windows menu system and Sancho is written in C. The menus allow the operator to command tasks that result in robot motion and also allow the operator to change viewing angles and other system parameters.

A generalized connection diagram of the new system, shown in Figure 5 and Figure 6, shows the detailed connection diagram for the first implementation of the system. Figure 5 shows how Sancho, the Application Program, is separate from the simulation system and Device Drivers and shows how

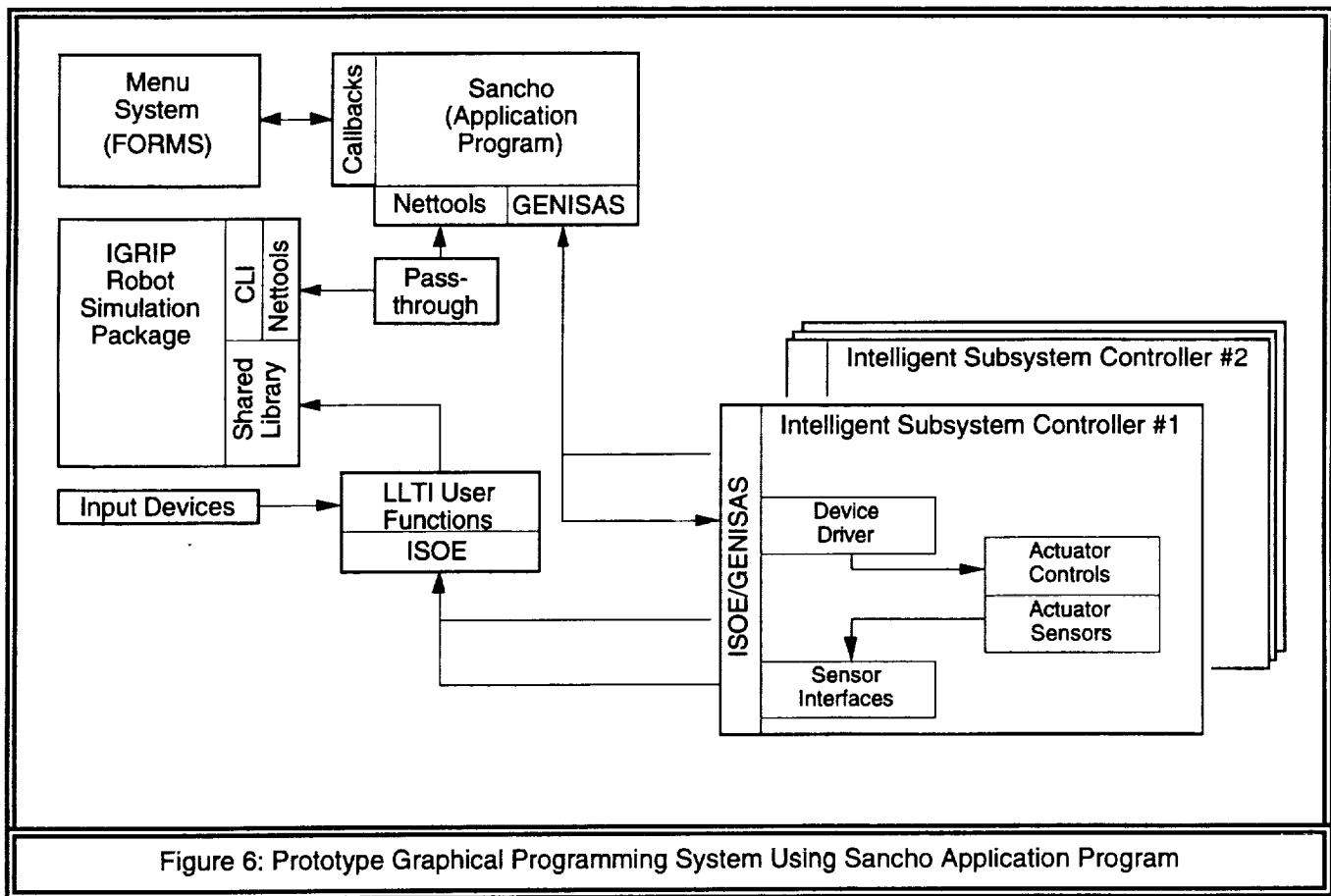


Figure 6: Prototype Graphical Programming System Using Sancho Application Program

the general structure of the new system corresponds to the GISC architecture.

Figure 6 shows how Sancho communicates Command Line Interface (CLI) commands to IGRIP through Nettools (a Deneb interface that uses TCP/IP) and device commands to the robots through GENISAS. The robot Device Drivers interpret commands from Sancho and command the robots to perform their motions. (For some robots, the Device Driver is an interface program that communicates with the robot's commercial controller, while in other robots, the Device Driver commands the robot servo systems directly.) The Device Drivers also monitor the robots' sensor values and communicate that data either back to Sancho through GENISAS or to IGRIP through the Low-Level Telerobotic Interface (LLTI) (a shared library interface that IGRIP provides for monitoring robots and input devices).

FUTURE WORK

Sandia develops prototype systems that are agile and flexible to meet pressing national needs. Sandia will use the experience derived in developing these

prototype systems to help formulate specifications for systems that industry will produce. Sandia is particularly focused toward developing robot-control architectures that support the evolution to more autonomous systems in a way that makes advanced technology accessible to the end user.

Most of the robot systems that are proposed for hazardous operations will require multiple robots, controlled by multiple personnel, and sharing common workspaces. These robots will likely need to be commanded by different personnel to achieve the various goals inherent in complex systems. This model is extensible to space systems. For example, assembly currently done in space with a master/slave telerobot interacting with an astronaut could be done by a material handler robot and a second robot with a dexterous manipulator.

While the tasks are different, significant portions of the robot hardware will be shared between different personnel. For example, the various demonstration systems mentioned earlier showed that the same robots can be used for a wide variety of tasks. The demonstrations showed that material handling, material processing, and environment sensing operations that share manipulators can operate more

efficiently and effectively than is possible using unique manipulators for each task. Safely sharing hardware will require development of control architectures that can be safely accessed by many different supervisory programs while maintaining single point-of-control.

This working environment calls for telerobotic control architectures optimized for dynamically changing workspaces. Robots will need to check that other robots are not tasked to cross their paths before they can be commanded. Operators will need to request and gain control of robots, perform their tasks, and relinquish control. We plan to work toward developing systems that can safely operate in these environments and provide optimal use of the robot systems for the various tasks.

Currently, Sandia is working to extend graphical programming in several directions that will allow these complex systems to be effectively and safely used. As described earlier, we are refining our techniques of constructing Supervisors to generically access the simulation systems. We are also developing ways to integrate new and existing technologies by providing generic software interfaces to key technologies including sensor fusion and path and task planning. Finally, we are refining our software approach to multiple robot control and shared access control of robots. Our current work in these areas is described below.

Sandia is using communications-based approaches to separate the application program from the simulation systems in the Graphical Programming Supervisors. Decoupling the Supervisor application programs from the simulation systems will provide necessary experiences in understanding simulation system requirements independently of a particular vendor's current options. This experience will allow Sandia to help define achievable system specifications. It will also help Sandia to explore and suggest interface features for the simulation systems. Finally, it will help Sandia to pinpoint and implement features that will be required to safely bring advanced technologies to the users.

Sandia has recently begun projects to implement Graphical Programming with a second simulation system, and is supporting another RTDP member lab to implement Graphical Programming on a third simulation system. Lessons learned on the detailed implementation of these systems will support building a general interface specification to simulation systems. The result of this work will facilitate

development of Supervisors that are independent of and portable between different simulation systems.

Sandia plans to integrate the results of its strong research program in path planning [15, 16, 17, 18, 19] into the GISC environment. Initially, path planners may be integrated through communications interfaces with the Supervisor's Application Program. Later, path planners may be integrated into commercial simulation systems. Our current research uses C-space models [20] for path planning because they provide computationally efficient workspace representations for planning collision-free motions. Path planners will need access to the dimensional database and will represent the dimensional information with unique internal representations that will be computed from the simulation system's geometric models. We are working to make that conversion process more practical.

Sandia also plans to integrate structured approaches to sensor fusion with Graphical Programming Supervisors. Sandia's MINILAB [21] system demonstrates that general architectures for sensor fusion are feasible, cost-effective solutions for integrating sensor information in the field. Recent technical advances in graphic display hardware, including texture mapping, make it possible to directly map and display sensor data on graphic surfaces in the simulation system. Simulation system software will soon be available to use these hardware capabilities.

New sensor fusion techniques will be extremely useful in robotic systems. For example, new hardware allows video and sensor-generated images to be mapped onto surfaces to let an operator accurately command a robot to reinspect areas identified in initial surveying operations. Volumetric-based data could be mapped onto surfaces to let the operator graphically locate *hot spots*, or be mapped onto critical parts of the robot to help the operator minimize dose counts to those parts. Surface-penetrating radar and other data could be mapped onto planes or *magic wands* that the operator would move through the model to better understand the environment. These sensor interfaces will improve efficiency by letting the operator directly command the robot to work on substances that would otherwise be invisible.

To better understand multiple-robot control, Sandia is developing several multiple-robot laboratories and the control software needed to control these robots concurrently. In one lab, Sandia has built a coarse/fine manipulator system from two separate robots to refine control techniques applicable to

robot systems like that used in the underground storage tank demonstration at Hanford. In another laboratory, Sandia is teaming a large pedestal robot (a Puma 762) with a gantry robot to explore tele-robotic control strategies for robots that completely share their workspaces. A common interest in these systems will be in developing reusable supervisory software that can be applied across many applications. Sandia then plans to apply experiences gained in these two efforts to develop strategies for multi-operator control environments.

CONCLUSIONS

Sandia has developed and is refining Graphical Programming, an advanced robot control approach that uses visualization software to preview and monitor robot motions on a task-by-task basis. By using the Generic Intelligent System Controller approach and commercial visualization software, these systems are faster to implement and operate, safer to use, and cheaper overall than competing teleoperation or autonomous systems.

Recent systems development efforts have given Sandia a strong base of experience in extending graphical programming to a wide range of operations. Sandia is implementing the application programs for Graphical Programming Supervisors as separate programs that interact with the simulation software through a communications interface. This approach facilitates better software reuse and simulation system independence. New robot technologies (including advanced path planning and sensor fusion) are being integrated into Graphical Programming to further enhance operator efficiency without taking control away from the operator or adversely affecting operational safety.

Telerobotic servicing of space assets poses many challenges for robot control development. New Supervisory approaches are being developed to allow multiple robots to be easily controlled for cooperative tasks by a single operator. Other techniques are being developed to allow multiple operators to better share common resources. These control approaches will be needed to allow robots to safely, efficiently, and cost-effectively perform space servicing tasks.

ACKNOWLEDGMENTS

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DIAGNOSING ANOMALIES OF SPACECRAFT FOR SPACE MAINTENANCE AND SERVICING

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ABSTRACT

Very often servicing of satellites is necessary to replace components which are responsible for anomalous behavior of satellite operations due to adverse interactions with the natural space environment. A major difficulty with this diagnosis is that those responsible for diagnosing these anomalies do not have the tools to assess the role of the space environment causing the anomaly. To address this issue, we have under development a new rule-based, expert system for diagnosing spacecraft anomalies. The knowledge base consists of over two-hundred (200) rules and provides links to historical and environmental databases. Environmental causes considered are bulk charging, single event upsets (SEU), surface charging, and total radiation dose. The system's driver translates forward chaining rules into a backward chaining sequence, prompting the user for information pertinent to the causes considered. When the user selects the novice mode, the system automatically gives detailed explanations and descriptions of terms and reasoning as the session progresses, in a sense teaching the user. As such it is an effective tutoring tool. The use of heuristics frees the user from searching through large amounts of irrelevant information and allows the user to input partial information (varying degrees of confidence in an answer) or 'unknown' to any question. The system is available on-line and uses C Language Integrated Production System (CLIPS), an expert shell developed by the NASA Johnson Space Center AI Laboratory in Houston.

INTRODUCTION

What is proposed is a system for diagnosing spacecraft anomalies which will provide an intelligence for servicing of satellites. The analysis of components responsible for anomalous behavior of satellites due to adverse interactions with the natural space environment is a very complex process. It is important to be able to make an accurate assessment in a timely and accurate manner when the problem becomes serious enough to requiring servicing. This approach that is being proposed is to take advantage of the new tools that have been developed to analyze, display, and interpret large data sets. Significant progress has been made to the extent that some are even suggesting that these powerful tools may even lead to schemes to predict flares and geomagnetic activity. An international workshop on artificial intelligence applications on solar-terrestrial physics to be held at Lund, Sweden, September 22-24, 1993, sponsored by NOAA, NASA/GSFC, Lund Observatory and the Swedish Science Research Institute has made such a suggestion.¹ Although prediction may be an optimistic long term goal for scientists, the engineers responsible for design and building the hardware would be satisfied if early warning schemes were available. Vampola, as Guest Editor for a collection of papers on solar effects on space systems found a consensus that the solar output of radiation, solar wind, and energetic particles depends on the solar magnetic cycle.² This fits in with viewpoint that radiation belt models should be based on years of magnetic activity maximum and minimum instead of sun spot maximum and minimum.³ NOAA's National Geophysical Data Center, (NGDC), has responsibility for collecting, archiving, analyzing, and disseminating solar-terrestrial data and information.⁴ NGDC makes a deliberate effort to apply these data

resources to the problem of spacecraft interaction with space environment.

Historical records that have been started fairly recently by NOAA, indicate that the anomalous behavior of spacecraft occurs when the elements of the upper atmosphere become unstable. Trends alone do not provide the answers to the anomaly, but they help focus on the problem. On-board instruments will improve the ability to forecast or provide early warning of events leading to the environments responsible for some of the anomalies.⁴ Design errors and quality control problems, workmanship, and wear can also lead to anomalies but these are in a category that engineers understand and can cope with.

The expert system that is under development will help those who have a need to diagnose the anomaly with the scientific and engineering expertise to assess the interaction that is taking place by the environment. As result of the heightened interest in spacecraft anomalies, no doubt due to the high geomagnetic activity that has been observed for solar cycle 22, the 1990 AIAA Sciences meeting included a special session at which seven papers related to spacecraft anomalies were presented. Since then these papers were updated and recently accepted for publication as a special collection on environmentally induced spacecraft anomalies.⁵ It is anticipated that these coordinated activities to update the knowledge base of the system will lead to a useful engineering tool for space maintenance.

DESCRIPTION

The tool that is being proposed is a rule-based online expert system for diagnosing inflight spacecraft anomalies system. It has features that provide an effective method for saving knowledge, allow sifting through large amounts of data, and home in on significant information. Most importantly, it uses heuristics in addition to algorithms which allow approximate reasoning and inference, and the ability to attack problems not rigidly defined. A microcomputer-based version that has essentially the same features is also under development by The Aerospace Corporation as a research system to accomplish the same results.⁶

The modularity of the expert system allows for easy updates and modifications. It not only provides scientists with needed risk analysis and confidence not found in the usual programs. but the window implementation makes it a more effective tool. The system currently runs on an IBM RISC 6000 at Goddard space Flight Center (GSFC). The inference engine used is NASA's C Language Integrated Production System (CLIPS).^{7,8} CLIPS is not only compatible with both C and Fortran languages, but it has features which include the ability to compile the rules and save them in a binary image file, thus allowing faster execution than a typical rule interpretive system. This feature qualifies CLIPS to be used as an expert shell, i.e., an environment where the rules can reside and be accessed. The architecture of the system is shown in Figure 1.

Besides the interactive knowledgebase, the system also provides access and display of information from the databases. As shown in Figure 1, the system has four databases, but more can be added as needed. This is the fact base for the collection of informative sources related to the topic of interest.

The attributes database is an ASCII file for launch and orbital information on satellites. Figure 2 shows the launch and orbital information in the Attributes database. While anomalies can occur in almost any orbit, it is possible to anticipate environmentally induced anomalies based on orbits. Vampola has summarized these probable causes for classes of orbits in his tutorial paper on spacecraft anomalies.⁹ These probable causes are also covered by rules and facts on the Knowledge Base.

Some examples of the nature of the anomaly database are given in Figures 3-6. The anomaly database, an ASCII file provided by the NGDC, contains information on about 300 historical anomalies. Figure 3 is a

listing of the types of problems considered for anomalous behavior. Figure 4 lists the satellites that are in the database. Some of the names are coded to hide the identity of the actual spacecraft. The seasonal distribution of TDRSS anomalies shown in Figure 5 was plotted from data in the Spacecraft Anomaly Database using IDL™ graphics. This file was provided by NGDC. The TDRSS-1 anomalies show no distinct seasonal variation in anomaly occurrence. This distribution has a very good probability of being random.⁴ Figure 6 is a plot of the TDRSS weekly SEU count for all observed SEUs. Since some of the SEUs are unobserved, the rate shown is considered a minimum. The spikes in August, September and October are due to solar flares. This experience led to changes to hardened devices for the following TDRSS spacecraft whence the problem ceased.¹⁰ The exception was TDRSS, which was lost with *Challenger*. Part of the problem of TDRSS-1 was an innocent desire to take advantage of advance technology. It was not realized at the time that as technology advances towards faster and lower power devices on a chip, the sensitivity to SEUs increases.¹¹

The environment database is an ASCII text file of the historical record of the geophysical parameter known as Kp, the planetary magnetic index, used to estimate the severity of magnetic storms within the Earth's magnetosphere. The solar flare database is an ASCII data file on the date and time-of-occurrence of X-class solar x-rays. These files are accessed by a C-language interface between the expert system and the ASCII file.

KNOWLEDGE BASE

The knowledge base consists of over two-hundred (200) rules and provides links to historical and environmental databases. Unlike its algorithmic predecessors, it can be flexible in the way it attacks complex problems. It more closely simulates the methods of human experts who use a combination of known empirically derived formulae, hunches based on degrees of certainty and experience, and even judicious "fudging" when specific data is lacking. The system output was verified by referring to historical case studies and historical data.

The architecture of the system was designed to emulate the way the user normally looks at data to diagnose anomalies. The expert system not only consolidates expertise in a uniform, objective, and logical way, but it also offers "smart" ways of accessing various databases which are transparent to the user. Then by applying various rules in its knowledge base, the system is queried, as appropriate, to arrive at a conclusion.

The current development of the system is able to attribute the causes of satellite anomalies to one of several possible categories, including surface charging, bulk charging, single event upsets (SEU), and total radiation dose. ("Unknown" is also a possible and plausible conclusion, depending on the quantity of data available. The architecture is such that other causes could be added if a satisfactory rule base were developed. The rule base includes the expert system rules that will be "fired" under control of the inference engine. The rules are entered in a defined "if-then" format. The user interface links to databases which include past environmental data, satellite data and previous known anomalies. Information regarding satellite design, specifications and orbital history need to be assimilated with previous anomalies data and environmental conditions, while addressing the specific circumstances of individual users.

LEARNING TOOL

One of the most beneficial aspects of the system is its use as a learning tool for diagnosing spacecraft anomalies. A user is initially given a choice between either 'novice' or 'expert' mode for the current session. If the user selects the novice mode the system automatically gives detailed explanations and descriptions of terms and reasoning as the session progresses, in a sense teaching the user about the topic

or topics. The expert mode, on the other hand, simply executes the session without giving these extra explanations, unless the user specifically requests them.

The user is also given the option of selecting which causes are to be considered. This selection determines a knowledge base sub-group, so that only rules in this specific environmental area are considered. In this way the user can learn what variables, information and data affect, and are important to, that cause. In addition to this, in the features described next, the user is actually able to access the relevant rules him/herself and other variables and facts which were determined by using these rules.

FUTURE WORK

The graphical outputs of the Anomaly Database were used as illustrations merely to make the point that these fact resources are readily accessed. They lend to the tool an advantage for analyzing and interpreting large data sets. The development of the engine or driver is considered adequate for the task. The fact base and knowledge base on the other hand need to be expanded. The correlation of cause and effects of solar terrestrial effects is a young science. Enough evidence has been collected by NOAA's NGDC that these environmental effects need to be considered serious. Workshops and special publications that update our knowledge on these environmental interactions should be used as resources for the knowledge base. New frames are also needed. Orbital debris has been recognized as a threat and algorithms exist that are easily accommodated by the expert system. Ionic scintillation related to noisy telemetry links and commanding errors are also candidates to be considered that should be used.¹² We are improving our EnviroNET network with the addition of an IBM Risc 6000. Once there, not only will the speed of the Expert System be increased, but with the use of X Windows the system will also be enhanced. The PC system is able to access the Spacecraft Anomaly Manager (SAM) software which was developed by the National Geophysical Data Center. The SAM program provides a full range of functions for managing, displaying and analyzing data. The on-line system does not have this type of data management as yet but it is something to consider. The Spacecraft Attributes Database does not presently contain information on electrical parts which is certainly an area that needs pursuing. It is noted that no GSFC scientific satellites are listed in Figure 2. This omission also should be rectified. The last issue is that of updating Kp values. Recent data can be received from satellite broadcasts by the Space Environment Center, Boulder, CO.

CONCLUSION:

A useful tool for diagnosing anomalies of spacecraft for space maintenance and servicing has been described. This tool combines the algorithmic capabilities of mathematical programs and diagnostic models with expert heuristic knowledge, and uses confidence factors in variables and rules to calculate results with degrees of human confidence associated with them. Since the causes of environmentally induced spacecraft anomalies depend not only on algorithms, but also on environmental conditions, rules and information can rarely be known with 100% certainty. Based on present experiences, the role for the expert system is for either quasi-real time, or post analysis. There is a need to greatly improve the knowledge base and rules in view of the correlation observations that are emerging out of NOAA's NDGC.

ACKNOWLEDGMENTS

We are indebted to the staff of NASA's Johnson Space Center's AI Laboratory for their cooperation in the use of CLIPS. The technical discussions with Dan Wilkinson at NOAA and Al Vampola were very helpful. The development of the graphs from the fact database were by Rick Durand, of the EnviroNET staff.

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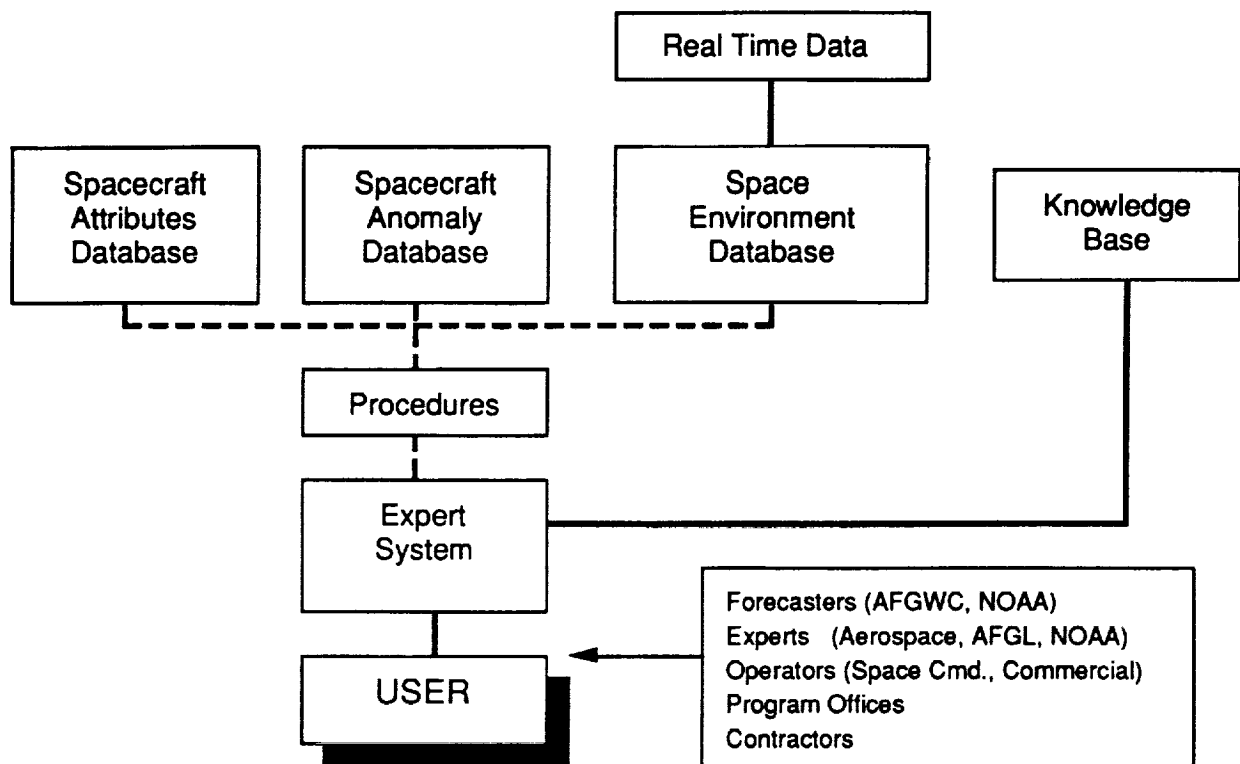


Figure 1. Expert System Architecture.

NAME	INCL	APOGEE	PERIGEE	LONG	LAUNCH DATE
OSCAR_32	90.3	1185	1017	-1	9-16-87
OSCAR_31	90.3	1183	1018	-1	9-16-87
DMSP	0.0	0	0	-1	6-20-87
GOES_7	0.1	37796	35783	277	2-26-87
FLTSCOM_7	4.3	35875	35703	-1	12-05-86
PLOAR_BEAR	89.6	1015	960	-1	11-14-86
NOAA_10	98.7	826	808	-1	9-17-86
GSTAR_2	0.1	35800	35775	255	3-28-86
SATCOM_K1	0.0	35794	35781	279	1-12-86
SATCOM_K2	0.0	35801	35774	279	11-28-85
NAVSTAR_11	63.4	20474	19887	-1	10-09-85
ASC_1	0.1	35791	35782	81	8-27-85
OSCAR_30	89.8	1260	1000	-1	8-03-85
OSCAR_24	89.8	1259	1001	-1	8-03-85
TELSTAR_3D	0.0	35804	35770	284	6-19-85
GSTAR_1	0.0	35779	35778	257	5-08-85
LEASAT_3	1.4	35809	35768	178	4-13-85
SCATHA	4.9	42577	28205	-1	1-30-79

Figure 2. Launch and orbital information on satellites contained in the database.

SPACECRAFT ENVIRONMENTAL ANOMALIES

Select all of the types of problems that are associated with this anomaly.

Yes

- <> PHANTOM_COMMAND
- <> LOGIC_UPSET
- <> ELECTRICAL
- <> MECHANICAL
- <> **SENSOR**
- <> SOFTWARE
- <> MEMORY
- <> THERMAL
- <> PART_FAILURE
- <> TELEMETRY_ERROR
- <> SYSTEM_FAILURE
- <> MISSION_FAILURE
- <> OTHER

Figure 3. Description of types of problems considered in anomaly database.

Select the name of the satellite that has experienced the anomaly.

OSCAR_32	TELSTAR_3D
OSCAR_31	GSTAR_1
DMSP	LEASAT_3
GOES_7	SCATHA
FLTSATCOM_7	UNKNOWN
POLAR_BEAR	
-> NOAA_10	
GSTAR_2	
SATCOM_K1	
SATCOM_K2	
NAVSTAR_11	
ASC_1	
OSCAR_30	
OSCAR_24	

Figure 4. Names of satellites that are in the anomaly database.

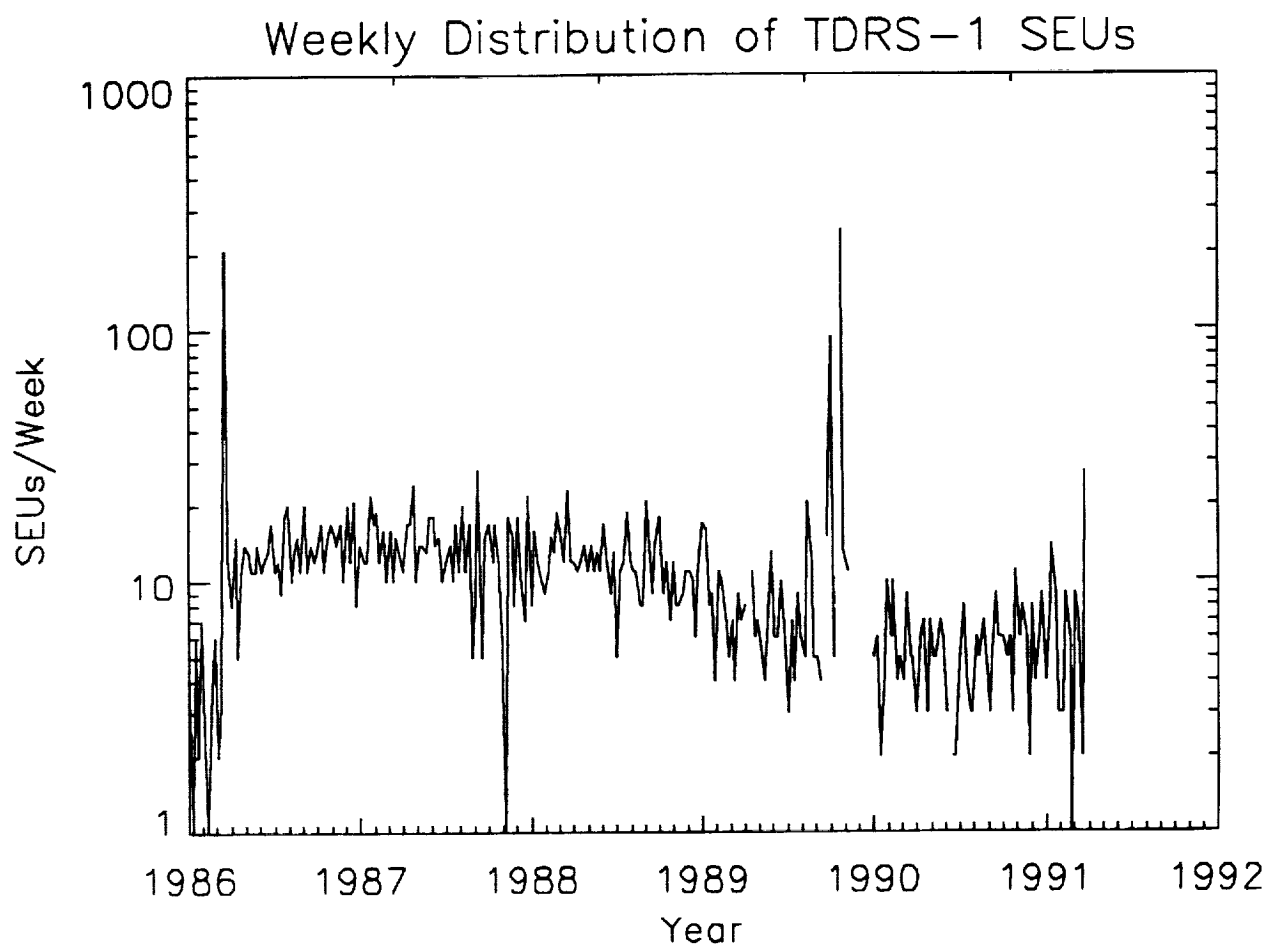


Figure 5. Graph made from data in seasonal distribution of TDRSS anomalies.
The distribution is considered random.
(Source NGDC)

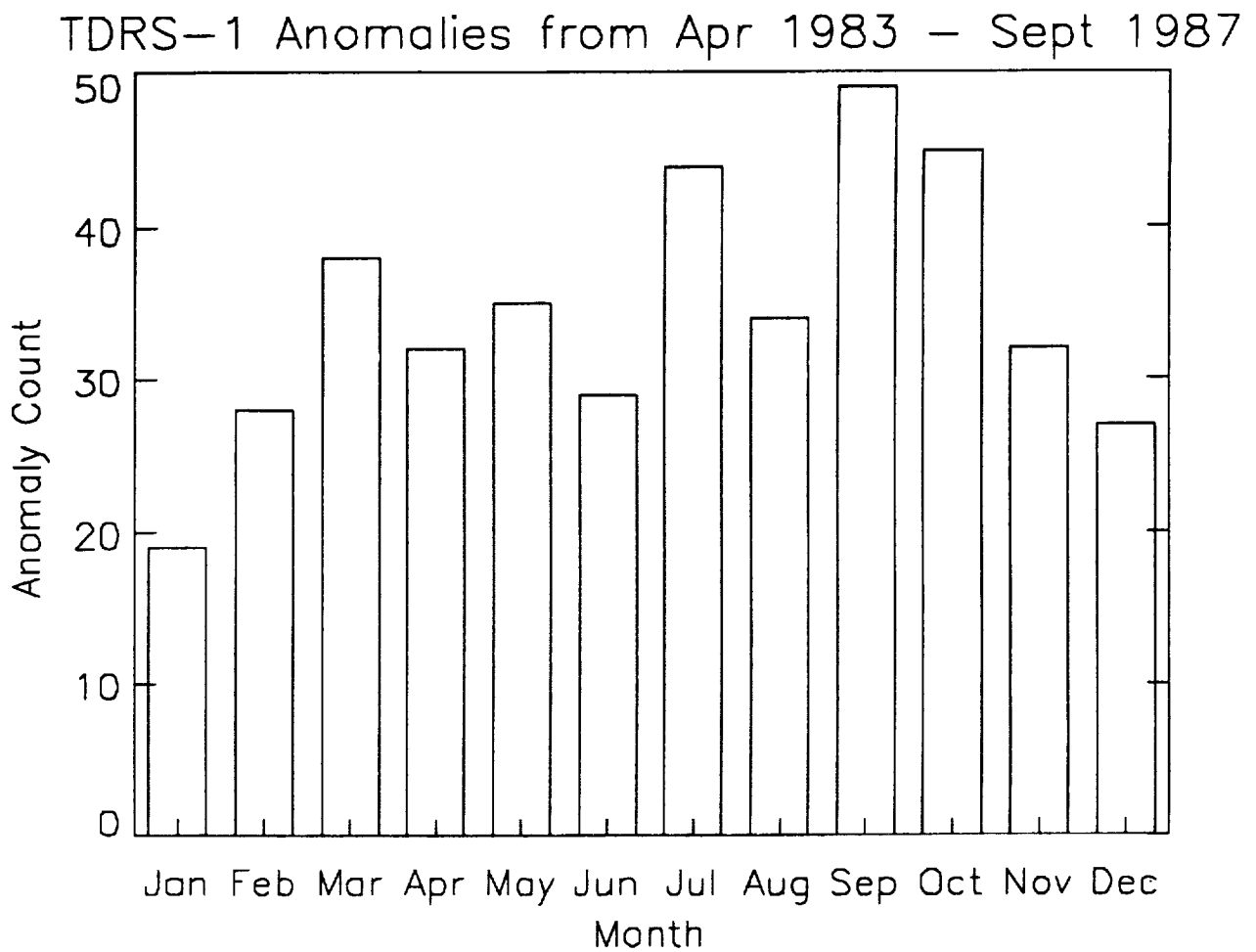


Figure 6. Graph made from data in anomaly database of anomalies on TDRS-1 weekly count for all observed SEU's. The rate shown is a minimum. The spikes in August, September and October are due to flares. (Source NGDC)

THE SCRAM TOOL-KIT

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ABSTRACT

This paper proposes a new series of on-orbit capabilities to support the near-term Hubble Space Telescope, Extended Duration Orbiter, Long Duration Orbiter, Space Station Freedom, other orbital platforms, and even the future manned Lunar / Mars missions. These proposed capabilities form a tool-kit termed Space Construction, Repair, and Maintenance (SCRAM). SCRAM addresses both Intra-Vehicular Activity (IVA) and Extra-Vehicular Activity (EVA) needs. SCRAM provides a variety of tools which enable welding, brazing, cutting, coating, heating, and cleaning, as well as corresponding non-destructive examination. Near-term IVA-SCRAM applications include repair and modification to fluid lines, structure, and laboratory equipment inside a shirt-sleeve environment (i.e. inside Spacelab or Space Station). Near-term EVA-SCRAM applications include construction of fluid lines and structural members, repair of punctures by orbital debris, refurbishment of surfaces eroded by atomic oxygen, and cleaning of optical, solar panel, and high emissivity radiator surfaces degraded by contaminants. The SCRAM tool-kit also promises future EVA applications involving mass production tasks automated by robotics and artificial intelligence, for construction of large truss, aerobrake, and nuclear reactor shadow shield structures. The leading candidate tool processes for SCRAM, currently undergoing research and development, include Electron Beam, Gas Tungsten Arc, Plasma Arc, and Laser Beam. A series of strategic space flight experiments would make SCRAM available to help conquer the space frontier.

INTRODUCTION

Today, we do not have enough on-orbit construction, repair, and maintenance capabilities to effectively support aggressive space programs: such as Hubble Space Telescope (HST), Extended Duration Orbiter (EDO), Long Duration Orbiter (LDO), Space Station Freedom (SSF), other orbital platforms, and manned Lunar / Mars missions. Therefore, it's critical that we expand our on-orbit capabilities and develop new tools to deal with the more demanding tasks that lie closely ahead. The Space Construction Repair and Maintenance (SCRAM) tool-kit will provide us with some of the tools needed to prevail through our space programs, and eventually help us conquer the space frontier. SCRAM provides tools for both our intra-vehicular activity (IVA) and extra-vehicular activity (EVA) needs.

Since the 1960's, extensive research and development (R&D) efforts have occurred, trying to achieve on-orbit welding capability. Consequently, several thermal processes have been investigated and are still being refined today. These include electron beam, gas tungsten arc, plasma arc, and laser beam. In addition to welding, however, other capabilities have been shown feasible with these same thermal processes. Accordingly, this paper establishes the term Space Welding and Thermal Tools (SWATT) to collectively identify several multi-function processes (tools) which are capable of welding, brazing, cutting, coating, heating, and even cleaning (see Figure 1). The SCRAM tool-kit has been devised to house SWATT and its complementary quality assurance and control tools, which would perform on-orbit in-situ non-destructive examination (NDE) of the workpiece. SCRAM would also house workpiece surface preparation tools and set-up assemblies. ***

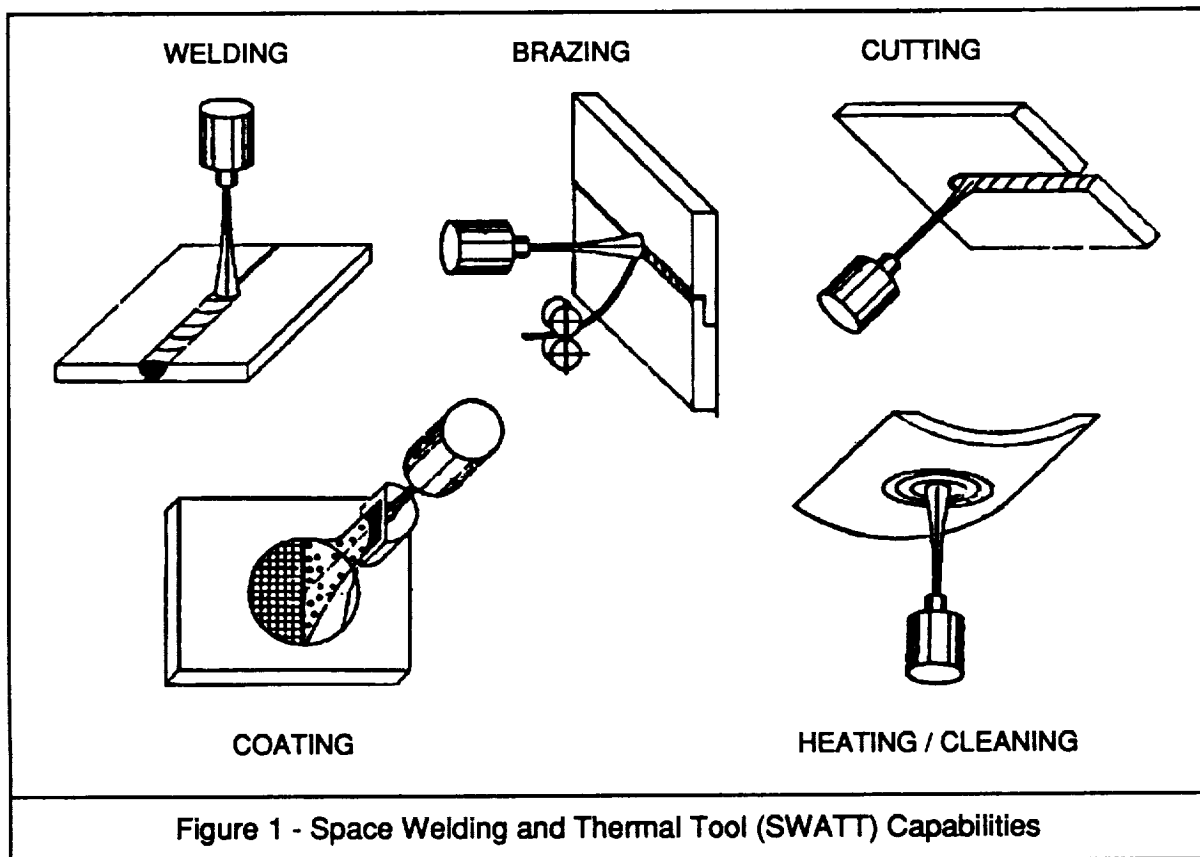


Figure 1 - Space Welding and Thermal Tool (SWATT) Capabilities

NEED FOR SCRAM

The need for SCRAM is manifested by the limitations of our current on-orbit capabilities. In-space joining, NDE, cutting, coating, heating, and cleaning are all tasks which cannot be effectively (if at all) accomplished with NASA's existing tools. SCRAM offers multi-function tools which will offer all of these new capabilities. Consequently, challenging space endeavors (see Figure 2) will become feasible.

*** Note: Detailed discussion of EVA-SCRAM application scenarios and performance and safety issues is presented in a separate paper at this Symposium, titled "EVA-SCRAM Operations."

Need for Better In-Space Joining: The in-space joining techniques, currently available to NASA, are limited to mechanical fastening and adhesive bonding. These techniques are rendered inadequate when compared to the following higher-performance joining characteristics of SCRAM's SWATT:

- Higher Joint Strength and Rigidity
- Better Joint Hermeticity
- Lower Joint Mass
- Simpler Joint Design
- Simpler Joint Manufacturing
- Higher Joint Reliability
- Broader Repair Versatility
- Lower Cost

Need for In-Space NDE: NDE of joints on-orbit is currently limited to simple visual inspection. In-space NDE is necessary to determine integrity and life-span of reusable on-orbit platforms. In addition, in-situ NDE is a necessary complement to SWATT operations (i.e. welding). NDE would provide in-space quality assurance and control of welded joints. SCRAM's NDE tools would provide accurate assessment of a joint's structural integrity (i.e. detection of cracks, voids, lack of penetration, misalignment) via electrical, ultrasonic, x-ray, and optical means, which far exceed the information gathered with a simple visual inspection. In addition, other SCRAM optical-NDE means would be used to monitor surface contamination / coating during or after a cleaning operation or a welding / cutting / coating operation.

Need for Better In-Space Cutting: In-space cutting is a task reserved only for emergency repair; routine construction would employ pre-cut and machined material. The in-space cutting techniques currently available to NASA are limited to sawing and chip-less blade cutting. These techniques have limited applications. Sawing operations generate debris which is difficult to contain in the micro-gravity / vacuum environment. Chip-less blade cutting is limited to few materials and workpiece geometries. SCRAM's SWATT "cutting torch" capability, would offer a repair tool which is more flexible with materials and workpiece geometries.

Need for In-Space Coating: Today, NASA cannot refurbish in space surfaces which have been eroded by atomic oxygen bombardment. SSF and any other platforms, which will remain in Low Earth Orbit (LEO) for long periods of time, will sustain significant damage to critical spacecraft surfaces, seriously degrading mission performance. Some of the surfaces being addressed are used as thermal radiators, telescope mirrors, electric conductors, and transmission or receiving antennae. Total replacement of such surfaces is currently the only alternative. However, the capability to re-coat such eroded surfaces would be achievable with SCRAM's SWATT.

Need for In-Space Heating: Currently NASA cannot locally heat and free a stuck antenna deployment joint (cold-welded in-place), or heat-treat structural elements which have lost material temper due to prolonged exposure to radiation and thermal gradients in space. SCRAM's SWATT would provide a localized heat-treating capability. This capability would also aid SWATT cutting, by introducing a



Figure 2 - Need for Space Construction, Repair, and Maintenance (SCRAM) Tools

thermal gradient across the cut plane prior to the cutting operation; this will yield a smoother cut edge [ref-1]. Moreover, SWATT's heating source could be used as a research tool for high temperature rapid-melt and re-solidification experiments (for both IVA and EVA experiments).

Need for In-Space Cleaning: Today, NASA cannot clean optical, solar collector, or thermal control surfaces which are permanently exposed to the extra-vehicular space environment. Performance of windows, mirrors, lenses, high emissivity radiator surfaces, and solar panel surfaces are gradually degraded by polymerized and cross-polymerized organic contamination (hydrocarbons and siloxanes), generated primarily by exposure with the vacuum and ultraviolet radiation environment [ref-4]. These contaminants, in-part, are generated by spacecraft outgassing products, fuel, and propulsion by-products. SCRAM's SWATT would provide means for cleaning such contaminants.

SCRAM APPLICATIONS

SCRAM's SWATT and NDE capabilities of welding, brazing, cutting, coating, heating, cleaning, and inspection lend themselves to various applications in near-term Shuttle and SSF missions, and in future manned Lunar / Mars missions.

Shuttle Missions: On-going Shuttle missions carry two tool-kits for in-flight contingencies. The IVA kit is called In-Flight Maintenance (IFM) tools, and is stowed in a middeck locker. The EVA kit is called Provisions Stowage Assembly (PSA) tools, and is stowed in the cargo bay. IVA- and EVA-SCRAM tools will complement and improve the IFM's and PSA's existing repair capabilities during contingencies. Longer duration Shuttle missions (EDO / LDO), with on-orbit stays reaching 30 to 90 days, will need to be capable of repairing punctures by orbital debris or damage by fatigue to the crew compartment, Spacelab module, tunnel adapter, external airlock, radiator panels, or vehicle structure (i.e. cargo-bay doors and latching mechanisms). In addition, shuttle servicing missions of LEO platforms and satellites could employ SCRAM for repair and maintenance of these spacecraft (i.e. cleaning of HST optics). SCRAM tools could be employed with Shuttle missions via manual or semi-automated operation modes (see Figure 3). Teleoperated SCRAM applications may also be feasible, should the Shuttle arm, the remote manipulating system (RMS), be improved for more dexterous operations (i.e. with the Dextrous End Effector now under development). In addition, teleoperation or even autonomous robotic operation of SCRAM may be achievable using a dedicated robotic slave arm (i.e. with the Servicing Aid Tool, also under development).

SSF Missions: SSF will present multiple opportunities for repair, maintenance, and construction over its life-span. SCRAM tools would become critical for repair of orbital debris- or fatigue-damaged habitation / laboratory modules, radiators, pressurized fluid systems, and structure (see Figure 4). Maintenance of surfaces eroded by atomic oxygen or degraded by contamination, and construction of modifications or expansions to the station structure, habitation / laboratory modules, and power and thermal systems, will become a routine well suited for SCRAM. Even general metallic labo-

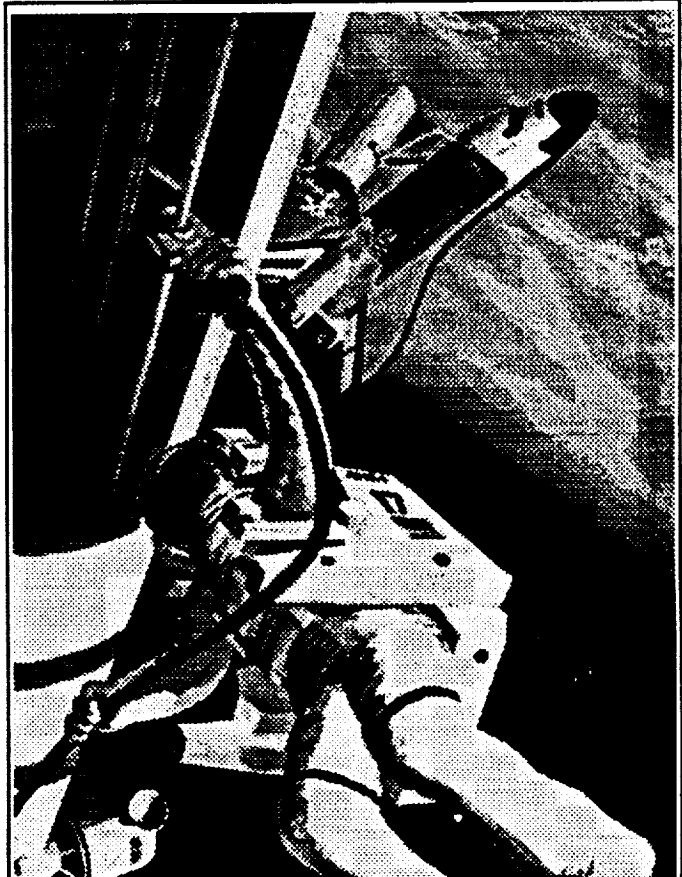


Figure 3 - Shuttle Servicing of Orbital Platforms

ratory equipment aboard SSF (i.e. containers, fluid lines, brackets) will require repair, maintenance, and modification; welding is commonly used for such purposes terrestrially.

Lunar Outpost Missions: The imminent renewal of manned Lunar missions will open a myriad of opportunities for SCRAM to be heavily employed both IVA and EVA in construction, repair, and maintenance of structures, habitation / laboratory modules, antennae, solar collector arrays, power plants, fluid lines (plumbing), surface vehicles, descent-ascent vehicles, and other various equipment (see Figure 5).

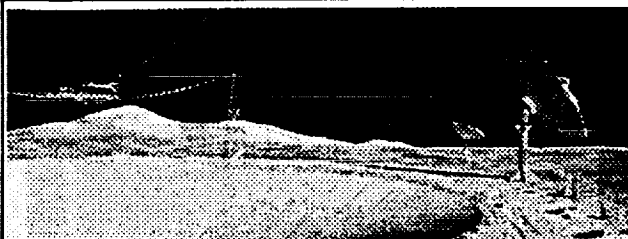


Figure 5 - Lunar-Based Antennae Construction

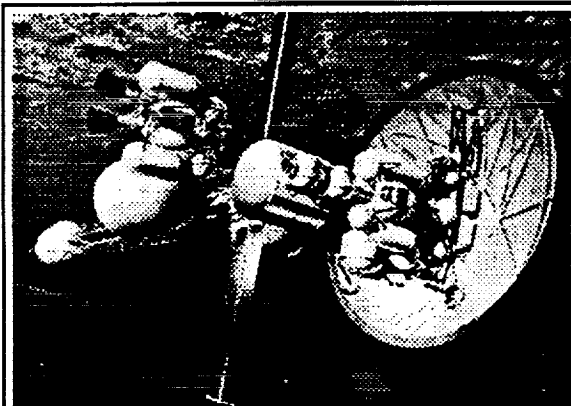


Figure 6 - Mars Orbital Transfer Vehicle's Aerobrake Construction

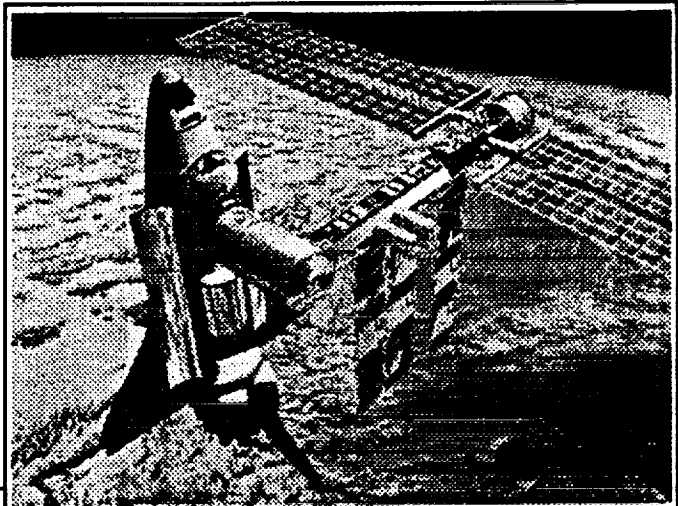


Figure 4 - SSF Construction, Repair, and Maintenance

Manned Mission to Mars: The eventual manned missions to Mars will consist of LEO preparation, interplanetary transfer, low Mars orbit, landing and exploration, and return-to-Earth phases. Over all these phases, manned Mars missions may employ

SCRAM tools, both IVA and EVA, on the orbital transfer, descent, ascent, and surface vehicles. The vehicles' construction, repair, and maintenance tasks suited for SCRAM will involve structures, habitation / laboratory modules, aerobrakes, antennae, solar collector arrays, radiators, power plants, nuclear shadow shields, fluid lines, and other various equipment (see Figure 6).

SCRAM PROCESSES

The SCRAM tool-kit is based on SWATT and complementary NDE tools. SWATT employs a combination of electron beam (EB), gas tungsten arc (GTA), plasma arc (PA), and laser beam (LB) processes to accomplish welding, brazing, cutting, coating, heating, and cleaning

tasks. Complementary in-situ NDE tools employ electrical, ultrasonic, x-ray, and optical processes to accomplish in-space quality assurance and control. Even though some of these SWATT and NDE processes overlap in their capabilities, each process exhibits unique and essential characteristics. Therefore, all of the processes are essential to effectively support anticipated SCRAM applications.

EB-SWATT: The EB process accelerates and directs a dense stream of high-velocity electrons upon an electrically conductive surface, to which the kinetic energy of the electrons is transferred as heat. Changing the beam focus varies the EB's intensity and consequently its capabilities (i.e. welding vs. cleaning). EB is limited to EVA (vacuum) operation only.

GTA-SWATT: The GTA process employs an ionization medium, provided by an inert gas, to transfer an arc from a non-consumable tungsten electrode to an electrically conductive surface. The high electric current, flowing through the arc and into the workpiece, generates heat. Changing GTA's current and ionization-gas flow-rate parameters allows various IVA and EVA capabilities (i.e. welding vs. coating). Vacuum operation is enabled using a Rockwell patented hollow tungsten electrode, through which an ionization medium (argon) is provided.

PA-SWATT: The PA process accelerates and converges a hot plasma, heated within the PA device by an arc, upon any surface whether electrically conductive or not. Changing PA's current and plasma-gas flow-rate parameters allows various IVA and EVA capabilities (i.e. welding vs. cutting). Vacuum operation is enabled using arc-jet space propulsion technology.

LB-SWATT: The LB process employs a high-power coherent monochromatic light beam for heating any material at the beam's point of focus. The LB is generated by either an Nd-YAG crystal or a CO2 gas, and may be directed and focused upon the workpiece by a system of mirrors, lenses, and fiber-optics. Changing LB's power and focus allows various IVA and EVA capabilities (i.e. welding, cutting).

Electrical-NDE: SWATT fabrication (i.e. weld) quality information is largely contained in the process' electrical feedback signals. These signals can be sampled by a voltage tap and a Hall-effect current transducer. This consequent electrical feedback can be compared after the SWATT operation to predetermined acceptable limits, or the feedback can be processed real-time by a computer allowing adaptive control of SWATT's operation parameters. SCRAM's electrical NDE methods, for post-fabrication detection of flaws, also includes eddy-current techniques.

Ultrasonic-NDE: SCRAM's ultrasonic-NDE processes employ both contacting and non-contacting methods for generating ultrasonic waves, including piezoelectric transducers with built-in dry couplants, and electro-magnetic-acoustic transducers (EMAT).

X-Ray-NDE: SCRAM's X-ray radiography is one of its most powerful and reliable methods for NDE due to its direct flaw visualization capability.

Optical-NDE: SCRAM's optical-NDE processes for surface flaw detection include holography, shearography, and speckle interferometry. These methods are based on the interaction between the object and a laser beam, providing optical fringe patterns. Dynamic thermal gradients, caused in LEO every 45 minutes by passage through the terminator, may provide sufficient stress on the workpiece to support SCRAM's optical-NDE processes. In addition to flaw detection, SCRAM employs optically stimulated electron emission (OSEE) and laser fluorescence techniques for characterizing surface contamination or coating by metal vapor deposition.

DEVELOPING SCRAM

R&D efforts to achieve SCRAM capabilities, need to target combined interactions between the following varying factors: (1) SCRAM processes (i.e. SWATT, NDE), (2) intra- and extra- vehicular operational environments (i.e. microgravity, vacuum, atmosphere, background radiation, thermal gradients), and (3) workpiece materials and geometries (i.e. stainless steels, aluminums, titaniums, Inconels, composites). In addition, R&D efforts need to focus on the various SCRAM operation modes (manual, telerobotic, semi-automated, fully-automated) and their implications on crew and mission safety. These R&D efforts should maximize utility of ground based space simulation tools, such as KC-135 parabolic flights, vacuum chambers, neutral buoyancy water tanks, and numerical modelling. R&D efforts should obviously continue and proceed to space-based validation and demonstration using Shuttle Small Payload experiments (i.e. Get Away Special, Complex Autonomous Payload, Hitchhiker), Spacelab IVA experiments (i.e. glove-box), and Shuttle EVA experiments (i.e. cargo-bay mounted workstation). Some of this R&D has been completed, but much still remains to be done.

R&D efforts pursuing development of SWATT and NDE have mainly occurred, and continue, in the former Soviet Union (Russia and Ukraine) and in the US. However, the Japanese and Europeans have also entered this field of endeavor. Today, EB-SWATT development is being led by the Paton Institute of Ukraine, the GTA-SWATT by Rockwell International Corporation of the US and NPO Tekhnomash of Russia, the PA-SWATT by NASA Marshall Space Flight Center (MSFC), and the LB-SWATT by University of Tennessee-Calspan (CO2 laser) and University of Alabama (Nd-YAG laser). Development of SCRAM NDE tools is being led by NASA Langley Research Center (LaRC).

EB-SWATT Status: The former Soviet Union, via the Paton Institute in Ukraine, successfully accomplished the following R&D for in-space EB: ground based vacuum chamber tests, microgravity simulation aircraft flight tests, on-orbit spacecraft autonomous flight experiments (with Soyuz-6), on-orbit space station autonomous experiments (with Salyut-6, -7, and MIR), ground-based neutral buoyancy water tank EVA simulation tests, and finally on-orbit manual EVA experiments (off of Salyut-7, and MIR, see Figure 7) [ref-1]. These aggressive efforts have resulted in Paton's in-space EB tool, which is known as "URI" or the "Versatile Hand Tool (VHT)." Today, the VHT is incorporated into MIR's on-board tool base. In-fact, the VHT has already been applied in real operations, including truss construction (by welding joints), emergency repair of a broken antennae (by cutting it loose), and refurbishment of solar panel performance (by cleaning debris off panel surfaces) [ref-2]. The VHT's performance with US alloys, and safety characteristics under NASA on-orbit operation standards are yet to be determined. Currently, NASA Goddard Space Flight Center (GSFC) is pursuing funding for an extensive series of Shuttle experiments to safely and effectively characterize in-space EB methods with Paton devices. NASA GSFC plans to incorporate a yet to be announced consortium of US experts, composed of NASA centers, other government agencies, industry, and universities.

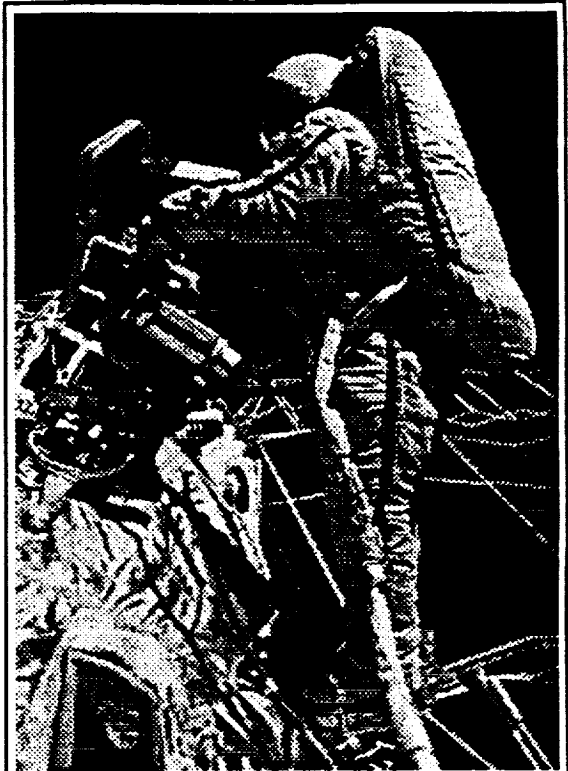


Figure 7 - Former Soviet Union EVA Manual Welding Experiment

GTA-SWATT Status: Rockwell International Corporation of the US successfully accomplished the following via Independent R&D, and some direct contracts from NASA MSFC and a NASA Headquarters In-STEP program: development of hollow electrode patents for GTA in a vacuum (4,803,339 & 5,149,932), ground based vacuum chamber tests, microgravity simulation KC-135 flight tests of semi-automated and manual welding tasks, development of an autonomous Get Away Special (G-169) Shuttle payload for on-orbit testing (see Figure 8), KC-135 flights of G-169, design of a more capable Shuttle Welding Experiment Platform (SWEP), ground-based neutral buoyancy water tank EVA simulation tests of semi-automated welding tasks, and designs of on-orbit Shuttle IVA and EVA experiments [ref-3]. Currently, NASA GSFC is pursuing funding for an extensive consortium-developed series of Shuttle experiments to safely and effectively characterize in-space GTA methods. Outside of the US, NPO Tekhnomash of Russia has successfully accomplished efforts very similar to Rockwell's. In August 1992, Tekhnomash presented photographs of their in-space EVA-GTA torch prototypes, including manual and semi-automated orbital versions. Tekhnomash is preparing to test these in space. In summary, all ground-based evaluations of the in-space GTA promise success and effective applications on-orbit.

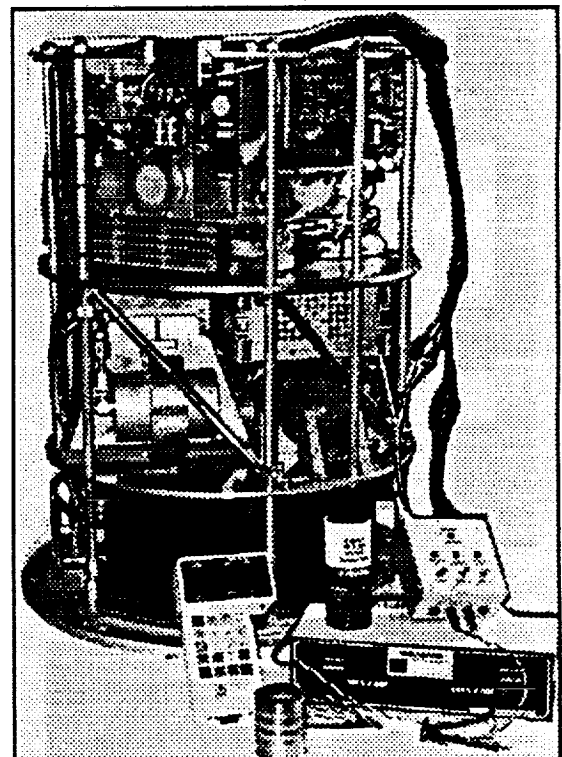


Figure 8 - Rockwell's Get Away Special GTA Welding Experiment

PA-SWATT Status: NASA MSFC and a California based sub-contractor, which specializes in arc-jet propulsion technology, are currently developing a PA device for vacuum operation. The potential for this technology's successful development is high. But, few details are known at this time, due to the infancy of the technology and its consequent proprietary nature.

LB-SWATT Status: The University of Tennessee-Calspan is currently pursuing development of a Shuttle-Small-Payload-type (cargo-bay) LB experiment with a CO2 laser. This experiment is manifested for flight around 1995, and is being funded through a NASA Headquarters' Center for the Commercial Development of Space. On the other hand, University of Alabama in Huntsville conducted microgravity-simulation-aircraft flight experiments on NASA MSFC's KC-135. These experiments targeted LB with Nd-YAG laser. The University of Alabama is currently pursuing funding to continue this work. Even though lasers seem to be the "thing of the future," LB's near-term utility in space suffers from very high power requirements.

NDE Status: Development of NDE processes has been primarily focused on terrestrial applications. However, these developed NDE technologies, for the most part, are almost directly applicable to on-orbit operations. Extensive R&D remains to be done in the conversion of these terrestrial NDE technologies into on-orbit compatible tools [ref-5].

DESCRIPTION OF THE SCRAM TOOL-KIT

Since the Space Shuttle is the only near-future space construction, repair, and maintenance shop, SCRAM is designed for Shuttle use. The SCRAM tool-kit supports both IVA and EVA operations. Consequently, SCRAM is separated into two distinct tool-sets.

The IVA-SCRAM Set: The IVA-SCRAM set of tools would be stowed in the Shuttle's Middeck Lockers (see Figure 9). It is anticipated that two lockers would be required, one for IVA-SCRAM's computer-controlled power supply unit, and the other for IVA-SCRAM's SWATT, NDE, consumables, and other support devices. IVA-SCRAM's computer-controlled power supply (hardware and software) would be a derivative of the Centaur III

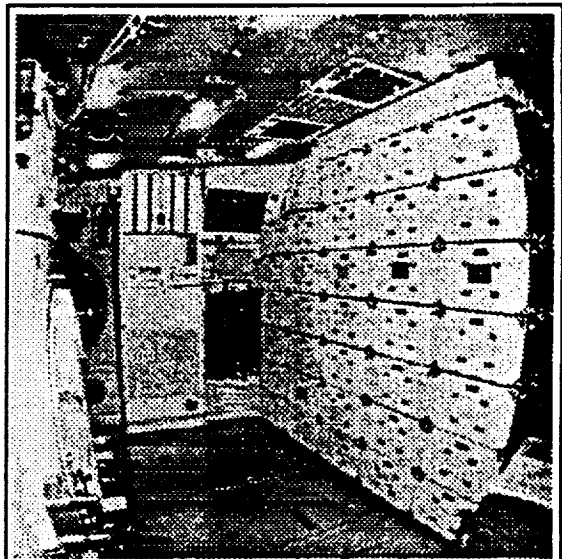


Figure 9 - IVA SCRAM Stowage

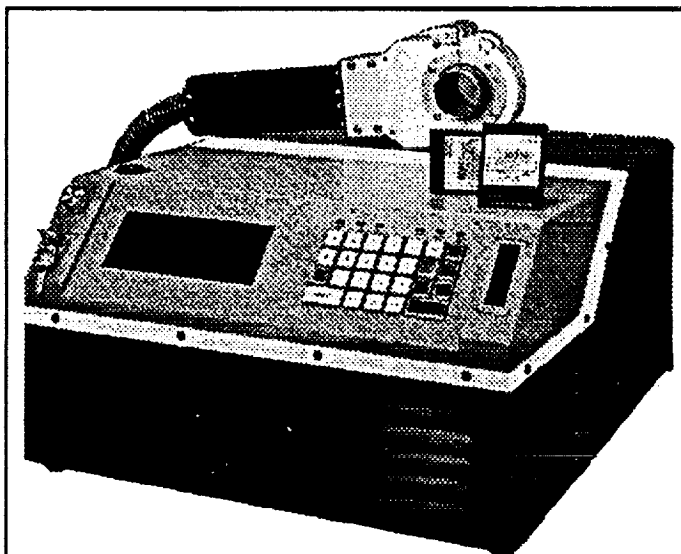


Figure 10 - Dimetric's State-of-the-Art Automated Programmable Welding System

150PTW, developed by Dimetrics of Talley Industries (see Figure 10). The Centaur III is commercially proven in terrestrial food, dairy, beverage, pharmaceutical, biomedical, semiconductor, nuclear, aircraft, and aerospace industries. It provides user-friendly programmable interfaces with the operator, and employs read / write memory cassette cartridges which allow use or modification of pre-programmed procedures (i.e. for welding). IVA-SCRAM's power supply would process Orbiter power and distribute it under computer control to the SWATT and NDE devices. SWATT devices suitable for IVA would include a manual GTA welding torch and a semi-automated GTA orbital welding head (see Figure 10). The GTA devices would be supplemented with electrical and ultrasonic NDE. In addition, the IVA-SCRAM

set would include safety devices for protection against temperature extremes, electrical shock, contamination (i.e. argon shielding gas), and radiation (i.e. EMI, ultraviolet, infrared, intense light). Portable workstation set-up and workpiece surface preparation tools would also be included.

The EVA-SCRAM Set: The EVA-SCRAM set of tools would be stowed in the Shuttle's cargo bay. But, due to the more demanding extra-vehicular environment, extensive flight hardware and software would be required to facilitate EVA-SCRAM operations. Therefore, EVA-SCRAM would be designed to maximize use of existing and upcoming Shuttle EVA facilitating tools, including the telerobotic RMS, Dextrous End Effector (DEE), and Servicing Aid Tool (SAT). A Cargo Bay Stowage Assembly (CBSA) type tool carrier (see Figure 11) mounted to the cargo bay's sidewall could be employed for stowing workstation set-up assemblies, workpiece surface preparation tools, SWATT, and NDE tools. The CBSA "type" locker" provides EVA crewmember with proper foot and hand restraints so that tool boards can be transferred onto the Extravehicular Mobility Unit (space suit) and supporting tool caddies, such as the Manipulator Foot Restraint (MFR) (see Figure 12). The Flight Servicing System (FSS) locker may also be used for both tool stowage and transportation to the worksite using the RMS. The CBSA or FSS would contain a specialized harness for interfacing the modular EVA-SCRAM tools with power, control, coolant, and consumables (i.e. ionization gas). The harness could be routed along the RMS (i.e. using velcro straps) and be connected to a Get Away Special (GAS) Canister, which would contain SCRAM's computer controlled power supply unit, radiator, and consumables. The GAS canister would provide a one atmosphere dry nitrogen environment, allowing the use of non-vacuum hardened support equipment (similar to IVA-SCRAM's - see Figure 10). The GAS canister would also provide standard interfaces to Orbiter power and aft flight deck control. In the near-term, SWATT devices suitable for EVA would include EB, GTA, PA, and LB. These SWATT devices would be supplemented with electrical, ultrasonic, optical, and x-ray NDE tools. In addition, the EVA-SCRAM set would include safety devices for protection against temperature extremes, electrical shock, contamination (i.e. metal vapor), and radiation (i.e. EMI, x-ray, UV, infrared, intense light).

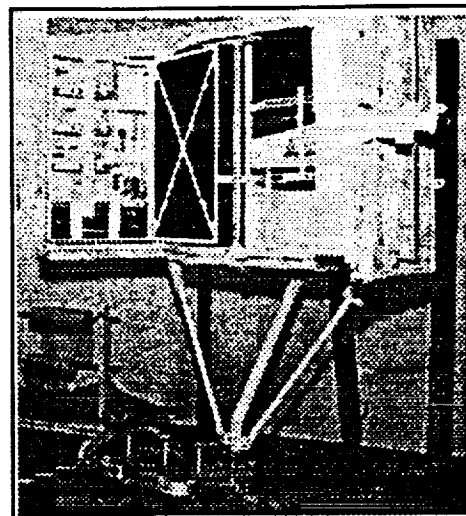


Figure 11 - EVA SCRAM Stowage

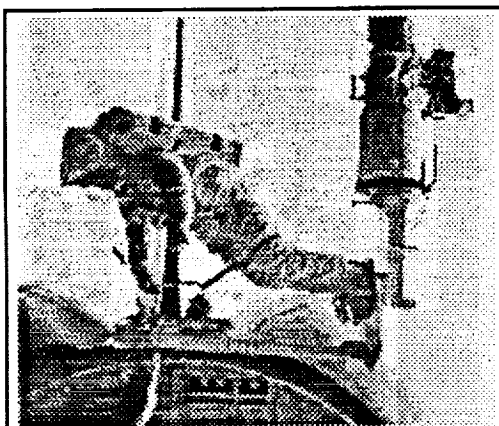


Figure 12 - RMS-MFR Supporting EVA SCRAM

CONCLUSION

Today, we have the technologies necessary for developing a SCRAM tool-kit. However, validation and demonstration of SWATT and NDE technologies in space, by the US, have yet to occur. With increasing Shuttle mission challenges and upcoming endeavors such as SSF, SCRAM tools can provide critical construction, repair, and maintenance capabilities needed in the harsh frontier of space. Flight experiments are necessary to complete the development of SCRAM tools, and their incorporation into the nation's Space Exploration Initiative. Experiments, targeting all SWATT and NDE processes, should be cost-effectively carried out with the same flight platform, such that the various processes' capabilities can be comparatively characterized and evaluated against near-term applications. Shuttle Small Payloads are effective for carrying out safely an autonomous series of such experiments. Consecutively, more demanding Spacelab glove-box IVA experiments and Shuttle cargo bay EVA experiments can be undertaken to validate and demonstrate manual, telerobotic, semi-automated, and fully-automated SCRAM operation modes for near-term applications.

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SPACEHAB I MAINTENANCE EXPERIMENT

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Abstract

The SpaceHab I flight on STS-57 served as a test platform for evaluation of two space station payloads. The first payload evaluated a space station maintenance concept using a sweep signal generator and a 48-channel logic analyzer to perform fault detection and isolation. Crew procedures files, test setup diagram files, and software to configure the test equipment were created on the ground and uplinked on the astronauts' voice communication circuit to perform tests in flight. In order to use these files, the portable computer was operated in a multi-window configuration. The test data was transmitted to the ground allowing the ground staff to identify the cause of the fault and provide the crew with the repair procedures and diagrams. The crew successfully repaired the system under test.

The second payload investigated hand soldering and de-soldering of standard components on printed circuit (PC) boards in zero gravity. It also used a new type of intra-vehicular foot restraints which uses the neutral body posture in zero-g to provide retention of the crew without their conscious attention.

As initially conceived, Space Station Freedom was to be a highly automated, highly productive port in space. All the main systems would contain automated fault detection and isolation capability to aid in maintenance. Failed units would identify themselves and be replaced by the crews using a limited list of tools. Equipment meeting a group of approximately 30 attributes like these were designated orbital replacement units (ORU's). These requirements were in the program requirements documents of the space station.

As the program developed, costs grew, problems were identified, and it was subjected to numerous revisions. The universal automated fault detection and isolation capability requirement was removed during the revision in the summer of 1990. The effect of this decision was to increase the probability that more systems, as compared to components, would have to be changed on orbit. The increase in up and down mass for maintenance would have an adverse impact on normal operations and payloads.

This impact prompted an effort by the Tools and Diagnostic Equipment Subsystem of the Manned Systems to provide common test equipment in addition to the common tools in its charter. This test equipment was to give the crew the ability to actively test the various systems and isolate the faults to as low a level as possible. The intent was to allow changing of a component, such as a transformer, instead of a black box.

In a parallel effort, the Marshall Space Flight Center (MSFC) was developing plans to support the users of the space station with special test equipment. The lab support equipment included a battery charger, a logic analyzer/oscilloscope, and a multimeter. When MSFC started to implement their plan, the duplications became obvious and the program elected joint development of the common equipment to reduce costs.

The equipment selected to meet the maintenance needs and the lab support equipment needs were the Tektronics 1230B logic analyzer/oscilloscope and the Hewlett Packard 8116A sweep signal generator. The logic analyzer/oscilloscope is a 48 digital channel test instrument capable of testing PC boards and a dual channel analog oscilloscope. It is computer controllable through a RS-232 interface, and is triggered to store the data array by relationships among the active channels. This data may be displayed or stored in a DOS file which can be transferred over the

RS-232 interface. This transfer capability allows the data to be downlinked to the ground and displayed on instruments there.

The sweep signal generator can produce standard test signals, i.e., sine, square, triangular, and ramp waves and dc voltages.

Selection of the equipment had been completed and materials and electromagnetic interference characteristics were being investigated when an opportunity arose.

SpaceHab, Inc., was formed to take advantage of the Space Transportation System's capabilities to carry diverse payloads. By providing an integration function and a vehicle, the SpaceHab module, the company will provide an important service to small payloads. SpaceHab contracted with Alenia Spazio, an Italian aerospace organization, to build the modules. The contract to perform the integration of the payloads into the vehicle was given to McDonnell Douglas Space Systems Division (MDSSC), Huntsville, Alabama.

On the first flight of the module on STS-57, some of the volume and weight capability was not taken by customers. This available resource was acquired by NASA and offered to internal offices having a need to perform flight testing.

The development of the maintenance diagnostic equipment for the space station had advanced to the point at which a flight test was feasible, and the offer of resources was accepted. Weight and volume were reserved for the Space Station Tools and Diagnostics System (TDS). Initially, this area included three experiments: the Diagnostic Equipment (DE) experiment, the Soldering Equipment (SE) experiment, and the Battery Charger (BC) experiment. As the design of the experiments matured, the weight limitation caused the BC experiment to be dropped.

One goal of the TDS-DE was to operate the space station maintenance diagnostic equipment in the zero-g environment. A scenario was developed to simulate the proposed maintenance concept of the space station. In this concept, when an equipment failure is discovered, the failure is analyzed by the flight and ground crews and any descriptive information is given to the system engineers. The system engineers develop a test to isolate the fault based on using the programmable test equipment on board. The test procedures, appropriate schematics and diagrams,

and the program to configure the test equipment are uplinked to the flight vehicle. The crew uses the program to configure their equipment and the procedure to setup and perform the test, aided by the schematics and diagrams.

The data from this test is then downlinked to the system engineers who either develop a repair procedure or develop a further test. The repair files, containing procedures, schematics, and diagrams, are uplinked to the crew who then restore the equipment. Testing, where appropriate, would be done in a similar manner. Demonstration of this uplink and downlink capability was also a goal of the TDS-DE experiment.

Since the multiple files would have to be operated or referenced at arbitrary intervals, the normal DOS environment was replaced by using a Microsoft product that allowed several applications to be active. Evaluation of this technique was a third goal of the TDS-DE experiment.

Because the TDS-DE was considered to be a payload on the SpaceHab module, specific resource usage was required by MDSSC, the payload integrator. This requirement skewed the test somewhat, in that a timeline for the crew was needed before the failure would normally have been discovered. This timeline and the procedures and data were developed around a test assembly, used to simulate the system under test. The test assembly was a frequency counter with a jumper wire across two pins on a terminal strip. It contained test points to provide signal tracking through the circuitry and power status and connectors for the signal generator and logic analyzer. The repair consisted of relocating the jumper wire.

The soldering test was an outgrowth of a soldering test which had been flown on the KC-135. As conceived, the test used battery-powered soldering tools. In practice, the number of solder connections was too high for the battery-powered tools and it was necessary to use commercially available DC powered tools. The tasks required soldering and de-soldering wires to 44 test points on two PC boards. These test points included various types of connectors (turret, pad, etc.). Wicking material was selected to remove the solder during the de-solder process.

Concern that soldering was a hazardous process led to the requirement for containment of any particulate matter generated

during the soldering process. The containment device developed consisted of a shroud over the MDSSC-supplied work bench.

Special foot restraints to react to small forces generated during labor intensive tasks were developed. Normally, an acclimated crew prefers to float freely in the vicinity of the work. Exertions of small forces are adequate for them to remain in the desired position. For extended work in one area, foot loops are available. Some muscular exertion is required to maintain the foot in the restraint, which is a cause of hot spots and cramps. The engineer involved in the TDS-SE had been a test subject for evaluation of the space station foot loops on the zero-g aircraft. On the basis of his experience there and his knowledge of the soldering restraint requirements, he developed IVA foot restraints using the same principle as the old "golden slippers" EVA foot restraints. These foot restraints are open in the center with bars behind the heels and over the instep. They mounted to the handrails of the single SpaceHab rack below the MDSSC-provided work bench. They were installed for launch.

As an aside, this was my first experience as a payload provider. The other equipment I have provided was as part of the vehicle and was supported by the internal resources in the provisioning of the safety material. This was not the case for the SpaceHab I flight. It was necessary for me and my staff to prepare the data needed for the safety review process. I did not anticipate the type of data needed to satisfy this requirement. Once the requirements were understood, the required data was provided.

The result of the experiments was proof of the maintenance concept. The TDS-DE procedures were uplinked as planned, the data was downlinked, the repair procedure was performed by the crew inflight, and the equipment was tested successfully after the repair.

The crew was able to display the procedures and diagrams simultaneously.

The TDS-SE was highly successful. More than the one solder and de-solder board were completed. Analysis of the solder joints shows results consistent with preflight training. The foot restraints were well received and have been requested for future SpaceHab flights.

**A STANDARD SET OF INTERFACES FOR SERVICEABLE SPACECRAFT
BY
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Abstract

One key element required for effective space logistics activity is the development of standard spacecraft interfaces. To this end, the NASA Space Assembly and Servicing Working Group has created the Interface Standards Committees composed of mechanical, electrical, fluid, thermal, and optical committees. The objective of the ISC is to create international spacecraft standards to support space maintenance and servicing. Recently, ISC panel discussions have described the need for a "Standard Set" of interface hardware standards for satellites and platforms and to develop international standards for each of these critical interfaces. The set is to include: Navigation Aids; Grasping, Berthing, and Docking Interfaces; and Utility Connectors.

1.0 INTRODUCTION

The Space Assembly and Servicing Working Group (SASWG) is a NASA organization with over 700 individual members from government, industry, and academia dedicated to the study of enabling technologies for spacecraft maintenance and servicing. To this end, the SASWG has created the Interface Standards Committees (ISC) composed of mechanical, electrical, fluid, thermal, and optical committees with approximately 60 voluntary members from NASA, U.S. Space Command, U.S. Air Force, U.S. Navy, and industry personnel. It is the objective of the ISC to create international spacecraft standards to support space maintenance and servicing.

The SASWG ISC is currently engaged in 10 standards projects. Draft documents have been referred to professional standards organizations to become standards, guidelines, or recommended practices. To date, the American Institute of Aeronautics and Astronautics (AIAA), the Electronic Industry Association (EIA), and the Society of Automotive Engineers (SAE) have accepted SASWG ISC interface standards projects. The ISC provide these standards organizations with the technical expertise required to prepare standards, guideline, and recommended practices. After review by the professional standards organization, documents are adopted and referred to the ANSI for referral to international standards organizations.

Each professional standards organization is accredited by American National Standards Institute (ANSI) to develop American National Standards. Only the ANSI serves as the U.S. member of international standards organizations such as the International Standards Organization (ISO), the International Electrotechnical Commission (IEC), and the Pacific Standards Congress (PASC).

While the SASWG has set an objective to create international spacecraft standards to support space maintenance and servicing, it should be noted that there are other compelling reasons to support international spacecraft standards. Joint U.S. Government and industry activity is needed to support private sector interests in government-to-government standards negotiations, since it is unlikely that industry alone will provide the necessary financial support for U.S. representation. Also, industry cannot perform an adequate role of negotiator to assure a means for U.S. manufacturers to meet international standards and continue to have access to international markets.

Recently SASWG spacecraft standards panel discussions have described the need for a "Standard Set" of interface hardware standards for satellites and platforms. The set is to include: Navigation Aids; Grasping, Berthing, and Docking Interfaces; and Utility Connectors (electrical power, data, and fluid connectors, as required by spacecraft for on-orbit maintenance). It is the objective of the SASWG to develop international standards for these critical interfaces.

2.0 DISCUSSION

2.1 Current SASWG Interface Standards Projects

Documents have been referred to professional standards organizations for review and approval.

American Institute of Aeronautics and Astronautics

- 1) Guideline for Grasping / Berthing / Docking Interfaces - Approved by AIAA Serviceable Spacecraft Committee on Standards (AIAA SS COS) (AIAA G-056-1992)
- 2) Standard Interface for Remote Manipulator System Payload Deployment and Retrieval Grapple Fixture - Proposed to AIAA SS COS
- 3) Standard Interface for Magnetic End Effectors - Proposed to AIAA SS COS
- 4) Guideline for Serviceable Spacecraft Utility Connectors - Proposed to AIAA SS COS

Electronic Industry Association

- 5) Electrical Connector - Sub-Miniature - Approved by EIA Standard Committee CE 2.0
- 6) Electrical Connector - Large - Approved by EIA Standard Committee CE 2.0
- 7) Fiber Optic Connector - SASWG ISC Project

Society of Automotive Engineers

- 8) Preparation of Specifications for Metric Fluid Couplings for Spacecraft Servicing - Approved by SAE Committee G-3 (MAP2261)
- 9) Standard Interface for Hex Head Bolt and Wrench - Proposed to SAE Committee E-25
- 10) Guideline for Replaceable Thermal Insulation Interfaces - SASWG ISC Project

2.2 SASWG Interface Document Preparation Methodology

The SASWG ISC standardization process is performed in six steps:

- 1) Identify and discuss key standards issues during face-to-face meetings and report in SASWG ISC Minutes.
- 2) Prioritize candidate hardware interfaces projects by consensus vote.
- 3) Identify committee members from industry and government and elect a project leader.
- 4) Prepare draft standards, guidelines, and recommended practices (mostly performed with communication by facsimile and telecon).
- 5) Refer draft documents to professional standards organizations for review and approval.
- 6) Attend professional standards organizations committee meetings and provide consultation, especially for technical requirements unique to spacecraft design and operations.

3.0 DOCUMENTS PROPOSED TO THE AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS (AIAA)

3.1 Grasping / Berthing / Docking Interfaces

This guideline provides technical information for the design of three mechanical interfaces required for spacecraft servicing --- grasping by telerobotic or visual manipulation, berthing of payloads or spacecraft, and docking of spacecraft. Achieving a degree of commonality individually and collectively for this general class of interface will simplify the servicing of a variety of orbital replaceable units (ORU's), Attached payloads, platforms, Space Station Freedom, satellites, and other passive and mobile spacecraft. The invaluable experience of past missions from Gemini to the Shuttle Orbiter provides the basis for the information contained in this document.

3.2 Remote Manipulator System Payload Deployment and Retrieval Grapple Fixture Interfaces

This standard establishes the interface design requirements for three standard grapple fixtures - Flight Releasable Grapple Fixture (FRGF), Rigidized Sensing Grapple Fixture (RSGF), and Electrical Flight Grapple Fixture (EFGF). Design requirements are provided for the Grapple Fixture interface and Extravehicular Activity (EVA) release interface. It should be noted that there are three new non-standard grapple fixtures models - Flight Releasable Light Weight Grapple Fixture (LWGF), Auxiliary Grapple Fixture (AGF), and Electrical Light Weight Grapple Fixture (ELWGF). The light weight grapple fixtures are a solution to the weight / budget problems of payloads.

3.3 Magnetic End Effector Interface

This standard provides interface requirements for use by robotic arms with a magnetic end effector for grappling ORUs, satellites, structures, tools, and other serviceable spacecraft payloads during space operations. The interface aspects are mechanical (dimensional), structural, performance, thermal, electrical, and operational. A Magnetic End Effector has been developed to provide a dexterous end effector for the Shuttle Remote Manipulator System (RMS), and will be tested in space during a flight demonstration in 1994.

3.4 Utility Connector Interfaces

This guideline reviews the development of utility connectors for spacecraft servicing systems. Utility connectors are designed for fully automated remote operation, separate from and independent of any docking mechanism, operation after a docking mechanism is rigidized, and are compatible with both single point and three point docking mechanisms. Technical information is provided for the development of standard interface design of utility connectors intended to be for a variety of applications where multiple utilities are required in a single connector. The connector may include electrical power, data, and fluid ports. This system is considered vital for the development of serviceable spacecraft.

4.0 DOCUMENTS PROPOSED TO THE ELECTRONIC INDUSTRY ASSOCIATION (EIA)

4.1 Electrical Connectors, Rectangular, Blind-Mate, Scoop-Proof

This standard provides terminology, description and requirements of a blind-mate, scoop-proof, rectangular shell series of electrical connectors for serviceable spacecraft for use during space and ground support activities. Aspects such as size, alignment, mating force, material requirements, reliability, durability, weight, electrical and physical characteristics, and temperature range are covered. This standard is intended to assist project managers, designers, and others concerned with electrical connectors in aerospace technology toward standardizing usage with respect to serviceable spacecraft.

4.2 Electrical Connectors, Rectangular, Blind-Mate, Scoop-Proof, Low-Force, Sub-Miniature

This standard is for a rectangular electrical connector is similar to the document above, except for the size and locking mechanism. This connector is smaller, and may utilize release levers.

5.0 DOCUMENTS PROPOSED TO THE SOCIETY OF AUTOMOTIVE ENGINEERS (SAE)

5.1 Preparation of Specification for Metric Fluid Couplings for Spacecraft Servicing

This approved SAE Metric Aerospace Recommended Practice (MAP) establishes the requirements for preparing a specification for fluid couplings for spacecraft servicing. The objective of this document is to provide design, development, verification, storage, and delivery requirement guidelines for the preparation of specifications for fluid couplings and ancillary hardware for use with serviceable spacecraft designed for use in the space environment. The couplings shall be capable of re-supplying storable propellants, cryogenic liquids, and gases to a variety of spacecraft.

5.2 Hex Head Bolt and Wrench Interfaces

This standard provides design and materials requirements for a 8 and 12 millimeter hex head bolt to spacecraft fastener. Dimensions and clearances were determined to assure bolt and wrench compatibility over the temperature extremes of space as part of a Special Project prior to the preparation of a draft standard for spacecraft fasteners.

6.0 CONCLUSIONS

The purpose of the NASA Space Assembly and Servicing Working Group Interface Standards Committee is to prioritize spacecraft mechanical, electrical, fluid, thermal, and optical interface projects selected by member consensus; prepare draft standards, guidelines, and recommended practices; refer to professional standards organizations; and assist with document review, approval, and referral to international standards organizations. A "Standard Set" is needed for serviceable spacecraft. The set will consist of (1) navigation Aids, (2) grasping, berthing, and docking Interfaces, and (3) utility connectors (electrical power, data, and fluid connectors). Standardization of interfaces has been proven effective for aircraft manufacturing, servicing, and maintenance. Internationally recognized standard interfaces are a driver to the development of serviceable spacecraft and the establishment of a global spacecraft maintenance infrastructure. Interface standards have to be imposed to force cost savings from on-orbit maintenance.

7.0 ACKNOWLEDGMENTS

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