**HUMAN FACTORS ANALYSIS
AND DESIGN METHODS
FOR NUCLEAR WASTE
RETRIEVAL SYSTEMS**

MASTER

VOLUME I

**HUMAN FACTORS DESIGN METHODOLOGY
AND INTEGRATION PLAN**

JUNE 1980

Submitted to:

**Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94500**

Copy 5 of 10

ANACAPA SCIENCES, INC.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

HUMAN FACTORS ANALYSIS AND DESIGN METHODS FOR NUCLEAR WASTE RETRIEVAL SYSTEMS

VOLUME I HUMAN FACTORS DESIGN METHODOLOGY AND INTEGRATION PLAN

Steven M. Casey
ANACAPA SCIENCES, INC.
Santa Barbara, California 93102

June 1980

DISCLAIMER
This document contains information that is the property of the United States Government. It is being made available to the public for informational purposes only. It is not to be used for any other purpose without the express written permission of the United States Government. The United States Government makes no warranty, expressed or implied, for the use of the information contained herein. The use of the information is at the user's risk. The United States Government is not responsible for any damages or losses resulting from the use of the information contained herein.

Prepared for
LAWRENCE LIVERMORE NATIONAL LABORATORY
NRC Waste Management Program
Livermore, California 94550

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PREFACE

This is one of four documents being prepared for the purpose of providing human factors engineering methodology and guidelines for the design and development of a nuclear waste retrieval system. The methodology presented in this document is a variation of systems development procedures developed over the last three decades by human factors engineering analysts. The areas of design responsibility of the human factors team have been outlined, and the methodologies applicable to the development effort have been identified.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	1
HUMAN FACTORS ENGINEERING INPUT IN SYSTEM DESIGN . . .	2
REVIEW OF THIS SERIES OF DOCUMENTS	3
Volume I: Human Factors Design Methodology and Integration Plan	3
Volume II: A Compendium of Human Factors Design Data . . .	6
Volumes III and IV: The Computerized Event-Tree Analysis Technique	7
HUMAN FACTORS ENGINEERING IN SYSTEM DEVELOPMENT	9
INTRODUCTION	9
HUMAN ENGINEERING IN COMPLEX SYSTEMS	10
HUMAN FACTORS ENGINEERING AND DESIGN DECISIONS	12
AREAS OF RESPONSIBILITY OF THE HUMAN FACTORS TEAM . . .	14
OVERVIEW OF THE HUMAN FACTORS ENGINEERING DESIGN CYCLE FOR WASTE RETRIEVAL SYSTEMS	16
PRELIMINARY DEVELOPMENT	23
FUNCTION ANALYSIS	24
Identify System Requirements	24
Specify System Functions	27
Develop Mission Profiles and Mission Scenarios	35
Develop Decision/Action Diagrams	38
FUNCTION ALLOCATION	40
Identify Allocated Functions	42
Develop Alternative Man-Machine Configurations	43
Develop Alternative Functional Flow Diagrams	45
List Operator and Machine Functions	46
Collect Function Allocation Data	46
List Advantages and Disadvantages of Alternative Configurations	52
Develop Function Allocation Evaluation Matrix	54
Select Man-Machine Configurations	58
Provide Preliminary Personnel Requirements Listing	59
Perform Computer-Aided Function Allocation	60
Develop Human Factors Checklist	60
TASK DESCRIPTION	61
Organize Functions into Categories	62
List Tasks	62
Order Tasks	66
TASK ANALYSIS	66
Identify Permissible Control/Display Components	66
Select Appropriate Control/Display Components	67
Identify Operational Factors	70
Integrate Control/Display Components	72

	Page
Develop Operational Sequence Diagrams	72
Develop Information Flow Process Charts	76
Perform Timeline Analyses	79
Perform Computerized Event Tree Analyses	79
EQUIPMENT DEVELOPMENT	83
LARGE WORKSPACE LAYOUT.	84
Perform Correlation Analyses	84
Perform Link Analyses.	85
COMPARTMENT LAYOUT.	89
Measure Static Dimensions of User Population	89
Consult Anthropometric Data.	90
Evaluate Designs with Manikins	90
Implement Computer-Assisted Anthropometry Analyses	95
Develop Reduced-Scale Models	95
Develop Soft Mockups	96
Develop Hard Mockups.	97
Test Designs with Anthropomorphic Dummies and System Users	98
Analyze Dynamic Workspace Requirements.	98
Assess Visual Requirements	99
CONTROL/DISPLAY DESIGN AND ARRANGEMENT	100
Organize Controls and Displays	102
ENVIRONMENTAL SYSTEMS DESIGN AND MEASUREMENT	107
Select Appropriate Environmental Standards	107
MAINTENANCE SYSTEMS EVALUATION	108
Verify Maintenance Systems Design	108
PERSONNEL SUBSYSTEM DEVELOPMENT.	111
JOB DESIGN	112
Organize Tasks on Basis of Location	112
Assign Tasks to Jobs.	112
MANNING REQUIREMENTS ANALYSIS	115
Determine Staffing Requirements	115
Develop Work/Rest Cycles	116
Develop Methods of Performance Appraisal.	117
SELECTION PROGRAM DEVELOPMENT.	118
Specify Abilities and Skills	118
Select Appropriate Tests.	119
TRAINING PROGRAM DEVELOPMENT	120
Cluster Job Tasks	121
Identify Training Phases	121
Identify Training Goals	122
Develop Training Aids	122
JOB PERFORMANCE AID DEVELOPMENT.	123
Determine JPA Content	124
Determine Method of Information Utilization	124

	Page
Field Test JPA's	125
Develop Final JPA Format	125
OPERATIONAL TEST AND EVALUATION	127
HARDWARE AND WORKSPACE DESIGN VERIFICATION	128
Develop and Utilize Equipment Checklists	129
Verify Correct Human Engineering of Controls	131
Verify the Interpretability of Displays	132
Verify Important Workplace Dimensions	132
HABITABILITY VERIFICATION	132
Verify Environmental Standards	133
MAINTAINABILITY ASSESSMENT	134
Develop and Utilize Maintenance Checklists	134
Conduct Maintenance Performance Evaluations	134
Conduct User Interviews and Surveys	135
TRAINING AND JOB AID EVALUATION	135
Perform Follow-Up Training Evaluation	135
Perform Follow-Up JPA Evaluation	136
SYSTEM PERFORMANCE ASSESSMENT	136
Evaluate Manning Arrangements	136
Evaluate System and Subsystem Performance	137
Assist With Safety Program Development	138
REFERENCES	139

LIST OF FIGURES

Figure		Page
1	Human factors engineering system development cycle	18
2	A simplified version of a first-generation flow diagram to be used in function analysis	29
3	Sample chart of listing of functional constraints surrounding a system function	30
4	Second-generation flow diagram reflecting all basic system functions	32
5	A sample third-generation functional flow diagram for survey and mapping activities.	33
6	A hypothetical, simplified function flow diagram of selected CET functions with emphasis on those functions targeted for in-depth function allocation studies	36
7	A simplified, graphic mission profile for canister removal operations with hypothetical activity durations.	37
8	An example of a simple decision/action diagram describing a hypothetical series of events involved in the survey of a row of emplacement canisters.	39
9	Sample listing of alternative man-machine configurations for alignment of CET to floor flange.	44
10	A functional flow diagram of alternative 1 for alignment of CET to floor flange	47
11	A functional flow diagram of alternative 2 for alignment of CET to floor flange	48
12	A functional flow diagram of alternative 3 for alignment of CET with floor flange	49
13	Sample listing of operator and machine functions for various design configurations	50

Figure		Page
14	Sample listing of advantages and disadvantages of each alternative configuration.	53
15	Sample listing of criteria and resulting coefficients for man-machine configuration study of CET alignment with floor flange	55
16	Sample listing of weightings for alternative configurations for man-machine configuration study of CET alignment with floor flange	57
17	Sample function allocation matrix for choosing one of three man-machine configurations for aligning the CET with floor flange	58
18	Sample form for developing task statements	64
19	Sample form for developing task descriptions	68
20	Basic symbols used in Operational Sequence Diagrams	73
21	An example Operational Sequence Diagram of the events (hypothetical) involved in aligning the CET with the CWSRS port gate	74
22	Symbology for Operational Sequence Diagram shown in Figure 21	75
23	Symbology for Flow Process Chart	77
24	Flow Process Chart for an operator determining orientation of emplaced canister	78
25	Simplified timeline of hypothetical CWSRS operator activity	80
26	Example Correlation Analysis Chart for determining communication links between crew members during canister handling activity	86
27	Initial Link Analysis Diagram indicating links between operators and components	88
28	Finalized Link Analysis Diagram depicting two operators and related equipment	88

Figure		Page
29	Side view of 5th percentile operator standing at hypothetical CWSRS operator station	93
30	Top view of 95th percentile operator standing at hypothetical CWSRS operator station	94
31	A hypothetical visual map of the areas capable of being viewed from one operator station aboard the CET	101
32	Sample Spatial Operational Sequence Diagram for selected tasks in the CET	106
33	Example job description form for CET/COM operator	114
34	Sample equipment checklist for verifying the design of doors, hatches, and passageways on a Plug Removal Machine . .	130

LIST OF TABLES

Table		Page
1	Gross system functions for retrieval of all canisters in a drift.	28
2	Selected human engineering handbooks and design guides containing anthropometric data	91
3	Clusters of job tasks for CET/COM operation	121
4	Training phases for CET/COM alignment	122

EXECUTIVE SUMMARY

The overriding objective of the effort represented by this series of documents is to help ensure the highest possible level of waste retrieval system reliability by providing initial human engineering recommendations and a methodology for the design of systems to be operated and used by humans. The approach required the development of three major products:

- A methodology for performing human factors engineering analyses and related research and design activities during the design and construction of the retrieval system, along with a program plan defining the areas of responsibility of the human factors group during system development;
- A source book of human factors data containing recommendations on the design of controls, displays, workspaces, and working environments associated with all retrieval system components; and
- A computerized technique for assessing operator reliability in critical retrieval system operations.

Together, these products provide a methodology which, if followed, should increase system effectiveness and reduce the probability of incorrect, consequential operator actions during retrieval operations.

This system, as it is presently conceptualized, is intended to be used for the removal of storage canisters (each canister containing a spent fuel rod assembly) located in an underground salt bed depository. The waste retrieval system will consist of (a) data processing equipment, vehicles, and electronic equipment for identifying canisters and mapping their orientation, (b) remining vehicles for grading the floor and walls of the drifts, (c) equipment for attaching a floor flange to the emplacement, (d) vehicles for removing and transporting both degraded and intact plugs and canisters, and (e) equipment and facilities for handling, packaging, and transporting canisters to a surface receiving station. The complex nature of many of these man-machine settings necessitated the development of a plan for ensuring that the "human element" is fully considered in waste retrieval procedures and related equipment.

HUMAN FACTORS ENGINEERING INPUT IN SYSTEM DESIGN

Human factors engineering, a recent and logical outgrowth of modern technology, can be summarily defined as a discipline which concerns itself with the design of human-used and human-operated equipment and all related training and operational procedures. The human factors engineer recognizes that the reliability of any large system can only be as great as the reliability of the weakest element, which, due to improper design of the man-machine interface, often appears to be the human operator. From a human factors point of view, however, system errors are usually not the "fault" of the human operator, per se, but rather, the result of a mismatch between the design of equipment or job tasks and the capabilities of the human user. Equipment intended for human use should be designed according to the physical and mental limitations and capabilities of the people who will use the equipment. Equipment or systems which exceed the mental or physical capacities of human operators violate this principle. When the consequences of "human error" are as great as they may be in the waste retrieval process, it is imperative that human factors guidelines be followed when designing human-used equipment.

Every complex, man-made system relying on the skills of human operators for any or all phases of system operation requires human engineering input during various stages of system design. System development projects which fail to incorporate human engineering practices into the design of work places, working environments, and training and selection programs often result in systems which are inefficient, overly hazardous, and costly to maintain. Regretfully, it is only when the system goes into actual operation that earlier deficiencies in developmental input come to light, requiring expensive redesigns and retrofits. Human factors engineering, if performed at the appropriate stage of system development, has proven to be invaluable in many aspects of man-machine system development:

- Training requirements and costs can be reduced by tailoring training courses and materials to the precise needs of operators.
- Manpower utilization can be increased when jobs are properly structured and more efficient operator work stations are designed.
- System down time and costs due to equipment failures can be drastically affected when human factors engineering principles are followed in the design of maintenance equipment and procedures.

- Overall system effectiveness can improve due to increased user acceptance, fewer accidents, and higher levels of operator performance.

Important facets of large systems, like those mentioned above, become increasingly more expensive to institute as time goes on, and sometimes impossible to institute once the system becomes operational. The importance of early human engineering design input cannot be overemphasized.

REVIEW OF THIS SERIES OF DOCUMENTS

To fulfill the needs of this project, four volumes were prepared which, together, outline the role of human factors in the design of a waste retrieval system. **Volume I, Human Factors Design Methodology and Integration Plan**, describes the role of human factors engineering during the development of the waste retrieval system. **Volume II, A Compendium of Human Factors Design Data**, contains data on the design of system hardware which may be used in the waste depository and the waste retrieval equipment. **Volume III, User's Guide for the Computerized Event-Tree Analysis Technique**, outlines the procedures for describing and analyzing all operator tasks and establishing event probabilities using a computer technique. **Volume IV, Computerized Event-Tree Analysis Technique**, provides a description of CETAT and a listing of the computer programs. Together, these four documents provide an overview of a human factors methodology to be followed during the design of the waste retrieval system, and supply concrete guidelines and data for the design of equipment which will be operated and/or used by human operators.

VOLUME I: HUMAN FACTORS DESIGN METHODOLOGY AND INTEGRATION PLAN

The methodology presented in Volume I has been structured around a basic systems development effort involving preliminary development, equipment development, personnel subsystem development, and operational test and evaluation. Within each of these phases, the recommended activities of the human engineering team have been stated, along with descriptions of the human factors engineering design techniques applicable to the specific design issues. Explicit

Only those techniques having possible relevance to the design of the waste retrieval system have been reviewed.

In addition to outlining the human engineering methodologies adaptable for the development of waste retrieval systems, Volume I is intended to provide the framework for integrating human engineering with the rest of the system development effort. The activities and methodologies reviewed in this document have been discussed in the general order in which they will occur, although the time frame (the total duration of the development program in years and months) in which they should be performed has not been discussed. As will become evident to the reader, human engineering input must be made at very specific stages of system development if it is to have optimum impact on system effectiveness.

The first analytical activity of the human factors group is traditionally called "function analysis." Function analysis involves the specification of the assorted functions to be performed by system components. At this point in time, a determination has not been made as to how these functions should be performed or whether they are executed by manual or automatic control systems.

After having identified the system functions, the next step involves deciding how these assorted functions should be allocated between human operators and machines. Human factors engineers and other persons familiar with the capabilities of human operators and automatic control systems begin to make the determination as to which element--man or machine--will control various operations. Functions which allow the designer to capitalize on the fine motor control of the experienced operator may be assigned to the human; functions which require rapid, repetitive, mechanical operations may be assigned to a machine. The fundamental concept during function analysis is to distribute tasks among men and machines and arrive at the most reliable and efficient combination of system control.

Towards the end of the function analysis and function allocation phases of development, specifications for the general types of equipment to be used in each system process may be initiated. It becomes appropriate to start describing the tasks which operators will be required to perform, along with general descriptions of the skill levels necessary for successful task completion. Task analysis is one of the major cornerstones of human engineering activity, and the information

gathered and organized during this phase of development is relied upon throughout many of the system development activities. Although numerous task analysis methods have been developed over the years, the end result of the technique is generally the same--a highly detailed description of each operator's behavior (sensing, processing, and reacting) necessary for task completion.

At the stage where the activities to be performed at each work station have been specified, techniques for analyzing the relationship between all elements of the system--operators and machine elements--can be implemented to determine the most efficient flow of information and arrangement of work space. Functional mockups of operator work stations are then constructed and evaluated using personnel representative of the people who will operate the system. Assorted experiments may need to be performed to determine the feasibility of new and untried man-machine configurations. Computer modeling and various diagramming techniques may be used to analyze and redesign the flow of information and sequencing of events within the system. This entire process continues until the final design has been developed and/or a design freeze has been instituted.

While the first working prototype is being constructed, the human factors team would continue to develop what is known as the personnel subsystem. Having previously identified the skill and knowledge requirements of various tasks, job categories and job descriptions can be developed. The material generated during functional analysis and task analysis, as well as the analytical results of the experiments and investigations (operational sequence and flow diagrams, for example), can be utilized to specify the duties associated with each job.

Relying on the results of the task analysis and the activities performed during the equipment design phase, all of the instructional materials for job training and job execution--generally called "job performance aids" (JPA's)--must be developed. This also includes manuals for executing troubleshooting procedures, and instructions and information for maintenance personnel. Human factors personnel should (a) provide guidelines for selecting the appropriate material to be included in the job performance aids, (b) identify the appropriate reading difficulty of the material, and (c) develop the most efficient method for formatting the material.

At the point where an operational version of the system becomes available (in this case, working versions of all retrieval vehicles and control centers, and canister handling facilities), the human factors operational test and evaluation should begin. The human factors group should submit a document which outlines the procedures to be followed during this evaluation. The purpose of this effort is to verify that the system performs as it was originally intended. As such, machine elements and personnel must be evaluated to determine if they meet the original performance requirements. The personnel themselves should be studied and interviewed to assess their attitudes and opinions concerning jobs and tasks. Studies of training programs must take place and potential personnel selection criteria should be evaluated. Lastly, the effectiveness of all operational manuals and maintenance job performance aids must be evaluated and improved upon, where necessary.

VOLUME II: A COMPENDIUM OF HUMAN FACTORS DESIGN DATA

Volume II is a compilation of human factors engineering design recommendations and data. Design guidelines from a variety of sources were evaluated, edited, and expanded for inclusion in the document, and, where appropriate, portions of text from selected sources were included in their entirety. A review of the preliminary human operator functions involved in each phase of the retrieval process was performed, resulting in the identification of areas of design emphasis upon which this document should be based. Documents containing information and design data on each of these areas were acquired, and data and design guidelines related to the previously identified areas of emphasis were extracted and reorganized.

To develop the list of areas of design emphasis, the system functions described in Report UCRL 15025 prepared by International Engineering Company for Lawrence Livermore Laboratory, "Retrieval System for Emplaced Spent Unreprocessed Fuel (SURF) in Salt Bed Depository: Baseline Concept Specifications and Mechanical Failure Probabilities" were reviewed. For each system function, actions were first assigned to operator and/or machine, and the operator functions were then described. Separate lists of operator functions were developed for each of the areas of retrieval activities—survey and mapping, reminding, floor

I
7
flange emplacement, plug and canister overcoring, plug and canister removal and transport, and CWSRS activity. These functions and the associated man-machine interface were grouped into categories based on task similarity, and the principal topics of human factors design emphasis were extracted. These topic areas are reflected in the contents of the 12 sections of the document.

Each of the sections and related topic areas of Volume II should be considered as part of one of three larger content areas. The initial chapters provide data and recommendations for different aspects of hardware design. The issues and guidelines discussed in these sections are centered around the man-machine systems likely to be present in the retrieval system; e.g., standard controls and displays, controls for remote manipulators, electronic displays, and systems for monitoring and sensing equipment and environmental variables. The central chapters review the topics of illumination, large man-machine work areas, maintainability, environmental quality, and noise and vibration--factors which should be considered when designing all working environments. The last chapters provide data on human information processing capabilities and human body dimensions. These data should be used when selecting codes for information presentation, and when determining operator capacity for performing specific tasks. The anthropometric data are to be used when designing all physical work spaces used by human operators.

VOLUMES III AND IV: THE COMPUTERIZED EVENT-TREE ANALYSIS TECHNIQUE

Volume III provides detailed instructions for using the Computerized Event-Tree Analysis Technique (CETAT), a program designed to assist a human factors analyst in predicting event probabilities in complex man-machine configurations found in waste retrieval systems. The instructions describe how to (a) identify the scope of a CETAT analysis, (b) develop operator performance data, (c) enter an event-tree structure, (d) modify a data base, and (e) analyze event paths and man-machine system configurations. CETAT simplifies the tasks of the experienced systems analyst by organizing large amounts of data and performing cumbersome and time-consuming arithmetic calculations. The principal uses of CETAT in the

systems analyst by organizing large amounts of data and performing cumbersome and time-consuming arithmetic calculations. The principal uses of CETAT in the waste retrieval development project will be to develop models of system reliability and evaluate alternative equipment designs and operator tasks. Although CETAT was developed specifically for use in the analyses of retrieval systems, the technique is applicable to the study of other systems within the waste depository.

Volume IV provides an overview of the subroutines within CETAT, along with a description of how these subroutines interact with one another. A complete listing of the programs is also included in this document.

HUMAN FACTORS ENGINEERING IN SYSTEM DEVELOPMENT

INTRODUCTION

The purpose of this document is to provide an overview of the recommended activities and methods to be employed by a team of human factors engineers during the development of a nuclear waste retrieval system. This system, as it is presently conceptualized, is intended to be used for the removal of storage canisters (each canister containing a spent fuel rod assembly) located in an underground salt bed depository. The depository will consist of central vertical shafts with horizontal drifts radiating outward. The storage canisters, approximately 16 feet in height and 14 inches in diameter, will have been placed, in vertical holes, at intervals of roughly 10 feet, along the floor of the drift. A large concrete plug will have been placed atop each canister. The waste retrieval system, as presently envisioned, will consist of (a) data processing equipment, vehicles, and electronic equipment for identifying canisters and mapping their orientation, (b) remining vehicles for grading the floor and walls of the drifts, (c) equipment for attaching a floor flange to the emplacement, (d) vehicles for removing and transporting both degraded and intact plugs and canisters, and (e) equipment and facilities for handling, packaging, and transporting canisters to a surface receiving station. This document, and the others in this series, have been developed for the purpose of implementing human factors engineering principles during the design and construction of the retrieval system facilities and equipment.

The methodology presented herein has been structured around a basic systems development effort involving preliminary development, equipment development, personnel subsystem development, and operational test and evaluation. Within each of these phases, the recommended activities of the human engineering team have been stated, along with descriptions of the human factors engineering design techniques applicable to the specific design issues. Explicit examples of how the techniques might be used in the analysis of human tasks and

equipment required in the removal of spent fuel canisters have been provided. Only those techniques having possible relevance to the design of the waste retrieval system have been reviewed.

In addition to outlining the human engineering methodologies adaptable for the development of waste retrieval systems, this document is intended to provide the framework for integrating human engineering with the rest of the system development effort. The activities and methodologies reviewed in this document have been discussed in the general order in which they will occur, although the time frame (the total duration of the development program in years and months) in which they should be performed has not been discussed. When the time frame surrounding the development effort becomes more finalized, it will be necessary to schedule the human engineering activities so they can be executed in a timely fashion. As will become evident to the reader, human engineering input must be made at very specific stages of system development if it is to have optimum impact on system effectiveness.

HUMAN ENGINEERING IN COMPLEX SYSTEMS

Every complex, man-made system relying on the skills of human operators for any or all phases of system operation requires human engineering input during various stages of system design. System development projects which fail to incorporate human engineering practices into the design of work places, working environments, and training and selection programs often result in systems which are inefficient, overly hazardous, and costly to maintain. Regretfully, it is only when the system goes into actual operation that earlier deficiencies in developmental input come to light, requiring expensive redesigns and retrofits. Human factors engineering, if performed at the appropriate stage of system development, has proven to be invaluable in many aspects of man-machine system development:

- Training requirements and costs can be reduced by tailoring training courses and materials to the precise needs of operators.
- Manpower utilization can be increased when jobs are properly structured and more efficient operator work stations are designed.

- System down time and costs due to equipment failures can be drastically affected when human factors engineering principles are followed in the design of maintenance equipment and procedures.
- Overall system effectiveness can improve due to increased user acceptance, fewer accidents, and higher levels of operator performance.

Important facets of large systems, like those mentioned above, become increasingly more expensive to institute as time goes on, and sometimes impossible to institute once the system becomes operational. The importance of early human engineering design input cannot be overemphasized.

Human engineering techniques have been utilized in many major system development projects, particularly in high technology settings. Human factors engineers have played major roles in the development of spacecraft systems and have been closely involved in the development of numerous sea and land-based weapon systems. The system development techniques of the human factors engineer have also been used extensively throughout the development of dozens of airborne systems, particularly in the design of cockpits in high-performance aircraft. The increasing level of complexity of human-operated systems, as well as the restrictive environments in which some systems must operate, mandate that special attention be directed toward each link between humans and machine components.

The branches of the armed forces were among the first to recognize the importance of human engineering during system development due to the inherent complexity of modern military equipment and the consequences of system failure. This need has been recognized as being so important that military contractors are required to follow human engineering system development guidelines outlined in MIL-H-46855 and adhere to the human engineering equipment design data provided in MIL-STD-1472.

Although the traditional settings for human engineering research and development have been in military systems, the increasing complexity of industrial processes has resulted in the expansion of human engineering into new areas. Human engineering is often an integral part of development projects for industrial manufacturing processes. The techniques involved in function analysis, function

allocation, task and skill analysis, equipment design, and workplace design have proven effective in increasing system output, reducing system errors, and improving worker satisfaction. Human factors and ergonomic input has been important in the development of operator stations and equipment, operational procedures, and operator training programs for railroads (Iiyama, 1980), steel mills (Ong & Buck, 1978), farm equipment (Adams et al., 1976), hospitals (Schiroy & Drury, 1976), oil refineries (Reinberg et al., 1976), submarines and deep sea divers (Bachrach et al., 1975), and assorted manufacturing systems (Corlett, 1973).

Some commercial industries, however, notably the nuclear reactor manufacturers, have been negligent in their efforts to incorporate human engineering in the developmental phases of man-machine systems. Although widely recognized by the human factors community for some time (Seminara et al., 1976; WASH-1400, 1975; Swain, 1975), deficiencies in nuclear power plant control room design have only recently attracted the attention of regulatory agencies and the nuclear power industry. Swain and Guttman (1980) have recently published a review of human reliability techniques applicable to nuclear power plant control room design containing multiple examples of how plant operators, particularly during emergency conditions, must (a) locate poorly labeled controls, (b) read displays of poor legibility, (c) move about an inefficiently arranged control room, (d) interpret poorly designed feedback signals, and (e) interpret wordy and poorly designed operating manuals. The far reaching consequences of "human error" in this operating environment and the high cost of redesigning existing facilities are two sound reasons for incorporating human engineering systems design techniques at the earliest possible stages of system development.

HUMAN FACTORS ENGINEERING AND DESIGN DECISIONS

It is important to define the role of the human engineering team (the terms "human factors," "human engineering," and "human factors engineering" are used interchangeably) during system development. The human factors group must be considered as an integral part of the design team during the development of the waste retrieval systems. Although much of this group's time may be spent performing assorted analyses, experiments, and walk-throughs for the purpose of

providing answers to questions asked by other design personnel, this group must be given a strong voice in final design decisions. Ideally, the human engineering group should be capable of providing relevant design data and recommendations, and the design engineers should be responsive to the findings and recommendations of the human engineering group.

Design engineers and human factors engineers alike must accept responsibility for the final product of the system development effort. Human factors engineers, generally psychologists with training and experience in industrial engineering, statistics, and experimental design, are notorious for their general lack of tact and bad rapport when dealing with designers (Degreen, 1970). Meister (1971) has provided what are probably the best recommendations on how members of the human engineering team should present design concepts and recommendations to other design team members. Design engineers, on the other hand, are renowned for their failure to consult available human engineering design manuals and related data. Even when their designs contain many inadequacies, design engineers will fail to consult human engineering design manuals when they are made readily available (Meister, 1967; Meister & Farr, 1967). Possibly, the most serious fault of design engineers is that they develop patterns of design which they continue to repeat--even when these designs are not particularly effective or do not meet original system functional requirements. These facts can only serve to emphasize the importance of having a complete system development plan prior to the design effort, a plan which clearly defines the roles and activities to be performed by the various members of the design team. The activities and responsibilities of the human engineering group should be spelled out in contractual form prior to beginning the development effort. Furthermore, management must recognize human factors engineering as a discipline within itself, and provide the human factors group with the power to impact system design.

To fulfill their part of the arrangement, the human factors group must demonstrate its ability to meet development deadlines and provide deliverables at prescribed times. Delivery of reports and the results of assorted projects must be synchronized with the activities of other units of the design team. The human factors team must provide a schedule, describing the deliverables at all points

during the design cycle. Complete documentation throughout the human engineering effort should be assured; in the later stages of system design, there is a high degree of reliance on the products of the function analysis and task analysis phases occurring early in the program. The procedures and results of the numerous simulations and experiments performed during development must also be documented.

AREAS OF RESPONSIBILITY OF THE HUMAN FACTORS TEAM

What should be the exact areas of responsibility of the human engineering design team? The human factors team should be responsible for four traditional areas during the waste-retrieval development cycle:

- **Workplace layout and equipment design.** Human factors personnel must work with the other development groups in designing all operator work stations. This activity must include:
 - Selecting, designing, and arranging controls and displays.
 - Establishing the appropriate dimensions and physical characteristics of work stations.
 - Arranging multi-man-machine work areas to provide optimal communication and interplay between operators and system components.

This aspect of human engineering activity is relevant to the design of survey and mapping work stations and vehicles, remining vehicles, floor flange emplacement vehicles, plug overcore and plug removal vehicles, canister transporters, canister handling facilities, and communication centers.

- **Design for maintenance.** Human factors engineers should be actively involved in the design of maintenance systems on all retrieval vehicles, in canister handling facilities, and in communication centers. They should be held responsible for assuring that maintenance systems are "human engineered" and that all components requiring maintenance are accessible, replaceable, and/or repairable. This area of human engineering pertains to all aspects of the retrieval system hardware--vehicles and fixed operator work stations, alike.
- **Development and design of job aids.** The human factors group must assure that all job aids contain material directly relevant to operator tasks and requirements, and that the aids and related

materials are organized to facilitate easy referencing and comprehension. Job aids are generally considered to be anything that reduces the specialized operator skills or training required to perform a task. Job aids can be found in various forms, including instructions, checklists, diagrams, blueprints, technical manuals, motion pictures, and filmstrips. They could be extremely effective in reducing training costs and time in many jobs throughout the retrieval system.

- **The work environment.** Human factors engineers should be held responsible for studying the effects of various working environments and providing recommendations on necessary environmental changes, operator tasks, and work-rest cycles. The environment in which people work--just like controls, displays, training, and job aids--directly affects operator reliability and efficiency. For this reason it is, and traditionally has been, considered as an area of responsibility of the human factors engineer. With reference to the waste retrieval system, human engineers must be involved in the specification of acceptable levels of environmental variables, including light, temperature, noise, humidity, ventilation, and vibration. Of particular importance will be the ambient temperature of the drifts within which operators will be required to work. High ambient temperatures within the depository drifts may require special work-rest cycles, special clothing, modifications of physical and mental tasks, or isolation of operators in air conditioned vehicles.

In addition to the above responsibilities, the human factors engineering team should be involved in the following design areas:

- **Emergency and egress systems.** The human factors group should be closely involved in the design of all emergency systems and procedures. In addition to determining if emergency equipment has been properly designed, human factors personnel should study and assess the effectiveness of emergency procedures. It must be determined if emergency systems, as designed, enable operators to meet prescribed levels of performance during stressful, emergency conditions. As an example, retrieval vehicles must be designed to enable operators to escape in the event of a vehicle fire or radioactive contamination. Once these emergency procedures have been designed, tests should be performed to verify that the system enables the removal of operators within an established time limit.
- **Retrieval events and sequencing.** Early in the development cycle, human factors personnel should be involved in the analysis and design of the basic procedures to be followed during canister removal. Ideally, human engineering input should be brought into play at the earliest possible stage of system conceptualization. Many engineering design recommendations have already been

made, however, which will profoundly impact the design of operator tasks and equipment.

Prior to finalizing the basic retrieval system, as outlined by Bhaskaran and McCleery (1979), human factors engineers should be provided the opportunity of suggesting alternative methods of performing retrieval tasks. General designs should not be finalized until human factors engineers have had the opportunity to analyze the basic system functions and perform a preliminary allocation of tasks to men or machines.¹

- **System information feedback requirements.** As stated above, one of the principal areas of human factors work will be to design and arrange individual operator work stations. This includes, of course, the selection and design of all types of visual, auditory, and tactile feedback to the operator. When analyzing total system requirements, however, human factors personnel should assist in determining the necessary communication links between retrieval vehicles and facilities, and identify the necessary system monitoring and feedback requirements for safe management of the retrieval vehicles and facility. Human factors engineers should be called upon not only to design the displays which present information to operators, but to actually select the types of information to be displayed to operators. Their contributions should not be superficial; human factors engineers should not only be expected to develop ways of displaying the information handed to them by other engineers. They must be intimately involved in the selection of the information presented to operators.

OVERVIEW OF THE HUMAN FACTORS ENGINEERING DESIGN CYCLE FOR WASTE RETRIEVAL SYSTEMS

This document is one of four volumes of a series which, together, outline the role of human factors in the design of a waste retrieval system. **Volume 1, Human Factors Design Methodology and Integration Plan**, describes the role of human factors engineering during the development of the waste retrieval system.

¹For example, the preliminary design calls for a retrieval vehicle which has an automatic steering system and an automatic indexing system. After study, it could be decided that a more reliable system would involve operator steering control and operator-controlled indexing. Furthermore, additional changes in vehicle configuration may eliminate the need of having the remote guidance, indexing, and plug removal capability.

Volume II, A Compendium of Human Factors Design Data, contains data on the design of system hardware which may be used in the waste depository and the waste retrieval equipment. **Volume III, User's Guide for the Computerized Event-Tree Analysis Technique**, outlines the procedures for describing and analyzing all operator tasks and establishing event probabilities using a computer technique. **Volume IV, Computerized Event-Tree Analysis Technique**, provides a description of CETAT and a listing of the computer programs. Together, these four documents provide an overview of a human factors methodology to be followed during the design of the waste retrieval system, and supply concrete guidelines and data for the design of equipment which will be operated and/or used by human operators.

The human engineering aspect of system design should be thought of as a progressive, iterative process with a series of feedback loops to earlier events. Although it is intended to be flexible and dynamic, the human factors system development cycle involves a logical sequence of development activities. Figure 1 illustrates the four phases of system development, the areas of emphasis during each phase, and the specific activities and methodologies of the human engineering team during waste retrieval system development.

Assuming that human factors personnel are brought into the development process early on, the first analytical activity which should be performed is traditionally called "function analysis." Function analysis involves the specification of the assorted functions to be performed by system components. At this point in time, a determination has not been made as to how these functions should be performed or whether they are executed by manual or automatic control systems.

After having identified the system functions, the next step involves deciding how these assorted functions should be allocated between human operators and machines. Human factors engineers and other persons familiar with the capabilities of human operators and automatic control systems begin to make the determination as to which element--man or machine--will control various operations. Functions which allow the designer to capitalize on the fine motor control of the experienced operator may be assigned to the human; functions which require rapid, repetitive, mechanical operations may be assigned to a machine. The fundamental

Figure 1. Human factors engineering system development cycle.

concept during function analysis is to distribute tasks among men and machines and arrive at the most reliable and efficient combination of system control.

Towards the end of the function analysis and function allocation phases of development, specifications for the general types of equipment to be used in each system process may be initiated. It becomes appropriate to start describing the tasks which operators will be required to perform, along with general descriptions of the skill levels necessary for successful task completion. Task analysis is one of the major cornerstones of human engineering activity. The information gathered and organized during this phase of development will be relied upon throughout many of the system development activities yet to be performed. Although numerous task analysis methods have been developed over the years, the end result of the technique is generally the same--a highly detailed description of each operator's behavior (sensing, processing, and reacting) necessary for task completion.

At this point in the development cycle, the functions of the human factors group begin to diverge. Ideally, some individuals continue to emphasize the personnel subsystem, and further specify the skill and knowledge requirements necessary for each task.

The central human engineering effort would involve close work with other members of the design team. Human factors personnel should assist in designing progressively more specific systems. At the stage where the activities to be performed at each work station have been specified, techniques for analyzing the relationship between all elements of the system--operators and machine elements--can be implemented to determine the most efficient flow of information and arrangement of work space. Functional mockups of operator work stations are then constructed and evaluated using personnel representative of the people who will operate the system. Assorted experiments may need to be performed to determine the feasibility of new and untried man-machine configurations. Computer modeling and various diagramming techniques may be used to analyze and redesign the flow of information and sequencing of events within the system. This entire process continues until the final design has been developed and/or a design freeze has been instituted.

While the first working prototype is being constructed, the human factors team would continue to develop what is known as the personnel subsystem. Having previously identified the skill and knowledge requirements of various tasks, job categories and job descriptions can be developed. The material generated during functional analysis and task analysis, as well as the analytical results of the experiments and investigations (operational sequence and flow diagrams, for example), can be utilized to specify the duties associated with each job.

Relying on the results of the task analysis and the activities performed during the equipment design phase, all of the instructional materials for job training and job execution--generally called "job performance aids" (JPA's)--must be developed. This also includes manuals for executing troubleshooting procedures, and instructions and information for maintenance personnel. Human factors personnel should (a) provide guidelines for selecting the appropriate material to be included in the job performance aids, (b) identify the appropriate reading difficulty of the material, and (c) develop the most efficient method for formatting the material.

At the point where an operational version of the system becomes available (in this case, working versions of all retrieval vehicles and control centers, and canister handling facilities), the human factors operational test and evaluation should begin. The human factors group should submit a document which outlines the procedures to be followed during this evaluation. The purpose of this effort is to verify that the system performs as it was originally intended. As such, machine elements and personnel must be evaluated to determine if they meet the original performance requirements. The personnel themselves should be studied and interviewed to assess their attitudes and opinions concerning jobs and tasks. Studies of training programs must take place and potential personnel selection criteria should be evaluated. Lastly, the effectiveness of all operational manuals and maintenance job performance aids must be evaluated and improved upon, where necessary.

Blank

PRELIMINARY DEVELOPMENT

Preliminary development, the initial phase of the human engineering development plan, is actually the keystone of the entire human factors engineering design methodology. It is during this phase that the functions of the waste retrieval system will be assigned to human operators, machines, or a combination of operators and machines. The way in which functions are allocated between men and machines will determine (a) whether the original performance requirements are met, (b) the development costs, (c) training costs, (d) manning costs, (e) maintenance costs, and (f) overall system reliability.

Function analysis first involves developing a description of the functions to be performed by the system. Most system functions have already been specified in preliminary planning documents. However, it is advisable for the human factors team to develop its own documents according to the format listed in this section. The team must determine system requirements, specify system functions, develop mission profiles and scenarios, and develop decision action diagrams. These activities are described in this section.

In the next phase of preliminary development, the human factors group is given the job of allocating functions between men and machines. This activity requires the group to develop alternative man-machine configurations for each of the system functions being studied. Each of these alternative configurations are then studied with the aid of functional flow diagrams. After determining the advantages and disadvantages of each alternative configuration, and collecting data to support the analysis of each configuration, a function allocation matrix is developed. This matrix provides a crude but useful technique for deciding which configuration meets the system requirements.

After allocating functions, the individual operator tasks are to be determined. Methods are provided for listing and ordering tasks, and examples of task descriptions are given. During task analysis, the human factors group should be required to select appropriate control and display components on retrieval vehicles

and stationary work stations, integrate control and display components develop operational sequence diagrams, develop flow process charts, and perform timeline analyses. At the conclusion of preliminary development, a firm foundation for the next major phase, equipment development, will have been provided.

FUNCTION ANALYSIS

This effort should include two steps: the specification of system requirements and the analysis of system functions. Although these steps are considered to be independent, they must not necessarily be followed in a steadfast sequence. This particular stage of system development is considered to be very iterative, and requires temporal flexibility on the part of the human engineering team. The iterative nature of the methodology, however, should not be reflected in the contents of function analysis documents. These documents should clearly state system requirements, the system functions, and the special considerations and constraints therein.

IDENTIFY SYSTEM REQUIREMENTS

Identify and document the system requirements of the waste retrieval system. Review existing development planning documents and assemble a brief but thorough summary for human engineering personnel.

Although most, if not all, of the waste retrieval system requirements have been specified in early planning documents, the human engineering team should be required to develop its own tailored list of system requirements. The principal purpose of the human engineering list of system requirements will be to familiarize the human factors team with the central developmental issues, and to facilitate production of the lists of functional requirements occurring later in the program. As Meister (1971) has said, "...the analyst will find it useful to start his work by examining system requirements; the reason is that sometimes these requirements have not been clearly expressed and consequently the specification of required human functions and equipment may be inadequate."

The human factors team should make use of a number of documents when preparing the system requirements. These include the request for proposal, the statement of work, as well as numerous other documents developed at the outset of the waste retrieval program (Bhaskaran & McCleery, 1979; Hudson & McCleery, 1979).

The system requirements section of function analysis documents should contain the following information:

- **The System Mission.** This section should be brief and relatively simple to produce. The purpose of the waste retrieval system, stated in the simplest terms possible, is to (a) identify emplaced spent fuel canisters requiring removal from salt, (b) prepare the emplacements for removal of the canisters, (c) remove canisters from emplacements and transport them to a transfer station, and (d) transport canisters to a surface receiving station. The retrieval of spent fuel canisters may be necessary for a variety of reasons, including the need to (a) periodically inspect canisters to assess canister and encasement integrity, (b) remove, inspect, and repackage degraded canisters, (c) transfer canisters to an alternate depository, (d) remove spent fuel for reprocessing.
- **System Performance Requirements.** This aspect of the system requirements effort involves specifying the qualitative and quantitative characteristics of system performance requirements. It is anticipated that these performance requirements will become more specific with time. However, this first version should include a thorough review of the following topics.
 - (a) **Projected Life of the System.** Retrieval of canisters may occur at any time from the date of emplacement of the first canister to the final closure of the facility--a span of roughly 60 years. Retrieval vehicles and systems must remain operational throughout this period.

(b) **Rate of Canister Retrieval.** The maximum rate of canister retrieval will be the maximum rate of emplacement.² Although it will be absolutely necessary to have the capability of retrieving canisters at this maximum rate, in all likelihood only a few canisters will be removed each day. This maximum rate of retrieval would only be required if the facility had to be emptied or all canisters had to be repackaged and re-emplaced. The human engineering team must be provided with the following information to make rational decisions concerning rate of canister retrieval and subsequent system development:

- (1) The required rate of canister retrieval.
- (2) The anticipated task-completion times for each phase of the retrieval operation.
- (3) The number of back-up vehicles of each type.
- (4) The expected life of each vehicle.
- (5) The anticipated down time of each type of vehicle.

(c) **Task Performance Tolerances.** Preliminary estimates should be made of the minimum level of performance acceptable for broad categories of tasks. For example, all retrieval vehicles must be capable of being driven through drifts X feet in width. This will influence the handling characteristics and possibly the width of the vehicles. Other engineering limitations, like those imposed by the size of emplacement canisters and holes, should be considered due to their impact on the design of the tasks involving emplacement and removal of canisters.

- **Environmental Factors Affecting System Performance.** The human engineering team must consult other engineers and available documents to develop lists of all relevant environmental variables which may, in any fashion, influence system operations. Two of the topics which must be investigated and discussed in this phase are the levels of radiation present in the working environment and the associated ambient temperature in filled depository drifts. The human engineering team should also be concerned with the importance of illumination, humidity, ventilation, and noise and vibration from heavy equipment.

² Rather than moving ahead with the production and manning of a full-scale retrieval system, one capable of removing 36,000 canisters (or 48 canisters during each of three 8-hour shifts working 250 days per year) each year (Hudson & McCleery, 1979), it may be advisable to develop a set of contingency plans. An operational system capable of removing a small number of canisters daily could be manned, with plans for the rapid construction of remaining vehicles and consequential manning of the enlarged system if the need to remove 36,000 canisters per year should arise. Certainly there is no purpose in moving ahead and constructing a large fleet of retrieval vehicles if the probability of all of these vehicles being used is quite low.

- **System Constraints.** The human factors team should also investigate and document certain system constraints, like special maintenance requirements. Limitations on the number of vehicles and systems available to perform specific operations may place constraints on the amount of time available for maintenance operations. Similarly, the need to have operators isolated from radioactive material during certain retrieval operations imposes constraints on system design. One major constraint will be the possibility that some canisters will be degraded, necessitating an overcoring process for safe canister removal. This has considerable impact on the amount of time required to remove a canister from an emplacement.

SPECIFY SYSTEM FUNCTIONS

Specify, by further analyzing system requirements and available documentation, the system functions. Execute this step by identifying sequential categories of system functions. Provide progressively more specific descriptions of system functions using flow charting techniques.

The analysis of the system functions and requirements begins with an examination of each of the major operations that must be performed in waste retrieval. These system functions and requirements will become increasingly more specific as this phase of system development proceeds. The analysis and specification of the system functions leads directly into the next phase of development, the assignment of system functions to man or machine.

The task of identifying the functional requirements of the waste retrieval system can be broken down into six steps (a modification of Meister, 1971). These steps should be followed in the human engineering effort and reflected in the organization of the functional analysis document.

List Major System Operations

List sequentially the major system operations which must be performed to retrieve spent fuel canisters.

Assuming a full-scale retrieval operation is undertaken in which an entire drift of canisters is to be retrieved, the principal system functions might be listed as they are in Table 1.

TABLE 1
GROSS SYSTEM FUNCTIONS FOR RETRIEVAL OF
ALL CANISTERS IN A DRIFT*

1. Identify drift and emplacements for canister retrieval.2. Survey and map emplacement drift.3. Re mine emplacement drift.4. Emplace floor flanges.5. Remove plug.6. Remove canister.7. Transport canister to underground receiving station.8. Transport canister to surface receiving station.9. Repeat steps 5, 6, 7, and 8 until all canisters have been removed.

*In the system development cycle, it is traditional for the assignment of tasks to men or machines to have not taken place at this stage. The current waste retrieval system design, however, does specify how these functions will be executed.

Describe Gross System Functions

Describe the gross system functions in the form of a functional flow diagram.

At this stage of system development, functional flow diagrams traditionally do not indicate if an operator or a machine performs a given function. A simplified version of this basic flow diagram, which can be called a first generation flow diagram, is illustrated in Figure 2. It should reflect the sequential listing of functions presented in the first functional analysis listing. Each block of the functional flow diagram should contain a verb-noun phrase that might be a function of the system.

Assess Factors and Requirements

Determine the effect on system functions of the environmental factors, performance requirements, and system constraints noted in the analysis of system requirements.

Figure 2. A simplified version of a first-generation flow diagram to be used in function analysis.

There will be numerous factors which will influence the design of equipment and procedures. After having developed the first functional flow diagram, these factors can be taken into account and listed systematically. This process may be facilitated by developing a list of all constraining factors for each of the functions listed in Table 1. As an example, a few of the constraints surrounding the gross function, "Remove Canister," have been listed in Figure 3. A complete listing for each functional group should be generated in a similar format.

GROSS FUNCTIONAL CONSTRAINTS	
GROSS SYSTEM FUNCTION: REMOVE CANISTER	
ENVIRONMENTAL CONSTRAINTS	
1.	Environment is potentially radioactive.
2.	Ambient temperature is approximately 100°F.
3.	Illumination must be provided.
4.	Noise levels could exceed exposure standards.
5.	Ventilation must be provided.
6.	Humidity levels may be high.
PERFORMANCE CONSTRAINTS	
1.	Alignment with emplacement should be completed in X minutes.
2.	Alignment must be performed within X amount of tolerance.
3.	System must be capable of grasping canister within X amount of time.
4.	Removal system must adapt to varying requirements; canisters may not be perpendicular to the surface.
SYSTEM CONSTRAINTS	
1.	Operators must be capable of rapid egress if environment is radioactive and vehicle is disabled.
2.	Canisters may be tilted from the vertical.
3.	Operator must be kept isolated from canister.
4.	Some canisters may be degraded.
5.	Emplacement rooms are one-way; work must proceed from back to front.

Figure 3. Sample chart of listing of functional constraints surrounding a system function.

Add New Constraints

Add the new constraints listed in "Assess Factors and Requirements" to the first generation functional flow diagram which reflects the constraints and possible events during each system function.

As illustrated in Figure 4 (a more detailed functional flow diagram of retrieval functions), second generation charts should begin to reflect all basic system functions. Specifying system functions at this stage of system development is often more difficult than specifying operator tasks during task analysis. The reason for this is simple: it is admittedly difficult to determine the level of specificity of a system function statement, particularly when these events occur in sequence. The flow diagram presented in Figure 4 is a simplified version, but it is representative of what would be expected of a second generation functional flow diagram. Third generation functional flow diagrams, one of the final products of functional analysis, provide very specific descriptions of system procedures.

Specify Function Inputs And Outputs

Specify the inputs to, and the outputs from, each system function previously listed. Develop third generation functional flow diagrams, one for each of the major system functions, describing in detail the necessary inputs and outputs of each function.

At this stage of development, the objective is to develop a functional description of the system which falls short of defining the individual operator tasks within each function. It is the appropriate point in time, however, to begin specifying the required inputs in each process. The product of this effort should be a series of detailed functional flow diagrams, each providing a description of inputs, processes, and output at each system phase. Figure 5 indicates the level of detail which should be present in each of these diagrams.

Figure 4. Second generation flow diagram reflecting all basic system functions.

Figure 5. A sample third generation functional flow diagram for survey and mapping activities. Assumption is made that an entire drift of canisters is to be surveyed and mapped.

Develop Final Functional Flow Diagrams

Develop final functional flow diagrams with indicators as to which functions must be evaluated during function allocation studies.

The principal purpose of this last step in the function analysis phase is to identify the points in the system where decisions must be made concerning the allocation of tasks to human operators or to machines. The first step requires the development of even more detailed functional flow diagrams than were developed in previous steps.

The human factors analyst must begin by analyzing the inputs and outputs to each of the system functions specified in previous steps. For example, assume that just the surveying portions of surveying and mapping activity are being analyzed. After the emplacement crew has obtained plots and maps of emplacements to be studied and is ready to enter the drift, tests must be performed to determine if the environment is safe for entry. Someone, somewhere, must activate and/or read and interpret a radiation level detector. The acceptable output of this function is that the level of radioactivity is safe and the next test should be performed. Some aspect of the system must test gas content and display the results to an operator. The same is true for any other environmental variables. The finding that conditions are safe upon entry into a drift does not, by any means, indicate that conditions will be acceptable at a later point in time. It becomes evident that a function must be provided for continuously monitoring the important environmental variables (radioactivity and gases) while operations are proceeding. The entire functional operation—that involving monitoring environmental conditions—would be tagged as a function requiring further analysis to determine how the operations within this function will be performed.

At this stage of function analysis, a very detailed functional flow diagram should be emerging. Due to the large number of steps involved in retrieval operations, it may be necessary to develop a number of separate, but continuous, functional flow diagrams, complete with detailed descriptions of required inputs to and outputs from each system function or operation. After having developed the flow diagrams, the system functions or groups of system functions requiring function allocation analyses should be identified. A simple and direct way to do

this will be to display the completed functional flow diagrams and shade those boxes requiring analysis. Each shaded section should be numbered for later reference. Figure 6 has been provided to illustrate how such a diagram might be developed and portrayed. In this example, the flow diagram covers the events spanning CET travel to CET alignment in the CWSRS. The shaded areas pinpoint the functions which require study to determine how (what combination of human or machine actions) the function will be executed. In addition to numbering each of these study areas, it may be advisable to provide labels or brief descriptions to facilitate later work. Although some of these functions may be described and allocated in existing engineering plans, the human engineering team should be expected to list these function analysis topic areas along with those areas that have not yet been defined. The fact that some functions have already been assigned to operators or machines does not necessarily mean that these functions, in the present configurations of operations, can be executed at required levels of performance.

DEVELOP MISSION PROFILES AND MISSION SCENARIOS

Develop a graphic profile of the major mission functions and the sequence in which they will occur. Fully describe, in narrative form, the events implied by the profile.

Mission profiles and mission scenarios could probably be adequately defined at the present stage of development. Even so, the exercise might prove useful to the human engineering team in that it could serve to familiarize them with retrieval concepts and, more importantly, result in the identification of human engineering issues. The process involved in developing a comprehensive description of a system forces the analyst to critically evaluate aspects of design which might otherwise be overlooked.

In addition to providing a description of the sequential steps in executing a mission, a good mission profile should specify basic performance requirements of each phase of the system. A simplified mission profile, like that portrayed in Figure 7, pictorially describes each phase of the mission and the specific time performance requirements of each phase of the mission. Prior to developing more

Figure 6. A hypothetical, simplified function flow diagram of selected CET functions with emphasis on those functions targeted for in-depth function allocation studies.

Figure 7. A simplified, graphic mission profile for canister removal operations with hypothetical activity durations. Mission profiles, in detailed form, provide a means for portraying precise mission performance requirements.

detailed and task-specific mission profiles, the human engineering team must be provided with data on specific operational requirements; e.g., how fast can the vehicles safely travel, how far must they travel, how many canister unloadings can be anticipated each hour, what is the duration of each unloading, etc. Mission profiles are typically part of the description of system requirements and occur at the earliest possible phase of human engineering activity.

Mission scenarios are traditionally narratives which describe the events implied by the profile. They, too, should be included as part of the description of system requirements and should be developed early in the development program. As is the case for the mission profiles, most of the descriptive information for writing general scenarios has been made available in earlier design documents. The human factors team must be provided with more specific performance requirements, however, before comprehensive profiles and scenarios can be developed.

DEVELOP DECISION/ACTION DIAGRAMS

Develop decision/action diagrams indicating system decisions and operations.

Decision/action diagrams are similar to functional flow diagrams (Geer, 1976a) in that they diagram the flow of system events. They are different, however, in that they diagram the flow of system data and indicate decisions and operations. Decision/action diagrams are often called information flow charts, and are analogous to the charting methods used by computer programmers. They are typically utilized in the later phases of function analysis and require quite specific descriptions of the system elements. The information for developing decision/action diagrams usually comes from mission profiles and scenarios. When developed in the function analysis phase of development, decision/action diagrams do not typically specify if decisions or actions are performed by operators or machines. Figure 8 provides an example of a decision/action diagram for a hypothetical series of events involved in surveying an individual emplacement. Although the functions are described in detail, no assumptions should be made at this point as to which component--man or machine--performs each function.

Figure 8. An example of a simple decision/action diagram describing a hypothetical series of events involved in the survey of a row of emplacement canisters.

FUNCTION ALLOCATION

Function allocation, the human factors engineering activity involving the assignment of functions to machine or human control (or an appropriate combination of human and machine control), should be viewed as another cornerstone of the human engineering effort; it is a design activity having tremendous potential impact on the retrieval system. The manner in which functions are assigned to operators and machines will determine equipment and maintenance costs, system reliability, system performance, training requirements, and manning requirements. In view of its importance, this activity must receive a substantial amount of attention and effort.

It is imperative that the human engineering team work closely with design engineers during this effort. This is required for a number of reasons. First, human factors analysts often do not have the technical expertise required for making design decisions concerning the allocation of functions to machines. It will be necessary for the human factors team members to consult with knowledgeable design engineers during function allocation studies. Secondly, design decisions need to be made very rapidly during this stage of development. If the human factors group is not working closely with the design team, critical decisions having long-range implications may be made without the necessary human factors input.

At the outset of system design, design engineers and human factors specialists often take two divergent tacks when allocating functions between man and machines (DeGreen, 1970). Design engineers typically try to automate the system to the greatest extent possible and assign the rest of the functions to the human operator. This can result in a system which is functionally inflexible, unreliable, and expensive to build and maintain. It may also result in an underworked and undermotivated work force. Human factors specialists, to take the opposite extreme, often attempt to assign too many tasks to the human, a practice which results in a flexible and reliable system, but one having high training and manning costs. The optimum is obviously an approach which capitalizes on the benefits of each of these two methods. Functions which are best performed by machines should be placed under automatic control; functions which are best performed by humans should be placed under manual control. The purpose

of function allocation during the human engineering effort is to assign either man or machine, or a combination thereof, to functions so that performance congruent with the original requirements can be achieved.

As with other phases of the design process, the development plan for function allocation presented herein represents the ideal sequence of design-related activities. In reality, function allocation is an iterative process which may continue well into following design stages. Functional requirements may change as time passes, and functional approaches once believed to be feasible may be found to be infeasible. Although this document contains a clear plan for performing human factors function analysis activities during waste retrieval system development, modifications of this plan should be anticipated as design requirements are modified.

An additional topic which should be mentioned is the importance of documenting the steps involved in function allocation. This documentation is important for a number of reasons. First, clear and well documented function analysis studies are easier to perform than studies which are not documented and recorded. When function allocation issues concerning similar topics arise, it is helpful to have the results of previous studies--particularly if the results of experiments, interviews, and design meetings have been well documented. Second, when the human engineering team approaches design team members with design recommendations, it is imperative that they have data--the results of experiments and/or interviews--to support their recommendations. Design engineers will be more inclined to implement these recommendations if they have a full appreciation for their bases. Third, proper documentation during function allocation will facilitate communication between various design groups. One design team should be aware of the basic nature of the activities of other design teams. Fourth, thorough function analysis documentation will be one of the principal sources of information for specifying equipment requirements. Once functions have been allocated between men and machines, the specific types of electrical and mechanical hardware necessary for each part of the system can begin to be specified. Last, records kept during function analysis will serve as the foundation for performing the next phase of human engineering activity--task analysis. Properly

maintained records will allow the human engineering team to begin their next tasks with minimal effort.

The managerial staff of the waste retrieval development project must recognize that the activities performed by the human factors group during function allocation may span a considerable amount of time. With the large number of subsystems in the retrieval operation--data management, surveying, mapping, mining emplacement preparation, plug and canister removal, and canister transport and handling--the design of all of the involved tasks and equipment could require one, two, or even three years. It is possible that while function allocation studies are being conducted with one specific aspect of the system, the human engineering team may have moved well beyond this stage in other areas, where functions have already been allocated and operator work stations are being designed.

The following are activities which should be performed by the human factors team during function allocation. It should be understood that these steps represent the ideal, and that modifications in these steps will surely occur.

IDENTIFY ALLOCATED FUNCTIONS

Determine which functions within the retrieval operation have and have not been allocated to operators or to machines. Determine if those functions which have been allocated present a man-machine configuration capable of meeting pre-established performance requirements.

The human factors engineering team should first consult preliminary design documents to determine which functions have already been allocated to operator and/or automatic control. If certain functions have been allocated to operators and/or machines in fashions contrary to human engineering practice, management should be made aware that the human factors team sees a need to examine and possibly reallocate these functions within the system. As stated before, improperly allocated functions can have far reaching consequences in terms of eventual system performance and cost; questionable configurations should be called to the attention of design engineers before the designs are finalized.

It is also very likely that many of the major system functions which have already been allocated will have numerous subfunctions which have not been allocated. The human factors team should be held responsible for identifying those subfunctions requiring study.

Using each of the gross system functions (survey and mapping, remining, floor flange emplacement, plug removal, etc.) as a basis for organization, the human factors team should prepare a list of all areas in which function allocation decisions should be made. The list should also identify the subfunctions within previously-allocated functions requiring study and allocation. The flow diagrams created during function analysis should be extremely useful in the development of this list.

DEVELOP ALTERNATIVE MAN-MACHINE CONFIGURATIONS

Develop alternative man-machine configurations for each of the functions listed in the previous step. Utilize the recommended formatting techniques when documenting these configurations.

The human factors team should now begin to develop a list of all alternative man-machine configurations for each system function present in the aforementioned list. The usual approach in performing this activity involves making a one-page summary of the alternative configurations for each function. First, a brief description of the function is listed. Schemes where function descriptions are replaced with a letter or numeral, requiring the analyst to reference back-and-forth between various documents, should be avoided. In columnar form, develop a description of each of the function allocation configurations being considered (Figure 9). In most cases it will be adequate to define three alternate configurations. One configuration should place nearly all emphasis on the operator, a second configuration should place primary emphasis on a machine, and a third configuration should emphasize both operator and machine. The human factors team must work with design engineers during this descriptive phase, although the analysis of the various configurations occurs at a later stage.

ALTERNATIVE MAN-MACHINE CONFIGURATIONS		
FUNCTION: ALIGNMENT OF CET TO FLOOR FLANGE		
ALTERNATIVE 1 (OPERATOR PRIMARILY)	ALTERNATIVE 2 (MACHINE PRIMARILY)	ALTERNATIVE 3 (MAN-MACHINE MIX)
Operator of CET usually detects floor flange and ground markings leading up to emplacement, aligns CET with ground markings so that they appear on video monitor (camera on underside of vehicle), regulates forward and lateral CET movement so video camera and sighting aids are aligned with ground markings, stops vehicle when situated directly over ground target (center of floor flange gate).	Operator of CET, when entering an emplacement corridor, steers CET over a guide wire (within tolerances), activates control causing automatic tracking system to engage, tracking system guides vehicle down corridor, operator activates control telling system to stop at next emplacement, tracking system stops CET over floor flange gate and moves out of drive mode.	Operator of CET, when a few feet from the emplacement, aligns CET over guiding wire (within tolerances), activates control causing automatic tracking system to engage, tracking system controls lateral movement of vehicle, operator controls rate of forward movement of CET, operator monitors video display (camera on underside of vehicle) and stops forward motion when CET (and display) is aligned with ground target (center of floor flange gate).

Figure 9. Sample listing of alternative man-machine configurations for alignment of CET to floor flange.

Even with the present state of development of the waste retrieval engineering drawings and plans, there exists a tremendous amount of leeway in terms of the design of the individual procedures and equipment within each of the functional steps, many of which have already been specified. For example, the existing design calls for the development of a canister extraction/transporter which will be aligned with the floor flange. It is anticipated that this alignment task must be performed within strict tolerances.

There are a number of design alternatives which should be evaluated as potential solutions to the requirement for accurate alignment. First, the alignment task could be performed solely by the operator of the CET. The operator might utilize markings placed on the floor flange and leading up to the floor flange in making his approach. Video cameras underneath the CET would provide accurate feedback to the operator. A sighting device could be superimposed on this camera image to assist in the alignment operation. If the task is properly designed, the assignment of this function to the driver of the CET might prove to be an efficient and reliable method for achieving CET alignment.

Another possibility might be, as has been suggested in the preliminary design documents, to place this alignment operation under automatic machine control. After grading and floor flange emplacement, a guiding wire would be placed on the floor of the emplacement room leading up to each emplacement. Presumably, the operator would turn the CET over to automatic control, which would then guide the vehicle over the floor flange, stopping at the appropriate location. This system may be functional, but possibly difficult to maintain and operate in the working mine environment.

Another possibility would be to allocate segments of the alignment task to machines and other segments to operators. The lateral movement while transporting up to and over the emplacement could be placed under automatic control as discussed above, and the control of forward motion (and the task of stopping the vehicle) could be assigned to the operator who would need to monitor a visual display and stop the vehicle at the appropriate point over the emplacement. These are just three of the many man-machine configurations which can be developed for this particular task.

DEVELOP ALTERNATIVE FUNCTIONAL FLOW DIAGRAMS

Develop a functional flow diagram of each of the man-machine configurations listed in the alternative man-machine configurations form.

The technique for developing a functional flow diagram discussed earlier should now be employed to describe the subtasks, as they are outlined in each column of the man-machine configuration chart. The level of detail in each of

these charts should be quite high, allowing the analyst to fully comprehend the implementation of each approach. Example functional flow diagrams of the three alternative configurations for CET/floor flange alignment are provided in Figures 10, 11, and 12.

LIST OPERATOR AND MACHINE FUNCTIONS

List the operator functions and machine functions necessary for performing each of the listed alternative man-machine configurations.

The analyst should list, in the order in which they are performed, the specific operator actions for each of the alternative man-machine configurations listed in Figure 9. During this task, the configuration described in the figure and the flow chart developed in the previous step should be referenced. Attempts should be made at developing a list of operator functions which are of greater detail than the functions listed in the flow chart. After having completed the list of operator functions, a list of required machine functions should be written. The level of detail in these functions should mirror that found in the operator functions. This procedure should be repeated for each of the man-machine configurations on the alternative man-machine configuration sheet. Example listings of operator functions and machine functions for each of three hypothetical alternatives for CET and floor flange alignment are presented in Figure 13.

COLLECT FUNCTION ALLOCATION DATA

Collect data related to the alternative man-machine configurations. Base these data on interviews with subject-matter experts, design engineers, available human engineering practices and knowledge, and, if necessary, experiments.

The process of collecting data on assorted man-machine configurations is one of the most important in function allocation. It is during this stage that the human factors team must gather the information to allow them to determine the feasibility of executing each function with each man-machine configuration.

Figure 10. A functional flow diagram of alternative 1 for alignment of CET to floor flange.

Figure 11. A functional flow diagram of alternative 2 for alignment of CET to floor flange.

Figure 12. A functional flow diagram of alternative 3 for alignment of CET with floor flange.

ALTERNATIVE MAN-MACHINE CONFIGURATIONS		
FUNCTION: ALIGNMENT OF CET TO FLOOR FLANGE		
ALTERNATIVE 1 (OPERATOR PRIMARILY)	ALTERNATIVE 2 (MACHINE PRIMARILY)	ALTERNATIVE 3 (MAN-MACHINE MIX)
Operator of CET usually detects floor flange : : : target (center of floor flange gate).	Operator of CET, when entering an emplacement : : : gate and moves out of drive mode.	Operator of CET, when a few feet from the : : : target (center of floor flange gate).
OPERATOR FUNCTIONS	OPERATOR FUNCTIONS	OPERATOR FUNCTIONS
<ol style="list-style-type: none"> 1. Visually detects ground marking. 2. Guides CET over marking. 3. Turns on video system. 4. Monitors video, tracks over marking. 5. Stops CET on a flange. 6. Turns off video. 	<ol style="list-style-type: none"> 1. Steers CET to center of corridor. 2. Turns on tracking control. 3. Signal CET to stop. 4. Turns on video. 5. Inspect alignment. 6. Turns off video. 7. Turns off tracking control. 	<ol style="list-style-type: none"> 1. Steers CET to center of corridor. 2. Turns on tracking control. 3. Turns on video. 4. Monitors video, regulates forward motion. 5. Stops forward motion when over flange. 6. Turns off video. 7. Turns off tracking control.
MACHINE FUNCTIONS	MACHINE FUNCTIONS	MACHINE FUNCTIONS
<ol style="list-style-type: none"> 1. Displays marking under vehicle along with sight on camera. 	<ol style="list-style-type: none"> 1. Tracks over guide wire, controls forward and lateral motion, stops over flange. 2. Displays video picture. 	<ol style="list-style-type: none"> 1. Tracks over guide wire, controls lateral movement of vehicle during forward motion. 2. Displays video picture.

Figure 13. Sample listing of operator and machine functions for various design configurations.

Data can be gathered from a variety of sources. Initially, members of the human engineering team should present the alternative configurations to design engineers to discuss the feasibility of executing functions with configurations having much dependence on machine control. Based on their past experience, design engineers should be capable of providing basic information concerning the feasibility of alternative approaches, and should be able to direct human factors team members to sources of information on the performance capabilities of the hypothetical machine components. Equipment catalogs and equipment manufacturers can be helpful in this respect.

Experts in the design and performance capabilities of various kinds of hardware should be consulted whenever possible. In addition to supplying valuable information concerning design techniques, these subject-matter experts may also be capable of supplying information on the cost of design alternatives, as well as the maintainability and reliability of the configurations.

If, after having consulted design engineers and subject-matter experts, the necessary data have not been acquired, it may be necessary to conduct one or more in-house experiments to determine the feasibility of utilizing one configuration or another. These tests, often called verification tests, are performed on alternative man-machine configurations to determine which configuration allows the performance requirements to be met. Verification tests often involve unique configurations, and must be performed if the proposed approach is a new one.

As an example of a verification test which might be performed during development of the waste retrieval system, the man-machine configuration relying on the operator as the principal source of control for aligning the CET with the floor flange is an approach which may have lower manufacturing costs and be easier to maintain. Prior to accepting or rejecting this configuration, however, the human engineering team must conduct a verification test to determine if an operator can, within the prescribed limits of performance, align a large vehicle with a ground site using a remote video camera and a ground mark. A relatively inexpensive simulation of this task could be conducted by using a large vehicle, similar in size and design to the proposed CET, equipped with a video camera mounted on the underside of the vehicle. A representative sample of subjects

would then be tested on their ability to align the vehicle with a simulated floor flange (painted on the floor). These data would indicate if this man-machine configuration allows the population of operators to align the CET with the floor flange within the required time and distance limits. Care should be taken to assure that the sample of operators have been given adequate training on the task before their performance is evaluated.

LIST ADVANTAGES AND DISADVANTAGES OF ALTERNATIVE CONFIGURATIONS

Develop a list for evaluating the strengths and weaknesses of each configuration in meeting the primary performance requirements. Include in this list assessments of the impact of each configuration on cost, maintenance, and reliability.

The human factors group should now complete the process of collecting and organizing data on alternative design configurations. The most logical place for this information to be recorded is on a continuation of the alternative man-machine configurations form presented earlier. In its final form, this sheet describes the alternative man-machine configurations under study, the operator and machine functions necessary to execute the function and, lastly, the advantages and disadvantages of each man-machine configuration.

In addition to being certain that each configuration can or cannot meet the original performance requirements (e.g., identify an emplacement and be positioned over the floor flange in less than five minutes with less than one cm of positioning error), the analyst must consider the potential impact of the system on maintenance requirements. A highly automated system, while meeting the performance requirements with little difficulty, may require a more highly trained maintenance staff. Such a system might also be less reliable in the long run, and certainly will have a higher development cost. A manual system, on the other hand, may have reduced maintenance costs, lower development costs, and higher reliability, but may not meet the original performance requirements. All relevant factors must be considered and listed in the man-machine configuration evaluation sheets (Figure 14).

ALTERNATIVE MAN-MACHINE CONFIGURATIONS		
FUNCTION: ALIGNMENT OF CET TO FLOOR FLANGE		
ALTERNATIVE 1 (OPERATOR PRIMARILY)	ALTERNATIVE 2 (MACHINE PRIMARILY)	ALTERNATIVE 3 (MAN-MACHINE MIX)
Operator of CET usually detects floor flange : : target (center of floor flange gate).	Operator of CET, when entering an emplacement : : gate and moves out of drive mode.	Operator of CET, when a few feet from the : : target (center of floor flange gate).
OPERATOR FUNCTIONS	OPERATOR FUNCTIONS	OPERATOR FUNCTIONS
1. Visually detects ground marking. : :	1. Steers CET to center of corridor. : :	1. Steers CET to center of corridor. : :
MACHINE FUNCTIONS	MACHINE FUNCTIONS	MACHINE FUNCTIONS
1. Displays marking under vehicle along : :	1. Tracks over guide wire, controls forward : :	1. Tracks over guide wire, controls lateral : :
EVALUATION		
ADVANTAGES		
1. Increased flexibility for unexpected situations. 2. High system reliability. 3. Minimal maintenance requirements. 4. Low cost.	1. Lower operator workload. 2. Brief execution time. 3. Lower training costs.	1. Lower operator workload. 2. Brief execution time. 3. Lower training costs.
DISADVANTAGES		
1. Longer execution time. 2. Higher training costs.	1. Higher equipment costs 2. Higher maintenance costs. 3. Longer equipment down time. 4. Operator must still use video to verify alignment.	1. Equipment costs greater than Alternative 1, but less than Alternative 2. 2. Higher maintenance costs than Alternative 1.

Figure 14. Sample listing of advantages and disadvantages of each alternative configuration.

DEVELOP FUNCTION ALLOCATION EVALUATION MATRIX

Develop a function allocation evaluation matrix to assist in the evaluation of man-machine configurations. Identify the appropriate criteria for evaluation, assign weights to criteria, and complete the matrix.

One technique which has proven useful in evaluating candidate configurations is the evaluation matrix, sometimes known as a "function allocation screening worksheet" (Geer, 1976b). The purpose of this matrix is to provide a consolidated review of the advantages and disadvantages of each configuration, evaluated according to weighted criteria. Some factors will surely be considered more important than others, and the evaluation matrix provides one means of accounting for these weights and providing a summary of the merits of each configuration.

The first step in developing the matrix is to select the criteria against which each alternative will be evaluated. Although each subsystem may have special requirements which necessitate the development of specific criteria, the criteria of cost, performance, reliability, maintainability, safety, producibility, manpower, and training should be included in the analysis of most every alternative. List these criteria on a form similar to that illustrated in Figure 15. The purpose of this form is to assist in the assignment of weights to each evaluation criterion (Hagen, 1967; Meister, 1971). In practice, it is rare for designers to quantize decisions in the fashion presented below. However, this method does force designers into making their decision biases more visible. Moreover, Meister (1971) has found that the method discussed below does force designers into making valuable criterion judgements.

After having listed each of the criteria for the function, weights are to be assigned by comparing each criterion with every other criterion (Figure 15). Each time two criteria are compared, a "1" is assigned to the criterion judged to be more important, and a "0" is assigned to the criterion judged to be less important. Comparing each criterion to every other criterion results in a table of zeros and ones. Next, count up the number of ones in each row and enter the total in the appropriate column. Sum these values to arrive at a grand total. Lastly, to arrive at the weighted coefficient for each criterion, divide each row's total by the grand total and enter the result in the last column. The total of the weighted

FUNCTION: ALIGNMENT OF CET TO FLOOR FLANGE			
CRITERIA	CHOICE TALLY	TOTAL	WEIGHTING COEFFICIENT
1. PRECISION PERFORMANCE REQUIREMENTS	1111111	7	.25
2. TIME PERFORMANCE REQUIREMENTS	0111110	5	.179
3. RELIABILITY	0011110	4	.14
4. COST	0000000	0	0
5. MAINTAINABILITY	0001110	3	.107
6. MANNING	0001000	1	.036
7. TRAINING	0001010	2	.071
8. SAFETY	0111111	<u>6</u>	<u>.214</u>
		28	.997

Figure 15. Sample listing of criteria and weighting coefficients for man-machine configuration study of CET alignment with floor flange.

coefficients should approximate 1.00. It should be understood that all design team members should assist in deciding on the relative importance of each criterion. Information on reliability and other engineering related factors must be gathered through interviews with the appropriate members of the design team.

Having developed a weighted coefficient for each criterion, the assorted man-machine configurations developed earlier can now be compared. It is necessary, however, to first develop a quantitative basis for evaluating as many criteria as possible. With reference to potential system cost, for example, reference past documents on the cost of developing, manufacturing, and maintaining each alternative configuration. Include the associated costs of having larger or smaller manning requirements, training requirements, and maintenance requirements. Although some of the values required to perform this type of cost estimate must be estimated, most should be available by conducting interviews with design engineers and equipment manufacturers. The point to be stressed at this juncture is that these decisions should be based on objective data whenever possible.

After having gathered the data, compare the alternative man-machine configurations on the basis of the listed criteria. For each criterion, the weighting is performed in much the same manner as it was earlier. An example table of weighting is presented in Figure 16. Note that each alternative has been compared to each other alternative for every criterion. When one alternative has been judged superior to another, a "1" is placed in the choice tally column. A "0" is placed in the choice tally column next to the alternative judged to be inferior in the comparison. As before, the total number of tallies are summed for each criterion and divided into the total tally for each alternative.

In the final step, the criteria are again listed down the left side of the table (Figure 17), along with the weighted criteria scores. This score is multiplied by the choice coefficient listed in Figure 16, and a total score is obtained and listed under the appropriate column in the table. After completing the table and adding all the final scores, the matrix indicates which alternative, 1, 2, or 3, surfaces as the most attractive according to the identified criteria and the weights placed on each criterion. The total scores listed in Figure 17 might represent the results of an analysis to determine which alternative, 1, 2, or 3, represents the best man-machine configuration for aligning the CET with the floor flange. Please note that all values, comparisons, and scores are purely hypothetical and do not necessarily reflect the merits of each configuration.

As can be seen from the above example, there are numerous decisions to be made in deciding which of many available man-machine configurations represents the most attractive, all-around configuration. The procedure outlined above is intended to organize this process and help ensure that the final selection is based on quantitative data and expert judgment whenever possible. As such, the results represent the total merit of each configuration, based on the selected criteria, data, and relative judgments of designers and human factors analysts.

FUNCTION: ALIGNMENT OF CET TO FLOOR FLANGE				
CRITERIA	ALTERNATIVE CONFIGURATIONS	CHOICE TALLY	TOTAL	CHOICE COEFFICIENT
PRECISION PERFORMANCE REQUIREMENTS	ALT. 1	00	0	0
	ALT. 2	11	2	67
	ALT. 3	10	1	33
TIME PERFORMANCE REQUIREMENTS	ALT. 1	00	0	0
	ALT. 2	11	2	67
	ALT. 3	10	1	33
RELIABILITY	ALT. 1	11	2	67
	ALT. 2	00	0	0
	ALT. 3	01	1	33
COST	ALT. 1	11	2	67
	ALT. 2	00	0	0
	ALT. 3	01	1	33
MAINTAINABILITY	ALT. 1	11	2	67
	ALT. 2	00	0	0
	ALT. 3	01	1	33
MANNING	ALT. 1	00	0	0
	ALT. 2	10	1	33
	ALT. 3	11	2	67
TRAINING	ALT. 1	00	0	0
	ALT. 2	11	2	67
	ALT. 3	10	1	33
SAFETY	ALT. 1	00	0	0
	ALT. 2	10	1	33
	ALT. 3	11	2	67

Figure 16. Sample listing of weightings for alternative configurations for man-machine configuration study of CET alignment with floor flange.

FUNCTION: ALIGNMENT OF CET TO FLOOR FLANGE			
CRITERIA	ALTERNATIVES		
	1	2	3
1. PRECISION PERFORMANCE REQUIREMENTS X .25	0.0	0.168	0.08
2. TIME PERFORMANCE REQUIREMENTS X .179	0.0	0.120	0.060
3. RELIABILITY X .14	.094	0.0	.046
4. COST X 0.0	0.0	0.0	0.0
5. MAINTAINABILITY X .107	0.072	0.0	0.036
6. MANNING X .036	0.0	0.012	0.024
7. TRAINING X .071	0.0	0.048	0.006
8. SAFETY X .214	0.0	0.071	0.143
TOTAL	0.144	0.419	0.395
	3RD CHOICE	1ST CHOICE	2ND CHOICE

Figure 17. Sample function allocation matrix for choosing one of three man-machine configurations for aligning the CET with floor flange.

SELECT MAN-MACHINE CONFIGURATIONS

Select the man-machine configuration projected as having the best chance of meeting the system functional requirements.

The previous discussion on the development of a decision matrix is a somewhat crude method for selecting the best man-machine functional configuration. The method is, however, one way to guarantee that function allocation decisions are based on performance data and not on the unsupported opinions of one designer. The single, most important point to remember during the entire function allocation process is that these decisions have far-reaching consequences, affecting not only system performance but manning requirements, training requirements, system reliability, and system cost. The long projected life of the waste retrieval system requires that these function allocation decisions be based on (a) a thorough

analysis of the performance requirements and (b) the peripheral (but potentially critical) factors such as maintenance, reliability, training, and manning.

PROVIDE PRELIMINARY PERSONNEL REQUIREMENTS LISTING

Develop a preliminary list of personnel requirements, outlining the number of personnel required to perform each of the gross system functions (survey and mapping, remining, floor flange emplacement, plug removal, etc.), and the number of operators required to man each piece of equipment.

Although the issues and steps central to the development of the personnel subsystem are described in detail later in this document, a preliminary estimate of personnel requirements should be developed at the end of function allocation. At this stage in development, the system requirements and system functions have been specified, and the functions and subfunctions have been allocated between men and machines. Accurate predictions of operational personnel requirements can therefore be developed, as well as gross estimates for the manning required for maintenance.

The document describing these preliminary personnel requirements should specify the number of POM's, CET's, PET's, etc., to be built for the system, as well as the number of vehicles and pieces of equipment to serve as back-ups and spares. Further data should be provided on how rapidly each team or team member should be expected to perform basic functions. In toto, the described system must meet the original performance requirements specified at the outset of the project.

Of particular importance will be the estimates of the number of support personnel required to operate the system. Communications technicians, computer programmers, managers, and maintenance personnel should all be considered. This preliminary analysis is intended to provide a frame of reference for human factors engineers and system designers throughout the equipment development phase.

PERFORM COMPUTER-AIDED FUNCTION ALLOCATION

Derive and evaluate various alternatives for allocating functions to operators and equipment using the Function Allocation Model (FAM) of the Computer-Aided Function Allocation and Evaluation System (CAFES).

Whitmore and Parks (1974) have developed a Computer-Aided Function Allocation and Evaluation System which contains a submodel called FAM (Function Allocation Model). These programs were developed to reduce the time consuming activities of the human factors analyst, particularly time spent on function allocation studies. The objectives of FAM are to "identify and organize system functions to an allocatable level, and to rank order function allocation schemes (by performance effectiveness) that satisfy mission requirements" (Geer, 1976b).

To use FAM for studying and allocating system functions, the analyst first develops a list of system functions. Data from other submodels within CAFES are used to describe and evaluate the system functions. FAM then computes probability of overall mission success for various function allocation candidates. Using other submodels within CAFES (Workload Assessment Model), the analyst can have FAM reallocate and refine system functions, and develop new predictions of system success. FAM and many of the other submodels within CAFES may be useful to the human factors team in their efforts to allocate system functions and manage data collected throughout the waste retrieval development cycle, and is mentioned here as an alternative methodology to the manual method discussed above.

DEVELOP HUMAN FACTORS CHECKLIST

Develop a checklist from the human engineering design standards provided in Volume II and MIL-STD-1472 to assist in the evaluation of categories of equipment being identified at the end of the function allocation phase.

Although not a human engineering methodology per se, the human factors team may consider developing a checklist to evaluate the performance requirements of the equipment being selected during and after function allocation. While assorted man-machine configurations are being evaluated and identified, such a checklist might serve as a useful design verification technique. Equipment being

selected or purchased can be evaluated according to the criteria listed in these documents. When function allocation studies reach a level of detail involving the finer aspects of equipment detail design, such a checklist could be used, for example, to rate the characteristics of various displays. This rating data could be included in more detailed function allocation studies discussed earlier.

TASK DESCRIPTION

The derivation, description, and analysis of tasks should begin soon after the man-machine allocation of functions has been completed. There are multiple reasons for developing task descriptions and conducting task analysis, the most important of which is that the resulting information will be used to specify detailed equipment design in the next major stage of development. Task description and analysis also provides the major portion of the data for specification of the skill levels of the personnel required to operate each aspect of the system, the exact number of personnel required to operate the system, the level of knowledge required to operate each aspect of the system, and the level of training to achieve adequate task performance.

It is important that the activities involved in task description and analysis not be reduced to a routine check off of items. The procedures and techniques presented in this document should be viewed as a means of achieving a desired program output—namely, a thorough description of each and every operator behavior necessary for operation of all phases of the waste retrieval system. Task analysis is widely recognized as the most popular method of system analysis in human factors work.

In task description and analysis, the first step is to organize the system functions identified in earlier steps into the basic categories in which they occur—operations, maintenance, and support. Once organized, the discrete tasks performed within each of these functions are listed. A step-by-step procedure for writing these task statements has been provided. These tasks are then placed in the sequence in which they are performed, and the subtasks within each of the tasks are identified, where necessary.

ORGANIZE FUNCTIONS INTO CATEGORIES

Order retrieval system functions into categories based on their purpose; e.g., operations, maintenance, or support.

The first step in developing task descriptions is to order all of the retrieval system functions identified in function analysis and function allocation into groups based on the basic purpose of the function. All functions involving activities in emplacement drifts will most likely be placed in the operations category. All maintenance functions, including preventive and corrective maintenance performed on all mining and retrieval vehicles and equipment in the CWSRS, should be placed in the maintenance category. All functions related to communication, operations planning, and possibly data management and processing would fall into the support functions category. This organization of system functions is to be performed solely for the purpose of simplifying the following steps in describing tasks.

LIST TASKS

Identify all operator tasks within each of the system functions, and develop a description of each task following the procedures outlined below.

Although the process of describing each operator task in a large system can be tedious and sometimes time consuming, it is not a particularly difficult aspect of preliminary development. This aspect of task description and analysis does, however, require a thorough familiarity with the retrieval system requirements and the existing state of equipment development. It is also important for the individuals developing the task listing to keep in close contact with design specialists to verify that the hardware elements and related procedures described in the task statement do not conflict with engineering capabilities.

The following description represents a summary of the steps involved in developing a task list. A more thorough methodology, one specifically designed for using the Computerized Event-Tree Analysis Technique, is the subject of Volume III of this set of documents.

Function Ordering

Develop a listing of retrieval system functions organized according to the order in which they are performed.

To perform this task, the human factors team need only consult earlier documents on retrieval system functions. The functional flow diagrams developed during function analysis should be the most relevant source of information.

Task Statement Derivation

Develop a task statement for each of the operator activities necessary for executing each system function. Include in each task statement information on the nature of the operator action, the object of the operator action, and the purpose of the action.

Many methods for writing task statements have been developed over the years, each approach tailored to the specific requirements of the development project. The procedures outlined here are intended to provide a direct, streamlined approach toward writing task statements. The identification of tasks, per se, poses few problems, but the content of the statements and, more specifically, the level of detail the task statement describes does require some decision making. As a general rule, it is advisable to write task statements in as much detail as the present state of system development will permit. Abstract task statements must often be made more specific at later stages of design when the detailed information is needed.

Each task statement should contain an action verb (describing the specific behavior of the operator), a noun (the object of the behavior), and a statement about the purpose of the behavior. It is generally advisable to develop a form similar in content to Figure 18 to assist the analyst in developing each task statement and recording relevant data. At this time it may be appropriate to identify the general type of control required to perform the task, if it has already been specified; this point of man-machine interface may be modified, however, when the next generation of task analysis occurs.

FUNCTION DESCRIPTION		CHECK ONE	OPERATION	X	TASK NO:
TRANSFER CANISTER TO THE CWSRS			MAINTENANCE SUPPORT		
TASK INFORMATION					
OPERATOR ACTION	OBJECT OF ACTION	PURPOSE OF ACTION			
Moves	CET canister vertical movement control	Lower canister into Canister Transfer Basket			
TASK STATEMENT					
Moves control into position to lower the canister into the Canister Transfer Basket					
PRECEDING TASK					
Observe green indicator light verifying that the Canister Extraction Transporter gate is fully opened.					
FOLLOWING TASK					
Observe (a) status of control to verify operator action, and (b) indicator light indicating that canister has been lowered into the Canister Transfer Basket.					
LOCATION OF TASK PERFORMANCE					
Cab of CET. Operator in voice communication with CWSRS operator.					
SEGMENT OF WORK CYCLE IN WHICH TASK IS PERFORMED					
After port alignment and before exit to remove next canister.					
DISCRETE OR CONTINUOUS TASK					
Operator's function is discrete. Lowering of canister halts automatically when at bottom.					
FREQUENCY OF PERFORMANCE					
After removal of each canister—four times in eight-hour shift.					
LIKELIHOOD THAT TASK PERFORMANCE IS REQUIRED					
Probability is 1.0 that task is performed with removal of a canister.					

Figure 18. Sample form for developing task statements.

Task statement derivation begins by identifying the function within which the task occurs. In the example in Figure 18, the task of lowering the canister into the Canister Transfer Basket is prefaced with a statement on the general function--transferring the canister to the CWSRS. The function should have already been classified as an operation, maintenance, or support function. It is also necessary to assign a number to each of the tasks to assure that they are examined in their proper sequence. Begin developing the task statement by identifying the operator action, the object of the action (usually a control or display), and the direct purpose of the action. With this information, the analyst can then write the actual task statement. It is necessary for each task statement to have the same format: action verb, object of the action, and a brief description of the purpose of the action. Each task statement should deal with a single action of a single operator, usually interfacing with one piece of equipment.

After completing the statement, record the task statement for the preceding task. Record the task statement for the task which follows this task when it becomes available. Having the three tasks on the same page should provide a clearer frame of reference for studies of the task at hand.

Additional information should be recorded on this form, including the location at which this task is performed and the segment of the work cycle in which the task occurs. It is also appropriate to make a determination on the discrete or continuous nature of the task—which is also a function of the type of control selected for task execution. As is the case for the object of action (control or display) of the task, the discrete or continuous nature of the task may be modified during later analyses. Lastly, it is necessary to record data on the frequency with which the task is performed. The task used in the example, lowering the canister into the Canister Transfer Basket, will be performed each time a canister is removed from an emplacement. If a full-time canister extraction effort has been undertaken, a single operator may repeat this task approximately four times during an eight-hour shift. Information on the likelihood of task performance is also recorded on the form. This estimate will be of particular importance when studying the tasks involved in maintenance as well as the tasks occurring during emergencies.

ORDER TASKS

Arrange the tasks within each function into the order in which they are performed.

If, for some reason, the task descriptions within each function have not already been placed in the order in which they are performed, they should be organized in this manner at this time. The groups of tasks (functions) should also be placed in chronological order, so that the complete sequence of tasks--from the decision to retrieve a canister to the transport of the canister to the surface--can be examined.

TASK ANALYSIS

The initial step in task analysis is to perform a preliminary analysis of the control/display components required to perform each of the listed tasks. Available human engineering data should be referenced when selecting the controls and displays to be used when executing each task. After having identified the most appropriate controls for each task, controls and displays can begin to be grouped on the basis of their function.

The next phase of this effort involves a number of graphic techniques for describing, in detail, each operator action and the relationships between the actions of different operators. Human factors personnel should employ Operational Sequence Diagrams, timeline analyses, and possibly other techniques in their efforts to develop the most efficient interfaces between operators and their equipment.

IDENTIFY PERMISSIBLE CONTROL/DISPLAY COMPONENTS

Identify the equipment control and display components which will permit the task to be performed. Analyze the input and output characteristics of the task and develop a list of equipment components which will permit execution of the task as it was defined during function allocation and task description.

Most man-machine configurations should be well established at this point. However, it will now be necessary to define the exact nature of the equipment with which the operator will interface while executing the task. The manner in which

tasks are allocated between operators and machines, as well as the nature of the task itself, will determine what type of control is selected. It is during this stage of system development that design engineers and members of the human factors team should consult Volume II, "A Compendium of Human Factors Design Data." Information on the appropriate characteristics and uses of assorted controls and displays is provided in this document.

The human factors team must become actively involved in specifying the exact nature of the controls and displays used in each task. Controls must be selected so they match the input requirements of the task. It is also the job of the human factors team to insure that individual controls conform to human engineering design standards in terms of their size, shape, color, and operating characteristics.

To illustrate by way of example, for the task of lowering the canister into the transport basket, there are many different controls which will allow the operator to input the required information—a selection of one of two alternatives. A toggle switch, bat-handle switch, push button, foot switch, push-pull control, trigger, or a pointer knob with detents could be used for making the necessary operator input. All the operator need do in this hypothetical situation is indicate the desired position of the canister—up or down. This information should be listed in the appropriate section of a task description sheet like that in Figure 19.

SELECT APPROPRIATE CONTROL/DISPLAY COMPONENTS

Select the control and/or display from the list of permissible equipment components which best meets the requirements of the task.

The selection of the single, most appropriate control will be influenced by the controls being used for other tasks in the operator's work station, the available space, the relationship of the control to the display, inherent control/display movement relationships, and other factors, like whether the operator will be wearing gloves.

FUNCTION DESCRIPTION	TRANSFER CANISTER TO THE CWSRS	TASK NO. 13
TASK DESCRIPTION	Moves toggle switch into down position to lower the canister into the Canister Transfer Basket.	
PERMISSIBLE EQUIPMENT COMPONENTS		
(A control having two alternatives: up and down) toggle switch, bat-handle switch, push button, foot switch, push-pull control, trigger, pointer knob.		
SELECTED CONTROL/DISPLAY COMPONENTS		
Two-way toggle switch. When vertically oriented, provides best control/object movement relationship.		
	CONSIDERATIONS	
COMMUNICATION REQUIREMENTS	CET operator in open voice communication with CWSRS operator. Actions of CET are displayed to CWSRS. Information relayed via electrical cable or radio.	
CONTINGENCY REQUIREMENTS	Backup manual system available if control fails. Interlocks present so canister can't be lowered unless CTB is present <i>and all gates are open</i> .	
MAINTENANCE REQUIREMENTS	Develop operator checkout procedure for controls/displays to be performed periodically. Easy access to controls required for corrective maintenance.	
FEEDBACK REQUIREMENTS	Feedback that toggle is in position (detent). Feedback (white light) that canister is actually moving downward. Feedback (green light) that canister is at bottom of cask.	
INPUT/OUTPUT CHARACTERISTICS	Initial input is output from previous task. Operator input is discrete. Force requirements according to HFE toggle switch design. Display lights in proper relationship to control.	

Figure 19. Sample form for developing task descriptions.

To continue with the previous example, the controls and displays used in lowering the canister into the Canister Transfer Basket have been analyzed and the information placed on the form in Figure 19. Because of the up/down motion of the canister while being raised and lowered, it makes logical sense to use a control having up and down motion. Due to the frequency with which this task will be performed (each time a canister is removed), it will be necessary to place the task under semi-automatic control, a man-machine configuration which (hypothetically) has been decided upon during function allocation. The operator, after aligning the CET with the port gate and performing the preliminary tasks like establishing communications with the CWSRS and opening gates, moves some kind of switch to lower the canister. The canister would then be lowered under a fixed rate of speed into the basket. When it has reached the bottom (or a predetermined distance) the lowering mechanism would automatically shut off and the operator would be notified that the canister is contained within the basket. Placing this operation under complete operator control might create undue demands on the operator, particularly for a task which must be performed (potentially) many thousands of times.

In the sequence of events involved in lowering the canister, the operator would just move a two-position toggle switch from the top (up) position to the down position. This would cause the canister to be lowered automatically. A series of interlocks might be built into the system so that this switch is deactivated if all conditions are not proper; e.g., a gate has not been opened or an empty Canister Transfer Basket is not underneath the port gate. While the canister is being lowered, a white light (indicates system is in operation) would be lit, indicating that the canister is being lowered. When the canister reaches the designated point within the basket, the control system might (a) automatically stop downward movement, (b) turn off the white indicator light indicating that the motion has stopped, and (c) display a green light at the "switch down" position, indicating that the task has been fully executed and the operator may proceed. After having decided that a two-directional toggle switch is the most appropriate control for the task, this information is recorded on the task information sheet along with a finalized task description which identifies the type of control to be used in executing the task. If, after having moved the toggle switch to the down position,

the white indicator light does not come on and a red indicator light (which might be described in another task) does, the operator must execute an alternate series of tasks involving the non-automatic canister raise/lower system. The above scenario is hypothetical, but should provide an idea as to the level of detail necessary in analyzing each task. All of this information would be entered on the task description sheet in Figure 19.

IDENTIFY OPERATIONAL FACTORS

Examine the tentative control and/or display components in terms of communication requirements, contingency requirements, maintenance requirements, feedback requirements, and input/output characteristics.

An important aspect of the control/display component analysis is analyzing and recording the task in terms of potentially critical factors. These factors are listed below, along with brief descriptions of what each examination should include. The results of the examinations should be recorded in the appropriate spaces on the task description form (Figure 19).

- **Communication requirements.** For performance of a given task, it may be necessary for the operator to be in communication with other operators, remote or nearby, or other pieces of equipment. Although the operator behaviors associated with a communication related action would be classified as a separate task, it is advisable to note the communication requirements of the task and record them on the task description form (Figure 19).
- **Contingency requirements.** Contingency requirements are usually emergencies, but may also include non-emergency conditions in which an operator has performed a task improperly or the equipment has malfunctioned. With reference of the canister transfer task discussed above, a malfunction of the automatic system may require an alternate means of executing the task. In this example, the response to this contingency is to use the non-automatic backup system, although this is only one of many possible ways of meeting this requirement. Other possible contingencies for this task might be (a) an unexpected radioactive environment outside the cab of the CET, (b) a canister stuck between the CET and the Canister Transfer Basket, (c) an unanticipated or inadvertent movement of the CET, or (d) any of a number of equipment failures. These should all be noted and accounted for when analyzing and possibly redesigning the task. Most importantly, a determination must be made as to how these various contingencies will be displayed to the operator.

- Maintenance requirements. Maintenance can be either preventive or corrective. It will be necessary to assure that the control/display component is accessible and repairable. Special displays may be necessary for diagnostics on corrective maintenance tasks.
- Feedback requirements. Feedback to the operator is an exceedingly important aspect of almost every operator task. A thorough analysis of the information requirements of the operator and the most appropriate means of displaying this information to the operator must be performed. Referring to the canister transfer process, the operator must be presented with and perceive a signal that (a) the control has been activated (proper control feedback, e.g., detent action), (b) the needed operation is being performed (e.g., a white light indicating that the canister is in the process of being lowered), and that (c) the operation has been completed according to standards (e.g., a green light indicating that the canister is in the correct position in the Canister Transfer Basket). It is also necessary to analyze the feedback requirements for abnormal conditions. Some type of signal must indicate to the operator that the procedure has not been fully executed, and all diagnostic information necessary for taking corrective action must be provided.
- Input/Output characteristics. The analysis of the input/output characteristics should include a determination of the input intensity (e.g., if the task involves a display, the intensity of the signal), the input duration, the operator's output force requirements, and a study of the input/output relationships (e.g., which controls activate which displays).

³ A factor which merits close attention is the source of the information feedback being displayed to the operator. In their critique of nuclear power plant control rooms, Swain & Guttman (1980) discuss instances in which control room indicator lights signal the position of a valve (open or closed) after the operator has made a control input. The difficulty lies in the source of the feedback; the indicator light does not signal the actual state of the valve but, rather, the position of the switch. When a valve malfunctions, the operator is led to believe (if he is not totally familiar with the characteristics of the feedback system) that the valve is in the required position. Indicators which signal the occurrence of events must receive their input from the primary source, as opposed to a secondary source which may or may not provide data on the actual state of the system.

INTEGRATE CONTROL/DISPLAY COMPONENTS

Reduce the number of control/display components, if it is appropriate to do so, by integrating and combining functions.

In a complex system in which an operator must perform many separate tasks from the same basic work station (which will probably be the case with the Canister Extraction Transporter and the Canister Overcore Transporter) it is often necessary and practical to reduce the number of control/display components by integrating functions. This can be accomplished in three ways:

- Combining an input with an output. Switch lights or illuminated pushbuttons can be used to combine these functions.
- Combining multiple inputs. Multilegend and multifunction input/display devices can be used with unrelated tasks.
- Combining multiple outputs. A rotary switch, for example, can be used to replace several toggle switches.

DEVELOP OPERATIONAL SEQUENCE DIAGRAMS

Develop detailed Operational Sequence Diagrams (OSD) for each retrieval operation, depicting the interactions among operators, the activities of each operator, and the sequence in which all events occur.

The Operational Sequence Diagram is believed by many to be the most powerful manual analysis technique of the human factors engineer (Kurke, 1961). It has proven to be extremely useful in analyzing tasks in situations where many operators must work in synchrony to execute a task. The OSD allows the analyst to depict the links between all operators involved in an operation, and develop an exceptionally detailed portrait of synchronous and sequential man-machine events. It is probably the most effective noncomputer-based method for modeling a system or series of events prior to construction of the system.

Although the finalized Operations Sequence Diagram may vary from one analyst and/or project to another, the underlying framework is basically the same in most analyses. A set of symbols, often selected by the analyst, are chosen to represent assorted operations, events, or processes, including decisions, operations,

transmissions, or the storing of information, for example. Although a simplistic standardized symbology has been developed (Figure 20), the analyst should feel free to select his own symbols and labels to meet the needs of the analysis.

Figure 20. Basic symbols used in Operational Sequence Diagrams (Van Colt and Kinkade, 1972).

It is standard procedure to arrange the symbols so the sequence flows from top to bottom of the diagram. It can be useful to include information on durations of events along the left margin of the chart, if such time data are available. A few options exist for arranging the columns of the diagram. In most OSD's, two, three, or four operators are identified with major column headings; within each operator column there can also be a number of event categories. In the example in Figure 21, these categories have been labeled as (a) receiving, (b) decision, (c) action, and (d) transmit, but the final layout should depend on the preferences of the analyst and the characteristics of the system being described. The symbology for Figure 21 is presented in Figure 22. Another option involves labeling these columns as different areas of the work place, as opposed to categories of behaviors and events.

Figure 21. An example Operational Sequence Diagram of the events (hypothetical) involved in aligning the CET with the CWSRS port gate. Accompanying symbology is shown in Figure 22.

LEGEND	LINKS
DECISION	A AURAL E ELECTRICAL
RECEIVE VOICE COMMUNICATION	V VISUAL S SPEECH
DISPLAY	P PHOTO IMAGE
OPERATION	T TACTILE K KEYCARD ENTRY
TRANSMIT INFORMATION
OPERATOR TRAVEL
MONITOR
STORE INFORMATION	
DOUBLE SYMBOL: CONTINUOUS/AUTOMATIC CONTROL	

Figure 22. Symbology for Operational Sequence Diagram in Figure 21.

When analyzing functions which require the movement of operators from one work station to another, it is advisable to label the location of performance of activities described in the latter approach; such analyses usually highlight inefficient procedures and make alternate, more efficient tasks and task procedures more visible.

The information for constructing OSD's can come from functional flow diagrams, decision action diagrams, task descriptions, or scenarios. It is important to remember that the OSD is not just a descriptive technique but, rather, a method for describing task events and identifying machine tasks, operator tasks, procedures, and man/machine equipment arrangements which can be modified to improve the efficiency with which operations are performed.

In addition to providing invaluable design-related information, detailed OSD's are valuable to other aspects of system development. Validated OSD's can be employed in training programs as a method of describing tasks and task sequences. Operation manuals and job performance aids may contain information based on the OSD, or contain the actual diagram. Most importantly, OSD's should be used to evaluate designs and event sequences, and to analyze alternative arrangements when initial designs and task sequences are determined to be unacceptable. The technique is the most appropriate method for pictorially representing a number of interrelated system events.

DEVELOP INFORMATION FLOW PROCESS CHARTS

Develop Flow Process Charts (FPC's) describing the sequence of operator activities or the flow of information through the system at the task level using standard FPC symbology.

The Flow Process Chart can be used with or in place of the Operational Sequence Diagram as a technique for diagramming operator activities or information transfer. As with the OSD, events are indicated with a set of symbols, and the flow proceeds from the top to the bottom of the page. Typically, the FPC utilizes the symbology shown in Figure 23 (Geer, 1976a). The alphabetic codes are usually placed inside the "Transmit" and "Receipt" symbols to indicate the mode of transmission. Unlike the OSD, the Flow Process Chart is not particularly intended to portray the interactions among multiple operators. Nor is it intended to illustrate the flow of information or tasks between operators at various locations. The FPC should therefore be used only in the analysis of a single operator station.

LEGEND	LINKS
OPERATE	V VISUAL
INSPECT	E ELECTRICAL
TRANSMIT	S SOUND (VERBAL)
RECEIPT	IC INTERNAL COMMUNICATION
DECISION	EX EXTERNAL COMMUNICATION
STORAGE	T TOUCH
	M MECHANICALLY
	W WALKING
	H HAND DELIVER

Figure 23. Symbology for Flow Process Chart.

An example Flow Process Chart for the function of determining the orientation of a canister in an emplacement is presented in Figure 24. In this hypothetical sequence of events, the operator performs the tasks of measuring radioactivity, positioning the equipment, operating the equipment, and receiving and storing the test results without the assistance of other operators. As is the case with Operational Sequence Diagrams, single-lined symbols are performed by the operator; double-lined symbols are performed by a machine. Decisions as to how to next proceed can be made by either the operator (single-lined) or the machine (double-lined).

Figure 24. Flow Process Chart for an operator determining orientation of emplaced canister.

PERFORM TIMELINE ANALYSES

Develop timelines describing the time-critical sequences of operator and machine tasks to serve as a basis for evaluating tasks and potential operator workload.

Timeline analysis is a simple, popular technique for examining the parameter of operator task execution time. Timelines are usually developed (a) to verify that tasks can be performed within the allotted time period, and (b) to identify incompatible tasks needing to be reanalyzed. Data derived from previously developed flow diagrams, function allocation studies, and Operational Sequence Diagrams should be useful in developing timelines.

Figure 25 portrays a simplified timeline of the hypothetical sequence of events involving an operator in the CWSRS. Timelines should be developed in operations such as this where multiple activities must be performed simultaneously or when tasks must be executed within strict time constraints.

PERFORM COMPUTERIZED EVENT-TREE ANALYSES

Develop a descriptive computer model of the retrieval system or selected aspects of the system for the purpose of simulating the occurrence of system events and developing estimates as to the reliability and processing of various designs.

A number of computerized techniques for simulating the flow of information or material through a system have been developed over the past few years (Johannsen & Rouse, 1979). The human engineering team may be required, or may recognize the need, to develop a simulation model of retrieval events and subsequent operator tasks. Among the computerized techniques used by human factors analysts are THERP, TEPPS, SAINT, Q-GERT, and the Siegel-Wolf model. Each of these techniques is discussed below.

- THERP, the Technique for Human Error Rate Prediction, is a computerized technique for estimating human error rates in man-machine systems. The use of THERP involves defining and listing tasks, and estimating task error rates and the consequences of errors on system operation. The technique is most useful during the critical task analysis stage. THERP outputs may be used (a) to determine if the system performs within acceptable reliability

CWSRS CONTROL OPERATOR

Figure 25. Simplified timeline of hypothetical CWSRS operator activity.

limits, and (b) to analyze alternative configurations and their effects on operator error probabilities. The major drawback of THERP is acquiring accurate human reliability data for use in the model. (Swain, 1964; Swain and Guttman, 1980).

- TEPPS, the Technique for Establishing Personnel Performance Standards (Smith, et al., 1969), is also designed to assess the impact of operator errors. It is intended to be used to allocate system requirements among system operators. Unlike THERP, TEPPS uses performance and time data based on judges' estimates (human factors analysts), possibly a more realistic approach to acquiring meaningful human performance data, considering the questionable general applicability of the THERP data. The basic limitation of TEPPS is in its "inability to handle both continuous and decision making tasks" (Geer, 1976).
- SAINT, the Systems Analysis of Integrated Networks of Tasks (Pritsker et al., 1975), and Q-GERT, the Graphical Evaluation and Review Technique (Pritsker, 1966), are simulation packages for the study of large systems. Both SAINT and Q-GERT have been used to evaluate human operator procedures, in conjunction with other, mechanical system components. Both techniques, if used properly, can be valuable analytical and design tools. Perhaps the greatest drawback to their use is the considerable time required to construct SAINT and Q-GERT descriptive models.
- The Siegel-Wolf model (Siegel and Wolf, 1961; 1969), a computer technique for simulating a defined sequence of operator actions, has proven useful in the analysis of loosely defined crew systems. The model emphasizes time-dependent characteristics of tasks, and requires that specific input data (mean execution time, the standard deviation, and the probability of success) be provided.

Blank

EQUIPMENT DEVELOPMENT

The human factors engineering team, having completed function analysis studies, function allocation analyses, and task descriptions and analyses, should now direct its attention toward the actual design of retrieval system hardware. It should be understood that the equipment development phase of the human engineering development effort does not always follow an easily-defined sequence of activities. The necessary human engineering input into equipment development can be so unpredictable that the human factors team should be experienced enough to employ any acceptable methodologies in meeting design requirements. This variability in employed methodologies should not, however, modify the task of the human engineering team, which is to ensure that retrieval system equipment is designed in accordance with accepted human factors design practices.

This section of this document discusses candidate human engineering activities and methodologies to be performed within each of five general equipment design topics: large workspace layout, operator work station design, control/display design and arrangement, environmental systems design, and maintenance systems evaluation. The methodologies discussed within each section are not listed in any particular order, nor do they represent an exhaustive list of the methodologies which might be used in performing human factors analyses.

The principal purpose of performing any human engineering test is to collect data for design decision making. In many cases, the human factors team may only need to consult available human factors design guides, like Volume II of this series, to obtain answers to design questions. In other cases, the human factors team will be required to consult design guides for available data, and conduct in-house experiments to collect data which are not readily available. In any event, most, if not all, of the methodologies discussed in this section should be utilized during the development of retrieval system equipment.

LARGE WORKSPACE LAYOUT

Within the retrieval system, there are a number of settings in which (a) one operator will be manning a number of separate pieces of equipment in a single, large workspace, and (b) multiple operators will work together to operate related equipment in a single workspace. Operators within the CWSRS must work in concert in preparing transport baskets and receiving material from Canister Extraction Transporters. The arrangement of men and equipment in a workspace such as this will determine manning requirements, task demands, and safety and efficiency of CWSRS activities. The design of the retrieval system data processing facility, although presently loosely defined, will also require the input of the human factors team in arranging men and equipment. Other facilities associated with retrieval operations, including communication centers and planning rooms, should also be organized only after human factors analyses have been performed. The primary purpose of the human factors activities performed during large workspace layout is to identify the important relationships between operators, and between operators and equipment, and to organize these elements in the most efficient configuration possible.

PERFORM CORRELATION ANALYSES

Develop Correlation Analysis Charts to identify all links, communication or control, between operators and/or equipment. Where there are links between these components, determine the number of low priority links, medium priority links, and high priority links.

The Correlation Analysis Chart, developed after the Operational Sequence Diagram and before Link Analysis, is intended to identify communication and control links between operators, and between operators and equipment. It is generally simple to use and requires a minimal amount of time to complete. The data developed for the correlation matrix is particularly useful in performing Link Analysis, the task analysis methodology in which links between operators and equipment are studied and system components are rearranged to minimize the length and complexity of links. In addition to being the principal input to Link Analysis, the Correlation Analysis Chart is valuable in (a) designing crew stations,

(b) developing communication systems, (c) identifying personnel requirements, and (d) developing training programs.

An example Correlation Analysis Chart describing all communication links between crew members in a hypothetical canister handling system is presented in Figure 26. Note that the crew positions are listed down the lefthand column of the page. By means of a diagonally-arranged matrix, each crew position is connected to each other crew position. The depicted crew positions might represent the complement of personnel involved in the transfer of canisters at the CWSRS and the transportation and handling of canisters in the CWSRS, the Shaft Transfer Room, and the Canister Storage and Feed Room. This hypothetical arrangement involves nine individuals: two Canister Storage and Feed Room operators, two Shaft Transfer Room operators, three CWSRS operators, a CET operator, and an operator in a central communications center. During task analysis, the duties of each of these positions should have been clearly defined. The purpose of the present analysis is to identify all of the required communication links between personnel involved in canister transfer, handling, and vertical transport, and to categorize these links on the basis of their implied priority. It can be seen, according to this example, that there must be an efficient communication link between the CET operator and the CWSRS control operator, but no communication link is necessary between the CET operator and the Shaft Transfer Room control operator, for instance. Similarly, selected operators should have the capability of communicating with operators in other areas of the facility, although this communication system need not have a prominent place in control/display design.

PERFORM LINK ANALYSES

Perform Link Analyses of large workspaces in which single or multiple operators must interact with multiple pieces of equipment. Identify the workspace arrangement which minimizes operator travel to other operators and equipment.

Link Analysis is one of the most widely used tools of the human factors engineer. The purpose of the methodology is to identify all links between operators and equipment, and to arrange the elements of the workspace so as to minimize the travel and/or communication links between workplace elements. The simplest and

Figure 26. Example Correlation Analysis Chart for determining communication links between crew members during canister handling activity.

most traditional Link Analysis method is the simple graphic technique, in which all elements of the workspace are depicted on paper. Computerized Link Analysis techniques have also been developed (Cullinane, 1977; Haygood et al., 1964).

In standard Link Analysis formatting, squares are used to represent equipment, and circles are used to represent operators. The first step in the analysis involves placing both the squares and circles on paper in any arrangement, and then drawing lines between the operators and equipment to signify the linkages between system elements (Figure 27). The data generated during Correlation Analysis is particularly useful in performing this task.

One effective method of studying and depicting links involves drawing all links (lines) between system elements for the duration of a specific task. Each time an operator must communicate with another operator, or read information from a display, a line is drawn between the operator and the other unit (man or machine). In a finalized version of this analysis, multiple single links can be represented by narrower lines. The width of the link lines might also be used to represent the importance of the link between two elements. After indicating all links, rearrange the operators and components so that the frequent (or important) links are close together (Figure 28). If two operators are expected to communicate visually and verbally, as in Figure 28, they must be placed in close proximity. Equipment which is occasionally operated by either operator should be accessible to both operators, and equipment which is operated by a single operator should be located in close proximity to that operator.

Link Analysis is also used to evaluate existing workplace arrangements. In their recent analysis of nuclear power plant control rooms, Swain and Guttman (1980) provide an example of a Link Analysis which identified an inefficient--and hazardous--arrangement of equipment and operators. Every time an operator required certain plant information, he had to walk across the facility to read a display. The analysis indicated that he spent a significant portion of his time traveling between his work station and assorted controls and displays throughout the control room. These components should have been arranged so that they were easily and immediately accessible to the operator.

Figure 27. Initial Link Analysis Diagram indicating links between operators and components.

Figure 28. Finalized Link Analysis Diagram depicting two operators and related equipment.

COMPARTMENT LAYOUT

The process of designing individual operator compartments or work stations involves many techniques, most of which are concerned with the physical characteristics and requirements of operators and the consequential arrangements of workspace components. The human factors engineering teams should be expected to play a major role in designing operator work stations, and assuring that operators are provided the necessary space for performing their tasks. The human factors team should also be held responsible for assuring that operator work stations are designed to provide maximum operator comfort within the realistic confines of the task setting.

The design and analysis of operator compartments must involve the construction of models and mockups. Mockups are extremely useful for design conceptualization, design experimentation, training, and public relations (Seminara & Gerrie, 1966). First generation mockups are usually inexpensive and simple to construct. Operator workspaces should then be evaluated to assure that they accommodate the range of sizes of the user population. This should be accomplished through the use of various anthropometric techniques and walk-throughs involving both large and small system users.

MEASURE STATIC DIMENSIONS OF USER POPULATION

Measure and record selected, static body dimensions of representative retrieval system operators using standard anthropometric instruments.

If the physical characteristics of the population of retrieval system operators are significantly different from those of a population for which anthropometric data are readily available, studies of the population of retrieval system operators will have to be performed. With a limited set of instruments, it is possible to gather accurate data on linear dimensions such as stature, sitting height, eye height, etc. The tools listed below are commonly used in making simple, linear measurements.

- **Anthropometer.** Although anthropometers come in many shapes and sizes, each consists of a graduated rod with one fixed and one sliding perpendicular branch. This instrument is typically used in measuring large, linear, body dimensions.

- Sliding compass. Somewhat similar to the anthropometer, the sliding compass is most appropriate for making smaller body measurements, such as the breadth of the hand or foot.
- Spreading calipers. Also found in many shapes and sizes, spreading calipers are useful in measuring diameters of the head and other irregular body parts.

CONSULT ANTHROPOMETRIC DATA

Consult available tables of anthropometric data for information on physical dimensions of user population.

There will undoubtedly be circumstances in which the human factors team must consult existing tables of anthropometric data to develop appropriate workplace designs. Prior to consulting these tables, the human factors group must identify the characteristics of the population of retrieval system operators; e.g., young, healthy, American males and females. Table 2, from Roebuck et al. (1975), provides a summary of human engineering and design guides containing anthropometric data.

EVALUATE DESIGNS WITH MANIKINS

Evaluate design engineering drawings using scaled anthropomorphic templates of the population of operators. Verify that clearances, control surface heights and dimensions, movement space, and seating arrangements accommodate the range of retrieval system operators.

Once manikins of the range of system users have been acquired or developed, the process of evaluating engineering drawings is a relatively simple matter. To create the templates, the human factors team must first develop a description of the population of system users. The range of dimensions of critical body lengths must be identified, and top views, side views, and frontal views of 5th percentile and 95th percentile operators should be developed. One-half scale or quarter-scale, clear, plastic, articulated manikins are then developed, each representing a different view of different sized operators. Inexpensive, articulated manikins of 5th and 95th percentile young American males are readily available, and will probably be appropriate for use in analysis of retrieval vehicles

TABLE 2
SELECTED HUMAN ENGINEERING HANDBOOKS AND DESIGN GUIDES
CONTAINING ANTHROPOMETRIC DATA (Roebuck et al., 1975)

TITLE AND CONTENTS	AUTHOR, DATE, AND PUBLISHER
<p>Human Engineering Guide for Equipment Designers. General guide to human engineering, contains limited tables of anthropometric data, body motion limits, strength. Very well illustrated.</p>	<p>Woodson, W. E. (1954) University of California Press Also: Woodson, W. E. and Conover, D. W. (1964) 2nd ed., University of California Press Berkeley, California</p>
<p>Annotated Bibliography of Applied Physical Anthropology in Human Engineering. Abstracts, tabulated data, figures, and charts from 121 references. 149 references.</p>	<p>Hansen, R., Cornog, D. Y. and Hertzberg, H. T. E. (1958); WADC Technical Report 56-30 (ASTIA Document AD 155622) Aero Medical Lab Wright Air Development Center Air Res. and Dev. Command USAF, Wright-Patterson Air Force Base, Ohio</p>
<p>The Measure of Man. A collection of charts and organized, stylized design dimensions for workspace layout by industrial designers.</p>	<p>Dreyfuss, H. (1960), 2nd ed. (1967) Whitney Library of Design 18 East 50th Street New York, New York</p>
<p>NASA Life Sciences Data Book. Size and motion--condensed percentile graphs, males and females, skeletal weights, work space dimensions, pressure suits dimension, sitting area, surface area, radiation area, CM, moments of inertia, limits of motion, hand-grip strength, arm strength, leg strength, G-effects.</p>	<p>Editor: Webb Associates, Yellow Springs, Ohio First edition (June 1962) Director of Aerospace Medicine Office of Manned Space Flight Headquarters National Aeronautics and Space Administration Washington, D. C. 20025</p>
<p>Human Engineering Guide to Equipment Design. Anthropometric criteria by dimension for a variety of populations. Workspace and maintenance design criteria. A very extensive collection of anthropometric information for military and civilian human engineering design.</p>	<p>Morgan, C. T., Cook, J. S., Chapanis, A., and Lund, M. W. (Eds.), 1st ed. (1963) McGraw-Hill Book Co., New York Van Cott, H. P. and Kinkade, R. G., (Eds.), 2nd ed. (1972) U.S. Government Printing Office Superintendent of Documents, Washington, D. C.</p>

TABLE 2 (CONT.)

TITLE AND CONTENTS	AUTHOR, DATE, AND PUBLISHER
Human Engineering Design Criteria Standard MSFC-STD-267A. Anthropometric data for workspace and maintenance design criteria.	George C. Marshall Space Flight Center National Aeronautics and Space Administration (1964)
The Human Body in Equipment Design. A very large collection of anthropometric data for engineering design, which forms the major part of the text. Also contains variety of other human engineering data and design recommendations.	Damon, A., Stoudt, H. W., and McFarland, R. A. (1966) Harvard University Press, Cambridge, Mass.
Anthropometrics for Designers. A limited collection of data, some with special interest to clothing designers, such as section on growth rates and on body typing. Contains some workspace layout data and design approaches, also some control design recommendations.	Croney, J. (1971) B. T. Batsford, Ltd., London Van Nostrand Reinhold Co., New York
AFSC DH 1-3. Design Handbook, Series 1-0. Personnel Subsystems, Chapter 2, Human Engineering. A comprehensive application-oriented compilation of human engineering data and rules. Continually updated.	U.S. Air Force, Headquarters Air Force Systems Command, 2nd ed. (1972) Wright Patterson Air Force Base, Ohio

and work stations. The human factors team should first determine that the potential population of retrieval system operators does not differ significantly from the range of dimensions of the population of young, American males. The use of a drafting board manikin in evaluating a hypothetical CWSRS operator control station is illustrated in Figures 29 and 30.

Figure 29. Side view of 5th percentile operator standing at hypothetical CWSRS operator station.

Figure 30. Top view of 95th percentile operator standing at hypothetical CWSRS operator station.

IMPLEMENT COMPUTER-ASSISTED ANTHROPOMETRY ANALYSES

Evaluate dimensions of crew work stations on board retrieval vehicles and in stationary centers using computerized anthropometry techniques.

A few computerized techniques for evaluating crew workspace requirements have been developed (Kilpatrick, 1972). These may be useful in evaluating reach and work envelopes, and comparing these requirements to the surrounding structure. BOEMAN (Hickey et al., 1968) has been developed to mathematically generate operator movement envelopes, but its principal use is for the design of aircraft cockpits. Another computer-assisted technique, Crewstation Geometry Evaluation (Geer, 1976a) has also been developed for evaluating crewstation geometry. CGE, a subprogram within CAFES, is intended to evaluate "...the physical compatibility of a seated crewmember of any size with any crewstation based on a specific crewstation design" (Geer, 1976a). The anthropometric data used to construct the computer-generated envelopes are stored as a file within the CGE program.

DEVELOP REDUCED-SCALE MODELS

Develop reduced-scale models of multi-man-machine work areas complete with skirts for clearances for operators and maintenance personnel.

Reduced-scale models of operator work stations can be extremely useful in evaluating lines of sight, visual angles, and assorted geometric characteristics which cannot be evaluated with standard two-dimensional drawings. Reduced-scale models can be built to a ratio as small as 1:16 and still be effective tools for evaluating workplaces. The reduced-scale model is to serve as a tool for evaluating the integrated workspace and, as such, models should contain representations of most physical objects within the work station. Plastic skirts should be placed around equipment to represent (a) operator clearances, (b) maintenance clearances, (c) cable clearances, and (d) ventilation clearances. These models are extremely useful in evaluating lines of sight, a topic discussed under visual requirements analysis.

Models of multi-man-machine work areas should be studied to determine if operators can move conveniently from one area to another. These models should also be useful in determining if the visual communication requirements between operators (direct lines of sight) can be met with various configurations. The link analysis procedure described earlier, together with the scale model, provides an effective technique for determining the effectiveness and efficiency of various equipment and operator arrangements.

DEVELOP "SOFT" MOCKUPS

Construct "soft" mockups of operator compartments using paper, foam, cardboard, and other inexpensive materials to evaluate basic reach and operator clearance requirements.

One of the first steps in designing and evaluating operator work stations is to construct soft or paper mockups. It is anticipated that mockups will be developed for operator work stations on all retrieval vehicles, as well as operator work stations in the CWSRS and other stationary retrieval system facilities.

Soft mockups are constructed using inexpensive and easily modifiable materials. After developing preliminary layout drawings, cardboard, foam, paper and inexpensive plastics are used to fabricate the workspace. Full-scale drawings of controls and displays should be taped or pasted onto control panel surfaces. When dimensions are found to be inappropriate (large and small operators should be required to "use" the workspace), the fabricated "components" can be moved or reshaped as necessary.

Both large (95th percentile) and small (5th percentile) operators should be tested in the work station to determine if clearances and reach requirements are adequate. Large operators should determine the dimensions of clearances for the knees and head, for example, and small operators should determine distances between the working position and controls.

DEVELOP HARD MOCKUPS

Construct hard mockups of retrieval system operator work stations using sturdy materials such as plywood and sheet metal. Develop mockups of displays and controls which can be arranged and rearranged on display panel surfaces. Evaluate workspace and visibility requirements using representative retrieval system operators.

Hard mockups, made from plywood, pine, resins, and sheet metal, can be used for the performance of more thorough anthropometric studies of operator workspaces. In addition to evaluating overall appearance, hard mockups allow the evaluation of reach, vision, control operability, egress, ingress and crew comfort (Roebuck et al., 1975). Hard mockups should be durable enough to provide the realism necessary for crew station evaluation, but flexible enough to examine alternative arrangements of specific components.

The control panel surfaces of hard mockups are often coated with metallic paint, which allows magnetic-backed control display faces to be stuck to the surface. These displays are realistic representations of all control and display components of the operator station. They can be arranged and rearranged on control surfaces until the appropriate configuration has been identified. Simulations with representatives of the user population should be conducted to evaluate the assorted configurations. Studies, some of which are described in later sections, should be performed to determine the best arrangement of components. Representative operators should be tested in their ability to enter and leave operator compartments, under both normal and emergency operating conditions. The limits of adjustability of chairs, work surfaces, and controls should also be determined with the hard mockup, again with the assistance of small and large members of the user population.

Selected sections of the mockup should be made of transparent materials so as not to interfere with the use of anthropometric devices and photographic measurements. Attention should also be directed toward assuring that adequate (and realistic) air circulation and lighting is provided.

TEST DESIGNS WITH ANTHROPOMORPHIC DUMMIES AND SYSTEM USERS

Evaluate crew compartments using full-size anthropomorphic dummies and/or system users.

The human factors team may choose to utilize full-scale anthropomorphic dummies in their evaluation of crew compartments. Full-weight, articulated dummies might be used in the evaluation of crew compartments on board retrieval vehicles, but this is unlikely. Rather, if full-scale dummies are used at all, they should be lightweight, accurately configured, anthropomorphic dummies designed to evaluate space requirements and clearances. In all probability, candidate retrieval system operators will represent a more convenient--and definitely more cooperative--source of anthropometric data.

ANALYZE DYNAMIC WORKSPACE REQUIREMENTS

Perform analyses of dynamic workspace requirements using long exposure still photographs, motion pictures, gliding cyclograms, or chronophotography.

It will be necessary to analyze the dynamic movement requirements of operators within each retrieval system operator station, particularly those operator stations on board retrieval vehicles. There are four photographic techniques which should prove useful in performing the analyses of operator movements.

- Long exposure still photography. This technique is primarily used to obtain operator movement envelopes or to trace the movement pathway of a point on the body. Both the background and the subject should be black or dark, and point sources of light are placed on the body parts to be studied. Flashing light sources can be used to indicate movement velocities. Scaled grids adjacent to or behind the subject are helpful in interpreting the image.
- Motion pictures. It is not desirable to use motion pictures in movement analysis when each frame must be individually analyzed. Motion pictures can be useful, however, in analyzing the gross movement requirements of tasks.
- Gliding cyclograms. With gliding cyclograms, the film is transported across the field at a constant rate. It is a seldom used technique, but is extremely appropriate for studying repetitive arm movements in limited space which cannot be measured with long exposure still photography.

- **Chronophotography.** When non-repetitive operator activity (like a single limb extension or contraction) is to be studied, chronophotography, also called interrupted light photography, should be employed. The technique involves a constant source of illumination that is interrupted by a slotted rotating disk. Complex records can be gathered on a single frame of film. The rate of rotation of the disk will determine the sampling rate and the number of images recorded on the photographic frame. The technique is particularly useful in measuring work envelopes.

ASSESS VISUAL REQUIREMENTS

Perform analyses of visual requirements and capabilities using scale models and full-size mockups of operator work stations.

Once full-scale mockups and scale models of retrieval system work stations have been constructed, human factors engineers can perform simple but important studies to determine if operator visual requirements will be met with the proposed design. After having determined the visual information requirements of operators at each station, the models and/or mockups can be used to determine if the proposed designs meet the criterion.

A simple shadow casting method involving full-scale mockups can be used to determine exactly what an operator can be expected to see from his work station. A light source placed at the eye position of a 5th percentile operator (worst case) will cast light on all areas which can be readily viewed from the working position, and obstructions will cast shadows on all areas which cannot be seen from that vantage point. If the previously established visual requirements are not met by the design, it may be necessary to (a) modify the shape of the console, (b) move obstacles, (c) provide mobility for the operator, or (d) provide an additional means of viewing required objects and areas with cameras or optical aids.

A similar technique involves the use of scale models. A point source of light (LED) can be placed inside the model at the operator's eye position. The area surrounding the work station can then be mapped, using a small mirror if necessary, to determine the areas in which there are and are not direct lines of sight to the operator. By placing the mirror inside the model and orienting it toward the operator's eye position and the LED, it can be determined, by noting if the light is reflected in the mirror, if that particular area can be seen from that eye position.

After mapping the area of visibility on the model, the information can be translated to a two-dimensional drawing showing which areas can and cannot be seen by the operator. It is customary for a number of alternative models of particularly important operator stations to be constructed, as will probably be the case with the CET operator station(s). The visibility capabilities of each configuration can then be mapped and contrasted. The viewing provided by mirrors, optical devices, and video cameras can also be added to the "visual map," an approach which has been illustrated in Figure 31.

CONTROL/DISPLAY DESIGN AND ARRANGEMENT

One of the central areas of human factors activity will be in the design, selection, and arrangement of controls and displays in retrieval system operator stations. The task analyses performed earlier in the human engineering effort, as well as the data provided in Volume II, will be the principal sources of information during this effort. A few, selected methodologies should also be applied when the human factors team determine the proper placement and arrangement of controls and displays in work stations. The standard methods generally involve some variation of Link Analysis.

The process of designing controls and displays according to human engineering design and guidelines is not a design methodology, per se, but the activity should be recognized as a distinct element of the design cycle. During this activity, human engineering team members must employ their skills and past experience in selecting the safest and most reliable control systems available. They should first refer to the task-specific information generated during task analysis and, if it has not been done prior to this time, they must identify the exact control components for each retrieval system work station. The human engineering design data and recommendations provided in or by Volume II, MIL-STD-1472, VanCott and Kinkade (1972), Woodson and Conover (1964), and numerous other design guides should be consulted.

Figure 31. A hypothetical visual map of the areas capable of being viewed from one operator station aboard the CET.

ORGANIZE CONTROLS AND DISPLAYS

Organize controls and displays within each operator work station according to accepted human engineering practice. Utilize the techniques of standard Link Analysis, Diagrammatic Link Analysis, and Linear Programming, if required.

As discussed in Volume II of this series, and other human engineering guides listed in the reference section, concisely stated principles for the organization of controls and displays have been provided. These principles should be followed when arranging controls and displays in retrieval system work stations. It is also important for groups of related controls to be identified with one or more of the identification techniques discussed in equipment design guides.

There are a number of techniques which may prove helpful in developing the best control/display arrangement. These include Link Analysis applied to control/display arrangement, Diagrammatic Link Analysis, and Linear Programming. These methodologies are discussed in this section.

Develop Control/Display Configurations

Consult human engineering design guidelines, task analysis, and the results of control/display grouping analyses to develop the most efficient and reliable control/display configuration in retrieval system work stations.

When arranging controls and displays with any of the following methods, it is important not to override the fundamental principles of control and display visibility, control clearance, control/display adjacency, and control/display direction-of-movement relationships. All of these considerations are discussed in the section on panel layout in Volume II. Only after (a) the completion of task analysis, (b) the specification of all control/display components, and (c) the incorporation of control/display components (or facsimiles) into work station mockups, can meaningful decisions on appropriate methods for grouping be made.

Control panel and work station arrangements are most often based on the functional relationships between controls. If this method of arrangement is deemed most appropriate, controls and displays used in executing the same tasks should be grouped in logical fashions.

It is sometimes judged appropriate to arrange controls and displays according to the sequence in which they are operated or read. This is particularly true for tasks which must be performed numerous times during a work shift. It may also be judged appropriate to arrange a family of related controls and displays according to the sequence of operation after these components have been grouped according to their functional relationships. Therefore, in some cases it is appropriate to combine methods--functional grouping and sequential grouping--when arranging controls and displays.

The frequency of use is another criterion for arranging controls and displays. As discussed in Volume II, displays and controls used most frequently should be placed in the most prominent position in the work station. The same is true for warning displays which, although used infrequently, are of exceedingly high importance. Controls and displays not directly related to the principal task of the operator (lighting, environmental control, and low priority communications, for example) should be situated in the peripheral regions of control/display surfaces.

Once controls and displays have been grouped, the human factors engineering team should specify the techniques for accentuating control/display groups. These techniques are also discussed in the section on panel layout in Volume II, and cover the use of (a) color and shading, (b) outlines, (c) panel relief, (d) panel inserts, and (e) alternating slopes.

Perform Control/Display Link Analyses

Perform Link Analyses of control panel components in retrieval system work stations. Identify the control panel layout which minimizes communication and control links, and maximizes operator effectiveness.

As discussed earlier under the section on large workspace layout, Link Analysis is one of the most widely used human engineering design techniques. In addition to being an effective method for arranging the components of a large, multi-man-machine workspace, Link Analysis is often used to analyze and arrange the components of a single control/display panel.

The basic technique does not differ significantly from that discussed earlier. First, all control and display components to be included within the workspace are drawn on paper. Secondly, all functional communication links and/or functional control links are indicated (McCormick, 1970). Functional communication links include (a) visual links from man to man or equipment, (b) auditory and/or voice links from man to man, man to equipment, or equipment to man, (c) auditory, nonvoice links from equipment to man, and (d) tactile links from man to man or man to equipment. Functional control links include (a) control links from man to equipment, (b) eye movement links, (c) manual and/or foot movements, and (d) body movements. The human engineering analyst must determine which link types are to be analyzed, and upon what criterion—link frequency or link importance—the analysis will be based. After indicating all links, rearrange the control/display components to meet the criterion. The final control/display arrangement should minimize operator eye movements, operator search time, and operator dwell time. Link Analysis typically results in an arrangement in which controls and displays are grouped both functionally and sequentially. Those groups of controls and displays found to be the most important and/or used most frequently should then be located in the most prominent areas of the control panel.

To collect the data required for Link Analyses, the human factors team may find it necessary to utilize eye movement recording techniques or sophisticated performance recording devices in conjunction with equipment mockups or simulators. In particular, eye movement records can be especially useful in determining which controls and displays are used most frequently. The components can then be rearranged with the frequently-used controls and displays in the most prominent positions. These methods may be required in the design of operator stations on board the CET and COM due to the expected complexity of CET and COM operator tasks.

Develop Spatial Operational Sequence Diagrams

Develop Spatial Operational Sequence Diagrams for analyzing control and display arrangements.

Similar to the Operational Sequence Diagram discussed earlier, the Spatial Operational Sequence Diagram is a diagrammatic representation of visual, auditory, and control links between an operator and a console. The flow of data or events is indicated with a set of symbols, as is the case with the OSD. In Spatial OSD's, however, the symbols and links are superimposed atop an illustration of the operator and work station. The technique is especially useful in verifying work area layouts (Geer, 1976a). The Operational Sequence Diagram illustrated in Figure 21 is shown in the form of a Spatial Operational Sequence Diagram in Figure 32.

Develop Linear Programs for Optimizing Arrangements

Develop linear programs for the optimization of a selected criterion in the arrangement of controls and displays.

Linear programming can be applied to the arrangement of components in the workspace. The use of linear programming is only appropriate in very complex systems, and may not be a cost-effective technique during design of retrieval system equipment. It is possible, however, that some very complex control stations may be built within the depository, namely, operator workspaces in central communication and control facilities, which may require the use of quantitative control/display arrangement techniques.

Linear programming has been called a "...statistical method that results in the optimizing of some criterion or dependent variable by manipulation of various independent variables. The optimum in some cases would be the minimum and in other cases the maximum—whichever is the desired value in terms of the criterion" (McCormick, 1970).

Linear programs typically involve the use of frequency and accuracy data. Task procedures developed during task description and analysis, as well as data from experiments with human subjects, provide the necessary information for the

- ① Move rotary dial
- ② Receive voice communication
- ③ Move rotary dial
- ④ Receive voice communication
- ⑤ Index CET
- ⑥ View display
- ⑦ Auto alignment with CET
- ⑧ Activate display
- ⑨ Display of emplacement
- ⑩ Verify alignment

Figure 32. Sample Spatial Operational Sequence Diagram for selected tasks in the CET.

program. As one example, Freund and Sadosky (1967) developed a utility value based on the product of response frequency for each control, and the accuracy of reaching to various areas of the control panel. The program was used to identify the arrangement of the controls on the panel area which optimized the total cost, this being the sum of the utility costs in various control panel areas. Linear programming often results in a number of "equally optimum" arrangements of controls, an optimum arrangement defined as the configuration(s) providing the greatest total utility.

ENVIRONMENTAL SYSTEMS DESIGN AND MEASUREMENT

The underground environment of the waste depository poses many constraints on the design of retrieval systems. Most importantly, design team members must be cognizant of the fact that optimum operator performance can only occur within a limited range of environmental conditions, and that deviations from these limits will surely degrade system performance. The human factors team should be assigned the tasks of specifying the range of environmental conditions permissible in each retrieval system workspace, and verifying that these limits have not been exceeded in the operational system.

SELECT APPROPRIATE ENVIRONMENTAL STANDARDS

Consult the task description and task analysis information developed earlier, and identify the general categories of human activities to be performed by operators in each retrieval system work station. In consideration of the activity requirements, specify the environmental conditions under which retrieval system operators should be expected to work.

The human factors team must, at the very least, concern itself with seven environmental variables:

1. Ambient temperature
2. Humidity
3. Air quality (e.g., gas content)
4. Air flow
5. Noise
6. Vibration
7. Illumination

Recommended levels and limitations for each of these variables have been provided in Volume II and in other human engineering guides. It will be important for the human factors team to set limits for each variable based on (a) the Occupational Safety and Health Act and other occupational workplace laws, (b) the known effects of environmental variables on human performance (at levels below those allowed by law), and (c) the characteristics of the tasks to be performed in the environment, including their duration and physical, mental, and perceptual requirements.

MAINTENANCE SYSTEMS EVALUATION

Throughout the development of retrieval system equipment, the human engineering team should be actively involved in designing maintenance tasks and the equipment and operator tools associated with these tasks. Therefore, it is not totally appropriate to state that the human factors team, in a discrete step in retrieval system development, shall provide input for the design of maintenance tasks and equipment. Rather, as retrieval system vehicles and stationary work stations are developed, the human factors team should oversee the design activities to assure that basic principles in maintainability design are being followed.

VERIFY MAINTENANCE SYSTEMS DESIGN

Provide recommendations for the design of maintenance tasks and associated tools, and verify that maintenance procedures conform to the maintainability checklist provided in Volume II.

As discussed in Volume II, members of the human engineering group must verify that all parts requiring maintenance are accessible, and that the level of accessibility is a reflection of the frequency with which the part must be serviced. Components should be designed to be replaced with the greatest ease possible, and large, removable components should be provided with handles and/or wheels to simplify service. Human engineers should also verify that ample workspace has been provided for execution of each maintenance task, and that work positions are not unreasonably awkward or dangerous. Volume II should be consulted for information on these and other recommended maintainability design practices.

The most direct way of guaranteeing that maintenance tasks and equipment have been designed according to acceptable maintainability practices is through the development and use of a checklist. One such checklist covering seven basic areas of maintenance system design--safety, handling and removal for replacement, fasteners and tools, alignment and keying, manual control layout, workspace configuration, and accessibility--is provided in Volume II. It is recommended that the human engineering team, as well as other design team members, utilize this list during retrieval system development.

blank

PERSONNEL SUBSYSTEM DEVELOPMENT

From the moment functions are allocated between men and machines, operator jobs and the associated manning requirements of the retrieval system will be continually defined and redefined. The way in which functions are allocated between men and machines, and the final assignment of tasks to job categories, will greatly influence system manning requirements, training requirements, selection requirements, and the design of operation manuals. It must therefore be recognized that the tasks involved in developing what is known as the personnel subsystem occur throughout the system development cycle.

Although listed in the general order in which they are performed, the following five human engineering activities will, in all probability, be conducted concurrently with the equipment development cycle and while prototype retrieval system equipment is being built. Job design, the principal activity in personnel subsystem development, involves the grouping of tasks on the basis of the location of their performance, the timing of their execution, and the skills and knowledge required for their completion. These task groupings are then used to define individual operator jobs. Having complete job descriptions, the human engineering team can assist in specifying the manning requirements for the retrieval system. Shift work cycles, work/rest schedules, and methods for performance appraisal should be developed. The human factors team should play an active role in specifying the personnel selection requirements for the retrieval system. The skill and knowledge requirements for performing each job will help determine the methods used for selecting retrieval system operators. The development of training programs should also be the concern of the human engineering group. Training requirements need to be specified, and the most cost-effective methods for training operators must be developed. Lastly, the human factors group should oversee the development of manuals and instructional aids for operational and maintenance personnel. Material must be written at the appropriate reading level, and the format of materials should facilitate rapid and accurate retrieval of information.

JOB DESIGN

As with the other activities of personnel subsystem development, the process of designing and defining jobs will span much of the development cycle. Job design is an iterative process, and must be performed within the framework provided by the total personnel subsystem. Jobs requiring high levels of skill will require special procedures for identifying qualified job applicants during personnel selection, and jobs requiring high degrees of knowledge will place extra demands on training programs. Most importantly, the job structure within the retrieval system will determine manning requirements and will have long range impact on the cost of operating the system. The way in which individual jobs are designed will also have tremendous impact on individual operator performance. Jobs involving little operator activity will result in boredom and performance deficits, and jobs requiring too much of the operator will result in inaccurate operator output.

ORGANIZE TASKS ON BASIS OF LOCATION

Organize all tasks on the basis of the locations in which they are performed. Develop a separate organization of tasks reflecting the knowledge and skill requirements necessary for task performance.

Prior to organizing tasks into job categories, it will be necessary to organize tasks on the basis of where they are performed. Having completed task analyses and most phases of equipment design, the organization of tasks will be self evident. This is an important step in job design, however, because it provides a logical basis for determining which tasks can be encompassed under a single job title.

The second phase of job design involves organizing tasks on the basis of their skill and knowledge requirements. Tasks involving exceptionally high levels of skill and knowledge should generally not be coupled with lengthy, simple tasks requiring low levels of skill.

ASSIGN TASKS TO JOBS

Group tasks related in function, time, and location into logical job categories. Consult previously developed timelines, Operational Sequence Diagrams, and other task descriptions which may be helpful in deciding on and organizing tasks.

It must be recognized that the way in which tasks are assigned to individual operators will impact individual operator performance, training costs, selection costs, and overall system manning costs. DeGreen (1970) has provided the following guidelines for organizing tasks into jobs:

- Tasks assigned to one job should require similar and related knowledge and information.
- Tasks assigned to a given job should be done in the same location.
- Tasks closely related in function or in time should be assigned to the same job.
- Tasks assigned to the same job should relate to the same equipment or subsystem.

In contrast to jobs involving operation of the system components, maintenance jobs tend to develop more slowly and are somewhat less predictable. It is often more difficult to acquire the necessary data and information to fully describe a maintenance job before the system is operational. Knowing, at the very least, the preventive maintenance requirements of retrieval system components, basic job descriptions for maintenance jobs should be developed before the system becomes operational.

The data and job descriptions developed during this phase will also be extremely helpful later on in training and selection programs. Concise job descriptions are very useful in assisting applicants in their decisions to apply--or not apply--for various jobs. Combined with the information developed during task description and analysis, job descriptions provide the foundation for developing training programs.

The final result of the job design process should be a series of detailed job descriptions. Job descriptions must include (a) the job title, (b) information on the location of the work, the environment in which the work will be performed, and the relationship of this job to other positions, and (c) descriptions of all tasks to be performed as part of the job. An example job description form is presented in Figure 33.

JOB DESCRIPTION	
JOB TITLE	CET/COM OPERATOR
LOCATION OF WORK	
Seated at one of two control stations within the Canister Extraction Transporter or the Canister Overcore Machine.	
WORK ENVIRONMENT	
CET/COM operator compartment maintained at 65°F - 72°F. Minimum air flow of 30 cubic feet (0.85 m ³) per minute for each operator. Gas content at normal levels. Controllable cabin lighting levels.	
RELATIONSHIP TO OTHER POSITIONS	
Works together with other operator in CET/COM to transport and position CET/COM over canister emplacement. Operator may be required to operate systems at each of two stations within CET/COM.	
TASK DESCRIPTIONS	
<ol style="list-style-type: none"> 1. Transports CET/COM through depository drifts utilizing standard vehicular controls. 2. <i>Accesses canister extraction schedule and related data from computer using keyboard.</i> 3. Indexes CET/COM over floor flange using information from video displays and sensors. 4. Raises CET/COM cask to vertical position. 5. Monitors radiation and other environmental sensors. --etc.-- 	

Figure 33. Example job description form for CET/COM operator.

As a final note, it is important to point out the issues surrounding the topic of job diversification. To increase the flexibility of the workforce, it is often desirable to train operators for a number of different jobs and/or tasks. When a given operator is ill or unavailable, other operators can perform the job temporarily or permanently. This means, however, that more than the absolutely necessary number of people must be trained for a given job, and that each individual must be trained for many jobs. Although this system is flexible and may

result in a higher level of worker satisfaction due to the increased variety of work, the training and selection costs associated with the method will be considerably higher than those associated with less job diversification. The human factors team should be required to assist in determining the appropriate level of job diversification within the retrieval system.

MANNING REQUIREMENTS ANALYSIS

Manning is defined as "...the organization of various jobs into an operation, and the specification of the number of people needed for each of the jobs in the operation" (DeGreen, 1970). The human factors team must conduct manning studies to meet the following objectives (DeGreen, 1970):

- To assure that daily activities are performed at the required level of speed and accuracy.
- To schedule all work/rest cycles conducive to optimum operator performance, safety, and comfort.
- To provide for all emergency actions.
- To assure that there are as few jobs as possible within the system.
- To assure that system operators will require as little training as possible.

DETERMINE STAFFING REQUIREMENTS

Review system performance requirements and subsystem operation requirements. Determine the level of staffing needed to operate the retrieval system at the required level of performance.

The human engineering team, by consulting engineering drawings, operational and maintenance timetables, engineering reliability analyses, operating manuals, equipment lists and descriptions, task summaries, and job descriptions, should begin to determine the exact number of personnel required to operate retrieval subsystems at the required levels of output. As stated earlier, a number of contingency plans may need to be developed and executed depending on the rate at which canisters must be retrieved. If only a moderate number of canisters are

to be retrieved for periodic inspection, then the manning requirements would conceivably be quite low. Under this contingency, it may be advisable to select and train only a few highly qualified applicants, each capable of performing many retrieval system jobs. In any event, the predicted rate of canister retrieval during the first years of operation of the system will determine the staffing requirements. The human engineering team must acquire this information as soon as it becomes finalized.

The required rate of retrieval will determine the number of daily shifts of retrieval system personnel, as well as the number of individuals working during a given shift. If two or even three shifts must be employed, the shift times and frequency of shift changes should be selected on the basis of (a) operator tasks, (b) operators' preferences for shift work, and (c) the effect of shift work on health and social life.

With regard to the type of operator tasks and shift work, it is generally recognized that the major impairment of performance occurs during the night shift (Folkard & Monk, 1979). Furthermore, operators tend to adjust more quickly to shift work when they must perform cognitive as opposed to psychomotor tasks. These and other factors must be considered when developing the manning schedules. The most important effects of shift work, however, can be on the workers' health and social life. Personal preferences for working day and night shifts must be recognized, and schedules conducive to healthful adjustment and optimum performance must be selected. The task of (a) selecting the duration of shifts, (b) the starting and stopping times of shifts, and (c) the frequency of shift changes should be assigned to the human factors team.

DEVELOP WORK/REST CYCLES

Develop appropriate work/rest cycles for families of retrieval system jobs based on required operator output and environmental constraints.

The variety of jobs within the retrieval system will require that each job, particularly those jobs requiring physical output in high temperatures, be analyzed, and that the constraining environmental or task variables be specified. Tasks requiring unusually brief work periods due to environmental constraints, as is the

case with many tasks in high-temperature metal and nonmetal mines, must be identified, and standards for work/rest cycles should be developed. Remote manipulation tasks are also known to be extremely demanding of operators; work performed remotely by retrieval vehicle operators or in hot cells may require special work/rest cycles.

DEVELOP METHODS OF PERFORMANCE APPRAISAL

Develop and document methods for the appraisal of worker performance.

The human factors team should be involved in the development of performance appraisal methods. Reliable means of evaluating actual operator efficiency or performance should be developed prior to retrieval system operation, and instructions and/or training procedures required for implementation of the performance appraisal plan should be provided. Although operator performance appraisal may seem only tangentially related to the development of systems for removing spent fuel from salt, this topic is an important component of the personnel subsystem of the depository. Methods must be developed for assuring that operators are evaluated on the basis of their performance, and not the subjective opinions of a supervisor.

Five basic categories of performance appraisal techniques are available for consideration (DeGreen, 1970). On-the-job measures involve actual observations of the operator while he/she performs the task at the work station. The evaluator must be fully versed in the execution of the task and follow pre-established guidelines for evaluating operator performance. Evaluations may also involve performance tests, where the task is controlled for the purpose of testing. The subject is aware that he is being tested, and the actual equipment is being used. Simulators and mockups can also be used in evaluating performance, as is the case with commercial airline pilots. Less expensive techniques involve the use of paper and pencil tests. A schematic job test requires a subject, using pencil or pen, to indicate the proper sequence of events on schematics of work stations. Lastly, paper-and-pencil job knowledge tests can also be administered to assure that operators are maintaining information necessary for reliable task performance.

SELECTION PROGRAM DEVELOPMENT

Lack of previous experience with an identical or even similar system poses problems for those individuals who must develop the procedures for selecting personnel to operate the system. Developing personnel performance criteria for a novel system will be an exceptionally difficult task, one which must be based on careful study of operation tasks and the required levels of skill and knowledge.

With reference to the selection program, it should be recognized that changes in the selection criteria will impact the nature of the training program. More stringent selection criteria will provide subjects requiring less training. The pool of applicants, however, must be considerably larger than the number of openings if the criteria are to be set high. The retrieval system being unique, it may be advisable to set strict selection requirements during the first phases of operation of the system, and relax these criteria as time passes and the operation of the system becomes more stabilized.

Prior to establishing the procedures and tests for selecting applicants, it will be necessary to identify the needs of each job class. The physical abilities, skill and knowledge requirements, and personality traits necessary for performing each job must be specified. At this point, the tests and procedures which will identify individuals possessing these abilities, skills, and traits can be selected or developed.

SPECIFY ABILITIES AND SKILLS

Identify the physical skills or abilities, perceptual capabilities, job knowledge, job skills, and personality variables required for each class of jobs.

Each class of retrieval system jobs must be studied, and the basic abilities necessary for each must be identified. Initial analyses should specify the physical requirements of each job. If unusually tall or short personnel are required to perform a job, these requirements should be noted, although it is inadvisable to develop tasks and jobs which place these kinds of constraints on personnel selection. Strength requirements, however, are sometimes necessary for certain jobs. If such is the case, it will be necessary to identify the exact strength component to be selected, as well as the methods for measuring this component.

Perceptual capabilities, like normal uncorrected vision of 20/20 and normal hearing response, must also be specified. Job knowledge, knowledge considered to be "background information" (DeGreen, 1970) necessary for job performance, should also be identified. In contrast to the job peculiarities learned during training, job knowledge is that information known by the applicant before training, like knowing how to program a computer. Skill, in contrast to knowledge, is what a person can do, not what the person knows. Demonstrated skill in operating a teleoperator or a mining vehicle might be chosen as a required characteristic of a qualified operator. Retrieval system operators may also be selected on the basis of personality. Individuals fearful of working underground, working in isolation in a mine, or working near radioactive material should be selected against.

SELECT APPROPRIATE TESTS

Select the appropriate tests for identifying qualified retrieval system operator candidates.

It is anticipated that a number of selection procedures must be developed for retrieval operations, one for each class of retrieval system workers. After having identified the basic ability, knowledge, skill, and personality requirements of each job, it is appropriate to select those tests which have proven to be effective in identifying individuals with the required characteristics. The Buros Mental Measurements Yearbook (Buros, 1972) is the most consolidated index of paper and pencil tests.

Four basic types of tests may be considered for evaluating applicants. Job element tests may be used to assess an applicant's basic aptitude in an area, rather than his/her actual experience. Job element tests might be developed to determine how well an applicant can do the job at the present time. For example, applicants having had past experience in mining or nuclear waste handling might perform better than nonexperienced applicants on a job proficiency test. Applicants having experience maintaining heavy equipment might be expected to perform better than nonqualified applicants on a maintenance proficiency test. Biographical inventories can be used for collecting data on related past experience, and, if ample research time is available, these data can be studied to determine which variables

best predict future operator performance. Information tests can be developed to determine the level of knowledge an applicant has in a given area, but care must be taken to ensure that the knowledge requirements are directly related to future operator performance.

As a final note, the use of training programs as selection devices should be mentioned. It may be deemed necessary to relax the selection requirements for retrieval operators and accept a larger number of people into the training program. Performance during and after training can then be used as a basis for identifying those trainees capable of manning various positions. Although this approach may select the most qualified applicants, it would be extremely costly to implement.

TRAINING PROGRAM DEVELOPMENT

Although the treatment herein is relatively brief, the development of the training programs for retrieval system operators should be considered as another central component of personnel subsystem development. During this phase of human factors activity, the human engineering group should specify (a) exactly what is to be learned during training, (b) the techniques for determining the adequacy of learning, and (c) the methods for presenting the training material. Potential system operators, subject matter experts, psychologists specializing in training systems design, and equipment designers should serve as valuable sources of information during training program development. The products of task description and analysis methods, like Operational Sequence Diagrams, will prove to be invaluable sources of data during this activity.

After determining exactly what needs to be taught to trainees, the method of imparting this material is selected. Whether the selected technique involves self instruction, classroom instruction, or computer assisted instruction, the method must match the type of material being presented and the actual work context in which the learned material must be put to use. Tremendous variability from one program to another requires that the training technique be selected on the basis of analytical studies or experiments. As an example, studies of electronics maintenance has shown on-the-job training to be ineffective in teaching troubleshooting (Bond, 1970). Training involving instruction on equipment

components and analytical methods has proven to be a far more effective approach to teaching this skill. In a similar vein, studies of emergency procedure training in nuclear power plant control rooms has shown that the conditions surrounding training must be far more realistic, and that these procedures must be rehearsed periodically after training for them to be retained by the operators (Swain and Guttman, 1980). In summary, the method used to develop knowledge and skill in trainees must be tailored to the individual job and task.

CLUSTER JOB TASKS

Organize the tasks of each position into clusters around which a training program can be structured.

In an effort similar to that of job design, groups of tasks within each job should be identified, and an outline of a training program reflecting this organization should be written. These groups of tasks will represent training segments. As an example of the type of organization required, Table 3 indicates 10 clusters of tasks which might be identified for the training of CET/COM operators.

TABLE 3
CLUSTERS OF JOB TASKS
FOR CET/COM OPERATION

1. Principles of retrieval system operation2. Preliminary equipment checkouts3. Daily activity planning4. CET/COM transportation5. Communication functions6. Alignment activities7. Canister overcore activities8. Canister removal9. CWSRS procedures10. Emergency procedures

IDENTIFY TRAINING PHASES

Identify the principal phases of training instruction, and select an objective encompassing several days or weeks of instruction.

Within each of the clusters listed during the previous task, the phases of training instruction should be identified.

For example, within the category of CET/COM alignment, there are many phases, including those listed in Table 4.

TABLE 4
TRAINING PHASES FOR
CET/COM ALIGNMENT

1. Special nomenclature of alignment 2. Initial alignment procedures 3. Operation of automatic alignment equipment 4. Alignment verification 5. Vertical alignment 6. Vehicle stabilization 7. Connection with floor flange 8. Seal verification

IDENTIFY TRAINING GOALS

Specify the goal of the unit of training instruction listed in training phase identification, as well as the method of instructional presentation, the required activities of the student, and the method of evaluating student performance.

Each training unit listed in the previous step, designed to span one or two days of instruction, must have an instructional goal. If the student were being instructed on communication terminology, for example, the goal might be to master a specified set of numeric codes. Acceptable performance (our goal) would require mastery of this set of codes; i.e., recall all codes with perfect accuracy.

As stated above, the method of instruction must be tailored to the training task at hand. In some training phases it may be necessary to utilize mockups of equipment or even realistic equipment simulators, while in others, simple illustrations and pictures may suffice. Human factors engineers should conduct brief experiments, when necessary, to compare one technique to another. They should direct their efforts toward identifying the simplest, least expensive, and easiest-to-maintain training method which results in the required level of trainee performance.

DEVELOP TRAINING AIDS

Develop training aids, including wall charts, transparencies, mockups, and simulators, if necessary, to assist in the teaching of operational procedures. For each training phase, select the aids which meet the exact instructional requirements.

The most obvious tool for instructing trainees on equipment operation and procedures is the equipment itself. However, for numerous reasons, it is not always practicable or advisable to allow trainees to practice with real equipment. Real equipment may be expensive to operate. Mockups and/or simulators are often cheaper to operate and require less service time. An inexperienced operator may actually damage the equipment during training, or worse yet, injure himself or other individuals. Real equipment also does not provide the feedback necessary for rapid learning. Specially made simulators and trainers can be designed to emphasize selected tasks, and provide supplemental feedback which would not be present if the real equipment were being operated. For a review of how to develop training devices, see Cream et al. (1978).

Each training phase identified earlier will undoubtedly require the development of training aids. These might be operating mockups, nonoperating mockups, cutaway mockups, animated panels, transparencies, wall charts, movies or photographs. In directing the development of these aids, the human factors group must determine that the purpose of the aid is being fulfilled through its use; i.e., the aid is facilitating the learning of information or a skill defined by the training phase. For example, when equipment components must be identified or task procedures are to be memorized, a simple mockup or even picture of the equipment may suffice. Less expensive aids are often better in that they can be produced in quantity, thus allowing each student to have his or her own aid. When more advanced skills are to be trained, it may be necessary to utilize simulators. In summary, training aids must be developed according to the needs of the training phase and the level of skill acquisition being taught. Simple tasks should require simple materials; complex psychomotor tasks require simulators or actual equipment.

JOB PERFORMANCE AID DEVELOPMENT

A job performance aid has been defined as a "...device, book, or other object that facilitates job performance by reducing the requirements imposed on the performer" (Folley, 1960). They have proven to be effective tools in reducing training requirements and costs, and improving operator effectiveness. Properly

designed JPA's can also broaden the range of skill of an operator by providing guidance on infrequently performed activities, or by supplying additional helpful information on tasks which are occasionally performed under adverse circumstances.

The development of JPA's first involves identifying the information which can be contained in a JPA. Secondly, the best method of presenting the information must be identified, and the JPA should be tested on a small sample of users. In their final form, JPA's must be made readable and structured according to the sequence of task performance.

DETERMINE JPA CONTENT

Determine what task-specific information should be contained in the JPA by (a) studying the list of activities involved during task execution and (b) selecting tasks and activities which can be provided ample treatment in the JPA format.

As in previous development steps, the task descriptions written during preliminary development are to serve as the main input of information for this activity. After assembling a listing of tasks and subtasks required of each activity within a job, human factors analysts should examine each major task as a whole, and determine what information can be effectively contained in a job performance aid, as opposed to being learned by the job incumbent during training. Infrequently performed tasks, as well as tasks which may require special information when unique circumstances arise, should be included.

DETERMINE METHOD OF INFORMATION UTILIZATION

Study the tasks and activity-related information to be included in the JPA, and determine the way in which the information will be utilized by the job incumbent.

It is important for the task-specific information contained in the JPA to be organized in a fashion which facilitates quick and easy access. The information will be of little or no use if the operator is unable to locate it when necessary. An important step is determining exactly what information the incumbent is likely to have when he consults the JPA. The available information should determine the manner in which the information in the JPA is accessed.

FIELD TEST JPAS

Conduct a small-scale tryout of the Job Performance Aid to identify its undesirable features.

In conducting a tryout of the JPA, it is important that someone not familiar with the task or the development of the JPA be used as a subject. This individual, or group of individuals, should be requested to perform the task in question utilizing the JPA. It is not necessary for the trial to be conducted on the actual equipment; mockups or simulators will suffice for this simple evaluation. Interviews with the subject(s) should occur after task completion, and problem areas in the JPA should be identified.

DEVELOP FINAL JPA FORMAT

Develop a final version of the Job Performance Aid, providing reliable and rapid transfer of information to the viewer.

The final organization of a JPA will determine its ultimate usefulness to the system user. Initially, it is mandatory that all JPA's developed for the retrieval system be written at an appropriate reading level. Operating manuals and JPA's are typically written by engineers for engineers. Operators with high school educations have a difficult time comprehending this material, as is the case in nuclear power plant control rooms (Swain and Guttman, 1980). In general, information which must be read quickly and accurately should be written at the fourth to sixth grade level. Similarly, pictorial, as opposed to written, presentation is sometimes more appropriate, particularly when a simple step or idea must be conveyed rapidly. Steps requiring detail and not having time constraints are usually best presented in written form.

Blank

OPERATIONAL TEST AND EVALUATION

Retrieval system development managers must recognize that the development effort does not come to an abrupt stop the moment the system becomes operational. As in all major man-machine system development projects, deficiencies in control system design, the arrangement and scheduling of personnel, and the design of performance aids will surely surface after the system becomes operational. The human factors team should be actively involved in the evaluation of the operational system to verify that the system meets the original performance requirements.

The objectives of the human engineering team during operational test and evaluation are as follows (VanCott and Kinkade, 1972):

- To determine operational difficulties with the system and to identify ways to improve deficient products or processes.
- To determine the operational usefulness of the system and develop effective methods and standards.
- To refine maintenance requirements in terms of personnel, skills, and training, and to establish performance standards for carrying out maintenance tasks.
- To collect data on organizational and personnel skills and on training to refine requirements established earlier in the program.
- To evaluate the adequacy of the manning structure, the organizational hierarchy, and the training program.
- To provide final training for operational crews and to integrate the entire system and operations.

Most importantly, human factors engineering operational test and evaluation is conducted to ensure that the required level of operator and maintenance performance is achieved. The results of these activities should, of course, be documented. This report can serve as verification that the contractual requirements have been met. When deficiencies in system design are uncovered during

test and evaluation, the discrepancies between the required levels of performance and that provided by the operational system must also be documented, along with plans for modifying the system.

Five fundamental areas of human engineering test and evaluation activity are discussed in this section: hardware and workplace design verification, habitability verification, maintainability assessment, training and job aid evaluation, and system performance assessment. Human engineering evaluation methodologies and tasks are listed under each of these activities. Many of the methodologies and tasks may be utilized in the evaluation of different aspects of the system. For example, evaluation checklists, a simple but very effective technique for determining if systems have been designed according to human engineering practices, should be used during hardware and workspace design verification, as well as during maintainability assessment. The same will be true for interviews and surveys, in which system operators are provided the opportunity of stating their likes and dislikes. Similarly, brief experiments may be conducted during the assessment of individual operator performance, as well as during the evaluation of training procedures and job performance aids.

The five areas of human engineering test and evaluation activities listed in this section need not be performed in the sequence in which they are presented. Furthermore, many of the specific evaluations listed in this section may have been performed earlier on prototype equipment. Obviously, evaluations of such subsystems need not occur if they have already been performed. However, it is crucial that the integrated operations of the retrieval system be evaluated to verify that system components are interacting as they should.

HARDWARE AND WORKSPACE DESIGN VERIFICATION

This phase of human factors engineering test and evaluation is to be performed to ensure that all retrieval system equipment has been designed according to the guidelines provided in Volume II and other human engineering guides for equipment design. Although the human factors team will have specified appropriate designs prior to construction of equipment components, in all probability, modifications will have been made by contractors responsible for the

manufacture of the equipment. Four distinct activities should be performed by the human engineering group during the verification of hardware: (a) develop and utilize checklists to evaluate hardware, (b) verify that controls have been designed according to specifications, (c) evaluate the interpretability of displays, and (d) verify important anthropometric dimensions.

DEVELOP AND UTILIZE EQUIPMENT CHECKLISTS

Develop and utilize detailed equipment checklists to verify that equipment has been designed according to accepted human engineering standards.

If detailed equipment checklists were not developed during the equipment development phase, they must be developed at this time. First, each primary item of equipment, a Plug Overcore Machine, for example, should be the subject of a detailed equipment checklist containing items from each of nine equipment component categories listed below:

1. Steps, platforms, railings
2. Doors, hatches, passageways
3. External operating components
4. Controls
5. Displays
6. Workspace
7. Labels and markings
8. Fasteners and connectors
9. Packaging

Figure 34 has been provided as an example of a checklist, adopted from HFTEMAN (Malone et al., 1976), containing items for verifying the design of doors, hatches, and passageways in a Plug Overcore Machine. It should also be noted that each of the equipment component categories should be evaluated according to the seven human factors considerations listed below:

1. Location/arrangement
2. Size/shape
3. Direction/force
4. Information
5. Visibility
6. Use conditions
7. Safety

These human factors considerations are reflected in the checklist presented in Figure 34.

EQUIPMENT			
PLUG REMOVAL MACHINE			
EQUIPMENT COMPONENTS			
DOORS, HATCHES, AND PASSAGEWAYS			
CHECKLIST ITEM	ACC EPT ABLE	NOT ACC EPT ABLE	NA OP PLI CABLE
<ol style="list-style-type: none"> 1. Are wall hatches flush with the floor where structurally possible? 2. Can hatch handles be reached from normal approach positions? 3. Are handholds integrated with doors and entryways for stability? 4. Is fixed equipment a minimum of three inches from swept area of doors? 5. Are handles operable with gloved hand? 6. Is hatch handle unlocking force 20 pound maximum? 7. Is overhead hatch opening force 50 pound maximum (5th% arm, hand strength)? 8. Do handles release up, aft; catch and lock down, forward? 9. Is hatch handle release 90° maximum? 10. Is hatch handle force five pound minimum? 11. Is door opening force 10 pound maximum? 12. Is color of handle different from color of door? 13. Is the correct movement of the hatch handle diagrammed? 14. Are exits clearly identified under reduced lighting? 15. Is "see thru" provided on doors and hatches, where possible? 16. Do hatches open with a single motion of the hand or foot? 17. Where "step downs" exceed 27", are steps or foot rests provided? 18. Are handles uniform in their operation? 			

Continued on next page

EQUIPMENT			
PLUG REMOVAL MACHINE			
EQUIPMENT COMPONENTS			
DOORS, HATCHES, AND PASSAGEWAYS			
CHECKLIST ITEM	ACC E P T A B L E	NA OC T E P T A B L E	NA OP T I C A B L E
19. Are doors and emergency exits easily reached?			
20. Can escape openings be opened in a maximum of three seconds?			
21. Are escape openings free of obstructions and do they permit passage with special equipment?			
22. Is glass in doors shatter proof?			

Figure 34. Sample equipment checklist for verifying the design of doors, hatches, and passageways on a Plug Removal Machine.

VERIFY CORRECT HUMAN ENGINEERING OF CONTROLS

Verify that controls in each work station have been designed according to human engineering guidelines.

Upon receipt of all retrieval system equipment, the design of control systems must be evaluated. This should be accomplished by referencing human engineering guides for equipment design and the design specifications developed during equipment development. Human factors people must verify that (a) the right control for each operation has been selected, (b) control-display relationships are in accordance with population stereotypes, (c) the correct type and amount of control resistances have been provided, (d) proper control coding has been provided, (e) all controls have been labeled in the proper fashion, (f) controls have been situated and designed to prevent accidental activation, and (g) controls have been grouped and arranged according to logical bases.

VERIFY THE INTERPRETABILITY OF DISPLAYS

Verify that, under actual conditions, all visual, auditory, and tactile displays provide information which can be perceived and interpreted at the required level of detail.

Under actual operating conditions, the interpretability of displays can be dramatically degraded due to the effects of noise, vibration, light levels, and electronic interference. While the system is in actual use, displays must be evaluated to determine if visual, auditory, or tactile information is displayed as originally intended. Ear phones and speakers, for example, must be evaluated while other equipment is being operated nearby to determine if signals can be reliably interpreted above background noise. As another example, visual displays may be affected by unanticipated sources of glare. When operators cannot accurately and reliably interpret displayed information, the sources of interference must be eliminated or attenuated, or the display system must be modified.

VERIFY IMPORTANT WORKPLACE DIMENSIONS

Verify anthropometric dimensions of workspaces which are important to operator comfort, crew mobility, and task execution.

Upon the receipt of manufactured retrieval system equipment, human factors team members should verify that workspaces have been designed strictly according to the specifications developed during equipment design. If proper anthropometric studies were performed with mockups, it should be unnecessary to do much more than verify the dimensions of workspaces in real equipment. If, however, it is determined that equipment does not accommodate the population of system users, it will be necessary to employ the techniques discussed under the section on compartment layout in re-specifying the characteristics of retrieval system operator stations.

HABITABILITY VERIFICATION

Although all relevant environmental limits should have been established during equipment development, it will be necessary to determine if the requirements have been met in the operational system.

VERIFY ENVIRONMENTAL STANDARDS

Verify that work compartments, once in their actual operating environments, meet the environmental standards established during equipment design.

As with some of the previously discussed phases of operational test and evaluation, the central purpose of this activity should be to verify that environmental criteria have been met. Actual tests of the system, and studies concerning the establishment of criteria, should have been conducted earlier with mockups and prototypes. If, however, it is determined that a standard has not been met or a standard was inadequate from the outset, human factors analysts must document those deficiencies and press for their correction. At a minimum, the following variables must be examined at each workstation.

- **Illumination.** Ambient workplace illumination ranging from .005 to 25,000 footcandles can be measured with a photometer to determine if light-level requirements have been met. The adequacy of visual displays can be verified with a spot brightness meter, used to measure the brightness of an area of one degree or less.
- **Noise.** A sound level meter and analyzer, or an octave band analyzer, can be used to verify compliance with noise levels. This instrument, when used in the operating environment, should determine compliance with background noise levels, and identify levels which will interfere with speech and hearing, or present an occupational hazard.
- **Vibration.** The amplitude and frequency of vibration in retrieval system vehicles should be measured with a vibration meter and analyzer, or a specially equipped octave band analyzer.
- **Temperature.** Workplace temperature, once equipment has been placed in the depository, should be measured using dry and wet bulb thermometers.
- **Air flow.** Air flow within all workspaces including vehicle compartments, stationary workspaces, and living quarters, should be verified using an anemometer or similar instrument capable of measuring air flow in the range of 0 to 1000 feet/minute.
- **Relative humidity.** Verification of recommended levels of relative humidity should be made with a hygrometer, psychrometer, or sling psychrometer.

- Air content. An assortment of the many types of gas and air testers available should be used to verify compliance with air content requirements.

MAINTAINABILITY ASSESSMENT

After retrieval system equipment has been in operation long enough for maintenance operations to begin, evaluations of maintenance procedures and equipment must occur. The operator procedures required for maintenance service, the tools used by technicians, and overall maintenance system performance must be assessed.

DEVELOP AND UTILIZE MAINTENANCE CHECKLISTS

Develop human engineering maintenance checklists to assist in the verification of properly designed maintenance equipment and procedures.

A maintainability checklist, similar in content to that presented in Volume II and similar in design to Figure 34, should be developed and used to evaluate maintenance systems throughout the retrieval system. This checklist must cover the topics of accessibility, the utilization and packaging of equipment, the design and coding of equipment connectors, conductors, fasteners, labeling of controls and displays, and maintenance test equipment. Poor designs must be identified and scheduled for redesign.

CONDUCT MAINTENANCE PERFORMANCE EVALUATIONS

Evaluate the performance of maintenance personnel during observational studies of maintenance operations.

Evaluations of maintenance operations should be conducted, not for the purpose of evaluating maintenance personnel, per se, but to identify procedures and related equipment that may be causing avoidable maintenance problems. Observers and/or video cameras should be positioned in maintenance garages to record the frequency and duration of various activities. Maintenance personnel might also be requested to maintain logs of their activities, a simple but effective way of determining which maintenance operations are accounting for the bulk of maintenance effort. Particularly cumbersome or time-consuming maintenance procedures should be identified and modified.

CONDUCT USER INTERVIEWS AND SURVEYS

Conduct interviews and/or surveys with maintenance personnel to assist in identifying ineffective maintenance practices, procedures, or equipment.

An evaluation of the maintainability of retrieval system equipment would be incomplete without interviews with maintenance personnel. Structured interviews, usually conducted with groups of three to four workers, should be exceptionally helpful in identifying procedures which are causing problems, or equipment having unanticipated rates of repair. Additional requirements on the part of personnel, like supplementary job performance aids, should be noted, and difficulties in acquiring parts or replacement units must be brought to the attention of the appropriate retrieval system offices.

TRAINING AND JOB AID EVALUATION

The level of skill required to operate retrieval system equipment should have been determined in previous phases of system development. Furthermore, the methods for measuring the skill levels of trainees should also have been determined. During operational test and evaluation, the human factors group must verify that (a) operators are meeting the skill requirements, (b) the skill requirements are appropriate, and (c) job performance aids are being used and providing helpful information to operators.

PERFORM FOLLOW-UP TRAINING EVALUATION

Conduct interviews and studies, if necessary to determine if retrieval system training programs are providing competent operators.

To evaluate operator training, the best approach may be to conduct extensive interviews with personnel after the retrieval system has been in operation for a number of months. Assuming that only those operators with demonstrated skill in retrieval tasks (as indicated by their performance with simulators or real equipment during training) are working in the depository, the most valuable information may once again come from interviews. Operators should be interviewed, and their opinions on the relevance of training programs and the

adequacy of performance assessment procedures must be sampled. If content analyses of these interviews reveal (a) deficiencies in operator training or (b) unreasonably strict or liberal operator performance requirements, these issues must be investigated more thoroughly with additional performance studies.

PERFORM FOLLOW-UP JPA EVALUATION

Conduct interviews and make detailed observations of personnel as they use job performance aids. Determine the value of the aids which are provided, and identify requirements for additional aids, where needed.

Job performance aids may be evaluated in the same fashion as training. Interviews and, in this case, questionnaires may prove helpful in soliciting comments on the usefulness of manuals and job performance aids. Although JPA's are to have been evaluated during their development, some final modifications may be required after experience with them in the operational system. Operators may also indicate the need for additional job performance aids, in which case the job performance aid procedures discussed earlier should be repeated.

SYSTEM PERFORMANCE ASSESSMENT

During system performance assessment, human factors team members are to determine if man-machine systems within retrieval subsystems meet original performance requirements. This activity should involve studies of the effectiveness of manning schedules, evaluations of operator performance on tasks, and the development of a system for collecting accident and critical incident data.

EVALUATE MANNING ARRANGEMENTS

Determine the effectiveness of established work schedules, work/rest cycles, and staffing by interviewing job incumbents and reviewing retrieval system activity reports and records.

Although the work schedules, work/rest cycles, and levels of staffing were determined on the basis of earlier studies, these aspects of the personnel subsystem must be evaluated after the system has gone into operation. Initially, interviews

with operators should be performed to determine if, in their opinion, there are any major problems with staffing, work/rest cycles, or shift schedules. As with all other interviews during operational test and evaluation, interviewees must be guaranteed anonymity, if they so desire. These interviews should be followed by in-depth studies of retrieval system activity records, in which it should be determined if retrieval activity, on a shift-by-shift basis, is meeting the requirements originally set forth.

EVALUATE SYSTEM AND SUBSYSTEM PERFORMANCE

Evaluate retrieval system activity records to determine if the rate of canister retrieval is meeting original requirements, and study individual man-machine subsystems within the retrieval process are performing at the required levels of speed and accuracy.

Activity records must be analyzed to determine if canister extraction is occurring at the required rate. With reference to retrieval subsystems, records should also be analyzed to determine if activities are being performed as they should. Equipment or task-execution bottlenecks must be identified, and procedures modified where necessary.

Although there are literally dozens of instrumentation procedures available for measuring performance output, it is felt that a few trained observers can reliably assess the performance effectiveness of man-machine systems in retrieval operations. Observers can record task completion times, if necessary, and identify elements of tasks which create problems for operators. These observers must, of course, be completely familiar with the operation of the subsystem they are observing. When operator tasks are not being executed with the ease or accuracy originally required, modifications in equipment or operator training programs must be developed.

ASSIST WITH SAFETY PROGRAM DEVELOPMENT

Assist in the creation and initial management of a safety program designed to process data on incumbent suggestions, critical incidents, and accidents.

While the intentions of most industrial safety programs are honorable, many result in the unintentional coverup of accident data. Due to the pressure to minimize accidents and injuries, employees may fail to report incidents for fear of being reprimanded. A safety program should be instituted with the idea that its purpose will be to receive (a) reports of accidents, (b) reports of critical incidents, and (c) comments from workers on the safety of various procedures. These data, in turn, will be analyzed in an effort to identify modifications in equipment or procedures. Special attention should be paid to the procedures for reporting the critical incident, an often overlooked source of safety data. Furthermore, every effort should be made to encourage suggestions from workers on the redesign of equipment or procedures.

REFERENCES

- Adams, S. K., Buchele, W. F., & Boyd, M. M. Human factors in grain harvesting equipment design. **Proceedings of the 8th Congress of the International Ergonomics Association**, 1976, 50-55.
- Bachrach, A. J., Egstrom, G. H., & Blackmun, S. M. Biomechanical analysis of the U. S. Navy Mark V and Mark XII diving systems. **Human Factors**, 1975, 17, 328-336.
- Bhaskaran, G., & McCleery, J. E. (L. O. Hannah, ED.). **Retrieval system for emplaced spent unprocessed fuel (SURF) in salt bed depository: accident event analysis and mechanical failure probabilities**. International Engineering Company, for Lawrence Livermore Laboratory, supported by Nuclear Regulatory Commission, October 1979.
- Bond, N. A., Jr. Some persistent myths about military electronics maintenance. **Human Factors**, 1970, 12, 241-252.
- Buros, O. K. **The seventh mental measurements yearbook, Vols I and II**. Highland Park, New Jersey: The Gryphon Press, 1972.
- Corlett, E. N. Human factors in the design of manufacturing systems. **Human Factors**, 1973, 15, 105-110.
- Cream, B. W., Eggemeier, F. T., & Klein, G. A. A strategy for the development of training devices. **Human Factors**, 1978, 20, 145-158.
- Cullinane, T. P. Minimizing cost and effort in performing a link analysis. **Human Factors**, 1977, 19, 151-156.
- DeGreen, K. B. **Systems psychology**. New York: McGraw-Hill, 1970.
- Folkard, S., & Mark, T. H. Shiftwork and performance. **Human Factors**, 1979, 21, 483-492.
- Folley, J. D. (Ed.). **Human factors methods for system design**. Washington, D. C.: The American Institute of Research, for Office of Naval Research (AIR-290-60-FR-225), 1960.
- Freund, L. E., Sadosky, T. L. Linear programming applied to optimization of instrument panel and work place layout. **Human Factors**, 1967, 9, 295-300.
- Geer, C. W. **Analyst's guide for the analysis sections of MIL-H-46855**. Warminster, Pennsylvania: Boeing Aerospace Company for Naval Air Development Center, 1976a.

- Geer, C. W. **Navy manager's guide for the analysis sections of MIL-H-46855.** Warminster, Pennsylvania: Boeing Aerospace Company for Naval Air Development Center, 1976b.
- Hagen, W. C. **Techniques for the allocation and evaluation of human resources.** Orlando, Florida: Martin Marietta Corporation (Report OR 8735), March 1967.
- Haygood, R. C., Teel, K. S., & Greening, C. P. Link analysis by computer. **Human Factors**, 1964, 6, 3-70.
- Hudson, E. E., & McCleery, J. E. **Retrieval system for emplaced spent unprocessed fuel (SURF) in salt bed depository. Baseline concept criteria specifications and mechanical failure probabilities.** Livermore, California: Lawrence Livermore Laboratory, May 1979.
- Iiyama, Y. Systems-ergonomic approaches to design and operation of today's railroads. **Human Factors**, 1980, 22(1), 15-24.
- Johannsen, G., & Rouse, W. B. Mathematical concepts for modeling human behavior in complex man-machine systems. **Human Factors**, 1979, 21, 733-747.
- Kilpatrick, K. E. A biokinematic model for workplace design. **Human Factors**, 1972, 14, 237-247.
- Kurke, M. I. Operational sequence diagrams in system design. **Human Factors**, 1961, 3, 66-73.
- Malone, T. B., & Shenk, S. W. **Human factors test and evaluation manual, Volumes I, II, and III.** Point Mugu, CA: Essex Corporation for Pacific Missile Test Center (TP-76-11C), 1976.
- McCormick, E. J. **Human factors engineering.** New York: McGraw-Hill, 1970.
- Meister, D. Men should fit machines. **Engineer**, Nov.-Dec, 1967, 8, 19-21.
- Meister, D. **Human factors: theory and practice.** New York: Wiley & Sons, 1971.
- Meister, D. & Farr, D. E. The utilization of human factors information by designers. **Human Factors**, 1967, 9, 71-87.
- Military standard: human engineering design criteria for military systems, equipment and facilities.** Washington, D. C.: Department of Defense, (MIL-STD 01472B) 1974.
- Military handbook: human engineering requirements for military systems.** Washington, D. C.: Department of Defense (MIL-H-46855), 1968.

- Ong, C. S., & Buck, J. R. Operator workloads and mill performance effects due to design changes. **Proceedings of the Human Factors Society**, October 1978, 16-20.
- Pritsker, A. A. B., **GERT, Graphical Evaluation and Review Technique**. Santa Monica, California: The Rand Corporation (RM-4973-NASA), April 1966.
- Pritsker, A. A. B., Seifert, D. J., Sigal, C. E., & Wortman, D. B. **New SAINT concepts and the SAINT II simulation program**. Wright Patterson AFB, Ohio: Aerospace Medical Research Lab (AMRL-TR-74-119), April 1975.
- Reinberg, A., Vieux, N., Laporte, A., Ghata, J., & Migraine, G. Quick adjustment of circadian rhythms in shiftwork of an oil refinery. **Proceedings of the 6th Congress of the International Ergonomics Association**. 1976, 507-509.
- Roebuck, J. A., Kroemer, K. H. E., & Thompson, W. G. **Engineering anthropometry methods**. New York: Wiley Sons, 1975.
- Schiro, S. G., & Drury, C. G. Operator-oriented evaluation methods for medical emergency radio systems. **Proceedings of the 6th Congress of the International Ergonomics Association**. 1976, 72-76.
- Seminara, J. L., Gerrie, J. K. Effective mockup utilization by the industrial design-human factors team. **Human Factors**, 1966, 8, 347-360.
- Seminara, J. L., Gonzalez, W. R., & Parsons, S. O. **Human factors review of nuclear powerplant control room design**. Palo Alto, California: Electric Power Research Institute (EPRI NP-309), November 1976.
- Siegel, A. J., Wolf, J. J. A technique for evaluating man-machine system designs. **Human Factors**, 1961, 3, 18-28.
- Siegel, A. J., & Wolf, J. J. **Man-machine simulation models**. New York: Wiley Sons, 1971.
- Smith, R. L., Westland, R., & Blanchard, R. **Technique for establishing personnel performance standards, Vol. 1**. Personnel Research Division, Bureau of Naval Personnel (Report PTTS-70-5), December 1969.
- Swain, A. D. **THEPP**. Albuquerque, New Mexico: Sandia Laboratories (Report SC-R-64-1338), August 1964.
- Swain, A. D. **Preliminary human factors analysis of zion nuclear power plant**. Washington, D. C.: U. S. Nuclear Regulatory Commission (NUREG-76/6503, SAND-76/0324), October 1975.
- Swain, A. D., & Guttman, H. E. **Handbook of human reliability analysis with emphasis on nuclear power plant applications**. Albuquerque, New Mexico: Sandia Laboratories for U. S. Nuclear Regulatory Commission (Draft Report NUREG/CR-1218), April 1980.

VanCott, H. P., & Kinkade, R. G. (Eds.) **Human engineering guide to equipment design.** Washington, D. C.: U. S. Government Printing Office, Superintendent of Documents, 1972.

WASH-1400 (NUREG-75/014): Reactor safety study--an assessment of accident risks in U. S. commercial nuclear power plants. Washington, D. C.: U. S. Nuclear Regulatory Commission, October 1975.

Whitmore, D. C. & Parks, D. L. **Computer aided function-allocation evaluation system, phase iv, Vol. 1.** Boeing Aerospace Company (D180-18433-1), December 1974.

Woodson, W. E., & Conover, D. W. **Human engineering guide for equipment designers** (2nd ed.). Los Angeles: University of California Press, 1973.