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# PROCEDURES FOR INCLUDING HUMAN ENGINEERING FACTORS IN THE DEVELOPMENT OF WEAPON SYSTEMS

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# FOREWORD

This report was prepared by the American Institute for Research under Air Force Contract No. AF33(616)-2986, Project No. 5-(7-7192) entitled "Human Engineering Analysis of Weapon Systems," and Task No. 71633 entitled "Development of Procedures for Systematic Inclusion of Human Engineering Factors in the Development of Weapon Systems." The project was administered by the Psychology Branch, Aero Medical Laboratory, Directorate of Research Wright Air Development Center, with Mr. Julien M. Christensen serving as Project Engineer.

Users of this report are invited to submit to the Psychology Branch comments which will be useful in improving the material contained in this document.

This report has been released to the Armed Services Technical Information Agency, Knott Building, Dayton 2, Ohio. It has also been released to the Office of Technical Services, Department of Commerce, Washington 25, D. C. for sale to the general public.

The authors are grateful to Mr. Julien M. Christensen for his interest in this work and for his many helpful suggestions throughout the course of its preparation. Special thanks are due to Mr. Christensen and Mr. Robert McGehee of the Psychology Branch who provided the authors with an outline of human engineering procedures which they had developed for use with two weapon systems currently being developed. Mr. Melvin J. Warrick of the Psychology Branch also made several suggestions that significantly improved the final report. Acknowledgment is also due to Dr. Robert B. Miller, Principal Investigator, for his contribution to this report.

Space precludes individual acknowledgment of the efforts of the many other persons who contributed to this report. Very special thanks are due to members of the Psychology Branch, Aero Medical Laboratory, and to the twenty-five design engineers and psychologists who gave generously of their experience and time to criticize and suggest improvements in a previous version of the report.

Information in this report is based on weapon system development procedures in effect during the course of this contract (1955-1956).

ABSTRACT

At each stage in the development of a new weapon system appropriate action must be taken regarding the eventual role which men will play in operating and maintaining the completed system. The use of systematic procedures for solving problems and making decisions with respect to these human engineering factors, and for articulating them with other aspects of system development, assures that the weapon system emerges as a maximally effective man-machine system.

This report is intended to suggest systematic procedures for the human engineering of developmental weapon systems. A brief discussion of man-machine systems and the role of human engineering in their design is followed by a design schedule. This schedule suggests at what points and in what ways human engineering should be accomplished. Following the design schedule, procedures that may be used to assess and solve human engineering problems are suggested. Finally, human capabilities and limitations are discussed from the point of view of the man as a system component.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

Jack Bollerud
JACK BOLLERUD
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
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CHAPTER 1

# THE DESIGN OF MAN-MACHINE SYSTEMS

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[1] Manuscript released by the authors 31 October 56 for publication as a WADC Technical Report.

## Overview

Since World War II a large amount of human engineering information has been available to system designers in guides, design handbooks and technical reports. This information has been of great value in providing designers with data on human capabilities and limitations applicable to such detailed design areas as displays, controls and work place arrangement.

Many human engineering[2] problems, however, cannot be solved simply by matching a given design problem with appropriate data. Facts without procedures for their systematic application are of little value. Often the designer may not know when a human engineering problem exists. Or, he may encounter a problem too late in development to permit its solution.

This chapter discusses the philosophy and introduces the application of human engineering procedures to the design of weapon systems.

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[2] The term "human engineering" is used throughout this report because of its common acceptance. Actually, this report is concerned almost wholly with engineering psychology--the application of the techniques and facts of the science of psychology to problems of system design. Other aspects of human engineering such as the application of anthropometry and physiology to the design of systems have not been discussed here.

## • Introduction

### Why This Report Was Written

A survey of the opinions of human engineers conducted prior to the preparation of this report, revealed a need for answers to the following questions:

1. At what point in the developmental program should human engineering first occur?

2. What problems demand needed state-of-the-art studies?

3. In what way may man-machine function allocation and crewmember assignment be accomplished?

4. What kinds of information should be gathered and how can decisions be made for determining usable work areas, establishing control and display requirements and preparing work procedures?

5. What kinds of considerations should enter human engineering evaluations?

These are more questions of method and approach than of fact. They occur early and remain late in the developmental program.

### Purpose

The purpose of this report is to suggest procedures for identifying and methods for solving a number of human engineering problems. Through its use the system designer will be better able to articulate human engineering on a new system with other events occurring during the development.

The objectives of this report are based primarily but not exclusively upon the responsibility of the Wright Air Development Center to provide human engineering assistance to the Directorate of Systems Management, Air Research and Development Command. Considerations falling in human factors areas such as anthropology, physiology and safety, which do not fall within this area of responsibility, have been untouched or treated only superficially. Procedures for preparing training and training equipment requirements, which have been covered elsewhere (21), have not been included. Methods for maintainability design may also be found elsewhere (see especially 11).

Major emphasis is placed upon a human engineering design schedule to which procedures for functions analysis, man-machine and crewmember allocation, work and component design, and human engineering evaluation may be tied.

Who Will Use This Report

This report was prepared for the use of all persons who participate in the human engineering of weapon systems. Such persons will include:

1. Air Force personnel responsible for the formulation of system requirements.

2. Personnel in industrial contracting organizations with cognizance over design decisions which will affect the human component or human performance in the system.

3. In-service personnel concerned with the design and evaluation of weapon systems: Weapon System Project Offices, appropriate Laboratories, and individuals with subsystem responsibility.

A Word About the "Human Engineer"

Human engineering is only one of the many fields of knowledge contributing to the design of weapon systems. Neither its relative newness nor the fact that it is based on specialized information about human performance makes human engineering basically different from other design disciplines.

The human engineer, whether he is called by that or some other name, is a member of a design team and must work closely with other members of that team. In this report, no distinction is made between the human engineer and other members of the design team. Instead, major emphasis has been given to human engineering problems and procedures. The extent to which various team members contribute to the solution of these problems and the application of the procedures will depend upon the structure of the design team and the nature of the design problem being solved.

Some Limitations and Assumptions

Inasmuch as the design process is necessarily a highly complex one, involving many separate acts of invention and many different types of scientific knowledge, each system presents new problems that require new approaches and unique methods for their solution.

It is recognized that adequate human engineering cannot be accomplished solely through the application of already known or established techniques. However, by following a general set of procedures, by using them as flexible guide lines rather than as firm prescriptions, a considerable amount of trial and error can be eliminated.

At the risk of being idealistic,and at times unrealistic, this report provides procedures intended for application to a wide variety of weapon systems--missiles, manned aircraft, ground systems, etc. To obtain this generality, it was necessary to ignore many special considerations and contingencies involved in the design of particular types of systems. This means that the individual designer must rely upon his own judgment in modifying or short-cutting procedures for a particular system.

Several specific limitations are worth noting:

1. No attempt has been made to present human engineering information that can readily be found elsewhere in usable form.

2. No attention has been given to methods for modifying these procedures to fit the needs of different types of organizations.

3. Only a very gross indication of the sequence in which procedures should be applied is given in this report. In many cases it is left to the individual designer to decide when previous decisions should be modified, procedures should be re-applied, or several steps should be conducted concurrently rather than successively.

This report is based on the following assumptions:

1. Human engineering cannot be divorced from other aspects of system design.

2. Acts of invention involved in the design of a system cannot be reduced to routines, but best guesses, hunches and timely judgments are often the best and only resource in meeting developmental schedules.

3. Operational requirements for the system establish the scope of good human engineering. As with the other design specialties, it may even be necessary to violate commonly accepted human engineering principles for the attainment of important operational objectives.

## • Evolution of Design Philosophy

During the past 150 years the philosophy of system design has been profoundly influenced by advances in the sciences of engineering and human behavior and by shifts in the roles of men and machines as system components.

### Machine-oriented Design

The first systems were simple man-powered devices built around a single human operator. Machines replaced certain human capabilities, extending their range and precision, but they did not replace man himself. Central to every man-machine system was the man; starting and stopping work, controlling system performance, detecting and correcting errors, and performing maintenance.

The philosophy of systems at this time was machine oriented. The designer's approach to the human operator was largely subjective. As long as the care, feeding and operation of machines was relatively simple, the average adult could be relied upon to carry out an assignment.

With the advent of power machines, the role of the human operator became more peripheral. Machine power replaced man power. Machine operations became self-initiated and self-sustained. Even certain maintenance functions could be performed automatically.

It was discovered that the trend toward machine-oriented design could be pushed even further through the use of systematic techniques for personnel selection and training. By fitting the human operator to the demands of existing equipment, work output could be increased and waste reduced. Little emphasis was placed on simplifying the job by modifying the machine to fit the man. The machine rather than the system was emphasized in design.

### Man-oriented Design

Extensive automation in modern equipment has freed man from many manual tasks, limiting his activities to those functions not economical or feasible for machines.

With this shift in roles, the demand for continuous high quality operator performance has increased. Whereas previous systems could tolerate large variations in component performance without breakdown, the new demand was for systems capable of working within extremely close tolerances. This, in turn, increased the accuracy requirements imposed on man.

This demand for increasingly fine tolerances was accompanied by the development of more complex equipment. Some of this equipment was inadvertently designed so men could not perform their required operating or maintenance functions easily, quickly, and without error.

A new discipline called "human engineering" assumed a role in the design of systems compatible with the capabilities and limitations of human components.

At first this new philosophy of man-oriented design was devoted primarily to criticism of machines already in advanced or prototype stages of development. This effort, while beneficial, was wasteful. Time and money had to be spent in making changes, or valid recommendations were passed over to meet budget or schedule limitations.

### System-oriented Design

During the past decade there has been an increasing tendency to regard the man and the machine as part of an over-all system. Instead of selecting the man for the machine or designing the machine around the man, each component is planned for the system and the mission which it is to accomplish.

System-oriented design is concerned primarily with meeting given objectives. The machinery, the men, or both, which might be used to meet these objectives are of secondary importance. The major purpose is to achieve a given tactical, strategic, logistic or defensive goal in the shortest time by the most direct developmental route, with the least amount of money, trial and error.

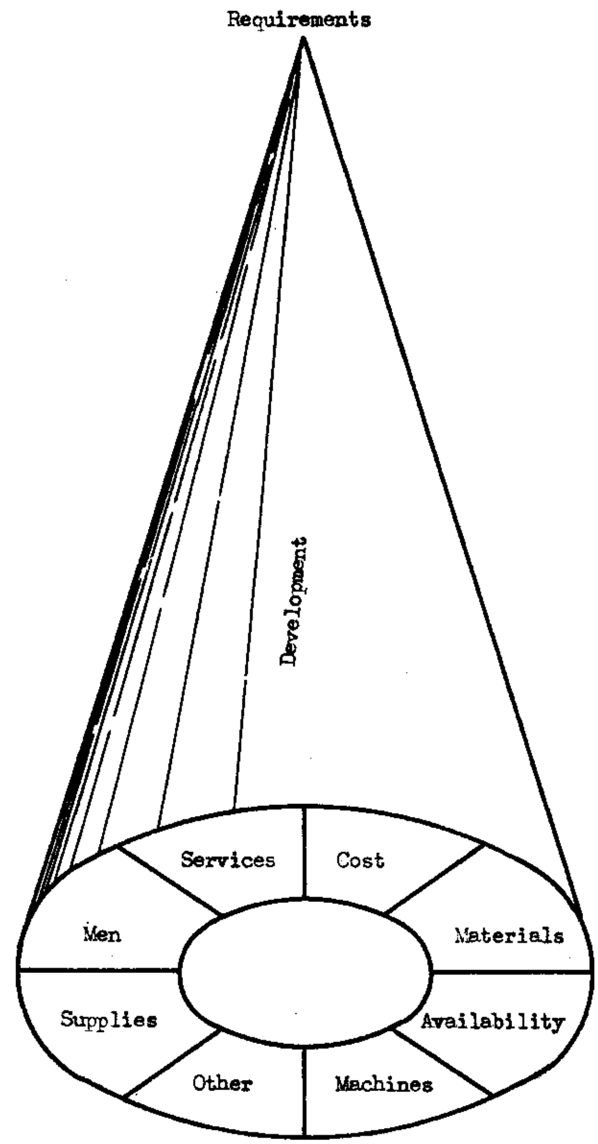
This approach differs in emphasis from the man and machine design approaches discussed above. It stresses the need to delineate, well in advance of any consideration of the hardware or men who will serve as components, conditions under which a given system will perform and the functions needed to fulfill this performance capability. When this has been done, the design team works on the development of a system of components which will fulfill the requirements that initiated the developmental process. Only if design and development proceed in this manner can there be reasonable assurance that the completed system will not be a patchwork of compromise and revision.

## • Definition of a System

A weapon system, like any other man-machine system may be defined as any group of activities, involving men and machines, directed toward the solution of a given set of problems. A system consists of both objects and processes. The objects of a system are its operating environment, machines and men. The processes of a system are the ways in which these objects interact with one another to achieve given ends.

In designing systems it is convenient to think of the human being as a component with many of the features of hardware components. By thinking in this way it is possible to consider realistically the selection of human beings and hardware components in similar terms: as items subject to stress, and breakdown, and with limits and capabilities.

Figure 1. Summary of a System



• An Overview of Human Engineering in Weapon System Design

Human engineering is that aspect of system design concerned with achieving optimal system performance through effective utilization of human capabilities. In order to achieve its objectives adequately, human engineering must begin early in the design sequence and be active throughout each successive developmental phase.

The developmental history of every complex system involves a series of successive approximations. Each design approximation having implications for human performance should be a joint human engineering and equipment engineering effort. In this way human engineering can make its maximum contribution without unnecessary waste of developmental effort.

Human engineering is a complex process, and its description in a report of this type must necessarily risk oversimplification if a cumbersome treatise is to be avoided. Also, any description of human engineering and systems procedures on one day will be partially outmoded on the next. As requirements for radically new systems emerge, new procedures must be developed. Despite these difficulties, an attempt has been made to provide a unified description of current human engineering procedures which will be useful, at least for the immediate future.

The remainder of this chapter is devoted to an overview of the various aspects of system design to which human engineering can make a contribution. Chapter 2 presents a design schedule which suggests appropriate human engineering activities for each design stage. Chapters 3-8 describe human engineering procedures for the various design stages in detail. Chapter 9 provides a brief introduction to the capabilities and limitations of the human as a system component. In Chapter 10 references to detailed sources of human engineering design data are provided.

Allocation of Functions to Men and Machines

Shortly after the formulation of the General Operational Requirement for a system, decisions must be made as to whether there will be human components in the system, and generally what their roles will be.

To make these decisions four types of information are needed: a statement of system requirements, a statement of the capabilities needed to meet these requirements, hypothetical mission profiles, and ground support flow charts.

The statement of system requirements is a comprehensive list of those things which the weapon must be able to do. The statement of capabilities is a list of available or projected techniques, equipment or subsystems in each requirement area. Human component capabilities as well as instrumented capabilities are included. The mission profiles and flow charts are graphic descriptions of the missions which the weapon is expected to perform and the things which must be done to the system before and after a mission.

When these items have been prepared, the list of capabilities in each requirement area is indexed to the mission profiles. In most cases a number of different capabilities can be used to satisfy a particular requirement. By examining the relative merits of each capability with respect to the requirements, it will be possible to select that alternative which will most adequately fulfill these requirements.

When it has been determined that one or more human components will increase the effectiveness of the system, the various functions assigned to men are examined to determine which should be combined in individual crewmen. Novel as well as traditional crew assignments should be considered.

Next, general performance descriptions must be prepared for the activities to be carried out by each crewman. These descriptions should be prepared in a way which will reveal over- or under-loading of any individual. The relationships among crewmen may be shown on revised mission profiles and organizational diagrams.

## Design of Equipment, Work Space and Procedures

In modern weapon systems, the design of subsystems and equipment, work space, and operational procedures is a series of successive approximations and must take place concurrently if maximum system effectiveness is to be attained. Although these items are discussed sequentially below, that they must taken place concurrently should be kept in mind throughout the discussion.

Once the functions of the human operator have been determined, all equipment and subsystems should be designed toward the accurate and reliable execution of these functions.

The first step in the design of equipment for use by operators is to determine the required man-machine linkages. These may then be broken down into input and output requirements. Input requirements will include the types of visual, auditory or other incoming information needed by the operator or technician for such activities as controlling, monitoring, or checking system performance.

Output requirements will consist of the classes of response which must be made by the operator to control various aspects of system performance, or to obtain additional information.

From these general requirements, classes of controls and displays may be established. Often an entirely new display or control medium may be indicated. Compromises are better made later in the developmental program. Following these general considerations, secondary decisions as to the shape, coding, location and other characteristics of the equipment can be made.

The design of work space layouts will include provisions for seating, physical movement of the operators, operational maintenance, and other factors permitting optimal person-person contact and man-machine interaction.

Such layouts should first be based primarily on the size and mobility requirements for operators, including emergency procedures as well as normal activity sequences.

It is likely that some compromises between these factors and system considerations will be necessary. If, for example, aerodynamic considerations require a small diameter airframe, upright seating of the operator may be impossible. Other positions may affect the location and layout of equipment, and even the shape, mode of activation and required force may require modification.

Another important human engineering area is the design of optimal work procedures. In general, procedures must be developed to cover each linkage between man and machine. It is necessary in establishing efficient work procedures to consider such factors as over-all task load, fatigue, and work environment if variability and error are to be kept to a minimum.

The Preliminary Operational Concepts and Preliminary Operational Plans, prepared by using commands, will provide useful sources of data for preparing work procedures. Other useful data may be found in Technical Orders, reference manuals, regulations, military specifications and Standing Operating Procedures (S.O.P.'s) from previous, similar systems.

It is important that the design of all work procedures include provisions for handling the variety of contingencies which an operator may encounter but which cannot be stated as routines.

### Checking Operator Performance Descriptions

Performance descriptions based on provisional operator assignments must be continually rechecked as equipment and work procedures become firm. Consideration should be given to fulfillment of mission requirements, duplication of effort, the handling of emergencies, and task over- or under-load. A regrouping of equipment or operators or changes in task sequences may reduce problems of over- or under-load.

### Design of Training Devices

The design of training equipment must parallel the development of the system. From early design drawings and equipment analysis, a tentative list of tasks to be trained can be provisionally determined. Often the same information used in the design of position descriptions or work procedures may be used to specify conditions for efficient learning.

From the duties obtained through this analysis, essential skills and knowledges may be abstracted. These are then translated into a set of practice exercises and devices. Consideration should be given to the use of inexpensive demonstrators and practice devices as well as simulators in those cases where either special practice may be required or it is unnecessary to simulate the operating environment.

It is often difficult to keep training devices up to date with all of the latest modifications of operational equipment. Consideration of human factors can aid in deciding when such modification will actually affect training and should be incorporated in training equipment.

Evaluation

Throughout the entire course of system development, various products are being designed and tested. Major evaluations occur at special and final Mockups and at Development Engineering Inspections, when either a complete model or a model of a subsystem is available. Any product which affects the man or which is affected by his performance, should be evaluated for possible errors and needed changes.

The use of standardized checklists during system evaluations will help to insure that important features, such as error-likely, dangerous, or inefficient conditions, are not ignored.

Two types of checklists can be used. The first, is a list of items which can be checked against parts lists, blueprints and design drawings. Such a list can save considerable time at Mockups, where time is precious, and at the same time familiarize the evaluator with the system. It would contain items against which the inclusion and location of a particular item (e.g., control or display) could be checked. In many cases location and inclusion are prescribed in military specifications or in such manuals as Handbook of Instructions for Ground Equipment Designers (HIGED) or Handbook of Instructions for Aircraft Designers (HIAD). Such a list (3) has been prepared for the Wright Air Development Center.

A second type of checklist is of use at the Mockup itself, or at Development Engineering Inspections and Operational Suitability Tests. It contains more detailed items on scales and dials, information presentation, control forces, and the like, which cannot be checked except by reference to a mock-up or actual prototype of the system. A checklist of this second type has also been prepared (28).

By using these checklists throughout the developmental history of a system, accurate records may be kept which will be of value at succeeding phases of development and for the design of subsequent systems.

CHAPTER 2

# DESIGN SCHEDULE

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## Overview

The development of a weapon system is complex--requiring numerous interlocking decisions, documents and activities. The schedule presented in this chapter is intended to help the designer systematically incorporate human engineering into a system during its development. Steps to be taken at each stage in the developmental cycle are suggested. Procedures for accomplishing these steps are to be found in subsequent chapters of this report. Because the history of each system is always unique, the cycle presented here is necessarily abbreviated and generalized.

The extent to which this design schedule is useful will depend upon the kind of system being designed and the point in its development at which human engineering is begun. Where possible all of the steps should be followed, even if they are to serve only as a check on the adequacy of already established decisions.

Some of these steps may be the exclusive concern of inservice personnel, especially those which occur early in the design sequence. Others, particularly those in the design of the developmental model, will be the primary concern of contractor personnel. Still others may involve the joint particpation of both inservice and contractor personnel.

Throughout the entire development cycle research will be necessary. An attempt has been made throughout this report to spell out the requirements for particularly critical research areas.

- General Human Engineering Principles

More important than any other principle is the necessity for thorough familiarity with the mission of the system. The elements employed must be integrated to form a complete system. It can no longer be assumed that a system is to be designed for the man, or the man molded to the system.

Only by reappraising each decision before it has been rendered into hardware can human engineering requirements imposed upon a system be reasonable. Since design decisions inevitably interact with one another, considerable compromise will almost always result. But this compromise can be accomplished without undue sacrifice to the final effectiveness of the system if each separate decision is reviewed and coordinated with other designers and design agencies. Major changes incorporated after production tooling is established will be expensive and time consuming.

- Stages in System Development

The following design schedule is based upon major stages that usually occur in the development of a system. Each stage is initiated and supported by one or more developmental documents. These stages and documents are discussed here in relation to the human engineering contributions that can be made in their preparation and the human engineering activities that should parallel their appearance.

It should be remembered that the stages presented in this schedule are not successive but often overlap or parallel one another. Each new system will undoubtedly depart in

• Summary of Steps in the Human Engineering of a Developmental Weapon System

| Stages of System Design | Steps in Human Engineering (see Chapters 3-8) |
|---|---|
| Preparation of system requirements | 1. Review the requirements for the system |
| Conduct of the Design Study (Feasibility Studies) | 2. Study alternative capabilities<br>3. Prepare mission profiles for the airborne vehicle<br>4. Prepare flow charts for ground support<br>5. Perform capability research |
| Development Planning | 6. Allocate functions within the airborne vehicle<br>7. Allocate functions within the ground support area<br>8. Perform a time and link analysis<br>9. Assign functions to individual crewmembers<br>10. Initiate research as indicated |
| Design of the Development Model | 11. Prepare performance descriptions<br>12. Analyze individual operator work-loads<br>13. Study operator contacts<br>14. Perform operator performance research<br>15. Delineate usable crew station work areas<br>16. Delineate usable work areas within crew stations<br>17. Determine the location and installation of components<br>18. Perform research on alternative workspace layouts<br>19. Analyze human information requirements<br>20. Analyze human response requirements<br>21. Design displays, controls and operator console<br>22. Determine auxiliary job supports<br>23. Prepare procedures<br>24. Perform research for the integration and simplification of equipment |
| Evaluation of the Development Model; Testing and Fabrication of the Prototype Model; Production | 25. Evaluate drawings, plans and blueprints<br>26. Evaluate mockup, development and prototype equipment<br>27. Evaluate engineering change proposals |

some measure from this ideal sequence. At the end of this chapter (p. 21) a sample time chart for a hypothetical developmental cycle of a weapon system is presented to show the relation between developmental phases and human engineering objectives.

Preparation of System Requirements

The General Operational Requirement (GOR) is the first major document to be prepared in the developmental cycle. It provides criteria for the developmental planning of a specific weapon or support system and contains statements of an operational need arising from a described Air Force mission. Prepared by Headquarters, USAF, the GOR is written in terms of an extended time period.

Since the GOR serves as a basis for specific design planning, it is desirable that human engineering contribute to its preparation through providing advice on the kinds of human engineering requirements that can reasonably be made at this stage in development.

At this point in development the GOR should be used as a basis for a review of the requirements of a system, prior to functions allocation. Procedures for this review are presented in Step 1 of Chapter 3 of this report (p. 25).

Conduct of the Design Study

A Design Study (DS), initiated through contractors by Headquarters ARDC, following Headquarters USAF approval, is a detailed analysis of the feasibility of the GOR. Its objective is to specify what military characteristics and capabilities could be reasonably expected to fulfill the requirements presented in the GOR.

At this stage, human engineering assistance should be provided to the Directorate of Systems Management, ARDC, in the preparation of a Statement of Work to prospective contractors for the Design Study.

Before and during the Design Study, an analysis of alternative existing or projected human and equipment capabilities that could be used in the system should be made. A procedure for analyzing these capabilities is suggested in Step 2 of Chapter 3 (p. 26).

When a statement of capabilities has been prepared, the GOR should be examined to determine what mission the weapon system is expected to perform. Steps 3 and 4 of Chapter 3 (pp 28 and 30) suggest procedures for preparing detailed mission profiles for the airborne vehicle and flow charts for ground support equipment that can later be used in allocating functions to men and equipment.

At this time it is also desirable to initiate studies on the nature of the human capabilities expected to be utilized in the weapon system. This should include an appraisal of personnel requirements for manning the system. The problem of capability research is discussed in Step 5 of Chapter 3 (p.31).

Development Planning

A Development Plan, issued by Headquarters ARDC represents a plan for the development, test and support of the system requirement stated in the GOR. This plan, evolved from the results of the Design Study, includes a general description of the system, design specifications or military characteristics, and comments upon personnel requirements, system maintenance and maintainability, human factors, training and logistics.

When this plan has been approved by Headquarters USAF, a Development Directive authorizes the development of a system in accordance with the Plan.

At this point the allocation of functions within the air vehicle and ground support areas should be started. Procedures for functions allocation are to be found in Step 6 and 7 of Chapter 4 (pp. 37 and 40). These steps result in a determination of the activities to be performed by humans. It is not until later, however, that these functions are allocated to individual operators.

After the Development Directive has been issued, a Preliminary Operational Concept is prepared by the Deputy Chief of Operations presenting a general description of the system, its intended use, its expected operational capabilities and limitations, detailed specifications for airfield and base requirements, expected theater of employment and turnaround time. Assistance in determining items in the Preliminary Operational Concept affected by the human component should be provided to the Deputy Chief of Operations at this stage.

In turn, the Preliminary Operational Plan will provide information useful in performing a time and link analysis of human operator activities. These analyses, which are described in Step 7 of Chapter 4 (p. 40), provide data upon which decisions about the assignment of functions to individual crewmembers can be made.

Shortly after the Preliminary Operational Concept has been formulated, a Preliminary Operational Plan is prepared. This Plan indicates the mission, tactics, unit manning, training requirements and lead times, and operational ready requirements for the weapon system.

From this Plan information that might affect later human engineering should be determined. This may include the geographic location of the complete weapon system and related special environmental problems, stresses resulting from the nature of the mission, and lead times for subsequent human engineering activities.

As soon as the general classes of activities required of individual crewmembers are known, rather intensive research on problems affecting operators in the system can be initiated. Research of this type is briefly discussed in Step 10 of Chapter 4 (p. 44).

Design of the Development Model

After the establishment of a Weapon System Project Office by ARDC and AMC, the Design Competition is initiated. This competition is an invitation to industry to submit specific design proposals which will satisfy the Development Plan.

Human engineering assistance by contractor personnel in the preparation of Design Proposals should make use of prior documents and human engineering decisions. Such proposals should provide guidelines for subsequent human engineering. Documents useful from a human engineering standpoint are MIL-T-4857, MIL-A-8730, MIL-I-6252C, MIL-D-8034, MIL-D-7579, MIL-E-4158, MIL-S-9412, MIL-M-8555, and MIL-S-9411. Other useful sources of information at this point include ARDC Manuals 80-1, 80-4, and 80-5.

After the evaluation of the Design Proposals by Headquarters USAF, ARDC, and AMC, a contract is awarded to industry. From this point development is a continuing process, consisting of successive approximations to that system which will fulfill a specified Air Force need.

One of the first major items to be prepared by the contractor will be operator performance descriptions. These descriptions indicate along a time base the activities to be performed by each operator. Procedures for making these descriptions are presented in Steps 11, 12, and 13 of Chapter 5 (pp. 51, 54, 54).

Paralleling these performance descriptions, a detailed analysis and delineation of usable crew station work areas should be made. General procedures for this activity are described in Steps 15 and 16 of Chapter 6 (pp. 61 and 63). Step 17 in Chapter 6 discusses the problems of locating and installing components for human use (p. 63) and Step 18 (p. 64) discusses research on alternative workspace layouts.

Throughout the design of the development model it is necessary to conduct frequent and thorough reviews of modifications and refinements in various design areas that may affect the human operator. This should be accomplished in close coordination with the various design specialties. Training and training equipment design, which is not discussed in this report, should have been under active consideration for a considerable period of time, as early as the preparation of operator performance descriptions. Frequent consultation with inservice laboratories will be valuable in keeping both research and development consonant with Air Force human factors requirements.

While it will have been necessary for some consideration to have been given to the selection of displays and controls as early as the Design Proposal, more intensive and detailed control-display design cannot be accomplished until somewhat later. Steps 19 to 22 in Chapter 7 (pp. 67-70) discuss problems in analyzing human information and response requirements, and discuss general methods for designing displays, controls, operator consoles, and auxiliary job supports. Research in the simplification and integration of equipment, directed principally toward reducing the number of needed displays, should be started early in the design of the developmental model. A brief discussion of equipment research is presented in Step 24 of Chapter 7 (p. 71).

To assure adequate human performance, maximally useful technical orders, operating instructions and training materials, it is necessary that procedures for the performance of each operator job be prepared. These should be based closely upon the operator performance descriptions prepared earlier in development. Suggestions for preparing these procedures are outlined in Step 23, Chapter 7 (p. 70).

## Evaluation and Testing

As various major subsystems and components appear during the course of system design, it is natural that they be evaluated from a human factors standpoint.

A considerable amount of time can be saved if human engineering evaluation begins with a study of drawings, plans and blueprints.

It is essential that changes proposed as a result of human engineering evaluations be coordinated with other laboratories and organizations involved.

These evaluations should be done by both contractor and inservice human engineering personnel. A tool that may be of use for evaluating paper plans is discussed in Step 25 of Chapter 8 (p. 77).

More formal evaluation will occur at Mockups, Development Engineering Inspections, and at the Operational Suitability Test. It is at such inspections that such features as the adequacy of lighting, workspace layout, and display and control design will be determined. A second tool useful in conducting these evaluations from a human engineering standpoint is discussed in Step 26 of Chapter 8 (p. 80).

Inservice human engineering personnel will provide assistance to the Directorate of Systems Management with respect to the results of the various evaluations occurring throughout development.

Once the system goes into operational use, human engineering assistance is often required in preparing and evaluating Engineering Change Proposals. Specific procedures for this stage are discussed in Step 27, Chapter 8 (p. 80).

Human engineering should not stop with the delivery of the system to its user. Continual close coordination of the design with using commands throughout the life of a weapon system will have valuable payoffs in suggestion human engineering improvements for the system and for the design of future systems.

**Sample Time Chart for a Hypothetical Development Cycle**

| Years | Developmental Phase | Human Engineering Objectives |
|---|---|---|
| 1 | Preparation of planning documents and conduct of design studies | Establish the extent and nature of human participation in the system |
| 2, 3 | Design and evaluation of the development model | Design of equipment and procedures for optimum human performance<br>Development Engineering and Mockups Inspections |
| 4 | Fabrication of the prototype model | Make final major design modifications based on human engineering requirements. Only minor changes will be made after this phase |
| 5, 6 | Testing of the prototype model | Recommend allowable modifications to improve human performance in the system |
| ↓ | Production; engineering changes | Correct, where feasible, human engineering deficiencies and review engineering changes for effects on human engineering.<br>Monitor the weapon system in operational use. |

CHAPTER 3

# FUNCTIONS ANALYSIS

content

Step 1 - Review the requirements for the system
Step 2 - Study alternative capabilities
Step 3 - Prepare mission profiles for the inflight air vehicle
Step 4 - Prepare flow charts for ground support
Step 5 - Perform capability research

Overview

This chapter describes the initial steps to be taken in obtaining information necessary for the human engineering of developmental weapon systems. These steps include: (a) an examination of the requirements for the system, (b) a study of alternative capabilities which may be used to meet these requirements, and (c) the preparation of mission profiles to which capabilities may be indexed.

Information obtained from this analysis must be reviewed and revised continuously to keep it up to date with changes and refinements as they occur in the developmental program.

The functions analysis described in this chapter should be completed as early as possible in the developmental program and should be based upon the projected requirements for the system as they emerge from Headquarters USAF and Headquarters ARDC.

Should the functions analysis be made prior to the time the Development Plan is available, considerable reliance will have to be placed on the GOR and on information obtained from similar systems.

- Step 1 - Review the Requirements for the System

A review of the requirements for a system is an examination and listing of those things which the weapon system must be able to do and the limits within which they must be accomplished. The objective of this review is to establish guidelines for determining what kinds of human and instrumented capabilities are needed for the system.

Sources of Requirement Information

The General Operational Requirement (GOR) will be the earliest source of information for the functions analysts. In response to the problem presented in the GOR, Headquarters ARDC prepares the System Requirement and the Development Plan which present in greater detail the characteristics of the system and describe the range within which its capabilities must fall.

List the Requirements for the System

Here it is necessary to understand the particular function of the system in the command for which it is destined, and the requirements which the system must meet to fulfill its major objective within an operational area.

For systems in which an airborne vehicle is the major element, it is convenient to group requirements into two categories: airborne and support. For systems in which the air vehicle is not a major component, the breakdown of requirements will usually be unique to the system. Such requirements may include speed, load, accuracy, range, etc. These requirements all have implications to various subsystems, such as communication, protection, navigation, data processing, maintenance and transportation. For each of these potential subsystems, consideration should be given to the nature and extent of possible human involvement.

It should be remembered that a functions analysis is made of the requirements for a system and not of the equipment to be used in the system.

Subdivide Requirements

Each of the requirements listed for a system should be further broken down into subrequirements until a level of specificity has been reached that will later be useful in specifying what subsystems, equipment or ways of utilizing men may be provided to fulfill them.

Special attention should be given to the estimation of tolerance and time limitations which may be imposed upon or affect the human operator who may be expected to perform in a given requirement area. In some cases tolerances will be a function of a particular environmental or mission condition. Variations in tolerances with variations in conditions should be included in this listing.

Select and Subdivide Representative Missions

Select at least one mission to represent each type required of the weapon system. Divide the profiles of these missions into convenient time segments. These breakdowns provide a tool for the initial study of alternative capabilities.

Some typical mission segments are suggested below.

1. Preflight
2. Take-off or launch
3. Climb to altitude
4. Cruise
5. Attack
6. Return cruise
7. Landing or recovery
8. Postflight

List the implications of requirements for mission segments.

Determine or estimate how requirements vary for each mission segment. The precision with which these estimates should be made depends upon the extent to which a particular requirement is a critical factor in mission performance.

• Step 2 - Study Alternative Capabilities

The study of capabilities is a review of the possible contributions to each system requirement within each mission segment which can be made by men or equipment. This study should include a review of alternative available or projected equipment, alternative ways of utilizing humans, and alternative man-equipment combinations. For example, in the navigation requirement area, a human capability might be manual dead reckoning, an equipment capability could be an inertial system, and a man-equipment capability would be radar dead reckoning. Each of these examples constitutes an alternative capability for meeting the navigation requirement.

General Human Capabilities

While a necessarily complex and difficult process, the classification of human capabilities becomes more meaningful when man is projected into the system as a possible component. Suggested classes of human capability are:

1. Data sensing and filtering (e.g., target detection, scope interpretation)
2. Data collation and processing (e.g., emergency diagnosis, trouble shooting)
3. Decision making (e.g., whether to repair or replace a component)
4. Amplification and transformation of signals (e.g., reading scope signals through ECM noise)
5. Controlling, monitoring and correcting equipment performance (e.g., operating flight controls, assuming manual override on inertial system)
6. Information transfer (e.g., communication, programming autopilot)

Within any requirement area, the statement of human capability should clearly identify those activities or activity sequences that the human must perform in meeting a given requirement.

Evaluate and Screen Capabilities

As a result of the listing of equipment and human capabilities for each requirement area, it will become apparent that a number of alternative equipments, human activities, and combinations of both could be considered for filling a given requirement.

In order that either the human or component efforts can be appropriately channeled for further research and development, a number of alternatives must be eliminated at this point. Final decisions, however, will not be made until a later stage.

To the extent that the military characteristics of the air vehicle and ground support equipment have already been determined, certain assumptions may be made about size, weight and space limits, particularly in the air vehicle. These limits demand that two criteria be exercised in choosing among alternative capabilities: (a) any component must be utilized to its optimum capacity, and (b) duplication of components should be avoided except where there is good reason to believe that redundancy is necessary.

If these two criteria are to be met, it follows that the automatization of any function be justified on the grounds of the operator's inability to fulfill the function adequately. It is not sufficient merely to demonstrate that automatization will result in superior performance: There must be good evidence that the system requirements demand this superior capability and that its provision does not seriously compromise other aspects of system performance (5).

In addition to these considerations, each potential capability should be evaluated in terms of the following basic requirements:

1. Interchangeability
2. Cost
3. Expendability and availability
4. Maintainability
5. Flexibility
6. Reliability
7. Vulnerability

It is well to remember that up to this point capabilities have been treated as discrete entities that might be assigned to discrete requirement areas. Somewhat later it will be necessary to exercise more critical judgment over those capabilities that cut across requirement areas, and it may be found that a reassessment or reassignment of capabilities is necessary. Requirements which were earlier specified separately may now be combined. A final solution to this problem depends on mission data which permit one to determine where a given capability might effectively cut across or combine two or more separate functions.

Mission profiles are representations of the missions which a weapon system is expected to perform. They contain three basic elements: (a) a chart showing terrain and other discrete events that will be encountered at fixed points on a mission, (b) graphs and/or scales depicting factors which change during the course of a mission, and (c) requirement areas.

Since there will be considerably less latitude in the selection of capabilities and the allocation of functions for the airborne mission, mission profiles for the air vehicle should be prepared in advance of those for ground support.

Mission profiles should be composites of the most adverse conditions which the system is likely to encounter. They should, for example, be drawn to indicate the most distant target, the most difficult terrain, and most vulnerable flight path the system is likely to encounter. It should be necessary to prepare only one profile for each major type of mission.

• Step 3 - Prepare Mission Profiles for the In-Flight Air Vehicle

<u>The objective of this step is to provide a basis for determining what equipment or human capabilities can be used to fulfill functions for an airborne system.</u> Since these capabilities may vary for different mission segments and conditions, an optimal selection must be based upon a consideration of mission profiles.

Construct the Chart

Enter the following on a standard chart:

1. The locations of departure (launch or take-off) and target points.

2. Location of air refueling rendezvous, if applicable.

3. Check points to be used, if applicable.

4. A linear distance scale (superimposed upon the flight path).

5. The expected flight path, including turning points, etc.

6. Maximum range of various enemy defenses.

It may be convenient to use separate maps for each leg or segment of the mission.

Special factors, unique to particular weapon systems, may need to be included in addition to the above items.

It is worth pointing out that certain of the items suggested for inclusion on the chart, scales or graphs are based on the assumption that the nature of the airborne vehicle is known: i.e., whether it is manned or unmanned. Should this not be the case at this point in development, these items must be omitted.

Construct Graphs and Scales

Beneath the chart draw a primary scale of elapsed time. This will be nonlinear, except for periods of constant speed.

Below, and paralleling the time scale, include the following:

1. A graph indicating expected altitude if data are available.

2. A graph indicating the probability of encountering enemy defenses.

3. A graph containing anticipated Mach numbers.

4. Graphs indicating anticipated transverse and angular g's.

5. A scale indicating the frequency of communication with ground control or friendly aircraft.

6. A scale indicating interior and exterior environmental conditions.

Indicate Requirement Areas

In columns beneath the scales and graphs list each major requirement area and its subrequirements. Indicate for each, at points paralleling the time scale, where critical changes that will affect the requirement will occur. These changes can be inferred from the features marked on the chart and corresponding graphs and scales.

Indicate Mission Segments

Delineate the mission segments on the map, graphs, and scales, and each requirement area. It should be possible to do this by drawing vertical lines on the chart.

## • Step 4 - Prepare Flow Charts for Ground Support

Like the analysis of functions for the airborne area, a functions analysis for ground support is an analysis of requirements and not of equipment. Its primary objective is to establish the requirements to be fulfilled by ground support so that the men and equipment that can be used to fulfill these requirements may later be determined.

Procedures for performing a functions analysis for ground support are similar to those described for the airborne vehicle.

Ground support is defined as those operations and equipment necessary for the inspection, testing, handling, servicing, maintenance, overhaul, transport and decontamination of the major airborne system.

### Construct Flow Charts

Operations and procedures from line to base levels which are essential to a weapon should be studied through the use of flow charts. These charts should contain the following:

1. A time base marked off into intervals of not more than ten minutes.
2. The relative locations of all fixed or nonportable facilities (e.g., electronics shops, testing facilities, fixed fueling stations).
3. The normal pattern of flow of materiels and procedures from one facility to another (e.g., components, subsystems, testing, trouble shooting, etc.).

Indicate in the flow chart(s) requirements for each aspect of ground support. Give tolerances for each major requirement (e.g., servicing time). Do not attempt to indicate how many men will be used or where they will be located. This can be done when a more complete picture of ground support has been obtained (see Step 7, Chapter 4, p. 40).

Attempt to predict those items which may be major sources of unscheduled ground support activity, and show where they may be carried out.

Revise the locations of fixed facilities to obtain a relatively fool-proof system, in so far as this is possible at this time. Minimize distances between facilities; consider safety; anticipate likely breakdowns due to transportation, supply, enemy attack, and try to develop an arrangement which will minimize the effects of these breakdowns. Consider novel combinations where they may optimize ground support.

### Revise Flow Charts

Revise flow charts as additional data are available. Do not attempt, at this point, however, to detail the types of equipment or tools that will be used or the exact procedures to be followed by ground support operators. Incorporate only sufficient detail to permit a subsequent indexing of instrumented and human capabilities to each ground support requirement.

• Step 5 - Perform Capability Research

Analysis of the mission profiles or flow charts establish the nature and limits of conditions under which capabilities will have to be provided. Equipment capabilities will suggest the machine components with which the man will have to work. "State-of-the-arts" information will provide the basis for assumptions concerning the work environment and personal equipment which can be provided. Given the above information, the research problem becomes one of simulating the anticipated operational situation, measuring human performance and relating this to system performance.

The outcome of the steps presented in the chapter will be the following: (a) a review of system requirements, (b) a study of capabilities which may be used in meeting these requirements and (c) mission profiles and ground support flow charts. These items constitute information useful for allocating functions to men and equipment and to individual crewmembers described in Chapter 4.

Sample List of System Areas and Alternative Capabilities for the Air Vehicle of a Bomber*

| Requirements** | Mission Segments** | | | | | |
|---|---|---|---|---|---|---|
| | a. Takeoff or launch | b. Climb | c. Cruise | d. Attack | e. Return | f. Recovery or landing |
| 1. Propulsion | 1-a | 1-b | 1-c | 1-d | 1-e | 1-f |
| 2. Communication | 2-a | 2-b | 2-c | 2-d | 2-e | 2-f |
| 3. Fire control | 3-a | 3-b | 3-c | 3-d | 3-e | 3-f |
| 4. Navigation | 4-a | 4-b | 4-c | 4-d | 4-e | 4-f |
| 5. Emergency procedures | 5-a | 5-b | 5-c | 5-d | 5-e | 5-f |
| 6. Flight control | 6-a | 6-b | 6-c | 6-d | 6-e | 6-f |

6-d Flight control during attack

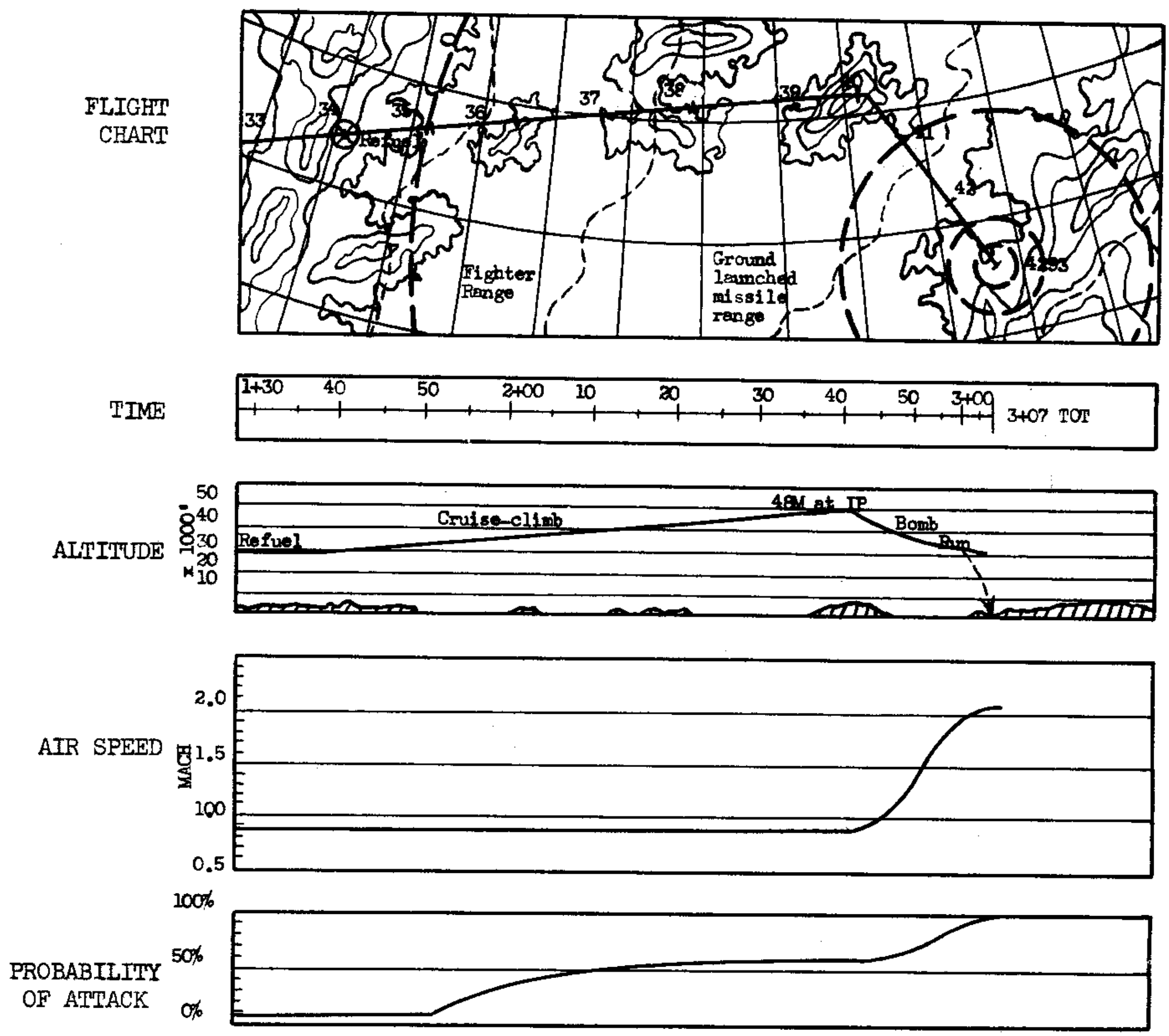
Tolerances: Pitch ±2°, Yaw ±1°, Roll ±3°, Airspeed ±2kts.
Must permit near-simultaneous attack by up to 3 interceptors.

| Alternative Capabilities | Strong Points | Weak Points |
|---|---|---|
| Pilot control | Good reliability, few gross deviations.<br>Evasion maneuvers easy to program.<br>Good flexibility in meeting contingencies. | Man should be freed of routine flight control to concentrate on tactical decisions.<br>Vulnerable to enemy attack and unfavorable environment. |
| Ground operator | Performance immune from all enemy defenses except ECM. Good over-all picture of tactical pattern.<br>Good flexibility. | Unreliability of target information and control signal.<br>Lack of accuracy when bomber nears target. |
| Automatic ground control | Control center not vulnerable to enemy attack.<br>Fine tolerances can be built in.<br>Rapid, accurate data-processing. | Poor flexibility in meeting contingencies.<br>Subject to equipment malfunctions.<br>Subject to jamming. |
| Automatic control within air vehicle | Fine tolerance can be built in.<br>Rapid, accurate data-processing.<br>Relatively invulnerable to enemy jamming. | Poor flexibility in meeting contingencies.<br>Subject to equipment malfunction.<br>Subject to environmental and enemy damage. |

* The top table shows how requirements may be matched to mission segments. The resulting cells, one of which has been expanded in the bottom table, provide a basis for evaluating which of a number of alternative capabilities will be most effective in meeting a requirement for a particular mission segment. For example, the flight control requirement during the attack segment can be fulfilled by pilot control, a ground operator and so on. When matched against the tolerances for flight control during attack each of these possibilities has shortcomings. The final selection is based on that capability which will provide the most effective flight control for the attack as well as for other segments.

** Cells having the same tolerances and alternative capabilities can be combined.

SAMPLE MISSION PROFILE
ATTACK SEGMENT FOR A HYPOTHETICAL BOMBER SYSTEM




System Areas

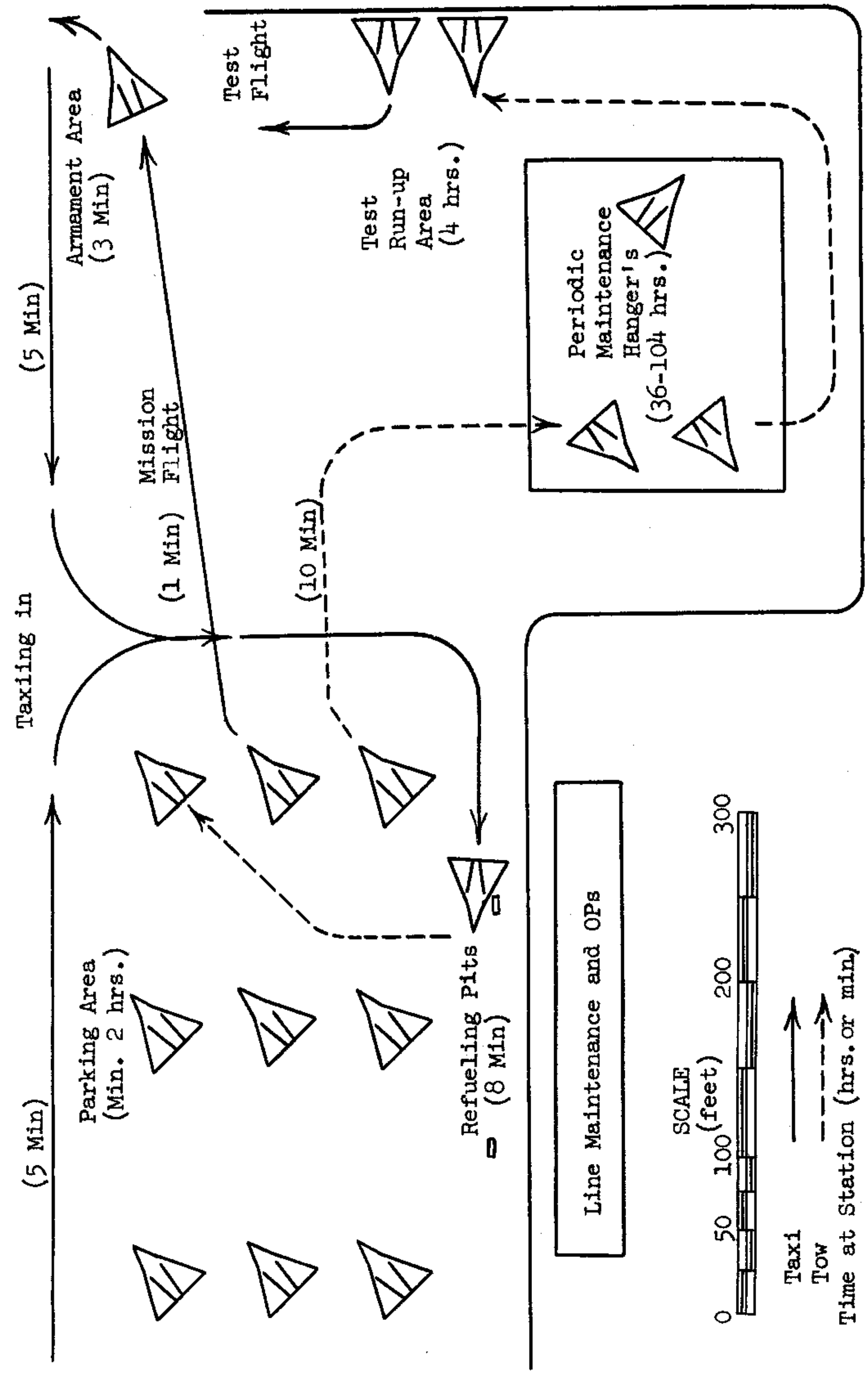
1. Propulsion
2. Communication
3. Fire control
4. Navigation
5. Emergency
6. Flight control

NOTE: Capabilities will be indexed to these areas according to procedures presented in Chapter 4.

● Functions Analysis
Sample Flow Chart

SAMPLE FLOW CHART

FIGHTER GROUND SUPPORT



CHAPTER 4

# FUNCTIONS ALLOCATION

content

Step 6 - Allocate functions within the airborne vehicle
Step 7 - Allocate functions within the ground support area
Step 8 - Perform a time and link analysis
Step 9 - Assign functions to individual crewmembers
Step 10- Initiate research as indicated

## Overview

A function of a system is any human or instrumented capability, or a combination of these, that may be used to satisfy a system requirement.

This chapter describes the steps to be taken in allocating functions to men and equipment and in assigning functions to individual crewmen. These steps include: (a) the allocation of functions within the airborne vehicle, (b) the allocation of functions for ground support, (c) time and link analysis, and (d) the assignment of functions to individual operators, maintenance and ground support personnel.

In some systems functions will have been allocated in the preparation of the Development Plan without human engineering consultation. This is often the case when a new system is to be a modification of a previous, similar system. In a few cases the number of men, especially those in the airborne vehicle, may also be specified as a requirement as early as the GOR or Development Plan. Ordinarily, it will be necessary to perform the steps described in this chapter as a check on the adequacy of these initial decisions.

- Step 6 - Allocate Functions Within the Airborne Vehicle

The purpose of this step is to decide whether there will be humans in the airborne vehicle and to determine what they will do if a human capability is assigned to it.

Decisions as to whether a given function will be instrumented or fulfilled by a human operator should be based on where that function falls in the mission, the best available knowledge concerning the capability, reliability and maintainability of equipment that might be incorporated in the weapon, and the best available knowledge concerning the capability of the human operator to perform the function(s) in question.

Functions should not be allocated on the basis of present AFSC's or current aircraft manning concepts. A fresh viewpoint is essential, and when compromises are necessary they should be made much later in the development program. Further, no attempt should be made to combine functions in a single individual at this time.

Will There Be a Man?

The inclusion of a human in modern weapon systems is more often a matter of necessity than choice. There is little reason to believe that any weapon of the near future will wholly dispense with human components for both operations and maintenance.

Unless provision can be made to eliminate the effects of expected environments, serious consideration should be given to ruling out man in those portions of systems where environments exist which:

1. are physiologically damaging,
2. are unnecessarily dangerous,
3. are physically uncomfortable,
4. tend to reduce motivation and alertness.

What Will the Man Do?

Once a decision has been made that there will be a man in any particular portion of the system, his role in fulfilling the required functions must be considered.

The functions of the operator in current systems fall into two broad categories: intrasystem and suprasystem (5). As an intrasystem element the operator may be treated as a component in a more or less selfcontained system in which he serves as a detection and control element while the equipment provides power and a means of actuation. As a suprasystem element the operator provides the flexibility of programming and decision making required to meet contingencies lacking in non-human system elements, and acts as an intermittent servo in the performance of a number of different systems or equipments. In this later capacity, the function of the operator may cut across several different requirement areas.

Examine the human operator with respect to each of these categories of function, comparing him with equipment which could fulfill the same functions automatically. This requires a survey of the kinds of things that men can do better than present-day machines, and vice versa.

Humans appear to be relatively superior to machines, in terms of our present understanding of human and equipment capabilities, with respect to the following (9, 30):

1. Ability to handle low probability alternatives (i.e., unexpected events), but they cannot always be expected to follow optimum strategies.
2. Ability to use perceptual constancies (e.g., to recognize objects and places despite varying conditions of perception).
3. Ability to use sequential dependencies in the real work (i.e., may profit from experience).
4. Sensitivity to a wide variety of stimuli; range of sensitivity, however, is restricted.
5. Originality in putting to use incidental intelligence picked up during the course of a mission.
6. Detecting signals in an overlapping noise spectrum (e.g., difficult to jam through ECM).
7. Capability for improvising and adopting flexible procedures (e.g., can reprogram easily and quickly; can vary performance tolerances readily).
8. Capability for tracking in a wide variety of situations, despite relatively poor tracking ability.
9. Capability to perform under some conditions of over-load and ability to select own inputs.
10. Ability to reason inductively (i.e., to make generalizations from specific observations)

Humans are relatively poor, with respect to machines, for the following:

1. Monitoring other men or machines.

2. Exerting large amounts of force smoothly and precisely.

3. Performing routine, repetitive tasks.

4. Computing and handling large amounts of stored information.

5. Ability to reason deductively (i.e., to use rules for processing information).

6. Responding quickly to control signals.

Human Limitations

In a subsequent chapter (Chapter 9) detailed attention is given to the problems of human capabilities and limitations. Here we have listed a few of the conditions which are likely to result in human error and which may serve as a basis for excluding man from the performance of certain functions:

1. Perceptual requirements which are beyond or near physiological limits or which conflict with established habit patterns.

2. Response requirements which are physically difficult, conflict with established habit patterns or which cannot be readily checked or monitored for their adequacy.

3. Decisions which require undue reliance on memory, must be preceded by extensive organization of information, or must be accomplished in too short a time in view of other necessary activities.

4. Communication requirements which interfere with other activities.

5. Tasks which over-load the human, which result in inadequate work load distribution during a mission or do not permit adequate or timely monitoring of mission status.

Index Capabilities to Requirement Areas

Examine the strong and weak points of each human and equipment capability remaining after the initial screening conducted in the previous chapter.

Take into account the general principles for allocating functions. Use as a basic point of reference the mission profiles. Supplement these data with the results of research, previous experience with similar systems, and interviews with training officials and operational personnel.

Insert under each mission segment that single set of capabilities most likely to satisfy each requirement. Take into account all of the critical changes and other conditions likely to obtain during each mission segment. This is obviously a critical point, and one which cannot be reduced to formula and should not be prescribed by fiat. More often than not good insight into the kinds of problems that can occur on a mission will be the best source of information. For example, extensive operation over ice would reduce the usefulness of radar dead reckoning. It would be necessary to provide an alternative capability for at least that portion of the mission.

For a detailed discussion of basic mechanical and human factors requirements for ground support equipment, see ARDC Manual 80-6, Handbook of Instructions for Aircraft Ground Support Equipment Designers.

## • Step 7 - Allocate Functions Within the Ground Support Area

The purpose of this step is to decide what kinds of activities will be performed by humans in the ground support area.

Using the mission data obtained in the previous chapter, allocate functions within the ground support area. Many of the principles suggested for the allocation of functions within the airborne vehicle will be applicable.

Consider the effects of the following factors on the capabilities provisionally allocated to ground support and to their performance:

1. Temperature
2. Moisture
3. Atmospheric pressure
4. Snow and ice
5. Sand and dust
6. Growth potential
7. Training time
8. Safety
9. Interchangeability
10. Manpower resources

## • Step 8 - Perform a Time and Link Analysis

A time and link analysis is an analysis of the number and duration of activities assigned to each potential element of a system. It provides an overview of what the crew component is expected to do at each point in the mission, an outline of the process of information exchange among men and between men and equipment, and data useful in the determination of crew size for each major component of the system. A major component of the system is a self-contained unit, such as the airborne vehicle or air traffic control station, in which a human is expected to perform.

### Outline Tentative Control-Display Needs

Do not be concerned with either the location or detailed characteristics of displays and controls. What is essential is the kind, frequency and duration of the discriminations and responses that will be expected of the human. These can only be inferred from an analysis of controls and displays.

Examine the list of human and equipment capabilities, and list the classes of displays and controls needed by the crew. This tentative list is a natural outgrowth of the information exchange process discussed above.

Group the provisional displays and controls under the requirement or subrequirement areas to which they refer.

## Prepare Time-Line Charts

For each requirement area prepare a time-line chart marked off into intervals not greater than ten minutes, with shorter intervals used as required. These time lines are detailed time bases of the mission profiles devised earlier. Index the control and display operations necessary for each requirement area to their respective time intervals.

Where computation or decision making precede or coincide with an operation and require an appreciable period of time, attempt to estimate their duration and code them to the time-line chart. It will be necessary to make some "best guesses" during this process because of the lack of detailed design information.

Group each requirement area and its time chart under the major component of the system to which it refers. Thus, there may be separate charts for operation of the airborne vehicle, for air traffic control, and for other ground support areas such as maintenance. See p. 47 for a sample time-line chart.

## Determine Points of Under- and Over-Load

Examine the time-line charts for each major component of the system and mark off those portions of the mission where significant under- or over-loading occurs.

Attempt to estimate the consequences of these under- and over-loads on the performance of the human and upon the total system and mission. Some factors that should be considered are:

1. Increased human or equipment error on an immediate or subsubsequent task.
2. Conflict of habit patterns.
3. Decreased flexibility of operator or system.
4. Consequence of over- or under-load on morale and motivation.
5. Possibility of redistributing the over-load activity in time.

Evaluate Linkage Values for Tentative Controls and Displays

Evaluate for each control and display how critical the links between it and the human operator are. This criticalness will be dependent upon at least the following factors:

1. Apparent difficulty of the operation involved.
2. Likely effect of errors on system performance and the likelihood that errors will occur.
3. Speed, accuracy and, where applicable, force required of the operator.
4. Total time in use.
5. Frequency of use.

Indicate appropriate values for each of the above factors for each control and display. In most cases precise data will not be available, and reliance must be placed on the best judgments that can be made. It may be useful to provide some type of over-all rating or ranking, but the fallibility of these over-all evaluations must be kept in mind during later use of link-analysis data.

To the extent possible, place the tentative controls and displays into groups which represent the operational modules of the various subsystems under each requirement area (e.g., engine instruments, engine controls). These groupings are for the convenience of the design team only and must not be taken as the final product.

• Step 9 - Assign Functions to Individual Crewmembers

Inspection of the revised time-line charts and examination of the nature and variety of the operational modules will suggest at least a first approximation to the crew size required for each major component of the system.

This approximation is refined through the process of assigning functions to individual crewmen. This estimate should represent the very minimum, but not necessarily an optimum crew size, and should be increased only when it becomes apparent that system effectiveness will be increased.

If, in any major component of the system, reducing human requirements by automatization or shifting of required functions to different points in the mission would reduce the number of men required, consideration should be given to these alternatives. Remember that reliability requirements may demand redundancy, and this may increase the number of men required.

Major System Components Requiring Only One Man

For major components of the system requiring only one man the problem reduces to assigning the controls and displays tentative spatial positions in a workplace. This assignment will help to answer two very important questions:

1. Can all of the required operational modules, controls, and displays be integrated into a workplace for one man?

2. Within the workplace provided will the man be able to do all of the things required of him?

If the answer to either of these questions is "no," it will be necessary to do one or more of the following:

1. Redesign controls and displays.

2. Automatize additional functions or shift their time of performance in the mission.

3. Add another man. (This will require a re-evaluation and revision of the previous steps.)

Considerations in Assigning Functions to Crewmembers

Although the paramount consideration is the total effectiveness of the system, there are certain auxiliary goals to achieve in assigning functions to crewmembers. Achievement of some may, at times, be antagonistic to achievement of others, so compromises may be required. Some of these auxiliary considerations are:

1. Keep skill requirements to a minimum.

2. In major components requiring more than one man, distribute the work load so similar skills are allocated to the same operator. This will minimize training requirements.

3. Assign functions in such a way as to facilitate crew coordination.

4. Make new configurations of displays and controls as similar to previous equipments as is compatible with good human engineering. This will keep difficulties in transitioning operators to a minimum.

5. Assign all of the controls and displays for a particular subsystem to the same operator. This will tend to keep problems of linkage between equipment and controls and displays to a minimum. It will also tend to insure that closely related functions will be required of a single operator.

6. If an operator has a reduced work load during certain parts of the mission, consider assigning redundant functions to him during these periods. For example, a bom-nav man may be assigned monitoring of flight instruments during landing and takeoff.

Spatial Allocation of Controls and Displays

It will be desirable to assign tentative workplace positions to modules, controls, and displays as they are allocated to the various operators. Tentative spatial assignments will have to be revised with the allocation of additional components to the workplace. Factors which affect spatial assignment follow:

1. Modules, controls, or displays which are not used for much of the mission but are highly critical in other respects may be placed in positions which are relatively inaccessible, if such placement does not increase the likelihood of error.

2. Previously developed equipment which will be incorporated into the new system may already contain controls and displays in a pre-established configuration. Redesign of such equipment may be unnecessary or unfeasible.

3. Linkages between equipment and controls and displays, particularly mechanical linkages, may restrict the possible locations of various control-display items.

4. The general configuration of the housing within which the workplace must be laid out may restrict available space.

It may be useful in this preliminary allocation of controls and displays to use a mockup of each crew position. Since detailed design of work space layouts cannot be accomplished until later, a simple and inexpensive cardboard mockup of the workplace is probably adequate at this stage. Such mockups are necessary to visualize a three dimensional work area and permit easy and rapid shifting of control-display items from one position to another.

• Step 10 - Initiate Research as Indicated

One type of research that can be initiated at this time is that of answering the question "how much can a man do without performance decrement?" It will supplement under- and overload analysis with experimental data.

It will not be feasible at this stage to provide close simulation of the functional characteristics for each subsystem. Nevertheless, it may be desirable to run through a number of sample missions with the best mockup available--even if all of the controls and displays are merely pictured and entirely nonfunctional. It will usually be possible to obtain a fair degree of simulation by making use of items from training devices, simulators, and operational equipment from similar previous systems.

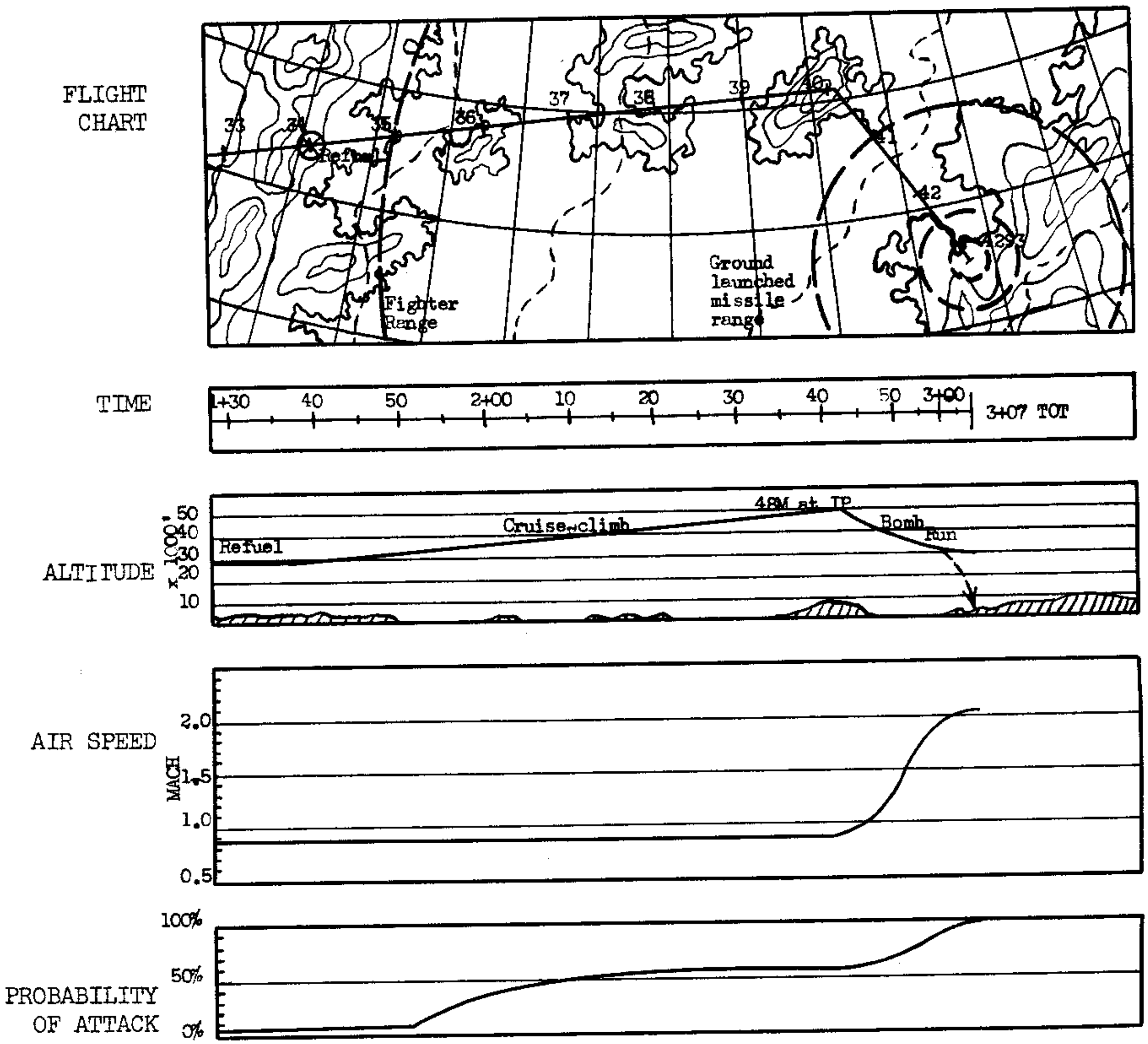
For simulated tracking operations it is necessary that concurrent tasks be as demanding as they will be in the operational situation. The most valuable sort of information obtainable from this type research is an indication of performance decrements due to operator over-load.

Regardless of the degree of simulation which can be achieved at this point, the experimenter must carefully program experimental missions. If units are functional, the information can be programmed into the displays, and control responses can be measured directly. If a mockup containing nonfunctional units must be used, the experimenter will have to provide verbal cues, and the subject will have to simulate the reading of displays and the making of control responses.

The experimental missions should vary from routine and uneventful ones, to the most difficult mission which can be anticipated. If performance does not break down under the most difficult conditions, the proposed allocation of functions can probably be accepted. If performance decrement does occur under any of the conditions, modification of the proposed allocation will be required.

It is also desirable at this point to obtain information on the standard times required to perform particular operations. Where these times can be obtained from equipment already in operational use, they will serve as a basis for determining standard times for new systems. These times will provide an indication of how long it takes to perform particular activity sequences, and will be especially useful in establishing optimal performance strategies for critical portions of a mission.

SAMPLE MISSION PROFILE
ATTACK SEGMENT FOR A HYPOTHETICAL BOMBER SYSTEM




Areas

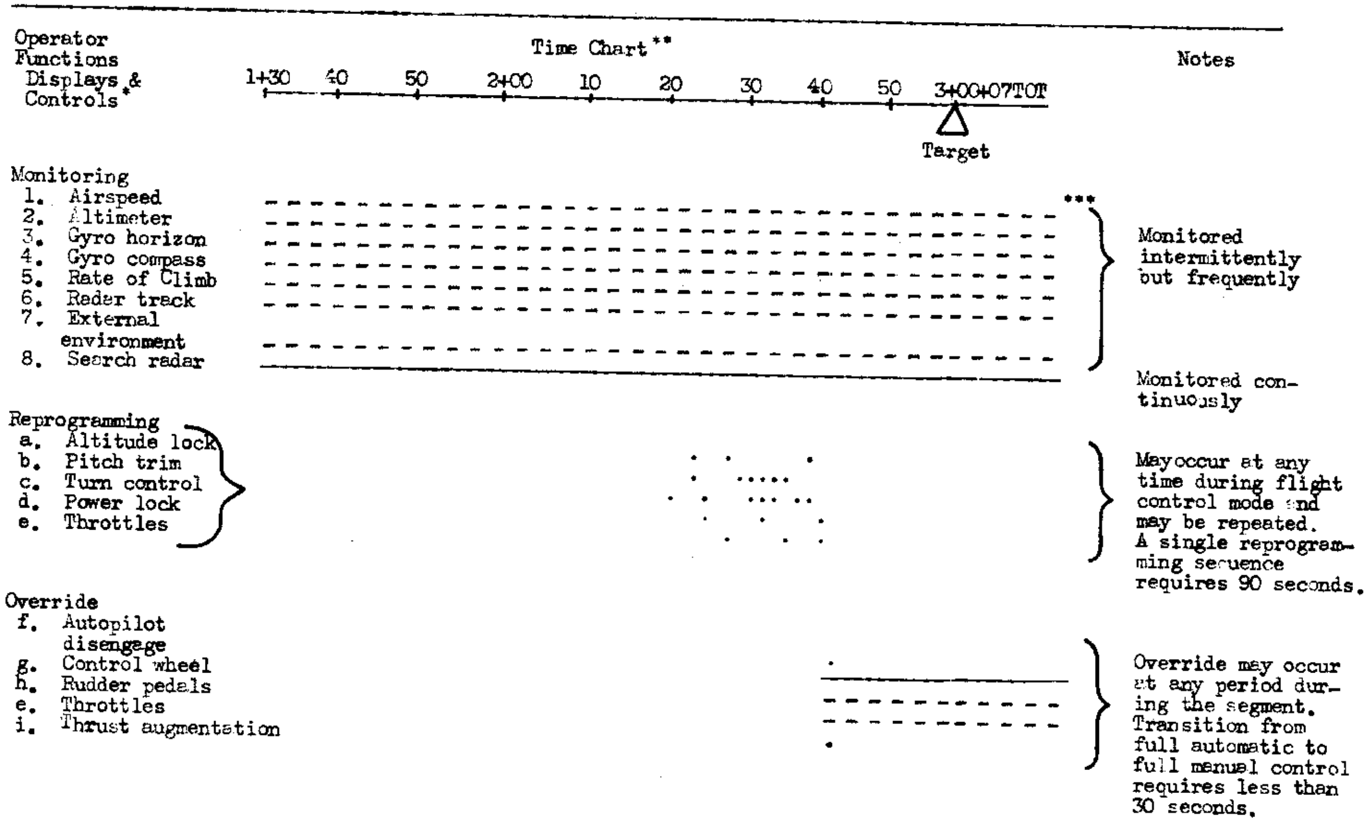
1. Propulsion
2. Communication
3. Fire control
4. Navigation
5. Emergency procedures

} The set of capabilities judged to be best for fulfilling each of these areas would be indexed in a manner similar to "flight control" below.

6. Flight control - Flight will be controlled by automatic equipment housed within the air vehicle. The operator will be able to override or reprogram the flight control system. The operator's decision to override will be based on his conclusion that the system is not performing adequately. His decision to reprogram will be based on tactical considerations.

Sample Time-Line Chart

Mission Segment – Attack
Requirement – Flight Control

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* Display items are numbered and control items lettered. These designations are useful in identifying a control or display in one function as the same item in another function.

** Time scale should conform to the time scale under flight map for the segment—converted to a linear scale.

*** Solid lines indicate continuous tasks; dashed lines indicate tasks performed frequently but not continuously; dots indicate discrete tasks.

CHAPTER 5

# OPERATOR PERFORMANCE DESCRIPTION

content

Step 11 - Prepare performance descriptions
Step 12 - Analyze individual operator work-loads
Step 13 - Study operator-to-operator contacts
Step 14 - Perform operator research

## Overview

Operator performance descriptions provide a valuable source of data for the delineation of usable work areas, layout of work space, design of controls, displays, instrument panels, and auxiliary job supports and preparation of work procedures. Indirectly, these descriptions also imply a great deal about the skills and knowledges needed to perform a given job and may serve as a basis for preparing training and training equipment characteristics.

This chapter suggests the steps to be taken in: (a) preparing useful operator performance descriptions, (b) analyzing individual operator workload, and (c) studying the relation of each operator to other operators. By "operator" is meant any individual who participates in the active operation or support of a weapon system.

Incomplete or poor performance descriptions may offset the benefits of otherwise good human engineering. To be of maximum use, these descriptions should be undertaken as soon as functions have been assigned to individual crewmembers. They should be reviewed and revised as detailed data become available.

In some of the concepts used in this step new terms or different uses of familiar terms may be found. It should be remembered that the function of these concepts is to provide a convenient, though somewhat arbitrary, basis for preceding from the general work cycles to the specific elements of a job. They do not represent absolute behavioral units.

## • Step 11 - Prepare Performance Descriptions

Operator performance descriptions have the following human engineering uses: (a) they provide a basis for identifying difficult or error-likely situations, (b) they provide data useful in detecting performance over- or under-load, (c) they serve as a basis for the preparation of procedures, (d) they provide data useful in the design of modules, controls and displays.

Major sources of information for preparing operator performance descriptions, in the order in which they are normally available, include: (a) experience with similar systems, (b) human engineering working papers resulting from the application of procedures outlined in Chapters 3 and 4, (c) blueprints and engineering drawings, (d) mockups, (e) research simulators, and test models.

### Identify Operator Work Cycles

A work cycle is a group of activities, having a common goal, performed by a given operator during a mission or mission segment. A work cycle represents the first, most molar item needed in the preparation of operator performance descriptions.

Ordinarily a work cycle will coincide with a mission segment and will describe the activities performed by a given operator during that segment.

Use a brief descriptive term or phrase to describe each operator work cycle. For example, during preflight maintenance one mechanic may "check out the weapon." Another may "check out the fuel and hydraulic system."

A work cycle will often coincide with an operator function. However, a work cycle may contain more than one function. It differs from a function in that it represents the temporal sequence in which activities are to be performed. A function represents a group of activities having a common goal but where the activities may not necessarily be performed consecutively.

Should it become apparent that a particular work cycle is the same as a cycle in a previous, similar system, it may not be necessary to go into further detail if the following conditions are met:

1. The activities within the cycle are the same as those on a previous similar system.
2. The equipment used is the same.
3. No new problems of communication, supervision or interaction are anticipated.
4. Cycles preceding and following the work cycle do not impose new requirements on activities within the cycle.
5. No new time-sharing requirements are to be met.

Identify Operator Tasks

An operator task designates a group of related activities performed within a work cycle. A task may occur more than once during a work cycle or mission.

Give each task a brief title to indicate what behaviors must be performed within the task. For example, the "loading" work cycle for a missile support operator might include such tasks as:

1. Removes weapon from storage.
2. Hoists weapon to transport vehicle.
3. Drives transport vehicle to launch pad.
4. Hoists weapon from transport vehicle to launcher.
5. Checks for proper seating of missile in launcher.

The level of detail possible in designating individual operator tasks will depend upon the extent to which tasks can be inferred from available information.

Again, it should be mentioned that the extent to which tasks are spelled out in detail for a given operator depends on whether or not the tasks are ones which are known on the basis of previous experience with similar systems.

Identify Job Elements

A job element is an arbitrary term used to designate the perceptions, decisions and responses required to complete a task. A particular job element may and usually does occur more than once during a task.

Job elements are relatively basic units of behavior. As such they will be useful in determining with considerable precision performance requirements, equipment design requirements, and the kinds of difficulties or errors the operator is likely to encounter in the performance of a job.

A complete description of job elements for a particular operator should contain the exact sequence of interactions between the operator and his equipment and between one operator and other operators. However, descriptions of performance need be carried only to a level of detail which will be of value in later evaluations of operator work load, in the design of displays and controls, or in the preparation of technical orders and training requirements.

Items which should be considered if the job elements for a particular operator are to be described should include at least the following:

1. Signals or other indications that inform the operator that a job element needs to be performed.

2. Temporal relationships to other job elements performed before, with or after the element.

3. Information needed to initiate a particular control action, including information from recall, from the environment or from other operators.

4. Decisions or calculations to be made in selecting a control action.

5. The controls to be activated and the actions to be performed.

6. Indications that tell whether or not a response was adequate.

7. Time, accuracy or other criteria imposed upon the job element.

8. Action to be taken if a response is inadequate.

Tasks may be arbitrarily divided into two groups: discontinuous and continuous. A discontinuous task involves a series of discrete steps, e.g., throwing a series of toggle switches. A continuous task does not involve discrete steps but target seeking or tracking (e.g., vehicle steering). A sample format for describing job elements in a discontinuous task is presented on page 57. This sample is presented in somewhat greater detail than will normally be required except for the most critical tasks. More detailed information on describing operator performance may be found in other sources (19, 20).

Prepare Operator Time-Line Charts

Show the duration of work cycles and tasks along mission time lines, marked off into manageable intervals. The duration of these intervals will vary depending upon the portion of the mission being examined. Indicate on this chart the duration of each work cycle and task by horizontal lines paralleling the mission time base line. Indicate mission segments by vertical lines cutting through task and work cycle lines. See page 58 for a sample operator time-line chart.

Tasks and work cycles shown on the time chart should be indexed to descriptions of work cycles, tasks, and job elements. The time-line chart provides a valuable aid to the analysis of individual operator work loads when used to supplement descriptions of work cycles, tasks, and job elements.

• Step 12 - Analyze Individual Operator Work Loads

At this point, the performance descriptions of each operator should be rechecked to insure that no operator is over-loaded at any time during the mission. Design and subsequent manning considerations must be aimed at those portions of the mission where performance demands are heaviest.

If a careful analysis of factors, such as that suggested in Step 6, reveals that performance requirements are excessive for any operator at any time during the mission, modify plans by redistributing or simplifying tasks.

• Step 13 - Study Operator-to-Operator Contacts

The study of operator-to-operator contacts is aimed toward optimizing communications among men in the system. This step should include at least the following:

1. Prepare a description of communications between major components of the system containing one or more men.

2. Prepare a description of communications within each major component containing two or more men.

3. Index messages identified in communications descriptions to a time-line chart.

4. Analyze communications descriptions and time-line charts, in conjunction with operator performance descriptions, to determine how communications among men in the system might be improved.

Descriptions of communications, both between and within major components, should contain at least the following for each message:

1. A code symbol to be used later in indexing the message to a communications time-line chart.

2. An indication of when during the mission the message is sent.

3. The sender and the receiver of the message.

4. Mode of communication; e.g., radio, intercom, direct voice, direct visual.

5. Nature of message; e.g., command, request for information, information to be used immediately or later in making a decision, aid to recall of procedures.

6. Content of message; wherever possible use the words or code signals that will be used.

7. Contingencies which dictate whether or not the message is transmitted.

Preparation of these descriptions should be more than a simple recording of previous decisions. It presents an excellent opportunity to evaluate, revise and supplement previous decisions concerning man-man interactions.

The communications time-line chart provides a convenient summary of communications load and suggests possible over-loads for the operator. When used in conjunction with communications descriptions and operator performance descriptions, they can be a valuable aid to the early diagnosis of inadequate communications design.

● Step 14 - Perform Operator Research

It may become apparent in the preparation of operator performance descriptions that certain tasks or job elements impose unusual performance requirements on the operator. At this point research should have as its aim the determination of the factors that produce performance errors as well as the study of ways in which errors may be reduced or eliminated.

Three important factors which must be considered in designing research studies at this point are: (a) sampling, (b) experimental controls, and (c) applicability of results. For further details concerning the conduct of human engineering studies refer to Chapanis (6) and to his bibliography.

Sample Format for Describing Discontinuous Tasks

Operator: Line Mechanic - Fire Control System

Work Cycle: 1 Adjust System Voltages. Performed every 25 hours a/c operation.
Task: 1.1 Adjust Power Supply Regulated Voltages. Requires 40 minutes. If any of the specified indications cannot be obtained, replace Power Supply unit - see Task 5.2.

| Job Element | Control | Action | Indication | Alternatives and/or Precautions |
|---|---|---|---|---|
| 1.1.1 | POWER switch | Turn to WARM UP | Inverter hums, pilot light comes on | Make sure covers are on high voltage units before starting task. |
| 1.1.2 | AC VOLTAGE (screwdriver) | Turn as required | AC voltmeter aligns to 117 ±4 volts | |
| 1.1.3 | | Wait maximum of 5 minutes | READY light comes on | If READY light does not come on, use press to test button. If light is burned out, replace it. |
| 1.1.4 | METER SELECTOR switch | Turn to 300 | | |
| 1.1.5 | +300 VOLTS ADJ. (screwdriver) | Turn as required | Meter indicates within green area | |
| 1.1.6 | METER SELECTOR switch | Turn to -150 | | |
| 1.1.7 | -150 VOLTS ADJ. (screwdriver | Turn as required | Meter indicates within green area | |

Sample Format for Describing Continuous Tasks

Operator: Pilot. F-1000 Interceptor
Work Cycle: 1 Climbing to altitude as directed by Ground Control
1.1 Accelerating to climb speed (in shortest possible time and in most favorable position to destroy unidentified aircraft).

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Job Element Variables

INPUTS

Needed input information:
1. Position, speed, and direction of unidentified aircraft (Provided by Ground Control).
2. Friendly or unfriendly aircraft.
3. Amount of fuel.
4. Position, speed, and heating of interceptor.

Disruptive or irrelevant inputs:
1. Air turbulence.
2. Background chatter from Ground Control.
3. Radio static.
4. Enemy jamming.

Critical time characteristics of inputs:
1. If fuel is limited, intercept may have to be made before the most favorable position for attack can be reached.

DECISIONS
1. Best course to follow in accelerating to climb speed.
2. When climb speed has been reached.

REQUIRED CONTROL ACTIONS

| Controls: | Actions: |
|---|---|
| 1. Control stick. | Standard-power boost and artificial back pressure. |
| 2. Rudder pedals. | Standard-power boost and artificial back pressure. |
| 3. Throttle. | Standard. |

FEEDBACK

Indications of adequacy of actions:
1. Airspeed indicator reads attained speed.
2. Direction indicator reads desired heading.
3. Attitude indicator shows level flight.

Delay, action to indication:
1. Airspeed indicator lags about two seconds during rapid acceleration.
2. Direction and attitude indicators have lag of less than .5 second.

CHARACTERISTIC ERRORS AND MALFUNCTIONS

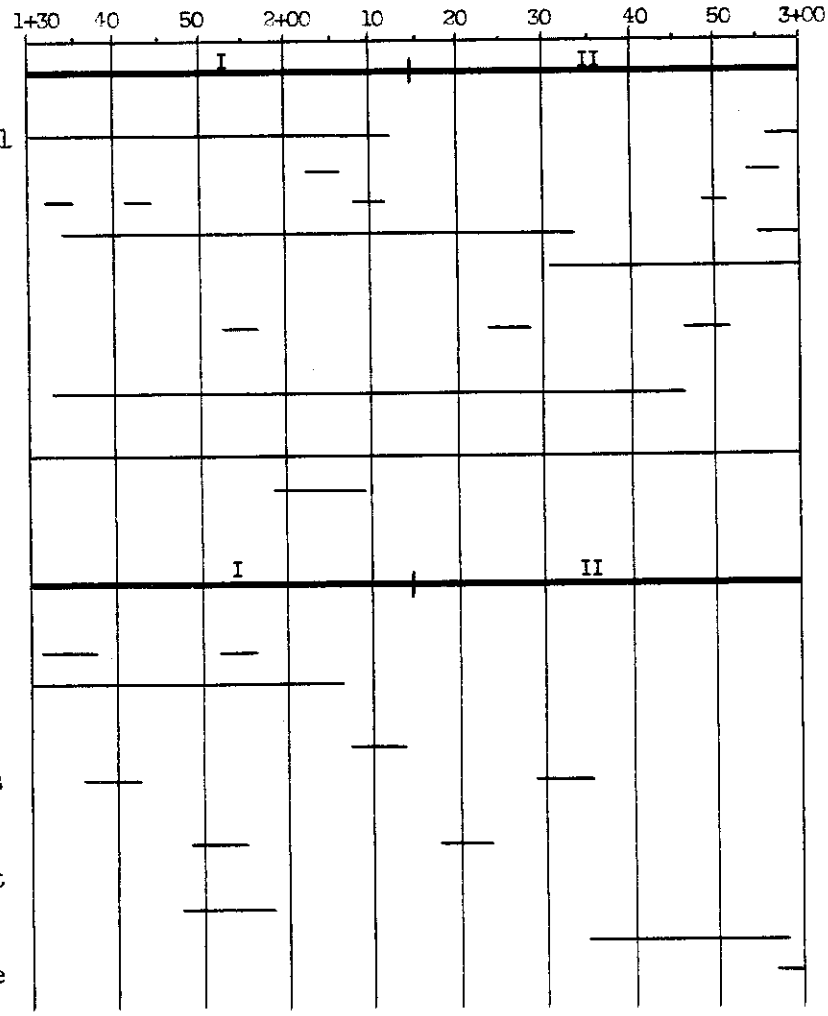
Climb may be started later than is efficient because of airspeed indicator lag.

CONTINGENCIES WHICH WILL AFFECT TASK

| Contingencies: | Effects on task: |
|---|---|
| 1. Ground Control loses target. | Pilot must decide whether to attempt unaided intercept or return to base. |
| 2. Target changes course. | Acceleration course may have to be revised. |
| 3. Ground Control detects escorts. | Attack attitude revised, changing point at which climb to altitude is started. |
| 4. Malfunction occurs. | Must decide whether or not to abort. |

Sample Operator Time-Line Chart*

Attack Segment for a Hypothetical Bomber System




Work Cycles
Pilot Tasks
1. Manual aircraft control
2. Autopilot adjustment
3. Trim actuation
4. Contact navigation
5. Radar navigation
6. Fuel management procedures
7. Scanning for aircraft emergencies
8. Scanning for enemy fighter
9. Bomb arming checkout

Bom-nav Work Cycles
Bom-nav Tasks
1. BNS checkout
2. Computer programming
3. BNS - autopilot lock in
4. Bomb drop computations
5. Ordinance arming procedures
6. Photographic equipment checkout
7. Bomb run tracking
8. BNS recycle and secure

---

* Tasks falling in work cycles are plotted along a time base. The duration of each task is indicated by a solid line. Heavy solid lines indicate work cycles.

CHAPTER 6

# WORK SPACE LAYOUT

content

Step 15 - Delineate usable crew station work areas

Step 16 - Delineate usable work areas within crew stations

Step 17 - Determine the location and installation of components

Step 18 - Perform research on alternative work space layouts

## Overview

This chapter describes the steps to be taken in determining the optimal allocation of space and arrangement of equipment for human use. These steps include: (a) the delineation of usable work areas for crew stations, (b) the delineation of specific work areas within crew stations, and (c) the location and installation of subsystems and components.

The advantages of effectively designed modules, controls or displays are realized to the extent that these units are properly located in the operator's work area. Although detailed design of units may begin simultaneously with the design of work spaces, final decisions on control and display design will be determined by their location.

## • Step 15 - Delineate Usable Crew Station Work Areas

The objective of this step is to decide what portions of a system may be allocated to crew stations. A usable crew station work area is defined as that space required by an individual wearing standard clothing and personal equipment to perform the movements demanded by a job. It should include:

1. Space for the human component and his display-control system.
2. Unobstructed free space for required hand or leg control movements.
3. Space for walking and seeing links between operators and/or equipment, if applicable.
4. Space or provision for quick entrance to and exit from the work area.

In accordance with Air Force policy on crew interchangeability, an operator of any size, wearing standard clothing and personal equipment, should be able to operate in any crew station (18). Exceptions for specialized flight categories are contained in AFM 160-1.

### Considerations for Allocating Work Space

Compromise between adequate space for human performance and practical limits imposed upon this space by major subsystems and components is usually unavoidable. Where compromise can be reached without affecting size, weight and center of gravity factors, the allocation of work space for the human component should take into account the following factors:

1. The visibility and movement requirements of a job.
2. The effects of intense acoustical noise, vibration and likely mechanical or toxological hazards.
3. Morale in terms of subjective feelings of confinement, restriction.

4. Emergency escape.

5. Human and equipment traffic flow.

6. Safety.

Specific requirements for the minimal allowable dimensions for work areas may be found in a number of sources (8, 13). Recent body size data are also available (12). The Air Force has suggested that plastic manikins be used to test the adequacy of work space allocations. Consideration must also be given to access dimensions which permit rapid and unimpaired removal or insertion of parts, tools and hands. It should be noted that work areas may need to be designed for greatly restricted movements, such as a pilot wearing a pressurized pressure suit. This would require especially well positioned emergency controls.

The most important consideration in allocating space for human use is the job the man is to perform. In aircraft, for example, the pilot and copilot require maximum external visibility. The flight engineer, radio or radar operator require little or no window space. Maximum use should be made of operator performance descriptions in determining work space needs for operators.

Construct Flow Charts

Construct a flow chart for each separate major component of the system involving human operators as an integral part. This chart should contain the following features:

1. A scale diagram of the component.

2. The location of fixed or non-portable facilities and the space occupied by them.

3. Windows, doors and escape exits, if applicable and known.

To this chart, add the following, and consider how each affects the operation of the man and the total system:

1. Human and equipment traffic flow patterns.

2. Talking and seeing links.

Where and how much space is required for each individual operator in the unit must be considered in the layout of equipment.

For each alternative arrangement of equipment and men determine the likelihood of breakdowns due to factors such as dense traffic flow, emergency escape, and transportation of bulky items of equipment. Consider any unique or nonstandard arrangement that will tend to optimize performance and reduce breakdowns.

Determine the space requirements for each operator, and indicate these by circles or dotted lines on the charts. If necessary, construct three dimensional models (e.g., aircraft interiors, shops, etc.) to test alternative arrangements.

Revise the work space flow charts as additional, more detailed information becomes available or changes take place in the design of the system.

## • Step 16 - Delineate Usable Work Areas Within Crew Stations

The objective of this step is to delineate within those areas allocated as crew stations, specific work areas for individual operators. Using the flow charts described above, determine, for a given crew or operator station, what portion of the total space will be usable by the operator. This space will include room for components, operator control movements, and auxiliary equipment. Allowance must be made for windows, exits and maintenance and servicing.

In an ideal work space the most frequently used and important displays and controls would be placed immediately in front of the operator. The less frequently used or less important displays will be located to the right and left. This arrangement requires a minimum amount of reaching and head turning.

When additional displays and controls must be added to this ideal work space, consideration should be given to placing equipment on the ceiling but within easy reach and view of the operator. Controls or displays out of the visual field or requiring rotation of the body will be less readily used in terms of operator time, accuracy and comfort.

In the workplace area, delineate features required by the operator: seating, controls, fixed escape dimensions, windows, displays, lighting, etc. On the basis of operator performance descriptions, place these in the most optimal arrangement, making compromises when necessary. Consider any unique or novel arrangement, that may increase the efficiency, speed and accuracy of the operator's performance. Take into account how the use of the work space may be affected by events occurring during the course of a mission as well as tasks and job element requirements (e.g., loss of cabin pressure, sustained buffeting, lightning).

There will be more freedom in delineating usable work areas for ground support than for a manned air vehicle. In either case the detail contained in work space diagrams should be sufficient to enable one to determine if each operator can meet his performance requirements within the work space assigned to him.

## • Step 17 - Determine the Location and Installation of Components

This step is concerned with the subsystems and components that have not previously been located. It assumes that the usable work space has already been established but that final decisions concerning the location of units have not yet been made.

Much of the information pertaining to the location and installation of particular components is either prescribed in Air Force requirement documents (13, 14, 15) or discussed in the many handbooks and guides available to system designers (2, 12, 22, 31). This information must be utilized to make sound decisions as to the location of items in the work space.

• Step 18 - Perform Research on Alternative Work Space Layouts

During the course of the development program alternative work space layouts may have been suggested. When a precise evaluation of alternative arrangements is required, it may be necessary to utilize either nonfunctional or functional mockups.

A relatively inexpensive way to perform work layout research is to construct a single mockup (e.g., a cockpit) that meets the space dimensions required by the operator. Add to this mockup those items that cannot be changed. Utilize the remaining usable space for alternative arrangements. Modular controls and displays, consisting of either nonfunctional or function units, individually packaged, which can be moved and located at will should be used.

Performance data should be obtained in terms of actual or expected errors, difficulties, safety, etc.

CHAPTER 7

EQUIPMENT DESIGN

content

Step 19 - Analyze human information requirements
Step 20 - Analyze human response requirements
Step 21 - Design displays, controls and operator consoles.
Step 22 - Determine auxiliary job supports
Step 23 - Prepare procedures
Step 24 - Perform research for integration and simplification. of equipment

## Overview

This chapter describes the steps to be taken in the detailed design and construction of the panels, controls and displays, and the auxiliary supports required by human components in weapon systems. These steps include: (a) the determination of human information requirements, (b) the determination of human responses requirements, (c) the detailed design of controls, displays and operator consoles, (d) the determination and design of auxiliary job supports, and (e) the preparation of procedures.

Inasmuch as the total number of different functions of humans in weapon systems is extremely large, it is not possible in this report to present more than a very general approach to the problems of equipment design. The many references containing detailed design recommendations (see Chapter 10), permit this chapter to concentrate on general procedures that may be helpful in identifying equipment design problems.

In general, the steps presented here will follow those in previous chapters. If equipment is to be designed for optimum human performance, human engineering consideration must be given to equipment design throughout the development program. In allocating functions to men it is necessary to have at least a rough idea of the controls and displays they will use to fulfill these functions. In preparing operator performance descriptions the plans for equipment design will have to be still more detailed. General configurations of equipment and control-display panels should be nearly finalized before work space layouts are prepared. It will probably be possible to defer most of the detailed design of displays, controls, instrument panels and auxiliary job supports until the previous steps have been completed.

Steps 19, 20, and 21 cannot be accomplished successively, but must be done simultaneously if optimal equipment design is to result.

## ● Step 19 - Analyze Human Information Requirements

These two steps, 19 and 20, lead to the identification of a set of requirements which can be translated into recommendations for displays, controls and operator consoles. Abstract from each operator performance description those items of information which are essential to the completion of prescribed tasks. It is suggested that consideration of the following factors will be of help in describing information requirements.

1. Time during the mission during which information will be used.

2. Work cycle, task and job elements within which information is to be used.

3. Whether or not the operator requires information to correct a present condition of the system or to plan a future course of action.

4. Data processing, decision making and overt responses which require the information.

5. How the information is used in the data processing, decision making and overt responses.

6. The precision with which the information must be presented to the operator in order to be useful.

7. The precision with which responses making use of the information must be made.

Consider information originating from the external environment and from other operators as well as information which is generated by equipment.

When all the information requirements have been determined, classify them as follows:

1. Identify and combine as a single requirement all of the times essentially the same information is required in different tasks.

2. Group all of the types of information which can be combined effectively in a single display (e.g., target range, azimuth and elevation).

3. Group all of the types of information which might come over a single communication channel (e.g., all verbal communications of aircrew members over intercom).

4. Group all of the types of information which might be incorporated in a single recall aid (e.g., chart, table, graph, checklist).

5. Group all of the types of information likely to come directly from a single source in the external environment (e.g., the various cues obtained from direct observation of a landing strip during approach).

6. Further classify the above groupings according to types of information which are commonly used together or in sequence.

● Step 20 - Analyze Human Response Requirements

Abstract from each operator performance description overt responses which the operator must perform in order to complete his prescribed tasks. Describe responses which deal with information transmission (e.g., verbal communication), written responses, movements from one facility or station to another, and control activation, considering the following:

1. At what times during the mission the response is made.

2. In what work cycle, task and job elements the response is made.

3. Whether the response can be discrete and essentially all-or-none or whether it must be continuously varied.

4. What information initiates and controls the response.

5. How the various types of information control the response.

6. The precision with which the information must be known.

7. The precision with which the response must be made.

When response requirements have been described, consider the following factors for their classification.

1. Identify and combine as a single requirement all of the times essentially the same control response is required in different tasks.

2. Group all of the responses which can be made effectively on the same control.

3. Group all of the information which might be transmitted over a single communication channel.

4. Further classify the above groupings according to types of responses commonly made together or in sequence.

Incorporate only sufficient detail in these two analyses (Steps 19 and 20) to permit a reasonably firm determination of the number and types of control and display elements required by the operator. When a work cycle or a task contains information and response requirements similar to those for a previous, similar system it will not be necessary to list each input and output. Obviously, the extent to which these steps will be of use in establishing display and control requirements depends upon the extent to which detailed information is available from individual operator performance descriptions.

## • Step 21 - Design Displays, Controls and Operator Consoles

The objective of this step is to provide detailed design recommendations for operator consoles, controls and displays based upon an analysis of the operator's information and response output requirements.

### Design Displays

Use the information analysis data in the detailed design of displays. In designing each display aim to provide the simplest, most direct source for the information required by the operator. Use human engineering guides and handbooks to suggest appropriate types of displays for the different types of information requirements.

### Design Controls

Use the response requirements analysis as the primary source of data for this analysis. In designing each control aim for a device which can be operated both quickly and accurately without introducing unnecessary engineering complications.

### Design Operator Consoles

A considerable amount of console design will have been accomplished during preceding steps. At this point, however, some final decisions have to be made. The detailed design of displays and controls may have caused integration of items previously planned and resulted in changes in size or shape. The analysis of information-response relationships may suggest desirable regroupings. This additional information should be used in preparing a finalized design of operator consoles.

• Step 22 - Determine Auxiliary Job Supports

Review the information and response analyses and the use of the detailed display-control designs for suggestions regarding auxiliary supports. Such supports may include the following items:

1. Recall aids such as graphs, charts, tables, checklists.
2. Hand-computing devices.
3. Tools.
4. Special lights.
5. Magnifying devices.
6. Filters.
7. Writing materials.
8. Signaling devices.
9. Safety and protective equipment.
10. Panel and other labels.

• Step 23 - Prepare Procedures

This step consists of the development of a set of procedures, based upon operator performance description data, to be used by individual operators in the performance of a job.

Adequate procedures should consist of step-by-step descriptions of what the operator is to do. Each step should include any diagrams, tables or illustrations necessary to supplement the written steps. Care must be taken to eliminate items of information which are not needed by the operator (e.g., unnecessary verbal or pictorial detail). Since most procedures will be performed under varying conditions, the contingencies which the operator may face must be considered.

When procedures have been prepared for an operator, they should be tested in a functional simulator. Attention should be given to correcting procedures which result in the following:

1. Excessive data-processing, especially computations.
2. Large amounts of short- or long-term recall.
3. Sustained over-load.
4. Error-likely conditions.
5. Hazardous conditions.

It is important, that procedures be prepared during equipment design and revised as changes in design details occur. Procedures will be of value in setting up selection requirements, in establishing manning tables, and in preparing operational and maintenance handbooks. These procedures will also provide a basis for determining training and training equipment requirements.

## • Step 24 - Perform Research for Integration and Simplification of Equipment

It is beyond the scope of this report to list or describe the many different techniques which might be used in performing this research. Even a partial list would include a variety of techniques borrowed from experimental and applied psychology, operations research, applied statistics, time and motion analysis, applied mathematics, and test engineering. It must be assumed that members of the design team will be well grounded in these basic research techniques and able to pursue the implications of advanced techniques that may be required in the solution of special problems.

### Experimental Comparison of Alternative Control-Display Items

Even with the most carefully prepared operator performance descriptions and information-response analysis, it will often be necessary to resort to research to determine which of a number of alternative control-display items will best fulfill operator requirements (6). The following conditions must obtain before research of this type becomes worthwhile.

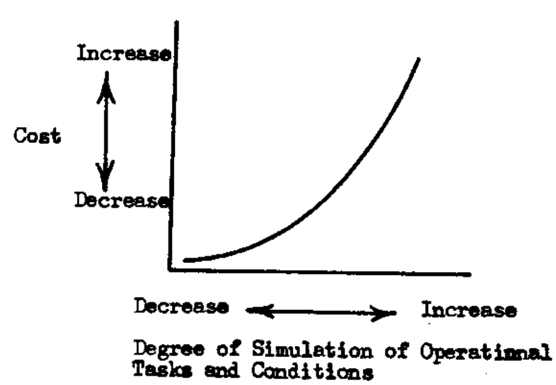
1. The design team is unable to predict with confidence, on the basis of all of the information available to it, which of the alternatives will optimize the operator's performance.
2. The likelihood that the differential effects of various alternatives on system performance will be great enough to warrant the cost, in terms of development time, effect on over-all system reliability or performance.
3. One additional factor which must be considered here is the possibility of applying the research findings to the design of future systems.

The development of apparatus for this research is considerably simplified if the alternative choices are among available controls and displays. If such items are not available, either simulated or prototype devices will have to be designed. Since the meeting of operational requirements is unnecessary for purposes of this research, engineering development should be the minimum necessary to provide adequate experimental apparatus.

Determination of the extent to which operational tasks and conditions should be simulated in this type of research is a major problem.

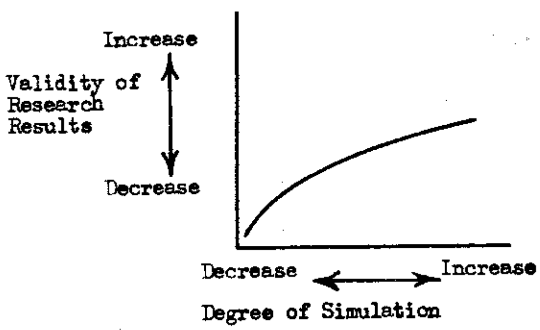
A curve showing the hypothesized relationship between cost and simulation is presented in Figure 2.

Figure 2. Hypothesized Tradeoff Curve for Cost and Degree of Research Simulation of Operational Situation.



A curve showing the hypothesized relationship between the extent to which research will agree with results in the operational situation and the degree of simulation achieved in research is shown in Figure 3.

Figure 3. Hypothesized Tradeoff Curve for Validity of Research Results When Applied to the Research Situation and Degree of Research Simulation.




If the relationships shown in these curves are valid, it is apparent that simulation beyond a certain point reaches a stage of diminishing return per unit cost.

A high degree of fidelity of simulation may be achieved without duplicating all equipment characteristics. For example, a preprogrammed photographic presentation may provide excellent simulation of a radar scope at only a fraction of the cost involved in developing the actual radar display.

Mission Simulation

Once the detailed design of controls, displays, and instrument panels has been completed, including the research on alternative control-display items discussed above, simulated missions can be run on research simulators or prototype equipment. These will provide valuable research data. In cases where a complete simulator is not available and prototype equipment is incomplete, gaps might be filled in with nonfunctional items from other systems. This alternative will decrease the degree of simulation of the operational conditions, but should still permit the drawing of useful inferences.

The purpose of this research should be to identify design features which cause the operator difficulty in meeting his task requirements. The following are useful in identifying such features:

1. Recording devices connected to each control to provide a permanent record of each control response.

2. Tape recordings of verbal communication during the mission.

3. Direct observation and recording by the experimenter.

4. Post-mission interviews to obtain evaluations and suggestions for improvement.

Attempt necessary redesign through modification of procedures; if this cannot be accomplished, equipment may have to be modified.

Evaluation of Proposed Modifications

Modifications to improve unsatisfactory design features identified during simulated missions should be fully evaluated to insure that they are real improvements. The most precise evaluation can be made by incorporating the proposed modification in a simulator and running subjects through additional missions. Where this is not feasible, it will probably still be possible to obtain useful data by simulating only a portion of the equipment and/or mission in the laboratory.

# CHAPTER 8

## SYSTEM EVALUATION

content

## Overview

This chapter presents a discussion of evaluation procedures for various phases of system development. These procedures are intended for use by inservice and contractor personnel. At critical phases it is highly desirable that contractor personnel evaluate human engineering factors before developmental reports and hardware are submitted for Air Force evaluation. A second, independent evaluation within the Air Force will increase the probability that undesirable features will be caught and corrected.

Even within a contracting organization it may be desirable to have human engineering evaluations done by a group separate from the design team. Such a group is likely to bring a new perspective to the evaluation which will be helpful in identifying problems and suggesting solutions.

## • Step 25 - Evaluate Drawings, Plans and Blueprints

Much information about the adequacy of human engineering design characteristics can be obtained prior to the time mockups, experimental or developmental models, or prototype equipment are available. Evaluations can begin as soon as decisions which affect the human have been made.

An attempt is made below to suggest some of the major types of human engineering information that should be evaluated from documents prepared during the developmental sequence.

### Evaluation of Functional Analyses

The evaluator's role during the initial phases of development should be primarily one of providing additional information and suggesting additional alternatives to the design team. Evaluation of early documents which appear prior to the allocation of system functions should include at least the following steps:

1. Determine whether any system requirements have been overlooked in assessing alternative equipment and human capabilities to meet these requirements. Point out the implications of such requirements to the allocation of functions.

2. Determine whether any reasonable alternative capabilities have been overlooked. If any have, state what they are and point out their desirable and undesirable characteristics.

3. Check over the alternative capabilities listed by the design team and determine in the light of the best experimental and operational data available, whether erroneous conclusions have been drawn concerning the strong and weak points of any capability.

4. Suggest the elimination of alternative capabilities which will obviously not be satisfactory to meet the system requirements.

5. Study mission profiles and ground support flow charts to determine whether any important conditions or contingencies have been overlooked. Suggest the inclusion of this additional information on the original profiles and charts. If

this is not feasible, request that additional missions be drawn which include the new information.

6. Make a careful appraisal of whether the functions analysis documents that are being produced are leading in a direction which will be helpful in later human engineering of the system. Suggest needed changes in general methodology to improve the value of data being evolved.

Evaluation of Functions Allocations

The evaluator must judge whether or not planning for utilization of the man makes effective use of human capabilities and takes account of his limitations. The evaluator should include at least the following steps:

1. Review decisions to use or not to use men in each major component of the system. Recommend reconsideration of any decisions which do not seem warranted on the basis of the information available.

2. Evaluate whether plans call for human capabilities to be matched appropriately to system requirements. Also, check that this matching is satisfactory for all phases of all different types of missions. Make recommendations for revising plans to improve the use of human capabilities.

3. Study time and link analysis data, checking for errors or omissions. Identify additional points of operator over- or under-load which the design team may have missed. Point out where over- or under-load points have been wrongly identified.

4. Determine whether the number of crewmembers planned for major components of the system and assignment of duties to each crewman is optimal. Suggest where the numbers of men used should be increased or decreased. Recommend how duties might be re-assigned.

5. Review the preliminary spatial allocation of controls and displays. Suggest needed changes in the positioning of these items.

Evaluation of Operator Performance Descriptions

The evaluator should determine early in the preparation of operator performance descriptions, the level and type of detail included useful in later design of equipment and work procedures. Where necessary, inadequate efforts should be re-directed. Techniques for avoiding inclusion of useless detail, reducing unnecessary redundancy, and otherwise short-cutting and improving the preparation of these descriptions should be suggested. Evaluation of operator performance descriptions should also include at least the following:

1. Review of operator performance and communications descriptions to determine if they accurately reflect total system planning. Correct inaccuracies.

2. Recheck to determine whether or not any human performance is required which is not described. Request that descriptions for this performance be prepared.

3. Verify analyses of individual operator work loads.

Evaluation of Work Space Layout Documents

Review documents, flow charts, and work space diagrams. Determine whether the decisions reflected in these plans have taken into account all of the information included in previously prepared and evaluated planning for work space layouts is in accord with the best available human engineering and time and motion data. Suggest re-design as required.

Evaluation of Information and Response Analyses

A small scale tryout of data from performance descriptions should be evaluated to determine whether or not efficient methods are being used. When this has been completed, special attention should be given to the classification of information and responses to insure that the analyses are comprehensive and will provide a satisfactory basis for detailed design of displays and controls. Check to insure that all information and responses included in a single category can most effectively be provided for by a single display or control.

Evaluation of Specifications

Checking through specifications and drawings for displays, controls, consoles, and auxiliary equipment may indicate items which will not be adequate for the purposes intended and thus save appreciable amounts of developmental effort. These items should be evaluated by comparing the detailed plans with appropriate information and response analysis data to reveal where plans are inadequate. Suggest how changes can most effectively be made.

Evaluation of Procedures

Review procedures to insure that all required tasks will be done in the most reliable, effective and error free manner. Give special consideration to the likelihood that performance decrement will be caused by conditions of stress. Check to insure that procedures are dovetailed to the design of equipment.

## • Step 26 - Evaluate Developmental, Mockup, and Prototype Equipment

The purpose of this step is to suggest factors that should be considered in the evaluation of equipment for human use.

### Evaluation of Mockups

Evaluation of mockups will be superior to evaluation of plans and drawings primarily because three dimensional spatial relationships, anticipated display readings, control responses, and equipment integration can be visualized easily from a mockup. The evaluator should make full use of this advantage by actually running through the task himself and by observing others.

### Evaluation of Development Model

Development models will provide the evaluator with his first opportunity to actually operate or observe the operation of the equipment. He should make full use of this opportunity to clarify any doubtful points that occur during his evaluation of documents.

### Evaluation of Prototype Equipment

Evaluations of prototype equipment should be based upon a careful analysis of discrepancies between actual speed and accuracy in operating and maintaining the equipment and requirements for optimum system performance. Personnel on which the measurements are made should be typical, in skill and training, of the personnel who will be available for routine operation and maintenance of the system. Field and environmental conditions should be simulated as fully as possible.

A major disadvantage with these evaluations is the expense of design changes at this stage and the delay in delivery of the weapon system.

## • Step 27 - Evaluate Engineering Change Proposals

Unsatisfactory Reports (UR's) should be examined for their possible human engineering implications as they relate to the total system. Solutions to conditions which degrade human performance and result in an adverse effect on system performance should appear in Engineering Change Proposals (ECP's).

Even proposals which are not based on human engineering defects may affect operator or maintenance performance. ECP's should be screened to identify those which will affect human performance so they can be given special human engineering attention.

Such proposals probably will affect one or more of the following:

1. Design or performance characteristics of controls or displays.
2. Design of work space layouts.
3. Operating or maintenance procedures.
4. Auxiliary equipments such as test equipment or other work supports such as maintenance diagrams.

Proposals which will affect any of the above should be reviewed from a human engineering standpoint to insure that modifications will not degrade over-all system and human performance.

•Checklists as Evaluation Tools

Checklists are commonly used as tools in evaluating the human engineering adequacy of systems. The assumption behind their use is that it is possible to determine in advance of an evaluation what categories of items will be critical to the performance of the human and the system as a whole.

Two checklists have recently been developed for human engineering evaluations of weapon systems. The first (3) is a checklist intended for use in evaluating plans. The second (28) is a checklist intended for use at Development Engineering Inspections and Mockup Inspections.

CHAPTER 9

# HUMAN CAPABILITIES AND LIMITATIONS

content

## Overview

The purpose of this chapter is to provide the design engineer with a general overview of human capabilities and limitations. This overview should serve as a basis for considering the human element as a system component.

In this chapter the human is treated in terms of three basic capabilities: (a) data-sensing, (b) data-processing, and (c) data-transmitting.

It is not within the scope of this report to present a complete discussion of human behavior. For those aspects of behavior which are considered special emphasis has been placed upon material not likely to be found in other sources. Detailed data available in other sources are not repeated here. Some of the material presented is hypothesis and conjecture; some is fact. Where data are available, references have been given. For detailed information pertaining to particular design areas, consult the references given in Chapter 10.

## • Man as a Data-Sensing Device

Six factors important to the selection and use of data-sensing capabilities are discussed in this section: (a) sensitivity, (b) capacity, (c) speed, (d) vulnerability, (e) stability, and (f) individual differences.

### Sensitivity

Each human sense organ has upper and lower sensitivity limits which define the range of energies to which the organ is normally responsive--energies capable of producing sight, hearing, taste, touch, and so on. Near-limit energies will produce unreliable sensing, and those near the upper limit may result in severe discomfort and possible physiological impairment.

The lower sensitivity limit is not a sharp cut-off point but a statistical region below which the probability of detecting a stimulus energy falls off rapidly. Traditionally, a lower sensitivity limit is defined in terms of that physical energy that can be detected 50 per cent of the time.

For the detection of small amounts of visual or acoustic energy, the eye and ear respectively are superior to many present day electro-mechanical data-sensors. For example, the amount of energy required to cause a noticeable sensation of light has been estimated at from 2.2 to 5.7 $\times 10^{-10}$ ergs, or between 58 and 148 quanta of light.

This represents a sensitivity 300,000 times greater than the most delicate radiometer (16).

Between its upper and lower sensitivity limits each sense organ is able to detect or "discriminate" differences among energies applied to it. Again, these "difference thresholds" are statistical rather than absolute. Depending upon how the measurement is made, the ear can distinguish between 300 to 1056 different pitches within its upper and lower limits (10, 24).

Both the upper and lower limits and differential thresholds vary considerably from individual to individual and from time to time. For example, factors definitely known to affect visual threshold measurements are the intensity, size, shape, and manner of presenting the stimulus: the background against which it appears, and the previous history of stimulation of the subject being tested.

Because of this large number of complex interacting factors, threshold data obtained in one context must be extrapolated to another context with care.

Although differential thresholds are traditionally established in the laboratory on the basis of a 50% probability of detecting a stimulus, to assure adequate data-sensing a probability of detection approaching 100% is required in the design of displays.

There is not a one to one relation between changes in the physical properties of a stimulus (e.g., its size, shape or color) and changes in the sensory or "subjective" experience of that stimulus. Certain non-linearities follow a general formula (26) which may be used to determine such factors as the physical size of distances on a scale of equally appearing (to the viewer) intervals.

In another respect this lack of a one to one relationship between a stimulus and the experience of it is a fortunate one for the human. It permits him to identify the same object under a wide variety of circumstances. For example, despite the change of the retinal image due to the spatial orientation of a cube, the observer is still able to preceive the object as a cube. This phenomena, which is called "constancy," applies to a variety of stimulus characteristics, including color, form, and size. This property makes humans superior to machines for such tasks as target identification, reconnaissance, and the like.

One undesirable characteristic of human sense organs is the tendency for both upper, lower and discrimination thresholds to fluctuate greatly with momentary conditions. Fatigue, boredom, stress, and previous stimulation are known to raise thresholds considerably. This fact must be taken into account when designing visual or aural warning systems, where even relatively intense signals may be unnoticed.

Another characteristic of sense organs is that a given stimulus may be masked by either a previous stimulus or a more intense stimulus. This is particularly true of hearing, where relatively small amounts of noise within a given frequency spectrum may mask or obscure needed voice or mechanical signals. The eye is considerably less sensitive to masking. In fact, it is generally superior to other data-sensing devices in reading signals through noise. This ability has been put to good use in scope interpretation, where target images are often obscured by ECM pips, snow or other interference.

Contrary to some types of electromechanical comparators, however, man may form biases about certain types of information. Whereas a comparator is able to obtain useful information from a scan in which as much as 60% of the presentation is obliterated by noise, man often relies on only one given pattern in an entire scan (such as a familiar shaped object) to identify the nature of the scan, ignoring other patterns. If this item of information is obliterated or incorrectly interpreted, he may not be able to carry out the proper action to the information presented.

Capacity

In order for a physical stimulus energy, such as an aural signal or a visual display, to be useful to man it must convey information. Information is any change which causes a change in stimulation.

When there is no change in the environmental energies acting upon a sense organ, the operator receives no information until the environment changes. When these changes are completely random (e.g., white or thermal noise) the operator has received a maximum of information. Neither a maximum of information or no information is of use in telling a man about his environment or how he must react to it. They do not permit him to act in a purposeful way.

Between these two extremes, however, is a range of organized energy patterns which falls within the range of sensory sensitivity and which conveys useful information. Speech sounds, pictures, pointer movements, are good examples. This information has utility because the human has learned to associate with it particular patterns of control action which he can or must make. Without such learned associations incoming stimulus information is meaningless. A traffic light conveys information to the driver only because arbitrary associations between changes in color and human control actions have been established through learning.

When the difference between its upper and lower thresholds is great and there are many discriminable differences between these thresholds, a sense organ is capable of receiving a large amount of information. This is especially true for vision and audition, where each discriminable difference in color, brightness, movement, pitch or loudness, represents a potentially useful item of information.

While it is theoretically possible for a separate response to be established for each discriminable difference that a human can detect, performance degradation occurs when either too much or too little information is presented at a given time. Although the upper and lower limits of human information transmission have not yet been fully established, men are probably not capable of transmitting more than 26 binary digits of information per second. The following table indicates some activities for which transmission rates have been determined.

Table 1. Rate of Information Transmission by Man for Sample Materials (4).

| Task | Maximum Transmission (bits/second) |
|---|---|
| Piano playing | 22 |
| Impromptu speaking | 26 |
| Reading aloud | 24 |
| Mental arithmetic | 24 |
| Typing | 17 |

Speed

Each sense organ has a characteristic lag between the onset of stimulation and the occurrence of a response to that stimulation. This lag is a function of the intensity of the stimulus energy, the latencies of the sensory end organs and nerve fibers, and the decay speeds of photo-chemical and other energy sensitive substances.

Consequently, the speed with which data are detected varies greatly under different conditions and from person to person. For example, the normal eye can focus on an object in approximately 160±10 milliseconds and move through a 40° lateral arc in 100 milliseconds. From 100 to 500 milliseconds may be required to identify and act upon the simpliest aural signal or verbal command (27).

Table 2. Perception-to-Action Tabulation Applicable to Any Craft, Any Speed (25).

| Action | Time to Complete, Sec. |
|---|---|
| Brain perception of what eye sees | 0.1 |
| Brain recognition | 0.4 |
| Decision | 4 to 5 |
| Physical reaction | 0.5 |
| Airplane reaction (approx.) | 2+ |
| Total action time | 7 to 8 sec. |

It is essential that the speed requirements for information response by humans be kept well above the lag of the sense organ being stimulated. Additional time must also be permitted for necessary data-processing decision making and control action. Decision time can be reduced by an appropriate preparatory set.

Vulnerability

Vulnerability is the susceptibility of a component to deterioration as a result of normal usage or enemy action. Like other components, the human data-sensing device is vulnerable to a number of factors.

The deterioration through usage, of the eye and ear, are relatively small. Except for permanent physiological damage caused by extremely intense, high frequency sounds or high intensity light flashes, human sense organs are capable of extremely rapid recovery. The eye and ear, for example, both fatigue very slowly. Impairment during fatigue is but slight.

Considerable temporary deterioration, however, can result due to possible enemy countermeasure techniques. Many of these techniques, of a psychological nature, have been used for centuries in warfare. The use of loud trumpets, reflected light from large mirrors, cause temporary hearing and visual loss as well as rather acute psychological trauma. Fortunately their action is limited to short distances.

In the electronic countermeasures area somewhat more effective techniques have been employed. Scope presentations have been jammed through the use of chaff, target repeater techniques, and so on. These have not been completely effective. In fact, at the present time most countermeasure techniques used to jam visual displays succeed in jamming the display but not the operator. His ability to read signals through noise and detect false targets, is high.

One solution that has not yet been tried, however, is to use ECM for the presentation of scope displays that produce physiological impairment, such as sleep, hypnotic-like states, vertigo and nausea. Work recently done by Walter (29) on photic driving may have some practical applications to this important field.

In summary, human data-sensing devices are not particularly vulnerable. Their biggest limitation is their vulnerability to the conditions inherent in the normal operational situation: shifts in light level requiring rather prolonged dark adaptation, engine noise cutting down on hearing efficiency, weather conditions cutting down on visibility, and the like.

## Stability

The stability of a component is its ability to perform consistently or reliably under normal and unusual conditions.

Like other data-sensing devices the human senses are subject to variation even under constant conditions. The reliability of detection, however, is relatively good. For example, upper or lower thresholds for hearing, seeing, and touch remain stable over long periods of time. Furthermore, as a result of continued practice, the stability of performance improves.

It is when the organism is subjected to severe momentary or prolonged stress that data-detection becomes unstable.

Stability in perceiving, identifying or handling complex perceptual patterns is less good, but even here, with considerable amounts of training and over-learning, the human can become a relatively stable data-sensing device.

Perhaps the major condition resulting in instability in data-sensing is time. Humans are relatively poor at monitoring tasks, where the organism plays a more or less passive role, and the quality of monitoring performance deteriorates rapidly with the length of the task. In this capacity, machines have proven to be better, both for monitoring other machines and men.

## Individual Differences

It has already been pointed out that wide individual differences exist in data-sensing abilities. Variation from eye to eye is probably considerably greater than variation from photo-cell to photo-cell. These individual differences may be attributed to age, intelligence, physiological condition of the subject, and especially to amount of training.

In designing a weapon system, where it is desirable to have relatively standard components capable of operating within a small range of tolerances, the problem of individual differences becomes a major one. Ideally, it would be desirable to achieve the same type of interchangeability of men that can be obtained with hardware components. Unfortunately with present selection techniques this does not seem to be possible.

The assumption must always be made in designing a new system that it will be operated and maintained by a wide variety of individuals. The level of difficulty of human tasks, therefore, must always be gauged to the capabilities of the most inferior individual expected to perform in the system. It is for this reason, for example, that so many present-day equipments are constructed along "go no-go" lines.

## Man as a Data-Processing Device

In this section, eight factors important in considering man as a data-processing device are considered: (a) human versus automatic computers, (b) memory storage, (c) decision making, (d) interpreting, (e) inferring, (f) numerial calculation, (g) estimating conditions, and (h) imagining.

### Human Versus Automatic Computers

In many respects the human component compares favorably with modern computers (1).

The entire brain, with its millions of nerve fibers, operates on less than 100 watts, whereas more than 100 million watts would be required to operate a similar mechanism consisting of transistors.

Although its power requirements are small, the speed of data-processing by humans is much slower than devices such as the ENIAC and MANIAC. Comparison of nerve fibers and vacuum tubes suggests the relative speeds of the brain and a computer. Whereas a single nerve fiber can be activated about 100 times a second, a vacuum tube can be activated up to a million times a second. To a certain extent this loss of speed is offset by the extremely large storage capacity of the brain.

The larger the memory storage capacity of a computer, the less information needs to be fed into it. Whereas the human is capable of storing from 1.5 million to 100 million binary digits of information, MANIAC's memory is limited to 40,000 bits. Compared to the size of most computers, the MANIAC is large, whereas the average bom-nav computer has a vastly smaller memory storage capacity.

In every case where there is an option between the human and an automatic computer, these factors should be taken into account.

As Brady (5) has indicated, even though automatic computers have certain advantages over humans (e.g., their ability to erase information completely) only when this superior performance is demanded by the system, should such a device be considered.

## Memory Storage

Despite the large storage capacity of the human, both for long and short-term recall, the speed and accuracy of human recall is poor.

Although extensive training is invaluable in reducing errors of recall, it may often by necessary to provide external supports as aids to recall. It is for this reason that research is currently being initiated in the development of aural and visual warning systems.

Errors of recall are greatest for information which is obtained during the performance of one task and must be applied in another context to another task.

One important area which requires research is that of checklists. It is not uncommon for the average operator to use a checklist for performing a sequence of actions. While he may not fail to consult the list and even read each item, he often fails to carry out the actions implied by the list. Thus, while reading the list becomes automatic, performing the indicated actions may not. One possible solution to this problem is to design checklists in such a manner that each successive item will not appear until the action has been indicated by previous items that have been performed.

It is worth mentioning that while human automaticity is often desirable in meeting standard or routine conditions, it is a distinct disadvantage when different conditions call for different responses. For this reason, it is often necessary to build into systems features which prevent the appearance of automatic human responses.

## Decision Making

The act of selecting from a number of alternative courses of action that one most likely to eliminate an out-of-tolerance condition or maintain an existing in-tolerance condition, is probably the least understood but most important function of the human in modern weapon systems.

In general, humans are superior to existing computers in making decisions for three reasons: (a) they are capable of inductive reasoning, (b) they are able to make inferences from one set of conditions to another, and (c) they are capable of making decisions in situations which they have not previously encountered.

Whereas the logic of computers is based almost entirely upon pre-programmed deductive reasoning, the human is capable of inductive reasoning. This gives him considerably greater latitude in decision making since it permits him, often without prior training, to determine when a decision must be made and what options are open to him.

We have already seen that the memory storage capacity of machines is limited. Man, however, is able to store large amounts of information, and although his recall is often imperfect, he is able to make inferences upon the basis of past experience about the likely outcomes of given courses of action. In some cases these inferences are based on guesses and hunches. This capability gives him considerable flexibility in dealing with unique situations for which all the relevant decision-making factors cannot be anticipated in advance.

Man's ability to make decisions in situations which he has not previously encountered, or to generalize from one situation to another, is still another asset in his favor as a decision maker.

Errors may occur in human decision making through inaccurate or inadequate recall of alternatives, through erroneous evaluation of conditions which affect their outcomes, or through inaccurate estimates of the success of a particular course of action. Rather than eliminate these errors through the use of automatic decision-making devices, it is often considerably less expensive to provide the man with relatively simple supports which will facilitate those aspects of decision-making in which he is weak. It seems reasonable, however, to provide simple aids which may be used in aiding the recall of alternatives, devices to aid in the evaluation of alternative outcomes, and techniques for speeding up the gathering of information relevant to particular decisions.

Numerical Calculation

If long-term computing demands are placed upon the human component, or if a large number of high speed computations are required, the human will make more errors and require more time than computers.

Estimating Condition

Estimating conditions is the process of assigning quantitative or qualitative values to displayed variables.

The accuracy of these estimations depends upon the extent to which a component is able to provide absolute or relative standards against which a given condition may be evaluated.

Where values of physical energies must be quickly and accurately appraised, mechanical devices are obviously superior to men. When, however, estimates of conditions depend upon subjective or unanticipated factors that cannot be preprogrammed, men will be superior.

Men use two kinds of standards in estimating conditions: (a) absolute and (b) comparative judgments. An absolute judgment consists of estimations based upon recall, where no standard other than past experience is available. Comparative judgments make use of other physical standards, and are consequently more reliable than absolute judgments.

Imagining

Analogies between men and machines break down at a number of points. One of these is man's ability to make use of recalled images of past events and to construct images of events that have not been directly experienced. These images permit man to manipulate experience independently of the physical objects with which this experience is concerned.

Since man is probably better able to work with images than with quantities, the designer should make use of this imagining capacity by using symbolic displays which evoke imagery.

• Man as a Data-Transmitting Device

By a data-transmitting device is meant any component which utilizes information to control another component. Humans act as data-transmitting devices through direct physical action on other objects (e.g., controls) or by communicating information to other humans.

In this section, five factors important in considering man as a data-transmitting device are considered: (a) reaction time, (b) rate and accuracy of control movement, (c) shifting from one control to another, (d) verbal response, and (e) man as a component subject to stress.

Reaction Time

Reaction time is a product of detection time, decision time, and muscular response time. In general, the shorter the allowed reaction time, the more difficult it is to learn and perform a task. When the stimulus input has to be remembered over some period of time during which other activities intervene, additional difficulty may arise in the recall of the earlier stimulus.

Usually the stimulus to action is preceded by a warning signal. The absence of distinctive warning signals preceding a stimulus increases reaction time.

Rate and Accuracy of Control Movement

Other things being equal, the more rapid and accurate the movement of a continuous control must be, the more difficult the task. This difficulty will also be a function of the length of control travel from one setting to another, and the required precision of the terminal adjustment.

## Shifting From One Control to Another

Rapid shifts from one control to another increase the possibility for error, especially if these shifts must be made when eye movements cannot precede and guide this shift. Beyond a certain minimum (depending on the body member in use) the further that controls used in rapid sequence are spaced from each other, the greater the error likelihood.

## Verbal Response

There are few jobs in which verbal or other symbolic communication (such as sending code) is not required as a vital link in man-machine operations. The determination of job requirements in aircrew positions, or of interceptor pilots, must necessarily include verbal communication. The scope of this manual makes it impracticable to do more than mention the topic. In any event, the requirement of verbal or other symbolic communication in which the operator is a link must be identified as an integral part of operator performance description, even though the specific requirements may be dealt with in the context of training and on-the-job operations. Adequate consideration must be taken to assure maximum clarity of communications, the elimination of noise, and the proper distribution of communications to men according to their function as system components.

## Man as a Component Subject to Stress

Like machine components, the performance of human beings is subject to the effects of environmental stresses. High and low temperatures, humidity, g-forces, and physical shock, may produce performance degradation when above given acceptance limits. Other factors produce stresses peculiar only to the human component. These will include glare, drugs, toxic substances, loss of sleep, incompatible response demands, and imminent danger. Although the human component may make mistakes under a stressful situation, certain minimal stress levels may facilitate and improve performance. Above this level the effects of stress are not necessarily cumulative. Whereas a machine component may break down completely under stress, the human has a high stress tolerance and will often rapidly recover from its effects.

CHAPTER 10

# SOURCES OF HUMAN ENGINEERING DESIGN DATA

content

- Bibliographies
- General references
- Auditory displays
- Controls
- Display-control relations
- Equipment design
- Maintenance
- Man-machine theory
- Operator comfort and safety
- Operator mobility
- Visual displays
- Work environment

At the present time a large amount of human engineering design information is available to the system designer in Air Force technical reports. However, there are also other excellent sources of design data to which designers may have convenient access but with which they may not be familiar.

The list below consists of a selected number of references divided into human engineering design areas. These items were selected because they are easily obtained or contain information not likely to be found elsewhere.

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DESIGN STUDY (DS)-A study to determine the characteristics of a system needed to satisfy a particular problem. The problem is stated in a General Operational Requirement and based on an examination of existing equipment and a review of promising techniques. (80-4)

DEVELOPMENT PLAN-A document that proposes an outline of a solution to the problem presented in the system requirement document. (80-4)

FLOW CHART-A chart containing a time base used in functions analysis for ground operation. It shows the location of fixed facilities, and the pattern of flow of materials and procedures from one facility to another.

FUNCTIONS ALLOCATION-The assigning or allocating to men and machines of those functions which they will fulfill to meet the requirements of the system.

FUNCTIONS ANALYSIS-An analysis and determination of those things a projected weapon system must do, a study of the alternative capabilities to meet these requirements, and the preparation of mission profiles and flow charts.

FUNCTION OF A SYSTEM-Any human and/or instrumented activity, or a combination of these, that may be used to satisfy a requirement for a system.

GENERAL OPERATIONAL REQUIREMENT (GOR)-A document which provides the criteria for development planning of specific weapon systems or supporting systems. General Operational Requirements emphasize the operational needs and not the means by which these needs will be satisfied. (80-4)

HUMAN ENGINEERING-The application of the facts, skills and techniques of the biological and social sciences to equipment design.

JOB ELEMENT-The perceptions, decisions and responses which the human is required to perform in the completion of a task.

MAJOR SYSTEM COMPONENT-A unit of a system (e.g., the airborne vehicle, vans, trailers, shops, depots, etc.) used to house an operator and/or with which the operator has immediate functional and physical contact.

MISSION PROFILE-A representation of the missions which a weapon system is expected to perform, including the type of terrain and other discrete events that will be encountered, points of departure, target areas, expected enemy defenses, altitudes, etc.

MISSION SEGMENT-A term descriptive of those activities normally accomplished by a system within part of a mission, e.g., preflight, take-off, launch, etc.

OPERATOR PERFORMANCE DESCRIPTION-A description of those activities and the temporal sequences in which they must be performed by the human as a component in a system.

PRELIMINARY OPERATIONAL CONCEPT-A document presenting a general description of a system and outlining its expected operational capabilities, limitations, and manner of deployment. (Air Force Regulation No. 5-47.)

REQUIREMENT-A statement of a goal or action which must be achieved by a system or any of its components.

TASK-A group of related job elements performed within a work cycle.

WEAPON SYSTEM-An instrument of combat, together with all related equipment, humans and skills, necessary to support and operate the instrument of combat as a single unit of striking power. (80-4)

WORK CYCLE-A group of tasks having a common goal, performed by a given operator during a mission or mission segment.

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