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OVERVIEW OF THE NAVSEA HUMAN ENGINEERING ROLE AND SHIP DESIGN

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— ERRATA —

AN OVERVIEW OF THE ROLE OF THE NAVSEA HUMAN FACTORS ENGINEERING PROGRAM IN SHIP DESIGN

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1.3 Human Factors Engineering in the Military

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General Note

The NAVSEA HFE Technology for Ships program referred to throughout the paper is managed by SEA 061R.

AN OVERVIEW OF THE ROLE OF THE NAVSEA

HUMAN FACTORS ENGINEERING PROGRAM IN SHIP DESIGN

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ABSTRACT

This paper provides a context within which the role of human factors engineering (HFE) for Naval ship design may be understood. HFE is defined and its history as part of engineering design teams is traced. The role of HFE in ship systems design is defined, the rationale for its inclusion in the design process is presented, the methodology whereby it is incorporated into the design process is detailed, methodology to assess the application of HFE is outlined, and the benefits that will accrue as a result of inclusion of HFE considerations in the design process are documented. The counterpoint to inclusion is illustrated through instances of design-induced human errors. A specific application of HFE in the acquisition process is illustrated through use of the Landing Craft, Air Cushion HFE program plan. The difficulties which may be encountered as the size of the target system expands, are described. Potential roadblocks to the required incorporation of HFE are examined for their source and possible ameliorative steps.

TABLE OF CONTENTS

1.0 INTRODUCTION

1.1 Background

The surface combatant ship represents one of the more complex man-machine systems in our nation's defense arsenal. The operations of a ship and of ship systems require a number of people serving a number of diverse roles, each with exacting performance standards, and under conditions that are often demanding and always hostile. The effectiveness of a ship's performance is a direct function of the performance of its personnel, who serve such vital functions as commander, decisionmaker, systems operator, information processor, transporter, operations monitor, plotter, maintainer, controller, planner, coordinator, communicator, inspector, navigator, supplier, and manager. These functions are required to be performed under conditions which are increasingly difficult. As a result, the role of man aboard ship will be more important, more difficult, and more demanding over the next twenty years. This is due primarily to the increased complexity and sophistication of shipboard systems. With expanded reliance on computers, electro-optical sensors, automated propulsion, distributed processing, advanced materials handling, "smart" weapons, advanced information processing and display, and informed control systems, shipboard systems are at the leading edge of the state of the art in several advanced high technology areas. This invariably results in equipment which is extremely complicated to operate and difficult to maintain.

The projected increase in the difficulty of activities performed by ship's personnel is also a function of the types of activity themselves. As the role of man shifts from system controller to system monitor and manager, the burden on the ship's personnel will increase due to the increased requirement for decisionmaking and intervention into automated processes. Under increased workloads error probabilities and consequences are usually greater for cognitive tasks as compared with manual control tasks. The difficulty of crew operations on ships of the future will also reflect advances in the capabilities of the threat. Over the next twenty years, dramatic changes are expected in required response time (downward) for detection, identification, and action, and in required system accuracy (upward) for decisionmaking and threat engagement. As systems become more complex, the information processing requirements associated with monitoring and managing these systems also increase. The information overload, already reported on today's ships, is likely to become worse over the next twenty years. The increased workload projected for ship's personnel will also result from the greater needs for coordination among sensors, systems, and ships. The requirement for increased coordination will follow from the tendency to design ship systems that are highly integrated. Ships of the future will probably require more maintenance by virtue of the complexity of their systems. Maintenance workloads for ship personnel are, therefore, expected to increase. Thus, it is apparent that while, on the one hand, the role of man aboard ships will be more important in the next twenty years, on the other hand, that role will be more difficult and demanding. We will be placing higher standards of performance on the crews and, at the same time, making their assigned tasks more arduous, complicated, and exacting.

In the context of projected systems and equipments, the concept of ship personnel readiness needs to be addressed by evaluators and planners. The major constituents of personnel readiness should be:

- Personnel availability
- Personnel capability
- Personnel performance
- Personnel productivity
- Personnel safety.

Personnel availability addresses the question of the presence of people in the numbers required to perform assigned activities. Personnel capability focuses on the skills and skill levels of personnel in terms of the skills and levels of skills associated with shipboard duties. Personnel performance addresses the question of the capabilities of personnel to meet systems performance standards given the systems hardware design, software, information and environment. Personnel productivity involves the capabilities of personnel to meet system output requirements, in terms of quantity (of a given quality) completed per unit time. Personnel safety has a direct effect on personnel availability, and addresses the extent to which personnel are capable of performing duties without risk of personal injury as a function of equipment design.

It is apparent that personnel availability is a function of ship manning levels, and that personnel capability depends on crew training. Personnel performance, personnel productivity, and personnel safety depend on one system element which is not usually addressed in questions of readiness. That element is human factors engineering.

1.2 Human Factors Engineering — Definition and History

Human factors engineering (HFE) is defined as the engineering discipline concerned with the design and evaluation of systems, hardware, software, documentation, environments, and communications specifically for the personnel who will operate, maintain, control and manage the system. Human factors engineering seeks to establish the interfaces between system personnel and the other elements of the system, and to ensure that these interfaces are designed with a concern for people's capabilities and limitations, requirements, and constraints.

By general consensus, the history of HFE is divided into three stages; pre World War II, World War II, and post World War II. The first phase is generally unrecognized and presumably began with prehistoric man fashioning tools for both the task and the user. Casual review of human history would indicate the progressive trend toward adapting equipment as well as environments to human use. More documented efforts followed including classic studies on work output related to shovel size for coal shovelling and the famous time and motion studies of the Gilbreths. Concurrent with these efforts was an expanding database on basic human capabilities being developed primarily in research settings. Thus, the history of the pre-World War II phase is generally related to two major disciplines, industrial engineering (concerned with work output and its measurement) and psychology (interested in factors related to learning, performance and personnel selection).

Subsequently, the field entered a phase which some have labelled, not so facetiously, "man versus the machine". HFE during World War II was largely research oriented with a strong applications orientation. The division of labor for equipment design and fielding was traditional. Engineers were responsible for design of new systems and equipment; psychologists were responsible for selection and training of men to use the equipment. During World War II, however, equipment (such as that in aircraft cockpits) seemed to become so complex that it exceeded the capabilities of men to operate it.

Experimental psychologists were enlisted to collaborate with engineers in designing various military equipment — aircraft cockpits, radar consoles, binoculars, gunsight reticles and controls, combat information centers, and synthetic training devices. Originally these researchers were interested almost exclusively in determining how best to display information to the senses, how to utilize human motor output, and how to secure good dynamic characteristics in controller systems.

The requirements for this equipment design research stemmed from the realization that traditional methods of design were not producing workable systems when the systems such as radar or sonar imposed special demands on personnel. Despite the best efforts of dedicated engineers and HFE specialists (frequently called engineering psychologists) a number of error-inducing designs were produced, some of which survive today. The classic example is the aircraft design reversing flap and gear retraction handles from the normal arrangement. These designs set the stage for man versus the machine. Interestingly, this anomalous handle arrangement was retained for at least two models of private aircraft through the 1980 model year.

HFE is probably still in the third stage of development. Based on lessons learned during the accelerated pace of development of World War II, it became obvious to most system acquisition mamagers that man was integral part of the developing system and his capabilities were as important a consideration as the equipment under design. This stage may be thought of as the "man-machine interface" phase. Systems have been continually considered to be a combination of man and machine with man as system operator and/or maintainer. System output has been considered to be a function of how well the machine has been designed for human interaction. This position will continue to describe the state of the art in most equipment design for the foreseeable future, but another trend may be emerging. The advanced wave of the 70's appears to be rolling toward what future historians may refer to as "man-machine symbiosis." The result will be a total integration of man in his work environment. As World War II saw a dramatic expansion of equpment capabilities, the 80's will experience a similar expansion. Areas such as artificial intelligence will force man and machine to be true partners in system operation and with this will come an additional impetus on design for the personnel component.

1.3 Human Factors Engineering in the U.S. Navy

According to NAVMATINST 3900.9A (Draft), "HFE is composed of the following elements as they apply to the system development process: human engineering, biomedical, manpower and personnel requirements, training, technical manuals, and test and evaluation." Each element is briefly described below.

1. The Human Engineering Element. Applies knowledge about human capabilities and limitations to the design of the equipment of the system, and to the entire system, to achieve desired system performance through the most effective and economical use of human performance capabilities.
2. The Biomedical Element. Provides for the promotion of health and safety, and for protection, sustenance, escape, survival, and recovery of personnel employed within the total system environment under both normal and emergency conditions.
3. Manpower and Personnel Requirements Element. This element develops manpower and personnel requirements to ensure that

enough trained people are available to operate, maintain, control, and support the system or equipment.

4. Training Element. Provides all training required to provide competent personnel for the roles in the system including:

   - Instructional System Concept
   - Training Devices and Simulators
   - Training and Economic Analyses.

5. *Technical Manuals (and other performance aids).* Develops technical manuals recognizing the education and training levels of users, and the presentation of that content to facilitate fleet operations, maintenance, and training. HFE applications include:

   - Analysis of the duties
   - Information identification
   - Information sequencing
   - Information presentation
   - Testing manuals or performance aids
     - accuracy
     - usability

6. HFE Test and Evaluation. Determines whether or not Navy personnel, with system training, can in fact operate, maintain, control and support the system in its intended environment. HFE testing generally assesses the following factors:

   - Proper application of human engineering requirements, criteria, standards and specifications to system design
   - Statisfaction of biomedical and safety criteria
   - Provision for efficient human performance in intended operational environment.

   It may also assess the adequacy of the following:

   - Manpower requirements information
   - Technical manuals or other job performance aids
   - Training and training equipment requirements.

2.0 ROLE OF HFE IN SHIP DESIGN

2.1 Background

Years of extensive testing of military systems have shown that there is frequently a significant difference between the potential, or designed, performance of a system and its actual performance. This "performance gap" can be attributed largely to the performance of the human component in the system. HFE is the technology capable of improving the performance of the human component, thereby narrowing the performance gap. Failure to apply this technology throughout the system development process reduces the likelihood that a system will meet its designed objectives when it is placed in operational use. Consistent application of HFE leads to actual field performance of a system that closely approximates its predicted performance. Issues of concern range from the apparently simple question of physical fit of system operator with the system hardware to the more complex question of the amount and quality of work which can be performed by the real user population under genuine battle conditions. HF engineers study system concepts to identify and remove sources of human error which could reduce system effectiveness.

The above discussion was adapted from Kaplan and Miles (1981) who were speaking primarily about Army systems. This same "performance-gap" conclusion can be attained through analysis of many Navy systems. ~~The draft NAVMATINST 3900.9A addressed this issue and provides a solution to the problem of incorporating HFE inputs into the design process.~~ The basic premise ~~of that instruction~~ is that HFE must be an integral part of research and development (R&D) planning, conceptual study efforts, exploratory, advanced, and engineering development projects of programs, equipment procurements, modifications, and system acquisition programs where the intended end product has human performance as an integral part. Unique requirements of each system or project, specific phase of the system life cycle at hand, scope of the system or project, and special management needs of the total program should be considered but, the priority of the HFE activities must be maintained.

There are several salient points that should be considered. The requirement for HFE begins with the inception of the system or project and continues throughout the life cycle. Each HFE element, as appropriate, should be defined, tailored, planned, developed, and implemented to best meet the needs of each system or program. (This is not intended as an "out" to ignore HFE, rather a recognition of the realities of varying projects having varying requirements). The system or project manager should coordinate HFE elements with integrated logistics support (ILS) elements. Prompt utilization will be made of the new concepts, techniques, and information developed as a result of R&D in the elements of HFE. The current NAVMATINST should be supplemented by more detailed HFE standards, criteria, specifications, and guides (See Appendix A for a bibliography). Manpower is both limited and expensive and should be treated as any other limited and expensive resource. Since it takes a long time to develop the personnel to use in a system, it is necessary to provide manpower and personnel planners with information on the manpower requirements of new systems and technologies as soon as it is available.

The current ~~NAVMAT~~ emphasis on HFE is intended to issure optimal system performance. This requires that a number of objectives be meet. For example, the human roles in a system should be defined to optimize their performance in relation to that specific system, and to efficiently use human capabilities to enhance total system effectiveness. Trained HFE specialists should assist in selection and design of equipment that people will be required to operate, maintain, support, and control. Developmental, Operational, and Production Acceptance Test and Evaluation of HFE elements should be planned and executed by, or in consultation with, HFE specialists. Furthermore, there is a requirement for review of HFE criteria, standards, specifications, and guides to insure prompt utilization of the results of research and development and of information from tests and evaluations. The result of these reviews will be implemented in both Navy and tri-service documents.

2.2 Ignoring HFE Technology

A major problem for modern ship systems is that HFE technology is being neither formally nor consistently applied to their design. The system user is being treated as an element of the system which can adapt readily to any system configuration. A host of other factors are serving as system design constraints, such as design-to-cost, reliability, value engineering, energy consumption, data processing capability, etc. Insufficient attention is being given to concerns such as the following: 1) that the system be operable and maintainable by ship personnel; 2) that the system design facilitate operator/maintainer procedures, decisions and actions; and 3) that ship's personnel possess the essential skills, knowledge, and level of understanding of system operation to enable them to effectively, safely and reliably perform assigned activities.

2.2.1 Determinants and Outcomes

HFE Technology has not been systematically applied to the design of ship systems for a number of reasons. The traditional areas of concern for HFE specialists have been aircraft and aircraft systems. The reasons for this may be somewhat speculative, but, if nothing else, failure to consider human anthropometry is much more obvious when pilots fail to fit in the limited cockpit space allotted. Many of the sophisticated advances of World War II were also incorporated in aircraft first. Based on these experiences, HF engineers may have chosen to work on familiar systems where their efforts were accepted. Thus, one reason for a lack of HFE inputs to ship system designs may have been the result of a limited number of skilled specialists, the majority of whom were employed by aerospace concerns. The design of surface ship systems was left to the traditional Naval architects and systems engineers very few of whom received training specifically directed to human engineering concepts.

HFE is very often viewed as being merely a systematic application of "common sense" and an adjunct to the real engineering of hardware and software components. Examples of the failure of common sense are common in operational systems. Kaplan and Miles (1981, p. 78) describe the case of a particular military aircraft:

> ...with variable-sweep wings. As the aircraft increased its speed, its wings were supposed to be swept further back. A decision had to be made about the control that initiated the wing movement. Common sense seemed to dictate that this control follow the pattern of the throttle. That is, when a pilot wants to go faster he pushes his throttle forward; therefore, he should also push his wing control forward. Looked at another way, it the pilot wanted the wings to move backward, he would push the control forward. This particular version of common sense turned out to be a mistake which frequently saw pilots engaging in control reversals. As it turned out, when pilots think about moving their wings backward, they associate this with moving the control backward. When they think about moving their wings forward, they associate it with moving the control forward. In this case, the common sense of reasonable people was insufficient to preclude a human-factors problem.

The conception that HFE is merely an adjunct usually relegates the HF engineer to a subsidiary consultant role. In this role, he is often not called upon until problems are noted well into the development cycle. Kaplan and Miles (1981, p. 79) provide an example of the absence of consideration of the man as the ultimate system user of a:

> ...visual target acquisition system, or VTAS, in aircraft. Such a system projects a gun sight in front of the gunner's eye. He can then turn his head, locate a target, hold the sight on the target, and inform a computer that he wishes to

attack that target. The computer locates the target by sensing the direction in which the gunner is looking. Early versions of such a system projected a gun sight onto a half-silvered mirror which was suspended by a wire in front of the gunner's eye. No one discovered in advance that people are made uncomfortable by having small objects dangling in from of their eyes. Also, the wire bent under G forces, interfering with its use. A later version projected the gun sight directly onto the gunner's helmet visor, producing a ring of light and various simple symbols.

Immediately prior to operational introduction, a human factors specialist tried out the system in a laboratory and discovered that it worked as advertised and was very impressive. He then took it outside and looked at the sky. He discovered that if one looked anywhere near the sun or any other bright object, the gun sight disappeared. At least this problem was corrected before the gun sight was fielded.

This may be thought to be an extreme example, and it is, but it is not a isolated case.

The HF engineer differs from the systems engineer who is primarily concerned that a design meets the specifications within operational constraints (environment), technical constraints, (reliability/packaging), performance constraints (accuracy/time to respond), and program constraints (funds/development schedule/available resources). In this context the human operator/maintainer is treated, at best, as a highly adaptable component who can contort to fit the hardware/software configuration. The HF engineer serves as the advocate for the operators, maintainers, and managers of the system. His role is to ensure the early consideration of the role of man to avoid the costly redesigns involved in the above examples.

Another factor may be the implicit belief that automation will reduce or nullify the role of man in system configurations. Although there may be a veneer of truth in this opinion (operators in automated systems may not appear as though they are doing anything), minor scratching of this surface will reveal a much more complex reality. Operators of automated systems may have a much greater burden imposed for monitoring, supervising, managing, information integration, and intervention in the event of failure of the automatic controller. The role of the maintainer may also be much more critical. There are a number of highly critical operations that must be considered in system design. Decisions must be made with the human in mind when functions are allocated between man and machine. There is no evidence to suggest a positive value is attached to design strategies that allocate all functions which may be easily automated to the machine and the remaining functions to the more adaptable, if somewhat fallible, man. Obviously the issue of automation will become increasingly important as concepts such as artificial intelligence are applied to operational problems and true man-machine symbiosis is approached.

Frequently there is the belief that HFE is applicable to very circumscribed areas of the ship design process, e.g., habitability and reduced manning. This belief ignores the wealth of evidence to the contrary and relegates HFE to an area well outside the mainstream design process. Ship system designers may view HFE as being only concerned with operator comforts, rather than the main HFE expertise in operator/maintainer performance and safety. Performance limits for man-machine systems are not usually limited by equipment reliability. In most cases, if funding and other constraints were unlimited, machine reliability could be assumed to be made arbitrarily high. Even if this assumption were true, overall system reliability could not approach unity if error-inducing designs are promulgated. History has shown that, although many designs are adequate to the task, a significant number of inadequate designs have been produced even in highly critical systems.

Perhaps the bottomline rationale for ignoring HFE may summed up by the statement, "We haven't needed it before, why do we need it now?" Slightly paraphrased, but more to the point, "We haven't applied it before, why should be apply it now?" There are sufficient examples readily available in Naval documents of personnel-related problems. This taken in combination with the shrinking manpower pool of dubious quality, yields an obvious answer. In the past we may generally have had the luxury of selecting well-qualified, highly motivated, superbly-trained operators and maintainers. This situation is not likely to eventuate for future ship systems.

2.2.2 Summary of Consequences

The overall results of failure to adequately include HFE technology in the design of ship systems are increased error rates, disproportionate workloads, extended time to maintain and repair, increased accident rates, delayed or erroneous decisions, unsatisfactory system performance and reduced system readiness. Specific examples of previous problems resulting from inadequate prior application of HFE to ship systems include: 1) loss of aircraft from carriers due to catapult operator error; 2) explosions of gun mounts due to operator errors (the Manley, DD940); 3) the tendency aboard most ships to keep the automatic boiler control system in the manual mode since operators do not know how to make the transition from automatic to manual; 4) the increasing difficulty in controlling current combat direction systems; and 5) fires and explosions aboard carriers attributed to human error in handling munitions (e.g., the Forrestal in 1967 and the Enterprise in 1969).

The Navy has recognized officially that HFE is not needless or a cosmetic concern for people which should be divorced from the main engineering effort. The Navy has determined that HFE exists for the sole purpose of ensuring the full readiness of systems personnel; and that the readiness of the crew directly affects the readiness of the ship.

2.3 Incorporating HFE Technology

In the United States Department of Defense, acquisitons of major systems are governed by a variety of directives, regulations, standards, and handbooks. MIL-H-46855, "Human Engineering Requirements for Military Systems, Equipments and Facilities," is directed specifically at the role of HFE in the acquisition process. This specification states, in part, that human factors program requirements are to include:

- Defining and allocating system functions. HFE principles and criteria applied to allocate system functions to
  - automatic operations/maintenance
  - manual operation/maintenance or
  - combinated manual/automatic operation/maintenance.
- Information flow and processing analysis.
- Estimates of potential operator/maintainer processing capabilities.
- Roles to be identified for humans such as
  - operator
  - maintainer

- programmer
- decisionmaker
- communicator
- monitor

are required. Estimates concerning load, accuracy, rate, etc., are also to be identified.

- Equipment identification. HFE principles and criteria are to be incorporated into the identification or selection of equipment that will be operated/controlled/maintained by man.
- Task analysis. Conducted and applied to design decision, analysis of manning levels, equipment procedures, etc.
- Analysis of critical tasks. Task analysis (above) extended to analysis of critical tasks to identify, for example:
  - information required by man
  - information available to man
  - information evaluation process
  - decision reached
  - action taken
  - body movements
  - tool required
  - job performance aids (JPA) required.
- Loading analysis. Crew/individual workload analysis is to be applied and compared to performance criteria.
- Preliminary system and subsystem design. HFE principles and data (MIL-STD-1472) applied to system/subsystem design.
- Detailed design. As above.
- Studies, experiments, laboratory tests. Research is to be conducted to resolve man/machine trade-off problem areas and other HFE and life support problems.
- Mockups and models. Mockups (3-D) to be constructed as an HFE design evaluation tool.
- Dynamic simulation (as required for HFE design).
- Design drawings.
- Workspace environment. This would include
  - atmospheric conditions
  - weather and climate
  - bodily acceleration
  - noise
  - safety (handholds, etc.).
- Test and evaluation. Planning, implementation and failure analysis.

The above listing describes the tasks that the current acquisition process requires in the course of procurement. The HF engineer is the most capable individual to accomplish these tasks. The remaining issues for incorporating human factors include:

- Areas of application
- Integration with other disciplines
- Evaluation of efforts.

2.3.1 Areas of Application

If naval ships are to be expected to perform effectively, HFE must assume a major role in design of man-system interfaces. HFE directly affects personnel performance, measured in terms of time to respond, time to complete, and number of errors committed by operators, maintainers, or decisionmakers. Application of HFE technology significantly reduces personnel performance time and error rates. Application of human factors engineering technology on the design of systems also has the effect of increasing personnel productivity for those systems. Personnel capability to produce is enhanced and personnel ability to restore failed equipments to operational conditions is expanded when HFE technology is applied in the design of systems. Application of HFE technology in the design of new ships will also have the effect of making these ships safer to operate, maintain, and inhabit. Hazards to personnel safety will be eliminated or at least guarded to prevent injury. With reduced accident rates, the availability of ship's personnel will increase. The areas of HFE concern for each interface type follow.

Type of Interface	HFE Concerns
• Functional	• Role of man vs. automation • Operator workloads • Assigned duties and responsibilities • Performance criteria.
• Informational	• Information loading • Data rates • Information formats • Feedback information • Transformation of data to information • Identification of information importance • System documentation, manuals, procedures.
• Environmental	• Temperature extremes • Noise levels • Vibration levels • Platform motions • Illumination levels • Confined workspace.
• Managerial	• Decisionmaking criteria • Diagnosis of faults • Supervision/command.
• Operational	• Vigilance requirements • Response time constraints • System readiness levels • Crew skills and skill levels.
• Cooperational	• Crew interaction • Team performance • Communications.
• Physical	• Control and display design • Design for maintainability • Software design • Habitability design.

2.3.2 Integration of HFE Technology

There is a requirement to incorporate inputs from HFE technology in the acquisition of ship systems. In order to accomplish this expeditiously and meaningfully a number of objectives must be met. NAVSEA developed an approach to accomplish the following steps:

- Identify HFE requirements at each acquisition cycle step
- Develop and apply criteria for technology assessment according to:
  - usability
  - impact on system design
  - cost
  - alternative technologies
  - potential for computerization
  - standardization
- Identify HFE inputs to products of the acquisition cycle
- Identify acquisition cycle information inputs to HFE activities
- Identify HFE windows (time periods) wherein required events must be completed with failure indications reported.
- Format acquisition cycle and HFE process into a timeline.

The report, "HFE Technology for Navy Weapon System Acquisition," is included by reference. The timeline mentioned above is included in this paper as Figure 2-1. The general approach follows from the requirements noted in MIL-H-46855. There is sufficient elaboration to insure that the ultimate system is designed for optimal operability. A full description of the report of that effort is beyond the scope of the present paper. The report included (1) A definition of the Navy Weapon System Acquisition process with supporting documentation. Major acquisition phases, milestones, events and activities were identified and formatted into a timeline. (2) A comprehensive review of the scientific literature identifying viable HFE methods, techniques, principels and data. These technologies were then described, along with methods of application for each. (3) An extensive assessment of each technology, in terms of meeting HFE requirements, as well as applicability and appropriateness within the acquisition cycle.

The report was presented in four sections: Section 1, the Introduction, provided general background information and defined the approach taken; Section 2 defined the Navy Major Weapon System Acquisition process and identifies HFE requirements within that process. Forty-seven major acquisition events, activities and milestones and 45 general HFE requirements were discussed; Section 3 has descriptions of over 70 HFE methods and techniques, as well as HFE principles and data sources. In addition, each method and/or technique was assessed according to its applicability to HFE requirements within the cycle; (4) the final section identified HFE technology shortfalls relevant to the HFE requirements. It also identified several emerging technologies that are suitable to fill the identified technology gaps.

Thus, there is a comprehensive document which describes in detail the applicability of HFE Technology within the various phases of the acquisition cycle. It is imperative that the value of HFE Technology be recognized and that HF engineers be included at the earliest stage of the acquisition cycle. If HFE inputs are delayed substantially (as is common) it becomes increasingly more difficult and expensive to effect these inputs.

2.3.3 Assessing HFE Application

In December 1981 the GAO concluded that;

> It has generally been the philosphy that technology will advance our capability to meet the mission needs and that man can adapt to the technology. Designers of weapon systems often do not consider the capabilities and performance requirements of the people who will operate and maintain the systems in the operational environment. It is therefore extremely important that weapon system reviews include an evaluation of the extent to which DOD considers manpower, personnel, and training needs and capabilities in the weapons system acquisition process.

The GAO proposed two approaches to accomplish this goal. The first involves a review of the manpower documentation required in the decision making process. The second involves an analysis of various organizational functions related to the weapons system acquisition process. Both approaches provide methods whereby the extent of HFE inputs may be assessed. The guidelines as proposed were not intended to be exhaustive. They do, however, provide a basic frame-work with in which GAO auditors could function.

Examples of the issues involved in the first approach include reviewing the Mission Element Need Statement (MENS) to determine if HFE constraints or opportunities were considered in the justification for the weapon system during program initiation (Milestone 0). Also, during this phase, there should be a review of lessons learned (HFE problems with existing similiar systems). If any existed, were steps taken to reduce the likelihood of human-induced system errors? The contractor selection process should be reviewed to determine if HFE considerations were included in the evaluation criteria. There should be evidence that the services provided HFE data in the request for proposal. Similar but more detailed, data requirements were noted for Milestones I, II, and III.

The second approach analyzes organizations to determine if essential ingredients such as manpower, training, and HFE considerations exist in the weapon system acquisition process. For example, before the decision to enter full-scale engineering development is made, the system's usefulness should be throughly tested and evaluated to derive an estimate of operational effective-ness and suitability. To insure operational effectiveness, the above con-siderations are important to such estimates. Therefore, the extent to which HFE considerations were included in the testing and evaluation of the system should be assessed. The following can be done:

- Determine if HFE problems appeared during tests on previous systems
  - were problems considered here
  - were solutions tested
  - were results incorporated
- Determine if personnel constraints were included
- Determine if design matches available personnel.

Although the approach outlined above is directed toward GAO auditors, there is no reason to restrict evaluation of HFE input evaluation to external auditors. Program managers should evaluate their own programs to determine the quantity, quality, and timeliness of the HFE inputs to the system acquisi-tion process. For example, there is an adequate and simple means to verify objectively at a relatively early point in system design that the hardware (and any software) has in fact been designed in accordance with the specified manpower characteristics. That means is the conduct of human factors engineering (HFE) test. A standardized methodology for the conduct of such a test has been available since 1976 when contract data item description DI-H-1334A (Report of HFE Test) was published by the Army. The other services adopted nearly all of it when the DOD Human Engineering Test Report, DI-H-7058 was published in 1979.

It should be noted that, even though this testing may be planned, experience has shown that it is frequently not accomplished. Sometimes it is cancelled outright (usually when the project has more requirements than funds), but often it is simply postponed — until after the decision which its results should have influenced. The usual justifications for this postponement are that "more important" testing had to be completed. Thus, the testing which has the greatest potential for revealing the adequacy of HFE inputs is frequently eliminated or performed inadequately. This will result in the type of performance gap noted earlier and will likely result in costly and time-consuming retrofits. The technology exists to counteract poor HFE design, it is up to program manager to insure its application.

2.3.4 Benefits from HFE Inclusion

In December 1980 the Naval Research Advisory Committee (NRAC) reported that man-machine technology (a primary emphasis of HFE), if used effectively, can result in significant improvements in operational effectiveness for the Navy. They also reported that inadequate use is made of man-machine technology during system development and that this is a contributing factor the the overall manpower problem facing the Navy. Application of HFE technology will (according to NRAC) result in:

- Design of effective man-machine interfaces
- Design within human information capabilities
- Ease of maintainability
- Compensation for human limitations
- Reduction in training requirements
- Increased job satisfaction
- Reduced accidents

In all cases, the final goal is optimum man-machine system performance.

The NRAC Study Group produced the following estimates of predicted benefits resulting from effective use of HFE Technology. The percentages indicate the judged improvements which could be obtained in representative, manned systems in the surface Navy. The numbers represent the combined opinion of knowledgeable experts. Even though the estimates are subjective, it seems that clear major improvements could be achieved in variables that are of fundamental importance to the Navy.

	Navy Goals	Potential Improvement
1.	System effectiveness and availability	30%
2.	Productivity Increase/Personnel reduction	20
3.	Job satisfaction and self-esteem	20
4.	Training Improvement	15
5.	Survivability	15
6.	Cost reduction	10
7.	Safety Improvement	10
8.	Retention of personnel	5
9.	Reduction in system response times	5

Another ,ay of determining benefits of appropriate application of HFE technology is to analyze relative costs and impact. Once again, this is a "best-estimate", but the figures would be impressive even if they only ball-park guesses. The list of recommended actions and costs, benefits, and pay-back periods appears in Figure 3-1.

3.0 APPLICATIONS OF HFE IN SHIP DESIGN

To illustrate a number of points made in preceeding sections the Human Engineering Program Plan for Landing Craft, Air Cushion (LCAC) will be reviewed. The LCAC case is an apparent successful integration of HFE technology for a relatively small system. The case of extension to larger combatants is also analyzed.

3.1 Applications to the LCAC

A general outline of the HFE program plan follows the required documentation quite closely and illustrates the requirement to modify the data item description to fit the particular procurement. The program outline follows (Bell Aerospace, 1981):

- Human engineering in subcontractor effort
  - subcontractor criteria
  - LCAC subcontractors
- Human engineering in system analysis and equipment procedure development
  - LCAC system analysis responsibility
  - general approach to systems analysis and equipment
  - procurement
  - analysis models
    - . gross analysis of tasks
    - . analysis of critical tasks
- Human factors in equipment detailed design
  - general approach to detailed design
  - human factors engineering drawing support
  - human factors record
  - human engineering checklist
  - human factors design for habitability
  - support during construction
- Derivation of personnel and training requirements
  - operability training analysis
  - maintenance training analysis
  - human engineering in procedures development
- Human engineering verification, test, and evaluation
  - general approach to verification, test and evaluation
  - mockups as part of human factors verification
  - test and evaluation
    - . general approach to human factors use of mockups
    - . overview of mockup activities
- Human engineering deliverable data products
- Time-phase schedule.

The outline indicates a generally well-planned HFE approach. The procedures outlined are backed up in the description of HFE Inputs.

> To assure that compatibility is maintained for all phases of LCAC design, human factors engineering will exercise control and approval of compliance with human engineering requirements through the Chief Engineer, Design Integration. A Human Factors representative shall be present at all design review meetings where human/vehicle interface is involved. Human Factors Engineering will review all drawings and signify approval prior to signoff by the Chief Engineer, Design Integration. Similarly, Human Factors Engineering will review all operating and maintenance procedures and make appropriate recommendations. Also, Human Engineering will be a working member of the software and integrated control system teams. To assure timely and valid inputs for LCAC training, Human Engineering has established a working relationship with Integrated Logistics Support.

Although the verbiage included in their program plan cannot guarantee proper application of HFE technology, the plan outlined above is descriptive of a conscientious approach.

3.2 Extension to Major Surface Combatants

The preceding program plan also points out on area of difficulty for total ship integration and assurance of HFE application. Bell indicates that four major subcontractos are involved in the LCAC project. For a major surface combatant (e.g., DDG-51) the potential number of subcontractors providing equipment with a man-machine interface may be quite large. Many of these systems are pre-existing and are considered to be "off-the-shelf" equipment. There is a very large, unresolved problem concerning integration of components which may or may not have been properly human-engineered during their development. Issues of design responsibility, cost-burden, and accountability (for overall system performance) remain. The task of selection and initial integration of pre-existing ship systems frequently occurs early in the development. Thus, it is imperative that HF engineers are involved at the outset of development.

3.3 Current Applications

The current emphasis has accelerated the application of HFE technology to ship and ship system design across a broad front. Many of these programs are similar to the LCAC HFE program plan described earlier, e.g., the LSD 41 has an HFE program plan which is to be carried out by the contractor consistent with required regulations and directives. This HFE activity will ultimately impact upon that program through ongoing and new LSD 41 system design, Land-based Test Site design, verification of existing LSD 41 systems, and the integration of new equipments. Other major ship systems acquisitions are receiving equally early HFE technology application consistent with required regulations and directives and program objectives. Specific applications of HFE technology in current and developing systems have been noted in a previous section. These applications include systems as diverse as weapons control and carrier arresting gear.

The evolutionary process of new system design is reflected also in modernization and update of existing ship systems. The Mk 86 Gun Fire Control

System (specifically called out by the GAO as having residual problems in several ownership categories) has received HFE technology application both from the cognizant Naval personnel and the prime contractor as it has gone through successive modifications. The development of SEAFIRE (an electro-optical sensor system) and its planned integration with the Mk 86 has resulted in renewed application of HFE technology both to operability (primarily control/display relations and functional flow of operation) and maintainability (impact on manning). The previously documented human errors with carrier launch and recovery systems have been addressed through modifications accomplished with the support of trained HF engineers. Planned applications of microprocessor-based control systems to carrier arresting gear and catapults are moving forward incorporating HFE inputs. The LSO console for the Helicopter RAST is now being fitted to the FFG 7 class with a thorough redesign according to HFE guidelines having been implemented.

These applications are being effective, but, for design-induced human errors to be reduced in fleet systems, applications must be made to both existing and developing ships and ship systems. The projected service life of the current inventory suggests that many problems will remain in the fleet well into the next century. Developing ship systems may see service (probably in modified form) beyond the life of the current or planned platforms for which they are earmarked. Current efforts are addressing known problems and attempting to obviate the occurrence of future problems. Of necessity, this current application is not the theoretical integration scheme laid out in the NAVSEA HFE program. Many operational systems are marginally productive with current designs and there will be a continuing requirement to develop modifications for these systems and upgrade them in accordance with HFE principles. Developing systems must have early application in accordance with NAVSEA HFE program if the cycle is to be broken and total fleet operability improved.

4.0 SUMMARY

In January 1981 the GAO published a report to the Congress entitled "Effectiveness of U.S. Forces Can Be Increased Through Improved Weapon System Design" (PSAD-81-17). This report concludes that many of today's military systems cannot be adequately operated, maintained or supported because the DOD does not pay enough attention to logistic support, quality assurance, and human factors during the design phase of the acquisition process. Three of the findings concerning human factors are the following: 1) human factors specifications, standards and handbooks used in designing and developing systems and equipment do not adequately address human limitations; 2) there are no common methodologies and data sources for use by system designers in forecasting skill levels of future military personnel; and 3) DOD testing policies and procedures do not identify and resolve potential human-induced failures during the developmental stages of the acquisition process.

NAVSEA has sponsored an effort designated "Human Factors Engineering Technology for Ship Acquisition" since 1975. The ultimate purpose of the effort has been to develop and demonstrate HFE design methodology which is specifically suited to development of new ship systems and to improving existent systems. A series of NAVSEA technical reports have been generated as the major result of this quickened interest in HFE requirements. The first, published in 1975, documents the feasibility of integrating HFE techniques and methodology into the total ship planning and acquisition process. The next report surveyed the ship systems acquisition process and assessed the applicability of available HFE methods, techniques, principles and data for meeting specific requirements in the process. This report developed computer based model design development processes in terms of HFE requirements such as operability and habitability design. Technologies were also identified according to their suitability for accomplishing individual steps in the processes. As a result, a number of HFE technology shortfalls were identified in areas where HFE needs obviously existed. Three subsequent reports document efforts to apply the model design processes promulgated by the second report to both new and existing Navy ship systems. Among those systems where model design has been applied are the new Mark 14 aircraft recovery system during its engineering development, the Helicopter Recovery Assist, Secure and Traverse (HRAST) system, the LSO workstation while undergoing redesign and the Mark 13 aircraft catapults undergoing evaluation. The purpose of each of these three pilot efforts was to refine the modeling processes by identifying problems encountered during application. As mentioned there is a report encompassing HFE integration within all Navy major weapon system acquisition efforts and details HFE requirements and the major weapon system acquisition process in a timeline for accomplishment.

Thus, the NAVSEA HFE Technology for Ships program already is addressing the three problems identified by the GAO as they apply the ship systems. What will be the continued direction of this impetus? Is it safe to conclude that the development of a coherent and comprehensive HFE technology for ships will be responsive to the ship system requirements projected for the future? HFE requirements will depend on three factors in future ships: the types of ships, the complexity of shipboard systems, and quantity and quality of personnel who are to man these future ships. HFE application will depend on that necessary evil — money. A recent article in National Defense (Seidenham, 1982) cited lack of money as the chief reason for noninclusion of HFE in systems planning.

> "Research and development funding is devoted to the system hardware and software. It is assumed that after the system is fielded people can be trained to use it. If you don't design to reduce human errors, training is not going to solve the problem."

Despite the apparent difficulty of citing positive instances of the contribution of HFE to overall system performance. There are several conceptual arguments for its inclusion which should be compelling. In the first place, the number of incident/accident reports citing the personnel factor is overwhelming evidence that the interaction of man and machines is not always error-free. These accidents cost far in excess of the typical HFE effort applied to the system that has been damaged. Obvious examples include slow catapult shots and incorrect arresting gear settings causing loss of multimillion dollar aircraft and often loss of life. More subtle examples abound, such as machinery damage from inadvertent errors. All of these instances can be traced to error-inducing design factors. The difficulty has been "selling" the use of HFE technology when there is no *a priori* evidence that such catastrophes will eventuate.

When HFE guidelines are not followed during development, systems which have sub-optimal man-machine interfaces will result. These systems often prove more difficult to operate. When systems are not being operated adequately by the available personnel, one possible response by managers is that the level of training in those personnel is inadequate. Therefore, what we have is a "well-designed" system with unskilled and untrained operators. The proposed solution to this problem is enhanced training. This scenario is likely to be true in some cases; however, a large number of systems have been found to be seriously deficient in design for operability. The commonly assumed solution, when these deficiencies are noted during development, is that training will overcome any residual deficiencies in design.

The implications of this strategy are shown in Figures 4-1 and 4-2 (taken from Benel & Malone, 1981). In Figure 4-1 the hypothetical relationship between operability and training and operability and HFE application is shown. This simplified depiction is intended to show that within broad limits it is possible trade-off HFE dollars for training dollars. (Of course, this ignores the fact that a modicum of each is absolutely necessary under nearly all circumstances.) Under various combinations of training and HFE outlays a given level of operability is possible (thus, the iso-operability curves). This may have no differential input to fielding a system because the dollar outlay would be constant for the initial operation.

The implications for life cycle cost are presented in Figure 4-2. HFE expenditures are maximal during development (and planned modernizations). Thus, there is a point at which HFE expenditures do not increase cumulatively. However, training costs are high during development and retain a moderate level of increase throughout the life cycle. Likewise, any modernization would cause an increase in training costs for new instructional technologies. The critical factor is that training costs increase cumulatively throughout the life cycle. Each case of attrition is an example of training dollars lost. Thus, there is a required constant input to compensate the lost training dollars. Proper application of HFE can be an effective cost-avoidance strategy.

HFE applications are indeed a "cost" to the development of a weapon system. As such, the use of HFE technology vies with other equally necessary and more traditionally accepted engineering disciplines for a limited pool of resources. HFE like a number of these other disciplines (e.g., supportability, maintainability) does not show necessarily any benefit during development. There is, however, a time when these disciplines do payoff and the payoff may be enormous. For example, personnel considerations are now estimated to represent 50% of a ships life cycle costs (Naval Sea Systems Command, 1979). Obviously, program managers have been tasked traditionally with delivering a system in time, within budget, and at or above a minimum level of operability. There has been no real provision to reward "excess" expenditures during development that result in savings that may only become obvious several years after fleet operations have commenced. Even then cost-savings may not be obvious, because the alternative less-costly-to-build, more-costly-to-own system does not exist for comparison.

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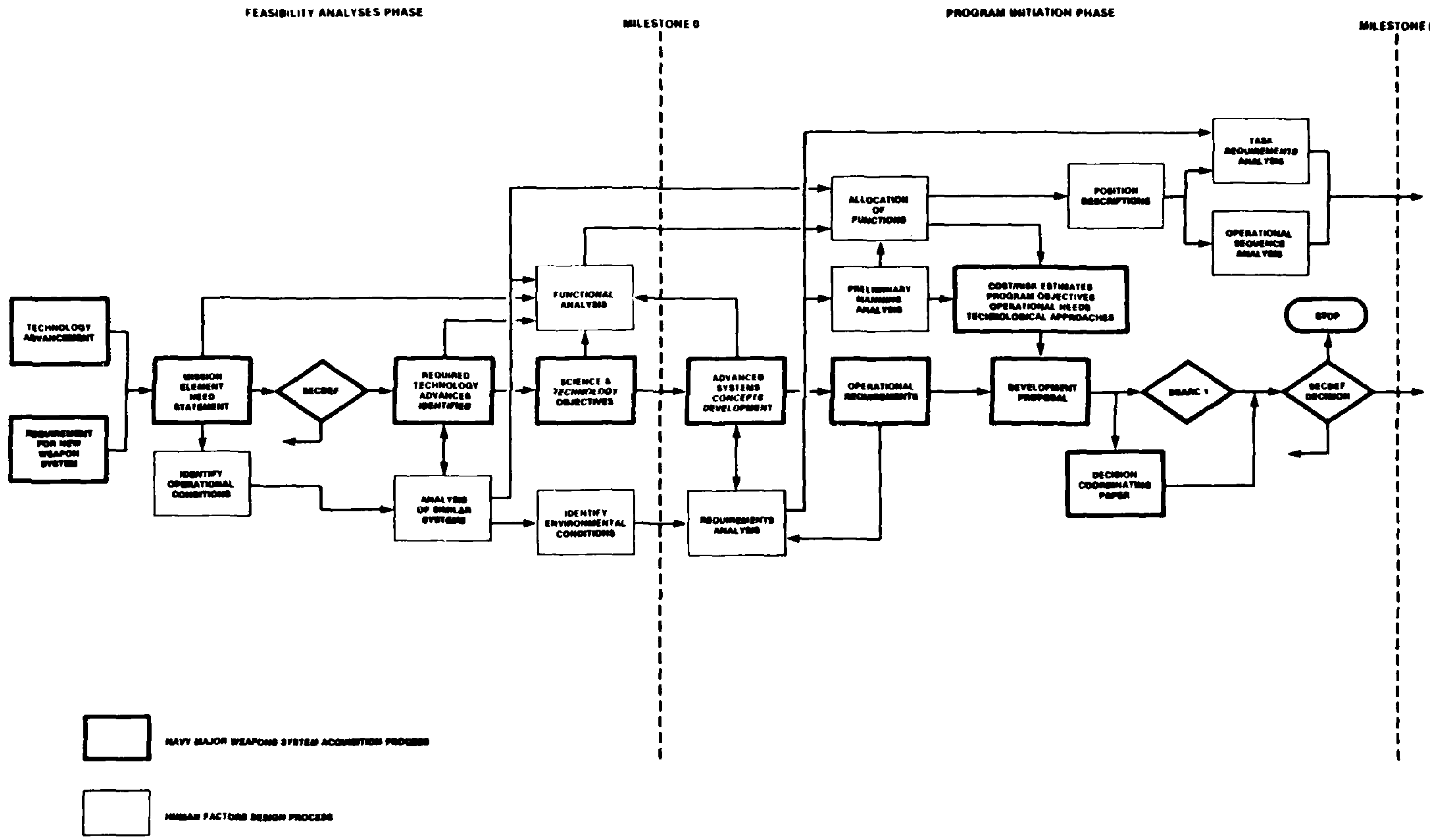
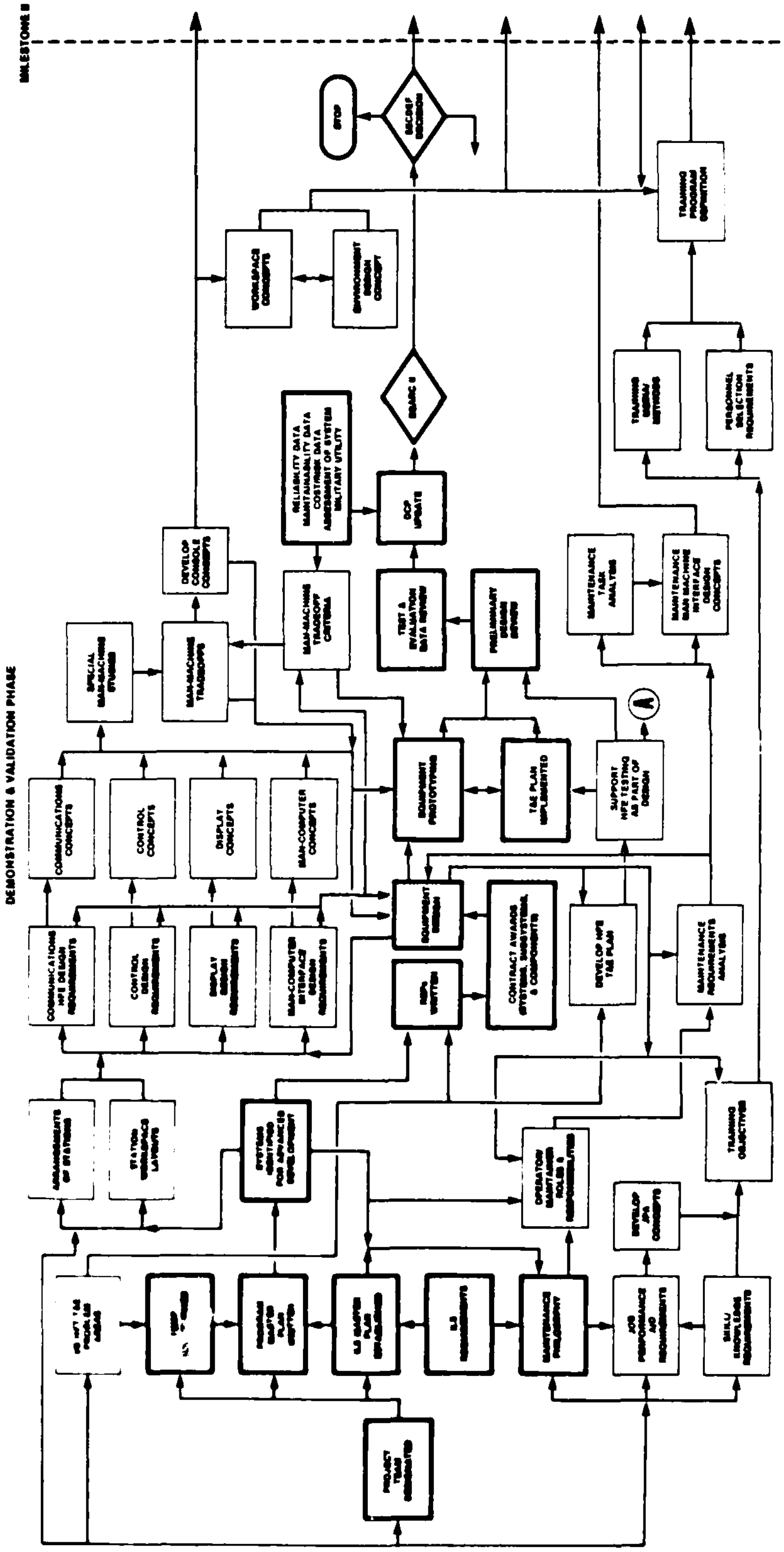
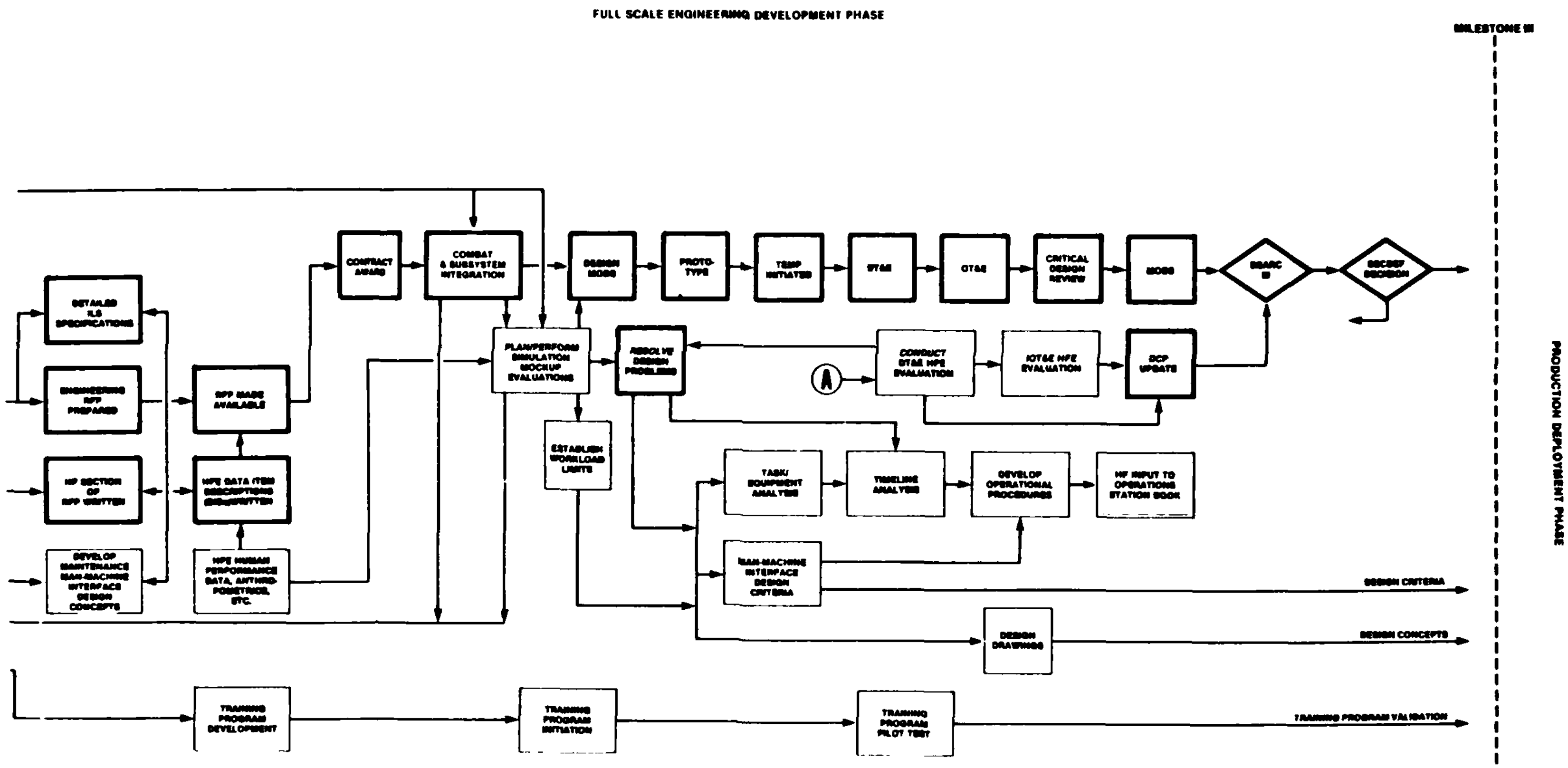


FIGURE 2-1.
INTEGRATION OF HFE INTO THE ACQUISITION PROCESS



DEMONSTRATION & VALIDATION PHASE
MILESTONE II
STOP
COMMUNICATIONS CONCEPTS
CONTROL CONCEPTS
DISPLAY CONCEPTS
MAN-COMPUTER CONCEPTS
SPECIAL MAN-MACHINE STUDIES
MAN-MACHINE TRADEOFFS
DEVELOP CONSOLE CONCEPTS
WORKSPACE CONCEPTS
ENVIRONMENT DESIGN CONCEPT
MAN-MACHINE TRADEOFF CRITERIA
RELIABILITY DATA
MAINTAINABILITY DATA
COST/RISK DATA
ASSESSMENT OF SYSTEM MILITARY UTILITY
DCP UPDATE
TEST & EVALUATION DATA REVIEW
PRELIMINARY DESIGN REVIEW
COMPONENT PROTOTYPING
T&E PLAN IMPLEMENTED
SUPPORT HFE TESTING AS PART OF DESIGN
MAINTENANCE TASK ANALYSIS
MAINTENANCE MAN-MACHINE INTERFACE DESIGN CONCEPTS
TRAINING PROGRAM DEFINITION
PERSONNEL SELECTION REQUIREMENTS
COMMUNICATIONS HFE DESIGN REQUIREMENTS
CONTROL DESIGN REQUIREMENTS
DISPLAY DESIGN REQUIREMENTS
MAN-COMPUTER INTERFACE DESIGN REQUIREMENTS
COMPONENT DESIGN
CONTRACT AWARDS (SYSTEMS, SUBSYSTEMS, & COMPONENTS)
DEVELOP HFE T&E PLAN
MAINTENANCE REQUIREMENTS ANALYSIS
RFPs WRITTEN
ARRANGEMENTS OF STATIONS
STATION WORKSPACE LAYOUTS
SYSTEMS IDENTIFIED FOR ADVANCED DEVELOPMENT
OPERATOR MAINTAINER ROLES & RESPONSIBILITIES
TRAINING OBJECTIVES
DEVELOP JPA CONCEPTS
MAINTENANCE PHILOSOPHY
JOB PERFORMANCE AID REQUIREMENTS
SKILL/KNOWLEDGE REQUIREMENTS
PROJECT TEAM DESIGNATED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PRODUCTION DEPLOYMENT PHASE
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ENGINEERING RFP PREPARED
HF SECTION OF RFP WRITTEN
DEVELOP MAINTENANCE MAN-MACHINE INTERFACE DESIGN CONCEPTS
RFP MADE AVAILABLE
HFE DATA ITEM DESCRIPTIONS (DIDs) WRITTEN
HFE HUMAN PERFORMANCE DATA, ANTHROPOMETRICS, ETC.
CONTRACT AWARD
COMBAT & SUBSYSTEM INTEGRATION
PLAN/PERFORM SIMULATION MOCKUP EVALUATIONS
DESIGN MODS
PROTO-TYPE
TEMP INITIATED
DT&E
OT&E
CRITICAL DESIGN REVIEW
MODS
DSARC III
RESOLVE DESIGN PROBLEMS
A
CONDUCT DT&E HFE EVALUATION
IOT&E HFE EVALUATION
DCP UPDATE
ESTABLISH WORKLOAD LIMITS
TASK/EQUIPMENT ANALYSIS
TIMELINE ANALYSIS
DEVELOP OPERATIONAL PROCEDURES
HF INPUT TO OPERATIONS STATION BOOK
MAN-MACHINE INTERFACE DESIGN CRITERIA
DESIGN CRITERIA
DESIGN DRAWINGS
DESIGN CONCEPTS
TRAINING PROGRAM DEVELOPMENT
TRAINING PROGRAM INITIATION
TRAINING PROGRAM PILOT TEST
TRAINING PROGRAM VALIDATION

Figure 3-1. Relative Costs and Impact of Suggested Actions

Suggested Action	Relative Cost	Relative Benefit	Payback Period
Apply Man-Machine Technology to System Design and Test	High	Very High	Short Range
Adapt Air system Design Approaches	Medium	High	Immediate
Expand Development of Man-Machine Design Criteria	High	High	Short Range
Enforce Strong Design Reviews	Low	High	Immediate
Establish a Navy Policy On Human Factors	Low	High	Immediate
Provide Manpower Guideline Constraints For New Systems	Low	High	Long Range
Include Human Factors Experts in Project Offices	High	Very High	Immediate
Provide Human Factors Design Tools	Medium	High	Short Range
Update Man-Machine Specifications	Medium	High	Short Range
Expand the Technology Base for Man-Machine Interface Design	Medium	High	Short Range
Track and Report Fleet Deficiencies	Medium	High	Immediate
Increase In-House Human Factors Capability	High	High	Immediate
Increase Contractor Attention to Man-Machine Interfaces	High	Very High	Short Range

Note: For relative costs:
- low = organizational or policy change
- medium = $1M or less
- high = over $1M

For payback period
- immediate = 1 year or less
- short range = 1 to 5 years
- long range = over 5 years

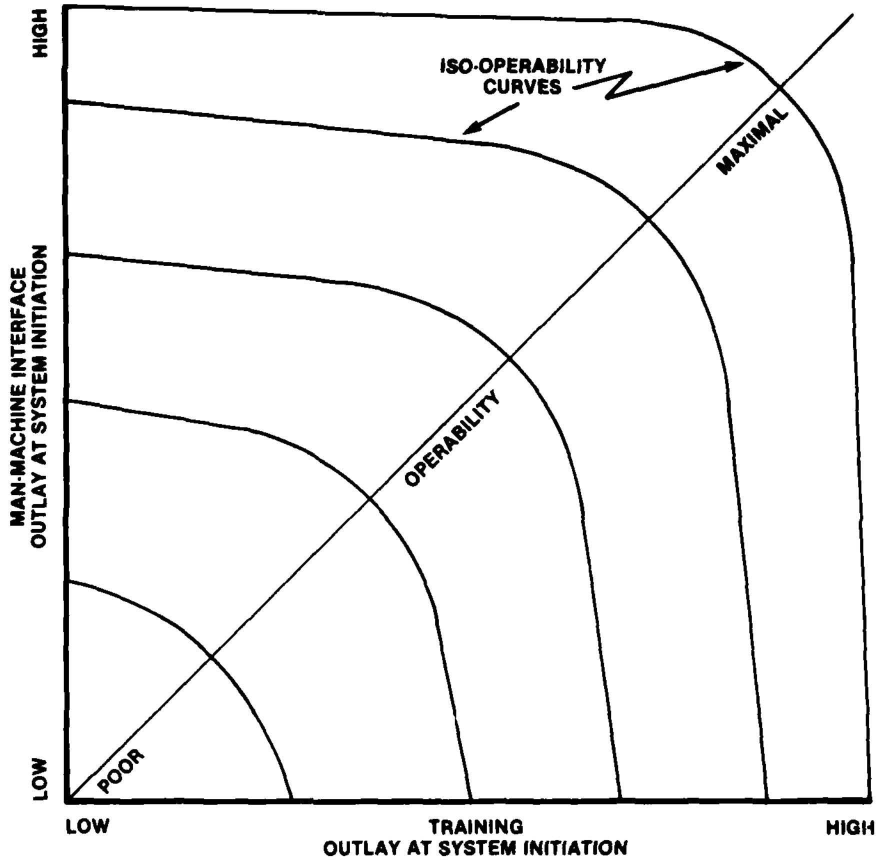

Figure 4-1 Hypothetical trade-off of training vs. HFE Costs

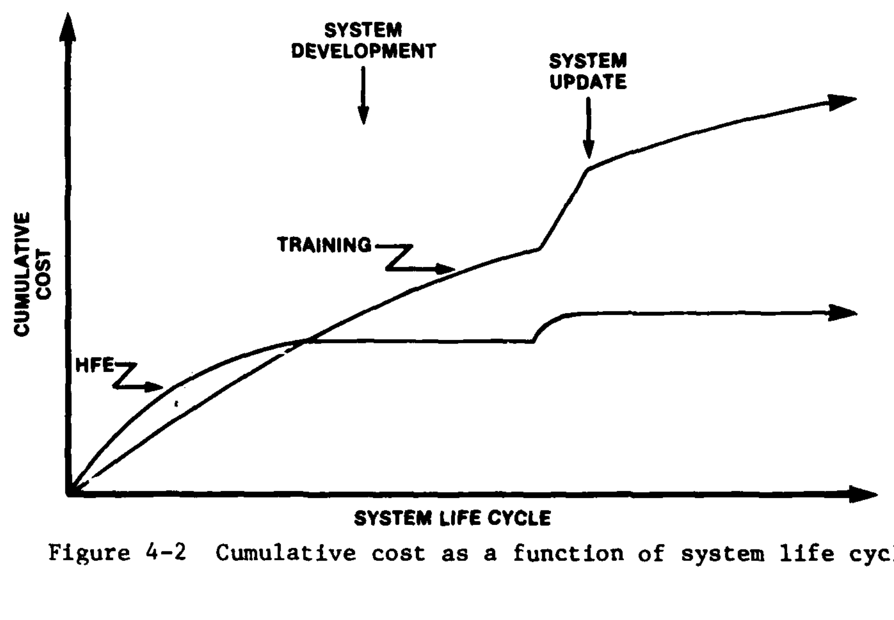

Figure 4-2 Cumulative cost as a function of system life cycle.