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Design Approaches and Tools to Enhance the Human Factors Engineering Design of Marine Systems

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Abstract

This paper presents progress in the design of advanced manning for marine systems, and progress in the development of human factors engineering (HFE) analysis and design tools that support the achievement of safe and effective HFE designs. The effort was directed at achieving safe and competitive levels of reduced manning for commercial Sealift ship, but the process and tools developed are considered to be applicable to marine systems in general.

A major contributor to the overall safety and effectiveness of marine systems is the performance and readiness of the crew. HFE initiatives are directed toward addressing personnel requirements in marine systems design. The driving objective of HFE is to influence design with personnel requirements and considerations. This is achieved through an approach that ensures that personnel considerations are addressed early in system development, that emphasizes attention to the role of the human vs. automation in system operation and maintenance, and that requires the use of simulation to model human performance and workload.

Ancillary objectives of HFE as applied to marine systems are: a) reduced manning as compared with baseline comparison systems; b) improved readiness of Sealift ships and systems due to reduced skills, reduced workloads, and task simplification; c) improved reliability of Sealift ships and ship systems due to an emphasis on software and a reduction of human error rates; d) improved personnel availability and survivability due to reduced hazards and accidents; e) enhanced system and equipment availability through reductions in time to repair; and f) enhanced system affordability, resulting from the reductions in manpower support cost, training cost, cost of systems unavailability, cost of human errors, and cost of accidents.

Tools developed as part of the effort address HFE issues and activities including: functions analysis and allocation, issue tracking, development of HFE design standards, task and operations performance simulation, selection of non developmental items, and hazards analysis.

1. Introduction

The objective of this paper is to describe and discuss human factors engineering (HFE) requirements, challenges, design approaches, and tools in the design of marine systems. HFE is the systems engineering discipline directed at integrating humans into complex systems. The discipline represents a collaboration of behavioral science and engineering to address the requirements for designing systems to reflect the capabilities, limitations, needs and expectations of human users, operators, maintainers, and managers. HFE is also known as ergonomics in Europe, human systems integration in the DoD and U.S. Navy, MANPRINT in the U.S. Army, Crew Systems Integration in NASA, and Prevention through People (PTP) in the U.S. Coast Guard. [1] As described by Malone [2], since HFE is a systems engineering discipline, it incorporates (1) a systems domain - the human element of the system, (2) a set of objectives directed at integrating the human into the system, (3) a methodology concerned with analysis and integration of requirements, design of system elements to meet these requirements, and evaluation of the adequacy of the design, (4) databases of design principles and standards and human performance capability data, and (5) measures of effectiveness. The relationships among these elements of HFE are depicted in Figure 1. Each of the elements is described below.

2. Human Factors Engineering Requirements

2.1 The HFE Domain.

The domain of HFE is the human in the system, specifically his or her roles, responsibilities, and requirements, and design features required of system hardware, software and procedures to enable the human to meet performance requirements in a manner that is safe for the human in the system, the general public, and the environment. HFE is primarily concerned with system integration, involving the integration of the human element of the system with the other system elements, including hardware, software, procedures, environments, information, organizational factors, other humans, and system products.

2.2 HFE Objectives

The first objective of HFE then is the integration of the human into the system. Objectives which support this integration include the requirements that HFE will:

- Influence system design with human requirements,
- Reduce the incidence and impact of human error,
- Reduce manning levels, and skill and training requirements,
- Enhance training effectiveness,
- Enhance the effectiveness of operating and emergency procedures,
- Eliminate or control of hazards to human safety and health.

HFE can be applied to the design of new systems or to the improvement of existing systems. In either case, there is a well established HFE process; the activities, events, and products of which are integrated with those of the system engineering process. A typical human engineering process is presented as Figure 2, showing the typical progression from analysis, to design, to evaluation. Characteristics of the HFE process are that it must be: a coherent, well-defined representation of the activities required to apply HFE in system design; requirements-driven; iterative; integrative; standardized, formalized, and tailorable; multi-disciplinary; verifiable; supportable; focused on product quality; and directed at risk reduction.

HFE methods represent the techniques of conducting specific steps of the HFE process. The process, (in the early phases of system development) is primarily concerned with human-system requirements analysis. This analysis begins with the identification, analysis, and integration of system functional requirements, leading to an allocation of functions to human performance or automation. The function allocation activity results in a determination of the required role of the human in specific functions to be performed by the system. Based on the human roles, the tasks and task sequences underlying human performance, and the requirements associated with performance of the tasks, are modeled in a task analysis.

After human roles and human performance requirements have been identified and analyzed, the HFE process addresses the design of human interfaces. HFE is fundamentally concerned with design: design of equipment to reduce human errors, design of information products, jobs and procedures, human-machine interfaces, and environments. The overall objective is to enhance the performance, productivity, and safety of people in systems, leading to improved system performance, productivity, and affordability.

Design methods include development of interface design concepts, conduct of modeling and simulation to assess alternate concepts, tradeoff analysis to select a concept, and application of HFE design standards to complete the detail design. The HFE design process and associated methods address specific aspects of the design of human interfaces in terms of:

- *design for usability* — usability is an attribute of a system which promotes an understanding on the part of the system as to what is going on in the system, what he or she needs to do next, and what response to expect of the system. It is also an index of the system's degree of responsiveness to user needs.
- *design for operability* — where systems are more operable, the probability of human error, the training burden, the number of required personnel, and the time to perform tasks are all reduced, tasks are simplified, and operators are more satisfied and less likely to be subjected to the adverse effects of psychological stress. When HFE has been applied to control systems, the operator is an integral part of the system, and is aware of what is happening in the system at all times.
- *design for maintainability* — application of HFE improves the maintainability of systems by ensuring that human-equipment interfaces are designed to consider human limitations, by designing working environments to be safe and supportive, by ensuring that procedures are unambiguous and consistent, by providing the information required of the maintainer in a readily understandable manner and by providing decision aids to support diagnostic and repair decisions.
- *design for safety* — The inclusion of HFE in system design and improvement directly impacts the safety of system personnel since one of the major objectives of HFE is to identify potential hazardous situations and to reduce the hazard through system design, implementation of alarms and warnings, and training.

When the design of human interfaces is complete, the HFE process addresses the evaluation of human integration into systems. The test and evaluation process includes evaluations of usability, operability, maintainability, and safety, as well as an assessment of the extent to which human interfaces are in compliance with HFE standards.

2.4 HFE Data Bases

The application of the discipline of HFE in the design of control systems relies on data from several sources. First of all the discipline relies on human performance capability data to identify requirements to support human performance in system operation. The discipline also relies on HFE design principles, guidelines, and standards in the detail design of human interfaces.

2.5 HFE Measures of Effectiveness

Measures of effectiveness (MOEs) are used: (1) to assess the adequacy of HFE application; (2) to evaluate the extent to which the system was designed in terms of HFE requirements; (3) to assess system alternatives in terms of HFE considerations; and (4) to evaluate human performance effectiveness and safety concerns in existing system improvement.

The scope of HFE activity in the design, development, test and evaluation of marine systems and structures is broad in that it encompasses all aspects of systems which impact, or are impacted by, human performance and safety. This paper focuses on three major distinct but interrelated HFE challenges in the design of marine systems and structures: (1) how to reduce the incidence and impact of human error; (2) how to reduce human workloads and system manning levels; and (3) how to ensure required levels of human cognitive performance.

3. HFE Challenges

The HFE challenge is to design systems which improve cognitive performance and minimize or eliminate human error. When the engineering analyst succeeds in performing the above, he/she can then develop and implement human-machine interface design concepts which incorporate reduced manning without the additional cost of increased skills or training, and have no adverse impact on human reliability or safety.

3.1 Improving Cognitive Performance

While the study of human cognitive function is highly complex and theoretical, an operational paradigm for considering human cognition (for the purposes of this paper) which follows classical control theory in the context of classical information processing theory. That paradigm basically is as presented in Figure 3.

Navy C^4I in the fleet today are characterized by information overloads and demands for rapid decision making. Such information overloads have resulted from the fact that sensors and sensor products have proliferated as diverse operational commands, recognizing their value, demanded the products. This has led to unnecessary ambiguities for the tactical commander.

In modern day warfare the life's blood of the military system is information. The HFE challenge is to provide the characteristics of needed information which make it useful and usable by the human. These characteristics include: the flow of information, the completeness, accuracy, timeliness, and usability of information, the availability of information when needed, and the extent to which information from different sources can be integrated into a meaningful representation of what is happening. The management of information has become the major issue for system effectiveness, the major challenge for system technology, and the major concern for HFE in the military today.

Another information management problem in today's C^4 systems is that information is typically conveyed in the wrong format - narrative messages, and in the wrong media - paper. AEGIS lessons learned have reported the problems resulting from the fact that non-real-time information is received as Naval message traffic or via voice channel and is separately maintained in paper form, making it extremely difficult to integrate it with tactical information displays. With the rapidly expanding diversity of information sources, a critical need exists in the Navy for more effective techniques to ensure information transfer timeliness, responsiveness, and appropriate granularity. Information transfer encompasses information communication and information dissemination. To be useful, needed information must be conveyed to the intended user so as to be available when required and at the level of specificity required.

The HFE need is to identify, develop, and integrate information management technologies that will reduce human error and operator cognitive workload while enhancing the decision-making and fighting capabilities of Navy C^4I personnel. The need is to effectively integrate information and provide information products to users so as to minimize reaction time and the probability of human error. The leading cause of human error is unavailability and/or inadequacy of needed information in an environment of information overload. The need for information integration is critical as commanders must sift through multi-sensor, multi-source, and multi-warfare information to determine the tactical significance of that information.

There is a critical need to improve the skills of personnel in the processing and handling of C^4I information. Naval C^4I systems of today are characterized by a number of training problems, including the fact that training is routinely used to compensate for poor human-machine interface design; training requirements do not usually influence C^{4}I system design; training is generally too much concerned with knowledge acquisition rather than information management skills acquisition; too little emphasis is placed on measurement of human performance as a result of training; and too little training systems development attention is given to team training as opposed to individualized training. The effects of these problems are: excessive training costs; excessive training pipelines; reduced training effectiveness; and reduced system performance.

3.2 Reducing Human Error

Human error represents the major threat to the safety and affordability of marine systems. The IMO Secretary General on World maritime Day in 1994 stated that up to 80% of accidents at sea are caused by human error. The IMO Secretary General concluded that “if we sincerely want to stop accidents from occurring, then I think it is obvious that we should concentrate our efforts on eliminating human error” (reference 3)

Human error refers to any situation where an observer fails to perceive a stimulus, is incapable of discriminating among several stimuli, misinterprets the meaning of a stimulus, makes an incorrect decision, fails to select the correct response, or performs the response in an incorrect manner. [4] A definition of human error states that it is an action that violates some tolerance limit of a system. Human errors have been classified as: errors of omission (tasks that are skipped); errors of commission (tasks performed incorrectly); sequential errors (tasks performed out of sequence); and temporal errors (tasks performed too early, too late, or not within the required time). Bea [5] in addressing the incidence of human error in marine structures, noted that high consequence accidents resulting from human error can be differentiated into those which occur in design, construction, and operation phases of the marine system’s life cycle. Unacceptable performance of a marine structure can be the result of improper design or construction of the system, however, the majority of compromises in the quality of a structure occur during the operating phase, and can be attributed to errors committed by operating personnel. Reference [5] cites evidence of major claims associated with commercial shipping during 1993 to conclude that human errors that occurred during operations were responsible for approximately 62 percent of the major claims.

Meister [6] distinguishes three types of human error in terms of the causes of the error: “system-induced errors”, “design-induced error”, and operator-induced error." System-induced errors reflect deficiencies in the way the total system was designed. They include mistakes in designating the numbers and types of personnel, in training, in data resources, in logistics, and in maintenance requirements and support. Design-induced errors result from inadequacies in the design of individual items of equipment. The resulting equipment characteristics create special difficulties for the operator which substantially increase the potential for error. Operator-induced errors can be traced directly to an inadequacy on the part of the individual who makes that error. They include errors resulting from lack of capability, training, skill, motivation, or from fatigue.

According to (reference 4) there are characteristics of people which have an influence on the frequency of errors. These include such factors as fatigue, disorientation, distraction, motivation, forgetting, complacency, confusion, incorrect expectancy, excessive stress, boredom, inadequate skills and knowledge, and inadequate or impaired perceptual or cognitive ability. Such factors can certainly contribute to the occurrence of errors, and in some cases even cause errors.

It is also well established that factors external to the individual can influence the potential for human error. Elements of the job or task, design of equipment, operating procedures and training can all affect the potential for error. These external factors can be classified as situational factors and design factors. Situational factors include those aspects of the operational setting, other than design, which influence human error incidence. These include: task difficulty, time constraints, interfering activities, poor communications, and excessive workloads.

Design factors include aspects of the system hardware, software, procedures, environment and training which affect human error likelihood. Design factors encompass such aspects of the system as: human-machine interface design features; information characteristics (availability, accessibility, readability, currency, accuracy and meaningfulness); workspace arrangement; procedures; environments; and training.

In a 1980 report to Congress entitled “Effectiveness of US Forces can be increased through improved weapon system design,” the GAO reported that poor design of equipment can significantly increase the probability of error- induced failures once a system is deployed. The GAO lists design characteristics which impact error potential to include: indicators and readouts not readily visible, parts not readily accessible, overly complex visual aids, unclear labeling and instructions, and awkward equipment layout and arrangement. The GAO study quoted above reported that at least 50 percent of the failures of major military systems are due to human error. The GAO listed five “types” of human errors which cause the most failures. These include: 1) failure to follow procedures, 2) incorrect diagnosis, 3) miscommunications, 4) inadequate support, tools, equipment and environment, and 5) insufficient attention or caution.

Human error is associated with a "significant majority" of marine accidents. [7] In the air transportation industry, human error has played a progressively more important role in accident causation as aircraft equipment has become more reliable, and efforts to reduce such error have grown accordingly. Until recently however, little attention has been paid to human-induced accidents in the maritime industry. Catastrophic accidents such as the *Exxon Valdez* grounding in March 1989 and the grounding of the oil tanker *Braer* off the coast of Scotland have focused attention on the importance of HFE in manning, operating, and maintaining marine vessels. Inadequate attention paid to HFE considerations such as equipment layout and design; training and selection of personnel; and documentation of roles, responsibilities and procedures will inevitably lead to "human error."

One method to understand the etiology of human error is to examine critical incidents where human error resulted in an accident. Toward this end, two marine accidents are briefly discussed in terms of the human-related errors that led to their occurrence. Each accident was investigated by the National Transportation Safety Board (NTSB), which has the responsibility to review the facts that surround major transportation accidents and issue a formal finding of causality. The NTSB also issues recommendations for preventing additional similar accidents to concerned parties such as the U.S. Coast Guard (USCG) and companies that operate the vessels.

Human error case study: the A.M. Howard. The grounding, subsequent capsizing, and sinking of the lift boat *A.M. Howard* in which 3 people were killed in October 1985 involved both equipment design and training deficiencies (reference 8). The *A.M. Howard* was contracted to conduct well tests in Breton Sound and was located at Hopewell. The National Weather Service had issued a hurricane warnings for waters in the Gulf Coast and Mississippi River areas. The master of the lift boat told the NTSB that the engineer on board told him that the reservoir engineer (who was employed by the contracting company) wanted the *A.M. Howard* to proceed to the well site that evening so the industrial personnel would be there to start work the next morning. The master did not confirm this report with the reservoir engineer, who was located in a trailer on the Hopewell dock, and proceeded down the Mississippi River Gulf Outlet Canal. At this time there were winds up to 50 mph, rain squalls and three to four foot seas in the canal. The master expressed reservations about proceeding to the work site to his supervisor via radio and was told to use his own judgment.

Several minutes later the *A.M. Howard* experienced trouble with the starboard engine. The lift boat became grounded on rocks, backed off, and proceeded toward Hopedale. The engineer checked the boat's void for water, found none, and both he and the master assumed there was no damage from the grounding. Several hours later, the master felt the lift boat list to starboard. He immediately attempted to jack the boat up, to no avail, and decided to abandon ship. Three crew members who were sleeping in the deckhouse drowned when the *A.M. Howard* sank. The master swam to the canal bank and was rescued. Further rescue attempts were made by the USCG but there were no more survivors. When the *A.M. Howard* was salvaged, several fractures in the boat's hull were found.

In its investigation of the accident, the NTSB made the following findings:

(1) The *A.M. Howard* was not certified by the USCG, nor was it required to be under current regulations.

(2) The master of the *A.M. Howard* was not a licensed operator of lift boats, was not required to be so, and had received no special training in lift boat operations. The other crew members (engineer and laborers) had never been aboard the *A.M. Howard* prior to October 25, had no formal training in vessel operations, and did not participate in any kind of emergency drill aboard the lift boat.

(3) The master of the *A.M. Howard* should have recognized that the weather conditions were unfavorable to the safe operation of the lift boat and should not have departed Hopedale. He did not understand the increased risks imposed by the weather due to insufficient training in lift boat operations, vessel navigation, and stability of the company's lack of written operating procedures pertinent to the safe operation of the lift boat.

(4) Although the master did not believe the grounding caused any damage, he should have directed the engineer to make periodic checks of the boat's void for flooding and should have inspected it for damage because the vessel was not equipped with a high water alarm or automatic pump in the void space.

As a result of its investigation and findings, the NTSB recommended to the company, the USCG and the Offshore Marine Service Association that:

(1) lift boats be equipped with high water sensors and a drainage system that includes an automatic pump or manually started pump which can be operated from the pilothouse,

(2) masters be provided with clear and precisely written operation manuals which provide information on vessel loading procedures, deck load restrictions, jacking procedures, inspections of unmanned en-

gine spaces, the weather conditions under which the vessel can safely operate, and the importance of briefing the industrial persons aboard on the vessel's safety equipment,

(3) the USCG require that lift boats be operated by a licensed officer or operator.

This accident clearly illustrates how lack of proper training, procedures, and equipment resulted in several poor decisions by the master. The decision to leave Hopewell and continue to the work site can be described in human error theory terms as a failure to shift to knowledge-based behavior. [9] The master, who had a third-grade education, was following orders from the company but had ultimate responsibility for operation of the vessel. He failed to adapt to the changing environment. Even with his poor decision to continue despite the adverse weather conditions, the master could have mitigated the consequences by periodically inspecting the vessel's void area for damage and flooding. The engineer was unfamiliar with the vessel and could not conduct a proper inspection; however, the presence of a high water alarm would have alerted them to the flooding. This failure to adapt to the changing environment resulted from a lack of information that could have been provided by appropriate equipment. Sufficient training in lift boat operations would have also provided more information on inspection procedures. This accident was attributed entirely to human error by the NTSB.

Human error case study: the Exxon Valdez. The influence of inadequate or inappropriate administrative policies, as well as plain poor judgment, on human-induced accidents is further illustrated by the *Exxon Valdez* case [10] in which 258,000 barrels of crude oil were spilled into Prince William Sound, Alaska. As noted by the NTSB, the probable cause of the accident was summarized as follows:

> "...the grounding of the *Exxon Valdez* [was due to] the failure of the third mate to properly maneuver the vessel because of fatigue and excessive workload; the failure of the master to provide a proper navigation watch because of impairment from alcohol; the failure of the Exxon Shipping Company to provide a fit master and a rested and sufficient crew for the *Exxon Valdez*; the lack of an effective Vessel Traffic Service because of inadequate equipment or manning levels; inadequate personnel training; and deficient management oversight; the lack of effective pilotage services "(p.v).

As with the *A.M. Howard* incident, the grounding of the *Exxon Valdez* can be traced to a single decision: the master's decision to leave the third mate in charge of piloting the vessel through a narrow channel that had ice on one side and a reef on the other. His inappropriate decision was not due, however, to insufficient training, time or workload pressures, or lack of information; rather, it stemmed from alcohol impairment which resulted in very poor judgment. Had the third mate been sufficiently well-rested and appropriately trained, he may have been able to successfully navigate the *Valdez* through the dangerous area. However, the company's manning policies produced an over-worked and fatigued crew, and the complicated navigation task was beyond the third mate's capabilities. The company also did not have a sufficient program for identifying, monitoring, removing from service, and treating employees with chemical dependency problems.

At several points, the disaster could have been averted. Had the Vessel Traffic Center maintained appropriate policies and equipment, the watchstander could have alerted the third mate to the impending danger from Blight Reef. Because the Center's watchstander did not use a higher range scale on his radar screen, he was unable to monitor the *Valdez* to the site of the grounding and provide any such warning. If vessels transiting the length of the Valdez Arm had been plotted instead of monitored, the ice conditions could have been recognized and information provided to departing ships earlier.

Both the *Exxon Valdez* and *A.M. Howard* accidents can be traced back to decision-making errors on the part of a person in charge. The inappropriate decision led to a series of actions which resulted in the accident. While not all transportation accidents are so clear-cut, in most cases, some kind of erroneous decision plays a role. Why do people make bad decisions? In most cases, the person may have had:

- inadequate or faulty information (from displays or other equipment, from other people, or from procedures or manuals)
- lack of timely information
- lack of experience or knowledge (training)
- reduced capacity to process information (due to bio-medical problems such as fatigue, stress, alcohol impairment, etc.)

These types of errors occur in what human error theorists call "rule-based" or "knowledge-based" behavior [9]. Knowledge-based behavior occurs at relatively high cognitive level, in which the person analyzes the environment, forms a goal, and carries out a sequence of behaviors to reach that goal. If the environment is not analyzed correctly or contains inadequate or misleading information, this inadequacy will in turn influence the person's decision making. Rule-based behavior occurs at a lower cognitive level and involves remembering a rule to invoke a sequence of steps or tasks appropriate to a given situation. Errors occur when steps are left out, not sequenced properly, or the wrong sequence is invoked. The lowest level is skill-based behavior in which over-learned, manual actions are carried out without much conscious control. Errors are due to sensorimotor problems, or invoking the wrong sensorimotor schema.

3.3 Reduced Manning

The Navy ship constitutes one of the most complex weapon systems in the US arsenal. It is a multi-personnel system with complements of up to 6,500 conducting multiple operations (e.g. air warfare, shore bombardment, surface warfare operations, search and rescue operations, etc.) in multi-warfare environments (AAW, ASW, ASUW, EW and strike). It operates as an independent combatant, member of a squadron, or as an element of a battle force.

The surface ship systems employed in the fleet today, and those being designed for the fleet tomorrow, make severe demands on the readiness, performance effectiveness and physical capabilities of personnel who must operate and maintain them. These systems are complex and extremely demanding on the sensory, motor and cognitive skills and decision-making capabilities of personnel. Add the increasing capability of the threat, the need to conduct multi-warfare scenarios, and the need to integrate, coordinate and interpret data from multiple sources and it becomes evident that we are rapidly approaching the limits of human capacity and capability.

The expected operating environment of the next generation of naval systems will impose extreme information loads on the personnel responsible for operating and maintaining shipboard systems. The complex combination of systems, equipment and personnel and requirements for rapid planning, scheduling and deployment of mission elements in the naval environment may converge to impose an untenable workload on the human operator. Cognitive workload will continue to be particularly high for shipboard personnel due to a variety of interdependent elements, including increases in the number and rates of decisions which stem from increases in the complexity and quantity of data that must be processed. Traditionally, such increases in workload have been compensated for by commensurate increases in manning. However, current and projected budgetary constraints coupled with demographic data projecting a continuing reduction of military-aged people over the next 20 years, reduce the feasibility of this solution.

The requirement to reduce the manning levels of new military systems as compared with predecessor systems is becoming a fact of life. Projected DoD budgets demonstrate a definite trend toward reduced manning. CNA analyses have shown that a significant reduction in manning is one of the most important factors in the affordability of new technology ships and systems. The overall importance of optimized manning has been recognized at the highest levels within the Navy and has led to such efforts as the CNO's Smart Ship Project, the Surface Combatant of the 21st Century (SC 21) which will be manned with 50% of the personnel on baseline ships, and requirements for the SSN 21 attack submarine to be manned at almost 25% below that of its predecessor. [11]

Similar efforts are underway to reduce manning on Sealift and commercial maritime ships. The Strategic Sealift Technology Development program within NAVSEA is examining the issue of reduced manning as a means to achieve international competitiveness. [12]

Given the current dramatic downsizing of the military on a worldwide basis, a reduction in manpower requirements for a given system is highly desirable. Designing for a reduced crew size without concomitantly reducing physical and cognitive work loads, however, can necessitate the assignment of higher caliber personnel and result in increased training time. Reduced force size also requires that each available system be a force multiplier, i.e., one that yields significantly more effect per unit, dollar, crew billet, etc. Such systems generally involve significantly higher technical sophistication, and, in turn, require personnel with higher capabilities and increased training time, as well as creating greater risk for safety and/or health problems. The HFE challenge is to develop and implement human machine interface design concepts which incorporate reduced manning without the additional cost of increased skills or training, and with no adverse impact on human reliability, effectiveness, or safety.

4. Design of Human Interfaces

HFE is primarily concerned with design of human machine interfaces to reduce the incidence and impact of human error. In consonance with integrating humans into the system, the objectives of the HFE design approach are to enhance cognitive performance, reduce the incidence of human error, decrease workload and reduce the overall manpower. The HFE design approach utilizes analytical techniques and lessons learned to formulate solutions which meet the stated objectives. The major lesson learned at Three Mile Island was that human errors can result from grossly inadequate equipment design, procedures, and training rather than simply from inherent deficiencies on the part of the operators. It was also apparent that erroneous expectancies played a key role in that the mental models formed by the operators (i.e., their cognitive performances) were completely contradictory to what was happening in the plant. These faulty expectations themselves were the result of human-machine interface design problems which denied the operators access to information that was critical to a correct diagnosis while at the same time inundating them with irrelevant, confused, and often contradictory information (reference 13).

HFE is concerned with integrating the human element of the system with the other system elements, including hardware, software, procedures, environments, information, organizational factors, other humans, and system products. To understand how HFE impacts these system elements it is important to recognize how the discipline designs the human interfaces in a system. The various human interfaces encountered in a marine system can be described in terms of classes of human interface. These classes of human interfaces include functional, informational, environmental, operational, organizational, cooperational, cognitive, and physical interfaces. The components and design requirements for each class of interface are described below.

4.1 Functional Interfaces.

Components The elements of functional interfaces include (a) the roles of humans versus automation in system operation, control, maintenance and management; (b) human functions and tasks; and (c) roles of system personnel in automated processes (e.g., monitoring, management, supervision, intervention, etc.).

Design Requirements The major issue is the role of the human vs. automation. In dealing with human-computer systems the issue is not so much defining the allocation of system functions to human or machine performance as defining the role of the human in the system. The emphasis on the role of human in the system acknowledges the fact that the human has some role in every system function. In some cases that role may encompass actual performance of the function or task, or it may involve monitoring automated performance.

It is also important to realize that an assigned role for human performance may change with changes in operational conditions. Thus a task optimally performed by a human under certain conditions of workload, time constraints, or task priority, may be more optimally automated under other conditions.

4.2 Informational Interfaces.

Components These interfaces constitute the information needed by a human to complete a function or task, required characteristics of the information (source, accuracy, currency, quantity), and protocols and dialogues for information access, entry, update, verification, dissemination and storage.

Design Requirements Modern maritime systems depend on information. The need is for design concepts, criteria, tools, and data to support the development of systems to manage the flow of information throughout the system, and maximize the accuracy, timeliness, and usability of information. The management of information has become the major issue for system effectiveness, and the major challenge for system technology. The criteria for adequate information interfaces include the availability of information when needed, in a readily readable and understandable format, and presented at the level of specificity needed for operator decision making and action.

4.3 Environmental Interfaces.

Components This class of interface is concerned with the system physical environment (illumination, noise, temperature, vibration, ship motion, weather effects, etc.), workspace arrangement, facility layout and arrangement, and environmental controls.

Design Requirements This class of human interfaces will be optimized by determining requirements for environments which are within performance, comfort and safety limits, designed in terms of task requirements with consideration for long term as well as short term exposures. Criteria also include determinations that facility designs and arrangements are based on what people must do in them; that arrangements reflect traffic patterns and cargo transfer requirements; that environmental limits comply with standards; that provisions for environmental protection have been included in the design; and that biomedical requirements and risk areas have been resolved.

4.4 Operational Interfaces.

Components Operational interfaces include operating, maintenance, and emergency procedures; workloads; personnel skill requirements; personnel manning levels; and system response time constraints.

Design Requirements The major impacts of operational interfaces are on human error probability, and safety. Design criteria for procedures address the extent to which required levels of human performance can be assured given time constraints. HFE improves the accessibility, content, and organization of procedures by ensuring that the procedure is complete, correct, clear, concise, current, consistent, and compatible with the reading/language/skill levels of the users.

Criteria for human workloads include concerns for the impact of workload on human error frequency, and on manpower requirements. Methods to reduce workloads, and manning, include function automation, consolidation, simplification, and elimination.

1) Determining the potential for <u>function automation</u> to reduce workload entails defining for which func-

tions is increased automation feasible, identifying the role of the human for functions where the level of automation has been increased, and determining how automation will modify task sequences and reduce human error.

2) Determining the potential for <u>function simplification</u> to reduce workload/manning focuses on identifying the potential for reducing physical, cognitive, and perceptual-motor task demands. The overall objective is to reduce: amount of information to be processed, complexity of the processing, number of decisions and options to be handled, complexity of actions, needs for interactions with other operators, extent and complexity of communications, task performance accuracy required, special skills and knowledge required, levels of skills, the level of stress associated with the performance of tasks under representative mission conditions, and time constraints.

3) Determining the potential for <u>function consolidation</u> and cross training to reduce workload entails determining tasks for which consolidation and cross training is feasible; identifying the role of the human for tasks for which consolidation/cross training has been implemented, and defining how consolidation/cross training will modify task sequences and reduce the likelihood of human error.

4) Determining the potential for <u>function elimination</u> to reduce workload requires identifying how system functions can be eliminated or off loaded to sites external to the system.

Criteria for optimizing personnel skill and manning requirements address the ability of humans to effectively and safely perform assigned tasks under constraints of personnel availability and capability. System response time criteria impact human error probability.

4.5 Organizational Interfaces.

Components. Organizational interfaces include the factors impacting the organization of system management functions, policies and practices, personnel jobs, and data.

Design Requirements. Criteria for optimization include determinations that position descriptions are based on functions allocated to the position and include duties, jobs, responsibilities, levels of authority, tasks and decisions appropriate for each position; that assignment of duties and tasks to each position is realistic; that duties and jobs are consistent with those found in existing systems; and that data required to perform functions and tasks are available, current, and identifiable.

4.6 Cooperational Interfaces.

Components These interfaces are primarily concerned with communication, collaboration, and team performance.

Design Requirements HFE objectives in optimizing communications are directed at improving both the media and the message. Specific requirements for media design include speech intelligibility and communications device operability. HFE concerns for the message include message standardization, use of constrained language, controlled syntax, and restricted vocabulary, methods of coding message priority, and human error potential in message transmission.

Concerns for collaboration and team performance center around the requirements for crew resources management with emphasis on team interaction, leadership/followership, clarity of communications, workload distribution, cooperative problem solving, and tutoring.

4.7 Cognitive Interfaces.

Components. Components of the cognitive class of human interfaces include decision rules, information integration, problem solving, instructional materials and systems, short term memory aids, cognitive maps, and situational awareness.

Design Requirements. For cognitive interfaces the focus is on design for usability, and conceptual fidelity. The major requirement for a human-computer system is that the interfaces be <u>usable</u> to the human. In this context usability of a system interface refers to extent to which: (a) human-computer interfaces have been designed in accordance with user cognitive, perceptual, and memory capabilities; (b) software command modes are transparent to the user; (c) displays are standardized and are easily read and interpreted; (d) the user is always aware of where he or she is in a program or problem (situational awareness); (e) procedures are logically consistent; (f) user documentation is clear, easily accessed, and readable; (g) on-line help is available and responsive; (h) the user is only provided with that information needed when it is needed; and (i) the user understands how to navigate through a program and retrieve needed information.

The importance of the design for usability in software development is evident in that: (a) the human computer interface comprises from 47% to 60% of the total lines of code; (b) a graphical user interface accounts for at least 29% of the software development budget; and (c) 80% of costs associated with the software life cycle (design, development, implementation, and maintenance and operation) accrue during the post-release maintenance phase of the life cycle, and furthermore, 80% of this maintenance is attributable to unmet or unforeseen user requirements. Therefore, 64% of the life cycle costs associated with a software system is due to changes required to improve the interface between user and computer.

As stated above, a great majority of the accidents reported in complex control systems result from human error. A major cause for human error in these systems is the fact that the human is operating on the bases of erroneous cognitive expectancies concerning what is the problem, what the system is doing, and how it will respond. In attempting to diagnose a problem event, an operator relies on expectancies. These expectancies are developed based on information presented to the operator, his procedures and training, his past experience, design conventions, and, when all else fails, his intuition. Expectancies will support the diagnosis when the cognitive model that the operator has of the system is in close agreement with what is actually happening, i.e. has high conceptual fidelity.

A clear example of how low conceptual fidelity turned a routine equipment failure into an almost catastrophic event was the accident at Three Mile Island. For 138 minutes a highly skilled and motivated crew of operators repeatedly failed to diagnose the problem, resulting in release of radiation of the order of 1200 millirem/hour into the atmosphere and the evacuation of thousands of residents. What caused the disparity between what the crew thought was going on, and what was actually happening in the course of the accident? The answer is clear when consideration is given to what the operators had to work with in attempting to develop a true conceptual model. In attempting to resolve the problem at TMI, the operators were presented with:

- Over 100 illuminated annunciators requiring the operator to recognize the problem from the pattern of alarm activation,
- No annunciator indicating that the reactor had tripped,
- A supposedly direct display of pilot operating relief valve (PORV) status, which was wrong!
- No training or procedures addressing this particular problem,
- No display of many of the variables critical to a correct diagnosis,
- No display of coolant at the core, the single most important determiner of plant safety,
- Strip charts of critical parameters, such as pressurizer level, which were almost impossible to read,
- Annunciators (750 total) which are not functionally grouped nor prioritized and which were of no real use to the operator,
- Arrangement of Emergency Safety Features indicators most of which were out of sight to the operator,
- Little or no compliance with design conventions and HFE standards.

4.8 Physical Interfaces.

Components. Physical interfaces include the physical, structural, and workstation elements with which the human interacts in performing assigned tasks. Interfaces include: workstations, control panels and consoles, displays and display elements (screens, windows, icons, graphics), controls and data input and manipulation devices (keyboards, action buttons, switches, hand controllers), labels and markings, structural components (doors, ladders, hand holds, etc.), and maintenance design features.

Design Requirements. The major requirement for the optimization of physical interfaces is the development of design concepts which are: (1) in compliance with HFE design guidelines and standards; and (2) demonstrated to be operable, usable, maintainable, and safe through use of mockups, models, and simulations.

The results of applying HFE in design are:

1) displays which are meaningful, readable, integrated, accurate, current, complete, clear, uncluttered, readily associated with control actions and other related displays, and responsive to information requirements,

2) controls which are reachable, identifiable, operable, consistent, compatible with expectations and conventions, and simple to use,

3) consoles and panels which include the required control and display functions which are arranged in terms of functions, sequence of operations, and priorities,

4) procedures which are logical, consistent, straightforward, and provide feedback,

5) communications which are standardized, consistent, intelligible, clear, concise, identifiable, prioritized, and available,

6) environments which are within human performance, comfort and safety limits, designed in terms of task requirements, and consider long term as well as short term exposure.

5. Design For Reduced Manning

In dealing with reduced manning, the HFE approach is to establish manning requirements based on workload measures, and to design the human machine interfaces to ensure that system operations and maintenance can be safely and effectively completed with reduced levels of manpower. The underlying rationale of the HFE strategy for manning reduction, human error reduction, and cognitive performance enhancement involves efforts to reduce the physical and cognitive workloads imposed on shipboard personnel, and apply HFE design standards to simplify operations. This permits workload redistribution between machines and people and among crew members. It fosters consolidation of existing operator positions, simplification of operator tasks, and reduction of overall ship manning levels. The potential for reducing manning and reducing human error potential through improved task simplification and improved human-machine interface design has been well demonstrated.

The central HFE issues in manning and error reduction are the allocation of functions to man or machine, establishing and defining the role of the human in the system and allocating optimum workload to maximize human performance. Function allocation is based on an assessment of the differential capabilities and limitations of men and machines in terms of the requirements of a specific function. There is an increasing need for interactive dialogue between humans and computers in automated systems. It underlines a requirement to consider the interactions between human and machine because few operations are either purely manual or totally automated; most are "semi-automatic". The role of the human in automated operations is as activator, monitor, manager, and under certain circumstances, as the intervening decision maker, taking over control from the automated process. With these considerations in mind, it is apparent that the active focus of HFE must be on determining the role of the human in the system, rather than merely allocating functions to human or machine performance.

The major techniques to reduce ship's manning through HFE design include 1) application of HFE design principles, standards and methods: 2) determining strategies for task simplification; and 3) developing decision aids and performance aids. The first two techniques are process-oriented. They are concerned with workload and manning reduction through the application of HFE design processes. The third technique is product-oriented in that it involves aids provided to the operator or maintainer at the respective worksite.

The methods used by the HFE specialist can best be described in the context of a HFE design process of which the HFE tools comprise essential components. Figure 4 provides a conceptual representation of the HFE design process. Implementation of the conceptual process occurs by conduct of the steps presented in Table 1.

Table 1. HFE Reduced Manning Process Steps

Step 1	Identify baseline systems and conduct missions/function analysis
Step 2	Reverse engineer the allocation of functions to human or automated performance in the baseline system(s) to identify rationale and problems
Step 3	Identify HFE lessons learned, issues, and hi-driver missions, functions, conditions, and tasks
Step 4	Allocate functions and model the role of human vs. automation
Step 5	Develop HFE technology requirements
Step 6	Identify workload reduction targets and strategies: determine reduction potential through: function automation
Step 7	Conduct a task analysis to identify task requirements
Step 8	Conduct simulations to assess workloads and human performance
Step 9	Identify design & readiness requirements to support reduced manning

The HFE process proceeds from a front-end analysis of requirements and constraints to a determination of the alternate roles of man in the system. These candidate role-of-man concepts are assessed through workload simulation and, based on the results of the simulation exercises, an optimum role-of-man concept is selected. The role-of-man concept then drives the establishment of the reduced manning concept. HFE design principles, standards and methods are then invoked to produce a design concept that implements the manning and error reduction approach, and the design concept is simulated or mocked-up and assessed through empirical evaluations.

Front-end analysis is a critical element in any application of HFE. Essentially a front-end analysis focuses on the identification, analysis and integration of requirements which will comprise the basis for HFE design concepts and design criteria. Front-end analysis from a HFE perspective provides the groundwork for all later human-machine interface design decisions.

Design and development of the system equipment, software, procedures, work and environments associated with the system functions requiring personnel interaction should include a HFE effort. This effort converts the mission, system and task analyses data into detailed design or development plans. These plans create a human-machine interface that will operate within human performance capabilities, meet system functional requirements, and accomplish mission objectives. The final developed design is the culmination of the initial planning, system analyses, criteria and requirements application and engineering effort.

6. HFE Tools

Several tools have been developed to assist the application of HFE methods and data in the acquisition of maritime systems. One of these is the HFE Integrated Decision/Engineering Aid (IDEA). IDEA was developed by Carlow International under joint funding by the U.S. Army Human Research and Engineering Directorate (HRED) of the Army Research Laboratory, the U.S. Navy Space and Naval warfare Systems Command (SPAWAR), the U.S. Naval Sea Systems Command (NAVSEA), and the Defense Advanced Research Projects Agency (DARPA). The guiding principle behind the design of the IDEA software is that the HFE manager/analyst should have at his or her fingertips all of the requirements, guidance, instructions, processes, procedures, methods, tools, and data needed to establish and conduct a timely and complete HFE effort.

The major requirements imposed on HFE which are inherent in the IDEA system, are: 1) personnel considerations and requirements must influence system design; 2) HFE must have a central role in the affordability assessment; 3) HFE must drive the system risk assessment; 4) HFE must maximize the quality of acquired products; 5) HFE must attend to requirements for concurrent engineering; 6) the HFE process must address the emphasis on use of commercial products and standards; 7) the HFE process must include requirements for prototyping, simulation and modeling; and 8) HFE must include requirements for specifying system operational performance objectives.

IDEA includes a standardized and formalized HFE process tied to the events, activities, products and milestones of each phase of the materiel acquisition process (MAP) and incorporating a set of automated tools to support the application of the HFE process. The elements of the IDEA system are:

1) The HFE process,
2) An integrated HFE information system,
3) Automated HFE analysis tools,
4) HFE analyst productivity enhancement tools,
5) HFE information tools,
6) A report generator for producing HFE plans and reports.

6.1 HFE Tools for Enhancing Cognitive Performance

Tools for enhancing cognitive performance include the IDEA Cognitive Analysis Tool, and on-line decision support systems.

IDEA Cognitive Analysis Tool. The IDEA Cognitive Analysis Tool (I-COG) supports identification of cognitive tasks, and constraints on task performance (limited duration, frequency, constraints on information availability, and availability of additional personnel for team performance tasks). The tool supports the identification of cognitive requirements associated with task performance, including requirements associated with information reception and integration, decision making, problem solving, short term memory, diagnosis, and understanding of the situation.

On-line Decision Support Systems. Decision support systems include such implementations as on-line help, intelligent tutoring, design to support collaborative operations, tele-maintenance, intelligent communications manager, operator's or maintainer's associate. The decision support systems available today either play out a scenario for the operator to enable assessment of probable outcomes, or they simply provide consultation and advice. To enhance cognitive performance, decision support systems will need to reduce the time to make a decision, and help the operator maintain a focus on what's important.

6.2 HFE Tools for Human Error Reduction

Tools for human error reduction include HFE design standards such as those contained in ASTM F-1166, accident reconstruction, and the IDEA Human Error Analysis Tool.

HFE Design Standards. HFE design standards are applied to ship systems design to reduce the potential for human error. The standards contained in ASTM 1166 (reference 14) were developed in the DoD (as MIL-STD-1472) based on best available data to reduce the incidence of human error. The Naval Research Advisory Council has estimated that simply applying HFE standards to the design of human machine interfaces will reduce the incidence of human error by at least 20%. HFE studies have reported that the benefit of applying HFE in the design of equipment and systems, in terms of reduction in human errors, may be as high as 50%.

Accident/Incident Reconstruction. This approach requires the reconstruction of a specific incident in order to analyze the role of human error as well as the adequacy of human machine interface designs, crew workload, communications, procedures, function allocation, workspace and environmental factors, and training. The tool employed in this approach is human-in-the-loop simulation, i.e. simulation of the accident or incident using a mockup, model, or actual equipment; personnel involved in the accident, if possible, or at least personnel representative of those actually involved; and reproduction of the operational, environmental, and mission conditions that were present at the time of the accident.

An example of an accident reconstruction was reported by Malone et al, [13] for the effort to determine the role of human error in the accident at Three Mile Island (TMI). A full-scale mockup of the TMI control boards and consoles was fabricated using photographs of panel segments. A scripted scenario of the accident was prepared, and the four persons who were on duty at TMI at the time of the accidents (two operators, the foreman, and the shift supervisor) walked through the scenario, verbally reporting why they chose the course of action that they did choose, and why they committed several additional errors in the attempt to diagnose the problem. Use of the accident reconstruction technique provided data that wouldn't have been available through other methods. It was only through the reconstruction of the accident that the important role of expectancy was identified. The crew had expected to identify the problem in the secondary system since that system had had problems over the several days prior to the accident. This led them to form a cognitive model of what was happening in the accident which was completely at variance with the actual events.

Human Error Analysis Tool. The IDEA Error Analysis (ERA) tool is a subset of the IDEA Task Analysis Tool. For each task analyzed in the task analysis, the analyst identifies potential or actually recorded error states, and identifies the error indication or cue that an error has occurred. The analyst then estimates the consequences of the error on human performance and safety, environmental safety, system and equipment readiness, and mission success. Finally, constraints on error recovery are identified for each error situation.

6.3 HFE Tools for Manning Reduction

The HFE tools which facilitate the design process include: the Role-Of-the-Human determination tool, the task sequencing NETWORK tool, and the SIMWAM workload simulation tool. This paper discusses these below.

Role-Of-Man Determination Tool. A critical issue in the HFE approach to manning reduction is establishing the human's required role of in the system. Human factors engineers have developed and proposed a number of techniques to guide the system developer in using function allocation. Of these, most rely on Paul Fitts early concepts, in the form of a "Fitts list." This is a list of parameters which we operationally associate with implementing system functions. Examples include the amount of information required to perform a function, the extent of physical strength required, functional accuracy requirements, and system or mission tolerance to errors and/or delays in functional initiation.

For many functions, the required function allocation's nature is quite clear. For example, machines perform complex number manipulations much faster than humans; therefore, allocating such a function to a human would be foolhardy. Conversely, (for the time being) humans perform better those functions which rely on sensory and/or perceptual abilities. The objective is to develop the optimal man-machine functional allocation.

The Role of the Human tool is an automated tool which assists engineers and developers in identifying alternate feasible roles of man in system operation and maintenance. Its operation consists of allocating functions to man, machine, or any combination of the two. The Role of the Human tool then processes the information and recommends an allocation strategy and the optimum role of the human in each system function.

Task Analysis. The assigned roles for each task are then exported to the IDEA automated task analysis tool (I-TASK) where specific requirements for task performance are identified for each task, under the specific allocation strategy and role assignments. I-TASK comprises a data bank of issues and concerns for human performance of system tasks as affected by the selected roles of the human and the machine in the completion of the tasks. For tasks which are cognitive in nature, by reason of the task itself or the assigned role of the human in the performance of the task, the task data are exported to an IDEA Cognitive Task Analysis Tool (I-COG) for a refined analysis addressing the cognitive aspects of required human performance, and the resultant task data are then imported back into the I-TASK Tool.

Workload Simulation Tools. HFE workload simulations involve modeling of functional and task sequences for individual operators and maintainers and for crews. These models identify function and task sequences associated with alternate function allocation approaches. A tool appropriate for task modeling is NETWORK. This tool permits the analyst to graphically establish the relationships and dependencies among functions and tasks and supports the identification of the complete set of tasks. Further, NETWORK automatically builds a database for later automated input to the simulation model. In the assessing adequacy of alternate function allocation strategies of roles-of-the human vs. automation, task sequences are modeled to reflect the distinguishing characteristics of each allocation approach.

The SIMWAM (Simulation for Workload Assessment and Modeling) tool then evaluates the allocation concepts. With SIMWAM, the developer can then determine and quantify the workloads and performance problems for each alternate allocation approach. This is possible for single and multiple operator systems.

SIMWAM is a task network simulation tool which can execute a network model previously defined by NETWORK. During a SIMWAM run, tasks are taken from the database when prior tasks are completed. If sufficient operators are available for a task, then it will be started. Input data which describe a task include a list of qualified operators and the number of these required to perform the task. In attempting to start a task, SIMWAM will assign operators who are currently idle. SIMWAM can also attempt to interrupt lower priority tasks in process to obtain operators for higher priority tasks. Operators are not necessarily human operators but can be any resource entity including equipment.

When a task is ready to start, SIMWAM draws a random sample from the probability distribution of duration for the task. While the task is in process, operator time is accumulated on the task. When the task is completed, it can take other tasks from the database. If the call is probabilistic, then one task out of several will be taken from the database depending on specified probabilities. Human error, equipment failure, or a hit or miss following weapon firing are events which could be accommodated by probabilistic tasks calls. A task can also call one or more tasks deterministically when a fixed sequence of tasks exists. Task calls can also be made conditional on events or variable values by means of user-written subroutines. This capability ensures that virtually any logical condition for the start of a task can be accommodated. For example, tasks required to process objects in a queue could be taken from the database only if there is one or more object(s) in the queue. As SIMWAM executes a network model it tracks mission time, task completions, task start and end times, time spent per task per operator, and operator utilization. At the end of a simulated mission, these data can be printed. At the end of a simulation run involving a number of missions, the means and standard deviations of mission data over the number of missions run can be printed.

SIMWAM is useful for addressing HFE issues in system development since task duration parameters can reflect equipment changes or automation; operators can be added or deleted to study workload; and effects of cross-training and task re-allocation can be evaluated.

Risk Assessment. The IDEA Risk Assessment Tool addresses cost, schedule, and design risks associated with the role-of-the-human concept. Current human system cost drivers, MPT drivers, human performance, and safety high drivers are identified for each alternative concept, and tradeoff decisions are identified.

7. Summary and Conclusions.

In summary, human factors engineering possesses the methods, tools and data to effectively and safely integrate humans into complex marine systems. These methods, tools and data are also effective in addressing three design challenges continually faced by HFE in the design of marine systems: improvement in cognitive performance; reduction of human errors; and reduction of human workloads and manning. The discipline of HFE brings to the resolution of these design challenges: (a) a top-down systems engineering approach, reflected in the HFE design process; (b) emphasis on the human domain in the system, and human performance, productivity, reliability, and safety; (c) formal analysis, design, and evaluation methods, including modeling and simulation; (d) emphasis on analysis and design of all interfaces between the human and other system elements, including hardware, software, procedures, environments, information, organizational factors, other humans, and system products; (e) measures of effectiveness for assessing HFE design concepts and conducting evaluations; and (f) a repertoire of automated HFE tools and data bases to support the application of HFE methods within the context of the HFE design process. With HFE application, it has been estimated that cognitive workloads and manning levels will be reduced by half, and the incidence of human errors will be reduced by from 40 to 60%.

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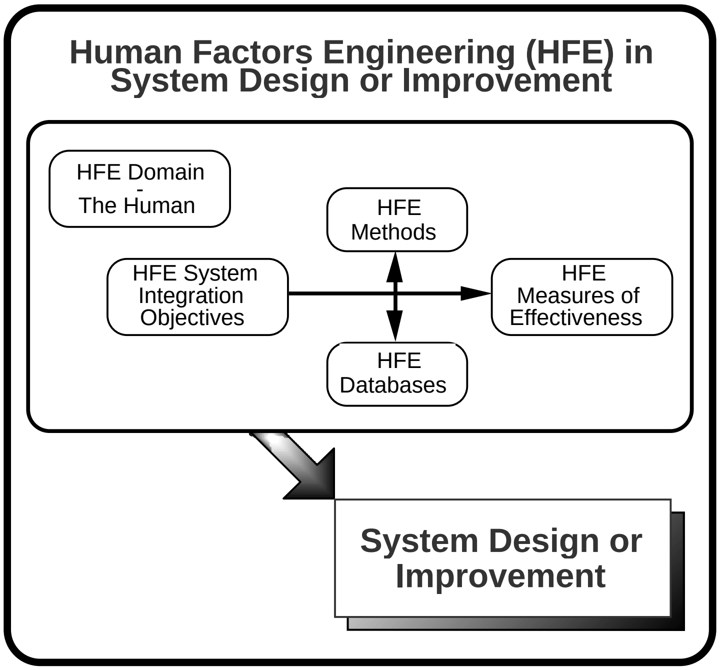

Figure 1
Human Factors Engineering Relationships in System Design or Improvement

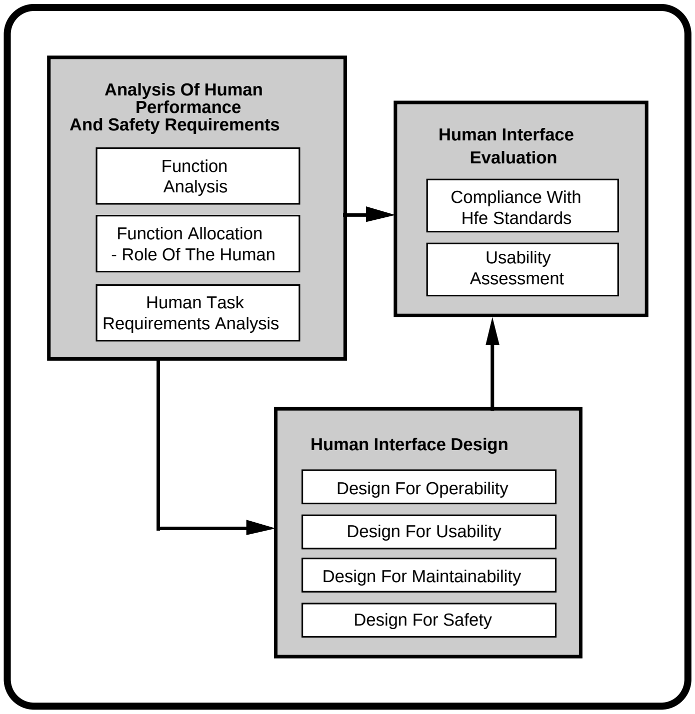

Figure 2
Typical Human Factors Engineering (HFE) Process

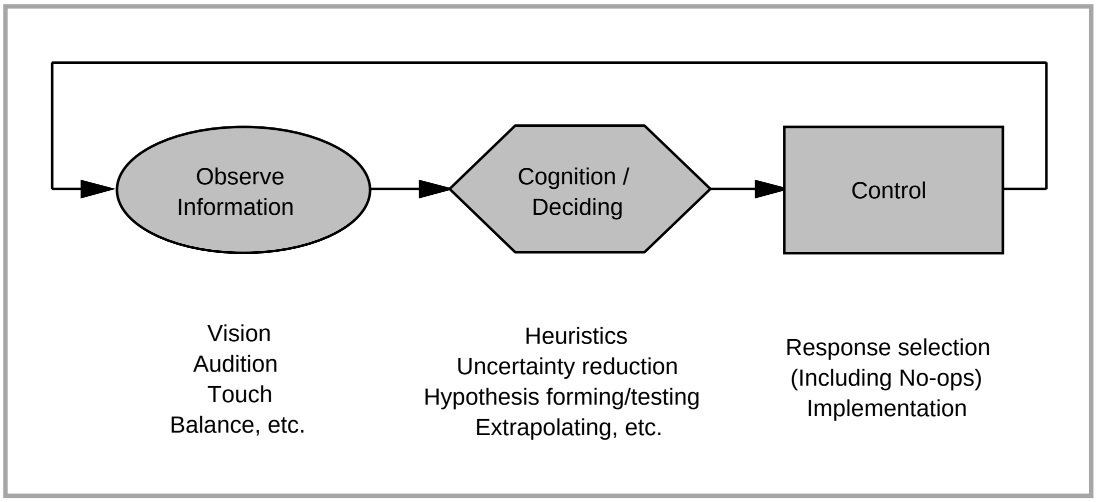

Figure 3
Simple Model of Cognitive Behavior

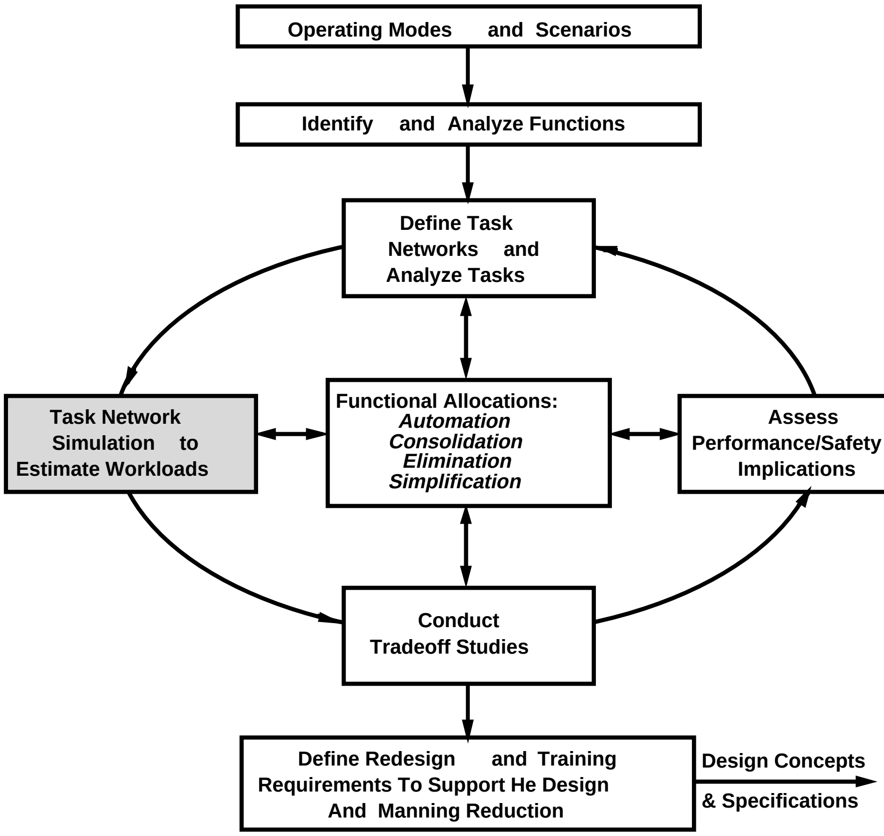

Figure 4
HFE Reduced Manning Process