NUREG/CR-2623
ORNL/Sub/81-9027/1

**OAK
RIDGE
NATIONAL
LABORATORY**

MASTER

**The Allocation of Functions
in Man-Machine Systems:
A Perspective and
Literature Review**

H. E. Price
R. E. Maisano
H. P. Van Cott

Work performed for
U.S. Nuclear Regulatory Commission
Under
DOE Interagency Agreement No. 40-550-75

**OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161

Available from
GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It has been reproduced from the best available copy to permit the broadest possible availability.

NUREG/CR-2623
ORNL/Sub/81-9027/1
Dist. Category RX

Instrumentation and Controls Division

THE ALLOCATION OF FUNCTIONS IN MAN-MACHINE SYSTEMS:
A PERSPECTIVE AND LITERATURE REVIEW

H. E. Price R. E. Maisano H. P. Van Cott

Manuscript Completed - November 1981

BioTechnology, Inc.
3027 Rosemary Lane
Falls Church, Virginia 22042
Under
9027
for Oak Ridge National Laboratory

Work performed for
U.S. Nuclear Regulatory Commission
Under
DOE Interagency Agreement No. 40-550-75
NRC FIN No. B0438

Date Published - June 1982

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. DEPARTMENT OF ENERGY
Under Contract No. W-7405-eng-26

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

Table of Contents

	<u>Page</u>
I. INTRODUCTION	1
II. AN HISTORICAL PERSPECTIVE	5
Machines in the Service of Man	5
Man in the Service of Machines	5
The "Disappearance" of Man	6
Man Versus Machine	7
Man in Combination with Machine	10
Human Requirements and Considerations Other than Performance	11
III. MODELS AND METHODS OF FUNCTIONS ALLOCATION	17
The "List Approach"	18
HEFAM	22
CAFES	24
SYSSIM	29
SAINT	34
HOS	37
Price-Tabachnick Descriptive Model (Hypothetical-Deductive Model)	40
Adaptive Allocation of Functions	46
IV. APPLICATIONS	49
V. ALLOCATION OF FUNCTIONS AND THE SYSTEM PROCESS	57
Design Versus Evaluation	58
System Development and the Allocation of Functions	59
Allocation-of-Functions Philosophy	65
VI. A PROCEDURE FOR THE ALLOCATION OF FUNCTIONS	67
Is System Automation Mandatory?	67
Is Function Automation Mandatory?	72
Is Human Participation Mandatory?	75

Table of Contents (Continued)

	<u>Page</u>
Hypothesized Human Participation	78
Testing Hypothesized Man-Rated Functions	87
Operator Acceptance of Automation	92
VII. THE ASSESSMENT OF FUNCTIONS ALLOCATION IN NUCLEAR POWER PLANT DECISION MAKING	99
Critical Decision-Making Element: Observation/ Data Collection	111
VIII. CONCLUSIONS	113
IX. REFERENCES	115
APPENDIX A DATA PERTINENT TO THE ALLOCATION-OF- FUNCTIONS PROCESS	A-1

List of Exhibits

<u>Exhibit</u>		<u>Page</u>
1	Core Performance Areas	20
2	Swain's List of Man and Machine Advantages	21
3	CAFES Submodels and Capabilities	26
4	Activities in the Price-Tabachnick Approach to Allocation of Functions	41
5	The Five Levels of Automation, as Developed by Mertes and Jenney	52
6	The Basic Issues of Personnel Performance Architecture	60
7	Principal Human Factor Activities in System Development	61
8	General Roles of Man in a System	63
9	Development of the Role of Man	63
10	Human Participation in Function Implementation	66
11	The Allocation-of-Functions Process	68
12	Example of a "Fitt's List".	69
13	Criteria for Assessing the Technical Feasibility of Automation	73
14	Criteria for Assessing the Economic Feasibility of Automation	74
15	Criteria that Limit or Preclude Human Participation in a System Function	76
16	Criteria that Define Unique Human Capabilities	77
17	Classification of Core Performance Capabilities	79
18	Questions for Determining the Human Participation for Each Function	84

List of Exhibits (Continued)

<u>Exhibit</u>	<u>Page</u>
19	Example of Chart for Recording the Process of Hypothesizing Human Participation 86
20	Summary of Technique for Testing Hypothesized Man-Rated Functions 88
21	Man's Senses as Informational Channels: A Comparison of the Intensity Ranges and Intensity Discrimination Abilities of the Senses 89
22	Chart to Record Results of Psychological Tests of Allocations 91
23	The Critical Effective Temperatures at Which Impairment May Be Demonstrated, According to Various Sources 93
24	Vigilance of 21 Female Workers Occupied with Time Paced and Monotonous Work 94
25	Chart to Record Data from the Tests Against System Constraints 95
26	Acceptance Principles From a Study of Commercial All-Weather Landing Systems 98
27	Decision Making in Emergencies 101
28	Decision-Making Model 102
29	Murphy Diagram for Activation/Detection 105
30	Murphy Diagram for Observation/Data Collection . . 106
31	Murphy Diagram for Identification of System State 107
32	Murphy Diagram for Interpretation of Situation . . 108
33	Results of Overall Evaluation 110

ABSTRACT

This report reviews the literature relevant to allocation of functions and presents a procedure for the allocation process applicable to nuclear power plant control rooms. An historical perspective of man's relationship with technology is given as background. Methods and models that have been developed to aid the allocation process are then considered, followed by examples of real-world applications.

The relationship of allocation of function to the system development process is outlined. The report then turns to the proposed procedure of the allocation process. This procedure, conducted in a series of steps, leads to decisions on what roles and functions man and machine will play in the complex man-machine system under consideration. These decisions are based on criteria developed from the literature on human and machine capabilities and limitations. The resultant hypothesized allocations are tested against environmental, system, and psychological constraints. Consideration is also given to human operator acceptance of automation, a crucial question with the increased use of computers and computer-based aids. An example of how this procedure might be applied to one aspect of the nuclear area is detailed. Lastly, suggestions for further work outline what still has to be done to implement the procedure in the evaluation and installation of automated and computer-based aids in nuclear power plants.

I. INTRODUCTION

This report concerns the allocation of functions between man and machine: the decision process whereby optimal roles can be determined for man and machine in a complex technology.

The story of man in relation to technology is one of the most fascinating chapters of human history. It is a story based on man's need for technology as an instrument of survival, marked by his continuing apprehension over its potential for harm. The relationship has been a dynamic one. Beginning as a master-slave relationship, with man in control, it passed through eras of infatuation and romance, of mixed love and hate, and is now evolving into a symbiotic partnership whose ultimate form cannot be foreseen.

Many forces influenced this story: industrialization; organized labor; war and its machinery; economics; politics; conflicting philosophies of man's purpose, dignity, and worth; and explosive technological growth. Perhaps the most important factor of all will turn out to have been the intelligent computer.

Throughout the history of technology, decisions have been made--more often unconscious and unrecorded than conscious and explicit--about the respective capabilities and the most desirable roles and functions for man and machine in the operation of any given technological system. This same lack of deliberation is evident in decisions about the newest and most complex man-machine relationship, the use of man and computers in process control.

In order to develop the most productive, safe, and satisfying balance between man and computer working together in a complex system, it is important to construct a systematic framework for that relationship--one based, first, on previous experience with such systems, and second, on a careful and detailed analysis of the respective capabilities of man and computer within that system.

The program represented by the project reported here is one such effort. Its purpose has been to examine the process by which the allocation of functions has taken place in certain industries (aerospace, defense, and process control), and then to outline an approach to the assessment of the role and functions of the operator in nuclear power plants in light of the findings from the experience of other industries. Based on the results of this analysis, criteria are proposed that could be generally applied to nuclear power plants to determine the optimum allocations of tasks and functions under a given design concept. To this end, the project has had two specific objectives:

- (1) Develop criteria for assessing design proposals and concepts of automation that employ computer-based operational aids. Criteria will be suitable for -
 - (a) review of specific proposals from utilities.
 - (b) preparation of guidelines and/or regulatory standards for promulgation to the utility companies.
- (2) Define a framework or model for a repeatable method of evaluating the safety impact of automation and other computer-based operator-aiding concepts from a human factors viewpoint.

The present report consists of a review of the analytic methods, models, and criteria that have been used to make decisions about the role and functions of man in complex systems. A preliminary approach to functions allocation is then described. This approach provides the initial framework for the further development, evaluation, and application of a method for functions allocation that is specifically tailored to the assessment of existing power plants and the operator aids proposed for them (e.g., Safety Parameter Display Systems, Disturbance Analysis Systems).

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

II. AN HISTORICAL PERSPECTIVE

The history of technology in relation to man can be said to have gone through five phases:

1. Machines in the service of man
2. Man in the service of machines
3. The "disappearance" of man
4. Man versus machine
5. Man in combination with machine.

Machines in the Service of Man

Throughout most of history, technology was used to service basic human needs. The first artifacts augmented human reach and muscle power. The bow, spear, axe, and lever enhanced man's ability to hunt game and to defend himself. Later, instruments were devised to extend the range of the human senses: the telescope, microscope, and signal mirror. Man controlled these simple systems, providing actuation and power, goals and plans, control, and the evaluation of outcomes. Devices such as these were fully understood by the users who constructed and used them. Most observers regarded such tools as beneficial and essential to human survival.

Man in the Service of Machines

As men were harnessed to the engines of warfare and to the machinery of the first "sweatshop" factories of 18th-century industry, the individual was no longer the locus of control but an element in a system devised, understood, and controlled by others. This prompted considerable controversy on religious and ethical grounds. A few extremists (e.g., Rousseau) even advocated

the abolition of machinery in favor of a return to older, more natural ways. But time's arrow is unidirectional; it never turns back.

The 19th century was a time of unparalleled growth in industrial technology. The steam engine and governor replaced muscle power and human regulation. The punched template of the Jacquard loom replaced human planning. Since massive amounts of goods of uniform quality could be produced at low cost with these new technologies, all but the factory worker and social critic envisioned a future filled with their bountiful benefits. Rapidly, the skills, tools, and even jobs of the craftsman were replaced by production machinery serviced by a growing force of workers that performed the repetitive and monotonous tasks of caring for and feeding machinery. It was claimed that the new mechanization created more jobs than had been eliminated, and few argued with any effect to the contrary.

The "Disappearance" of Man

As machines became a driving force in industry, commerce, and the economy, the engineer-inventor emerged as part of a respected and powerful elite. The fruits of geniuses such as Watt, Bell, Edison, and Steinmetz were acclaimed throughout the world, and the vision of a new and better life for mankind seemed to be within easy reach.

The greatest, most exciting challenge to technological ingenuity occurred with the advent of World War II. Vast new communications, weapons, and logistics systems were required, and an army of engineers was recruited to meet the challenge. Up to this point, the needs, role, and function of man as part of a system had not been an obstacle to the development of new

technology. The engineer used himself as a surrogate operator and concluded that if he could operate the system he had designed, then anyone else could do so as well. In comparison with the human operator, technology appeared to the engineer to be more familiar and more tractable. This resulted in a benign neglect of the relationship between hardware and the men expected to operate and maintain it. When problems of equipment operability or maintainability arose, the designer was faced with three options: (1) to automate a function that gave an operator trouble, (2) to blame the operator rather than the design and call for increased operator training or disciplinary action, or (3) to make a minor engineering retrofit to the man-machine interface in the hope that the problem would go away. The first of these options--automation--was by far the most popular approach.

With virtually unlimited development funding, engineers found in automation an exciting challenge that eliminated the need to be concerned with man, which, as a component, was difficult to characterize and to integrate with hardware. This indifference to the role and functions of man in early high technology accelerated the state of the art of automation, and for a time it seemed that there was practically no limit to the extent to which human functions could be replaced by sophisticated hardware. This period might be characterized as the "disappearance" of man from technology and engineering, and from consideration as an element essential to safe, efficient system performance.

Man Versus Machine

As technology grew still more complex, it became quite evident that the "human factor" was a troublesome issue that could no longer be ignored. Human error could not be passed off

lightly as a form of perversity. As the analysis of system failures and aborted missions demonstrated, most human errors were neither random nor perverse but traceable directly to poor equipment design. None of the standard remedies of automation, increased training, or engineering retrofits were good cures. Many human functions defied automation. Training seldom compensated for designs that exceeded the limited adaptive capacity of man. Engineering retrofits produced more problems than were corrected.

In despair, engineering project managers sought the advice of psychologists who had been drafted into military service. The new alliance was a strange one. Few engineers had any appreciation of behavioral science and few psychologists understood engineering. Constructive dialog was impeded by differences in approach, concept, and vocabulary. For a long time the psychologists were expected to devote their energies to generating acceptable but inexpensive retrofit solutions. These attempts failed, as they had before.

Gradually, as the new "engineering psychologist" became more familiar with the engineer's problems, attention began to center on the issue of the allocation of functions to men and machines, a topic that had never received more than fleeting consideration in the history of technology.

The first formal treatment of the allocation of functions appeared in a landmark article by Paul M. Fitts (1951), of the Ohio State University Aviation Psychology Department. Fitts attempted to qualitatively characterize those functions performed better by machines than by man and those performed better by man than machines. His original list is as follows:

Humans appear to surpass present-day machines with respect to the following:

1. Ability to detect small amount of visual or acoustic energy.
2. Ability to perceive patterns of light or sound.
3. Ability to improvise and use flexible procedures.
4. Ability to store very large amounts of information for long periods and to recall relevant facts at the appropriate time.
5. Ability to reason inductively.
6. Ability to exercise judgment.

Present-day machines appear to surpass humans with respect to the following:

1. Ability to respond quickly to control signals, and to apply great force smoothly and precisely.
2. Ability to perform repetitive, routine tasks.
3. Ability to store information briefly and then to erase it completely.
4. Ability to reason deductively, including computational ability.
5. Ability to handle highly complex operations, i.e., to do many different things at once. (p. 10)

For years, this paper was regarded as the definitive work on the topic.¹

Despite its publication, the Fitts list had little impact on engineering design practice because such criteria are overly general, nonquantitative, and not compatible with engineering concepts, and because they assume that functions will be performed by machines or by men alone. Engineers still tended to favor the automation of a function rather than the use of man and machine in combination to perform it. This era could also be characterized as one in which the "hardware" system was

¹Later, Fitts said that using the criteria contained in his list as the sole determinant of the allocation of function was to lose sight of the basic nature of a system containing both men and machines.

designed first, and only then was consideration given to how to get people to operate and maintain the system. Essentially all of today's nuclear power plants were designed in this way.

Man in Combination with Machine

The widespread introduction of the computer and microprocessor as major components of high technology systems had a profound impact on the manner in which both engineers and engineering psychologists viewed the role of man in relation to technology. As it became evident that some human functions could now be performed by computers more rapidly and accurately than by man, the roles of man as a computational device and control element diminished. Computer software was developed to handle many routine human functions. The storage, classification, and retrieval of large amounts of information, the integration of information, and the feeding of instructions to subsystems could now be handled automatically. Man could now be interfaced with the computer rather than directly with hardware. The computer became a highly flexible interface through which the man, now in the role of monitor and supervisor, could handle contingencies that could not be programmed for automatic control. The question of the allocation of functions, which had once been one of how to distribute system functions to machines versus men, now became one of how to share or combine functions between man and computer. This is the question that faces the nuclear industry today, along with the equally important question of the acceptability to the operator of any given sharing arrangement.

Human Requirements and Considerations Other than Performance

As system designers became aware of the sensitivity of system performance to human performance, they realized that man could no longer be dismissed in design. As a consequence, they began to ask the new breed of engineering psychologist, the "human factors" specialist, for quantitative information on man's characteristics as an engineering component--as a filter, amplifier, and transducer. While information of this type will always be essential to the integration of man into an engineered system, many designers have remained insensitive to those unique human characteristics (such as motivation, social factors, and response to perceived stress) that affect system performance but that cannot be reduced to engineering quantities.

The tendency to limit concern with man to his engineering properties prompted one commentator (Singleton, 1967) to declare that to regard man simply as another system component is to ignore the purpose of all systems. All systems exist, Singleton said, to serve some human need, directly or indirectly, and all directions ultimately must come from the user and the operator. This statement recognizes that man plays a unique role in relation to systems. In a similar vein, Price and Tabachnick (1968) stated that humans make a unique contribution to a system, and are not directly comparable to machines at all. Man must not only be considered as having some properties analogous to engineering components; special attention must also be paid to satisfying those limitations, capabilities, and needs unique to man. It is not enough to match the man to the engineering characteristics of a system, but engineering characteristics must accommodate for and match man's special properties. Even the best match between man and machine from an engineering

standpoint may not recognize that the operator might not find that match acceptable. Thus, while some had once hoped that a simple set of engineering rules could be devised to allocate functions to man and machine, it is now clear that the optimization of design is not necessarily the optimization of human performance in relation to that design.

For example, it is now possible for computers to perform many functions once performed by man. In some process control systems automation is so complete that, while man has not been excluded from system control, he operates only as a monitor and supervisor. In that role his interventions are limited to those infrequent contingencies and emergency events for which no adaptive computer response exists. A classical engineering approach would accept this fact without comment. However, man does not take kindly to the long periods of boredom and monotony that this newly assigned role can create. What are the consequences of accepting a design that almost entirely excludes man from action for long periods of time? Infrequently practiced skills deteriorate. Operators recognize this, and seek opportunities to maintain high levels of proficiency for handling the rare but stressful event which they may be called upon to respond to.

Operators, like all humans, are also curious. It is well known that computer users tend to "get into" computer programs to discover how they work, and perhaps to improve them, unless specifically prevented from doing so or provided with some other task regarded as meaningful and important. Recognition of distinctly human characteristics such as this must be considered in the allocation of functions, if the role assigned to man is

to be acceptable to him, even if it means that the resulting allocation adds to cost or imposes new requirements on design.

Social and psychological considerations must also be recognized in considering man's role in a system. If it has been rationally concluded that man must be part of a system, then it may also be necessary to give more functions to the human than had been intended. A related consideration is the danger of isolating an operator from other human contacts. Man exists within a social framework and his performance generally thrives on the support derived from others. This fact cannot be ignored, despite economic arguments to the contrary. The impact of change is still another consideration. In any society where a large measure of power rests with the general public, a change which might be viewed as detrimental must be handled with care. A recent introduction of robots into a factory produced such an outcry of protest from workers at the prospect of unemployment that sabotage occurred and the project was dropped.

Several authors (Sheridan, 1976; Thompson, 1976; Umbers, 1979; Whitfield, 1971) deal with the question of allocation of functions from a different perspective. They recognize that, because of certain unique and indispensable capabilities he possesses, the human operator will remain in most control room situations into the foreseeable future. Whitfield described these capabilities as human skill. One of the most important of these skills is the human ability to be flexible. Given a goal-oriented situation and the prerequisite knowledge, the human operator uses a variety of paths to attain a goal. These paths may involve using some functions in ways for which they were not originally designed. This flexible ability to devise innovative and adaptive strategies remains but a distant and unrealized goal of artificial intelligence analysts.

Another related skill possessed by humans is the ability to foresee and predict the consequences of control actions before the actions are actually carried out. This ability is based on an internal mental model of the process. Human operators develop models for processes for which no external model exists that would allow automatic control of the process. This unique human skill, Whitfield (1971) asserts, is justification for including a human operator in most systems.

The incorporation of these distinctly human skills and abilities into a prescription for man's role is a separate matter. Corkindale (1971) asserts that the allocation of functions cannot be reduced to a set of rules or formulae. For many systems, especially new systems, there is a lack of adequate data on the quantitative nature of human abilities on which to base allocations. Other authors have commented on the need for such a data base (Connelly & Webb, 1967; Parker, 1975; Swain, 1973; and Van Cott, 1979), and some efforts at creating useful data bases have been attempted. This is not to say that quantitative evaluations of needed prerequisite skills cannot be attempted for a particular function or system. This can, and indeed must, be done. But the allocation of functions remains a qualitative, judgmental process.

Chapanis (1965) makes two pertinent observations about the allocation of functions. First, he points out that a man-machine allocation is good only for one stage in the development of technology. Before the advent of computer control, for example, it was essential to manually control aircraft. This is no longer the case, and today, computers control many aspects of flight once controlled by a pilot. A function allocated to man at one point in technology's advance may be automated at a later time. Second, Chapanis points out that neither engineering

nor behavioral science is an exact science. In neither case is it now possible to make precise and accurate predictions about the performance that can be expected of man or machine in some as-yet-undeveloped system. Often an allocation must be altered when real parameter values are known and adjusted as design, test, and operational experience are accumulated.

A final but major consideration in any system is its cost-effectiveness. Cost alone must not force an allocation if it is clear that one allocation is superior in cost-effectiveness but will not produce acceptable and reliable system performance. Several writers (Chapanis, 1965; Webb, 1965) warn that the cost question is not as straightforward as it may sometimes seem. Cost estimates must include not only the cost of initial systems acquisition, but a variety of subsidiary costs as well. For a machine allocation, costs include installation, auxiliary equipment, maintenance, and repair costs. For a human allocation, costs include the costs of personnel selection and training, support facilities such as operating manuals, environmental controls, and maintenance.

In summary, the allocation of functions at the present time is not a simple matter of combining the best engineering features of man with those of machinery; for once a decision has been made that man must be included, a large number of social, psychological, and cost considerations must also be factored into the final configuration. Man exacts a penalty on a system but also makes a contribution that present and foreseeable engineering technology is compelled to use.

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

III. MODELS AND METHODS OF FUNCTIONS ALLOCATION

The number of considerations that enter any decision about the allocation of functions in the design of a man-machine system is so obviously large that some model is needed to organize all the relevant information in such a form that alternatives can be exercised, tested, and compared with one another. Matters of engineering compatibility and system reliability, issues of motivation and safety, cost considerations, and other factors must all be taken into account in trading off one functional configuration against others.

This section reviews the major attempts, some successful and others not, to develop and use models for allocating functions in the design, test, and evaluation of man-machine systems.

Some of these models, such as the CAFES and HOS models discussed later, are computer simulation models. Others are procedural models. Each makes varying demands on the user to supply data and provide constraints. Each appears to be best suited to a given problem, such as workload assessment or allocation of functions, for a particular type of system, such as an aircraft. Although not a simulation model, perhaps the most complete and comprehensive procedural model for performing the steps involved in the allocation of functions is that developed by Price and Tabachnick (1968).

What is needed, one concludes after reading the summaries of the models that have been developed to date, is something that does not yet exist: a simulation model, a procedural model for using the simulation iteratively throughout the course of system development, and a way of generating system-specific criteria against which given man-machine allocations may be

evaluated. It is clear that a simple list comparing man and machine capabilities does not provide these criteria; to date, all have been too general, too qualitative, and too tied to technological capabilities that quickly become obsolete to be of real value. Thus, it seems quite obvious that if the nuclear industry is to have a valid, accurate method either to allocate functions for new power plant designs or to assess designs already in existence, such an effort will have to entail a major development drawing upon the best that has been done, but adding elements and criteria specific to the nuclear power plant as a special man-machine system.

The "List Approach"

Beginning with the first allocation criteria devised by Fitts (1951), a number of attempts have been made to expand and improve on a "listing approach" and to identify the human characteristics data needed to make effective use of such lists.

The rationale for enumerating the different capabilities of men and machines in these lists was to take advantage of these abilities while at the same time avoiding a mismatch which could result in system performance degradation. Price and Tabachnick (1968) have said that it is equally as bad to have a machine do what a man can do better as it is to have a man perform tasks for which machines are better suited.

Fitts' original list indicated that human abilities were superior to those of machines in the areas of detection of threshold stimuli, storing of large amounts of information, judgment, pattern recognition, and inductive reasoning. Most of those abilities do not lend themselves to easy quantification, with the exception of the detection of threshold stimuli.

Abilities in machines that excel man's, such as repetitive tasks, computational ability, and performing several tasks at once, are ones that can be more easily quantified and modeled. This imbalance makes the use of the Fitts list difficult, and choices based on it are inevitably subjective. The Fitts list is also very general. It does not specify situations, activities, or values that would influence a particular allocation.

As part of a larger project on optimal human performance in systems, Price and Tabachnick (1968) compiled a great deal of the literature in the areas defined by the Fitts list. These data were divided into seven "core performance" areas. These areas, listed in Exhibit 1, were defined as performance areas that could be used to describe any system, and can be applied to the Fitts list. While there is not a one-to-one correspondence, each attribute in which man is superior to machines, or machine to man, can be subsumed under one core performance area. For example, under Fitts' list for superior human abilities is the storage of large amounts of information for long periods of time. Among those where machines are superior is short-term storage of information. Both of these abilities are parts of the general core performance of information storage. What differs is the relative abilities of men and machines. The goal of these authors was to provide a more comprehensive guide for those involved in allocation of functions than had been developed to date.

A group from Thompson, Ramo, Wooldridge, Inc. (TRW) (Mertes & Jenney, 1974) also compiled data on man and machine performance for identifying areas where automation could be applied to air traffic control. The TRW data and data organization is similar to that of Price and Tabachnick. However, the TRW report, being more recent, places greater emphasis on computers than had been done by Price and Tabachnik in 1968.

Exhibit 1
Core Performance Areas
(after Price & Tabachnick, 1968)

1. Sensing
2. Interpreting
3. Information Processing
4. Decision Making
5. Controlling
6. Monitoring
7. Information Storage

One of the most recent papers on the relative capabilities of man and machine (Swain, 1980) discusses techniques for improving human performance in production. The author lists characteristics which tend to favor humans over machines, and vice versa. Swain's lists are shown in Exhibit 2. While they are longer, they do not differ significantly from the lists that Fitts had developed 30 years earlier.

Edwards and Lees (1974) provide one of the best summaries of the advantages and disadvantages of using lists of man and machine abilities. They conclude that, while lists provide general rules for allocation, they are of limited utility.

Exhibit 2

Swain's List of Man and Machine Advantages (after Swain, 1980)

TEN CHARACTERISTICS TENDING TO FAVOR MACHINES OVER HUMANS

1. Monitoring men or other machines.
2. Performance of routine, repetitive, precise tasks.
3. Responding quickly to control signals.
4. Exerting large amounts of force smoothly and precisely.
5. Storing and recalling large amounts of precise data for short periods of time.
6. Computing ability.
7. Sensitivity to stimuli.
8. Handling of highly complex operations (i.e., doing many different things at once).
9. Deductive reasoning ability.
10. Insensitivity to extraneous factors.

FOURTEEN CHARACTERISTICS TENDING TO FAVOR HUMANS OVER MACHINES

1. Ability to detect certain forms of energy.
2. Sensitivity to a wide variety of stimuli.
3. Ability to perceive patterns and generalize about them.
4. Ability to detect signals (including patterns) in high noise environments.
5. Ability to store large amounts of information for long periods and to remember relevant facts at the appropriate time.
6. Ability to use judgment.
7. Ability to improvise and adopt flexible procedures.
8. Ability to handle low probability alternative (i.e., unexpected events).
9. Ability to arrive at new and completely different solutions to problems.
10. Ability to profit from experience.
11. Ability to track in a wide variety of situations.
12. Ability to perform fine manipulations.
13. Ability to perform when overloaded.
14. Ability to reason inductively.

HEFAM

The Human Effectiveness Function Allocation Methodology (HEFAM) program (Connelly & Willis, 1969) grew out of a larger, prior program sponsored by the Bureau of Naval Personnel. Originally the program involved an attempt to devise a cost/system effectiveness ratio that could be used as a basis for the allocation of functions. The notion of using a single ratio on which to base these allocations was abandoned when it became clear that the situation was more complex than could be expressed in a two-parameter format.

Efforts were then redirected toward the development of personnel performance effectiveness (PPE) measures. These were defined as measures of "the relative ability of the human component to perform operator functions adequately and in such a way that performance will lead always toward mission accomplishment." While this approach dealt adequately with system reliability, the reports make it clear that it is not the only parameter to be considered. The part played by the human operator in making unscheduled positive responses that are beneficial to the system and to mission accomplishment had been largely ignored. Yet this is one of the most unique and indispensable qualities of the human operator in systems that operate in an environment that is not completely controlled.

The development of PPE measures was also expected to serve the need of system designers for quantitative information on which to base functions allocation decisions. These decisions, as well as the determination of manning and training requirements, are often based on qualitative judgments. This is as true now as it was in 1967 when the report was written. The PPE indices were to be derived from a data base of human performance

characteristics. These indices were to be used, together with existing data on equipment performance effectiveness, as inputs to models of total system effectiveness. It was assumed that this approach would help to overcome the reluctance of systems designers to use human factors information in the early stages of system development.

This preliminary thinking then led to the HEFAM program. This program attempted to develop a methodology that would permit the quantification and optimization of equipment effectiveness, human effectiveness, equipment cost, and human cost. The goal was a workable cost-effectiveness methodology for man-machine function allocation. Quantification of human performance effectiveness was to be based on empirical observations derived from task analysis data for a large number of tasks. HEFAM proposed a hierarchical arrangement of actions, beginning with task elements. Task elements would have been combined into tasks, and tasks combined into functions. Data would have been collected on the observed (empirical) performance of all task elements, tasks, and functions where possible. The resulting data would be stored and retrieved to compute the probability of occurrence and effectiveness. These probabilities would also have become a part of the HEFAM data bank. Data and probabilities estimates would have been then used to derive a quantitative index of overall human effectiveness.

HEFAM was conceived as an automated system that could be used iteratively during a development cycle. Thus, predictions of human effectiveness would have been derived for many tasks and functions throughout the development of the system. These predictions would have become the basis on which man-machine functions allocation decisions would have been made.

HEFAM was never carried to its logical conclusion: the establishment of the data system and the derivation of formulae for arriving at probability estimates. The effort did, however, point out how functions allocation in a complex system must take cost into account.

The HEFAM experience, like other, similar model-development efforts, also pointed to the need for data on human effectiveness. In the few areas where such data do exist, there is even today an additional need for storage and retrieval systems that will allow effective use of the data.

Thus, one of the major conclusions of the HEFAM effort was that the allocation of functions involves much more than a simple comparison of man and machines in various functional capacities.

CAFES

The Computer-Aided Function Allocation Evaluation System (CAFES) is a system developed under the auspices of the Naval Air Development Center (Parks & Springer, 1976) to assist in providing human factors engineering input into the development of new weapon systems. However, CAFES and its methodology are applicable to the development of other systems as well. It was designed to be used by human factors engineers, and much of its usefulness derives from the combination of a flexible model with the experience of a skilled human factors analyst.

CAFES was designed around the questionable assumption that there is a great wealth of existing human factors data that are not being exploited. It was hoped that CAFES would allow these

data to be reused effectively. The CAFES concept would have allowed the human factors engineering data resulting from each new CAFES application to be entered into its associated data bank. So far, such data banks do not exist; but in theory each successive application would have tapped this growing data store. These data would then have been used for functions tradeoffs between man and machine, workload assessment, design of crew stations, and system simulation.

Nevertheless, CAFES is a design tool which, with the aid of the digital computer, was intended to speed up many phases of the human engineering process. The system is made up of six submodels. One of these, the data management system, is designed for the management of the other five CAFES submodels, which are shown in Exhibit 3. Of particular interest are the functions allocation model (FAM) and the workload assessment model (WAM).

As conceived, CAFES follows the traditional sequence of human factors engineering input to systems development. Necessary prerequisites for this input include information on operational requirements, mission scenarios, functional flow diagrams, mission time lines, and the constraints that each imposes. These provide the basis on which the human factors engineer (HFE) makes decisions about functions allocation.

The HFE using CAFES must identify and describe all tasks that must be accomplished for a mission. From this description, a non-allocated list of operational functions required by the mission is drawn up. This list is essential, since functions must be identified, characterized, and analyzed before they can be allocated.

Exhibit 3
CAFES Submodels and Capabilities (after Parks & Springer, 1976)

Function Allocation (FAM)	<ul style="list-style-type: none">• Best Crew Size• Best Automation Level• Optimum Task Allocation
Workload Assessment (WAM)	<ul style="list-style-type: none">• Verification of Allocations• Detailed Procedure Analyses• Optimum Crew Station Design
Computed Aided Crewstation Design (CAD)	<ul style="list-style-type: none">• Feasible Station Layouts• Sensitivity to Requirements, Constraints, Criteria
Crewstation Geometry Evaluation (CGE)	<ul style="list-style-type: none">• Verification of Detailed Configurations• Task Time Estimates
Human Operator Simulation (HOS)	<ul style="list-style-type: none">• Human Performance Estimates• Sensitivity to Behavioral Factors, Operating, Environments, etc.

The functions list is then broken into six data groupings for use by the FAM: task data, mission scenario data, table of constants (times, speeds, etc.), mission objectives, mission events, and allocation versions. These data groupings are then analyzed using the two major subdivisions of FAM: the mission evaluator and the procedure generator. The mission evaluator uses scenario task data about number of tasks, initial task times, and task durations. Priorities for certain tasks are designated by the HFE:

The mission evaluator program is an objective-oriented evaluator which looks at a mission as a series of intermediate objectives. Based on these objectives, allocation decisions are made. Reliabilities for each machine and operator combination are calculated. These allocation versions are dependent on candidate hardware and crew sizes that have been previously identified. Because it uses a high-speed digital computer, the mission evaluator can accommodate a large number of different allocations. These are ranked by the mission evaluator according to mission success probabilities calculated from task data. The mission evaluator can provide information to the HFE on overall mission reliability (based on individual equipment and operator reliabilities), task loads, and task reliabilities.

The procedure generator produces a detailed task sequence to perform a refined analysis of candidate allocations. The information provided by the procedure generator includes percentage of tasks completed, percentage of tasks interrupted, tasks not started, percentage of time operator is busy, and other, similar data. This information can be used (in conjunction with the data provided by the mission evaluator) to identify the best candidate allocations.

A candidate allocation can be appraised by using another CAFES submodel, the workload assessment model (WAM), to verify the feasibility of different allocations. The WAM works on information about the functions to be allocated, detailed tasks, candidate equipment, and especially detailed time lines and time constraints. WAM was an attempt to take a tedious and time-consuming manual task--one of the most important performed by the HFE--and apply the speed of computer-aiding to it. This allows the HFE analyst to do a more rapid and thorough job and to be confident about the selections that result.

Workload assessment traditionally involves taking each candidate allocation of functions and the task time lines associated with it and analyzing them for trouble spots. Periods of high workload and overload, tasks competing for the same resources, and threats to mission success based on these data are part of the assessment. Results from the analysis can be used to modify crew size, man-machine allocation, intra-crew task allocation, and task sequences. Since WAM accomplishes the analysis at a greater speed than can be done manually, more iterations and, thus, more candidate allocations can be evaluated. Workload can be assessed for a single crewmember or for an entire crew, and can be assessed overall for each or broken down by eight channels. These channels represent eight ways in which the human operator receives information and/or acts in response to it. Examples are seeing, hearing, hand movements, and foot movements. The model also provides options that allow the HFE to shift activities out of time sequences that are overloaded, but it does not allow one time segment to become overloaded to alleviate another. WAM supplies detailed information on workload as it relates to mission time lines, as well as task and subsystem activity. These are useful when considering optimum allocations. WAM depends on having an available data bank on the established times for tasks relevant to the accomplishment of the mission.

The results from the FAM and WAM analyses are then used within CAFES to approximate a total system concept. This is accomplished by using the computer-aided design (CAD) model to assist in crew station design and crew station geometry, so as to ascertain the best anthropometric fit between crew and crew station.

The CAFES system is a flexible, computer-based tool designed to assist in all phases of the system development process. Its purpose is not to provide answers to the problems that have traditionally been posed to the human factors engineer. Rather, its goal is to provide quantitative information based on the best available data and analyses so that HFE decisions are made with confidence.

CAFES depends on a broad knowledge of human and equipment performance abilities and reliability. Its inventors reemphasize the need for a data bank of this and other human factors engineering information. Since such a data bank does not yet exist, CAFES still depends on the training, knowledge, and expertise of the human factors engineer to arrive at sound solutions, but the system allows the HFE to do the job faster and more thoroughly than had been possible. Many other considerations have to be taken into account that CAFES was not designed to handle: size and weight limitations, maintainability, safety, and the availability of suitable technology also affect a final decision. Many of these are qualitative considerations for which CAFES cannot account.

SYSSIM

SYSSIM, or System Simulation (Ireland, n.d.), is a FORTRAN program developed for use on time-sharing systems in which a user interacts directly with the simulator.

SYSSIM was developed to simulate the operation of a wide range of systems that can be represented by functional flow diagrams, that require facilities for their operation, and that operate on discrete actions such as messages, targets, or people. SYSSIM can be used to evaluate alternative system

configurations, resource reliability, resource assignments, and functions allocations in terms of workloads, processing speeds, throughput rates, waiting times, and delays during critical operational phases. It was designed to reduce the need for special programming skills.

SYSSIM can simulate 400 functions and an unlimited number of simultaneous but completely separate processes represented by interconnecting functions. It can also simulate 40 distinct facilities (resource units, machines, or men) needed to perform functions. Priorities can be assigned to individual functions and to the transactions being processed.

A transaction is defined as the discrete entities (targets, messages) which flow through the system, modified by functions and processes. Transactions may not be assumed to be of equal importance, but are assigned priorities. Thus, with a variety of incoming entities, those of greatest importance are acted on first.

A function in the SYSSIM program is identified from the functional flow diagram. Functions are steps to be performed in a process, and processes are made up of functions. Functions are specified by a mean performance time (MPT). This is probabilistically modified by the standard deviation of the MPT on any particular run to simulate a real-world situation. Functions may also be assigned a priority (function priority, or FP). This allows individual functions within a process that have a significant impact on performance to access limited resources. The function priority can act in combination with the transaction priority to yield an overall priority, called an "instantaneous priority." This instantaneous priority for a

function/transaction combination is compared to all other "instantaneous priorities" and acted on in order of highest to lowest.

SYSSIM does not assume that all functions or processes can be performed simultaneously. Processes (groups of functions) are assigned facilities. A facility is a resource: a man, a computer, or a machine. The assignment of facilities is an option open to the person doing the simulation. In many cases, decisions about facilities are predetermined by the type of system being simulated. For example, if a radar system is being simulated, the detection of targets would almost inevitably be done electronically. However, the identification of target type (friendly or enemy) would probably be done by an operator. In a nuclear power plant, an example would be an alarm, a mechanical system, responding to an abnormality. The initial action taken in response to the alarm would probably be automatic, with a backup performed by an operator. These assignments are fairly standard throughout the nuclear industry. However, one advantage of a simulation is the ability to evaluate different combinations.

Once assigned, facilities (man, machine, or computer) are specified by mean time to failure (MTTF), mean time to repair (MTTR), and the standard deviations of these distributions. These values are entered by the person performing the simulation. For many mechanical systems, these reliabilities may be well known. However, there is more variability and other factors to consider when the facility is a person, a human operator. The simulation takes this into account.

One assumption concerning the MTTF for human operators is that most operator failures are not actually failures, but

rather scheduled (voluntary) or unscheduled breaks or interruptions in the work (rest breaks, lunch, shift changes). Therefore, it is assumed that many of these interruptions are at least partially under direct control of the operators and that the operators will act with the best interests of the plant in mind. Human operators are not known to willingly abandon actions (function, processes) before a logical stop point is reached. For example, if the process in question is rolling a sheet of steel, the operator normally would not stop the process before the entire sheet is completed. To do so might make it necessary to redo the entire process. If the human operator reaches a failure point (based on the specified MTTF) in the middle of a process, the simulation assumes that the human will attempt to complete the transaction. This also implies another provision in the simulation. Some processes will require more than one operator to be present at all times during the process. In such a case, having the human operator acting in a responsible manner implies that they will not leave such a process in the middle and that the necessary human operators will remain available until the completion of the process.

In many systems of the type SYSSIM was designed to simulate, the flow of transactions is not a smooth and continuous one. At times facilities will be idle, and at other times there will be more transactions to be processed than there are available facilities. To take this into account, SYSSIM is set up to act as if the facilities are fed by queue lines. Each new transaction must wait for the necessary facility to become available. Positions in these waiting lines are determined by the priorities already discussed. Obviously, if a facility is immediately available, there is no waiting. The simulation also allows for branching--transactions leaving one function and going to one or two or several alternative functions. This is handled on a probabilistic basis.

SYSSIM has the capability to test delays in critical phases of an operation by assessing the mean performance time and the time spent waiting for facilities to become available. A critical delay occurs when the time spent waiting for some facility exceeds a specified time limit or the time spent to perform a process exceeds the specified time. The simulation assumes that exceeding this critical time will lead to drastic consequences for the system or an overall reduction in system performance. In the example of a radar system, assume that a large number of targets are to be acquired by the system. If the time required by the radar operator to process one target is so great that the others will have to wait (in queue lines) to be processed, this would greatly increase the probability of a target not being processed. Assuming the targets may be hostile, this failure to process will lead to critical consequences. First, a response, such as interceptors, would have to be launched. But if targets turn out to be friendly (false alarms), this would involve unnecessary cost. If the targets were hostile and the processing delay allowed one or more to penetrate, the costs in destruction could be much higher.

SYSSIM also permits human backup functions to be simulated. In many cases where automation has been introduced, manual backup to machine functions will be required. However, differences in mean performance time between the machine and a human operator performing the same function will exist. SYSSIM allows these differences to be specified as different response time distributions.

The fidelity of a SYSSIM simulation depends on several factors. The first is a functional flow diagram. It must be accurate. Second are mean performance times and priorities for the functions and processes specified in the flow diagram.

These must be supplied by the person doing the simulation. For many systems these are known or are set by system requirements. A third important factor is information on facility assignments. These include facility reliability data, which is often not available for human operator tasks.

SYSSIM was designed to work with discrete process systems. Thus, its applicability to nuclear power operations may be limited. However, with suitable modification, SYSSIM might be adapted to continuous process systems as well.

SYSSIM's principal advantage is its ability to simulate large systems. Of particular interest is the fact that SYSSIM provides for the simulation of more than one human operator, which many other simulations cannot handle. SYSSIM also allows for a variety of allocations to be tested quickly. This capacity would be especially valuable in examining safety-related operator functions. In that context a SYSSIM simulation would allow preliminary examination of the specified time-test based on the best available information. This could be used as a guide in decisions on the allocation of functions. However, there are other considerations in that decision which cannot be handled by simulation. These include traditional human factors areas such as motivation, training requirements, and design of the work environment.

SAINT

The Systems Analysis of Integrated Networks of Tasks (SAINT) is a task analytic model designed to solve man-machine design problems (Wortman et al., 1975).

SAINT combines network modeling with simulation techniques. Networks are represented as a series of tasks performed by a crew of operators with necessary equipment and in the face of given environmental factors, for SAINT processes are specified by the use of branching, time, and operator characteristics. Branching refers to the direction of a process after a task is completed. In many processes branching is straightforward; after completion of one task, only one task follows. This is deterministic branching. SAINT also allows for probabilistic and conditional branching, in which branching depends on certain specified conditions having been met. All tasks have a time associated with them. SAINT provides a number of time logarithmic and Gaussian distributions which the user can select.

In SAINT, human operators associated with each task are defined by a set of characteristics, such as speed, accuracy, and stress. Not all characteristics need to be used for a given task. There can be one operator, joint operators, or any number of operators on a task or tasks; or, conversely, there can be tasks in which there are no human operators. Tasks that are cyclic in nature and that are done only if time is available may be simulated. This "gap-filler" tasks capability is another useful SAINT feature since it allows tasks to be added which, though not essential, challenge an operator or provide opportunities to practice seldom-used responses.

SAINT also contains an option that allows the user to create a function if the options available do not meet with the specifications of the process being simulated. All of SAINT is written so that no special knowledge of programming is necessary.

On any run, SAINT automatically collects statistics on operator idle time, busy time, stress (overload), and total time, as well as the time required to complete process networks. SAINT can handle changes in automation level, operator workloads, and changes in operator tasks caused by a reduction in the number of available operators.

SAINT appears to be similar to SYSSIM in its intent, though it does not have the capacity that SYSSIM possesses: SAINT cannot handle as many functions, processes, or operators. But, like SYSSIM, SAINT has the capability to model systems with multiple operators.

SAINT depends on being able to describe a process as a series of tasks. These tasks are then defined by specifying the relationships among tasks (branching), time constraints, and operator characteristics (specifying both the parameters for the individual operator and the number of operators). The resulting data, besides data on operator time use, include the times to complete a task the first time and times for completion each time the task is done, the time between completion of a task the first time and each other time, and delays that occur in the completion of tasks. However, the analyses provided by SAINT are at a fairly gross level.

SAINT is more suited for the study of large component processes than for the simulation of a final total system, and it appears to be capable of modeling the processes of a nuclear power plant. This is a capability not shared by many other models.

HOS

The simulation models that have been described so far are analytic models in which a system is described as a network in which timing and sequencing during each mission phase are defined by a user. The user predetermines all conditions to be simulated. These inputs fully describe the system, including the operator(s) that are to be simulated. Thus, success in modeling is almost totally dependent upon the completeness and accuracy of inputs supplied by the user.

The Human Operator Simulator (HOS), on the other hand, is a microprocess model (Strieb & Wherry, 1979). It contains a representation of the human operator. It is based on data on the abilities and capabilities of man in performing the variety of tasks that HOS was intended to study.

HOS is designed to evaluate overall system performance for any system in which there is a human operator functioning within the system. It is a collection of computer programs that allows simulation of a total system performing a complex mission. Three generalized models simulate operating characteristics of hardware, software, internal data sources, and the operator.

HOS simulates an operator as a goal-oriented element that can modify its behavior to suit a set of circumstances. It assumes (1) that human behavior is predictable and goal-oriented, (2) that such behavior can be described as a series of micro-events, (3) that man is a single-channel information processor, and (4) that an operator is well-trained and rarely makes mistakes or forgets procedures.

HOS uses a modification of FORTRAN to specify operator procedures and functions and hardware procedures and functions. The operator procedures describe the operator tasks, while operator functions describe the cognitive actions that the operator must take to perform those tasks. Hardware procedures describe changes which result from operator actions, while the hardware functions describe what has to be done by the hardware to accomplish these changes.

Unlike other models, the HOS user does not have to specify how an action is performed. HOS determines what is required to carry out a task and assign functions to that task. Functions are a set of models which simulate the human performing any of the variety of actions necessary to accomplish the tasks. These functional models include the need to move parts of the body, to make decisions, to recall and gather information, and to perform a control manipulation. Functions can be detailed to allow human behavior to be described at a micro-level. Each function has a characteristic time associated with it, and tasks times are calculated from these detailed human performance micro-models. They need not be supplied by the user, as is the case with other models. Results from HOS experiments demonstrate that forecasts of human task performance can be made with surprising accuracy. The HOS micromodels act as a totality. Preliminary test results have been quite encouraging. They indicate that, individually, each model may or may not be a faithful analog of the human activity it simulates, but together they act to provide a reasonable prediction of human operator behavior.

HOS has features of special interest. For example, component models can be changed to reflect anticipated circumstances. If HOS detects a problem in reaching a goal, it attempts to predict what the operator may do. If an overload condition arises in which an operator may take shortcuts or deviate from procedures to get the job done, HOS assumes that the human operator is motivated and thus will not normally make errors. While this may or may not be realistic, the HOS model allows a system configuration to be evaluated for obvious human engineering deficiencies. If errors occur, they are assumed to result from the operator being overloaded: having too many activities to perform at once, not having the correct information, or having displays not designed for the operator to obtain necessary information. These conditions lead to human error which can be traced to design problems that may be resolved by subsequent human factors input.

HOS' main use, then, is to test the allocation of functions to the human operator in a system. While SYSSIM provides a rough determination of the workload on crewmembers in a system, HOS provides a much finer screening of the single operator and the operator's interaction with a system.

Models such as WAM can give an overall picture of the human operator in the system. It does this for comparatively little cost. A hardware simulator of a system involves a great deal of expense; but it gives the most reliable and valid indication of how the human operator will act. HOS is capable of generating a great deal of information in a very detailed manner without the expense of a full-scale simulator. This information should allow decisions concerning the human operations role in the system to be made with confidence.

However, HOS can handle only one operator at a time. It also assumes that that operator is stationary, as in an aircraft cockpit. But for such a fixed operator, HOS helps to determine the functional requirements of a system, and assists in determining which functions must be assigned to man and machine to meet system goals. And as other, more general models do, it allows different allocations to be evaluated.

Price-Tabachnick Descriptive Procedural Model
(Hypothetical-Deductive Model)

The effort by Price and Tabachnik (1968) was part of a larger project to develop a procedural model for determining optimal human performance in aerospace systems, one aspect of which was to establish the role for man in a system and how to allocate functions to man, given that role.

Unlike other methods, which either deal with a data store on which decisions are based or use a simulation to evaluate candidate allocations, the Price-Tabachnick effort presents and describes a process which the human factors analyst can follow in order to make allocation-of-functions decisions. The authors derive this process from the system development cycle. They recognize that, while in many cases allocation has been considered as an independent issue, it should in fact be an integral part of system development. This process does not begin and end at set points. Rather, it is part of the entire concept of the role of man in the system. And since man is not a constant, it is unreasonable to make assumptions about his role without exploring all the pertinent aspects of that role throughout system development.

Exhibit 4

Activities in the Price-Tabachnick Approach to Allocation of Functions (after Price & Tabachnick, 1968)

ACTIVITIES FOR DETERMINING THE OPTIMAL ROLE OF MAN

- Activity 1. Hypothesize the Potential Basic Role of Man
- Activity 2. Hypothesize Potential Complementary and Support Role of Man
- Activity 3. Review Manned System Solution Feasibility
- Activity 4. Develop a Preliminary Crew Concept
- Activity 5. Analyze Personnel Support Requirements
- Activity 6. Review Potential Crew Role for Acceptance and Reliability
- Activity 7. Synthesize Optimal Crew Role

ACTIVITIES FOR DETERMINING THE OPTIMAL ALLOCATION OF FUNCTIONS

- Activity 8. Establish Feasibility of Man-Rated Allocation
- Activity 9. Develop Potential Man-Rated Allocations
- Activity 10. Review Allocation Potential Against Psychophysical Capacities
- Activity 11. Review Allocation Potential Against System or Function Constraints
- Activity 12. Review Allocation Potential Against Human Reliability
- Activity 13. Synthesize Man-Rated Allocations

The Price-Tabachnick approach consists of a series of activities for, first, determining the role of man in the system and, second, determining the proper allocation of functions, given that role. Those activities are listed in Exhibit 4. Each will be dealt with briefly here..

Before any consideration can be given to allocation, some idea of what man can do in the proposed system must be ascertained. This is the core of the first activity: to hypothesize the potential fundamental role of man. This step results in a statement about the types of actions that only man can perform to accomplish some system objective.

The second activity, to hypothesize the potential complementary and support roles of man, determines what additional performance man can contribute to the system and what performance must be contributed by man because man is in the system. The goal of this activity is to complete the picture of man in the system. If it is decided that man is going to be part of a system, it might turn out that, besides those tasks he must perform, there are tasks which may be beneficial to have man perform. This takes advantage of an already existing systems component: Man. But man also has needs that are unique, and these must be supported. Man places certain demands on the system which cannot be ignored; he must be protected and sustained. What form these demands take will depend on the type of system. Remember that this approach was developed for aerospace systems, where the need for protection and sustenance are greater; but each environment will have its own demands.

Activity 3 (review manned system solution feasibility) asks the question: Given the initial conception of man in the system, are there reasons for rejecting the concept of a manned

system? This may be due to incompatibility between the requirements for having man in a system (e.g., in a spacecraft, the weight of the life support equipment) and system parameters (overall weight limitation). Or it might result from areas where man's effectiveness is marginal, such as if man were required to respond to incoming data at a faster rate than is humanly possible. The idea is to reject an infeasible manned system concept before detailed development and design take place. This is not to say that if one manned concept has to be eliminated, another will not work. The goal is to identify good, manned solutions, not just manned solutions.

Activity 4, the development of a preliminary crew concept, defines the overall role of the crew in the system. From this concept, estimates of crew size, training and selection requirements, job aids, human engineering requirements, and performance proficiency requirements can be developed.

Activity 5 (personnel support requirements) establishes whether the crew concept developed in Activity 4 can be protected and sustained within the operational environment of the system, and that the required performance can be accomplished within the personnel constraints. This activity is the first detailed analysis of the overall man-machine concept. Completion of this activity can lead to identification of potential problem areas and enhance the probability of a successful integrated man-machine system.

Activity 6, the review of the potential crew role for its acceptability and reliability, deals with the very difficult areas of acceptance and human performance. Since man is not an automaton, he will not perform a job at peak level continuously, accurately, and safely until told to stop. Many variables

determine the level of human performance. Too often these have been ignored. This activity directs the analyst to consider factors such as these. The authors state that it has been found that humans are generally more accepting of systems which allow them to use acquired skills. Thus, in some cases, defining the role of a crewmember as a stationary monitor will be ill-advised. That is but one example. Many other factors need to be considered as well.

Activity 7, the synthesis of optimal crew size, is a review and compilation of previous activities. This allows remaining problems to be reduced and to be made manageable.

The next set of activities deals with the allocation of functions. At this point, instead of deciding if man will be in the system, the objective is to identify what specific performance will be required of man in the system. Activity 8 is intended to establish the feasibility of man-rated allocations and to eliminate candidate allocations that are clearly unreasonable to assign to man. A man-rated allocation refers to one which employs man as operator, monitor, or controller, as opposed to a machine. This activity attempts to further limit development to only truly feasible candidate allocations.

Activity 9, the development of potential man-rated allocations, deals with man carrying out different kinds of activities with different allocations. Alternative allocations may vary from man performing a manual task with no additional equipment, to man using equipment as an aid, to man as a monitor while an automatic system performs the task. This activity seeks to identify all feasible candidate allocations based on what is known about man's capabilities compared with those of

machines. Activity 10 is a review of allocation potential against psychophysical capacities. During this step the candidate allocation is reviewed against known data concerning the psychophysical capabilities and limits of man, to ensure that the allocation is in fact feasible for man to perform. This step is not a comparison of human against machine capabilities, but a test of human limitations. The step will determine whether man can, for instance, sense or discriminate incoming signals as required, or respond within time constraints of the candidate function.

Activity 11 is a review of allocation potential against system or function constraints. When it has been established that man can perform required tasks, candidate allocations must be evaluated with the extent of the system. The purpose of activity 11, therefore, is to review tentative allocations against constraints that may operate on the man-machine system. For example, if a man-allocated task must be performed in an environment inhospitable to man, such as extreme heat or high radiation, it matters little whether man can actually perform a task if constraints jeopardize his health or endanger his safety. Similarly, if man can perform a task, such as monitoring, but is required to do it for a period longer than he can reasonably be expected to maintain a high level of performance, the task might be better allocated to a machine or to a mechanized system with both man and machine. Data on the tolerance limits of man for such constraints as unusual environments is required to perform this activity.

Activity 12, to review allocation potential against human reliability, is one of the most difficult activities. Some factors that relate to human reliability have already been

mentioned: acceptance and performance. In general, however, human error rate data is usually not available to perform this activity in a fully satisfactorily manner.

Activity 13, synthesis of man-rated allocations, ranks candidate man-rated allocations for each system function. Like activity 7, this activity entails a review and synthesis of all allocations made in the process.

The approach advocated in the Price-Tabachnick report is the most comprehensive and complete description of an allocation process that exists today, because this, unlike the others, is a method and not a model. They are supplemental to one another: the method needs a similar model.

One beneficial by-product of an in-depth analysis of the type advocated is the determination of areas where knowledge gaps exist. The Price-Tabachnick report lists six such areas where research bearing on the allocation of functions needs to be done. Among the most important is research on task performance, task acceptance, human performance reliability, crew size, personnel performance achievement, and maintenance costs. The authors note that any model or technique suffers from a lack of data in each of these areas. Other writers have made similar claims.

Adaptive Allocation of Functions

An entirely different type of functions allocation may be evolving with the advent of computers which now have the ability to make certain types of decisions in a manner closely resembling that of a human operator. This is the concept of

adaptive computer aiding, or adaptive allocation of functions. In a system of this type, allocations between the human operator and machine components (computers, in this case) are not "all-or-none" assignments. Both the operator and computer may be able to make timely decisions based on the information available. The system is designed to be a cooperative (shared or symbiotic) effort between the operator and computer (Rouse, 1977). This reciprocity of functions, with man providing direction and control at one time and for one event, and the computer providing direction and control at another time or for another event, represents a departure from past systems in which man was hard-wired into a system with a rigid and fixed set of allocated functions. With adaptive computer-aiding, a form of sharing has become possible that capitalizes on the strengths of both man and computer but which introduces an altogether new perspective on functions allocation.

Research on systems of this type is still in its infancy. Crooks et al. (1974) report on a long-term research project designed to explore this type of system. Sinaiko (1971) gives an account of an experiment on naval antiaircraft systems which included one condition closely resembling an adaptive system. One point that all authors make when discussing this type of system is the conviction that it is essential that the final decision-making responsibility rest with the human operator. Therefore, the human operator should have, as part of his role, the option to override the computer when the operator determines that the situation warrants such an action. The goal, then, is not to replace the human operator or to imply that the computer can take over all the functions of the human operator, but rather to enhance system performance by using the best available resources.

IV. APPLICATIONS

As was made clear by the foregoing literature review, a considerable amount of effort has been devoted to the development of criteria, models, or methods for the allocation of functions. Furthermore, almost everyone who has published an article or report on the allocation of functions has stressed the importance of this process as part of the system development cycle. However, there are surprisingly few reports dealing with the application of any functions allocation criteria, models, or methods to the design of real systems. This is even more surprising considering that allocations occur at some point in every system design process, whether that decision is explicit or implicit. The few reports dealing with functions allocation applications are discussed below.

Moore (1977) prepared an actual functions allocation report for the F-18 aircraft. It should be noted that a decision document of this type is generally required, though seldom produced, for every major military weapon system. While the report prepared by Moore illustrates the end product of an allocation effort, it gives little insight into the process employed to arrive at the allocation. However, Moore does make the point that it is not possible to make an exact functions allocation at the very beginning of design. While an approximate one must be made, it nearly always must be modified as design proceeds. The present authors agree that this should be expected.

Wylie, Dick, and Mackie (1975) studied functions allocations for future military surveillance systems. They used two fundamentally different sources of knowledge concerning

man's functioning in surveillance systems. The first had to do with observable performance, that is, how well man actually performs a task assigned to him. The second source of knowledge concerning man's functioning was based on development of a model of human information processing that is used for the more general application. The results from this effort are classified and unfortunately cannot be discussed except in a general way.

Recognizing that the functions of surveillance systems could be performed by either man or machines or a combination, Wylie, Dick, and Mackie assigned a single numerical rating to each function to indicate the degree of operator involvement. Some functions rated low on human involvement; others rated high, meaning that a high degree of automation was judged to be necessary. The authors report that in the intermediate range of involvement, decisions regarding automations were the most difficult to make.

Mertes and Jenney (1974) conducted a similar study on automation applications in air traffic control (ATC) tasks. As a basis for decisions on what ATC functions should be automated, they examined 265 generic control tasks. Their method employed 32 judges from the fields of systems analysis, human factors, computer applications, and air traffic control to rate each task on its "automatability." The authors point out that this approach rests on two assumptions. First, the ATC system can be accurately described as a series of tasks. Second, performance characteristics for man and machines can be described on a continuum, with unique human capabilities at one end and unique machine capabilities at the other. Thus, the ratings for each task could be compared to indicate relative automatability.

The results of the ratings were treated mathematically to assign ranks to all tasks, and the ranks thus represent a continuum of automatability. As a validity check, the researchers compared some of the tasks in their study to comparable tasks in existing systems. The results show that of 22 identified tasks which had received ranks indicating high automatibility, 20 were found to be automated in the actual systems.

The last step in their approach was to subdivide the ranked tasks into five levels of automation. These levels are listed in Exhibit 5. The authors examined the tasks within each level for corresponding automation within existing systems in order to determine how tasks combined to form functional groups.

The report discusses the use of an automation index as a guide for what to automate in a system, and perhaps more importantly, as a guide for man-machine allocation in a backup system. If the automation index indicates that a functional grouping of tasks should be automated and these tasks do not rate highly on man's performance measures, then the best backup system might be another automated system, as opposed to a manual backup.

In summary, the Mertes and Jenney effort offers a singular technique for quantifying the amenability to automation of all the tasks identified for a particular system. However, the method is extremely dependent on experience with a similar reference system and the availability of "experts" familiar with that system. Additionally, the technique is time and labor intensive. Nevertheless, it is a rather complete attempt at dealing with automation and the allocation of tasks for air traffic control systems.

Exhibit 5

The Five Levels of Automation, as Developed by Mertes and Jenney (1974)

Level I - Automation of Computational Aids

At this order of automation, repetitive computation and routine data processing tasks, and maintenance of the system data base, are allocated to machines.

Level II - Automation of Aids to Decision Making

At this level, machines are assigned to more sophisticated data processing tasks. Machines begin to function as a means of alerting man to the need for a decision and providing him with data to assist his decision making.

Level III - Automation of Decision Making

At this level, many decision-making tasks, particularly those of a routine and repetitive nature, are assigned to machines.

Level IV - Automation of Communications

At this level, the machine replaces man in the air-ground communication loop for routine relay of information. Man is responsible for communications of a special or emergency nature. Virtually all strategic planning and regulation of traffic flow is also delegated to automated resources.

Level V - Full Automation

This level represents a hypothetical system in which man has no direct responsibility for regulation and control of air traffic. Man's role has become that of a system monitor and manager. He controls a complex of automated resources which, in turn, control aircraft.

An important conclusion can be drawn from the two preceding applications studies. Most applications use a general set of functions for an entire class of systems, with the rationale being to provide some guidance to the systems designer for the allocation of functions in future systems. This suggests that a basic approach to allocation of functions can be developed for classes of systems such as nuclear power plants, for which the types of human performance and criteria for acceptable or optimum human performance can be identified.

Several other reports deal with an evaluation of the allocation of functions, or with more general human factors considerations in real-world systems. Shackel, Beevis, and Anderson (1967) describe a human factors effort focusing on an automated system for handling the transfer of meat from the hold of a cargo ship to the waiting transport on land or inland canal. The report deals with all aspects of human factors, from the design of the work areas to the training that would be necessary for each operator. Part of the preliminaries for this effort included a suggested allocation of functions for the automated system. The overall effort identified and sought to deal with problems of the interface design for the system and the general aspects of ergonomics. This report demonstrated that it is not only in the military or the aerospace industries that ergonomics can make a positive contribution to the overall system effectiveness.

Lacy (1967) describes a classic case of human factors specialist designing tasks to be performed by man and by machine in a tea blending plant. Some of these tea-blending tasks were still being done by man with the aid of only simple tools. Others were done by a machine with an operator. The author

gives examples in which it was decided to combine several tasks and assign them to a human operator even if a machine could have been employed to perform some of these tasks. Part of this decision was based on the best use of available resources. Instead of having a machine and its operator idle much of the time, combining tasks created work which would occupy and challenge the operator. The report also points out one of the pitfalls of design allocations for plants which are not yet in operation. While it is possible to do research and simulations to assess tentative allocations, often the ergonomics or human factors specialist must wait so long to receive feedback on the success of these allocations that design has proceeded without the benefit of the assessment, based on hunch and educated guess.

Crawley (1974) reviews the human operator's role in a steel making plant now and in the future. He details the activities of present human operators and discusses how the introduction of computers into the control room is likely to alter that role. The need for information at various stages of the steel-making process is discussed. The effort again was to make an educated guess as to the effects that changes in technology will have on the human operator and control of particular plant processes. The author sees these changes as inevitable, but not as harmful or disruptive forces.

Van Boxtel (1977) also did a study of steel manufacturing. However, the study was an evaluation from a human factors perspective. The plant chosen was selected on the basis of the advanced state of automation present in the mill. The study, consisting mainly of interview data and direct observation, led the author to conclude that automation had not resulted in unacceptable human operator jobs and that automation should continue to be a tool of the operator. In this he is at

variance with other writers, who see automation and the human operator evolving to an interactive relationship. Van Bortel also discusses the allocation of tasks within the plant--but with respect to the operators in the plant, not between computer and operators. The author appears to be concerned with keeping the role of the operator a coherent and meaningful one in which training and authority reflect responsibility imposed on the operator.

In summary, the studies discussed above have either been applied to large classes of systems, such as military surveillance systems, or have dealt with the retrofit and redesign of working systems. There is a notable lack of work on applications to specific systems during design. In fact, most of the work in the allocation of functions area has been theoretical and has centered around the development of methods. Little formal evaluation of the success in the application of such methods has been attempted.

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

V. ALLOCATION OF FUNCTIONS AND THE SYSTEM PROCESS

The preceding chapters have provided a general review of the allocation of functions literature, including the criteria, methods, and models developed primarily in the context of military-aerospace systems. Based on this review of the human factors literature and an initial review of research and development on computer based aids, a preliminary approach to the allocation and assessment of functions in nuclear power plants is presented here.

The literature review has not uncovered any significant new approach to the allocation of functions since the development of the "Hypothetical-Deductive" approach by Price and Tabachnick (1968) (see Chapter III). This approach involves essentially a two-part process. First, the degree of potential human participation in the implementation of a function would be determined by applying certain assertions about the capabilities of man and machine and their limitations for meeting the performance required by the function. Essentially, this part establishes a hypothesis of functions allocation--in particular, man's participation. Second, the hypothesis should be systematically reviewed or tested, using the best available human performance data, to determine the feasibility of the hypothesized human participation. This part essentially validates the hypothesis by deductive methods. An adaptation of this approach has been developed for the present project, and is described in the remainder of this chapter.

Design Versus Evaluation

It is important to emphasize that the objective of this project is to develop a method and proposed criteria to assess design proposals and concepts of automation in nuclear plants. This is in keeping with the Nuclear Regulatory Commission's charter: to regulate--not design--nuclear power plants. However, it is considered necessary to pursue the allocation of functions as a design issue in the current phase of this project, for three important reasons. First, almost all the literature and previous work has been oriented toward design and toward the allocation-of-functions process as part of an overall system design. It is therefore easier to use the results from previous work if one maintains a design focus. Second, once a satisfactory design approach has been developed, no problems are anticipated in "reversing" this approach to be used for its evaluation of proposed designs. It is not uncommon for evaluation criteria to be derived from design criteria (this was largely the case in the development of NUREG-0700, *Guidelines for Control Room Design Review*). A final reason that might support the pursuit of a design approach at this time is the possibility that the NRC may choose to provide the nuclear power industry with guidelines for the design of future automated systems and the allocation of functions within them. While this is not the prime objective of this project, it has been discussed as a product that could be derived from its findings. Consequently, development of a future design-oriented approach to the allocation of functions is an intermediate goal of the present project and of this report.

System Development and the Allocation of Functions

This section establishes a setting for the allocation of functions in the total system development process. It emphasizes human factors activities in system development. Since it is assumed to be common knowledge, no comprehensive treatment of the system development process has been attempted.

In its simplest form, system development always confronts the human factors specialist with two basic questions. The first question is, What human performance is required? The answer to this question takes the form of a system and task analysis. The second question is, How is the performance potential obtained? The answer to this question is embodied in specifications for crew team manning and organization, personnel selection, training, job performance aids, and the human engineering and job design activities that will sustain and support personnel performance. Together, the answers to both questions represent what may be called "personnel performance architecture." The basic issues of personnel performance architecture are graphically represented in Exhibit 6.

A more expanded version of the personnel performance architecture activities in total system development is depicted in Exhibit 7. This shows that the function allocation activity must occur early in system development and that, once done, it will have a limiting effect on following design activities concerned with personnel performance architecture. A poor allocation, or a poor use of automation, early in system design becomes more difficult and costly to rectify as system design and development proceed. There are numerous examples in contemporary commercial and military systems where a poor

Exhibit 6
The Basic Issues of Personnel Performance Architecture

allocation of functions has resulted in degraded system performance. Furthermore, there is little likelihood that the effects of an initially poor functions allocation can be completely offset by an after-the-fact attempt to compensate for that poor decision by trying to improve the man-machine interface. Only small gains can be expected, for example, in achieving an optimum man-machine allocation through enhancements of control boards by means of paint, label, and tape techniques. Even the incorporation of graphic displays, such as a System Parameter Display or Disturbance Analysis System; may be only a partial remedy if the functions allocated to man were based on guesswork or mere tradition, and not an optimum man-machine relationship.

Exhibit 7
Principal Human Factor Activities in System Development

Before proceeding to a description of an approach for allocation of functions, it is necessary to deal briefly with the development of man's role. The final definition of man's role in a system occurs as a result of functions allocation and the nature of man's participation in each of those functions. Thus, determining man's role is an iterative process, but some key decisions must be made at the onset of the system development process to determine the general role of man in the system and his relative responsibility. The general roles of man in a system are depicted in Exhibit 8. These general roles are compatible with work being done at Oak Ridge National Laboratory on defining the operator roles in nuclear power plants (see Kisner & Flannigan, 1980, and Kisner, Fullerton, & Frey, 1981). Our approach to the initial development of the role of man is based on the answers to a series of questions presented in Exhibit 9. The answers to these questions define the basic role of man in a system. The specifics of this role are then modified during functions allocation. Thus, we make a distinction between the role of man and the functions of man: The role being defined before specific functions are allocated.

It is also important to note that the role of man is not determined simply on the basis of performance considerations, but must also consider such factors as man's unique limitations, the availability of personnel, the cost of humans as operators, and differences among individuals. The latter two factors will be discussed later. For the moment, a few of man's unique limitations are highlighted below:

Exhibit 8
General Roles of Man in a System

- **CONTRIBUTING CAPABILITIES NOT POSSIBLE WITH AN AUTOMATIC SYSTEM**
 - IDENTIFYING GOALS
 - DEVELOPING PLANS
- **OPERATION OF SYSTEM EQUIPMENT (PRIMARY OR BACK-UP)**
 - PROCESS CONTROL
 - RECONFIGURATION OF SYSTEM EQUIPMENT
 - INTERVENTION IN AUTOMATED FUNCTIONS
- **MONITORING SYSTEM EQUIPMENT**
- **DIAGNOSING SYSTEM MALFUNCTIONS**

Exhibit 9
Development of the Role of Man

- **CAN MAN'S UNIQUE CAPABILITIES BE SIGNIFICANT IN THE ATTAINMENT OF THE SYSTEM GOALS?**
 - MAN HAS THE ABILITY TO LEARN
 - MAN HAS THE CAPACITY FOR CREATIVE PROBLEM SOLVING
- **WHAT SYSTEM PERFORMANCE COULD BE IMPLEMENTED BY MAN?**
- **IF A ROLE FOR MAN IS JUSTIFIED BECAUSE OF HIS UNIQUE CAPABILITIES (QUESTION 1) OR PRIMARY PERFORMANCE ACTIVITIES (QUESTION 2), WHAT OTHER PERFORMANCE SHOULD BE ASSIGNED TO HIM TO TAKE ADVANTAGE OF HIS UTILITARIAN CAPABILITIES?**
- **WILL MAN'S UNIQUE LIMITATIONS CONSTRAIN HIS USE IN THE SYSTEM?**
 - MAN HAS CERTAIN PHYSICAL CHARACTERISTICS
 - MAN HAS PHYSIOLOGICAL NEEDS
 - MAN HAS PSYCHOLOGICAL NEEDS
- **WILL MAN BE LOCAL OR REMOTE TO THE PRIMARY SYSTEM?**

1. Man comes in only a single model. From a design point of view, man can be integrated into the system concept only as a complete "unit" with variable physical characteristics: dimensions, weight, and strength.
2. Man has certain performance limitations from the standpoint of such things as sensitivity, reaction time, number of information channels, rate of response, and tolerance to stress.
3. Man's performance has an associated cost. One pays a price for providing and maintaining reliable human performance. These costs are measurable in terms of: selection; training; maintenance of proficiency; manuals, handbooks, instructions, and job aids; biological support; and management. These costs are not always evident to the designer until a system is operational.
4. Man has physiological needs. Human performance deteriorates rapidly when physiological needs for nourishment, sleep, comfort, and health are not satisfied.
5. Man has psychological needs. Man's performance deteriorates over prolonged periods of high stress or inactivity. Human performance also changes significantly because of such psychological variables as motivation, frustration, conflict, and fear.

Allocation-of-Functions Philosophy

A common misconception about the functions allocations is that functions are allocated to either man or machine. This is not the case. In most situations, functions are implemented by a combination of people, hardware, and software. In short, functions are implemented by some degree of human participation coupled with some degree of mechanization or automation. Man and machine are not competitors. The allocation-of-functions process must therefore be thought of as a continuum rather than a dichotomy. It is true, however, that the endpoints of the continuum tend to define what may be termed manual performance at the one extreme and automated performance at the other. This concept is depicted graphically in Exhibit 10. This exhibit illustrates the continuum of man-related performance, which is any performance that can be obtained with man as a part of the design solution. For definition purposes the two extremes of the continuum may be defined as follows:

- Manual Performance. This implies that man performs a function. He conserves, reduces, or adds information and he supplies or controls energy.
- Automatic Performance. This implies that a machine performs the function by supplying whatever information or energy is required.

In summary, the philosophy for the allocation of functions is that most functions are man-rated. They require some degree of human participation. Therefore, allocation occurs on a continuum rather than as a dichotomy.

Exhibit 10
Human Participation in Function Implementation

VI. A PROCEDURE FOR THE ALLOCATION OF FUNCTIONS

In an ideal world the allocation of functions would be accomplished by the application of a mathematical formula or algorithm. Given a complete statement of the requirements of a system, and precise descriptive statements about the properties and dynamic capabilities of hardware, software, and man, one would be able to derive one or more combinations of hard and soft components that would satisfy system requirements.

At present, however, neither engineering nor human factors is an exact science. Engineering is an inventive process. Information on the quantitative nature of human behavior is incomplete. At its best, therefore, system engineering is characterized as a series of iterative approximations to the goals expressed in a statement of system requirements made by a design team.

With these limitations in mind, we propose here a set of steps which can guide a system engineering team in either the allocation of functions for a new system or the assessment of functions already allocated in an existing system, such as a nuclear power plant. These steps in the allocation-of-functions process are summarized in Exhibit 11.

Is System Automation Mandatory?

The first step in allocating functions or assessing the allocation of functions is to determine whether, for one or more technical or nontechnical reasons, total system automation is mandatory. This step is accomplished in part by comparing the goals and mission of the planned or existing system against the criteria presented in Exhibit 12. These criteria are expressed

Exhibit 11

The Allocation-of-Functions Process

Exhibit 12

Criteria for Total Automation

A system should be fully automated when a statement of its requirements or its present configuration meets one or more of the following criteria:

- Regulation or Policy. A system must be automated when regulation or public policy so dictate. This assumes that automation can be accomplished with available resources and known technology.
- Environmental Factors. A system must be automated when any form of human participation is precluded because the system or its environment either will not support human life or will create products or conditions that would endanger it. This assumes that an adequate life support system cannot be developed and that man cannot be remotored to a safe environment to perform essential system functions. Environmental criteria include:
 - Uncontained radiation (see Exhibit A-1)
 - Heat (see Exhibits A-2 to A-4)
 - Noise (see Exhibit A-5)
 - Atmospheric pressure and sudden pressure change (see Exhibit A-6)
 - Gravity
 - Chemical or biological substances (see Exhibit A-7)
 - Vibration (see Exhibit A-8).
- System Requirements and Constraints. A system must be automated when its performance requirements exceed or fall outside of the range of human capability. Performance requirements in the following areas may make automation mandatory. They are best expressed as a series of questions having qualitative or quantitative answers.
 - Controlling: Do system requirements demand operational response to be made at speeds which cannot be attained or maintained by a human operator? Does the system require that adjustments be made which are too precise for the human operator to make?

Exhibit 12 (Continued)

- Monitoring: Does the system require the human operator to maintain a state of alertness or preparation which is beyond the operator's normal limits? (Exhibit A-16)
- Sensing: Are there stimuli required by the system which are beyond the capability of human operators to perceive them? (Exhibits A-17 and A-18)
- Information processing: Are there information processing tasks, such as computations, which require performance beyond the normal range of the human operator? (Exhibits A-14 and A-15)
- Interpretation: Does the system require performance in areas such as classification or extrapolation (calculating accelerations) which are not possible for the human operator to perform within the limits of the system?
- Information storage: Do system requirements demand that the operator be able to store and retrieve large amounts of information in ways that are beyond human capabilities?
- Decision-making: Does the system require that the operator determine a course of action or make a selection from among existing procedural options in a shorter time than the normal operator is capable of making such determinations? (Exhibits A-11 and A-12)

as qualitative statements. When quantitative data exist, these are referred to by number. Examples of such quantitative limits, expressed as ranges or limiting characteristics, are presented in Appendix A.

If for any reason this comparison leads to the conclusion that total automation must be attempted, and that it can be accomplished under known resource, engineering, and policy constraints, then automation becomes a part of the normal engineering process and no further consideration need be given to the role of man in the system. On the other hand, if total automation is mandatory but not achievable, then the statement of system requirements will have to be either revised or abandoned. A revision may contemplate the inclusion of man.

In actual practice there are few instances in which it is immediately obvious that a total system must be fully automated. This is particularly true when system goals and functions are complex, when mission success is of vital importance, when the operating environment is unpredictable, or when a system failure would have vital safety and public health consequences. We do not include here consideration of the allocation of functions for simple, self-contained systems, such as regulators, timers, and other systems, in which total automation or mechanization can readily be achieved with existing technology and in which it would be degrading or uneconomical to assign such functions to man.

In the case of existing nuclear power plants, as well as those envisioned for the future, it is unlikely that total plant functioning can or should be automated. The number and modes of failure are simply too great to be reduced to an engineering

algorithm, and the consequences of failure are too severe to allow total automation to be contemplated seriously with known or foreseeable technology.

If the comparison of system requirements with the criteria shown in Exhibit 12 leads to the conclusion that not only is total system automation mandatory but that any form of human participation is precluded on the basis of environmental factors or human performance limitations, then the criteria listed in Exhibit 13 may be used to determine the technical feasibility of acquiring a totally automated system. If these criteria cannot be met, then it will be necessary either to abandon further development or to restate system goals and requirements in such a way that they can be automated or accomplished semiautomatically.

If it can be demonstrated that a system must and can be fully automated, then it is necessary to establish its economic feasibility. Criteria listed in Exhibit 14 are representative of those that may be used in making such a determination. This list is incomplete because it is not envisioned as being of importance in the development of a functions allocation procedure for nuclear power plant systems.

Is Function Automation Mandatory?

Most military and industrial process control systems that exist today, or are likely to exist in the near future, will require some form of human intervention. Therefore, the second step in allocating or assessing the allocation of functions will be concerned not with the issue of total system automation but with the automation of selected system functions. In nuclear power plants, for example, operators now have roles in establishing initial conditions and set-up, in minimizing event likelihood and severity, and in assisting in safety functions.

Exhibit 13

Criteria for Assessing the Technical Feasibility of Automation

A system can be automated if the following criteria can be satisfied.

- Component Availability. Are the necessary hardware and software components required by the system available off-the-shelf?
- Development Time. If components are not readily available off-the-shelf, can needed components be developed within the scheduled life-cycle development limit for the system or can that limit be revised to permit development and testing?
- Predictability. Can all system events (i.e., mission events and system failure modes) be predicted and handled by automation?
- Reliability. Is the expected reliability of the proposed system configuration adequate to meet system performance requirements?
- Failure. Can the consequences of expected system failures be compensated for by automatic back-up or otherwise prevented from exceeding acceptable limits?
- Safety. Can adequate safeguards against dangers to public health be fully automated?

Exhibit 14

Criteria for Assessing the Economic Feasibility of Automation

A system can be automated within economic constraints if it meets the following criteria.

- Cost-Effectiveness. Will automation of the system be more cost-effective than the use of a human operator to perform one or more system functions?* This assumes that inclusion of the operator is not precluded for reasons of life support or human performance limitations.
- Funding. Can all necessary costs of development, design, testing, installation, and automation be covered by known financial resources?

*Total system cost includes the cost of acquiring, automatically maintaining, and operating a fully automatic system. The cost of including one or more human operators or maintainers entails the aggregate costs of personnel selection, training, life support, staffing, attrition, and management, and the provision of supporting documents, manuals, job aids, and training devices.

These roles require capabilities which can be supported by inputs from process computers and plant systems but which call for man's unique ability to integrate information, detect patterns and trends, make decisions, reconfigure equipment, and evaluate outcomes. This step in the allocation process is therefore concerned with determining if there are system functions that preclude any form of human participation and that must be fully automated.

For this purpose, the criteria listed in Exhibits 12, 13, and 14 are again applicable. In addition, the criteria shown in Exhibit 15 apply. If the use of these criteria indicates that man is unable to perform a function, then the designer has three options: (a) to fully automate the function, (b) to provide machine or computer assists to offset or compensate for operator limitations, or (c) to use the operator in a back-up mode if the automatic function fails. In case the latter option is selected, it is important to anticipate the tasks of the operator as a back-up and to make whatever provisions are necessary to fully support that back-up function.

Is Human Performance Mandatory?

Human performance in a system is mandatory when the unique capabilities of man are required to implement a function. In general, the human operator will possess the unique capabilities shown in Exhibit 16. These are capabilities which cannot be duplicated by present engineering or software technology and will, in most instances, require some form of human aiding in order to provide the information, control options, and feedback needed for process monitoring, supervision, and control.

Exhibit 15

Criteria that Limit or Preclude Human Participation in a System Function

Consideration should be given to the exclusion of man in performing a function when one or more of the criteria below apply.

- Force Application. Large, precise, or extended applications of force preclude the use of man. Man's instantaneous peak force is limited to a mean force of 50 Newtons.
- Response to Stimuli/Signals. The human operator experiences a finite lag between the onset of a stimulus and the ability to make a response to it. This lag varies from a mean of 100 msec for auditory stimuli and approximately 120 msec for visual stimuli, to lags in excess of 1 second for responses involving a choice among alternatives.
- Precise Calibration and Measurement. Human operators are incapable of making precise measurements and calibrations.
- Reliable Response. Because of the variability of human response, man should be precluded from performing functions which require the unvarying repetition of one or more responses.
- Time Sharing. Under most circumstances man acts as a single-channel information processor and should ordinarily be precluded from performing multiple time-shared tasks.
- Continuous Performance. Man should be precluded from performing functions which cannot be interrupted or which require sustained attention for long periods of time (e.g., in excess of 20 minutes).
- Detection of Low Frequent Events. The operator should be precluded from performing functions which require the detection of rarely occurring stimuli, events, or conditions.

Exhibit 16

Criteria that Define Unique Human Capabilities

Human participation in the performance of a function is mandatory when that function requires one or more of the following capabilities.

- Develop a Strategy. Man's inclusion is mandatory when:
 - Operations cannot be reduced to preset procedures
 - The form and content of all inputs and outputs cannot be specified or predicted
 - The relationship between inputs and outputs may require restructuring during task performance.
- Integrate a Large Amount of Information. Man must be included in the accomplishment of a function when:
 - Signals must be detected against a noisy background
 - Patterns of information and trends must be extracted from several sources.
- Make and Report Unique Observations. Man must be included when a function requires that observation be made of:
 - The performance of others
 - The performance of self
 - Ephemeral events.
- Assign Meaning and Value to Events. Man must be included when performance of a system or function requires that meaning and relative values be assigned to events.

Hypothesized Human Participation

The application of the procedure for functions allocation and assessment presented so far must be regarded as a set of tentative, revocable hypotheses about the combination of components expected to provide the performance required by a statement of system goals and requirements. The majority of system functions will not be clear-cut candidates for either total automation or totally manual operation. Rather, they will be some combination of human participation and equipment and computer capabilities that have been judged to be capable of working together to produce desired performance at a necessary level of reliability. Thus, a major consideration in the allocation of functions will be to "hypothesize" the appropriate level of human participation in each system function. These hypotheses must be developed based on the best available data and knowledge concerning the capabilities and limitations of man and of equipment, and then assessed in light of development testing.

When it has been determined that human participation is likely to be required in performing a system function, that function may be termed a "man-rated function." In hypothesizing human participation in any function, the responsibilities of man may be described for each of seven "core" performance categories:

1. Monitoring and sampling information sources
2. Sensing information
3. Processing information
4. Interpreting and evaluating trends
5. Selecting or developing procedural strategies
6. Information storage and retrieval
7. Controlling.

Illustrations of the activities involved in each core performance area are shown in Exhibit 17. Listed are both examples of the capabilities, and the required resource characteristics. Terms in the left and right columns do not necessarily correspond on a one-to-one basis.

Exhibit 17

Classification of Core Performance Capabilities

Monitoring and Sampling

To maintain a state of readiness or preparation for receipt of inputs

<u>Examples</u>	<u>Required Resource Characteristics</u>
Search	High reliability in detecting signals
Surveillance	Monitoring specific physical energies
Vigilance	Monitoring of infrequent events
Watch-keeping	Monitoring scheduled or predictable events
	Continuous attention
	Monitoring of long-duration events

Sensing

To perceive external stimuli, to recognize a change of external state, to acquire data from the environment

<u>Examples</u>	<u>Required Resource Characteristics</u>
Perception	Sensing specific physical energies
Signal Detection	Sensing a stimulus against a background of noise
Signal Recognition	Sensing the same stimulus frequently
Discrimination	Sensing several similar stimuli simultaneously
Recognition of Discrete Change	Sensing quantitative values
Recognition of Dynamic Change	Simultaneous multichannel sensing

Exhibit 17 (Continued)

Information Processing

To transform, to organize, to break down, to combine, to operate on input data or signals

<u>Examples</u>	<u>Required Resource Characteristics</u>
Encoding/Decoding	Numerical computation
Sorting	High volume and/or speed of transactions
Filtering	Simple processing rules or specific programs
Ordering	Parallel or multichannel operations
Merging	Repetitive operations
Analysis	High accuracy or precision
Computation	

Interpreting

To construct, to derive, to translate, to assign meaning to data or signals

<u>Examples</u>	<u>Required Resource Characteristics</u>
Pattern Recognition	Assigning items to a large inclusive class by specific rules
Interpolation	Assigning a narrow range of meanings to inputs
Extrapolation	Estimation of rate of change, acceleration, or higher order derivatives
Prediction	Consideration of specific, predictable, or unambiguous inputs
Association	A minimum number of errors due to expectation or cognitive set
Classification	

Exhibit 17 (Continued)

Selection or Developing Procedural Strategies

To select among alternatives, to determine a course of action, to assess the validity of a proposition

<u>Examples</u>	<u>Required Resource Characteristics</u>
Hypothesis Formulation	Dependence upon complex procedures or operations
Induction/Inference	A large number of differentiations or integrations
Deduction	Deductive reasoning without reference to context
Probability/Contingency Estimation	Prediction based on variable whose nature and weightings are known in advance
Identification and Comparison of Alternatives	Selection among well defined alternatives
Comparison with Standards or Criteria	Invariant decision-making logic
Selection/Choice	Short time lags between scheduled events

Information Storage and Retrieval

To retain or to remain aware of information and, conversely, to recall or to bring forth previously acquired information

<u>Examples</u>	<u>Required Resource Characteristics</u>
Short-Term Memory	Rapid storage (ingestion) of large amounts of data
Long-Term Memory	Long-term storage with total recall
Total Retrieval/Recall	Infallible memory with the precise source of data accurately tagged

Exhibit 17 (Continued)

Information Storage and Retrieval (Continued)

<u>Examples</u>	<u>Required Resource Characteristics</u>
Selective Retrieval/ Recall	High speed and/or frequent memory search
Purging	Multichannel storage or retrieval Large buffer (immediate memory) capacity Storing of coded or numerical data Rapid and/or complete purging (erasure) of stored data

Controlling and Responding

To maintain a given level of operation, to adjust and correct for changes in requirements, to adjust for deviations from a prescribed optimum state

<u>Examples</u>	<u>Required Resource Characteristics</u>
Tracking	Generate a variety of movements in response to unpredicted changes
Adjusting	Detect discrepancies
Directing	Apply refined forces
Specific Force Generation	Apply variety of forces in large range of magnitude and duration
Response Latency (Reaction Time)	Respond rapidly and appropriately to apply force in a changing situation

For a function in which one or more of these categories of core human performance will be required, it is necessary to analyze that function to determine how that performance can be achieved under expected operational conditions and constraints and to identify the level of automation and the job aids that must be provided to support it. To aid in this analysis effort, it is useful to address each function with the series of questions illustrated in Exhibit 18 and to enter the answers as statements in a form such as the one shown in Exhibit 19. This helps ensure that a record is kept of the allocation and the reasons for making it. The outcome of these activities is a description of hypothesized human participation for each function of the system. By considering functions in this fashion, the level of equipment performance is also hypothesized.

If it has been determined that human participation in a system is mandatory, then it follows that, having made the decision to include man, additional duties and responsibilities can be allocated to man either to support the system or to ensure that the job of an operator is meaningful and challenging. For example, if it has been established that man is required to reconfigure a system by by-passing failed components, then it is also possible to provide the operator with such additional tasks as providing back-up to automated systems, keeping records, or monitoring other systems. We call these additional and optional human responsibilities "utilitarian performance." Utilitarian performance can be used to fill in and compensate for the lack of vigilant alertness associated with a job that might otherwise simply consist of prolonged monitoring and infrequent intervention. When utilitarian performance is included, it should be selected so as to develop coherent jobs--not a collection of unrelated tasks. The opportunity to add additional utilitarian duties to

Exhibit 18

Questions for Determining the Human
Participation for Each Function

- What is the function under consideration?
- What are the tasks involved in this function?

For each task:

Does this task involve Sensing?

What part of the Sensing do we give the human operator?

What part of the Sensing do we give the equipment?

Does the task involve Interpreting?

What part of the Interpreting do we give the human operator?

What part of the Interpreting do we give the equipment?

Does the task involve Information Processing?

What part of the Information Processing do we give the human operator?

What part of the Information Processing do we give the equipment?

Does the task involve Decision-Making?

What part of the Decision-Making do we give the human operator?

What part of the Decision-Making do we give the equipment?

Does the task involve Controlling?

What part of the Controlling do we give the human operator?

What part of the Controlling do we give the equipment?

Does the task involve Monitoring?

What part of the Monitoring do we give the human operator?

What part of the Monitoring do we give the equipment?

Exhibit 18 (Continued)

Does the task involve Information Storage?

What part of the Information Storage do we give the human operator?

What part of the Information Storage do we give the equipment?

- What is the total hypothesized human operation participation for the function?
- What is the total hypothesized equipment participation for the function?

Exhibit 19

Example of Chart for Recording the Process of Hypothesizing Human Participation

Function Title	Function Requirements	Subfunction (Tasks)	Hypothesized Human Participation	Hypothesized Machine Participation	Rationale

the core performance requirements of an operator also represents a way to distribute responsibilities among an operating crew in an equitable manner, and one which is in keeping with the requirements for crew structure and supervision.

Testing Hypothesized Man-Rated Functions

This step in the allocation procedure is the "deductive" part of a hypothetical-deductive process. Its purpose is to test the feasibility and validity of the potential man-rated allocations which were considered to be either mandatory or utilitarian. Exhibit 20 summarizes the technique for testing the hypothesized allocations. A three-stage approach is suggested. Testing can be accomplished either empirically, by the use of scaled-down or full-sized mockups, physical or computer simulators, or actual or prototype operational equipment; or analytically, using previous research data obtained from analogous situations. The level of testing will depend upon available time and resources. In this report, we will describe the analytic testing option. Each of the three stages under this option is summarized below.

Review Allocation Against Human Psychological Capacities.

The allocations decisions made so far were hypothesized without detailed consideration of basic human capacities. This activity is therefore a qualifying activity, insofar as potential allocations may be rejected as incompatible with basic psychological capacities. Inputs needed for this activity consist of quantitative data relative to the psychological capacities of man in the three basic areas of human functioning: sensory-perceptual, motor, and cognitive. Exhibit 21 is a sample of a type of data available in the psychological and human factors literature

Exhibit 20

Summary of Technique For Testing Hypothesized Man-Rated Functions

(1) REVIEW ALLOCATION AGAINST PSYCHOPHYSICAL CAPACITIES

- SENSORY-PERCEPTUAL**
- COGNITIVE**
- MOTOR**

(2) REVIEW ALLOCATION AGAINST SYSTEM OR FUNCTION CONSTRAINTS

- ENVIRONMENTAL**
- PERFORMANCE**

(3) REVIEW ALLOCATION AGAINST HUMAN RELIABILITY

- ERROR POTENTIAL**
- ACCEPTANCE**

TESTING CAN BE ACCOMPLISHED--

- EMPIRICALLY (MOCK-UPS, SIMULATORS, ACTUAL EQUIPMENT)**
- COMPUTER SIMULATION**
- ANALYTICALLY**

Exhibit 21

Man's Senses as Informational Channels: A Comparison of the Intensity Ranges and Intensity Discrimination Abilities of the Senses*

Sense	Intensity Range		Intensity Discrimination	
	Smallest Detectable	Largest Practical	Relative	Absolute
Vision	$2.2 \text{ to } 5.7 \times 10^{-10} \text{ ergs}$	Roughly, the brightness of snow in the midday sun, or about 10^9 times the threshold intensity	With white light, there are about 570 discriminable intensity differences in a practical range	With white light, 3 to 5 absolutely identifiable intensities in a range of 0.1 to 50 ml.
Audition	$2 \times 10^{-4} \text{ ergs/cm}^2$	Roughly, the intensity of the sound produced by a jet plane with afterburner or about 10^{14} times the threshold intensity	At a frequency of 2,000 cps, there are approximately 325 discriminable intensity differences	With pure tones about 3 to 5 identifiable steps
Mechanical vibration	For a small stimulator on the fingertip, average amplitudes of 0.00025 mm can be detected	Varies with size of stimulator, portion of body stimulated and individual. Pain is usually encountered about 40 db above threshold	In the chest region a broad contact vibrator with amplitude limits between 0.05 mm and 0.5 mm provides 15 discriminable amplitudes	3 to 5 steps
Touch pressure	Varies considerably with body areas stimulated and type of stimulator. Some representative values: Ball of Thumb—0.026 erg Fingertips—0.037 to 1.090 ergs Arm—0.032 to 0.113 ergs	Pain threshold	Varies enormously for area measured, duration of stimulus contact and interval between presentation of standard and comparison stimuli	Unknown
Smell	Widely variant with type of odorous substance. Some representative values: Vanillin— $2 \times 10^{-7} \text{ mg/m}^3$	Largely unknown	No data available	No data available

*Mowbray and Gebhard

which can be used for this purpose. Allocations may be rejected or the level of human participation modified based on psychological demands.

If allocation does not meet these tests, then several options are open. Exhibit 22 shows a chart which may be used to aid in these decisions. It may be possible to aid the human operator with instrumentation control or job aids to allow the operator to function within the system.

Another option is to modify human participation. It may be possible to change the allocated human participation without having to change the entire allocation. For example, if a function involved monitoring and controlling the system to ensure that the system remains within established limits, one allocation might have the human operator both perform the monitoring and take the needed control actions.

Even if the control action could be automated, it may be allocated to the operator to enhance the total operator job. Appendix A contains some examples of the types of psychological data which can be used to make these decisions (Exhibits A-11 to A-16).

Review Allocation Against System or Function Constraints.

The purpose of this activity is to further test the validity of the surviving man-rated allocations against criteria related to environmental and/or performance constraints. This is also a qualifying activity. A potential allocation may be rejected as incompatible with system or functional environment or performance constraints. For example, performance constraints, such as duration of the continuous monitoring task, may justify the

EXHIBIT 22

Chart to Record Results of Psychological Tests of Allocations

Function	Function Tasks	Sensory/ Perceptual	Motor	Cognitive	Can operator be aided to meet psychological needs of function?	Does human participation have to be modified?	Reject Allocation? (N/Y)

elimination of a man-rated allocation if a vigilance decrement is likely to occur. Much data exists to support testing at this level. Exhibit 23 is a sample of the relationship between human performance and room temperatures, illustrating the effect of one environmental constraint. Exhibit 24 is an example of the effects of duration on vigilance performance (signal detection and reaction time). Once again, testing of the hypothesized allocation could result in rejection of the allocation or modification of the extent of human participation. Exhibit 25 gives an example of the type of chart which can be used to record data resulting from the tests against the system or function constraints.

Review Allocation Against Human Reliability. This final test is perhaps the most difficult to perform--at least analytically. Data on human error is not well established, and the effects of user acceptance on performance are known, at best, only in a qualitative sense. Nevertheless, there are data sources and lessons learned from other situations which can be brought to bear on the testing at this point. The best currently available source for human error data is the *Handbook of Human Reliability Analysis With Emphasis on Nuclear Power Plant Operations*, published by NRC as NUREG/CR-1278 (by Swain and Guttman, 1980).

Operator Acceptance of Automation

The literature on operator acceptance of automation has been well searched by Frey and Kisner (1981), and no effort will be made to duplicate their efforts here. However, some aspects of operator acceptance that may affect the allocation of function are:

Exhibit 23

The Critical Effective Temperatures at Which Impairment May Be Demonstrated, According to Various Sources

Name and type of test	Investigator	Temperature (°F)	
		Max. at which performance remains normal	Demonstrable impairment
Typewriter code (scrambled letters)	Viteles	80	87
Morse code reception	Mackworth	87.5	92 ^a
Locations (spatial relations code)	Viteles	80	87
Block coding (problem solving)	Mackworth	83	87.5 ^a
Mental multiplication (problems)	Viteles	80	87
Number checking (error detection)	Viteles	80	87 ^a
Visual attention (clock test)	Mackworth	79	87.5 ^a
Pursuit (visual maze)	Viteles	80	87
Reaction time (simple response)	Forlano	93 ^{b, c}	—
Discriminator (complex response)	Viteles	80	87
Lathe (hand coordination)	Viteles	80	87 ^a
Pursuitmeter	Mackworth	87.5	92 ^a
Motor coordination	Weiner	64.5 ^c	91 ^a
Ergograph (weight pulling)	Mackworth	81 ^d	85.3 ^{a, d}
Bicycle ergometer (heavy work)	Liberson	64.5 ^c	91.5 ^c
Weight lifting (heavy work)	N. Y. Ventil. Comm.	64.5 ^c	70 ^c

^a Deterioration statistically significant.

^b Provided wet bulb does not exceed 86°F.

^c Effective temperature estimated from data in report.

^d Midpoint of a range of conditions.

Robert M. Gagne, (editor), Psychological Principles in System Development, 1962.

Exhibit 24

Vigilance of 21 Female Workers Occupied With Time Paced and Monotonous Work
(10 Light Signals Per 40 Min.).

Exhibit 25

Chart to Record Data from the Tests
Against System Constraints

Function	Function of System Constraint Environmental	Performance	Can the human operator perform within the constraint?	If not, can the operator be aided or pretested in the system within the constraint?

Job coherence. Automation can lead to jobs which are made up of uninteresting, unrelated, unchallenging leftover tasks, which can lead to unacceptance on the part of the human operator.

Responsibility/authority. Automation will allow a single human operator to control a larger number and greater diversity of tasks. Since in nearly all systems a human will ultimately be responsible for the fulfillment of the system objectives, this means that the amount of responsibility felt by the human operator will increase. The human operator should have corresponding authority to deal with this responsibility. The human operator should have the final supervisory control and decision-making power.

Losing touch. In many automated systems, the task of actual control has passed from the human operator to the automated system. This has led many to fear that the operator's skills will be lost. If at some point the operator must resume manual control, system performance could suffer because of the lost skills.

Social structure. In many systems which involve human operators, informal social support structures have evolved. Automation may pose a threat to these structures and care may have to be taken to preserve them.

The considerations given here are not easily quantified and will usually have to be dealt with on an individual system basis. The human factors specialist should play a major role in this aspect of systems design. In addition, operator opinion and participation should be solicited and given weight in making any final allocation of functions and design of jobs derived from these allocations.

The overall approach to deriving data regarding user acceptance can take a number of forms. Exhibit 26 is an example of some principles of user acceptance derived from a study by Price, Smith, and Behan (1964). A specific study of user acceptance of automation for nuclear power plants is underway at Oak Ridge National Laboratory. When completed, its findings should be a valuable addition to the criteria presented here.

Outcomes. At completion, the test of hypothesized man-rated functions will generally have one of three outcomes:

1. The function is not feasible for human performance and must be automated.
2. The function may be feasible, but the level and type of human participation has to be redefined.
3. It is a feasible man-rated function and can be further developed as part of the normal design activities.

Following the testing of hypothesized man-rated functions, the functions are synthesized into a statement of the total job which the operator will perform. This activity leads to a set of integrated design requirements and constraints across all functions. This product constitutes a major input into the system engineering phase of the project, where the actual design occurs. The next major effort, from the personnel performance architecture viewpoint, will be a task analysis for each function requiring human participation, based on the final design.

Exhibit 26

Acceptance Principles From a Study of Commercial All-Weather Landing Systems

ROLE EXPECTANCY

1. MEN ARE GENERALLY ACCEPTING OF SYSTEM ROLES WHICH GIVE THEM AN OPPORTUNITY TO EXERCISE AND, THEREFORE, MAINTAIN SKILLS WHICH THEY FEEL ARE IMPORTANT TO MAINTAINING THEIR POSITION IN THE OCCUPATIONAL AND SOCIAL STATUS SYSTEM IN WHICH THEY ARE IMMersed.
2. MEN ARE GENERALLY ACCEPTING OF SYSTEM ROLES WHICH PERMIT THEM TO VARY THEIR PROCEDURES AND THE MANNER OF ACCOMPLISHING THEIR TASKS, ON THEIR OWN INITIATIVE. ROLES THAT FAIL TO PERMIT A MAN TO VARY HIS PROCEDURES ON HIS OWN ARE GENERALLY LABELED MECHANICAL.
3. MEN ARE MORE ACCEPTING OF ROLES WHICH PERMIT THEM TO LEARN. IN A RECENT STUDY (UNFORTUNATELY, UTILIZING A SAMPLE OF ONLY SEVENTEEN) A CORRELATION OF +.61 (STATISTICALLY SIGNIFICANT AT THE .01 LEVEL OF CONFIDENCE) WAS FOUND BETWEEN HOW MUCH THE MEN FELT THEY WERE LEARNING ON THEIR JOB AND THEIR INTENTIONS TO RE-ENLIST.

AUTOMATION ACCEPTANCE

1. THE MORE SYSTEM EXPERIENCE A MAN HAS, WITH THIS EXPERIENCE INCLUDING EXPOSURE TO AUTOMATED EQUIPMENT, THE MORE ACCEPTING HE IS OF THE AUTOMATED EQUIPMENT AND THE MORE HE WILL USE IT IN THE PRESCRIBED MANNER.
2. THOSE WITH MORE STATUS, RESPONSIBILITY, AND AUTHORITY TEND TO BE MORE ACCEPTING OF AND MAKE MORE USE OF AUTOMATED EQUIPMENT THAN OTHERS.
3. WHERE FAILURE OF THE PERFORMANCE OF ITS FUNCTION BY AUTOMATED EQUIPMENT CAN ENDANGER THE LIFE OF THE MAN, HE IS LESS LIKELY TO ACCEPT AND USE IT DESPITE PRESCRIBED PROCEDURES.
4. THERE IS GENERALLY HIGH ACCEPTANCE, WITHIN THE LIMITS OF THE ABOVE THREE PRINCIPLES, OF THE AUTOMATION OF SERVO TASKS, PARTICULARLY THOSE WHICH MUST BE PERFORMED OVER LONG PERIODS OF TIME.
5. THERE IS GENERALLY RATHER LOW ACCEPTANCE OF AUTOMATION OF DECISION MAKING FUNCTIONS.

(FROM PRICE & CO-WORKERS, 1964.)

VII. THE ASSESSMENT OF FUNCTIONS ALLOCATION IN NUCLEAR POWER PLANT DECISION MAKING

In Section VI of this report we identified the core areas of human performance that must be considered in the allocation and assessment of functions in a system. One of these core performance areas is decision-making. In the opinion of the authors, the principal role of man (i.e., the operating crew) in a nuclear power plant is to make decisions. Other core areas of human performance (e.g., monitoring, controlling) assigned to the operator initiate, support, or are otherwise ancillary to decision-making. In this section we focus on decision-making as a core area of human performance, and explore one approach to the development of criteria that can be used to assess the extent to which the elements of the decision-making process have been effectively allocated to the operator and to other elements of the plant system (e.g., procedures, computer aids, training, displays, and controls). The example we have presented is suggestive. It is not complete even for the one critical decision element chosen. We anticipate, however, that subsequent phases of this functions allocation program will permit the development, evaluation, and application of the approach identified here.

Justification for assigning the decision-making role to man is based on the premise that the causes of off-normal plant conditions are so varied and complex, their remedies so event-specific, and the consequences of failure to mitigate an event so severe that decision-making should not be automated even if it were possible to do so. For this reason, it is likely that decision-making will be the single most important system responsibility to be considered in the allocation of functions

to man and machine, both in the design of new power plants and in the assessment of the effectiveness of functions allocations in plants that exist today.

The most critical decisions to be made in a nuclear power plant are those that must be made in emergencies, particularly in response to events for which no standard procedures exist. Under emergency conditions the decision process takes the general flow chart form shown in Exhibit 27 (Breen, 1981). While flow diagrams of this type are useful for some purposes, they reveal little of the problem-solving activity which is required of an operating crew, and which is so critical in event mitigation. To fully understand this process, it is necessary to model and assess the cognitive process of the operator.

Psychologists, economists, mathematicians, and, more recently, those interested in artificial intelligence, have developed analytical and empirical models of the cognitive aspects of decision-making. One of the most satisfactory for our purposes comes from the research of Rasmussen (1974, 1978, 1979, 1980). Based on his studies, Rasmussen produced a variety of diagrammatic decision-making models. An adaptation of one diagram by Pew, Miller, and Feeher (1980) makes explicit the cognitive elements that are only implicit in Exhibit 27. This model, shown in Exhibit 28, has several advantages. It incorporates cognitive elements. It applies to process control. It can be applied to a range of decision-making sequences which proceed in an orderly manner from observation to execution, as well as to sequences in which short-cuts are taken. And it makes it possible to treat complex decision-making as a branching process with a tree structure.

Exhibit 27
Decision Making in Emergencies (Breen, 1981)

Exhibit 28

Decision-Making Model (Adapted from Rasmussen, 1974, by Pew et al., 1980)

Pew et al. used the Rasmussen model to determine the relative importance of providing decision aids and other control room innovations (e.g., staffing, training, control, and display improvements) for each of the decision elements in plants.

These decision elements were given the following definitions:

- Activation (and detection) refers to that phase of decision making in which the operators determine that some abnormal condition exists which demands further investigation.
- Observation/data collection refers to the phase in which the operators are collecting information, from control room instruments or other sources, that will help them determine the nature of the abnormal condition.
- Identification of system state refers to the phase in which the operators abstract the information they have collected into a coherent representation of the current state of the plant. During this phase, they will usually identify what is wrong, although they may not yet understand why or how the abnormal condition developed.
- Interpretation of situation refers to the phase in which the operators determine the implications of the system state identified in the previous phase. During this phase, they will usually decide not only what is causing the abnormal situation, but also what the course of events is likely to be if no intervention occurs.
- Evaluation of alternatives refers to the high-level decision phase in which the operators consider the fundamental strategies open to them under the circumstances. During this stage, they are not concerned with carrying out the strategies, but rather with the probable consequences of the feasible alternatives.

- Task definition/selection of goal state refers to the first step in carrying out the general state for the system. At this stage they are concentrating on what they want to happen and not on how to do it.
- Procedure selection (and formulation) refers to the detailed plan by which they will endeavor to bring the system to the desired goal state. This plan may involve the execution of predefined procedures, either written or unwritten, or it may involve inventing new procedures to suit unforeseen circumstances.
- Procedure execution refers to the process of actually carrying out the sequence of actions determined in the previous phases. This phase couples back to the first and second phases, in that the operators must monitor the results of their execution to determine that the execution phase is proceeding as intended.

Using these eight decision element definitions, the authors then obtained information on the decision-making of operators in response to four off-normal plant events that had recently occurred,* and constructed "Murphy diagrams" of the operators' decisions. Murphy diagrams are named in honor of the legendary Murphy, who formulated the law that "If anything can possibly go wrong, it will." Four of the eight diagrams are presented in Exhibits 29 to 32. Each diagram breaks down one of the Rasmussen decision model elements, showing the decision-making activity, its "success" (S), and "failure" (F) outcomes, and the common proximal and distal reasons for error in performing the decision element. The authors use the terms "proximal" and "distal" to describe the immediacy of the probable cause or source of error in a failure (F) outcome.

*The four events were: (1) steam-tube rupture, (2) excessive cooldown followed by automatic safety injection, (3) loss of instrumentation followed by excessive cooldown, and (4) loss of feedwater.

Exhibit 29

Murphy Diagram for Activation/Detection (Pew et al., 1980)

Exhibit 30

Murphy Diagram for Observation/Data Collection (Pew et al., 1980)

Exhibit 31

Murphy Diagram for Identification of System State (Pew et al., 1980)

Exhibit 32

Murphy Diagram for Interpretation of Situation (Pew et al., 1980)

The authors then formed an eight-member panel composed of experts drawn from the operating staff of the plants at which the events had occurred, and from experts in human factors, control room engineering, and operation. Using the Rasmussen model and the definitions of its decision-making elements as guides, the panel was asked to analyze and evaluate information about the four plant emergency events.

The outcome of this analysis consisted of the combined ratings of panel members regarding the relative importance of each of the eight decision-making elements.

Exhibit 33 shows that, on a scale of 1 (least critical) to 7 (most critical), the highest mean ratings of importance were assigned to three decision elements: observation/data collection; identification of system state; and interpretation of situation. Murphy diagrams for these elements are presented in Exhibits 30, 31, and 32. These findings suggest that any technique for the assessment of the allocation of functions in existing nuclear power plants should emphasize and concentrate initially on criteria for these three key decision-making elements.

Given the results of the Pew study (Pew et al., 1980), it is possible to extract a set of criteria that must be met if success is to be achieved in implementing each of the elements in an operator's decision-making sequence for any off-normal plant event. This requires us to make two assumptions. First, it must be assumed that the Rasmussen decision elements and the "Pew-Murphy" diagrams are generic to off-normal events, and that the only difference from event to event will be the specific items of data collected by the operator from plant instrumentation. Second, since we cannot know for any operator

Exhibit 33
Results of Overall Evaluation
(From Pew et al., 1980)

OVERALL EVALUATION FORM

I. Based on your overall experience, estimate the practical importance of providing decision aids and innovations to assist each of the following aspects of decision making.

	Mean	StdDev
(a) Activation/detection:	4.50	2.12
(b) Observation/data collection:	5.88	0.93
(c) Identification of system state:	6.00	1.00
(d) Interpretation of situation:	6.00	0.87
(e) Evaluation of alternatives:	4.88	1.36
(f) Task definition/selection of goal state:	2.63	0.48
(g) Procedure selection/formulation:	2.88	1.36
(h) Procedure execution:	4.25	1.71

whether or not short-cuts in decision-making will be taken (i.e., proceeding directly from observation to procedure selection without taking intervening steps), we must assume that all steps may be taken and that each step should be fully supported by appropriate operator aids. Given that these are valid assumptions, we can illustrate how criteria for the assessment of the allocation of functions for the operator's decision-making function can be derived. For this purpose we used the Pew-Murphy diagram for observation/data collection shown in Exhibit 30. This diagram may be schematized and criteria derived from it as follows.

Critical Decision-Making Element:
Observation/Data Collection

Success requirement. Having detected an abnormal condition, to be able to acquire sufficient data to characterize the plant state.

Success criteria:

1. All acquired data must be pertinent to the abnormal condition. Necessary conditions for this criteria to be met include:
 - Operator must be experienced to specified level.
 - Procedures for data collection must be followed.
 - Operators must be trained to evaluate indications that may signal a condition outside the set of design-basis events.
2. All acquired data must be consistent and not in conflict. Necessary conditions for this criteria to be met include:
 - Indications of all malfunctioning equipment must be available to operator.

- There can be no deficiencies in display design that would lead to errors in data collection.
3. Acquired data must be complete.
 - Indications of equipment/display malfunction must be available to operator.
 - Support must be provided to the operator to preclude premature termination of data collection.
 4. Pending activities should not compete for operator attention.
 - Crew structure and size should be adequate to distribute workload under off-normal condition.
 - Aids should be provided to prioritize and cue required activities.

It is suggested that in subsequent phases of this program, efforts be made to expand on the approach suggested here, to evaluate the expanded approach on at least one power plant subsystem, and to use that evaluation experience as the basis for providing a method for assessing the allocation of functions in existing plants and for proposed operator aids to be used in those plants. It is felt that if the method can be applied to existing plants and operator aids, it can also be used in guiding the allocation of functions in designing new plants.

VIII. CONCLUSIONS

Technological advances have greatly altered the role of man in relation to systems, changing his function from that of a continuous control element to that of supervisor. More often than not, decisions about the role and functions of man have been unconscious and implicit. Aside from the lists of criteria first proposed by Paul Fitts and elaborated upon in subsequent years by others, lists of what man can do better than machines or computers, and vice versa, have not been employed systematically throughout system development and design; nor has anyone other than Price and Tabachnick (1968) developed a systematic method for considering man's role and function. Thus, while much lip service has been paid to the allocation of functions, and to criteria to be used for that purpose, little progress has been made in improving this aspect of the state of the art in system development.

Somewhat greater progress has been made in developing simulation models of military, air traffic control, industrial, and other systems that could be used to compare and evaluate alternative man-machine configurations. In fact, the state of the art in simulation model development has outstripped the ability of the simulation user to make logical use of these capabilities. Thus, the user finds himself with too little in the way of empirical data about human capabilities and limitations for exercising a simulation model, and also without a good method for making allocation-of-functions decisions at successive stages of development and design.

Based on what little literature exists, we conclude that the criteria, methods, and models for the allocation of functions to man, computers, and machines that have been developed in other

industries are, in general, applicable to the nuclear power plant systems and functions; however, a significant amount of specific "tailoring" and updating needs to take place. An overview of an approach that would fulfill this need is presented in this report.

In addition to the need for an approach to allocation of functions that is suitable for nuclear power plants, the following related questions should be answered in future research efforts:

- What are the effects of automation on operator vigilance, attitude, and motivation?
- What is the impact of automation and other computer-based aids on operator qualifications, training, procedures, and human engineering?
- What are effective methods for overcoming resistance to change?

IX. REFERENCES

- Anyakora, S.N., & Lees, F.P. Detection of instrument malfunction by the process operator. In E. Edwards and F.P. Lees (Eds.), *The human operator in process control*. London: Taylor and Francis, Ltd., 1974.
- Attwood, D. The interaction between human and automatic control. In E. Edwards and F.P. Lees (Eds.), *The human operator in process control*. London: Taylor and Francis, Ltd., 1974.
- Baum, A.S., & Drury, C.G. Modelling the human process controller. *International Journal of Man-Machine Studies*, 1976, 8, 1-11.
- Bergum, B.O., & Lehr, D.J. Vigilance performance as a function of task and environmental variables (Report No. 11). Ft. Bliss, TX: U.S. Army Air Defense Human Research Unit, 1962.
- Bisseret, A. Analysis of mental processes involved in air traffic control. *Ergonomics*, 1971, 14(5), 565-570.
- Bowen, H.M. The "imp" in the system. In W.T. Singleton, R.S. Easterby, and D.C. Whitfield (Eds.), *The human operator in complex systems*. London: Taylor and Francis, Ltd., 1967.
- Breen, R.J. Defense-in-depth approach to safety in light of the Three Mile Island Accident. *Nuclear Safety*, 1981, 22, 568.
- Broadbent, D.E., & Gregory, M. Division of attention and the decision theory of signal detection. *Proceedings of the Royal Society* (London), 1963, 158(b), 222-231.
- Chapanis, A. On the allocation of functions between men and machines. *Occupational Psychology*, 1965, 39(1), 1-11.
- Chu, Y.-Y., & Rouse, W.B. Adaptive allocation of decisionmaking responsibility between human and computer in multitask situations. *IEEE Transactions on Systems, Man, and Cybernetics*, 1979, SMC-9(12), 769-778.
- Colquhoun, W.P. The effect of "unwanted" signals on performance in a vigilance task. *Ergonomics*, 1961, 4, 41-51.
- Colquhoun, W.P., & Baddeley, A.D. Role of pretest expectancy in vigilance decrement. *Journal of Experimental Psychology*, 1964, 68, 156-160.

- Connelly, M.N., & Willis, J.E. The development of a human effectiveness function allocation methodology (HEFAM) (Research Memorandum SRM 70-11). San Diego, CA: Naval Personnel and Training Research Laboratory, Bureau of Naval Personnel, October 1969.
- Corcoran, W.R., Finnicum, D.J., Hubbard, F.R., III, Musick, C.R., & Walzer, P.F. The operator's role and safety functions. Windsor, CT: C-E Power Systems, Combustion Engineering, Inc., March 1980.
- Corkindale, K.G. Man-machine allocation in military systems. In W.T. Singleton, R.S. Easterby, and D.C. Whitfield (Eds.), *The human operator in complex systems*. London: Taylor and Francis, Ltd., 1967.
- Craft, P.C.R. Design methods for nuclear power plant system design. In W.T. Singleton, R.S. Easterby, and D.C. Whitfield (Eds.), *The human operator in complex systems*. London: Taylor and Francis, Ltd., 1967.
- Crawley, J.E. The present and future contribution of the human operator to the control of LD steelmaking. In E. Edwards and F.P. Lees (Eds.), *The human operator in process control*. London: Taylor and Francis, Ltd., 1974.
- Crawley, J.E. Human factors in the design and operation of automated plants. In *Human factors in metals plant operation and design*, Proceedings of the meeting of the Metals Society, London, 1977.
- Crooks, W.H., Artof, M., Weltman, G., & Freedy, A. Man/machine interaction in adaptive computer-aided control: Analysis of automated control allocation (Report No. PATR-1008-74-12/30). Woodland Hills, CA: Perceptronics, Inc., December 1974.
- Crossman, E.R.F.W. Automation and skill. In E. Edwards and F.P. Lees (Eds.), *The human operator in process control*. London: Taylor and Francis, Ltd., 1974.
- Danaher, J.W. Human error in ATC system operations. *Human Factors*, 1980, 22(5), 535-545.
- Daniel, J., Puffler, F., & Strizenec, M. Analysis of operator's work at various levels of automated production. In E. Edwards and F.P. Lees (Eds.), *The human operator in process control*. London: Taylor and Francis, Ltd., 1974.

- Davis, K.B., Weisbrod, R.L., Freedy, A., & Weltman, G. Adaptive computer aiding in dynamic decision processes: An experimental study of aiding effectiveness (Report No. PTR 1016-75-5). Woodland Hills, CA: Perceptronics, Inc., May 1975.
- De Jong, J.J., & Koster, E.P. The human operator in the computer-controlled refinery. In E. Edwards and F.P. Lees (Eds.), *The human operator in process control*. London: Taylor and Francis, Ltd., 1974.
- Department of Labor. Outlook for computer process control. In E. Edwards and F.P. Lees (Eds.), *The human operator in process control*. London: Taylor and Francis, Ltd., 1974.
- Devoe, D.B. Alternatives to handprinting in the manual entry of data. *IEEE Transactions on Human Factors in Electronics*, 1967, 8(1), 21-32.
- Drury, C.G. Human performance in manual process control. In T.B. Sheridan and G. Johanssen (Eds.), *Monitoring behavior and supervisory control*. New York: Plenum Press, 1976.
- Edwards, E., & Lees, F.P. *Man and computer in process control*. Huddersfield, England: H. Charlesworth & Co., Ltd., 1972.
- Edwards, E., & Lees, F.P. The influence of the process characteristics on the role of the human operator in process control. *Applied Ergonomics*, 1974, 5.1, 21-25.
- Ephrath, A.R., & Curry, R.E. Detection by pilots of system failures during instrument landings. *IEEE Transactions on Systems, Man, and Cybernetics*, 1977, SMC-7(12), 841-848.
- Faulkner, T.W. Variability of performance in a vigilance task. *Journal of Applied Psychology*, 1962, 46, 325-328.
- Fitts, P.M. (Ed.). Human engineering for an effective air-navigation and traffic-control system. Columbus, OH: Ohio State University Research Foundation, March 1951.
- Freedy, A., Davis, K.B., Steeb, R., Samet, M.G., & Gardiner, P.C. Adaptive computer aiding in dynamic decision processes: Methodology, evaluation, and application (Report No. PFTR-1016-76-8/30). Woodland Hills, CA: Perceptronics, Inc., August 1976.

- Freedy, A., Weisbrod, R., May, D., Schwartz, S., & Weltman, G. Adaptive computer aiding in dynamic decision processes: Analysis and design (Report No. PTR-73-101). Encino, CA: Perceptronics, Inc., October 1973.
- Gagne, R.M. (Ed.). *Human functions in systems: Psychological principles in system development*. New York: Rinehart and Winston, 1962.
- Garvey, W.D., Taylor, F.V., & Newlin, E.P. The use of "artificial signals" to enhance monitoring of performance (Report No. 5269). Washington, DC: U.S. Naval Research Laboratory, 1959.
- Goodstein, L.P., & Rasmussen, J. Man-machine system design criteria in computerized control rooms (Report N-7-80). Raskilde, Denmark: Riso National Laboratory, Electronics Department, February 1980.
- Gruber, A. Sensory alternation and performance in a vigilance task. *Human Factors*, 1964, 6, 3-12.
- Halsey, R.M., & Chapanis, A. Chromaticity-confusion contours in a complex viewing situation. *Journal of the Optical Society of America*, 1954, 44, 442-452.
- Hertzberg, H.T.E. Engineering anthropology. In H.P. Van Cott and R.G. Kinkade (Eds.), *Human engineering guide to equipment design* (revised edition). Washington, DC: American Institute of Research, 1972.
- Holt, H.O., & Stevenson, F.L. Human performance considerations in complex systems. *Science*, 1977, 195, 1205-1209.
- Hopkin, V.D. Conflicting criteria in evaluating air traffic control systems. *Ergonomics*, 1971, 14(5), 557-564.
- Huchingson, R.D. *New horizons for human factors in design*. New York: McGraw-Hill, 1981.
- Hunsicker, P.A. Arm strength at selected degrees of elbow flexion (Report No. WADC-TR-54-548). Wright-Patterson AFB, OH: Wright Air Development Center, 1955.
- Ireland, F.H. SYSSIM--A system simulation program for use on a time-shared computer. Moorestown, NJ: Systems Engineering, Missile and Surface Radar Division.

- Jerison, H.J. On the decrement function in human vigilance. In D.N. Buckner and J.J. McGrath (Eds.), *Vigilance: A symposium*. New York: McGraw-Hill, 1963.
- Jervis, M.W. Some practical aspects of distributed digital control systems. Gloucester, England: Enlarged Halden Programme Group, Central Electricity Generating Board, June 1980.
- Kahne, S., Lefkowitz, I., & Rose, C. Automatic control by distributed intelligence. *Scientific American*, 1981, 244(5), 78-90.
- Kirchner, J.H., & Laurig, W. The human operator in air traffic control systems. *Ergonomics*, 1971, 14(5), 549-556.
- Kisner, R.A., & Flanagan, G.F. A systems approach to defining operator roles. *IEEE Transactions on Nuclear Science*, 1981, NS-28(1), 1-6.
- Kisner, R.A., Fullerton, A.M., Frey, P.R., & Dougherty, E.M. A taxonomy of the nuclear plant operator's role. Oak Ridge, TN: Oak Ridge National Laboratory.
- Klemmer, E.T., & Frick, F.C. Assimilation of information from dot and matrix patterns. *Journal of Experimental Psychology*, 1953, 45, 15-19.
- Lacy, B.A. The design of the operators' tasks in a tea blending plant. In W.T. Singleton, R.S. Easterby, and D.C. Whitfield (Eds.), *The human operator in complex systems*. London: Taylor and Francis, Ltd., 1971.
- Livingston, W.L. (Chair). TMI--Technology, Methodology and Integration: The Impact of Three Mile Island on Nuclear Power Plant Computer Systems. Symposium presented at the Engineering Computer Forum, conducted by Edison Electric Institute, Dallas, Texas, September 15-17, 1980.
- Mackworth, J.F., & Taylor, M.M. The d' measure of signal detectability in vigilance-like situations. *Canadian Journal of Psychology*, 1963, 17, 302-325.
- Maltas, K.L., & Buck, J.R. Man/machine systems study of manual and automated hot strip mills (Report No. 66). West Lafayette, IN: Purdue University Schools of Engineering, Purdue Laboratory for Applied Industrial Control, May 1975.

- May, D.M., Crooks, W.H., & Freedy, A. Application of adaptive decision aiding systems to computer-assisted instruction (ARI Technical Report No. PATR-1023-76-1). Woodland Hills, CA: Perceptrics, Inc., March 1976.
- Meister, D., & Rabideau, G.F. *Human factors evaluation in system development*. New York: John Wiley & Sons, Inc., 1965.
- Mertes, F., & Jenney, L. Automation applications in an advanced air traffic management system--Volume III: Methodology for man-machine task allocation (Report No. DOT-TSC-OST-74-14. III). McLean, VA: TRW Incorporated, August 1974.
- Moore, J.P. F-18 functions allocation report. Prepared by McDonnell Aircraft Company, McDonnell Douglas Corporation, under Contract No. N00019-75-C-0424 for the Department of the Navy, Naval Air Systems Command, Washington, D.C., March 1977.
- Mowbray, G.H., & Gebhard, J.W. Man's senses as information channels (Rept. CM-936). Silver Spring, MD: The Johns Hopkins University Applied Physics Lab., May 1958. (Reprinted in H.W. Sinaiko (Ed.), *Selected papers on human factors in the design and use of control systems*. New York: Dover Publications, Inc., 1961.)
- O'Hanlon, J., Jr., & Schmidt, E.A. The effect on the level of vigilance of an adjacent secondary vigilance task (Report No. 750-4). Los Angeles, CA: Human Factors Research, Inc., 1964.
- Parker, J.F., Jr., & West, V.R. *Bioastronautics data book*. Washington, DC: National Aeronautics and Space Administration, 1973.
- Parks, D.L., & Springer, W.E. Human factors engineering analytic process definition and criterion development for CAFES (Report No. D180-18750-1). Seattle, WA: Boeing Aerospace Company, Research & Engineering Division, January 1976.
- Pew, R.W., Miller, D.C., & C.E. Feeher. Evaluation of proposed control room improvements through analysis of critical operator processes (Final Report NP-1982, Research Project 891). Palo Alto, CA: Electric Power Research Institute, 1981.
- Pollack, I. The information of elementary auditory displays, II. *Journal of the Acoustical Society of America*, 1953, 25, 765-769.

- Pollack, I., & Ficks, L. Information of elementary multi-dimensional auditory displays. *Journal of the Acoustical Society of America*, 1954, 26, 155-158.
- Poulton, E.C. The optimal perceptual load in a paced auditory inspection task. *British Journal of Psychology*, 1960, 51, 127-139.
- Price, H.E., & Tabachnick, B.J. A descriptive model for determining optimal human performance in systems--Volume III: An approach for determining the optimal role of man and allocation of functions in an aerospace system (including technical data appendices) (NASA CR-878). Chatsworth, CA: Serendipity Associates, March 1968.
- Price, H.E., Smith, E.E., & Behan, R.A. Utilization of acceptance data in a descriptive model for determining man's role in a system (NASA CR-95). Chatsworth, CA: Serendipity Associates, 1964.
- Rasmussen, J. On the reliability of process plants and instrumentation systems (Report No. R-7-68). Raskilde, Denmark: Riso National Laboratory, Electronics Department, February 1968.
- Rasmussen, J. Characteristics of operator, automatic equipment and designer in plant automation (Report No. R-30-68). Raskilde, Denmark: Riso National Laboratory, Electronics Department, October 1968.
- Rasmussen, J. The human data processor as a system component: Bits and pieces of a model (Riso-M-1722). Raskilde, Denmark: Riso National Laboratory, 1974.
- Rasmussen, J. Outlines of a hybrid model of the process plant operator. In T.B. Sheridan and G. Johanness (Eds.), *Monitoring behavior and supervisory control*. New York: Plenum Press, 1976.
- Rasmussen, J. Notes on diagnostic strategies in process plant environment (Riso-M-1983). Raskilde, Denmark: Riso National Laboratory, 1978.
- Rasmussen, J. On the structure of knowledge: A morphology of mental models in a man-machine system context (Riso-M-2192). Raskilde, Denmark: Riso National Laboratory, 1979.
- Rasmussen, J. The human as a systems component. In H.T. Smith and T.R.G. Green (Eds.), *Human interaction with computers*. London: Academic Press Inc., Ltd., 1980.

- Roebuck, J.A., Kroemer, K.H.E., & Thomason, W.G. *Engineering anthropometry: Methods*. New York: John Wiley & Sons, 1975.
- Ropelewski, R.R. L-1011 cockpit automation cuts crew workload. *Aviation Week & Space Technology*, 1979, 110(25), 46-53.
- Rouse, W.B. Adaptive allocation of decision making responsibility between supervisor and computer. In T.B. Sheridan and G. Johanssen (Eds.), *Monitoring behavior and supervisory control*. New York: Plenum Press, 1976.
- Rouse, W.B. Human-computer interaction in multitask situations. *IEEE Transactions on Systems, Man, and Cybernetics*, 1977, SMC-7(5), 384-392.
- Schakel, B., Beevis, D., & Anderson, D.M. Ergonomics in the automation of meat handling in the London docks. In W.T. Singleton, R.S. Easterby, and D.C. Whitfield (Eds.), *The human operator in complex systems*. London: Taylor and Francis, Ltd., 1971.
- Shea, D.J. Analytic techniques for creating a job design basis for a nuclear power plant operating crew. Paper presented at the CNSI Specialist Meeting on Operator Training and Qualifications (NUS Training Corporation), Charlotte, North Carolina, October 1981.
- Sheridan, T.B., & Johanssen, G. *Monitoring behavior and supervisory control*. New York: Plenum Press, 1976.
- Sinaiko, H. Human intervention and full automation in control systems. *Applied Ergonomics*, 1972, 3.1, 3-7.
- Singleton, W.T., Easterby, R.S., & Whitfield, D.C. *The human operator in complex systems*. London: Taylor and Francis, Ltd., 1971.
- Smith, H.T., & Crabtree, R.G. Interactive planning: A study of computer aiding in the execution of a simulated scheduling task. *International Journal of Man/Machine Studies*, 1975, 7, 213-231.
- Smith, H.T., & Green, T.R.G. *Human interaction with computers*. London: Academic Press Inc., Ltd., 1980.
- Spencer, J. An investigation of process control skill. In E. Edwards and F.P. Lees (Eds.), *The human operator in process control*. London: Taylor and Francis, Ltd., 1974.

- Stammers, R.B. Human factors in airfield air traffic control. *Ergonomics*, 1978, 21(6), 483-488.
- Steeb, R., Artof, M., Crooks, W.H., & Weltman, G. Man/machine interaction in adaptive computer-aided control: Final report (Report No. PATR-1008-75-12/31). Woodland Hills, CA: Perceptronics, Inc., December 1975.
- Steeb, R., Weltman, G., & Freedy, A. Man/machine interaction in adaptive computer-aided control: Human factors guidelines (Report No. PATR-1008-76-1/31). Woodland Hills, CA: Perceptronics, Inc., January 1976.
- Steeb, R., Weltman, G., & Freedy, A. Man/machine interaction in adaptive computer-aided control. In T.B. Sheridan and G. Johanssen (Eds.), *Monitoring behavior and supervisory control*. New York: Plenum Press, 1976.
- Strieb, M.I., Glenn, F.A., & Wherry, R.J., Jr. The Human Operator Simulator--Volume IX: HOS study guide (Report No. 1320). Willow Grove, PA: Analytics, September 1978.
- Strieb, M.I., & Wherry, R.J., Jr. An introduction to the Human Operator Simulator (Technical Report 1400.02-D). Willow Grove, PA: Analytics, December 1979.
- Swain, A.D. Design techniques for improving human performance in production. Albuquerque, NM: A.D. Swain, June 1980 (rev. ed.). (Originally printed by Industrial and Commerical Techniques, Ltd. (InComTec) in London, England, 1972.)
- Swain, A.D. Design of industrial jobs a worker can and will do. *Human Factors*, 1973, 15(2), 129-136.
- Swain, A.D., & Guttman, H.E. Handbook of human reliability analysis with emphasis on nuclear power plant applications (NRC NUREG CR-1278). Albuquerque, NM: Sandia Laboratories, April 1980.
- Thompson, D.A. The man-robot interface in automated assembly. In T.B. Sheridan and G. Johanssen (Eds.), *Monitoring behavior and supervisory control*. New York: Plenum Press, 1976.
- Tulga, M.K., & Sheridan, T.B. Dynamic decisions and work load in multitask supervisory control. *IEEE Transactions on Systems, Man, and Cybernetics*, 1980, SMC-10(5), 217-232.
- Umbers, I.G. Models of the process operator. *International Journal of Man-Machine Studies*, 1979, 11, 263-284.

- Van Boxtel, P.A.A. Human factors evaluation of the Hoogovens No. 2 hot-strip mill. In *Human factor in metals plant operation and design*, Proceedings of the meeting of the Metals Society, London, 1977.
- Van Cott, H.P., & Altman, J.W. Procedures for including human engineering factors in the development of weapon systems (Technical Report 560488). Dayton, OH: Wright Air Development Center, 1956.
- Van Cott, H.P., & Kinkade, R.G. (Eds.). *Human engineering guide to equipment design* (revised edition). Washington, DC: American Institutes of Research, 1972.
- Van Cott, H.P., & Warrick, M.J. Man as a system component. In H.P. Van Cott and R.G. Kinkade (Eds.), *Human engineering guide to equipment design* (revised edition). Washington, DC: American Institutes of Research, 1972.
- Walden, R.S., & Rouse, W.B. A queueing model of pilot decision-making in a multitask flight management situation. *IEEE Transactions on Systems, Man, and Cybernetics*, 1978, SMC-8(12), 867-875.
- Ware, J.R., Baker, R.A., & Sheldon, R.W. Effect of increasing signal load on detection performance in a vigilance task. *Perceptual and Motor Skills*, 1964, 18, 105-106.
- Webb, J.S., Willis, J.E., & Anderson, R.D. A selected annotated bibliography on cost-effectiveness and man/machine function allocation (Research Memorandum SRM 66-4). San Diego, CA: U.S. Naval Personnel Research Activity, August 1965.
- Weisbrod, R.L., Davis, K.B., Freedy, A., & Weltman, G. Adaptive computer aiding in dynamic decision processes: An initial study of dynamic utility convergence and decision aiding (Report No. PTR-1016-74-11). Woodland Hills, CA: Perceptronics, Inc., November 1974.
- Wherry, R.J., Jr. The Human Operator Simulator--HOS. In T.B. Sheridan and G. Johannsen (Eds.), *Monitoring behavior and supervisory control*. New York: Plenum Press, 1976.
- Whitfield, D. Human skill as a determinate of allocation of function. In W.T. Singleton, R.S. Easterby, and D.C. Whitfield (Eds.), *The human operator in complex systems*. London: Whitfield, Taylor, and Francis, 1971.

- Whitfield, D., Ball, R.G., & Ord, G. Some human factors aspects of computer-aiding concepts for air traffic controllers. *Human Factors*, 1980, 22(5), 569-580.
- Wickens, C.D., & Kessel, C. The effects of participatory mode and task workload on the detection of dynamic system failures. *IEEE Transactions on Systems, Man, and Cybernetics*, 1979, SMC-9(1), 24-34.
- Wiener, E.L. Multiple channel monitoring. *Ergonomics*, 1964, 7, 453-460.
- Wiener, E.L., & Curry, R.E. Flight-deck automation: Promises and problems (NASA Technical Memorandum 81206). Moffett Field, CA: Ames Research Center, June 1980.
- Wilkinson, R.T. Artificial "signals" as an aid to an inspection task. *Ergonomics*, 1964, 7, 63-72.
- Willis, J.E. Feasibility of the development and utilization of personnel performance effectiveness measures for man/machine function allocation decisions (Research Memorandum SRM 68-7). San Diego, CA: U.S. Naval Personnel Research Activity, Bureau of Naval Personnel, October 1967.
- Woodson, W.E. *Human factors design handbook: Information and guidelines for the design of systems, facilities, equipment, and products for human use*. New York: McGraw-Hill, 1981.
- Wortman, D.B., Sigal, C.E., Pritsker, A.B., & Seifert, D.J. SAINT II documentation manual (Report No. AMRL-HESS-74-4). West Lafayette, IN: Pritsker & Associates, Inc., December 1975.
- Wylie, C.D., Dick, R.A., & Mackie, R.R. Toward a methodology for man-machine function allocation in the automation of surveillance systems (U)--Volume I: Summary (Report 1722-F, Vol. 1). Goleta, CA: Human Factors Research, Inc., July 1975.

APPENDIX A
Data Pertinent to the
Allocation-of-Functions
Process

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

APPENDIX A

Much data exists which can aid in the decisions necessary for the allocation of functions. This appendix gives examples of data regarding both environmental limitations and the psychological capacities and limitations of the human operator.

Exhibit A-1

Effects of Acute Whole-Body External Radiation Exposure (From Woodson, 1981)

0.25 rems	25-100 rems	100-200 rems	200-300 rems	300-600 rems	600 rems or more
Immediate Effects					
No detectable clinical effects	Slight transient reductions in lymphocytes and neutrophils. Disabling sickness not common; exposed individuals should be able to proceed with usual duties.	Nausea and fatigue with possible vomiting above 125 rems.* Reduction in lymphocytes and neutrophils with delayed recovery.	Nausea and vomiting on first day. Latent period up to 2 weeks or perhaps longer.	Nausea, vomiting, and diarrhea in first few hours. Latent period with no definite symptoms, perhaps as long as 1 week.	Nausea, vomiting, and diarrhea in first few hours. Short latent period with no definite symptoms in some cases during first week.
Delayed Effects					
Delayed effects may occur	Delayed effects possible, but serious effects on average individual very improbable.	Delayed effects may shorten life expectancy in the order of 1%.	Following latent period, the following symptoms appear but are not severe: loss of appetite, and general malaise, sore throat, pallor, petechiae, diarrhea, moderate emaciation. Recovery likely in about 3 months unless complicated by poor previous health or superimposed injuries or infections.	Epilation, loss of appetite, general malaise, and fever during second week, followed by hemorrhage, purpura, petechiae, inflammation of mouth and throat, diarrhea, and emaciation in the third week. Some deaths in 2 to 6 weeks. Possible eventual death to 50% of the exposed individuals for about 500 rems.	Diarrhea, hemorrhage, purpura, inflammation of mouth and throat, fever toward end of first week. Rapid emaciation and death as early as the second week, with eventual death of up to 100% of exposed individuals.

Exhibit A-2
Tolerance to Low Temperatures
(From Woodson, 1981)

Legend:

- A--1-clo (light coveralls)
- B--2-clo (woolen underwear, coveralls, and jacket)
- C--3-clo (intermediate-weight flight clothing)
- D--4-clo (heavy flight clothing)

Subjects were seated and performing light work. Air velocity, approximately 200 ft/min; barometric pressure, 1 atm.

Exhibit A-3
Effects of Cold on Selected Task Performances

Legend:

A--tactile sensitivity, bare hand
B--simple visual reaction time
C--manual skill

Exhibit A-4

Temperature-Humidity Tolerability (with
conventional clothing)
(From Woodson, 1981)

Exhibit A-5
Potential Effects of High Noise Levels
(From Woodson, 1981)

When noise levels exceed 100 dB, potentially serious consequences occur, as shown below.

Noise Level, dB	Spectrum	Duration	Effects
105	Jet engine	2 min	Reduced visual acuity, stereoscopic acuity, and near-point accommodation and permanent hearing loss when exposure continues over a long period (months)
110	Machinery noise	8 hr	Chronic fatigue and digestive disorders
120	Broadband	1 hr	Loss of equilibrium
150	1-100 Hz	2 min	Reduced visual acuity, chest-wall vibration, changes in respiratory rhythm, and a "gagging" sensation*

*Subjects were wearing so-called protective aids to prevent hearing loss.

Exhibit A-6
Effects of High and Low Oxygen Levels
(From Woodson, 1981)

Partial Pressure of Oxygen, mm of Hg	Percent of Oxygen in Dry Air at Sea Level Pressure	Effect
Oxygen Excess		
456	60	Onset of oxygen poisoning after some hours.
167	22	Limit set in RN to control fire hazard in charcoal filters in nuclear submarines.
Normal		
160	21	Normal atmospheric level
Oxygen Lack		
137	18	Accepted limit of alertness. Loss of night vision.
		Earliest sign—dilation of the pupils.
114	15	Performance seriously impaired.
		Hallucinations, excitation, apathy.
100	13	Coordination impaired. Emotional upset.
84	11	Paralysis, loss of memory.
		Irreversible unconsciousness.
46	6	Death before symptoms apparent.

Note: The effect of falling oxygen is insidious, because it dulls the brain and prevents realization of danger.

Exhibit A-7
Skin Reaction to Chemical Substances
(From Woodson, 1981)

The table below presents a partial list of chemical substances and their action on the skin.

Agent	Reaction
Acids:	
Acetic	Dermatitis and ulcers
Carbolic	Irritation and erosion, eczema, and anesthesia
Chromic	Ulcers (chrome holes on the skin), inflammation, and perforation of the nasal septum
Hydrochloric	Irritation and ulceration
Hydrofluoric	Severe burning, erosion ulcers, and blisters
Lactic	Ulcers (if strong solution)
Nitric	Severe burns and ulcers
Oxalic	Local caustic action on the skin
Sulfuric	Corrosive action on the skin and severe inflammation of the mucous membranes
Alkalis:	
Calcium cyanamide	Irritation and ulceration
Calcium oxide	Dermatitis, burns, and ulcers
Potassium hydroxide	Severe burning, persistent ulcers, and loss of fingernails
Sodium hydroxide	
Sodium silicate	Thickening of the skin and ulcers on the fingers
Sodium or potassium cyanide	Blisters and ulcers
Salts:	
Antimony and its compounds	Irritation and eczematous eruptions
Arsenic	Skin darkening, perforation of the nasal septum, eczema around the mouth and nose, and possible loss of nails or hair
Barium	Eczema and cyanosis of skin
Bromine	Brownish stains and skin eruptions
Chromium (hexavalent compounds)	Chrome holes on the skin, perforation of the nasal septum, and eczematous eruptions
Mercury compounds	Corrosion and irritation and mercurial eczema
Sodium	Burns and ulcers
Zinc chloride	Ulcers of the skin and nasal septum
Solvents:	
Acetone	Dry (defatted) skin
Benzene	Dry (defatted) skin
Carbon disulfide	Dry (defatted) skin
Chlorinated phenols	Severe eruptions
Petroleum distillates	Acne and epithelioma
Trichlorethylene	Dry, cracked skin
Turpentine	Red, blistered skin and eczema
Dyes:	
Chlorinated compounds	Blisterlike eruptions
Dinitrochlorobenzene	Blisterlike eruptions
Nitro and nitroso compounds	Red skin and eczematous eruptions
Phenyl hydrazine	Blisterlike skin eruptions
Insecticides:	
Chlorophenols	Red skin, and blisters
Creosote	Pustular eczema, warts, and epithelioma
Fluorides	Severe burns and dermatitis
Pyrethrum	Red skin, blisters, and pimples
Rotenone	Red skin and blisters
Resins:	
Coal tar, pitch, and asphalt	Acute dermatitis, acne, inflammation, epitheliomatous cancer, eczema, and ulcers
Synthetics, e.g., phenol-formaldehyde	Extremely red and itchy skin
Synthetic waxes, e.g., chloronaphthalenes and chlorodiphenyls	Dermatitis and acne

Exhibit A-8
Effects of Vibration on Human Performance
(From Woodson, 1981)

Vibration Conditions	Measures	Effect	Source
Biodynamic Mechanisms			
± 0.15 – 0.35 g , at 0.9–6.5 Hz, low amplitude	Whole body vertical vibration, hand tremor, body equilibrium, foot pressure	Foot pressure constancy impaired at 3.5 to 6.5 Hz, error increase with intensity; no residual effects	Schmitz, Simons, and Boettcher, 1960
$\pm ng$, $\pm ng$, for $\frac{1}{2}$ hr	Body sway equilibrium	No effects	Hornick, Boettcher, and Simons 1961
$\pm g$, 2–20 Hz (intensities = $\frac{1}{2}$ short-term tolerance limits)	Control of pitch and roll of a chair	Wide individual differences; decrement between 3 and 12 Hz, worst at 6 Hz	Coermann, Magd, and Lange, 1962
$\pm g$, at 0, 2, 5, and 8 Hz	Orientation (orienting body position to face targets at 15, 30, and 60° from reference plane)	Only small decrement in accuracy; mean error < 0.5°	Ayoub, c. 1969
± 0.03 – ± 0.41 g , at 0, 3, 5, and 8 Hz	Leg muscular power (on bicycle ergometer)	No effects	Harrison, 1969
Various peak-to-peak accelerations at 1 Hz with 3 Hz, and 2 Hz with 6 Hz	Arm-hand steadiness	Positional errors significantly related to rms and frequency of vibration; 90% of error was periodic; 1 Hz with 3-Hz combination produced larger error; small (0.5–1 g) differences in acceleration had no effect	Clarke et al., 1965
Psychomotor Performance			
-0.25 g , at 2.4–9.5 Hz	Time to pick up markers and place in small circular areas	Completion time worst at 3.4 and 4.8 Hz	Guignard and Irving, 1960
$+0.5$ rms g , at 2–30 Hz (13-Hz peak power)	Digital decimal input with push button, toggle switch, rotary switch, and thumbwheel controls	Accuracy unaffected; insert times increased by 4%; push buttons and toggle switches were most rapidly used, with the former preferred; thumbwheels were most accurate	Dean et al., 1967
0, 0.2, 0.4, 0.6, and 0.8 rms g , for 5 min	Same	No effects for 0.2 and 0.4 rms g ; significant increase in insert time for 0.6 and 0.8 rms g ; speed: push buttons > rotary switches > thumbwheels; error rate: push buttons highest and thumbwheels lowest for high intensity vibrations	Dean, Farrell, and Hitt, 1967
$\pm g$, and $\pm g$, at 0.33 and 0.80 Hz at amplitude of -6.3 and -7.0 in	Nut and bolt assembly and disassembly; placement of probe through various sized holes	No effects at 0.33 Hz; time required increased by 30% at 0.80 Hz with no increase in accuracy	Seeman and Williams, 1966
Speech Intelligibility			
$\pm g$, at 10, 20, 30, 40, and 50 Hz	Intelligibility	Most effect at 10 and 20 Hz	Nixon, 1962
0.5 g , sinusoidal at 6 Hz; 0.75 g , at 4 and 8 Hz; 1.0 g , at 2–20 Hz	Intelligibility and quality	No effect on intelligibility at 65 dB; "quality" poorer than control condition	Nixon and Sommer, 1963
Audition			
5-Hz sinusoidal, 5-Hz random amplitude, 4- to 12-Hz random frequency	Frequency (pitch) change (1200 for 1600 Hz) at 86-dB tones of 0.25-s duration every second—detection	No effect	Weisz, Goddard, and Allen 1965
$\pm g$,	1200 Hz at 86 dB presented every 0.25 s for 1 s against a 74-dB, 30- to 3000-Hz white noise; pitch change at 86 dB (1600 for 1200 Hz)—detection	No effect	Holland, 1966
$+1$ g , ± 0.7 g , at 15 Hz (amplitude 0.036 in) for 30 min	TTS determined as function of vibration and noise versus noise alone (acoustical frequencies from 250–6000 Hz)	Extremely small vibration effect at low tone frequencies only	Guignard and Coles, 1965
Higher Mental Processes			
± 0.15 – 0.35 g , at 2.5 and 3.5 Hz	Mental addition	No effect	Schmitz, Simons, and Boettcher, 1960
$+g$, at 5, 7, and 11 Hz	Pattern matching and discrimination	No effect	Buckhout, 1964
0.40 rms g , random vibration	Navigational tasks in simulated low-altitude, high-speed flight	No effect	Schohan, Rawson, and Soliday, 1965; Soliday and Schohan, 1965
No vibration, no noise, no vibration; noise only; vibration plus noise; postvibration $+4.0$ g , at 70 Hz	Continuous counting at a given rate	Decrement, especially during 5–7 min of exposure; residual effects noted; 70% of decrement attributed to vibration (30% to noise) Ss over 36 showed greater decrement	Ioseliani, 1967

*Symbol > here indicates faster than.

Exhibit A-9

Height/Weight Ranges of U.S. Males/Females (Caucasian) (From Van Cott & Kinkade, 1972)

Age (yr)	Male				Female			
	Height (in.)		Weight (lb)		Height (in.)		Weight (lb)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	29.7	1.1	23	3	29.3	1.0	21	3
2	34.5	1.2	28	3	34.1	1.2	27	3
3	37.8	1.3	32	3	37.5	1.4	31	4
4	40.8	1.9	37	5	40.6	1.6	36	5
5	43.7	2.0	42	5	43.8	1.7	41	5
6	46.1	2.1	47	6	45.7	1.9	45	5
7	48.2	2.2	54	7	47.9	2.0	50	7
8	50.4	2.3	60	8	50.3	2.2	58	11
9	52.8	2.4	66	8	52.1	2.3	64	11
10	54.5	2.5	73	10	54.6	2.5	72	14
11	56.8	2.6	82	11	57.1	2.6	82	18
12	58.3	2.9	87	12	59.6	2.7	93	18
13	60.7	3.2	99	13	61.4	2.6	102	18
14	63.6	3.2	113	15	62.8	2.5	112	19
15	66.3	3.1	128	16	63.4	2.4	117	20
16	67.7	2.8	137	16	63.9	2.2	120	21
17	68.3	2.6	143	19	64.1	2.2	122	19
18	68.5	2.6	149	20	64.1	2.3	123	17
19	68.6	2.6	153	21	64.1	2.3	124	17
20-24	68.7	2.6	158	23	64.0	2.4	125	19
25-29	68.7	2.6	163	24	63.7	2.5	127	21
30-34	68.5	2.6	165	25	63.6	2.4	130	24
35-39	68.4	2.6	166	25	63.4	2.4	136	25
40-49	68.0	2.6	167	25	63.2	2.4	142	27
50-59	67.3	2.6	165	25	62.8	2.4	148	28
60-69	66.8	2.4	162	24	62.2	2.4	146	28
70-79	66.5	2.2	157	24	61.8	2.2	144	27
80-89	66.1	2.2	151	24				

Exhibit A-10
Human Physical Strength and Endurance
(From Woodson, 1981)

Typical endurance time in relation to force requirements.

Exhibit A-11

Reaction Time Comparisons of Sensory Input Channels (From Woodson, 1981)

Note: Signals should not occur at rates faster than about two per second unless some means are provided for anticipating the signal. Avoid alerting periods shorter than 0.1 s.

Exhibit A-12

Effect of Number of Response Choices (From Woodson, 1981)

As one might expect, when the number of response choices increases, the reaction time is lengthened. The table below illustrates this point.

Number of Choices	Mean Reaction Time, s
1	0.20
2	0.35
3	0.40
4	0.45
5	0.50
6	0.55
7	0.60
8	0.60
9	0.65
10	0.65

Exhibit A-13

Representative Manual Entry Rates
(Adapted from Devoe, 1967)

Exhibit A-14

Sensory Channel Capacity for
Multidimensional Stimuli
(From Van Cott & Kinkade, 1972)

Stimulus dimension	Channel capacity (bits)	Discriminable categories	Investigator
Size, brightness, and hue (varied together).	4.1*	18	Eriksen (1954).
Frequency, intensity, rate of interruption, on-time fraction, total duration, and spatial location.	7.2	150	Pollack & Ficks (1954).
Colors of equal luminance.....	3.6	13	Halsey & Chapanis (1954).
Loudness and pitch.....	3.1	9	Pollack (1953).
Position of points in a square (no grid).	4.6	24	Klemmer & Frick (1953).

* Note: The capacity of each dimension separately was approximately 2.7 bits.

Exhibit A-15

Sensory Channel Capacity for Different
Unidimensional Stimuli
(From Van Cott & Kinkade, 1972)

Sense	Stimulus dimension	Channel capacity (bits)	Discriminable categories	Investigator
Vision	Dot position (in space)	3.25	10	Hake & Garner (1951).
	Dot position (in space)	3.2	10	Coonan & Klemmer (in Miller, 1956).
	Size of squares	2.2	5	Eriksen & Hake (1955).
	Dominant wavelength	3.1	9	Eriksen & Hake (1955).
	Luminance	2.3	5	Eriksen & Hake (1955).
	Area	2.6	6	Pollack (in Miller, 1956).
	Line length	2.6-3.0	7-8	Pollack (in Miller, 1956).
	Direction of line inclination	2.8-3.3	7-11	Pollack (in Miller, 1956).
	Line curvature	1.6-2.2	4-5	Pollack (in Miller, 1956).
Taste	Salt concentrations	1.9	4	Beebe-Center et al. (1955).
Audition	Intensity	2.3	5	Garner (1953).
	Pitch	2.5	7	Pollack (1952, 1953).
Vibration (on chest)	Intensity	2.0	4	Geldard (in Miller, 1956).
	Duration	2.3	5	Geldard (in Miller, 1956).
	Location	2.8	7	Geldard (in Miller, 1956).
Electrical shock (skin).	Intensity	1.7	3	Hawker (1960).
	Durations	1.8	3	Hawker & Warn (1961).

Exhibit A-16

Task Conditions Affecting Signal Detectability During Prolonged Vigilance (From Van Cott & Kinkade, 1972)

Improved probability of detection		
Simultaneous presentation of signals to dual channels.....		Buckner & McGrath (1963), Gruber (1964).
Men monitoring display in pairs; members of pairs permitted to speak with one another; 10 minutes rest each 30 minutes of work; random schedule inspection by supervisor.		Bergum & Lehr (1962).
Introduction of artificial signals during vigilance period to which a response is required.		Garvey, Taylor & Newlin (1959), Faulkner (1962).
Introduction of knowledge of results of artificial signals.....		Baker (1960).
Artificial signals identical to real signals.....		Wilkinson (1964).
Decreased probability of correct detections		
Introduction of artificial signals for which a response is not required.		Colquhoun (1961).
Excessive or impoverished task load on operator.....		Poulton (1960).
Introduction of a secondary display monitoring task.....		Jerison (1963), O'Hanlon & Schmidt (1964), Ware, Baker & Sheldon (1964), Wiener (1964).
Operator reports only signals of which he is sure.....		Broadbent & Gregory (1963).
Change in probability of detection with time		
A short pretest period followed by infrequently appearing signals during vigilance.	High initial probability of detection, falling off rapidly.	Colquhoun & Baddeley (1964).
Few pretest signals before vigilance period.	Reduces decrement in probability of detection with time.	Colquhoun & Baddeley (1964).
Prolonged continuous vigilance	Decreases probability of correct signal detection.	Mackworth & Taylor (1963).

Exhibit A-17

Relative Discrimination of Physical Intensities
(After Mowbray and Gebhard, 1958)

Sensation	Number discriminable
Brightness.....	570 discriminable intensities, white light.
Loudness.....	325 discriminable intensities, 2,000 Hz.
Vibration.....	15 discriminable amplitudes in chest region using broad contact vibrator with 0.05-0.5 mm amplitude limits.

Exhibit A-18

Relative Discrimination of Frequency
(After Mowbray and Gebhard, 1958)

Sensation	Number discriminable
Hues.....	128 discriminable hues at medium intensities.
White light.....	375 discriminable interruption rates between 1-45 interruptions/sec. at moderate intensities and duty cycle of 0.5.
Pure tones.....	1,800 discriminable tones between 20 Hz and 20,000 Hz at 60-dB loudness.
Interrupted white noise..	460 discriminable interruption rates between 1-45 interruptions/sec. at moderate intensities and duty cycle of 0.5.
Mechanical vibration....	180 discriminable frequencies between 1 and 320 Hz.

Exhibit A-19

Frequency-Sensitivity Ranges of the Senses (Adapted from Mowbray and Gebhard, 1958)

Stimulus	Lower Limit	Upper Limit
Color (hue).....	300 nm (300×10^{-9} m.).....	800 nm.
Interrupted white light.....	Unlimited.....	50 interruptions/sec. at moderate intensities and duty cycle of 0.5.
Pure tones.....	20 Hz.....	20,000 Hz.
Mechanical vibration.....	Unlimited.....	10,000 Hz at high intensities.

Exhibit A-20

Stimulation-Intensity Ranges of Man's Senses (Adapted from Mowbray and Gebhard, 1958)

Sensation	Smallest detectable (threshold)	Largest tolerable or practical
Sight.....	10^{-8} mL.....	10^{10} mL.
Hearing.....	2×10^{-4} dynes/cm ²	$< 10^8$ dynes/cm ² .
Mechanical vibration.....	25×10^{-3} mm average amplitude at the fingertip (Maximum sensitivity 200 Hz).	Varies with size and location of stimulator. Pain likely 40 dB above threshold.
Touch (pressure).....	Fingertips, 0.04 to 1.1 erg (One erg approx. kinetic energy of 1 mg dropped 1 cm.) "Pres- sure," 3 gm/mm ² .	Unknown.
Smell.....	Very sensitive for some sub- stances, e.g., 2×10^{-7} mg/m ³ of vanillin.	Unknown.
Taste.....	Very sensitive for some sub- stances, e.g., 4×10^{-5} molar concentration of quinine sulfate.	Unknown.
Temperature.....	15×10^{-3} gm-cal/cm ² /sec. for 3 sec. exposure of 200 cm ² skin.	22×10^{-3} gm-cal/cm ² /sec. for 3 sec. exposure of 200 cm ² skin.
Position and movement.....	0.2-0.7 deg. at 10 deg./min. for joint movement.	Unknown.
Acceleration.....	0.02 g for linear acceleration..... 0.08 g for linear deceleration..... 0.12 deg./sec ² rotational acceleration for oculogyral illusion (apparent motion or displacement of viewed object).	5 to 8 g positive; 3 to 4 g negative. Disorientation, confusion, vertigo, blackout, or redout.

INTERNAL DISTRIBUTION

1-2. Central Research Library	15. P. M. Haas
3. Document Reference Section	16. E. W. Hagen
4-5. Laboratory Records Department	17. R. A. Kisner
6. Laboratory Records, ORNL RC	18. A. L. Lotts
7. ORNL Patent Section	19. F. R. Mynatt
8. J. L. Anderson	20. L. C. Oakes
9-13. P. R. Frey	21. W. H. Sides, Jr.
14. A. M. Fullerton	22. D. B. Trauger

EXTERNAL DISTRIBUTION

- 23. Office of Assistant Manager for Energy Research and Development,
Department of Energy, Oak Ridge Operations Office, Oak Ridge, TN
37830
- 24. C. L. Hogan, Fairchild Camera and Instrument Corporation,
464 Ellis Street, Mountain View, CA 94040
- 25-39. J. P. Jenkins, U.S. Nuclear Regulatory Commission, Room 102,
Nicholson Lane Building, 5650 Nicholson Lane, Rockville, MD 20852
- 40. J. V. Leeds, Jr., Professional Engineer, 10807 Atwell, Houston, TX
77096
- 41. C. A. McKay, Executive Vice President, Corporate Director of
Technology, The Foxboro Company, 38 Neponset Avenue, Foxboro, MA
30205
- 42. O. R. Meyer, Idaho National Engineering Laboratory, Box 1625,
Willow Creek Building, Idaho Falls, ID 83415
- 43. B. M. Oliver, Vice President, Research and Development, Hewlett-
Packard Company, 1501 Page Mill Road, Palo Alto, CA 94304
- 44. H. P. Van Cott, BioTechnology, Inc., 3027 Rosemary Lane,
Falls Church, VA 22042
- 45. H. E. Price, BioTechnology, Inc., 3027 Rosemary Lane,
Falls Church, VA 22042
- 46. R. E. Maisano, BioTechnology, Inc., 3027 Rosemary Lane,
Falls Church, VA 22042
- 47-48. DOE Technical Information Center, Oak Ridge, TN 37830
- 49-459. Given distribution as shown in NRC Category RX (10 copies NTIS)

DO NOT
MICROFILM