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Ergonomic Considerations in Launch Vehicle Design and Processing for Operational Efficiency

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Abstract

Ergonomics is the science of fitting the environment and activities to the capabilities, dimensions, and needs of people. Ergonomic knowledge and principles are applied to adapt working conditions to the physical, psychological, and social nature of the person. There have been numerous launch operations studies performed concerning processing operations at the Kennedy Space Center (KSC). These studies have not, to a significant extent, considered ergonomic principles in launch vehicle design and processing as a means for achieving the goals of operational efficiency.

Many launch vehicle design and processing goals or objectives have been proposed to increase the operational efficiency of current systems, or to improve the operational efficiency of future systems over that experienced by current systems. Future proposed design or processing objectives may not take ergonomic principles and guidelines into consideration. A few of the launch vehicle design or processing objectives currently under consideration and their associated concerns, from an ergonomic aspect, are:

- Paperless work documentation system and health related concerns with visual display terminal (VDT) and personal computer (PC) use.
- Automated vehicle health management and built-in test equipment (BITE) causing troubles with human reliability and cognition associated with human-machine systems.
- Hazardous operations scheduled for third-shift and problems associated with night-worker health.

This examinational paper is intended to inform the reader on some of the ergonomic principles that should be considered in the design and processing of launch vehicles for operational efficiency.

Introduction

Ergonomics is the science of fitting the environment and activities to the capabilities, dimensions, and needs of people. Ergonomic knowledge and principles are applied to adapt working conditions to the physical, psychological, and social nature of the person. The goal of ergonomics is to improve performance while at the same time enhancing comfort, health, and safety. In particular, efficiency, comfort, health, and safety problems can be solved by applying ergonomic principles. However no simple recommendations can be followed that will enhance all of these aspects simultaneously. Compromise is necessary to achieve a set of balanced objectives while ensuring user health and safety. While no one set of rules can specify all the necessary combinations, the use of the proper principles and concepts can help in making the right choices [Smith, p. 1121]. Although the terms "ergonomics" and "human factors" are often used interchangeably, they have evolved to have different meanings. Human factors engineering focuses more on the information aspects whereas occupational ergonomics tends to focus more on the physical aspects of the work-effort.

There have been numerous launch operations studies performed concerning processing operations at the Kennedy Space Center (KSC) [Rockwell, etc.]. Some of the stated goals of these studies were to:

- support future launch vehicle design;
- promote "operability";
- reduce operations cost;
- eliminate launch delays;
- achieve routine access to space.

These studies have not, to a significant extent, considered ergonomic principles in launch vehicle design and processing as a means for achieving the above mentioned goals. This paper is intended to inform the reader on some of the ergonomic principles that should be considered in the design and processing of launch vehicles for operational efficiency. Proposed suggestions for improvement are made. A reference list is provided in order for the reader to undertake additional research into this topical area.

Problem Definition

Many launch vehicle design and processing goals or objectives have been proposed to increase the operational efficiency of current systems, or to improve the operational efficiency of future systems over that experienced by current systems. These proposed design or processing objectives may not take ergonomic principles and guidelines into consideration. A few of the concerns, from an ergonomic aspect, associated with some of the launch vehicle design or processing objectives currently under consideration are listed in Table 1.

Table 1. Concerns with launch vehicle design or processing objectives

Vehicle Design or Processing Objective	Concern with Objective
1. Paperless work documentation system	• Problems with visual display terminal (VDT) and personal computer (PC) use
2. Automated vehicle health management and built-in test equipment (BITE)	• Human reliability and cognition associated with human-machine systems
3. Hazardous operations scheduled for third-shift	• Problems associated with night-work

This examinational report presents current literature and research results comprising the objectives and related concerns listed in Table 1. Additional literature and information may be found in the reference list provided.

The Space Shuttle system has been the subject of many studies with the goal of improving operational efficiency. An example of a vehicle performance design versus improved operational efficiency trade consideration follows. Current Space Shuttle hypergolic propellant systems servicing is extremely hazardous and performed at three different facilities at KSC. These facilities are the Orbiter Processing Facility (OPF), the Hypergolic Maintenance Facility (HMF), and Launch Complex 39 (LC-39). The hypergolic propellant used by the Space Shuttle, nitrogen tetroxide (N_2O_4) and monomethylhydrazine (MMH), offers some significant advantages. Hypergolic propellants can be stored for long periods of time and can be used in relatively simple engines that may be started and stopped easily.

However N_2O_4 and MMH are also highly toxic and corrosive, giving rise to human health risks and other problems. Launch processing personnel must be protected by special suits from exposure to carcinogenic or corrosive materials. When propellant technicians work with these fluids, other launch personnel must evacuate the area. Propellant systems servicing in the OPF and at LC-39 must be scheduled with processing of other Space Shuttle systems. Serial processing time is incurred in any facility with hazardous operations.

Figure 1 shows a proposed concept for a future single-stage to orbit (SSTO) space vehicle. Less toxic propellants (or methods for reducing or eliminating serial processing for hazardous operations) are desired for future space transportation vehicles. Future space systems must have much greater "operability" over that experienced by current systems in order to significantly reduce the cost of space transportation.

Literature Search

In the wake of the expanding use of VDTs, including PCs, concerns have been expressed about their potential health effects. Complaints include excessive fatigue, eye strain and irritation, blurred vision, headaches, stress, and neck, back, arm, and muscle pain. Other concerns include general physical discomfort, cumulative trauma disorders (CTDs), and potential exposure to electromagnetic fields (EMFs). Research has shown that these symptoms can result from problems with the equipment, workstations, job design or environment, or from a combination of these [OSHA, p. 2]. Some of the most common stressors, their related health effects, and their means of prevention are discussed briefly in the section *What the Ergonomic Guidelines Suggest.*

Figure 1. Future space vehicle concept

The current trend toward automation is altering the nature of human involvement in the human-machine systems, shifting the human contribution more toward the operation and maintenance of machines. A considerable amount of time is spent by the operator in monitoring the system. Due to its very nature, automation has given humans a host of new problems with serious consequences. For example, with regard to monitoring, problems of maintaining vigilance can exist. The amount of cognitive information processing required of the operator has also vastly increased with the growing scale and complexity of the systems to be monitored [Park, p. 990].

Every human-machine system contains certain functions that must be performed by a human operator. Even the so-called fully automated systems need human interventions in monitoring and maintaining. If the variability in human performance is recognized as inevitable, then it is easy to understand that when humans are involved, errors will be made, regardless of the level of training, experience, or skill. As the human-machine systems are required to become more reliable, human influence becomes more and more important. The effort that is sometimes spent in designing ultra-reliable equipment is often negated by human error [Park, p. 990].

The human organism is in its ergotropic phase (i.e., geared to performance) in the daytime, and in its trophotropic phase (i.e., occupied with recuperation and replacement of energy) during the night. Hence the night-worker approaches his/her work, not in the mood for performance, but in the relaxed phase of the daily cycle. Herein lies the essential physiological and medical problem of night-work. Another aspect is the burden it puts on family life, and the social isolation [Grandjean, p. 217].

The various bodily functions of both man and animals fluctuate in a twenty-four (24) hour cycle, called the circadian rhythm. Even if the normal influences of day and night are excluded, (e.g., in the Arctic, or in a closed room with unchanging artificial light) a kind of internal clock comes into play, the so-called endogenous rhythm. This varies in different individuals, but usually operates a cycle of between twenty-two (22) and twenty-five (25) hours. Both mental and physical working capacity show a characteristic circadian rhythm. Psychophysiological readiness for work is at a maximum in the morning, and in the second half of the afternoon, whereas it is poor immediately after the midday break and declines even more at night [Grandjean, pp. 217 - 221].

Detailed analyses has shown the quality, as well as the duration, of daytime sleep is impaired, as evidenced by a greater number of light sleep periods and more body movements. Comparison between sleepers in noisy surroundings and in a soundproof room showed that the disturbance was not caused by noise, but was an integral feature of daytime sleep. All these studies show that sleep following a night-shift is curtailed and of little restorative value [Grandjean, p. 220].

Until a few years ago there was a simple line of demarcation between manual work, performed by operatives, and brain work which was the domain of white-collar workers. Nowadays this distinction is less clear. Some jobs call for a good deal of mental activity without really coming into the category of brain work, e.g., information processing, supervisory work, taking important decisions on one's own responsibility. Moreover, this sort of work is by no means restricted to white-collar workers but is often delegated to manual operatives [Grandjean, p. 143].

The emotional state (or mood) which results from a discrepancy between the level of demand and the person's ability to cope defines occupational stress. It is thus a subjective phenomenon and exists in people's recognition of their inability to cope with the demands of the work situation. A stressful situation is a negative emotional experience that can be associated with unpleasant feelings of anxiety, tension, depression, anger, fatigue, lack of vigor, and confusion [Grandjean, p. 176].

Current Research Example

One example of current research related to the second design objective listed in Table 1 appeared recently in a *Human Factors* journal article [Adelman et al.]. An enabling technology for attaining automated vehicle health management and BITE is real-time expert systems. These needed expert system applications must make extensive use of specialized knowledge concerning all of the launch vehicle's various systems to solve real-time problems at the level of a human expert (i.e., the system engineer). The expert systems associated with vehicle health management and BITE will be an integral production aid to future launch processing personnel.

In the experiment discussed in the *Human Factors* article, the investigators studied the effects of different real-time expert system interfaces on operators' cognitive processes and performance. The results supported the principle that a real-time expert system's interface should focus the operators' attention on where it is required most. However, following this principle resulted in unanticipated consequences. In particular it led to inferior performance for less critical yet important cases requiring the operator's attention. For such cases operators performed better with an interface that let them select where they wanted to focus their attention. Performance with different interfaces and rule generation capability was explained by the effect of the interfaces on cognitive process measures [Adelman, p. 243].

An increasing body of empirical research demonstrates that the design of information and decision technology can significantly affect operator's cognitive processes and, in turn, performance. For example, previous research has shown that color and various tabular and graphic display formats interact to affect information retrieval speed and accuracy; that graphic formats can affect the nature of information acquisition and evaluation processes, thus affecting performance; and that information displays can affect processing strategies and cause preference reversals. The experiment reported in the *Human Factors* article added to this growing body of empirical research by demonstrating that a real-time expert system's interface can significantly affect operator's cognitive processes and, in turn, task performance [Adelman, p. 243].

What the Ergonomic Guidelines Suggest

Visual problems such as eyestrain and irritation are among the most frequently reported complaints by VDT operators. These visual symptoms can result from improper lighting, glare from the screen, poor positioning of the screen itself, or hard-copy material that is difficult to read. These problems usually can be corrected by adjusting the physical and environmental setting where the VDT users work. For example, workstations and lighting can and should be arranged to avoid direct and reflected glare anywhere in the field of sight, from the display screen, or surrounding surfaces. VDT operators also can reduce eyestrain by taking vision breaks, which may include exercises to relax eye muscles, after each hour or so of operating a VDT.[1] Changing focus is another way to give eye muscles a chance to relax [OSHA, p. 2].

Work performed at VDTs may require sitting still for considerable time, and usually involves small frequent movements of the eyes, head, arms, and fingers. Retaining a fixed posture over long periods of time requires a significant static holding force, which causes fatigue. Proper workstation design is very important in eliminating these types of problems. Some variables of work station design include the VDT table, chair, and document holder. An individual workstation should provide the operator with a comfortable sitting position which is sufficiently

[1] The National Institute of Occupational Safety and Health (NIOSH) recommends a fifteen (15)-minute rest break after two (2) hours of continuous VDT work for operators under moderate visual stress; and a fifteen (15)-minute rest break after one (1) hour of continuous VDT work where there is a high visual demand or reptitive work tasks.

flexible to reach, use, and observe the display screen, keyboard, and document. Some general considerations to minimize fatigue include posture support (back, arms, legs, and feet) and adjustable display screens and keyboards. VDT tables or desks should be vertically adjustable to allow for operator adjustment of screen and keyboard. Proper chair height and support to the lower region of the back are critical factors in reducing fatigue and related musculoskeletal complaints. Document holders also allow the operator to position and view material without straining the eyes or neck, shoulder, and back muscles [OSHA, pp. 2 - 3].

VDT operators also are subject to a potential risk of developing various musculoskeletal and nerve disorders such as cumulative trauma, or repetitive motion, disorders. Carpal tunnel syndrome (CTS) is one commonly recognized cumulative trauma disorder among VDT operators. CTS is caused by repetitive wrist-hand movement and exertion. CTS is the compression and entrapment of the median nerve where it passes through the wrist into the hand -- in the carpal tunnel. When irritated the tendons and their sheaths, housed inside the narrow carpal tunnel, swell and press against the nearby median nerve. The pressure causes tingling, numbness, or severe pain in the wrist and hand. CTS usually can be reduced by stopping or limiting the activity that aggravates the tendons and median nerve (e.g., data/keyboard entry), by maintaining good posture, or as a last resort, by surgery [OSHA, pp. 3 - 4].

The "proper" sitting posture at VDT workstations, postulated in many brochures and standard works, is the upright trunk posture with elbows down, forearms almost horizontal, and feet flat on the floor. The actual posture most commonly observed at VDT workstations resembles the posture of a car driver. Orthopedic studies suggest that resting the back on a sloping backrest transfers a relevant portion of the trunk weight to the backrest and reduces the strain on discs and muscles more than it does when sitting straight and upright. It is therefore concluded that VDT operators instinctively do the right thing when they prefer a reclined sitting posture and ignore the recommended upright trunk position. From studies on preferred settings, the guidelines shown in Table 2 for the design of VDT workstations can be proposed [Grandjean, pp. 76 - 77].

Table 2. Guidelines for the design dimensions of a VDT workstation

Item to Locate	Metric Measurement	English Measurement
Keyboard height (floor to home row)	700 to 850 mm	27.5 to 33.5 inches
Screen center above floor	900 to 1150 mm	35.5 to 45.3 inches
Screen inclination to horizontal	88^{o} to 105^{o}	88^{o} to 105^{o}
Keyboard (home row) to table edge	100 to 260 mm	4.0 to 10.3 inches
Screen distance to table edge	500 to 750 mm	19.7 to 29.5 inches
Knee level distance between table edge and back wall	Greater than 600 mm	Greater than 23.6 inches
Foot level distance between table edge and back wall	Greater than 800 mm	Greater than 31.5 inches

Another issue of concern for the VDT operator is whether the emission of radiation, such as X-ray or EMFs in the radio-frequeney and extreme low frequency ranges, poses a health risk. Some workers, including pregnant women, are concerned that their health could be affected by EMFs emitted from VDTs. The threat from X-ray exposures is largely discounted because of the very low emission levels. The radio-frequency and extreme low frequency EMFs are still at issue despite the low emission levels. To date however, there is no conclusive evidence that the low levels of radiation emitted from VDTs pose a health risk to VDT operators. Some workplace designs have incorporated changes -- such as increasing the distance between the operator and the terminal and between workstations -- to reduce potential exposures to EMFs [OSHA, p. 4].

Traditional approaches to reducing human error (or increasing human reliability) relied heavily on personnel selection, placement, and training, supplemented by motivational campaigns. These approaches leave much to be desired as cost-effective techniques for human error prevention [Park, p. 1002].

The first step toward reducing human error is to identify its causes correctly. All too often, the operators are blamed for making errors, producing defects, and initiating accidents, when in fact the poorly designed work situation itself is error inducing. In an improvement approach, a human engineer, systems safety engineer, or similarly trained specialist examines the situation to identify error-likely conditions. When deficiencies are identified, the specialist can assess the impact on errors and recommend changes. An alternative approach to identifying situation-caused errors involves worker participation, such as quality control (QC) circles. When the work situation is satisfactory and the tasks are reasonable, but the operator still makes frequent errors, the poor performance may be due to individual factors such as inadequate skills, deficient vision, poor attitude, etc. Tasks involving highly skilled performance or decision making with considerable responsibility (and risk) usually require certification, which should be renewed regularly. In most cases human errors can be reduced to a low level using these techniques. However, if human error remains above the tolerable level, then impact of the error on the system must be reduced. In other words the system must be designed to be tolerant to human errors [Park, p. 1002].

An increasing sickness rate has been observed among 'active' as well as former night-shift-workers. Night-shift-workers often misuse drugs, taking stimulants during the night and sleeping tablets during the day. The reasons for their increased liability to nervous disorders and stomach and intestine ailments are primarily chronic fatigue and unhealthy eating habits. The dominant symptoms of chronic fatigue are: weariness, even after a sleep period, mental irritability, moods of depression, and general loss of vitality and disinclination to work. The state of chronic fatigue is accompanied by an increased liability to psychosomatic disorders, which in night-workers commonly take the form of: loss of appetite, sleep disturbance, digestive troubles, and stomach ulcers [Grandjean, p. 223].

The actual cause of occupational sickness among night-workers involves the circadian rhythm and the disturbances arising from changing from day-work to the night-shift. A conflict is generated in the body of the night-worker by 'desynchronization' of his/her timekeeping mechanism. The 'working' cycle is opposed to the 'light - dark' and 'social contact' cycles [Grandjean, pp. 223 - 224].

Night-shift-work is burdensome and often leads to ill-health which can rightly be classified as occupational. Night-work is therefore a danger to health. Since there is no way of planning shift-work that significantly reduces this occupational risk, night-work should only be used when completely unavoidable [Grandjean, p. 230].

Mental work load is conditioned by the following:

1. The obligation to maintain a high level of alertness over long periods.
2. The need to take decisions which involve heavy responsibility for the quality of the product and for the safety of work people and plant.
3. Occasional lowering of concentration by monotony.

Human information processing consists of combining new information with what is already known, so providing a basis for decision-taking. As a rule information received must be combined with knowledge already stored in the brain and committed to memory in a new form. Decisive factors include knowledge, experience, mental agility, and the ability to think up and formulate new ideas [Grandjean, pp. 143 - 144].

Research on occupational stressors has come up with the concept of the person - environment fit. The basic assumption is that the degree of fit between the characteristics of a person and the environment can determine the well-being and performance of workers. Environment is used here in its largest sense and includes the social as well as the physical environment. Surveys as well as theoretical considerations suggest that the following conditions may become stressors in work environments:

1. Job control -- the worker's participation in determining the work routine, including control over temporal aspects and supervising work processes; lack of control may produce emotional and physiological strain.
2. Social support -- assistance through supervisors and peers; lack of support increases the load of stressors.
3. Job distress or dissatisfaction -- mainly related to job content and workload.
4. Task and performance demands -- characterized by workloads, deadlines, and demands upon attention.
5. Job security -- refers mainly to the threat of unemployment. Many workers worry about being made redundant.
6. Responsibility -- the crucial question is whether the amount of responsibility exceeds one's resources.

7. Physical and environmental problems -- including noise, poor lighting, indoor climate, or small, enclosed offices.
8. Complexity -- the number of different demands involved in a job; too high complexity can arouse feelings of incompetence and lead to emotional strain.

The eight stressors mentioned above are those which are often taken into consideration by social scientists evaluating people's experience with occupational stress [Grandjean, pp. 176 - 177].

Proposed Improvements

The first step toward improving space vehicle "operability" from an ergonomics (and human factors) aspect is to charter a Human Engineering department in the organization(s) responsible for accomplishing vehicle processing activities. The Human Engineering department would have the responsibility to continually search for ergonomic or human factors improvements to space vehicle processing activities. The central focus of this department relates to considering human beings in the design of facilities and equipment used in space vehicle processing. The objectives of the Human Engineering department are to enhance the functional effectiveness of people processing space vehicles at KSC and to maintain or enhance certain desirable human values in the process (e.g., health, safety, and satisfaction). This department must be a contract requirement on all space vehicle processing contractors to ensure its actuality.

The Human Engineering group should be responsible for ensuring the ergonomic guidelines for design dimensions of VDT workstations shown in Table 2 are complied with. To assist in this end, all VDT workstation equipment and furniture procurement orders should be reviewed for ergonomic compatibility. This group should conduct workshops and training courses to educate employees on the ergonomic guidelines. The Human Engineers should perform VDT workstation audits to assess the need for additional employee education and training or for workstation design requirements revision.

Human Engineering department specialists would assist in examining vehicle processing facilities and equipment to identify error inducing situations. Worker participation in identifying and mitigating situation-caused errors is vital. The Human Engineering department should facilitate and oversee the worker involvement. The Human Engineering department must be involved in developing personnel selection procedures and in establishing frequent training and retraining to minimize problems associated with increased mental work and occupational stress. These responsibilities are necessary to provide the means for the best person - environment fit. The Human Engineers should continually assess the conditions that may become stressors in work environments and implement corrective action when necessary.

Due to the health risks involved with night work discussed above, third-shift work should be avoided if at all possible. Additionally, anecdotal evidence indicates that the third-shift at KSC is very inefficient. Much of the currently scheduled third-shift activities are for performing hazardous operations to avoid interference with innocuous first- and second-shift processing activities. Hazardous operations require at minimum a local area personnel clear, and at worst a facility clear, resulting in serial processing time. One way to avoid both third-shift work and interfering with innocuous processing activities would be to construct off-line processing facilities for performing hazardous operations in parallel to other vehicle processing operations. Another way to accomplish this objective would be to use less hazardous materials if possible. Hazardous operations causing serial processing must be eliminated or reduced to the maximum extent practical.

Research Horizon

Human information processing has dominated research activity in American experimental and cognitive psychology since the early 1960s. In most cases the theories written over the years equate human information processing with discrete stages models. In discrete stages models information is processed by the human through a sequential series of stages. Figure 2 illustrates the Wickens model of human information processing. In a discrete stages model such as this, stimuli are believed to be transformed as they pass through various stages of processing within the human (the boxes in the figure). These stages are conceived discrete, which means that a later stage cannot begin processing until a prior stage is completed [Eberts, pp. 949 - 950].

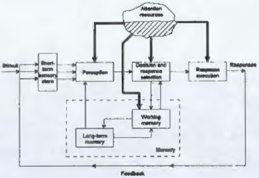

Figure 2. Discrete stages human information processing model

Recently in cognitive psychology, discrete stages models have been criticized and other models have been explored. The most promising of these alternative models are neural network models (also called connectionist models) in which information is assumed to be distributed and processed in parallel. Discrete stages models emphasize the structure of information processing whereas neural network models emphasize the process of information processing, particularly the dynamics and the learning aspects. The main advantage of the neural network approach to human information processing is that the processing occurs in parallel and is distributed. This solves many of the problems in using the serial computer analogy for human information processing. Another advantage is that these models are very good for pattern recognition. Solutions can be found based on partial information [Eberts, pp. 949 - 965].

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