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U.S. Coast Guard Research Project

Human Factors in Ship Design: Preventing and Reducing Shipboard Operator Fatigue

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Executive Summary

Human fatigue is alive and well in the marine industry. It has been the primary cause and a major contributing factor of numerous

maritime mishaps, such as EXXON VALDEZ and HERALD OF FREE ENTERPRISE. Unfortunately, ship design and construction guidelines, such as those published by class societies, do not adequately address this human element. The guidelines allow for harsh shipboard environments that are noisy, dimly lit, and have high levels of vibration. These conditions disrupt sleep, cause fatigue and intensify its effects. This report addresses shipboard operator fatigue and describes how it can be mitigated through engineering countermeasures in preliminary and post-production ship design.

Four major design areas are analyzed, including lighting, noise, vibration, and human-machine environments. This is precluded by a brief introduction to human fatigue that describes its effects and its causes. Each design area is than discussed and related to fatigue. Conclusions are written based on the findings of the research and recommendations are provided by the author.

There are a number of ways to combat shipboard operator fatigue; however, **this study only addresses the naval architecture and marine engineering design aspects.** Administrative issues, emotional stress, poor physical condition and drug/alcohol use will not be discussed in detail. The report describes factors that can be directly related to maritime operations and ship design characteristics such as living and working environments, physical/mental exertion, and disruption of sleep patterns and circadian rhythms.

Introduction

Human error resulting from fatigue-impaired performance has been identified as the cause of numerous transportation mishaps. Incorporating human factors into a ship's design can help combat fatigue, increase alertness, and decrease *human error.*

Human Error – Any deviation from a system performance standard which is caused indirectly or directly by an operator and which has significant consequences to the system operation in which it was made (Meister, 1985).

The study of engineering design and the use of human-machine environment systems is known as Human Factors Engineering (HFE). HFE discovers and applies information and research about human behavior, abilities, limitations, and other characteristics to the design of systems, devices, environments, and jobs for the productive, safe, effective, and comfortable use by humans.

Human Factors Engineering technology in ship design includes:

- techniques for defining the role of the human in complex systems
- simulation and modeling of crew workloads for manning reduction and assessment of operator/maintainer workloads
- advanced man-machine interfaces and decision aids to reduce human error and accidents, and enhance human performance and safety
- ship design methods and data, and
- techniques to enhance ship crew productivity thereby reducing manning requirements.

The following is a list of various names for Human Factors (Sind-Prunier, 1996):

- User-Centered Design;
- Engineering Psychology;
- Usability Engineering;
- Man-Machine Systems; and
- Human-System Integration.

The result of using HFE in ship design is a significant improvement in system reliability, operability, usability, maintainability, and safety. Of particular importance is the increased human reliability, which is a significant determiner of a system's overall reliability.

There are a number of factors that have been recognized concerning human factors and fatigue in the maritime industry. Dr. Paula Sind-Pruiner of United States Coast Guard Research and Development has listed just a few:

- When stressed, fatigued, overworked, etc., trained methods usually fail.
- Fatigue is alive and well in the maritime industry.
- There are competitive economic pressures to maximize vessel utilization.
- There are competitive economic pressures to minimize crew size.
- Failure to recognize the dangerous performance effects of fatigue
- Lack of knowledge concerning fatigue, and
- System lifecycle training costs often greatly exceed the incremental design costs.

This study will provide a detailed discussion on human fatigue and its affect on performance. Conclusions drawn from this research will provide specific guidelines that can be used by ship designers to help incorporate human elements into the design process.

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Background

Research was conducted under the supervision of Professor Thomas Lamb of the University of Michigan's Naval Architecture and Marine Engineering (NAME) Department. Articles and background research were done during the summer of 1998. Information was collected at the University of Michigan Media Union and on the Internet. Other information was gathered from discussions with Dr. Anita Rothblum of the Coast Guard Research and Development Center and Mr. William Sirois of Circadian Technologies, Inc. Coast Guard related issues in this field were discussed with LCDR Paul Szwed and LT Duane Boniface of USCG Headquarters. They provided specific direction and input that was particularly helpful.

The interpreting and compiling of this information continued into the fall semester. The formal development and plan of action was finished late in the fall term and was carried out through the winter term of 1999. Professor Lamb supervised the independent study project throughout this term. He approved the Plan of Action and Milestones and weekly meetings were held to discuss progress. There were also bi-monthly progress reports submitted to him that covered milestones, problems encountered and anticipated problems.

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1. Human Fatigue

Many factors affect a person's ability to be attentive and to remain alert. Stress, hunger, and boredom are a few examples. Frequently, one is affected by a combination of these factors, which impairs performance and can put lives and property in danger. One factor that has a significant impact on human performance is fatigue.

Fatigue drastically reduces human alertness levels and negatively affects job performance. Although fatigue is difficult to define, it can be generalized as "impaired alertness" (Sirois, 1998). Fatigue affects humans in different ways, although most people suffer from:

- decreased problem solving ability
- increased risk taking
- delayed reaction time
- moodiness
- inability to concentrate, and
- inattentiveness.

Logical reasoning and decision-making are affected by fatigue and it impairs human physical abilities such as strength, speed, coordination, and balance. Fatigue may result from:

- poor sleep quality
- sleep deprivation
- physical/mental exertion
- emotional stress
- disruption of circadian rhythms
- poor physical condition,
- and drug/alcohol use.

Everyone has felt the effects of fatigue. It is usually described as an uncontrollable urge to sleep or rest. It has also been described as a "fog" that comes over the brain at certain times of the day. Of importance is that **fatigue lowers alertness levels and impairs performance.**

Circadian Rhythms

The human body goes through a 24-hour cycle of biological processes. Examples include sleeping, waking, eating, changes in body temperature and altering hormone levels. This cycle is called the *circadian rhythm* and it is controlled by the human biological clock.

This natural rhythm of alertness is illustrated below in Figure 1 (Sirois, 1998):

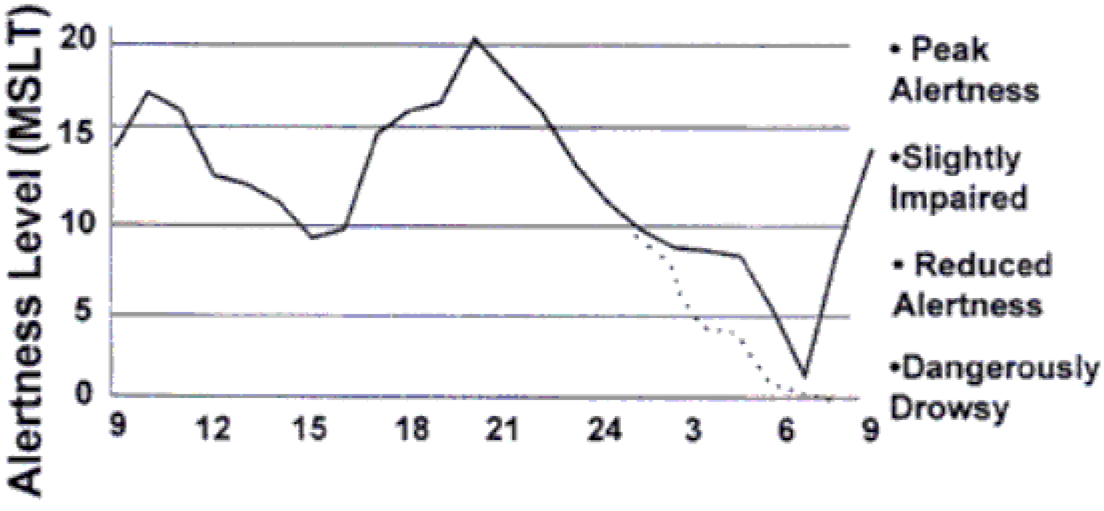

Figure 1 - Human Circadian Rhythm

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In 1955, studies were conducted on the daily performance of employees of a Swedish gas company. This gave researchers their first understanding of how the circadian rhythm affects human performance. Data showed that the majority of employee errors occurred at night, with the most noticeable peak between 1:00 a.m. and 3:00 a.m. A second peak was found between 1:00 p.m. and 3:00 p.m.

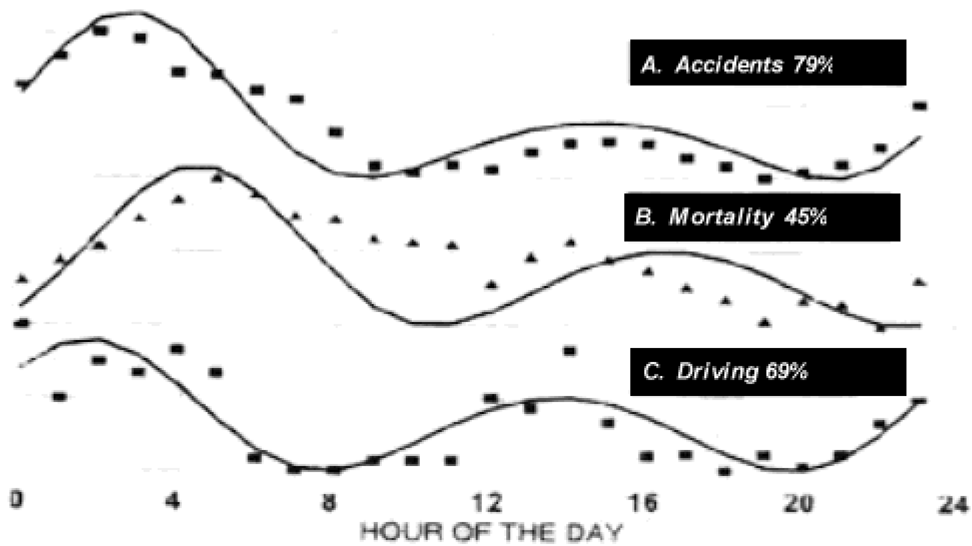

Figure 2 - Automobile Accident Rates at Time of Day

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Other human-error events have been documented and they have all shown similar. In the example below, data collected about automobile crashes resulting from fatigue were plotted. A two-peak pattern was evident and is similar to those in the Swedish study. The graph shows that the number of accidents is elevated between midnight and 6:00 a.m. and also between 1:00 and 4:00 p.m. These curves are shown in Figure 2.

Figure 3 (Sirois, 1998) is another depiction of fatigue-related car accident times and it shows a peak around 4 a.m., when there is very low traffic density.

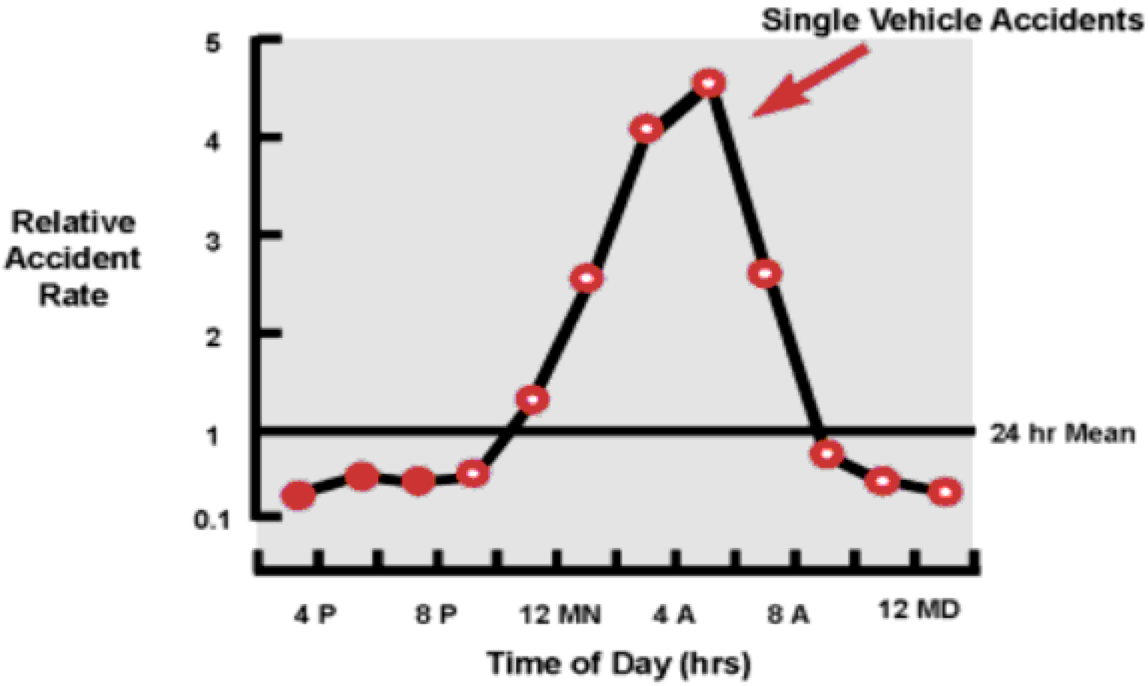

Figure 3 - Traffic Accidents and Time of Day

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The above curves have shapes and peaks that are similar to the circadian rhythm. The results of the Swedish gas company research, data collected about car crashes, and the analysis of other mishaps have all shown that the circadian rhythm has a significant impact on alertness levels and performance. However, other factors also affect alertness and performance. Two of these are (1) loss of the type of sleep needed to rejuvenate the body (restorative sleep) and (2) sleep deprivation, which is the complete lack of sleep for extended periods of time.

Sleep Issues
The need for sleep and its physiology are actively being researched. It has been determined that the human body requires "restorative sleep" in order to rejuvenate and be alert. Restorative sleep has four components:

Component	Description	Notes
1. Duration	Individual requirements are unique; minimum 7 - 8 hours in a 24-hour period.	Sleep loss effects are cumulative. See **Figures 4 and 5.**
2. Continuity	Sleep period must be uninterrupted.	Five stages of sleep; cycle throughout the sleep period. **See Table 2.**
3. Quality	Deep sleep/REM required for recuperation	Five stages of sleep. Each provides differing benefits.
4. Time of Day	Sleep during the day not as high quality as sleep during the night.	Circadian Rhythm is the driving factor. **See Figure 6**.

Table 1 - Components of Restorative Sleep

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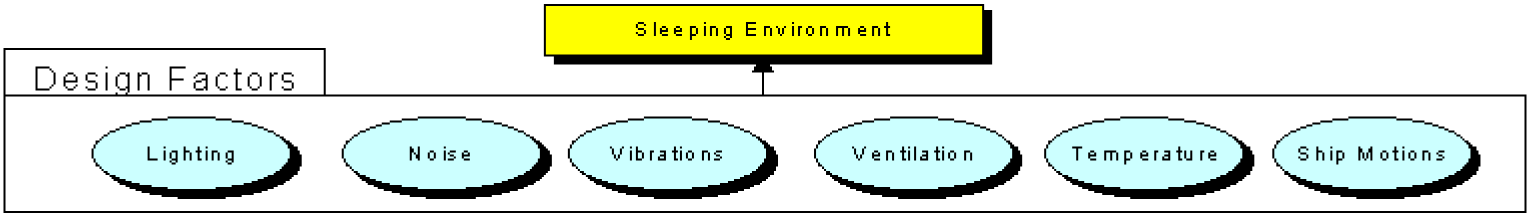
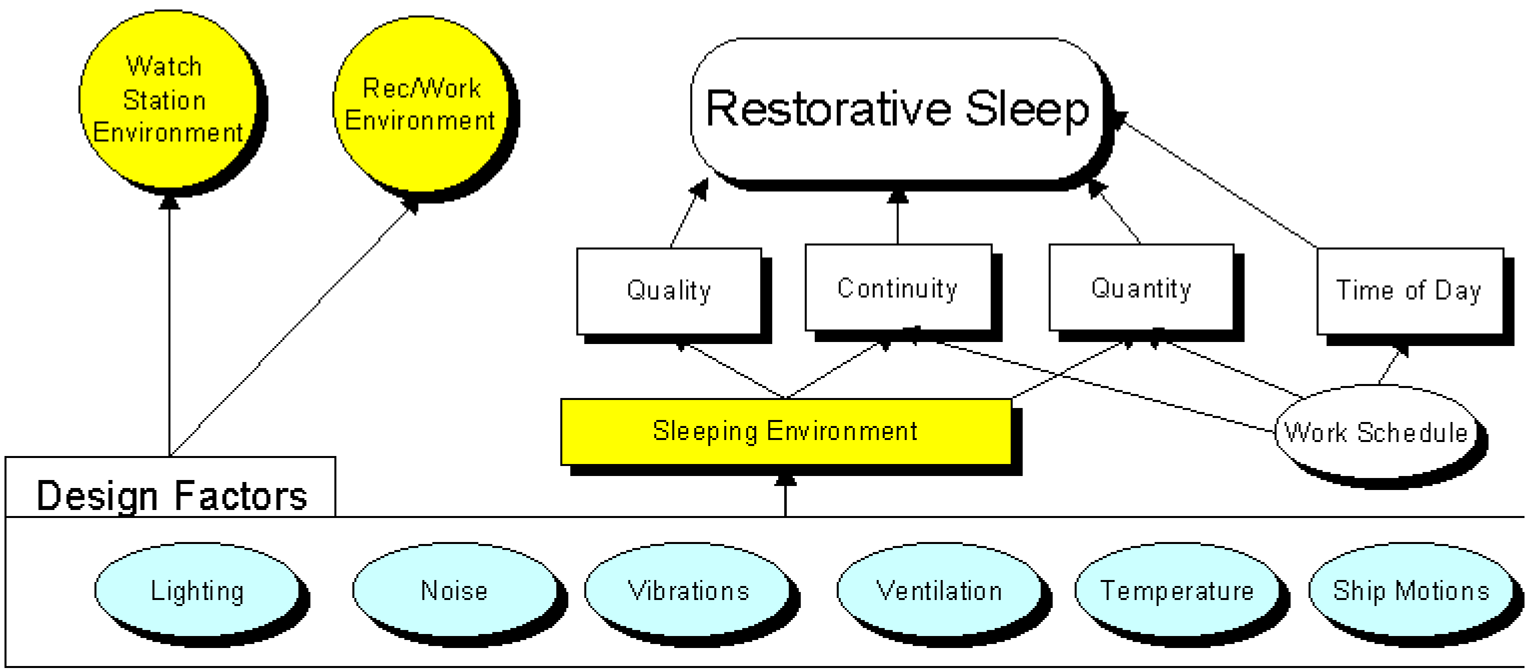
All the components are required in order for sleep to be restorative. The lack of any one of the components has a cumulative effect on a person's alertness level.



A proper sleeping environment is critical in ensuring that sleep is restorative. The design of the shipboard sleeping environment is directly controlled by naval architects and marine engineers. The six design factors that must be considered are illustrated below:

The sleeping environment determines a person's ability to get three of the four factors of restorative sleep, namely quality, continuity, and quantity. Quantity and time of day are impacted by work schedules and operational commitments. The design factors that create a good sleeping environment also impact the watch station, working, and recreational environments. These points are illustrated in the following diagram:



Sleep Duration
Individuals have different requirements for the hours of sleep needed to feel fresh and renewed the following morning. The vast majority of the human population requires seven to eight hours. Alertness levels as a function of sleep duration are shown below in Figure 4 (Sirois, 1998).

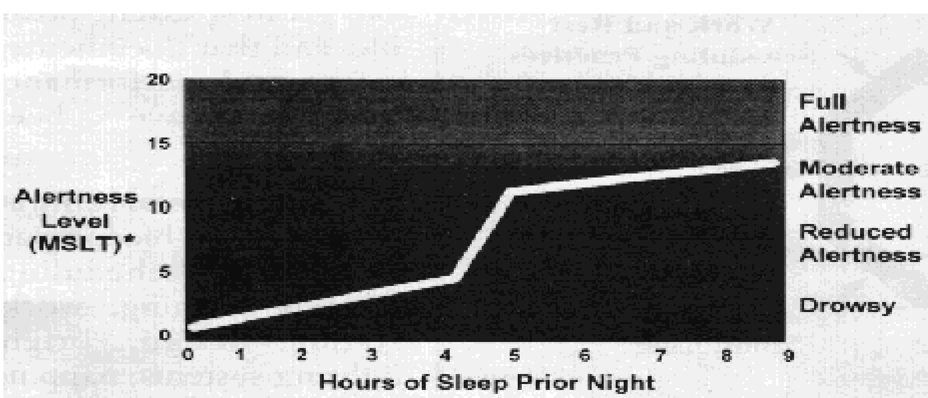


Figure 4 - Effects of Reduced Sleep on Alertness Levels

Note: In the above graph, the measure of alertness is the multiple sleep latency test (MSLT). This is a measure of how quickly a person falls asleep. An alert person takes the most time and a fatigued person takes less time.

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Any less than five hours sleep and the average person is found to be drowsy the next day. The graph also shows that the average person will likely not reach peak levels of alertness unless they have had eight or more hours of sleep. Unfortunately, most shipboard operators are not able to get this much sleep.

In a 1997 study called "A Survey of the Health, Stress, and Fatigue of Australian Seafarers," it was reported that almost 50% of Australian seafarers, while underway, only had four to six hours of sleep a night. The same is likely true of the US merchant fleet. Consecutive nights of short sleep duration results in the development of a cumulative sleep debt. This condition lowers initial energy levels and increases the effects of fatigue felt throughout the day. The effect on alertness from successive days of reduced sleep is shown in Figure 5 (Sirois, 1998).

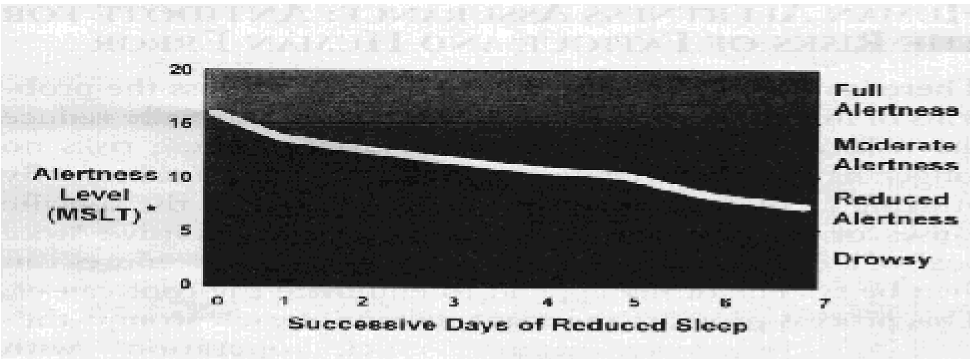

Figure 5 - Effect of Successive Days of Reduced Sleep on Alertness Levels

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Sleep Continuity and Quality

During a sleeping session, the human body cycles through different levels of sleep. These levels are known as sleep stages and each serves a different purpose for rejuvenating the body (the purpose of each stage is currently researched). This cyclical pattern of light sleep, deep sleep and rapid eye movement (REM) sleep is called sleep architecture. Table 2 lists and describes the five sleep stages.

Stage	Duration	Description	Effects	Notes
1. Transition	10 mins.	Phase between waking and sleeping	Asleep without knowing it	Microsleep and Automatic Behavior Syndrome (described later)
2. Light sleep	15 mins.	Light level of sleep	Feel briefly alert and refreshed	50% of all sleep is in this stage
3. Delta sleep	15-20 mins.	A deeper sleep		
4. Deep sleep	20-70 mins.	Deepest stage of sleep	Will feel groggy if awoken; occurs early in the night	Sleep Inertia (described later)
5. REM sleep	After 70-80 mins. of sleep	Dreaming state		

Table 2 - Stages of Sleep

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The entire cycle normally occurs in 90-minute periods, providing approximately four to five cycles in an 8-hour period. The proportions and duration of each stage are critical to the restorative quality of the cycle. Research has shown that **restorative sleep requires three to five uninterrupted sleep cycles.**

Experts currently believe that the third and fourth sleep stages are responsible for body restoration and REM for strengthening and organizing memory. The cycle continues throughout the sleep period, with each REM stage increasing in length. This is graphically depicted in Figure 6.

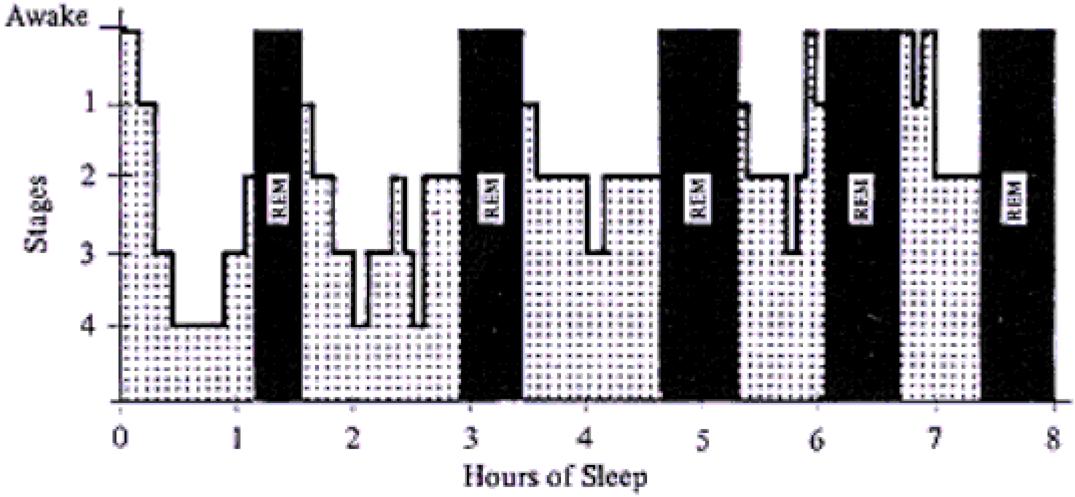

Figure 6 - Sleep Architecture

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Interruptions while sleeping, such as those caused by light, noise, and excessive vibration, tend to keep the body in the lighter stages (stage 2). This makes it difficult to transition to deeper sleep, thereby reducing the ability to get the important third, fourth, and fifth stages that are required for sleep to be restorative.

As shown in Figure 5, one day of reduced sleep is enough for a person to experience a decline in their alertness levels. The loss of sleep over a week's time causes dangerously low levels of alertness and this is when accidents are likely to occur. These same effects are felt by those who work late at night and through the early morning hours.

Irregular Schedules

Mariners who normally work during the daytime will show signs of reduced alertness when their schedule shifts and they work through the night. The resulting change to sleeping during the day will result in a sleep period that is not as restorative, since the body is naturally fighting to stay awake and be alert. Sleeping during the daytime also results in much shorter sessions of the required third and fourth stages and REM sleep. This leaves a person feeling fatigued and tired despite sleeping for six to eight hours.

The human body is just not intended to operate at night and sleep during the day.

The body can adjust to a change in schedule, but it takes a number of days to properly adjust. Problems occur when there is an abrupt shift or quickly changing schedule. A graphical depiction of why this is true is shown in Figure 7 (Sirois, 1998). The graph shows changes in body core temperature throughout the day, which directly relates to alertness. A drop in temperature naturally causes sleepiness.

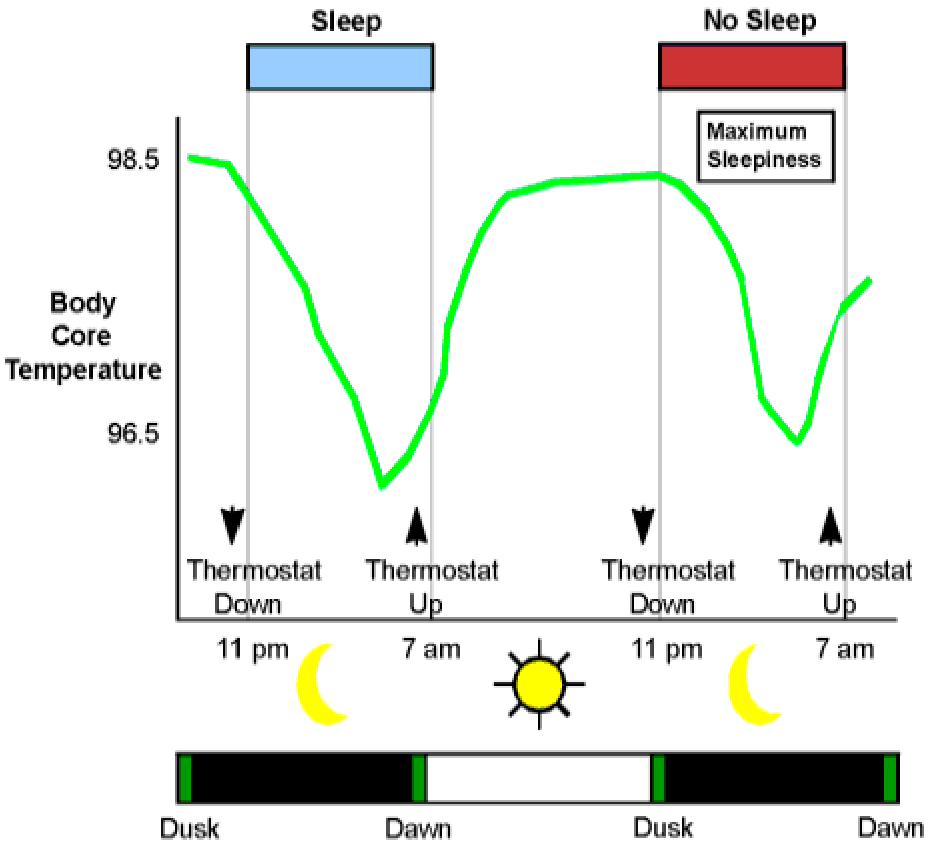

Figure 7 - Human Body Core Temperature Cycle

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The above figure shows what happens when there is a sudden shift in an operator's schedule. The operator was initially accustomed to sleeping at night and working during the day. The shift in the schedule required working at night. This shift put the body out of synch with its circadian rhythm and dangerously low levels of alertness settle in during the early morning hours.

Sleep Deprivation
Extended periods between sleep sessions deprive a person of the rest needed to remain alert. Sleep deprivation drastically reduces alertness levels after a person has been awake for more than fourteen hours. Figure 8 (Sirois, 1998) illustrates this point:

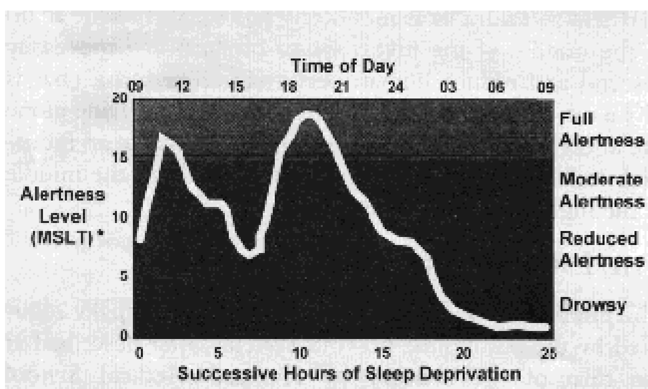

Figure 8 - Alertness Levels Over 24-Hours of Sustained Wakefulness

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Fatigue and Job Performance
Understanding why humans experience decreased levels of alertness is critical in combating fatigue. It is equally important to be aware of how this drop in alertness affects their performance. Individuals react differently to fatigue but there are common types of behavior exhibited by most. Four types that have been recognized are Automatic Behavior Syndrome, microsleep, sleep inertia, and chronic fatigue.

Automatic Behavior Syndrome is "sleeping with your eyes open." It usually occurs at night but also happens during the day when a person is fatigued. This type of behavior causes a person to go into a daze and greatly reduces their ability to recognize danger and deal with emergencies. Anyone who must remain stationary to perform a task that is not usually stimulating and does not require high levels of attention, such as the helmsman, most commonly exhibits this behavior.

Microsleep is the most dangerous and scary effect because the person actually falls asleep for short periods, as long as ten to fifteen seconds. When performing a dangerous task or monitoring safety critical evolutions, falling asleep for any amount of time can be fatal. Microsleep is what often causes car accidents and results in fatalities on dangerous job sites.

Sleep Inertia is that groggy feeling that is experienced for up to a half-hour after waking up. Managers and safety observers must be aware of sleep inertia and should act to prevent someone from performing tasks immediately after waking up. This is a very common problem because it always affects someone who just woke up, whether fatigued or not. Waking up from a deep sleep simply requires time in order to become oriented and to raise awareness.

The last side effect is **Chronic Fatigue**. This is the result of sleep deprivation and lack of restorative sleep. Behaviors exhibited by someone with chronic fatigue are tiredness, irritability, and mood swings.

Alertness Switches
Fatigue can be mitigated. "To consolidate and summarize a large body of research, the alertness of a person can be triggered by nine key internal and external factors which can be considered as the switches on the control panel of the mind." (Sirois, 1998) Dealing with fatigue then becomes a matter of understanding these switches and being able to activate them. The nine "switches" listed by Sirois are:

- Sense of Danger, Interest
- Time of Day
- Nutrition
- Environmental Sound
- Environmental Aroma
- Environmental Light
- Environmental Temperature
- Sleep Bank balance
- Muscular Activity

The environmental switches are relatively easy to control. The workplace should be cool and have adequate ventilation. During nighttime operations it has been shown that increased lighting helps someone stay alert (non-bridge watchstanders). The use of aromas and sounds, such as music, are having increasing success in combating fatigue. Some Japanese plants have found that using lemon scents greatly increase a worker’s alertness.

Other switches that can be controlled are interest, activity, and time of operations. The worker has to have a sense of interest in the work that they are performing. When a person loses interest, they start to lose the ability to stay focused. For example, night workers tend to have lower workloads and jobs are monotonous. Important meetings and work are normally done during the day, when more people are around and active. The result is a very mundane and less active schedule that causes fatigue and lack of attention.

The difficult switches to control are nutrition and sleep. Workers have very different ideas and most eat varying diets. When working at night, good nutrition seems hard to come by. Galleys are usually closed and meals are simply not normally consumed after midnight. Sleep is even harder to control. Although management can train and give workers recommendations about proper sleep, it is the individual’s responsibility.

Combating Shipboard Operator Fatigue
The nine switches of alertness provide excellent insight into measures that can be taken to prevent and reduce the effects of fatigue. They lead this research into areas of ship design where countermeasures can be included. Naval architects and marine engineers have direct control of these countermeasures. The following diagram lays out the determining factors of vigilance and shows areas where designers can have an impact:

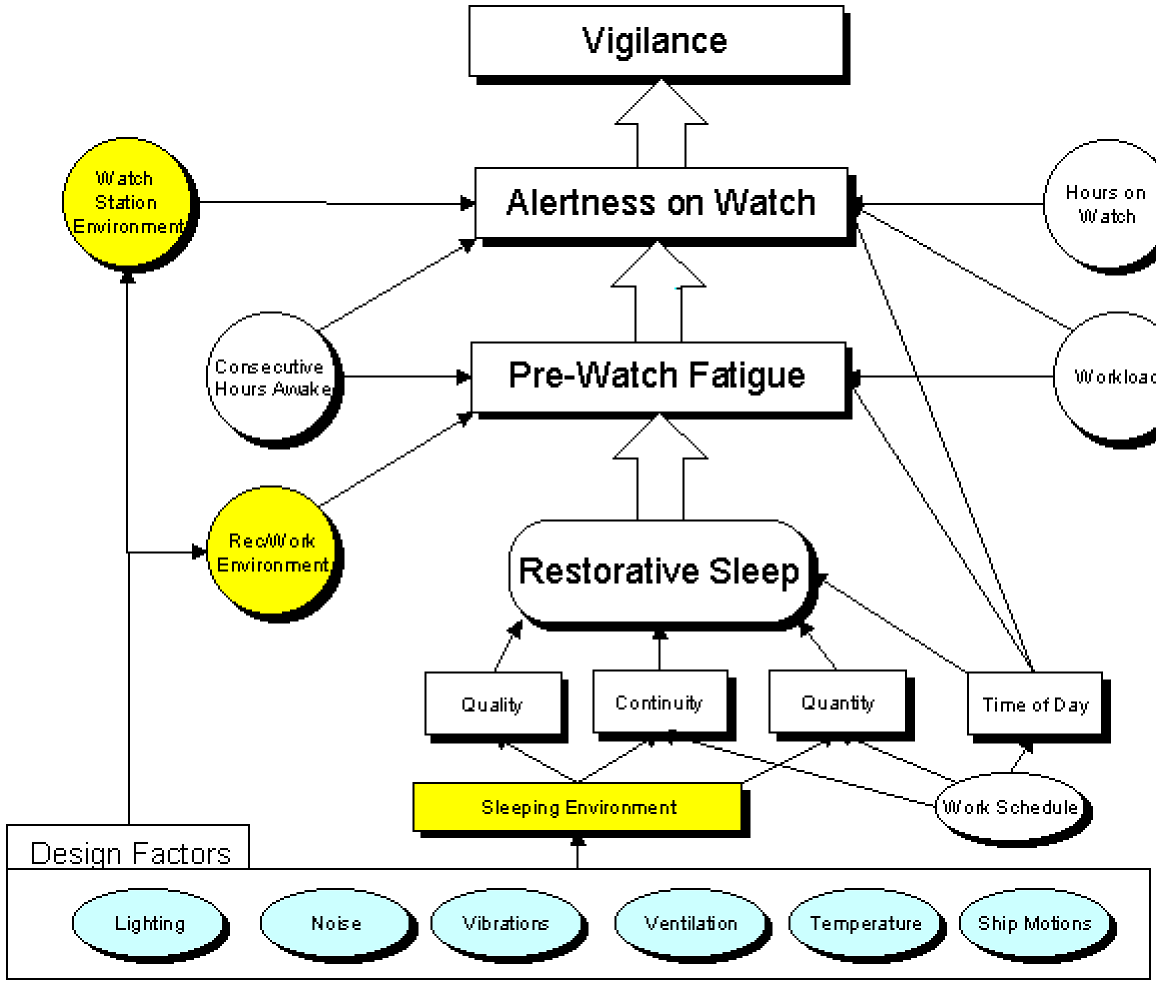

Figure 9 - Determining Factors of Vigilance

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The foundation of the diagram is the six design factors, all of which naval architects and marine engineer's can directly control. These factors determine how comfortable the working and sleeping environments are aboard a ship:

- lighting
- noise
- vibrations
- ventilation
- temperature, and
- ship motions

These all can be incorporated through the preliminary design of a vessel and maintained throughout ships post-production life.

Restorative sleep is the first requirement for vigilance. The diagram shows that the sleeping environment onboard a ship directly affects three of the four restorative sleep requirements. Time of day and quantity are primarily the responsibility of the individual and are affected by shipboard life. Despite this, the diagram shows that **there are six ship design factors that directly influence the ability of mariners to get restorative sleep.**

The design factors that create the sleeping and working environments onboard a ship also influence conditions experienced by watchstanders on the bridge and in the engine control station. These environments have an impact on the ability of a mariner to go on watch with minimal fatigue. Pre-watch fatigue is the second requirement of vigilance and involves minimization.

The level of alertness that a mariner has while standing watch is the function of the following:

- number of hours on watch
- workload
- consecutive hours awake, and

- watch station environment

As previously discussed, the watch station environment is a function of the same six design factors that create the sleeping, working, and recreational environments. At this point, it has been shown that the ship's design has a significant impact on the following:

- ability to get restorative sleep
- the amount of fatigue prior to watch, and
- the level of alertness while on watch.

These three conditions set the stage for vigilance and naval architects and marine engineers have the ability to control them.

The upcoming sections of this report will discuss the ship design factors in detail.

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2. Lighting

Light maintains the pace of the human biological clock, which directly regulates the circadian rhythm. The sun provides the amount of light needed to perform this regulation, even on cloudy days. The human body requires exposure to natural daylight in order to maintain a proper circadian cycle and for general health and well being. However, electrical sources of light have largely become the mainstay for crews aboard ships. Some members of a ship's crew spend the majority of their day within the confines of the vessel and below decks, where electric light is all that is available. This can create an irregular and shifting sleep cycle that leads to fatigue. The illumination levels onboard most ships are not enough to stimulate the body and help to maintain crew alertness.

Shipboard operators work in a 24-hour environment. Watch schedules frequently change and individuals work under incandescent or florescent lighting throughout the night. Unfortunately, the lighting that is typically installed aboard ships is not stimulating and fatigue settles in during the early morning hours.

Circadian Lighting Systems

Circadian lighting systems (CLS) have made it possible to alter the biological clock so that shift workers remain alert at night and get restorative sleep during the day. Although it may not be practical to shift a mariner's circadian rhythm, the high intensity that this system provides has been found to stimulate the body and lessen the effects of fatigue.

Circadian lighting systems come in many forms, ranging from a single set of lamps measuring two feet by three feet and up to the size of an entire control room. The system has a variable light output that can be manually controlled. There are also computer-controlled systems that have been developed. The computer-controlled systems keep track of each worker's shift schedules and can make changes accordingly. These systems have a high output that is normally in the range of 10,000 lux, which is more than 1,000 times greater than any level suggested by current class society and ASTM guidelines.

Research has shown that light has a greater effect on the human biological clock than once thought. The use of high intensity lighting to alter the circadian rhythm and increase alertness has been successful. Recent studies have shown that the illumination levels required to alter human biological clocks are much less than previously theorized. As much as a one-hour adjustment in the circadian rhythm, after just three days of five-hour exposures per day, has been accomplished.

An experimental installation of a CLS was recently done at a Connecticut nuclear plant. The night shift workers monitored the reactor cooling pool, a typically boring and uneventful task. Figure 10 (Internet) shows the CLS that was installed and some key findings listed:

Figure 10 - Nuclear Plant Control Room Using Circadian Lighting System (CLS)

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Key Findings of the Baseline Period Prior to Circadian Lighting System Installation

96% of the operators and shift managers reported to "struggle to stay awake" during the night shift.

One third of the operators and shift managers reported to have experienced a mistake or accident due to low alertness or fatigue.

100% of the operators and shift managers reported that fatigue or impaired alertness affected their ability to perform tasks in the control room efficiently on night shift.

Daytime sleep was reported to be less restorative and nearly one hour shorter when compared with off-shift sleep when working day or evening shift.

90% of the operators and shift managers reported that fatigue or impaired alertness affected their ability to commute home safely.

"What may pass for normal on midnight shift would be seen as impaired alertness on day or afternoon shift."
- Nuclear Plant Reactor Operator

Key Findings after Installation of Circadian Lighting System:

They are more alert while working the night shift, not struggling through the early morning "zombie zone."

They are better prepared mentally to react to developing situations in the control room.

They report increased productivity on night shift.

They consume less caffeine on night shift.

They feel safer and more alert on their commute home from night shift.

They sleep better and longer after working the night shift, waking feeling more refreshed.

Family relations have improved when working night shifts.

"I've been working night shift for 33 years and it has not been until now that I am able to make it through the night without struggling to maintain alertness."
- Shift Manager

"I am able to obtain a good, solid sleep during the day which I was never able to get before."
- Reactor Operator

"I am honestly impressed by the fact that my crew is not fighting fatigue."
- Shift Manager

"The benefits of the Circadian Lighting System for our operators exceeded our expectations." - Plant Manager

"This is the single greatest thing that management has ever done for the shiftworkers here at Connecticut Yankee."
- Shift Manager

Key Findings from Panel Operators
A total of eleven panel operators who worked the night shift in the control room under the Circadian Lighting System reported:

100% experienced enhanced alertness on the night shift.

100% experienced longer or better sleep after night work.

one operator reported shorter, but better sleep.

62.5% felt more alert on the commute home from night shift.

37.5% had no change in commute alertness.

100% adapted faster to night work.

67% had a positive family rating of the CLS.

33% report no difference.

100% had a positive impression of the CLS and support its future use.

The results obtained from installing the CLS are impressive. Using such a system has had a considerable impact on human performance and significantly increased the worker's alertness levels. The impaired performance experienced by these watchstanders before the CLS installation is similar to that of an engine room watchstanders on a ship. The same outcome would likely result if a CLS was installed in the engine room and control station of a ship.

Maritime Lighting Guidelines
Class society and ASTM guidelines for lighting provide recommended illumination levels for all the types of compartments on a ship. Illumination is the measure of light (luminance flux) falling on a surface. It is measured in lumen/m2, which equals one lux or 0.093 foot-candles (ft-c). Illumination decreases with the square of the distance from a point source. The following are a few examples of lighting intensities:

Typical Range Lux	Situation
100,000	Bright sunny day
10,000	Cloudy day
1000 to 2000	Watch repairman's bench
100 to 1000	Typical office setting
200 to 1000	Night sports field
1 to 10	Residential street lighting
0.25	Cloudy moonlight

Current design standards and guidelines on illumination levels in ship compartments are inadequate for maintaining watchstander alertness and do not mitigate fatigue. Illumination levels recommended in class society guidelines are based on **specific task performance** and compartmentation, not on human health and well being.

Table 3 is an excerpt from the American Bureau of Shipping (ABS) "Guidance Notes on the Application of Ergonomics to Marine Systems." It is an example of how illumination levels are applied to task performance and throughout areas of a vessel, without regard to fatigue and alertness.

Area or specific task	Recommended lux (ft-c)	Minimum lux (ft-c)

Control consoles (panels, switch boards, gauge boards)		
Front	540 (50)	325 (30)
Back	325 (30)	110 (10)
Control rooms (engine rooms, boiler rooms, generator, steering gear room, switchboard room)	540 (50)	220 (20)
Motor rooms (fan rooms, pump rooms, shaft alley)		110 (10)
Machine shops		
General	540 (50)	325 (30)
Bench work	1075 (100)	540 (50)
Corridors, passageway, stairways		
General	210 (20)	110 (10)
Shaft alley escape		32 (3)
Galley	755 (70)	540 (50)
Laundry		540 (50)
Medical spaces		
General	755 (70)	540 (50)
Examination area	1075 (100)	810 (75)
Offices		
Fine tasks (typing, book keeping)	755 (70)	540 (50)
Ordinary tasks (desk work, reading)	540 (50)	430 (40)
General office area	540 (50)	220 (20)
Storage	110 (10)	55 (5)

Table 3 - ABS Illumination Guidelines

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The link between natural sunlight and human well being has been established. Although artificial light will never fully replace natural sunlight, using full spectrum, high intensity lighting has been found to stimulate fatigued operators and help improve human performance by increasing alertness. Research has found that providing 1000 lux has a positive and stimulating affect on fatigued people.

The guidelines currently used by class societies are specifically task oriented, as shown above. The illumination levels required to shift circadian rhythms and have a stimulating effect on fatigued operators (~1000 lux) are greater than most of the values recommended by ABS.

Using CLS aboard ship is something that requires consideration by the ship design community and class societies. The systems are typically expensive but can be limited to use in areas such as the engine control room, berthing, and other frequently occupied areas. Mariners would also benefit in an overall increase in the illumination levels onboard ships. The higher intensity lights could be placed in passageways, recreation rooms, and the engine room.

Mariners would benefit from a shift in the focus of lighting guidelines, from task performance to human well being and mitigating fatigue. The use of CLS, which is designed with human well being and fatigue in mind, has been successfully tested and found to have a positive impact. Recent research has found the links between fatigue and lighting and taking the prescribed precautions, by increasing illumination levels onboard ships, will likely reduce the effects of fatigue caused by 24-hour operations.

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3. Noise

Noise can be defined as unwanted or undesirable sound. It is present in most compartments of a ship and it is difficult to avoid.

Noise comes from numerous sources including engines, generators, pumps, and air conditioners. There are many human physiological and physical impacts of noise in the workplace that cause fatigue and negatively impair human performance. Noise also affects sleep patterns and decreases the restorative quality of rest. Guidelines used to prescribe acceptable noise levels onboard ships are not designed with these factors in mind, but instead are established and used to prevent long-term hearing loss.

Long-term exposure to excessive noise can result in permanent hearing loss. The extent of the hearing damage is dependent upon noise intensity and frequency. Temporary loss of hearing is the result of short-term exposure to noise and can lead to permanent hearing loss. There are also physiological impacts of noise and these have not been adequately addressed in the guidelines used to establish acceptable noise levels. Although the physiological effects are less perceptible, they have a considerable impact on human performance and this makes them the most dangerous cause of noise induced fatigue.

The physiological changes that occur due to noise are the result of the natural "fight or flight" response of the human body. The body perceives all noise as a threat or warning of danger and continuously responds to it accordingly, even at low noise levels and while a person is asleep. Although it is understood that noise, such as from diesel engines, is not an actual sign of impending danger, the body continues to interpret it as such and physiological changes do occur.

Mariners working in a noisy environment tend to be moody, irritable, and unable to effectively deal with minor frustrations. Noise causes blood pressure to go up, increases heart and breathing rates, accelerates the metabolism, and a low-level muscular tension takes over the body ("fight or flight" effects). These are all things that lead to fatigue and they are not usually perceived by an operator. If the noise continues for long periods, the factors compound and it becomes harder to relax. The factors increase as the noise levels increase.

The physiological changes described above also occur when a person is asleep, affecting their ability to get restorative sleep and leading to fatigue. This issue will be discussed later.

Noise levels that cause the human body to respond in these ways vary with individuals. The Occupational Safety and Health Administration (OSHA) and numerous human factor design guidelines have prescribed values for intensities and exposure duration at which operators can safely be subjected to noise. The purpose of these guidelines is to protect the operator from permanent and short term hearing damage, not to prevent fatigue.

The sound levels and permissible duration exposure time per day given by OSHA are listed below and are a good generalization of standards used by the military:

Sound Level and Duration per day

Hours	Decibels [dB(A)]
8.0	90
6.0	92
4.0	95
3.0	97
2.0	100
1.0	105
0.5	110
0.25	115

The levels recommended by ABS in their "Guidance Notes on the Application of Ergonomics to Marine System" are shown below in Table 4:

Space	Maximum dB(A)	Preferred dB(A)
Work Spaces		
Machinery space (continuously manned)	90	85
Machinery space (not continuously manned)	110	95
Machinery control rooms	75	55

Workshops	85	70
Non-specified spaces	90	85
Navigation Spaces		
Navigation Bridge and chartroom	65	55
Listening post, including bridge wings and windows	70	60
Radio rooms	60	45
Radar rooms	65	55
Accommodation Spaces		
Cabins and hospitals	60	45
Mess rooms	65	55
Recreation rooms	65	50
Open recreation areas	75	65
Offices	65	55
Service Areas		
Galleys	75	65
Serveries and pantries	75	65
Normally unoccupied spaces		
Spaces not specified	90	85
* Table adapted from IMO Assembly Resolution A.486(XII)		

Table 4 - ABS Permissible Noise Levels*

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These figures are similar to the Lloyd's Register of Shipping's "Provisional Rules: Passenger and crew accommodation comfort", February 1999.

ABS and Lloyd's guidelines are acceptable for preventing hearing damage from high intensity noise, but they do not address the effects of long-term exposure to low intensity noise. Long-term exposure to noise keeps the human body in a constant state of agitation. This type of response occurs in the body even if the perceived noise is not consciously aggravating. Experts are still uncertain whether these responses build upon one another, leading to what is referred to as "diseases of adaptation."

Problems caused by this type of stress are listed below:

(a) Neuropsychological disturbances: headaches, fatigue, insomnia, irritability, neuroticism

(b) Cardiovascular system disturbances: hypertension, hypotension, cardiac disease

(c) Digestive disorders: ulcers, colitis

(d) Endocrine and biochemical disorders

(e) Sleep disturbance

Noise and Sleep
Noise affects sleep patterns, which greatly contributes to fatigue. It makes it difficult to fall asleep, can wake a person throughout the night, and pulls a person from deeper to lighter sleep stages. Nightly interruptions can get so frequent that a person may begin to forget that they were awoken and return to sleep very quickly. This pattern is particularly dangerous because the person is not getting enough deep sleep and will be drowsy the next day.

The noise levels at which sleep disturbances occur are low. Levels of 40 to 50 dBA (lower than a casual conversation) have caused difficulty in falling asleep and has extended the time of falling asleep to one hour. As the sound levels increase it becomes more difficult to fall asleep. Three other important findings are listed:

- 70 dBA is enough to significantly change the sleep patterns of most subjects.
- Long-term exposure to noise affects sleep.
- Short sound duration awakens more than long and steady noise.

The effect that noise has on sleep challenges designers of shipboard general arrangements. Finding the optimal location for sleeping quarters and crew recreation compartments is critical. Noise is an important factor and is not usually considered with fatigue in mind. An example of poor layout and design, which is familiar to the author, is the Coast Guard's 210' Medium Endurance Cutter (WMEC).

The Coast Guard's WMEC arrangement is a good example of designers not fully considering the human element. Three areas of the ship to analyze are the chief quarters, officer berthing and the engineering logistics office (ELO). The berthing compartments for chiefs and officers are located directly above major machinery spaces and adjacent to the engine room. These spaces are continuously noisy and experience high levels of vibration. There are frequent high intensity noises of short duration that occur as sewage is pumped and through the cycling of air conditioners. The compartments are also poorly lit. The ELO has the same problems and is a space where several of the crew spends hours working on computers and paperwork. These problems can be avoided in future designs as well as alleviated by reducing noise levels with insulation and soundproofing materials.

Noise Mechanics
Audible noise can be broken down into two categories: (1) airborne and (2) structure-borne. Airborne noise is what causes stress and hearing loss. Structure-borne noise induces vibrations that can damage machinery and marine structures. Both of these noise types vary in frequency and intensity. Examples of noise levels and their associated intensities are shown in Figure 11 (Internet):

Figure 11 - Noise Danger Chart

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The relation between frequency and intensity is shown in Figure 12 (Internet):

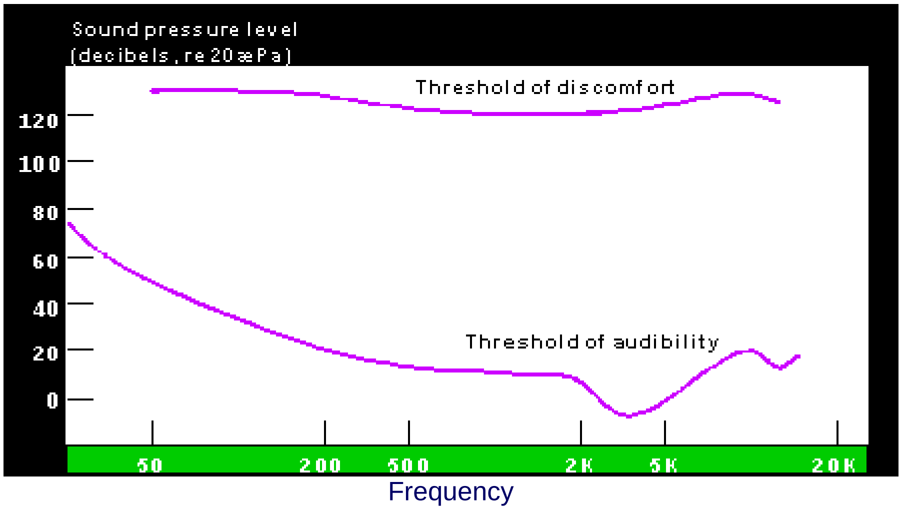

Figure 12 - The range of hearing (Stevens, 1951)

Noise Control
A ship designer must consider a number of different issues when designing to reduce and control noise. There are three locations where noise can be minimized and four basic methods of controlling it. These are listed below:

Locations for Noise Reduction	Examples
(1) The Source	Quieter equipment, good mufflers and exhaust systems
(2) The Path	Baffles, insulation, dampening tiles, noise curtains
(3) The Receiver	Soundproofing rooms, hearing protection

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Noise Control Methods:

- Isolation: Minimizes noise by reducing vibrations caused by machinery or equipment. Vibration-absorbing materials are used such as rubber mounts, pads, or springs. The type of material for an application is based on weight, vibration frequency, and desired degree of isolation.
- Barriers: Minimizes noise by blocking sound transmission through the use of high mass, resilient, or limp mass materials. Using more mass increases the effect and barriers work better at higher frequencies.
- Damping: Minimizes noise by adding mass to the vibrating structure or by connecting it to a surface that does not want to vibrate. Damping materials are selected by considering the thickness of the vibrating surface, the desired reduction, and the environment.
- Absorption: Minimizes noise with resonators and open-celled porous material, which converts sound energy to heat. Materials used are based on the noise frequency, desired reduction, and environment.

In most applications, the use of barriers is the most effective means of reducing airborne noise. In order for barriers to be effective designers must use the proper absorption materials. These materials can be heavy, expensive, and take up critical space. Despite this, specially enclosed workspaces can have as much as an eight to nine dBA reduction.

Vibration isolation is also an effective means of noise reduction. It can prevent both ship structure and human fatigue and prolongs machinery life. The damping of vibrating surfaces can reduce noise peaks and is very effective in reducing noise radiation from flat plane surfaces.

Although noise is an unavoidable issue in maritime operations, steps can be taken in the design stages of a ship to decrease noise effects. Post-production measures can also be taken to reduce noise levels. The current guidelines for noise exposure are acceptable for decreasing the chances of permanent hearing damage. They are inadequate for protection against the subtle physiological effects of long-term low intensity noise exposure that has been shown to cause fatigue and decrease alertness.

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4. Vibrations

Mariners experience shipboard vibrations caused by machinery, marine equipment and the ship's response to the environment. Vibrations resonate throughout the hull structure and the entire crew can be affected. The propagation of these vibrations along the decks and bulkheads subject the crew to whole body vibration and noise. Short-term exposure can lead to headaches, stress, and fatigue. Long-term exposure leads to hearing loss and causes constant body agitation. Maritime vibration guidelines keep levels low enough to prevent bodily injury but the recommended levels can cause fatigue and disrupt sleeping patterns.

The effects of whole body vibration are well studied and documented. Some of these effects are long term, such as musculoskeletal injuries, back disorders, and bone degeneration. These problems are can be avoided if designers follow the established vibration guidelines. An example of these guidelines is given at the end of this section.

Below is a list of common effects of whole body vibration.

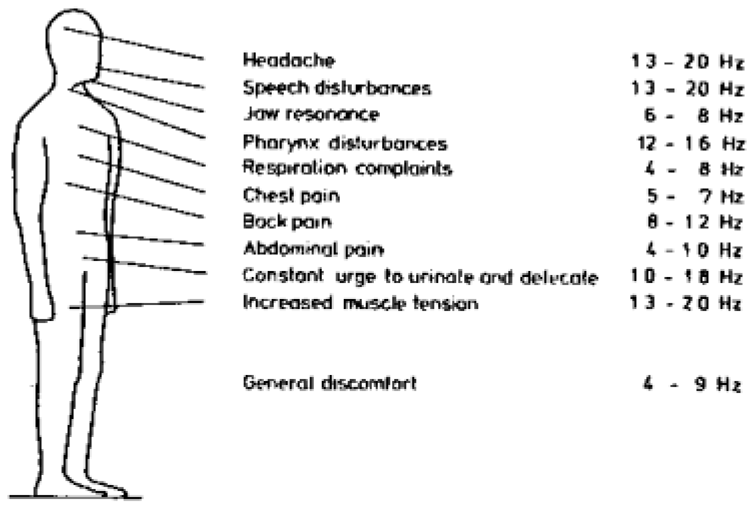

Figure 13 - Complaints in various organ regions in relation to stimulating vibration frequencies (Magid and Coermann, 1960)

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Physiological:

- Cardiac rhythm increases
- Respiration rhythm increases
- Blood circulation increases
- Vasoconstriction
- Endocrine secretions
- Central nervous system affected

Comfort and Performance:

- Pain
- Nausea
- Vision problems
- Posture
- Movement and coordination decline
- Force
- Perceptions altered

The above effects are sometimes imperceptible to the operator. They also occur at lower levels than those currently established by vibration guidelines.

Vibration Control

Vibrations created by engines, generators, and pumps can be reduced through damping and isolation. The methods used to reduce vibrations are similar to those used to reduce noise. Listed below are the three effective ways:

- Source Control
  - Reduce vibration intensity
  - Avoid resonance

- Path Control
  - Limit exposure time
  - Reduce vibration transmission (structural dampening)
  - Use vibration isolators

- Receiver Control
  - use vibration isolators
  - adapt posture
  - reduce contact area

Vibration noise, which is mechanical noise energy transmitted into the structure of a vessel, is best prevented through the isolation of the machinery from the hull. There are a number of ways to do this, including rubber padding and spring or rubber mounts. If the vibration energy cannot be isolated at the source than it should be dissipated along its path by using dampers.

Insulation is used to combat the airborne noise caused by vibrations and is designed to perform three functions:

- block noise from escaping the engine room
- absorb noise in the engine room
- dampen the vibration energy in the deck and overhead

Vibration noise can be reduced and contained by using high density and mass lead sheeting placed between two resilient materials. Acoustical foam or fiberglass can be used as a decoupler for the lead barrier, as well as being the absorption material.

Absorption is accomplished by dissipating noise energy as it passes through the outer layer of the insulation, to a core of lead, and is bounced back towards the noise source. Generally, lead core insulation is used on surfaces behind which people are located, and absorption-only material (no lead) is used on surfaces like hull sides, tanks, bulkheads against a fish hold, etc.

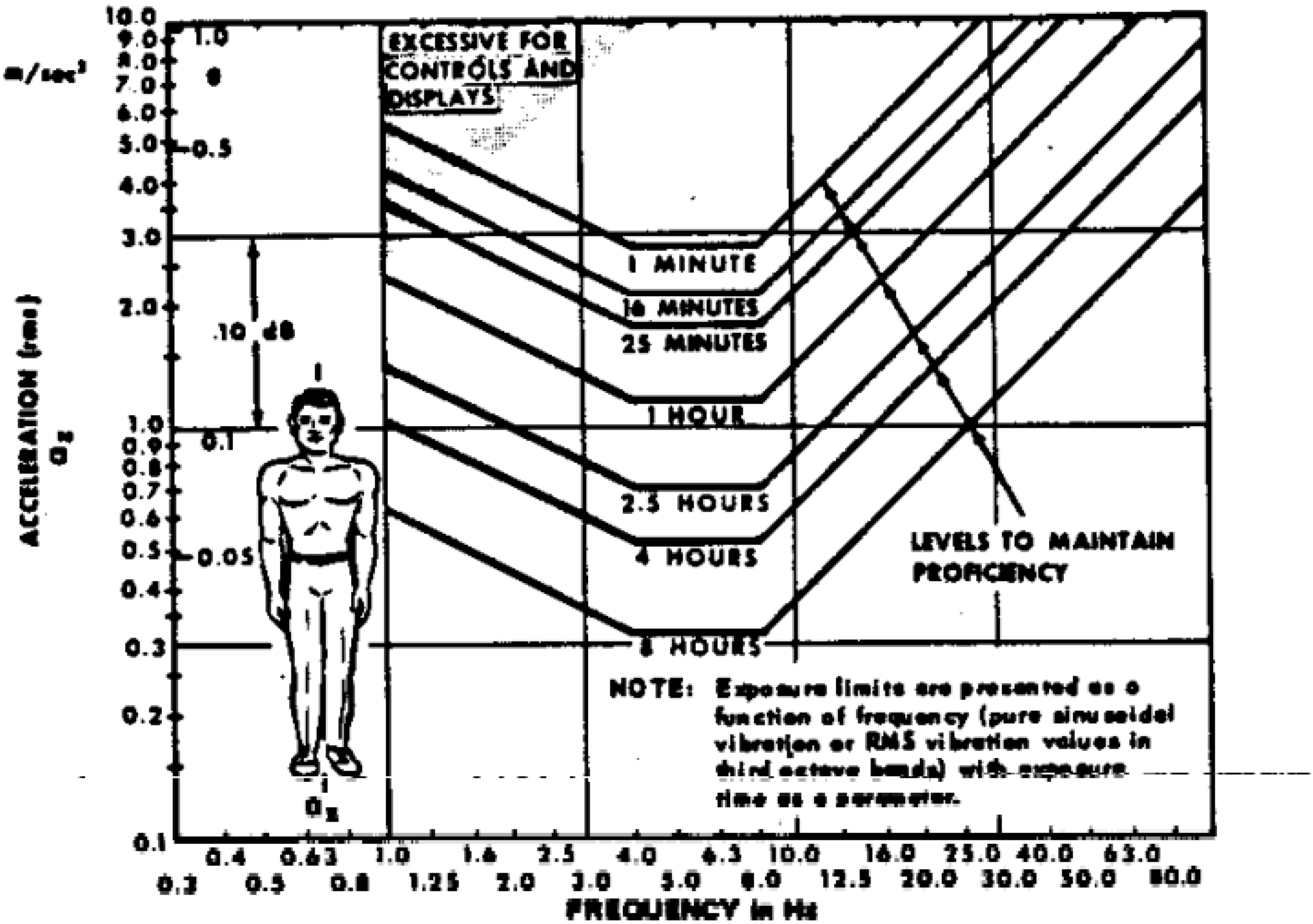
Outside of the engine room there are additional steps that can be taken to control vibration and noise. In smaller vessels the dry exhaust piping causes noise and radiates significant amounts of heat. High-temperature fiberglass insulation covered with an appropriate outside covering will minimize pipe and muffler shell vibration and noise.

One of the largest interior surfaces is the overhead, and its acoustical importance can be significant. There are large amounts of energy reflected in a vessel that has hard finished walls and overhead. An overhead that absorbs interior noise is superior to one that bounces it around. On the decks, carpets with acoustical underlayments absorb vibration energy and decrease noise from below.

Many procedures and materials can be used to keep vibration and noise levels under control in commercial vessels. It is important to understand what can be accomplished within a given vessel or with a particular problem. One solution will not apply to all of the problems, hence sound level and vibration reduction must be initiated with knowledge of the individual vessel and its owner's, operator's and designer's requirements clearly understood.

There are many things to consider when attempting to reduce vibrations and noise on a ship. Designers must consider the added weight and cost of suppression materials while realizing their benefit to the mariners. The development of future design guidelines will also need to consider these factors. The level of comfort provided by the current guidelines are sufficient but the recommended levels are high enough to aggravate or cause fatigue in human operators. Class society guidelines do not adequately address the human element and need to be reevaluated.

MIL-STD-1472C
2 May 1981



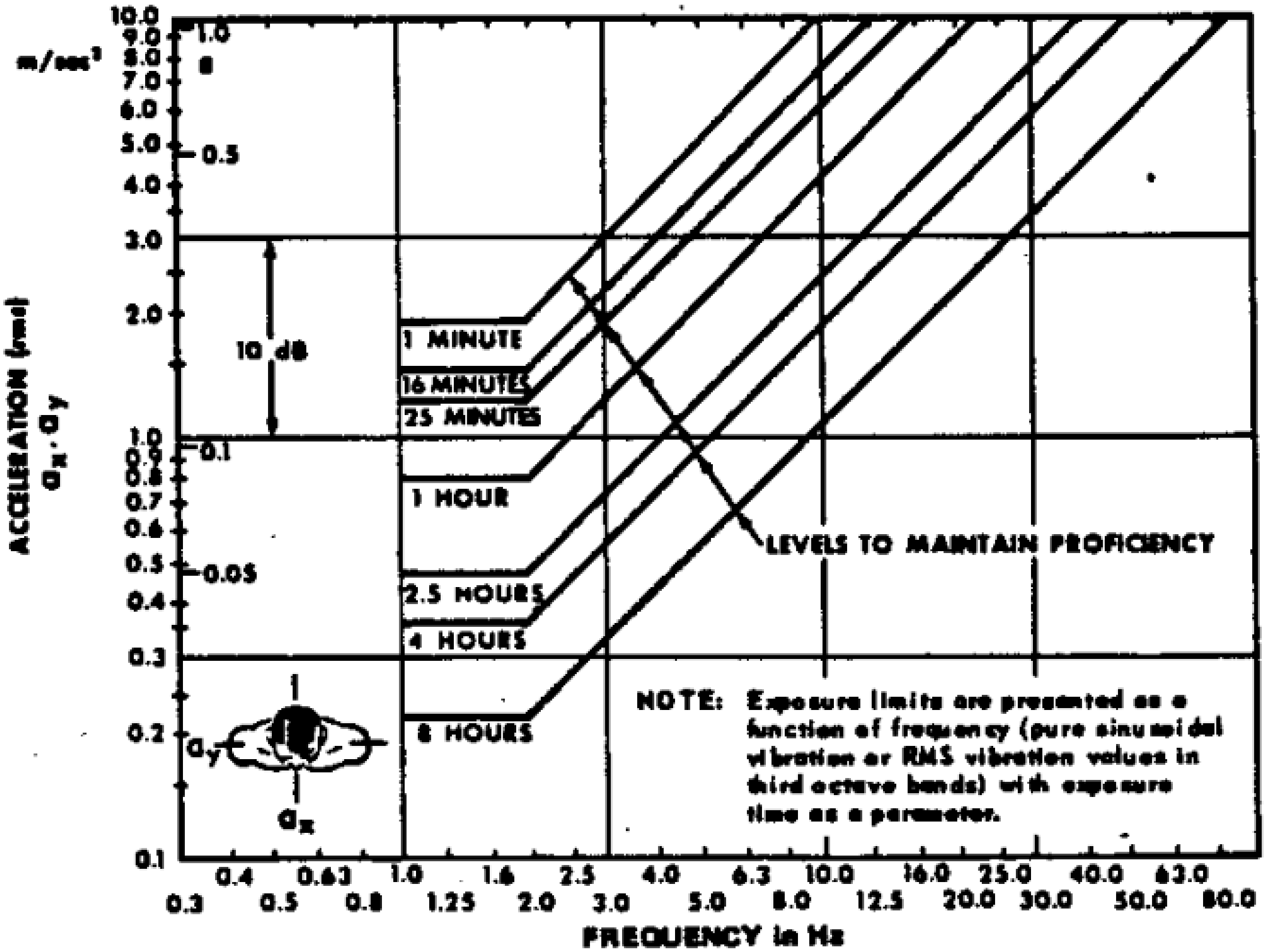


Figure 14 - Vibration Exposure Criteria for the Longitudinal (Upper Curve) and Transverse (Lower Curve) Directions with Respect to Body Axis

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5. Human-Machine Environments

Technology is advancing at an incredible rate. It is currently a necessity to use computer-controlled systems aboard ships in order to keep up with the improvements in marine equipment and machinery. Assigning functions to be performed by these computers and those to be completed by human operators is a highly debated topic and one that demands the attention of designers, operators, and technicians. Technology is being used onboard ships to reduce manning levels. This environment can over work the crew, causing fatigue and risking their lives and the ship.

Using automation and designing human-machine environments onboard ships poses a unique challenge for marine engineers. A ship is unlike any form of transportation. In many cases, a ship is underway thousands of miles from shore. This requires that the ship and its crew be a self-sufficient entity, able to deal with any number of possible accidents and emergencies. Using automation can reduce manning requirements but there is a point where the crew is just too small to remain alert, diligent, and able to safely operate the vessel. Determining the size of crew for a particular ship is a tough engineering problem, mainly due to economic pressures. Assigning computers to perform safety critical tasks does not come without failures and breakdown, which must be subsequently corrected by human operators.

Function allocation is defined as the assignment of required functions to instruments, computer/automated systems, and human operators. It can also be looked at as the assignment of human operators or systems to required functions. Each interpretation results in a similar outcome and both are equally critical factors in the design of human-machine systems

Assigning functions to available resources seems to be a rational and logical process, but this is currently being debated. There are a number of variables and considerations that must be taken into account when considering function allocation. This can make the process both rational and irrational, depending on the desired outcome. Examples of such factors include economics, manpower, technology, morale, motivation, fatigue, and monotony. There are also issues of considering what resource is best assigned to a task because humans and machines perform functions differently.

A human factors engineer by the name of Joseph Fitts devised a list of some of these tasks:

Humans surpass machines in:

- detecting visual, auditory, or chemical energy;
- perceiving patterns of light or sound;
- improvising and using flexible procedures;
- storing information for long periods and recalling appropriate parts;
- reasoning inductively;
- exercising judgment.
-

Machines surpass humans in:

- responding quickly to control signals;
- applying great force smoothly and precisely;
- storing information briefly and erasing information completely;
- reasoning deductively;
- performing repetitive and routine tasks;
- handling high complex operations.

This list has been described as controversial among experts who claim that it only compares the abilities of humans and machines and decides which is best for each function. Analyzing the list will prove that there are a number of combinations of functions that can be assigned to both humans and computers. How exactly to do this and defining a best practice for it is an engineering problem. Many solutions have been theorized but considering the number of variables and unforeseeable occurrences, it is unlikely that best practices will ever become clear. Consequently, there have been many accidents caused by improper allocation of resources.

A number of different approaches can be taken when confronting the problem of function allocation. Bent Schager (1998), a human factors engineer, has theorized one approach. He believes that no matter what the accident, logical steps led to its occurrence. Schager writes, "we must analyze both the technician's and the operator's roles in the chain of events as well as the compatibility between operators, technology and nature. The question is thus no longer whether a human factor is involved in an accident, but where in the chain of event the human factor is to be found."

Schager's theories take into account natural elements, mainly human abilities and weaknesses. He clearly states that factors such as fatigue, forgetfulness, stress, perception, and emotions are all a part of any human-machine environment. Applying this theory is the most applicable in any system where human safety and life are at stake. An important application is in the design of ship systems used for navigation or propulsion, since they directly affect the safety and well being of marine operators.

Two approaches can be taken in the design process of human-machine systems: (1) adapt humans to technology or (2) adapt technology to humans. Neither are as good as the following proposal, *optimize the adaptation of both humans and machines simultaneously.*

Human-Machine systems should be designed so that both the operator and the machine perform at an optimal level. This can only be accomplished when both the human operator and the machine have been analyzed and their strength and weaknesses are known. The human factors, such as fatigue, make it extremely difficult to come up with a foolproof design that can eliminate human error. Human-machine system and interface design is a challenge because (1) the environment in which these systems operate is dynamic and (2) both human and machines can be very unpredictable.

Fortunately, there are tools to help designers meet the challenge of constructing human-machine systems, such as safety system analysis and automation. Understanding how to use these tools can help designers to optimize shipboard systems.

The human operator should be perceived as an information processing system that gathers and interprets information in order to make decisions. The decisions and actions taken by an operator can therefore be related to the quality and correctness of the information given. Looking at it from this perspective requires designers to pay close attention to details such as information presentation, interface, and operator sensory perception.

There has been considerable research done on human-machine interface and working guidelines have been provided for information presentation, as well as in the use of switches and controls. Further considerations need to be given to other human factors, such as fatigue. The guidelines currently established for the "how, where, and why" of human-machine interface get pushed to their limits when confronted with a fatigued operator.

Fatigue and other human factor variables require special attention in the design of complex human–machine systems. The main goals of this type of system design is best stated as "the prevention of skill breakdown under threats from unplanned and uncontrollable aspects of the work environment, such as stress states or extreme levels of demands" (Hockey, Wastell, Sauer, 1998). One aspect of this approach has been to use automation to make life "easier." The idea that automation enhances safety and decreases human error seems to be a reasonable assumption, but is it actually a debatable topic.

The use of automation has become necessary in order to perform complicated tasks or to operate complex machinery. A major problem with this is that automation does not always work. Cott (1998) sites the following technology failure-related statistics (1971 to 1991):

- 10,227 **people killed** in 160 airplane crashes
- 2,046 in railroad accidents
- 6,998 in 22 ship disasters, and
- 5,353 in 24 industrial explosions

Cott also includes the over 231 million gallons of oil spilled into the oceans and industrial fires, all occurring in the same period.

The above events were all the result of shortfalls and failure in technology. These statistics raise many questions about the use of automation in safety critical operations. There are two schools of thought on this (1) pare down or limit the use of automation and (2) pursue even greater advances in the use of automation. This is another situation where finding a happy medium between the two may be the best answer.

Finding a workable level of automation in human-machine systems is not a simple task. The aviation industry has struggled with this problem for years. Advances in aviation have created planes that cannot fly without computer assistance and automation. The airline industry is also faced with operating larger planes and covering longer distances. The use of automation in this type of environment is a necessity that does not come without significant problems.

Earl Wiener (1998) cited the following example in a debate about the use of automation. It concerns an aircraft that had the ability to automatically balance the fuel in the left and right wing tanks. The system was able to sense a difference in fuel levels without input from the pilot and could automatically transfer fuel in order to balance weight. In theory, this is an excellent idea because it decreases the number of tasks to be performed by the pilots. The result in this example was a leak in one tank that caused the system to transfer all the fuel from the good tank. The pilots were completely unaware as the automated system performed its function and the result is apparent.

The above disaster provides an example of how quickly an innovation in fuel management automation can turn into a major catastrophe. It also provides a situation that can be analyzed in order to avoid such costly errors. Two ideas presented by Harold Blackman (1998), in the same automation debate, were related to this example. They are (1) *automation will reduce workloads* and *(2) automation will reduce human error.*

These two benefits of automation are also areas that cause a number of problems for human operators.

A reduction in workload is beneficial to the human operator in terms of task management but it tends to pull the operator "out of the loop." Using automation to monitor systems, such as in nuclear plant or industrial plants, eases the supervisory burden of such operators but can decrease the operator’s understanding of the systems status. In a high workload environment, operators can quickly lose control of a system if steps taken by automation are not readily displayed and understood. The automated system can quickly perform a number of tasks. This can leave the operator without a clear understanding of what happened in a systems transition or what is going to. System safety analysis tools, such as a fault tree analysis, and designing redundancy in the system are two approaches that should be taken in solving automation reliability problems.

The use of automation to decrease human error also contributes to the loss of an operator’s system status awareness. Computer controlled systems perform thousands of complex algorithms per second and their outcome may not always be apparent to the operator. The lack of understanding of the system status by the operator becomes a disadvantage in emergencies. When emergencies do occur, the operator may have little or no idea about what happened or where there was an error in the automation. The lack of information and understanding quickly puts the operator in a dangerous and sometimes hopeless situation.

Advanced automation often requires continual monitoring by human operators. Advanced technologies do fail and although their failure is a rare occurrence, the consequences of it can be high. Automation tends to lead to the use of unmanned systems, which can be inherently dangerous. Sheridan (1998) provides the following arguments as to why this type of automation is unacceptable:

- this type of automation is complex and therefore modes of failure are not always predictable;
- because automation gets smarter, human operators will have higher workload – especially sharper workload transients if

failure occurs – and therefore have more difficulty taking over control; and
- because for such systems, people will continually demand higher and higher performance and standards of safety.

Sherdian concludes by stating "insofar as human plus computer can do even marginally better than computer alone, people will continue to demand that a human be there." It is his opinion that there is no choice but to deem automation by itself as unacceptably safe for those circumstances where human lives are at stake.

G. Robert J. Hockey, David G. Wastell, and Jurgen Sauer (1998) performed a study to test the compensatory control model, which predicts human performance maintenance under stress at the expense of effort and increased selectivity. The study looked at the effects of sleep deprivation on human performance in an automated process control task. The automated system was a mock-up of a life support system for a spacecraft. The operator was responsible for overseeing and maintaining proper Oxygen and Nitrogen levels and cabin pressure. There were two types of operator control panel interfaces: machine centered (M-C), in which access to the system was scheduled by the computer, and human-centered (H-C), in which access was ad-lib. The operator was able to intervene and inspect the system when in H-C mode, but while in M-C mode could only take control when there was a problem.

The experiment listed the primary task as maintaining the three essential system variables within the prescribed range. Three secondary tasks were also given: (1) alarm acknowledgment, (2) tank level recording, and (3) maintain system failure log. It is clear to see that there are many similarities to this experimental environment and a maritime operational environment, for example, the operator had to maintain certain operating parameters with the machinery, take logs, and acknowledge alarms. There were a number of results of this experiment that can provide insight in to the use of the two types of interfaces.

A summary of the experiment's results are listed below:

- Under the unsupportive M-C interface, increased effort is directed mainly toward the protection of the primary task, resulting in greater decrement on the subsidiary task component
- Under the high level of support available for the H-C interface, increased effort might be effective in maintaining both the primary and secondary task components.
- Allowing more flexibility in the timing of monitoring and control actions, H-C might encourage the adoption of higher and more sustained levels of effort and more comprehensive performance protection.
- By contrast, the limited control possibilities of the M-C interface might mean that operators have to work harder simply to maintain primary task functions, while subsidiary tasks are relatively neglected.

There are a number of theories derived from these outcomes that can help explain why sleep deprived subjects operated better in the H-C environment. One is that active monitoring allows the operator to keep close track of what is happening to the system, which gives them better control over the long-term management of the system. Active monitoring may also result in a more effective response to emergent fault states. The overall maintenance strategy while sleep deprived (notably in the M-C mode) can be characterized as one of reactive control rather than preventative, which is normally associated with skill in process operators (Roth and Woods, 1988). Actions taken when faults occur in the M-C environment are usually made without the operator having a full understanding of what led to the problem.

The results of this experiment provide insight into the use of automation in maritime operations and the impact of fatigue. In the above example, it seems that fatigued operators had better success when they had more control over the system and were able to take a preventative approach to managing the system. In contrast, a reactionary approach gave operators less knowledge of plant status and they were not able to react successfully

The current economics of maritime operations has led the industry towards minimal manning. Technological advances have also led to major changes in the role of human operators, many of which remove the operator from the systems control. Some of these advances include automatic data logging, position fixing aids, restricted navigation aids, collision avoidance systems cargo planning aids, automatic route following, and maintenance diagnostic aids (Harding, 1975). In some cases, these types of automation have reduced crew sizes from 30 to 40 crewmembers, to 15 to21 (Lee and Sanquist, 1996). Automation has turned many mariners into system managers, responsible for coordinating and monitoring multiple automatic systems.

The use of automation on ships has had impacts on the deck department and engineering. Advances have been made in radar and progressed to radar enhanced with automated radar plotting aids (ARPA). Recently, electronic chart display information systems (ECDIS) are being used. Many countries are working on developing fully integrated bridges. The idea is to use multiple automated systems to produce a massive integration of navigation and ship control systems, possibly requiring the use of only one mariner on the bridge to acts as helmsman, lookout, and watch officer. Changes in the engine room have been no less dramatic.

The "old" system of engine room management generally consists of a wiper, water tender, an oiler, a fireman, and an engineer. Although the Coast Guard still uses this system, the merchant fleet desires to use minimal personnel in the engineering spaces. As of late, automation has enabled many engine rooms to go unmanned. The machinery and engine spaces are remotely monitored, allowing engineers to work there during the day and go "on call" during the night. This has significantly reduced costs in terms of manning but has greatly increased levels of stress among crew, especially captains. John Lee and Thomas Sanquist (1996) describe one ship's captain who said that having an unmanned engine room during voyages greatly increased his stress levels.

Using unmanned engine rooms aboard ships requires engineers to have a different skill base. Most of the knowledge previously required by engineer was machinery maintenance and operation. Unattended engine rooms require that an engineer have the ability to anticipate, identify and react to malfunctions, in order to maintain a reasonable level of reliability and safety. Most engineers currently require extensive training in how to operate the automation and perform troubleshooting. This is a much different and vast type of knowledge base than just basic diesel and generator operation.

The problems associated with fatigue and automation have been discussed. Lee and Sanquist (1996) have provided further examples of some of the problems associated with automation:

- Skill degradation.
- Inadequate feedback resulting in misunderstanding.
- Miscalibration in trust of automation, leading to misuse.
- Fewer physical demands but greater cognitive load.
- Enhanced workload peaks and troughs.
- Inadequate and misleading displays.
- Reduced opportunity for learning.

Many of the above examples are aggravated by fatigue. Automation typically leads to operators remaining stationary to oversee the operation of the plant. A fatigued operator can increase their alertness through physical activity, such as walking around and inspecting machinery, as well as reading gauges. The use of automation has eliminated the need to do this and has transferred the physical workload to the cognitive workload, which is most affected by fatigue.

Considering the information on human fatigue, human-machine interface, and automation, it is clear that these issues require further research. Ship designers and operators will continue to be confronted with innovations and advancing technology that may or may not make maritime vessel operation easier and safer. Being able to identify what types of automation are most useful and having the ability to design acceptable interfaces are important skills that designers must posses when looking towards the future.

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6. Incorporating Human Factors into Ship Design

Understanding the human factors in ship design and being able to incorporate them into the design process is a challenge. Recognizing the need to do so is also not an easy task. Other industries have been more decisive in using human factors in their engineering design process (railways, FAA, etc) and the maritime industry is now becoming more aware of the issues. As of yet, there is no best practice for using human factors engineering in the ship design discipline and more research is required before one can be properly developed.

The economic pressures felt by ship owners and the advances in technology in the maritime industry are significant. Innovation in ship design and improvements in marine equipment have given mariners the ability to reduce crew sizes and increase cargo capacity, but possibly at the expense of safety, crew comfort and system reliability. It is and will continue to be a battle between profit and safety as long as the marine industry focuses heavily on crew minimization and cargo maximization. Incorporating human elements into ship design will require the industry to take a step back and look at where they are and where they want to be.

There is the possibility of naivete on the part of designers and operators. Many designers and operators may believe that sticking to currently established regulations and guidelines is being "safe." Doing so is not necessarily a bad practice but looking at guidelines and using what information is currently available about human elements is a much better way of doing business. It is always important for designers and operators to keep on top of recent developments in maritime design and operation, but this is not always possible.

Naval Architects have access to numerous guidelines and regulations concerning human factors in ship design. These tend to be very broad in scope and address ergonomic issues. Although the current guidelines help to promote an environment that is relatively safe for humans, they are not sufficient to have a significant impact in the battle against fatigue.

Designers must be educated on the issues in human factors and use their skills to analyze and evaluate their design process, paying close attention to human aspects. Ship design requires paying attention to many factors, such as navigation systems and cargo transport. Failing to adequately consider the human element in ship design increases the risk of a casualty or marine disaster.

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7. Conclusions

(1) Naval architects and marine engineers have incorporated human factors into ship designs for many years. Unfortunately, ergonomic issues such as switch use and console design have been the predominate considerations. Designing a shipboard environment that (a) mitigates the effects of fatigue and (b) maintains or improves human alertness has not been seriously considered. Guidelines that read "should be designed to control vibrations to a level that will permit safe operation and maintenance" are not adequate to prevent or reduce operator fatigue.

(2) The marine industry is currently recognizing the need to address fatigue and human performance in shipboard operations. Ship design guidelines can be improved by incorporating the research done on sleep and fatigue by other industries, such as aviation, chemical, and railways. However, much of this research is new and only in the preliminary stages.

(3) The marine industry is faced with a number of issues that might impede the effective integration of the human element into ship design. Some of these are:

- economic pressures to maximize vessel utilization
- economic pressures to minimize crew sizes
- the need to move cargo farther and faster
- failure to recognize the impact of fatigue on human performance
- inadequate knowledge and understanding of fatigue and its causes

4) Economic factors curtail the marine industry's incentive to combat shipboard operator fatigue. In addition, current ship design standards and guidelines (class society, ASTM, etc.) do not effectively address the human elements of fatigue and alertness. The following are examples of these design factors: Lighting:

- Illumination levels, intensity, and color spectrum onboard today's ships are inadequate for stimulating a fatigued crew. Current guidelines recommend illumination levels that are much lower than what is needed to affect the circadian rhythm and maintain or improve alertness.
- Circadian Lighting Systems are extremely effective in preventing fatigue and increasing alertness. They are having positive impacts in other industries that perform 24-hour operations, but CLS is expensive. Fluorescent lighting is commonly used because it is cheap, easy to maintain, and provides the illumination levels suggested by the Code of Federal Regulations, military specifications, and guidelines established by class societies and ASTM.

Noise/Vibrations:

- Noise and vibration levels on ships are regulated, but the currently recommended levels affect a ship's crew and can cause fatigue. The existing guidelines only focus on noticeable conditions such as hearing loss, headaches, and nausea. The long-term low intensity noise and vibration exposure, which puts the human body in a constant state of aggravation and affects human sleep patterns, is not considered.
- Using advanced noise/vibration suppression methods drops noise levels below what is currently suggested or required by standards and guidelines. The required insulation and dampening materials add weight and are expensive. Therefore, there is no justification for using them.
- Human and Machine Environments:
  - The use of automation transfers physical loads to mental and cognitive loads, which suffer the most when a person is fatigued.
  - Physical activity, such as inspecting operating marine systems and reading gauges can help to stimulate a fatigued operator and increase their alertness. Automation has enabled watchstanders to monitor systems from a central location and decreased the need for roving the engine room.
  - Automation has put system operators into a supervisory role and this tends to take them "out of the loop." The result is operators being forced to take a reactive approach to emergencies, rather than a preventative one.
  - The use of a one-man bridge and an unmanned engine room is attractive to ship owners. This drastically reduces operating costs and increase cargo capacity.

(5) Many of the advances in technology aboard ships are used to decrease manning levels and decrease operating costs, not to increase safety and improve system reliability. The following question needs to be asked: "Does an increase in the use of automation, to such a point that ships transit from Point A to Point B automatically and engineering plants run without human supervision, increase overall safety and reliability of maritime operations?" The answer to this question is debatable, but current research leans towards NO.

(6) The need to remain profitable, not the human element, over-rides the philosophy behind ship design. For example, designers have been putting container ship deckhouses further aft than normal. Two reasons for this are (a) it increases cargo capacity and

(b) it enables shipyards to more easily add and remove machinery from engineering spaces. Unfortunately, this changes the ship motions felt by the crew. [The best ride on a ship is on the lowest deck, on the centerline, and amidships. Although ship motions were not addressed in depth by this paper, they do affect performance and cause fatigue. Placing deckhouses farther aft puts crew quarters and the bridge in a bad location for experiencing ship motions. The human element has again been overlooked or disregarded for the tradeoff of profit.]

(7) Defining a best practice for incorporating human factors into ship design is a long-term engineering problem. This problem is compounded by the quick advances and improvements in technology and increasing economic pressures. Increasing manning requirements and reducing the amount of automation used aboard ship, which may prevent over working crews and increasing safety, appears to be an illogical step in the backwards direction.

(8) Understanding and using human factors in ship design still requires research. Much of this research is only in the preliminary stages. There is no clear-cut path to the prevention of fatigue and the reduction of human error. It will take a large-scale effort on the part of the marine industry to recognize the impact of using human factors engineering in reducing fatigue, increasing performance, and decreasing human error. This is impeded by strong economic pressures and guidelines that do not address fatigue in ship design.

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8. Recommendations

- Expand research on shipboard operator fatigue to explore (a) how the shipboard environment affects crew fatigue, (b) effects of fatigue on the performance of maritime operations, (c) other measures that prevent and mitigate fatigue, e.g. alternative watchstanding, and (d) "best practices" for incorporating the human element into ship design.
- Analyze common shipboard environments, e.g. container, LNG, towing, cargo ships, and perform a cost benefit analysis on preliminary and post-production design measures that can be considered to (a) improve crew and operational safety, (b) prevent and mitigate fatigue, and (c) increase human alertness and performance. The analysis should look at improving lighting, decreasing noise, reducing vibrations, ensuring adequate ventilation, and improving other environmental factors.
- Develop SNAME guidance on ship design factors that affect crew fatigue and engineering countermeasures that can be applied in a ship's preliminary and post-production design. Target NAME undergraduate and graduate students by incorporating human factors, specifically shipboard operator fatigue and alertness, into existing academic curriculums.
- Continue to address fatigue at IMO and further the effort by introducing current and past research on sleep and the impact of shipboard environmental factors (lighting, noise, vibrations, etc.) on crew fatigue.
- Develop class society guidelines for the design of shipboard working, recreational, and sleeping environments, specifically addressing environmental factors, such as lighting, noise, and vibration, and their impact on fatigue. For example:
  - Increase illumination levels aboard ships. Use minimum of 1000 lux for engineering spaces, crew berthing, recreational areas, and other compartments that are normally occupied by a ship's crew. This includes the bridge during daytime operations. Use 10,000 lux circadian lighting systems in the engine control room and in office spaces.
  - Decrease existing noise level guidelines by 10% or more. Decrease overall shipboard noise levels as much as possible. Target noise critical areas, such as berthing, recreational, workspaces, and watch stations, to concentrate the effect of noise reductions. (Acceptable levels for individual spaces can be determined through a cost-benefit analysis that looks at specific noise-reduction measures and their impacts on the ship's compartments.)
  - Decrease vibration levels by increasing the use vibration-reduction measures. Specifically, isolate machinery from the hull structure and dampen resulting vibrations as much as feasible.
- Conduct studies on the use of automation onboard ships and develop a best practice for its use in the marine industry. Use this research to educate mariners, owners, and designers on the advantages and disadvantages of the increased use of automation in maritime operations.
- Ensure that the research conducted on fatigue and human performance by other industries, such as aviation, highways, and railways, is considered in current and future research on fatigue in maritime operations.

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9. References

Blackman, H. S. & Sheridan, T. B. & Van Cott, H. P. & Wickens, C. D. (October 1998). Smart Automation Enhances Safety: A Motion for Debate. *Ergonomics in Design*. (pp.19-23).

Hancock, P.A. (July 1998). Allocating Functions Rationally. *Ergonomics in Design*. (pp. 20-29).

Hancock, P.A. & Scallen, S.F. (October 1996). The Future of Function Allocation. *Ergonomics in Design*. (pp. 24-29)

Hajarnavis, Hitesh R. & Stein, Martin. *Fatigue at Sea*. Cambridge, Massachusetts: Circadian T