An Overview of the Scientific Literature Concerning Fatigue, Sleep, and the Circadian Cycle

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Introduction

This document provides a brief review of the scientific research relating to issues of pilot fatigue arising from crew scheduling practices. A massive amount of research has been conducted on such issues as the environmental conditions that contribute to the occurrence of fatigue, acute and chronic sleep debt and their effects on performance, and the influence of the circadian cycle on alertness. This paper attempts to identify major trends in this literature that might be of value in addressing scheduling regulatory issues.

The paper is organized into seven sections. The first section, "What is Fatigue," attempts to provide a functional definition of fatigue that serves to define the scope of issues that need to be considered, including variables that contribute to the occurrence of fatigue and methodologies for assessing the impact of fatigue on human functioning.

Section two, "Indications and Effects of Fatigue," briefly reviews the human performance and physiological indicators of fatigue. The intent is to identify possible decrements in performance that could have a safety impact. This section also briefly addresses the complexities involved in measuring fatigue levels. As this section explains, fatigue is a complex concept that does not always produce expected measurable decrements in performance.

Section three, "Fatigue and the Aviation Environment," addresses the issue of fatigue within the aviation environment. Before changes are made to existing regulations, the question of whether there is a problem that needs to be resolved should be addressed. Available research on the extent of fatigue within the aviation environment is reviewed. In addition, factors that complicate the assessment of the extent of the fatigue problem in an operational environment are also described.

A pilot's level of alertness at any time depends upon a complex interaction between a number of variables. Four variables, in particular, need to be considered: time on task, time since awake, any existing sleep debt, and the pilot's own circadian cycle. Section four, "Standard Duty Period," describes the research trends pertaining to time on task and time since awake while section five, "Standard Sleep Requirements," addresses acute and chronic sleep debt, including recommendations for sleep debt recovery. Section six, "The Circadian Cycle and Fatigue," which looks at the research on circadian cycles and their implications for back-of-the-clock and transmeridian flying. Finally, section seven, "Augmented Crews," looks at the limited data on the use of augmented crews to extend duty periods.

What Is Fatigue

The objective of the regulations proposed in the NPRM is to identify scheduling constraints that will minimize the impact of pilot fatigue that arises from duty time and sleep debt due to crew schedules. The term, "fatigue," has yet to be defined in a concrete fashion (Maher & McPhee, 1994); Mendelson, Richardson & Roth, 1996). Fatigue, as addressed in the human performance literature, refers to "deterioration in human performance, arising as a consequence of several potential factors, including sleepiness" (p. 2). Sleepiness, in contrast, has a more precise definition: "Sleepiness, according to an emerging consensus among sleep researchers and clinicians, is a basic physiological state (like) hunger or thirst. Deprivation or restriction of sleep increases sleepiness and as hunger or thirst is reversible by eating or drinking, respectively, sleep reverses sleepiness" (Roth et al., 1989, cited by Mendelson, Richardson & Roth, 1996, p. 2).

In keeping with current thinking on the concept of fatigue, Maher and McPhee's approach is used here:

> "Fatigue" must continue to have the status of a hypothetical construct, an entity whose existence and dimensions are inferred from antecedent and consequent events or variables" (p. **3-4).**

This means that fatigue is treated as a concept that occurs in response to predefined conditions and has physiological and performance consequences. The antecedent conditions of interest here include:

- Time on **task,** including flight time and duty period duration
- Time since awake when beginning the duty period
- Acute and chronic sleep debt
- Circadian disruption, multiple time zones, and shift work.

The objectives of this document are to review the scientific research in order to:

- Identify the impact of these antecedent variables on human performance
- Relate these variables to appropriate physiological measures that have been demonstrated to be accompanied by decrements in human performance

Identify, to the extent possible, limitations and requirements concerning duty period durations, minimum sleep requirements, etc. that should be reflected in the regulations.

Indications and Effects of Fatigue

The massive literature on fatigue has identified a number of symptoms that indicate the presence of fatigue, including: increased anxiety, decreased short term memory, slowed reaction time, decreased work efficiency, reduced motivational drive, decreased vigilance, increased variability in work performance, increased errors of omission which increase to commission when time pressure is added to the task, and increased lapse with increasing fatigue in both number and duration (Mohler, 1966; Dinges, 1995). Many of these symptoms appear only after substantial levels of sleep deprivation have been imposed. A review of the literature that involved fatigue levels likely to be experienced by pilots suggests that a common fatigue symptom is a change in the level of acceptable risk an individual will tolerate.

Brown et al. (1970) had subjects drove for four 3-hour sessions. The performance measure used was a count of the number of occasions in which the subject executed what the experimenter considered a risky passing maneuver. When driving performance between the 1st and 4th sessions were compared, a 50% increase in the occurrence of risky passing maneuvers in later sessions, when subjects were presumably more fatigued, was obtained.

This change in the level of acceptable risk was confirmed by Barth et al. (1976) and Shingledecker and Holding (1974) who found that fatigue caused subjects to engage in greater risk taking activity in an effort to avoid additional effort. In the Shingledecker and Holding study, subjects performed 36 choice-of-probability (COPE) tasks, which involved locating a fault in one of three removable banks of one-watt resistors, each with varying degrees of probability that the bank had failed. Twenty-eight days separated the first and last three sets of six trial blocks. In this interim, the experimental group received 24 to 32 hours of continuous work on different monitoring-type fatiguing tasks immediately preceding the second trial block set, while the control group did not. The experimental group was found to shift their selections toward riskier, but less effortful strategies, and made more errors when compared with their own non-fatigued results or control group results. Also, subjects who reported they were tired, although not exposed to intentionally fatiguing activities, behaved similarly. Barth et al. performed a similar experiment, except that fatigue was induced by either a variable pitch/speed bicycle ergometer or a treadmill.

In the aviation domain, this strategy of avoiding effort when fatigued has recently been reported. Neri et al. (1992) found a change in strategy toward risk taking in naval pilots during carrier landings. Risk taking behavior also appears in the form of over reliance on automated systems (Graeber, 1988). This increased passivity, which takes the form of a mental aversion to or avoidance of further effort, is common in both the sleep deprived state and when the individual is experiencing the diurnal low point for body temperature during the circadian trough (Hamilton et al., 1972).

A report of some of the occurrences moments before the crash of the aircraft carrying Commerce Secretary Ron Brown further illustrates the type of inaction typical of fatigue (Newman, 1996). Although the pilots detected an error on approach a full minute before the crash, they made no attempt to correct the error—a common characteristic of fatigue. This is due to a reduced level of adherence to one's normal standard and a reduced ability to cognitively make a connection between cause and effect. One may recognize a problem but not translate its effect due to lack of full comprehension of the situation or simple failure to initiate an action.

Related evidence exists that fatigued workers are satisfied with lower performance and that perceived errors go uncorrected. There is a "loss in the ability of the worker to perceive and adjust to new aspects of the task. The worker seems unable to shift quickly and effectively from one subpart to another" (Broadbent, 1953; cf. Horne, 1988). The latter quality has been found to be a factor when aircraft crews are concentrating on one problem and allow other problems to develop due to neglect.

In the case of the 1985 China Airlines Flight 006 mishap, the pilot became focused on the loss of power in one engine, neglecting other flight duty tasks. Major structural damage and 2 serious injuries occurred when the aircraft experienced more than 5 g's during its uncontrolled descent from 31,000 feet to 9,500 feet, before control was regained (Lauber & Kayten, 1988). Contributing fatigue factors to the accident were the Captain's failure to properly monitor the airplane's flight instruments, over-reliance on the autopilot after the loss of thrust due to engine failure, and performance of duties during the Captain's circadian trough. The accident occurred 4 to 5 hours after the time he had been beginning sleep during the 6 nights preceding the accident.

In the Guantanamo Naval Base accident, the pilot was so focused on finding a strobe light that he failed to respond to other crew members' warnings that they were approaching a stall speed (NTSB Aircraft Accident Report, 1993). In an investigation of Air Force C-5 mishaps or near mishaps, it was reported that 55 percent were related to attentional focus problems and 24 percent to decision making problems (Majors, 1984).

Some symptoms of fatigue are similar to other physiological conditions. For example, with fatigue one's ability to attend to auxiliary tasks becomes more narrow, very much analogous to the effects of alcohol (Huntley et al., 1973; Moskowitz, 1973), hypoxia (McFarland 1953), and heat stress (Bursill, 1958). Dawson and Reid (1997) evaluated performance after 17 hours awake and found performance degraded to a level equal to that caused by a blood alcohol concentration (BAC) of 0.05 percent. At 24 hours, performance decrements were equivalent to that of a 0.10 BAC. After ten hours of sleeplessness, the decline in performance averaged .74 percent per hour.

Finally, Harrison and Horne (1979) found that sleep loss resulted in a difficulty of generating the ideal word or phrase for the idea or thought the person wanted to convey. In addition, there was a loss in intonation and an overall dullness which suggested loss of interest. The authors suggest that this may very well result in personal communication problems in real life situations.

Effects of Fatigue and Sleep Loss on the Brain

Sleep is mainly a restorative process for brain function. Horne (1991) states that this restoration is primarily a function centered on the cerebral cortex of the brain. This is consistent with the findings of Perelli (1980), who found that a high time since awake significantly increased the threshold for information processing. Pternitis (1981) found that dominant EEG frequencies in power plant operator shift workers showed a progressive decline, with each shift beginning in the morning and continuing to night shift. Morning shift employees showed EEG readings of 12-30 Hz, evening shift workers 6-12 Hz, and those on duty during the night shift, 2-6 Hz. Gevens et al. (1997) has shown that observable performance decrements are preceded by observable EEG brain wave changes that clearly indicate decreasing attentional focus. These EEG changes are observable some time before noticeable performance decrements occur. Howitt et al. (1978) measured EEG activity in operational pilots and found that under high workload situations the fatigued pilots' EEG rose to only half the level of those displayed by fresh pilots.

Another physiological measure of fatigue and sleep is brain glucose levels. All tissue of the body, whether it be heart muscle, kidneys, lungs, or the brain, works electrochemically, and conforms to one principle: the more work done, the more fuel used. Thus, by measuring glucose utilization, oxygen consumption, and blood flow in the brain, areas which are very active during various tasks can be determined.

Thomas et al. (1993), using positron emission topography (PET) scan has provided strong physiological evidence that sleep loss is accompanied by a decrease in brain glucose metabolism. The areas most involved were the prefrontal cortex, the inferior parietal cortex, and thalamus. During **48** hours sleep deprivation, the overall brain glucose utilization declined 7 percent, while in the areas of higher order thinking declines ranged from 10 to 17 percent (Thomas, 1997). Although these reductions seem relatively minor over a **48** hour period, Gold (1995) recently found that comparatively small blood glucose changes could significantly enhance cognitive performance in a variety of subjects including healthy young adults, elderly, and severe states of pathology such as Alzheimer's and Downs Syndrome patients.

PET scans of recovery sleep, taken sequentially through the night and synchronized with EEG changes, show that slow wave sleep appears to have its greatest effects on the same brain areas that Thomas et al (1993, 1997) showed were most affected by sleep loss (Braun et al., 1997). This indicates that areas of the brain involved in alertness, attentional focus, concentration, short term memory, drive and initiative, problem solving, complex reasoning, and decision making are the greatest beneficiaries of deep sleep (Lamberg, 1996).

Since the front brain is responsible for analysis of information, judgment, planning, decision making, and the initiation of actions, it is not surprising that NTSB found decision making abilities suffered with high time since awake.

> The orderly planning and sequencing of complex behaviors, the ability to attend to several components simultaneously, and then flexibly alter the focus of concentration, the capacity for grasping the context and gist of a complex situation, resistance to distraction and interference, the ability to follow multi-step instructions, the inhibition of immediate but inappropriate response tendencies, and the ability to sustain behavioral output... may each become markedly disrupted (Restak, 1988).

Many of the functions described by Restak are the same functions necessary to **a** pilot's ability to competently fly an aircraft.

Measuring Fatigue

Although the studies just listed do show performance decrements due to fatigue, other studies have shown no effect (e.g., Rosenthal, 1993), particularly when sleep loss levels up to 24 hours, or small chronic partial sleep loss levels of only one or two hours per day are used. The lack of definitive results in partial sleep deprivation studies may be due to differences in testing procedures. Rosenthal tested on four separate occasions, whereas others tested only once per day. In a more severe sleep deprivation study, Thorne (1983) made the testing instrument the primary task, which lasted 30 minutes of each hour. As sleep loss became increasingly greater, subjects became slower. Therefore, the time to complete the self-paced task increased about 70 percent, and at times doubled.

Evans et al. (1991), in a review of fatigue in combat, clearly stated that studies using embedded testing, such as Thorne (1983), Angus and Heslegrave (1985), and Mullaney et al. (1981), consistently show greater effects of fatigue and sleep loss performance decrements than short duration isolated intrusive tests. Belenky et al. (1986) notes that continuous embedded testing reveals larger performance decrements sooner than does intermittent testing. In Angus and Heslegrave (1985), analysis of results found a 28% decrement in encoding/decoding performance and a 43% decrement in logical reasoning after 24 hours awake. Haslam (1982), using non-embedded testing, found no decrements and 29%, respectively.

The greater sensitivity of embedded testing is not surprising given that they measure performance for a more prolonged period. Brief, intrusive psychometric tests, in contrast, are novel and act as a rest break, distraction, and temporary stimulus, thereby increasing short term mobilization of effort thus boosting performance. The use of such an instrument would function similar to the effect Chambers (1961) found in an industrial output study where output remains higher when a worker was switched to different jobs periodically than to stay at one job.

Another explanation for the varying effects of performance due to fatigue is that performance is, in part, dependent upon the circadian physiology of the subject. Subjects experiencing circadian dysrhythmia or operating during their circadian trough are more likely to yield substandard performance.

Also, motivation can play a major role in the relationship between fatigue and performance. "Both experimenter and subject motivation can have a large impact on results, particularly in the behavioral and subjective domains. Motivation effects are frequently most apparent near the end of studies (where performance improvement is sometimes found) but also may account for the difficulty in showing decrements early in periods of sleep loss" (Bonnet, 1994, p. 50).

In addition to embedded testing, other parameters considered to increase sensitivity in testing for fatigue and sleep loss performance decrements include continuous performance, prolonged vigilance, and multiple task jobs, similar to what is shown to work in decrement due to noise (Belenky 1986; Dejoy, 1984). Self-paced tasks have been reported to be less affected by sleep loss than tasks that are faster work-paced (Johnson & Naitoh, 1974). Fatigue effects tend to be minimal when tasks are self-paced, brief, highly motivating, and feedback is given. On the other hand, tasks which involve sustained vigilance and attention, the use of newly acquired skills, and new information retention tend to challenge short term memory. This is because work-paced tasks accelerate the rate of information processing, thereby decreasing the reserve capacity of brain function.

Roth et al. (1994) support long monotonous objective testing and the MSLT as good measures of sleep loss decrement and sleepiness, respectively. McFarland (1953) considered the deterioration of skills over time a promising framework for the study of fatigue. This has recently been attempted in aviation research by Neville et al. (1992) through the use of flight data recorders for measuring parameters of flight over time. This procedure may be the best avenue yet for truly measuring performance decrements in an operational setting.

Microsleeps

Performance measures have obvious value for assessing the effects of fatigue and sleep-related variables. Microsleeps are another useful approach. Microsleeps were first recognized by Bills (1931) and were first called "blocks." Over the intervening years they have also been called "gaps," "lapses" and, more recently, "microsleeps." The physiological drive to sleep can result in a microsleep lasting a few seconds to a few minutes. The latter terminology is the result of EEG recording showing that during these lapses in information processing, subjects momentarily slip into a light sleep. This occurs with the eyes open and usually without the knowledge of the individual, **an** observation first reported by Miles **(1929).** Bonnet and Moore **(1982)** found that before **50** percent of normal subjects became consciously aware of falling asleep, they had been asleep two to four minutes. These intermittent lapses in consciousness impair performance by leading to errors of omission due to missed information. In serial tasks that are work paced, microsleeps can also lead to error of commission and, if frequent enough or long enough, can lead to loss of situational awareness.

Microsleeps have been shown to be a useful approach to assessing the effects of time of day on sleepiness levels. EEG brain wave changes confirm that pilots experience greater sleepiness and decreased alertness between **2:00** to **4:00** a.m. (Gundel, **1995).** Alpha waves in EEGs indicate micro events or micro sleeps and have been found to be three times greater during night than during day flights (Samel, **1995).** Samel et al. **(1997)** found that during outbound flights, pilots experienced **273** microsleeps or an average of **1.38** microsleeps per pilot per hour. On return flights the following night, pilots experienced **544** microsleeps or **2.47** microsleeps per hour per pilot. Both feelings of fatigue and the occurrence of microsleeps increased as duty time progressed. Rosekind et al. **(1994)** also observed micro sleep in pilots and a progressive increase as flights progressed, particularly in the latter portion of the flight. These findings confirm both the physiological occurrence of microsleeps in commercial aviation pilots, and the accumulative nature of fatigue in successive night operations.

The beneficial effects of taking breaks have also been demonstrated by measuring microsleeps. Workers performing continuous tasks without breaks (Bills, **193**1; Broadbent, **1958)** or suffering from sleep loss began to demonstrate signs of micro sleeps much sooner than those with rest breaks or getting adequate rest, respectively (Kjellberg, **1977b).**

The research cited in this section suggests that fatigue may be a factor in the aviation environment due to direct performance decrements and, indirectly, through microsleeps that disrupt pilot functioning. The next section looks at data relating to the occurrence of fatigue in the aviation environment.

Fatigue And The Aviation Environment

The unique characteristics of the aviation environment may make pilots particularly susceptible to fatigue. Environmental factors such as movement restriction, poor air flow, low light levels, background noise, and vibration are known causes of fatigue (Mohler, 1966). In addition, the introduction of advanced automation into the cockpit has changed the nature of the job for many pilots. Hands-on flying has been replaced by greater demands on the crew to perform vigilant monitoring of these systems, a task which people tend to find tiring if performed for long periods of time. For example, Colquhoun (1976) found that monotonous vigilance tasks could decrease alertness by **80** percent in one hour, which is correlated with increased EEG theta activity or sleep-like state. Since physical activity and interest in the task can help to minimize the decline in performance due to continuous work and sleep loss (Wilkinson, 1965; Lille, 1979), automation may contribute to increased drowsiness in pilots suffering from fatigue or sleep loss. Also, as will be shown below, these cognitive-based activities may be susceptible to the effects of fatigue.

Although these environmental characteristics are suggestive, the actual extent to which fatigue is a safety issue needs to be assessed. A study of ASRS incident reports suggested that 21% of incidents were fatigue-related. This figure was challenged by Baker (1996), who pointed out that the database is a biased system due to self reporting, and the data were further biased by the researchers' interpretation of the reports. Kirsch (1996) argues that the actual ASRS estimate is four to seven percent. Graeber (1985) clarifies the situation as follows:

> *An* initial analysis of NASA's Aviation Safety Reporting System (ASRS) in 1980 revealed that 3.8 percent (77) of the 2006 air transport crew member error reports received since 1976 were directly associated with fatigue (Lyman & Orlady, 1980). This may seem like a rather small proportion, but as the authors emphasize, fatigue is frequently a personal experience. Thus, while one crew member may attribute an error to fatigue, another may attribute it to a more directly perceived cause such as inattention or a miscommunication. When all reports which mentioned factors directly or indirectly related to fatigue are included, the percentage increases to 21.1 percent (426). These incidents tended to occur more often between 00:00 and 06:00 [local time] and during the descent, approach or landing phases of flight. Furthermore, a large majority of the reports could be classified as substantive, potentially unsafe errors and not just minor errors.

In a study of flightcrew-involved major accidents of domestic air carriers during the 1970 through 1990 period (NTSB, 1994), one conclusion pertained directly to the issue of fatigue: "Half the captains for whom data were available had been awake for more than 12 hours prior to their accidents. Half the first officers had been awake more than 11 hours. Crews comprising captains and first officers whose time since awakening was above the median for their crew position made more errors overall, and significantly more procedural and tactical decision errors" **(p. 75).** This finding suggests that fatigue may be an important factor in the carrier accidents. Because the study involved only domestic carrier accidents, it remains unclear as to whether other fatigue-related factors, such as long flight times and circadian disruption due to multiple time zones would also appear as causative factors. On the basis of this study, the NTSB recommended that the FAA address the issues of flight duty times and rest periods.

Although the results of this study are suggestive, the actual impact of fatigue has yet to be determined. Since no real effort has been made to identify the effects of fatigue in accident and incidence investigation, it is difficult to assess the magnitude of the problem. In addition, it is possible that self-reporting systems, such as ASRS, may be affected by the inability of people to accurately assess their own fatigue levels (Sasaki et al., **1986;** Richardson et al., **1982;** Dinges, **1989).** Subjective evaluations of sleepiness have not been found to be reliable except in extreme sleepiness. Rosekind and Schwartz (1**988)** noted that the scientific literature generally demonstrates a discrepancy between subjective reports and psychophysiological measures, the result being underestimations of one's level of sleepiness (cf. Dement & Carskadon, **1981).** Dement et al. **(1978)** and Roth et al. **(1994)** reported that some subjects judged themselves alert, when in fact they were in the process of falling sleep.

Graeber et al. **(1986),** summarizing the collaborative efforts between European, Japanese, and American investigators to evaluate sleep in long haul aircrews, reported that subjective evaluations are sometimes erroneous as to the true nature of the psychophysiological state of sleepiness. These results were obtained in two separate studies by Dement et al. **(1986)** and Sasaki et al. **(1986).** Mullaney et al. **(1985)** also found that subjects subjectively felt that they performed better under sleep loss conditions when paired with another subject, when in reality it had no effect on actual performance decrements. Rosekind et al. **(1994)** found pilots unable to subjectively evaluate changes in performance due to a short inflight nap. Although pilots did show physiological improvements in alertness, they could not subjectively notice a difference. Belenky et al. **(1994)** points out that due to the psychophysiology changes in higher order cognitive judgment areas with fatigue and sleep loss, these changes automatically preempt ones ability to evaluate his or her own performance accurately.

One possible reason for these findings is that the presence of certain factors masks sleepiness and the absence of other factors unmasks sleepiness. Environmental factors that have a masking affect include noise, physical activity, caffeine, nicotine, thirst, hunger, excitement, talking about something interesting, etc. For example, Howitt et al. **(1978)** found that sleep deprived pilots in operational settings felt no noticeable fatigue once flight preparations were under way and flight commenced. This explanation is supported by research that used the multiple sleep latency test (Dement et al., **1986,** Sasaki et al., **1986;** Rosekind et al., **1994;** Roth et al., **1994).** In contrast to the subjective evaluation, the multiple sleep latency test asks subjects to quietly lie down, close their eyes and try to sleep. This in essence removes many of the masking factors, whereas subjective alertness in relation to EEG recording appears to have better correlation because both can be recorded in the same environmental setting. Ogilvie et al. **(1989)** reported that subjective sleepiness responses to the Sanford Sleepiness Scale only reached significance when subjects were entering stage I sleep. Thus it may be that when EEG alpha and theta activity appears there is truly a feeling of sleepiness.

Although masking reduces perceived feelings of sleepiness, it does not counteract the effects of fatigue on performance. Kecklund and Akerstedt (1**993)** conclude that although sleep-deprived subjects may not feel their sleepiness or fatigue due to environmental variables, the sleep pressure is still latently present.

Standard Duty Period

The first regulatory issue that needs to be addressed concerns the duration of the standard duty period. “Standard” is used here to refer to duty periods that do not involve window of circadian low (WOCL) effects or time zone changes. The primary focus of the standard duty period issue addresses the buildup of fatigue as a function of performing the various tasks involved in a duty period. Six factors that may need to be considered are:

- Time on task
- Time since awake
- Task type
- Duty period extension
- Cumulative duty times
- Environmental factors.

Each of these factors is discussed below.

Time-On-Task

There appears to be some consensus that the effects of time-on-task on performance are difficult to assess (e.g., Maher & McPhee, 1994) and are affected by a number of variables, including time of day, the nature of the task, the subject's motivational level, and if fatigue or sleep loss are already present (Dinges & Kribbs, 1991; Maher & McPhee, 1994; Mendelson, Richardson & Roth, 1996). In spite of this, performance on many laboratory tasks follows a similar curve (Vries-Griever & Meijman, 1987): relatively low starting performance, followed by optimal performance, which then declines due, presumably, to fatigue. The points at which optimal performance begins and then starts to degrade varies with the task. For some cognitive tasks, optimal performance is achieved after about five hours, then declines to its lowest levels after 12 to 16 hours on task (Spencer, 1987; Nicholson, 1987). Some tasks, such as monitoring tasks that require high levels of vigilance, show performance decrements after shorter durations. Colquhoun (1976) found that monotonous vigilance tasks could decrease alertness by 80 percent in one hour based on increased EEG theta activity which correlates with a sleep-like state. Reductions in task performance over time are also accompanied by an increased need to sleep, as shown by Lisper et al. (1986), who found that car drivers showed an increased likelihood of falling asleep after 9 hours of driving.

Time-on-task measures for a single task may have limited applicability to the aviation domain as the pilot's job involves performing a number of tasks during a given duty period. Switching between individual tasks may override some of the effects of fatigue due to time-on-task. Studies which have investigated the effects of extended shift durations on worker performance may be relevant as they assess fatigue and performance as a function of the set of tasks that are performed during a shift rather than performance decrements that accrue on a single task. In a manufacturing environment (Rosa & Bonnet, 1993), the number of errors made was relatively high at the beginning of the shift, then decreased because of re-familiarization with the task. Optimal levels were reached within a few hours, then declined over the eight-hour shift. In general, workers on 12-hour shifts became considerably more fatigued than in more traditional eight- to 10-hour shifts (Rosa & Colligan, 1987). This finding has been confirmed in nurses (Mills et al., 1983), industrial shift workers (Colligan & Tepas, 1986), night shift workers (Rosa & Colligan, 1987), sea watch workers (Colquhoun, 1985), and truck drivers (Hamelin, 1987). The latter study also found an increase in the number of accidents that occur when 12-hour shifts are used.

This increased likelihood of accident risk due to long duty periods has been found in other studies. The relative risk of an accident at 14 hours of duty rises to 2.5 times that of the lowest point in the first eight hours of duty. Askertedt (1995) reports accident risks to be threefold at 16 hours of duty, while Harris and Mackie (1972) found a threefold risk in just over 10 hours of driving. These levels of risk are similar to that associated with having narcolepsy or sleep apnea

(Lavie et al., 1982), or a blood alcohol level of 0.10 percent. Wegmann et al. (1985), in a study of air carrier pilots, argued for a duty period of 10 hours with 8.5 hours or less of flight duty period.

Time Since Awake

The results of an NTSB analysis of domestic air carrier accidents occurring from 1978 to 1990 suggest that time since awake (TSA) was the dominant fatigue-related factor in these accidents (NTSB, 1994). Performance decrements of high time-since-awake crews tended to result from ineffective decision-making rather than deterioration of aircraft handling skills. These decrements were not felt to be related to time zone crossings since all accidents involved short haul flights with a maximum of two time zones crossed. There did appear to be two peaks in accidents: in the morning when time since awake is low and the crew has been on duty for about three to four hours, and when time-since-awake was high, above 13 hours. Similar accident peaks in other modes of transportation and industry have also been reported (Folkard, 1997). Akerstedt & Kecklund (1989) studied prior time awake (four to 12 hours) and found a strong correlation of accidents with time since awake for all times of the day. Belenky et al. (1994) found that flight time hours (workload) greatly increase and add to the linear decline in performance associated with time since awake.

Task Type

The effects of task type, as they contribute to the buildup of fatigue, need to be considered from two perspectives:

- Whether certain activities can be excluded from duty period time
- Whether certain activities are inherently more fatiguing and may need to be restricted.

The current regulations regulate only flight time. No limits are provided for duty time. The regulations proposed in the Notice of Proposed Rulemaking 95-18 (NPRM) allow for the concept of “assigned time,” which also is unregulated as to maximum limits. The extent to which activities categorized as non-flight time or assigned time contribute to fatigue has yet to be empirically ascertained. However, it is clear that these activities would contribute to fatigue in the form of time since awake. Consequently, it may be appropriate to limit these activities in either of two ways:

- With respect to when they occur relative to flight time so as to avoid pilots achieving high time-since-awake levels during flight time periods.
- Provide maximum levels for these activities comparable to duty period time levels.

The second issue pertaining to task type concerns activities which are known to be inherently more fatiguing. One such activity is the approach and landing. Gander et al. (1994) found that increases in heart rate occurred during the approach and landing phases when compared with other duty period activities. Because heart rate increase is a common measure of workload, this suggests that proposals to limit landings for flights that have other known fatigue factors (e.g., time since awake, window of circadian low, extended flight duty periods) may be appropriate.

The relationship between task type and fatigue buildup in the aviation domain remains to be determined. The demands placed on long-haul pilots are clearly different from those of the regional carrier pilot flying many legs in a propeller-driven airplane with limited automation. Flights across the ocean typically involve a single leg of six or more hours. The main task-related fatigue sources in this case are boredom and cognitive fatigue due to vigilance. The regional pilot, in contrast, may be more susceptible to fatigue due to the high workload involved in performing six or more takeoffs and landings. For this reason, it may prove necessary to develop separate regulations that are appropriate for each major type of operation.

Duty Period Extensions

The research cited on duty period duration suggests that duty periods at or above 12 hours are associated with a higher risk of error. This factor, together with the time-since-awake factor, suggests that extended duty periods also involve a higher potential for crew error. In determining maximum limits for extended duty periods, consideration also needs to be given to other fatigue-related factors that could contribute to excessive fatigue levels during extended duty periods, including number of legs, whether the flight impinges on the window of circadian low (WOCL), and time since awake.

Cumulative Duty Time

No data were found that provide guidance for maximum duty times over longer time periods, such as one month or one year.

Environmental Factors

The physical environment of the cockpit is a source of other factors that can contribute to fatigue (Mohler, 1966). Factors such as vibration, poor ventilation, noise, and the availability of limited automation can contribute to the buildup of fatigue or accelerate its onset when coupled with time since awake, number of legs, and whether the flight involves the WOCL. This may have implications for regional carrier pilots who fly propeller-driven aircraft.

Conclusions

The research cited suggests an increase in the likelihood of error as duty periods are extended beyond 12 hours. This finding is especially critical for extended duty periods which are likely to occur under conditions (e.g., weather) that, in and of themselves, may increase the probability of crew error.

The interactions between multiple fatigue-related factors must also be considered. Separately, duty period duration, time since awake, number of legs, and environmental factors contribute to fatigue buildup. When any one of these factors reaches a high level, consideration should be given to reducing the maximum allowable levels on these other factors. Time since awake also has obvious implications for reserve assignments and for pilots who commute.

Standard Sleep Requirements

Standard Sleep Requirements and Off-Duty Period

There is a generally consistent body of research which demonstrates that most people require an average of **8** hours of sleep per night to achieve normal levels of alertness throughout daytime hours without drowsiness and to avoid the buildup of sleep debt (Carskadon & Dement, 1982; Wehr et al., 1993). This figure is based upon a range of studies that used several approaches, including:

- Historical levels of sleep
- Measures of daytime alertness
- Sleep levels achieved when given the opportunity to sleep as long as desired.

Webb and Agnew (1975) reported that habitual sleep around the turn of the century was about nine hours. A 1960 study of more than 800,000 Americans found that 13 percent of men and 15 percent of women, ages 35-65, slept less the seven hours with **48** percent of both obtaining less than eight hours of sleep per night ***(Wake UpAmerica,*** 1993). By 1977, one in eight Americans reported getting six or fewer hours of sleep per night (Schoenborn & Danchik, 1980). By 1983, just six years later, that number had jumped to one in four (Schoenborn & Cohen, 1986).

The average distribution of habitual sleep ranges between 5.5 and 9.5 hours per night, and includes 95 percent of the adult population with an average of 7.5 hours (Horne, 1988). Most researchers seem to agree with this figure (Levine et al., 1988; Carskadon & Roth, 1991, Dinges et al., 1996; Bonnet & Arand, 1995). However, Webb (1985) reported considerable individual differences in habitual sleep in a sample of more than 30,000 individuals from 11 industrial countries. In this study two percent were reported to sleep less than five hours per night, while five percent reported sleeping more than 10 hours. These averages have been reported in similar findings across various population groups.

Most researchers advocate an average sleep requirement for adults of 7.5 to 8.0 hours per day (Levine et al., 1988; Carskadon, & Roth, 1991; Dinges et al., 1996). Although early on, Dement et al. (1986) indicated that 9 hours was necessary for optimal alertness throughout the day, Horne considered ***6*** hours "core sleep" sufficient. Although Horne's advocacy of ***6*** hours core sleep has detracted somewhat from what most sleep researchers now feel to be optimal sleep, it has not dislodged the weight of evidence.

Carskadon (1991) reports that **87** percent of college students habitually sleeping seven to 7.5 hours per night had difficulty staying awake in the afternoon with 60 percent reporting actually falling asleep. When compared with Horne's advocating only 6 hours of "core sleep," these responses seem to suggest that, although the subjects specify a habitual amount of sleep above Horne's putative 'core,' their sleep is insufficient. The six-hour core amount does not seem to apply to many, based upon the self-perceived adequacy of sleep.

Roehrs et al. (1989) showed that when short or long sleepers were required to stay in bed for ten hours, all subjects slept about an hour longer than usual. The result was that all subjects improved in their alertness, vigilance, and reaction time needed for driving or monitoring modern control panels. Divided attention performance showed significant improvement, and central task performance showed somewhat better improvement than peripheral task performance. Daytime sleepiness decreased for both groups, but to a greater extent for the individuals who previously reported suffering from sleepiness. Subjects who were usually sleepy were more alert, and those who usually functioned at a high level became even sharper (Carskadon et al., 1979).

Allowing just one hour extra sleep per night over four night resulted in a progressive reduction in daytime sleepiness of nearly 30 percent when measured by the Multiple Sleep Latency Test (MSLT). Allowing sleepers who typically slept 7.5 hour per day to sleep ***ad libitum,*** other researchers found that sleep time increased 28 percent from 7.5 to 9.6 hours. (Taub, 1981; Webb & Agnew, 1975). Taub (1976) studied the magnitude of differences between regular (7 to 8 hours) sleepers and long **(9.5** to **10.5** hours) sleepers when their sleep was phase shifted three hours forward or backward. They also examined changes when both groups had sleep periods extended or reduced. Although results showed degrees of impairment from the acute alterations in sleep pattern by both sleep groups, the **7-to-8** hour sleepers consistently showed greater impairment. Carskadon and Dement **(1981, 1982)** found that extending the total time in bed from eight hours to ten in **18** to 20 year old subjects allowed them to increase their total sleep time on average more than one hour. This resulted in a significant improvement in daytime alertness which only appeared after the second night of extended sleep, suggesting a repaying of sleep debt. The researchers felt that this improvement supported suggestions that eight hours of bed time may represent a chronic sleep deprivation condition in young adults. Scores on alertness showed a stair-step response with the length of sleep per night as well as with the number of nights. Thus scores for alertness were better for ten hours of sleep than for eight, eight were better than five, and two nights with five hours were better than seven nights with five hours which were better than scores with no sleep.

In a slightly different research design, Wehr **(1993)** found in a four-week test that young adults allowed to sleep as long as they desired, slept in excess of **10** hours a day during the first three days. This was followed by three days of about **9** hours. The remainder of the **28** days leveled off at an average of 8.5 hours per night. Their habitual base-line sleep was 7.2 hours. The initially higher level of sleep is interpreted as repayment of chronic sleep debt. A similar sleep requirement figure of **8.4** hours was reported by a Walter Reed research team **(1997)** in an interim report. Thus both sleep extension studies and historical data indicate that optimal sleep requirement appears to be between **8** to **9** hours sleep with an average of about **8.5** hours, considerably higher than habitual sleep figures.

The benefits of sleep are presently considered to be logarithmic in nature, with the initial hours showing significantly greater benefits that diminish as one approaches his or her optimal sleep level. This accounts for how many can sleep less and appear to still function normally. However the findings of Rohre **(1989)** and Taub and Berger **(1976)** indicate that during the first six hours of sleep, performance is restored to a satisfactory level under normal conditions, although alertness and vigor may still be diminished. In the hours beyond six hours of sleep the restoration process further restores alertness and vigor and the brain's capacity to handle situations above that of normal and for longer periods.

An example of this is best illustrated by Samel et al. **(1997)** where the second of two night flights showed a considerable reduction in tolerance and an increase in fatigue after only three hours of flight whereas on the first night fatigue did not set in until after **8** hours. Thus, the additional hours served as a reserve capacity against workload (Howitt et al., **1978)** or hours of duty (Samel et al., **1997;** Gundel et al., **1997).**

Other Variables

Individual Differences In Sleep Requirements. Many of the studies described above showed that there appears to be a considerable variability in individual sleep needs. Thus, the eight-hour sleep requirement represents the average of sleep needs, but does not take into account of the needs of those individuals who require additional sleep and who represent a fair percent of the population.

Age-Related Changes In Sleep Requirements. With age there is a significant decline in habitual nightly sleep due to increased nighttime awakenings (Davis-Sharts, 1989; Webb & Campbell 1980; Carskadon et al., 1982; Miles & Dement, 1980; Carskadon et al., 1980). In older individuals, habitual nighttime sleep is accompanied by increased daytime fatigue, sleepiness, dosing, and napping. This increase in the number of sleep periods approximates normal sleep quantity and appears to indicate that sleep requirements remain the same over a person's adult lifetime (Miles & Dement, 1980; Habte-Gabr, 1991). These studies suggest that older crew members may have particular difficulties in achieving sufficient sleep as part of a normal duty schedule (cf. Carskadon, Brown & Dement, 1982).

Logistical Issues. A number of studies have investigated the issue of the amount of sleep that is actually achieved as a function of the length of the off-duty period. These studies demonstrate that off-duty periods that appear to provide an acceptable sleep opportunity may not, in reality, be sufficient. In one study, reductions in sleep of two to three hours per 24 hours occurred when the time between shifts or work was reduced to only nine hours (Knauth, 1983). In the **NASA** studies of short-haul pilots (Gander et al., 1994; Gander & Graeber, 1994), pilots reported an average of 12.5 hours off-duty time between duty periods, but only obtained 6.7 hours rest.

Observations of nurses on 12 hour shifts working 12.5 hours with 11.5 hours off between shifts obtained an average of 6.9 hours sleep (Mills et al., 1983). Another study of long-haul and short haul-truck drivers (WRAIR, 1997) showed that short-haul drivers with similar rest periods between shifts obtained even fewer sleep durations.

Commercial truck drivers' (FHWA, 1996; Mitler et al., 1997) sleep/off duty schedules are shown in Table 1. When truckers (C1-10) had 10.7 hours off duty between 10 hour day shifts, sleep durations of only **5.4** hours were achieved. On a 13-hour day shift (C4-13) with 8.9 hours off between duty periods, sleep durations averaged 5.1 hours. On 10-hour rotating shifts (C2-10) with 8.7 hours off duty, the sleep time was 4.8 hours and after a 13-hour night shift (C3-13) with 8.6 hours off, the resulting sleep diminished to only 3.8 hours. In quick changeovers with **8** hours off between shifts, Totterdell (1990) found that workers only acquired 5.14 hours sleep. Kurumatani (1994) found a correlation ($r=.95$) between the hours between shift and sleep duration. They concluded that at least 16 hours off duty time were needed between shifts to ensure 7-8 hour sleep, a conclusion reiterated in a recent review (Kecklund & Akerstedt, 1995).

Condition	Hours off-duty	Hours in Bed	Hours asleep
C1-10 day	10.7	5.8	5.4
C2-10 rotating	8.7	5.1	4.8
C3-13 night	8.6	4.4	3.8
C4-13 day	8.9	5.5	5.1

Table 1. Truck drivers shift type and off duty hours in relation to time spent in bed and sleep time. (1996)

A partial explanation for such small amounts of sleep between quick shift changeovers may be the result of apprehension or fear of over sleeping. Torsvall and Akerstdt (1988) showed that ships' engineers on call show reduced sleep but also a decreased quality of sleep which they attributed to apprehension. This has also been found in physicians in smaller hospitals and appears to be followed by increased sleepiness during the following day (Akerstedt & Gillberg, 1990).

Other reasons for the low levels of actual rest achieved is due to the other activities that must be performed during the off-duty period. For pilots on layovers, these activities include getting to and from the hotel, meals, and personal hygiene. These activities clearly take away from the time available to sleep (Samel et al., 1997).

Reduced Rest

Research on the effects of sleep reduction on physiological and task performance has failed to provide a consistent picture of how much sleep may be reduced before a significant impact on performance occurs. Some of the reasons for this were described previously in the section entitled "Measuring Fatigue." Carskadon and Dement (1981) reduced subjects' sleep to only five hours per night over seven days, resulting in a 60 percent increase in sleep tendency. Based on this study and others, Carskadon and Roth (1991) conclude that as little as two hours of sleep loss can result in both performance decrements and reductions in alertness. Wilkinson (1968) varied sleep quantity by allowing subjects 0, 1, 2, 3, 5, or 7.5 hours in which to sleep. Significant decreases in vigilance performance were found the following day when sleep was reduced below three hours for one night or fewer than five hours for two consecutive nights. Carskadon, Harvey and Dement (1981) found increased daytime sleepiness, as measured by the MSLT, after one night of sleep reduced to four hours in a group of 12-year-olds, although performance decrements were not found.

Restriction of sleep in young adults to just 5 hours increases sleepiness on the MSLT the next day by 25 percent and by 60 percent the seventh day (Carskadon & Dement, 1981). When sleep was reduced to five hours or less, performance and alertness suffered and sleepiness significantly increased (Wilkinson et al., 1966; Johnson, 1982; Carskadon & Roth, 1991; Gillberg & Akerstedt, 1994; Taub & Berger, 1973; Carskadon & Dement, 1981). A recent study of Australian truckers found that 20 percent of drivers sleep 6 hours or less and account for 40 percent of the hazardous events reported (Arnold et al., 1997). During Operation Desert Storm, the pilots of the Military Airlift Command flights obtaining only 11 hours sleep in 48 hours were found to be in danger of experiencing difficulties in concentrating and staying awake (Neville et al., 1992). Further pilot observations indicated that to prevent fatigue in these pilots, at least 17 hours of sleep in 48 hours (7.5 hours/ 24 hours) were required.

Dinges (1997) showed significant cumulative effects of sleep debt on waking functions when subjects were restricted from their usual 7.41 hours sleep to only 4.98 hours (sd .57 hrs) of usual sleep (67 percent). Across the seven or eight days of sleep restriction subjects showed increasing levels of subjective sleepiness, fatigue, confusion, tension, mental exhaustion indicators, stress, and lapses increasing in frequency and duration. These escalating changes provide strong evidence that partial sleep restriction similar to that experienced by pilots has cumulative effects similar to those found in total or more extreme partial restriction.

In contrast, Hockey's (1986) analysis of partial sleep deprivation study findings revealed minimal performance changes but there were significant reductions in vigilance, efficiency, and increased subjective sleepiness with and mood deterioration.

These results suggest that reducing rest by an hour should have little impact on a pilot's performance if the pilot is well-rested prior to the reduced rest. If the pilot is suffering from sleep debt prior to the reduced rest, there may be an impact on the pilot's performance. If so, a reduced duty period should follow the reduced rest period in order to compensate for the possibility that the pilot may be more susceptible to time-since-awake effects.

Required Recovery Time

Complete recovery from a sleep debt may not occur after a single sleep period (Carskadon & Dement, 1979; Rosenthal et al., 1991). Typically, two nights of recovery are required (Carskadon & Dement, 1979; Kales et al., 1970), although the required recovery period may depend on the length of prior wakefulness (Carskadon & Dement, 1982). For example, Kales et al. (1970 found that restricting sleep to 5 hours per night for 7 days, which more closely resembles crew sleep patterns, required only a single extended night of sleep of 10 hours for full recovery. Morris (1996) found fatigue resulting from the loss of 4.5 hours of sleep in one night was not adequately restored in spite of 9 hours of sleep on one recovery night. Studies of C-141 crews flying to Southeast Asia during the Vietnam Conflict found that three nights were required before sleep returned to normal on the fourth night (Hartman, 1971). These results were observed even though the crews averaged 7.5 hours sleep per night.

The research also suggests that sleep debt following extended flight duty periods will only be effective if the sleep opportunity occurs at a time when the individual's circadian cycle will support effective utilization of that opportunity. The quantity of sleep gained depends more upon the circadian phase at which sleep is attempted rather than the length of prior wakefulness (Strogatz, Kronauer & Czcisler, 1986; Wever, 1985; Aschoff et al., 1975).

Conclusions

There appears to be substantial evidence that a minimum of eight hours of sleep is required for most people to achieve effective levels of alertness and performance. This rest level also enables the individual to cope with reduced rest should the need arise. Achieving the required eight hours under layover conditions depends upon the length of the off-duty period. The data suggest that an off-duty period of ten hours may not be sufficient to support an eight-hour sleep opportunity.

Reducing the rest period by an hour should have little effect on pilot alertness and performance if the individual is well-rested. Reduced sleep, when accompanied by an existing sleep debt, diminishes performance and the ability of the individual to maintain alertness throughout the duty period, especially if a long time since awake is involved.

Recovery from sleep debt often requires two nights of rest. This result puts into question the effectiveness of extending the off-duty period following an extended duty period. Also, if no sleep debt is allowed to accumulate, it is not clear that weekly breaks are required. However, the data suggest that sleep debt is likely to accumulate if 10-hour off-duty periods are used.

The Circadian Cycle And Fatigue

Biological Circadian Rhythms

Chronobiology is the study of time-dependent changes in various levels of the physiologic organization from the organism as a whole, to the cell, to the genetic material itself. These changes regularly reoccur in a predictable rhythmic fashion and are referred to as oscillations. The oscillations appear as waves, and the time to complete one full wave cycle is called a "period." They are divided into three groups by length of the rhythm. Ultradian are rhythms of 20 hours or less, Circadian encompasses rhythms between 20-28 hours, and Infradian are rhythms greater than 28 hours. The latter include rhythms called circaseptan (7 days, ± **3** days), circadiseptan (14 days ± **3** days), circavigintan (21 days, ± **3** days), circatrigintan **(30** days, ± 5 days) and circaannual (one year, ± **3** months). According to Haus & Touitou (1994) there is evidence of 7 day, 30 day and annual rhythms in humans, as well as the circadian and ultradian rhythms.

Circadian rhythms have been recognized for decades. Yet the biological clock that regulates the 24-hour physiological and behavioral rhythms was not identified until the 1970s. These two bilaterally located nuclei called the suprachiasmic nuclei (SCN) are located above the optic chiasm in the anterior hypothalamus. These nuclei are considered the circadian pacemakers. Destruction of these nuclei produce an arrhythmia and severe disruption between behavior and physiological parameters including the timing of food intake and sleep. They appear not to regulate the amount of either of these behaviors (Turek & Reeth, 1996).

Signals produced by the SCN are both hormonal and neural. Grafted nuclei without neural connections restore circadian rhythms of eating and activity. Melatonin secretions, however, are not restored, suggesting neuron control. Melatonin receptors have been found in the SCN and appear to be part of a feedback mechanism that causes shifts in the circadian clock. The SCN has been found to possess its own built-in rhythm. Evidence gathered thus far indicates that SCN receive information about the light-dark cycle via two neural pathways from the optic nerve; one from the retinohypothalamic tract and the other through the geniculohypothalamic tract. The latter pathway appears to provide information or signals that help with reentrainment after a shift in the light-dark cycle. But recent research appears to indicate that other photo receptors may also be involved in the entrainment process (Campbell & Murphy, 1998).

Peak levels of physiological functioning occur during the light phase of the light/dark cycle. This synchronization of physiological rhythms enhances work performance during the daytime and supports sleep at night by turning down the metabolic thermostat. The internal synchronization of the variable metabolic parameters with the light/dark cycle are tuned for optimal functioning. Over 100 biological rhythms are genetically generated within the human body, then entrained or synchronized to better work in concert (Wehr, 1996; Takahasi, 1996). The greater the synchronization between hormone production, metabolic rate, enzyme and neurotransmitter synthesis, the higher the amplitude of the rhythm and the greater the communication between the body's cells. Thus, the maintenance of a strong circadian rhythm carries with it considerable ramifications for good health, well-being, and functioning (Wehr, 1996).

The suprachiasmic nuclei, together with the pineal gland, function as metabolic and behavioral concert conductors in cue with environmental factors such as light/dark, meal timing, social interaction, and physical activity. This synchronization of internal and behavioral with the external environment around the 24 hour day (*circa*=about: *dies*=day) is called circadian rhythm entrainment.

Although other internal and external factors do play a role, the light-dark cycle is the major entrainment factor for most of the animal kingdom. For humans, though, the light-dark cycle is felt to be a relatively weak synchronization of the human circadian rhythm for two reasons. Compared to other animals, the light sensitivity threshold as a synchronizing factor is considerably elevated. For comparison, the light intensity required for circadian synchronization in a hamster is only .5 lux, whereas for humans estimates range from 1200-2500 lux (Reinberg & Smolensky, 1994). This raises questions about the adequacy of indoor lighting. Second, man is the only species that lives outside of the day/night cycle.

Social environment appears to play a more important role in entrainment. Social factors that can alter the biological clock regulation of circadian rhythms include temperature, flight duty, stress, meal consumption, and food presentation (Samel & Wegmann, 1987). Exercise or activity also appears to help retrainment after circadian disruption. Ferrer et al. (1995) cite evidence that physical fitness predicts how well a person adapts to shift work changes regardless of its entrainment potential. Individuals who are physically fit and exercise regularly have higher circadian rhythm amplitudes than unfit individuals, and those with high circadian rhythm amplitudes are more tolerant of shift work (Ferrer et al., 1995). This helps to explain why age-related flattening of circadian rhythms is related to increased sleep difficulties, poor adjustment to night work and transmeridian flights in those over 50.

Back of the Clock Operations, Circadian Rhythm and Performance

There is a substantial body of research that shows decreased performance during night shifts as compared with day shifts. The reasons for this decreased performance include:

- Circadian pressure to sleep when the individual is attempting to work.
- Circadian pressure to be awake when the individual is attempting to sleep.
- Time since awake may be substantial if the individual is up all day before reporting for

the night shift.
- Cumulative sleep debt increase throughout the shift.

Research conducted by Monk et al. (1989) indicates that subjective alertness is under the control of the endogenous circadian pacemaker and one's sleep-wake cycle (time since awake). When time since awake is long and coincides with the circadian low there is a very sharp drop in alertness, a strong tendency to sleep and a significant drop in performance (Perelli, 1980). Alertness is relatively high when the circadian rhythm is near the acrophase and time since awake is small. Monk (1996) argues that this cycle is consistent with the NTSB (1994) finding of a peak accident rate occurring in the evening. The strength of the circadian cycle is substantial. Akerstedt (1989) argues that, up to 24 hours without sleep, circadian influences probably have greater effects than time since awake.

In Japan, 82.4 percent of drowsiness-related near accidents in electric motor locomotive drivers (Kogi & Ohta, 1975) occur at night. Other landmark studies over the past several decades have documented the increase in accidents and error making. Klein et al. (1970) argue that their research with simulators proves that night flights are a greater risk than day flights. Their research found 75- to 100-percent mean performance efficiency decrements in simulator flights during the early morning hours, regardless of external factor such as darkness or increasing night traffic or possible weather conditions.

Task performance in a variety of night jobs has been compared with performance of their daytime counterparts, and results consistently show deterioration of performance on the night shift. Browne (1949) studied telephone operators' response time in answering incoming calls in relation to the hour of the day and found the longest response times occurred between 0300 and 0400 hours. Bjerner et al. (1955) examined gas company hourly ledger computations of gas produced and gas used over an 18-year period and found that recording error were highest at 0300 hours with a smaller secondary peak at 1500 hours. Hildebrandt et al. (1974), investigating automatic train braking and acoustical warning signal alarms set-offs, also found two peaks at 0300 and 1500 hours in these safety-related events. Similar finding have been reported in truck accidents (Harris, 1977) and in Air Force aircraft accidents (Ribak et al., 1983). Other accident analyses of time of day and hours of work show that both circadian rhythm and hours of duty play a significant role in the occurrence of accidents (Folkard, 1997; Lenne et al., 1997). In addition, the incidence of accidental injury nearly doubles during the night shift compared to morning shift, while the severity of injury increases 23 percent (Smith et al., 1994). Night nurses make nearly twice the patient medication errors as day nurses and experience nearly three times the auto accidents commuting to and from work (Gold et al., 1993).

Akerstedt (1988) reviewed the effects of sleepiness from night shift work and found that the potentially hazardous situation resulting from increased sleepiness during night shift is real and underestimated. Akerstedt (1988) also reports that fatigue in shift workers is higher than in day workers, highest in night workers, followed by morning workers. Overall, sleepiness among night workers is estimated to be around 80 to 90 percent. Roth et al. (1994) indicate that rates for workers falling asleep on the job while on night shift have been reported to be as high as 20 percent.

Night operations are physiologically different than day operations due to circadian trough and sleep loss. This carries a higher physiological cost and imposes greater risks of accidents. One of the most established safety issues is working in the circadian trough between 0200 and 0600. During this period workers experience considerable sleepiness, slower response times, increased errors and accidents (Mitler, 1991; Pack, 1994). Many recent accidents from various transportation modes have been associated with this circadian trough (Lauber & Kayten, 1988). Lyman and Orlady (1981), in their analysis of the Aviation Safety Reporting System researcher state that 31 percent of incidents occurring between 2400 to 0600 hours were fatigue related.

Gander et al. (1996) found that overnight cargo pilots exhibited partial adaptation to night work with a nearly 3-hour phase shift in the lowest body temperature, with subjective fatigue and activation peaking shortly thereafter. Despite this, pilots still experienced a three-fold increase in multiple sleep episodes (53 percent versus 17 percent) and a 1.2 hour sleep debt per night compared with pre-trip sleep length.

In some cases, the high fatigue levels found may be due to time since the last sleep. Pokorny et al. (1981) analyzed bus driver accidents over a five-year period and found that, although the time of day affected some incidents, one of the most important factors in driver accidents was how early drivers reported to work. Those reporting in between 0500-0600 had about six times as many the accidents as those reporting between 0700-0800. A peak in accidents also occurred two to four hours after beginning the shift.

If an individual has been awake for 16 to 18 hours, decrements in alertness and performance are intensified. If time awake is extended to 20 to 24 hours, alertness can drop more than 40 percent (WRAIR, 1997; Morgan et al., 1974; Wehr, 1996). A study of naval watch keepers found that between 0400 to 0600, response rates drop 33 percent, false reports rates 31 percent, and response speed eight percent, compared with rates between 2000 to 2200 hours (Smiley, 1996).

Samel et al. (1996) determined that many pilots begin night flights already having been awake more than 15 hours. The study confirms the occurrence of as many as five micro-sleeps per hour per pilot after five hours into a night flight. They also found that 62 percent of all pilots studied rated their fatigue great enough to be unable to fly any longer after their night flight. This explains earlier findings in long haul return night flights that showed significant physiological markers of higher stress. Upon return to home base after flying two night flights (outbound and return) pilots average 8 to 9 hours of sleep debt. Although flights varied from north-south and east-west with layover length from 14 hours to 4.5 days, sleep debt appeared similar. East-west flights had significantly longer layovers but were disruptive to circadian rhythms. The authors concluded that "During day time, fatigue-dependent vigilance decreases with task duration, and fatigue becomes critical after 12 hours of constant work. During night hours fatigue increases faster with ongoing duty. This led to the conclusion that 10 hours of work should be the maximum for night flying."

Gander et al. (1991) found in an air carrier setting that at least 11 percent of pilots studied fell asleep for an average of 46 minutes. Similarly, Luna et al. (1997) found that **U.S.** Air Force air traffic controller fell asleep an average of 55 minutes on night shift. A possible explanation for these sleep occurrences, in addition to circadian nadir, is the finding of Samel et al. that many pilots begin their night flights after being awake for as long as 15 hours.

The effect of time since the last sleep is even greater if a sleep debt already exists. ***An*** NTSB heavy trucks accident analysis (NTSB, 1996) clearly shows that "back of the clock" driving with a sleep debt carries a very high risk. Of 107 single-vehicle truck accidents, 27 drivers exceeded the hours of duty. Ninety-two percent (26) of these had fatigue-related accidents. The NTSB report also shows that 67 percent of truck drivers with irregular duty or sleep patterns had fatigue-related accidents compared to 38 percent in drivers with regular duty or sleep patterns. Irregularity resulted in a decrease of 1.6 hours on average in sleep with a total of only 6.1 hours compared to 7.7 hours in regular pattern drivers. The NTSB report indicated that they could not determine whether irregular duty/sleep patterns per se led to fatigue but some experimental data support this notion. The findings of the NTSB not only found shifted sleep patterns but this shift was coupled with sleep loss. Taub and Berger (1974), while maintaining sleep length, shifted sleep times and found that performance on vigilance, calculation tasks, and mood were significantly impaired. Furthermore, Nicholson et al. (1983) showed that irregular sleep/work resulted in increasing performance impairments which was further increased by time on task, cumulative sleep loss, and working through the circadian nadir.

Performance can also be affected by cumulative fatigue buildup across multiple days. Gundel (1995) found that pilots flying two consecutive nights with 24 hours between flights slept about two and a half hours less during their daytime layovers (8.66 hours versus 6.15 hours), and experienced a significant decline in alertness on the second night flight. Alertness during the first six hours in both flights appeared to be the same. The latter part of the second flight showed increased desynchronization of EEG alpha wave activity, indicating lower levels of alertness. Spontaneous dozing indicated an increased susceptibility sleep. Subjectively, pilots felt greater fatigue on the second night. Therefore, with time since awake being the same, sleep quality and quantity during the daytime layover resulted in increased fatigue.

Samel et al. (1997) monitored 11 night flight rotations from Frankfort to Mahe/Seychelles crossing three time zones. Pilots slept on average eight hours on baseline nights. On layover, sleep was reduced to 6.3 hours. Pilots arrived at SEZ after 22 hours of being awake (except for approximate 1.5 hour nap prior to departure). Fatigue scores increased over both outbound and inbound flights with 12.4 micro-sleeps per pilot outbound and 24.7 on return. Prior to the outbound FRA-SEZ flight 85 percent of pilots felt rested whereas on return only 30 percent reported feeling so. These studies document that night flights are associated with reduced sleep quantity and quality, and are accompanied by cumulative sleep debt.

Borowsky and Wall (1983) found that flight-related accidents in Navy aircraft were significantly higher in flights originating between 2400 and 0600 hours. The higher mishap incidence was felt to be the result of circadian desynchronization and disrupted sleep-wake cycle. Sharppell and Neri (1993) divided the operational day of navy pilots in Desert Shield and Desert Storm operations in to four quartiles beginning at 0601-1200 with 0001 to 0600 being the fourth quartile. They found that there was a progressive increase in pilots' subjective need for rest between flights as flights originated later and later in the day from quartile 1 to quartile 4. In addition multiple missions and cumulative days flying also increased the pilots subjective need for additional rest between missions. The latter effect is the cumulative effect of fatigue. As sleep time increased before a flight the subjective rest needed before the next flight decreased.

Sleep Patterns During The Day

Simply providing pilots with the opportunity to rest during the day may not be sufficient to compensate for the demands of night flying. Night workers have been shown to sleep on average one and a half hours less each day than day workers (Minors & Waterhouse, 1984). Depending on type of shift and rotation, there can be as much as three hours sleep deficit. Czeisler et al. (1980) showed that sleep duration was dependent on the circadian phase. Thus daytime sleep was significantly reduced compared to night time sleep.

The propensity to sleep is high during the night and low during the day. But there is a gradient effect in sleepiness. Between six and 12 hours awake, sleepiness in control subjects increased seven percent; between six and 18 hours, 28-37 percent (Minor & Waterhouse, 1987; Minor et al., 1986). This is the result of a myriad of other rhythms—hormonal, secretory, temperature—that orchestrate an internal environment for action during the day and for rest at night. The effect of circadian rhythm on performance is illustrated in the findings of a sleep deprivation study on multi-task performance. Czeizler et al. (1994) points out that alertness and performance would normally decline as a function of time since awake, except when coupled to the circadian rise in body temperature, the two functions stay relatively stabile through most of the waking hours. The beginning of a drop in alertness starts three to four hours prior to normal bedtime. At bedtime there is a sudden and dramatic—1 8-20 percent—fall in performance and alertness, coinciding with the rapid drop in body temperature.

Night work which requires daytime sleep has been shown to reduce the amount of sleep obtained whether on permanent night or rotating shifts (Colligan & Tepas, 1986). In quick changeovers with 8 hours off between shifts, Totterdell (1990) found workers only acquired 5.14 hours sleep. Kurumatani (1994) observed that workers getting off at 1600 hrs and required to began again at 2400 hours slept 2.35 hrs. On a similar shift change but getting off 1200 hrs and returning to duty at 2400 hrs workers were only able to get 3.0 hrs sleep. These researchers found a correlation (r=.95) between the hours between shift and sleep duration. They concluded that at least 16 hours off duty time were needed between shifts to insure 7-8 hour sleep, a conclusion reiterated in a recent review (Kecklund & Akerstedt, 1995).

Transmeridian Operations

Transmeridian operations create similar problems in attempting to work when the body wants to sleep and sleep when the body wants to be awake. The biggest challenge posed by multiple time-zone flights is the time required for the body to adjust to the new time zone. The period of adjustment appears to depend on the direction of travel. Adjustment appears to be faster after westward flights than eastward flights (Klein & Wegmann, 1980). Adjustment following westward flights appears to occur at a rate of about 1.5 hours per day while eastward-flight adjustment occurs at about 1 hour per day. This may be due to the body's inherent tendency to lengthen its period beyond 24 hours, which coincides with westward flights. These data also suggest that phase shifts below six hours can have a significant impact (Aschoff et al., 1975).

Aside from the obvious implications for transmeridian operations, these data also apply to reserve pilots whose protected sleep opportunity may vary as to its occurrence across assignments. Even if a protected time period is predictable, unless it includes the night hours, it may not provide an effective opportunity for sleep and thus may not lessen fatigue.

Conclusions

The following conclusions can be drawn from the research cited above:

- An individual's WOCL should be defined on the basis of the time zone where he/she resides, which may be different from the home domicile.
- Duty periods conducted during WOCL already carry a fatigue penalty due to the circadian cycle. Consequently, duty periods involving WOCL should be reduced.
- The number of duty periods involving WOCL that must be performed without time off should be limited.
- Because the circadian cycle is longer than 24 hours, each duty period should start later than the previous duty period.
- Reserve assignments should attempt to maintain a consistent 24-hour cycle.

- Direction of rotation for both back-of-the-clock flying and direction of transmeridian operations should be considered. Given the body's preference for extending the day, backward rotation should be used when possible.
- Transmeridian operations should be scheduled in accordance with either of two approaches:
  - For short periods, it may make sense to attempt to keep the pilot on home-domicile time.
  - For longer periods, reducing the duty period and providing more opportunities to sleep may be the best approach.

Augmented Crews

Little research has been performed to assess the effectiveness of managing fatigue through the use of augmented flight crews. However, two recent NASA projects have been initiated to study long-haul augmented flight operations (Rosekind et al., 1998). The first project used a survey to examine factors that promoted or interfered with sleep in crew quarters installed on aircraft. Results were collected from more than 1,400 crewmembers from three participating U.S. airlines. It was concluded that, even though some difficulties were noted, flight crewmembers were able to obtain a reasonable amount and quality of sleep while resting in on-board bunks. Further, the sleep obtained was associated with improved alertness and performance. This study also identified factors that could be used to develop strategies to obtain optimal sleep.

The second project was a field study that examined the quantity and quality of sleep obtained in on-board bunks during augmented, long haul flights. Data were collected from two airlines involved in different types of international operations, and a corporate operator. Preliminary results showed that crewmembers obtained a good quantity and quality of sleep. Additional analyses are presently being conducted.

Conclusion

A review of the scientific literature pertaining to fatigue, sleep, and circadian physiology was performed in order to identify the major issues that need to be considered in developing a regulatory approach to pilot fatigue and sleep debt. The conclusions developed for each issue reflect areas that might benefit from additional FAA consideration.

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