Crew Rest and Duty Restrictions for Commercial Space Flight: Recommendations Based Upon the Scientific Literature

August 30, 2007

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Final Report
DOT Volpe Center Contract No. DTRT57-05-D-30103, Task Order #10
Subcontract Purchase Order 4600003368 from The Aerospace Corporation

Prepared for
Volpe National Transportation Systems Center
U.S. Department of Transportation
Cambridge, MA 02142

PUBLIC RELEASE IS AUTHORIZED

CLEMSON UNIVERSITY

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (FROM - TO)
30-08-2007	Contractor Final Report	April 16 – August 30, 2007

4. TITLE AND SUBTITLE

Crew Rest and Duty Restrictions for Commercial Space Flight: Recommendations Based Upon the Scientific Literature

5A. CONTRACT NUMBER
DTRT57-05-D-30103

5B. GRANT NUMBER

5C. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)*

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5D. PROJECT NUMBER
FA2R DL411

5E. TASK NUMBER
Task Order #10

5F. WORK UNIT NUMBER
FA2R DL411

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Research and Innovative Technology Administration
Volpe National Transportation Systems Center
Aviation Safety Division
Cambridge, MA 02142-1093

8. PERFORMING ORGANIZATION REPORT NUMBER
DOT-VNTSC-FAA-07-11

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Aviation Administration
Office of the Assoc. Administrator for Commercial Space Transportation
Washington, DC 20591

10. SPONSOR/MONITOR'S ACRONYM(S)
FAA AST-200

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
PUBLIC RELEASE IS AUTHORIZED.

13. SUPPLEMENTARY NOTES
*Clemson University, 121 Freeman Hall, Box 340290, Clemson, SC 29634-0920, subcontractor to The Aerospace Corporation, El Segundo, CA 90245-4691, under contract to the Volpe National Transportation Systems Center -- Contract No. DTRT57-05-D-30103, Task 10.

14. ABSTRACT
Although the current crew rest and duty restrictions for commercial space transportation remain in place, the Federal Aviation Administration (FAA) continues to review the regulation on a regular basis for validity and efficacy based on input from scientific and operational communities. As a result, the FAA in cooperation with the Volpe Center and Aerospace Corporation commissioned Clemson University to review the scientific literature pertaining to crew rest and duty restrictions and to provide recommendations for those involved in commercial space transportation. This report reviews the scientific literature with regard to sleep, fatigue, and shift work. A selected review of existing crew rest and duty restrictions for the aviation industry is also reported. Recommendations are made for suborbital and orbital crew rest and duty based upon our current understanding of sleep, fatigue, and shift work.

15. SUBJECT TERMS
Commercial Space Transportation, Regulation, Reusable Launch Vehicles, Crew Rest

16. SECURITY CLASSIFICATION OF: A. REPORT	B. ABSTRACT	C. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19A. NAME OF RESPONSIBLE PERSON
U	U	U	UU	16	Ann R. DiMare

19B. TELEPHONE NUMBER (INCLUDE AREA CODE)
(617) 494-2757

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CREW REST AND DUTY RESTRICTIONS FOR COMMERCIAL SPACE FLIGHT: RECOMMENDATIONS BASED UPON THE SCIENTIFIC LITERATURE

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INTRODUCTION

In the interest of ensuring the safety of commercial space transportation, the Federal Aviation Administration (FAA) has developed rest and duty restrictions for Code of Federal Regulations (CFR) parts 417 - Launch Safety, 431 - Launch and Reentry of a Reusable Launch Vehicle (RLV), and 437 - Experimental Permits. These regulations were based upon crew rest requirements imposed by the Air Force at Federal launch ranges.

Although the current crew rest and duty restrictions remain in place, the FAA continues to review these regulations on a regular basis for validity and efficacy based on input from the scientific and operational communities. Consequently, when the FAA published the Experimental Permits for Reusable Suborbital Rockets final rule in 2007, it noted within the preamble that "Although the FAA is adopting the requirements [*duty and rest*] as proposed it does, however, intend to give [*the airline pilots association*] ALPA's comments and this issue the study and attention they deserve." Prior to the final rule, ALPA suggested "that the public interest is best served by a rest rule that incorporates principles that can be shown to provide fidelity to current scientific research and literature in the area of fatigue."

With this in mind, the FAA in cooperation with the Volpe Center and Aerospace Corporation commissioned Clemson University to review the scientific literature pertaining to crew rest and duty restrictions and provide recommendations for those involved in commercial space transportation. The goal of this effort therefore was to contribute to an improved commercial space transportation safety system by ensuring that ground support personnel and flight crewmembers are afforded the opportunity to obtain sufficient rest to safely perform their routine and emergency duties.

SLEEP

The literature is replete with studies demonstrating the impact a lack of sleep, especially quality sleep, has on performance. In general, the consequences of sleep loss and associated fatigue have been shown to negatively affect learning capacity (Curcio, Ferrara et al. 2006), memory consolidation (Karni, Tanne et al. 1994), mood (Dinges, Pack et al. 1997), alertness (Bonnet 1985), cognition (Cheshire, Engleman et al. 1992), coordination (Nakano, Araki et al. 2001), stress levels (Costa 1996), and reaction time (Vgontzas, Pejovic et al. 2007). These effects appear to be independent of the type of work being performed as deficits have been documented in areas as diverse as education (Curcio, Ferrara et al. 2006), healthcare (Montgomery 2007), driving (Lyznicki, Doege et al. 1998), manufacturing (Blachowicz and Letizia 2006), aviation (Bourgeois-Bougrine, Carbon et al. 2003), and more germane to this review - commercial space transportation (NTSB, Orbital Science Corp Mishap).

Arguably, all humans have experienced mental fatigue more than once in their lifetime and many have learned to cope with the adverse effects. Even so, fatigue continues to be a common causal factor identified in many accidents including major disasters like the grounding of the Exxon Valdez, the meltdown at the Three Mile Island Nuclear Power Facility, and the explosion at the Bhopal Refinery (Rosekind, Gander et al. 1994). Nevertheless, while coping mechanisms can be incorporated to mitigate the adverse impact of fatigue, the only lasting solution is quality sleep (Caldwell 1997) and the best way to promote quality sleep is through appropriate scheduling and rest requirements (Haus and Smolensky 2006).

Issues associated with how much sleep individuals need, when that sleep should be obtained and what quality sleep entails continues to be debated by scientists, management, and the workforce. However, one thing we can all agree on is that out of necessity, all humans must sleep. However just as eating does not make one a nutritionist neither does sleeping make everyone an expert in sleep and fatigue. Therefore, to fully understand human sleep one must first understand a little about circadian rhythms and sleep architecture.

Circadian Rhythms

The word "circadian" is actually derived from two Latin words *circa* (about) and *dias* (day). Indeed, circadian rhythms are biological processes that in most environments cycle about a normal 24-hour day regulating a variety of physiological processes, including: body temperature, neurotransmitters, hormones like cortisol and melatonin, heart rate, and core body temperature (Blatter and Cajochen 2007) . Indeed, the latter, core body temperature, may be the most sensitive and easily obtained measure of circadian rhythmicity. However, as important as those physiological processes are, even more important to space transportation is that performance is also directly related to one's circadian rhythm and the sleep/wake cycle (Fuller, Gooley et al. 2006).

As can be seen in Figure 1 the circadian rhythm and as a result, performance and sleepiness/alertness, generally reach a minimum between 3 a.m. and 6 a.m., known as the circadian trough (nadir), and a maximum (peak) between 2 and 8 p.m. (Waterhouse, Drust et al. 2005).

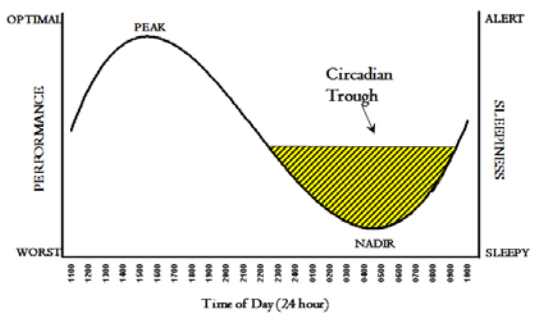

Figure 1. The human circadian rhythm.

Thought to be generated by the suprachiasmatic nucleus within the hypothalamus of the brain, the circadian rhythm is actually about 25 hours, not 24 as observed in most individuals. However, the circadian rhythm is "reset" to 24 hours daily by a series of external references, called zeitgebers (Revell and Eastman 2005). The most powerful of these zeitgebers is natural daylight (Lack and Wright 2007). In simple terms, the presence of sunlight signals the circadian pacemaker that it is day time, while the absence of sunlight indicates night time (Skene and Arendt 2006). With a few notable exceptions like Alaska and other polar regions where the normal light-dark cycle can be markedly different, daytime and nighttime cycles about a 24-hr day.

While sunlight is arguably the most important zeitgeber other references like social cues, meal times, exercise, and levels of naturally occurring hormones produced by the body can influence circadian rhythmicity (Eastman, Hoese et al. 1995; Revell and Eastman 2005; Grandin, Alloy et al. 2006). Regardless of the mechanism however, it is important to note that, the circadian pacemaker remains remarkably stable from day-to-day even in the presence of abrupt external changes such as sleep deprivation and/or time-zone changes (Beersma and Gordijn 2007).

Although consistent within an individual, circadian rhythms do vary slightly from person to person particularly as one gets older (Akerstedt 2007). For instance, there is some evidence that a subset of the population are naturally suited to day work (so-called morning larks) and others to night work (night owls) - yet this may be more subjective than physiological. Likewise, as people age it appears that their circadian rhythms shifts earlier in the day causing earlier rise and bed times (Gander, Nguyen et al. 1993).

Stages of Sleep

Recall that just as performance cycles about the circadian rhythm so do sleepiness and fatigue. Fortunately, sleepiness and fatigue are acute conditions typically relieved by a good night's sleep. Nevertheless, sleep is not just an opportunity to recharge one's batteries and dream. Nor is all sleep the same.

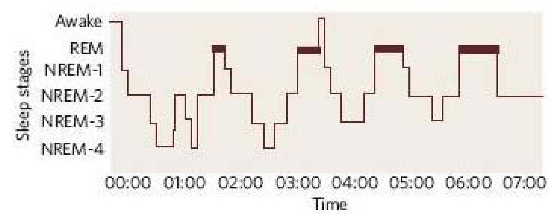

Figure 2. The typical sleep cycle for an adult.

Throughout the course of a sleep period, the body shifts through several stages of sleep characterized by changes in brain activity (Figure 2). The first stage (Figure 2; non-rapid eye movement stage 1 or NREM-1) is brief and consists of very light, transitional sleep. The second stage (Figure 2; NREM-2) is also a fairly light sleep and typically makes up the largest amount of total sleep time over the course of a sleep period. The third (Figure 1; NREM-3) and fourth stages (Figure 1; NREM-4) represent a deeper sleep characterized by slow wave brain activity. It is during these deeper slow wave sleep (SWS) stages where the recuperative work of sleep takes place. The final sleep stage involves rapid eye movement (Figure 2; REM) sleep involving brain activity that resembles being awake and is often associated with dreaming. While it is still unclear what role REM sleep plays, some believe that during REM sleep memories are consolidated and learning is reinforced (Karni, Tanne et al. 1994). Of note, as people age the normal sleep architecture becomes distorted with less time spent in SWS and REM sleep and more time in lighter stages of sleep (Gander, Nguyen et al. 1993; Van Cauter, Leproult et al. 2000).

The Best Time to Sleep

It is well established that the circadian rhythm plays a key role in controlling both the duration and quality of sleep (Beersma and Gordijn 2007). As a person nears the circadian trough several physiological and psychological changes take place including a drop in core body temperature, an increase in melatonin levels, and a natural increase in the pressure to sleep (Murphy and Campbell 1997). Even more important to commercial space travel, during the circadian trough a person’s alertness level decreases, their cognitive abilities drop, and performance reaches a minimum (Nakano, Araki et al. 2001). Clearly then, it appears that humans are “designed” to sleep during the night and operate during the day – we are not nocturnal animals. In fact, sleeping outside of the circadian trough often results in reductions in total sleep time, fragmented sleep, less SWS and REM sleep, and performance deficits (Akerstadt, Hume et al. 1997).

The Effect of Sleep Disruptions

In addition to sleeping during the circadian trough, it has been shown that sleep continuity is also a prominent factor influencing sleep quality (Wesensten, Balkin et al. 1999). Evidence suggests that periods of continuous sleep allow the body to reach the deeper, more restorative stages of sleep. In fact, it has been suggested that sleep which is disrupted can actually be more detrimental than no sleep at all because the body is unable to reach the deeper more restorative stages of sleep (Bonnet 1985).

Not only does waking up during the circadian trough result in a decrease in total sleep time and subjective sleep quality but it has also been shown to increase stress levels (Kecklund, Akerstedt et al. 1997). To make matters worse, when sleep disruptions are combined with the stress associated with highly demanding jobs and personal troubles, the effects on the individual can be exacerbated. In effect, a veritable “Catch-22” is created as disruptions in sleep cause stress which in turn can lead to known health effects made worse by job and life stress which in turn produces further sleep disruptions and other sleep-related problems (Akerstedt, Knutsson et al. 2002; Knudsen, Ducharme et al. 2007). One need look no further than the aviation accident record to find numerous examples of how sleep disruptions among aircrew during layovers and while off duty have impacted performance. To the extent that the experience of commercial space flight crews may be similar to their commercial aviation counterparts, this would seem to be an area of concern for the FAA and operators alike.

Sleep Requirements

While there are some individual differences, the scientists seem to agree that the average person needs roughly 8 hours of sleep each night to be properly refreshed (Akerstedt, Hume et al. 1997). A decrease by just a few hours from the recommended amount to as little as five hours of sleep per night can cause serious performance decrements (Dinges, Pack et al. 1997). More important, successive nights of sleep loss can lead to a condition known as *sleep debt*.

As the name implies, this sleep debt must be made up for to have a full recovery (Hardaway and Gregory 2005). Even a loss of 1-hour of core sleep per night can lead to performance deficits over time as seen in Figure 3. However, consecutive nights of 2, 3, and 4 hours of sleep per night can lead to alarming performance deficits. While there is not a one-to-one payback of sleep debt, it is known that after a week of sleeping five hours a night, it can take up to two full nights of sleep to fully recover (Dinges, Pack et al. 1997).

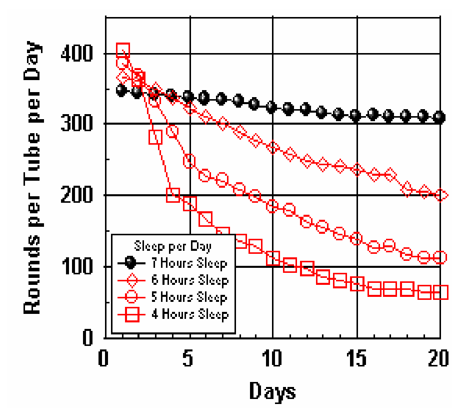

Figure 3. Performance deficits as a result of days of cumulative sleep loss (Source: Department of Behavioral Biology, Walter Reed Army Institute of Research.

Summary

- While all sleep is beneficial, SWS is more recuperative.
- The best time to sleep is during the circadian trough (between 2200-0800).
- Interruptions of nighttime core sleep reduce sleep quality and effectiveness.
- Individuals need roughly 8 hours of sleep to be properly refreshed.

- Sleep loss is cumulative and may take multiple nights of sleep to fully recover.

COUNTERMEASURES TO FATIGUE AND INSOMNIA

Ideally, people would always have the opportunity to obtain the quantity and quality of sleep necessary to ensure maximum performance. Unfortunately, there are many circumstances in which adequate sleep cannot be obtained. In these cases there are some options available to minimize the effects of inadequate sleep. In the case of fatigue, these are only short term fixes and should not be relied upon as long-term solutions. Some commonly used countermeasures to fatigue and insomnia are presented in **Table 1** and are discussed briefly below.

Table 1. Countermeasures to fatigue and insomnia.

FATIGUE	*INSOMNIA*
Non-Pharmacological	**Non-pharmacological**
Napping	Diet
Light Exposure	Exercise
Pharmacological	Routine Sleep Times
Caffeine	**Pharmacological**
Other Stimulants	Melatonin
	Alcohol
	Sedatives

Fatigue

Napping **-** Many people experience some form of fatigue during the following day as a result of sleep loss/disruptions. In these instances, daytime napping has been found to be an effective non-pharmacological countermeasure to fatigue. Napping has also been found to be especially beneficial when taken before the night shift or when an individual is required to remain awake when he/she would otherwise be asleep (Petrie, Powell et al. 2004).

That being said, the larger question is "how long does a nap have to last to be effective?" Not surprising, naps of 1-2 hours have been shown to significantly increase the level of alertness and to a lesser extent the level of performance (Vgontzas, Pejovic et al. 2007) and memory (Tucker, Hirota et al. 2006). However, even naps as short as 10 minutes can be restorative (Brooks and Lack 2006). Still others have demonstrated that naps as brief as 15 to 20 minutes increase the alertness levels of workers and increase the accuracy in vigilance tasks (Purnell, Feyer et al. 2002; Takahashi, Nakata et al. 2004).

Curiously, the point in the circadian cycle when a nap occurs does not seem to influence accompanying improvements in alertness, meaning that the time a nap is taken does not affect the benefits of the nap. Furthermore, the effects of sleep inertia, grogginess immediately following waking, do not appear to be a concern when short naps (i.e, less than 1 hour) are taken (Driskell and Mullen 2005).

Light Exposure - Exposure to bright light is another effective means to address fatigue. Recall that the light/dark cycle in humans plays an important role in synchronizing the circadian pacemaker (Duffy, Kronauer et al. 1996). Not surprising then, the exposure to specific types of bright light (i.e., those that simulate the natural wavelengths seen in sunlight) may be used to phase delay the body's circadian rhythm in some operational settings (Boivin and James 2002) and may also help in overcoming the effects of jet-lag due to rapid scheduling changes (Wetterberg 1994; Caldwell 2005; Revell and Eastman 2005; Lack and Wright 2007).

Perhaps more important to personnel working within space transportation, it has been shown that a single 4-hour exposure to light on the first day of the night shift can phase-delay the secretion of melatonin by 2-hours and thus delay the onset of sleepiness and fatigue and improve performance on the night shift (Dawson and Campbell 1991). Dark glasses may also help avoid resynchronization to the natural circadian rhythm and allow workers to adapt more quickly to nighttime shift work (Eastman, Stewart et al. 1994; Yoon, Jeong et al. 2002). There is also some evidence that bright light exposure during the day may help with fatigue by promoting better nocturnal sleep for workers (Wakamura and Tokura 2000).

Caffeine - Because of its abundance, over the counter availability, minimal side effects and low cost, caffeine is perhaps the most commonly used pharmacological countermeasure to fatigue. The use of caffeine improves performance and vigilance during periods of sleep deprivation (Caldwell 2005; Dagan and Doljansky 2006;Phillip, Taillard et al. 2006). Caffeine also improves reaction time. The use of 300-mg of caffeine may sustain performance levels for a period of 24 hours (Caldwell and Caldwell 2005).

In fact, some have suggested that when sleep needs to be delayed for a longer period of time, low doses of slow release caffeine may be a better countermeasure to fatigue than a nap (De Valck, De Groot et al. 2003). Then again, the use of caffeine as a countermeasure to fatigue might not be effective for all people. For instance, frequent users of caffeinated products may build a tolerance that renders the benefits of caffeine useless (Caldwell 2005). After 18 days of chronic use, many if not all individuals experience a complete tolerance to the effects of caffeine (Caldwell and Caldwell 2005).

Stimulants **–** Although less common in most civilian settings, the use of prescription and over the counter stimulants have also been used as a countermeasure to fatigue. For example, amphetamines have been used in some military operations but are still restricted from use in commercial aviation. Likewise, dextroamphetamine has been shown to improve pilot performance during sustained wakefulness (Caldwell 2005; Caldwell and Caldwell 2005; Wesensten, Killgore et al. 2005; Eliyahu, Berlin et al. 2007) while methamphetamine appears to improve performance in shift workers (Hart, Haney et al. 2005).

Unfortunately, the use of stimulants is accompanied by side effects which include the possibility of addiction and cardiovascular problems (Caldwell 2005). However, more recently, the use of modafinil, a stimulant boasting fewer side effects than traditional stimulants, has been researched as an alternative to other stimulants (Caldwell 2005; Gill, Haerich et al. 2006; Eliyahu, Berlin et al. 2007). Modafinil has also been given in multiple doses over a work shift to sustain wakefulness and improve vigilance (Lagarde and Batejat 1995).

Insomnia

Sleep hygiene refers to a group of behaviors that are typically utilized along with pharmacological aids to reduce insomnia. Like countermeasures addressing fatigue, those effective in reducing insomnia generally fall into two categories: non-pharmacological and pharmacological counter-measures.

Diet - One aspect of good sleep hygiene is diet. While the reasons for insomnia in shift workers vary, in general differences in the timing of meals, the unavailability of well balanced meals at night, and snacking all contribute to difficulties with sleeping (Atkinson and Davenne 2007). That being said, people who suffer from insomnia should avoid large meals (Morin 2006) and foods with high sugar or caffeine contents before bedtime (Atkinson and Davenne 2007).

Exercise - Another aspect of good sleep hygiene is exercise. Exercise later in the day can increase the depth and length of sleep during the night (Caldwell 1997). It appears that the increase of body temperature from exercise is associated with a faster sleep onset (Stepanski and Wyatt 2003). However, the timing of the exercise is important. Evidence suggests that exercise should be completed 5-6 hours before bedtime and avoided within 3 hours of sleep (Morin, Hauri et al. 1999; Morin 2006).

Routine sleep times - Creating a night time routine is also part of good sleep hygiene. Having a consistent bedtime and wake-up time may help in the treatment of insomnia (Caldwell 1997; Morin, Hauri et al. 1999). It has been suggested that having a consistent bedtime will begin to build a connection between the time of day and sleep, and eventually your body will start to automatically fall asleep at the same time every night (Caldwell 1997).

Melatonin - Melatonin is a naturally occurring chemical in the body that is known to induce sleep. As one might expect, the release of melatonin in the body depends on retinal light exposure. Put simply, sunlight inhibits melatonin release while the lack of sunlight permits natural melatonin stores to be released, inducing the onset of sleep (Cardinali, Furio et al. 2006; Skene and Arendt 2006).

If administered properly, exogenous melatonin (melatonin not naturally made by the body) administration has been used to phase shift the sleep cycle to overcome shift work or jetlag (Melatonin 2005; Skene and Arendt 2006). To overcome jetlag and shift work the onset of sleep either needs to be sped up or slowed down. When traveling eastwards or trying to sleep after working the night shift, administration of melatonin will speed up the onset of sleep and allow those affected to get onto the sleep cycle they desire. Melatonin can also be used to speed up the initial onset of sleep for people with insomnia.

Sedatives - Sedatives have been commonly used as a countermeasure to insomnia within the general population. However, within the civil aviation field, the use of sedatives and other hypnotics which induce sleep are generally banned (Caldwell 2005). Nevertheless, sedatives have been shown to be useful for inducing sleep at times when or in places that are not necessarily conducive to sleep (Caldwell and Caldwell 2005).

When considering the use of sedatives, care must be taken to choose the correct one. The available time for sleep must be considered, as sedatives with long half-lives (i.e., the time it takes to decay to half of the initial value), can cause performance decrements if a user is suddenly awoken for duty (Caldwell 2005; Caldwell and Caldwell 2005).

Antihistamines can also cause a sedative effect. However, like sedatives many antihistamines can produce drowsiness and decreased performance (Verster and Volkerts 2004). Notably however, all sedatives have detrimental effects on normal sleep architecture, the overall structure of a night's sleep. Sleep architecture includes succession of sleep cycles, the number of stages, and the length of time spent in each stage (Hirshowitz 2004).

Alcohol - The use of alcohol as a countermeasure to insomnia is generally not recommended. While the consumption of alcohol before bedtime has been shown to speed up the onset of sleep, like other sedatives, alcohol is known to disrupt normal sleep architecture leading to feelings of fatigue and sleepiness upon awakening (Vitiello 1997).

SHIFT WORK

Shift work is typically defined as work that occurs outside the hours of 7 a.m. to 6 p.m. (Blachowicz and Letizia 2006). Not at all uncommon, it has been estimated that somewhere between 20% and 25% of the U.S. population participates in some form of shift work (Akerstedt 1988; Costa 1996).

What makes this a topic of concern is that there is clear evidence that shift work can have a negative impact on worker performance and health (Haus and Smolensky 2006) regardless of the type of work being performed. For instance, prolonged shift work can lead to sleep disorders which in turn can cause medical (gastrointestinal and cardiovascular), social, economic, and quality of life problems (Schwartz and Roth 2006). Likewise, rotating shift work can also lead to a variety of health problems affecting body mass index, waist-hip ratio, and blood pressure (Sookoian, Gemma et al. 2007). Indeed, the circadian desynchronization and fatigue associated with rotating schedules can be quite severe and has been shown to lead to twice the accident rate of a fixed day or night shift (Gold, Rogacz et al. 1992).

Aviation

The effects of shift work are well documented within aviation (Rosekind, Gander et al. 1994). As one might expect, with long flights and multiple time zone changes aviation personnel often find themselves working at all times of the day and literally all points within their circadian rhythm (Lowden and Akerstedt 1998). Such operations can often lead to unintended sleep loss/disruptions particularly when aircrews are forced to sleep during a circadian peak. For instance, in a study of 12 British Airways pilots it was shown that both subjective and objective sleepiness increased during flights through the night. What's more, of these 12 pilots, 10 either involuntarily slept or showed evidence of sleepiness during the flight (Wright and McGown 2001).

Several scientific surveys have echoed similar concerns. For example, a survey of both long- and short-haul commercial airline pilots revealed that many aircrew have experienced fatigue effects directly related to shift work including small errors and slow response rates (Bourgeois-Bougrine, Carbon et al. 2003). In another study, nearly all the U.S. Army Aviation personnel surveyed reported that they had engaged in some form of shift work and nearly two-thirds said they did not get enough daytime sleep to properly adjust to the shift change (Caldwell and Gilreath 2001).

While obviously different than those involved in domestic flights, pilots involved in international flights are often required to fly outside of normal working hours over a period of several days. This has been shown to cause significant levels of fatigue and performance decrements – particularly during later flights in a trip (Petrilli, Roach et al. 2006). In addition to subjective feelings of fatigue and some cognitive effects, shift work has also been associated with a reduction in the ability of pilot's to visual search their environment – a particularly troubling finding given the visually demanding task of flying an aircraft (Suvanto, Harma et al. 1993).

Other 24/7 operations

Put simply, shift work is inherently fatiguing (Tvaryanas and Thompson 2006). Therefore, it should come as no surprise that the existence of shift work and subsequent fatigue extends far beyond aviation into many other service and industrial settings (Akerstedt 1988; Costa 1996). Consider, for example, healthcare. Roughly 30% of the full-time nurses surveyed by Blachowicz and Letizia, 2006 participated in some form of shift work or rotating schedule of day and night shifts.

Medical residents also face challenges associated with shift work and extended duty days. In fact, studies have shown that fatigued residents are at a higher risk of making serious medical errors (Surani, Subramanian et al. 2007). On the other hand, residents working a restricted schedule that allows for more sleep by limiting consecutive work hours to 16 hours have shown less than half as many attentional failures as residents on a more traditional schedule of 24-hours on-duty and longer (Lockley, Cronin et al. 2004). Similar shift work effects have also been identified for practicing physicians (Montgomery 2007).

Like physicians, truck drivers also frequently work through the night, a task that requires constant vigilance. Studies of truck drivers have revealed that they too experience higher levels of subjective and objective sleepiness during the circadian trough. In fact, in at least one study the degree of sleepiness could be predicted based on the total work hours of the driver and the time of arrival (Kecklund and Akerstedt 1993). These effects seem to be independent of whether the study took place on the road or in driving simulators (Rupp, Arnedt et al. 2004).

Firefighters face a slightly different challenge since they may have the opportunity to sleep during their shift but are subjected to sleep disruptions and abrupt waking during emergencies. A study involving waking firefighters up at different times during the night showed higher levels of subjective sleep complaints and irregular sleeping patterns particularly when woke up during the circadian trough (Takeyama, Itani et al. 2005).

Shift Work Scheduling Tools

To address fatigue related concerns associated with shift work, several shift work scheduling tools have been developed. While all offer some degree of assistance to those tasked with managing shift workers, differences do exist. To give the reader a sense of the variety of tools being used, a brief description of several will be presented below.

***TURNI*[1]** - TURNI (Abbink, Fischetti et al. 2005) was established for use by NS Reizigers, the Netherlands' Railway system, which operates 5,000 time-tabled trains per day with over 3,000 drivers and 3,500 conductors in 29 crew depots. The purpose of TURNI is to assign drivers and conductors to shifts and trains while following federally mandated laws and allocating the 'good' and 'bad' shifts fairly. This system adds in penalties for over-scheduling workers, multiple transfers, night shifts, and positioning shifts. The drawback of this system is that reassignment of duties due to disruptions is more difficult than with the manual distribution of duties.

***FAST* -** The Fatigue Avoidance Scheduling Tool (Eddy and Hursh 2001; Eddy and Hursh 2006). FAST was developed for use by the U.S. Air Force (USAF) as the computer user interface for their Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) model. The FAST interface allows the military scheduler to predict the performance levels of pilots based on past history such as sleep prior to assignment. FAST also allows for the construction of an optimal schedule based on the pilot's physiological condition and indicates when and if pharmacological aids will be needed to address fatigue.

What makes the FAST model particularly appealing is that it incorporates performance and alertness, sleep propensity and sleep intensity, equilibrium state, progressive sleep debt under extreme measures, and sleep timing. Recently the USAF has introduced the FAST interface to markets outside the military for potential use.

***ALTITUDE* -** ALTITUDE was developed for use by Air Transit in Canada which operates 18 aircraft and 1,200 flight legs per month with over 1,000 personnel. This model determines the best flight itinerary for each fleet, any repositioning of aircrafts needed, the release of aircraft, and maintenance schedules. The model incorporates maximum and minimum workload, the minimum rest time between scheduled flights for pilots, the maximum number of overseas trips without any time off, and other government and labor union contract rules while avoiding deadheads and minimizing the number of flight legs per duty period. The crew schedule for each month is completed in about three days and has helped lower the company's turnover rate (Desrosiers, Lasry et al. 2000).

***CrewResource Solver* -** The CrewResource Solver (Yu, Pachon et al. 2004) was developed by Continental Airlines which operates over 345 aircraft, 4,500 pilots and 1,100 flights daily. This model is composed of four modules: staffing, vacation, planning, and training. The staffing module incorporates pilot work hours based on contractual and government rules, identifies shortages and surpluses based on planned flight schedules and current staffing levels, and transfers or relocations of pilots based on their future flight schedule. The other modules incorporate vacation bids, training, available resources, new hires, and pilot availability.

***DISSY* -** DISSY (Emden-Weinert, Kotas et al. 2001) was developed for the European Union's bus and tram system. This model incorporates federal laws, union contracts and company agreements on weekly rests, nightly rests and maximum driving times. There is also a social aspect incorporated into the model that allows drivers to express their preference for shift types, duty types and days of the week. This model evenly distributes working times, hard shifts (shifts with multiple transfers) and length of shifts.

***ERG* -** ERG (Hare 1997) was developed for use by healthcare facilities and works with the ILOG's Solver library. This model generates shift rotations that satisfy staffing requirements, allows for part-time

[1] Unfortunately, several of the names of the shift work scheduling tools used acronyms that were undefined in any of the literature reviewed.

or full-time shifts and is flexible enough to be used to staff a variety of departments. The constraints of the model include baseline staff levels, minimum and maximum consecutive days worked, minimum and maximum number of hours per shift and week, shift change restrictions and allowable shifts.

CREW REST AND DUTY TIME REQUIREMENTS

In order to be fully alert and at optimal performance levels for flight, requirements for crew rest and duty/flight restrictions have been developed governing bodies worldwide. A sampling of those requirements for air carriers and NASA are reviewed briefly below.

Crew Rest Requirements

Within the U.S. crew rest within the airline industry is defined as the period of time when the pilot is free of all duties and responsibilities from the airlines (FAA 2007C). However, the definition varies widely depending upon the regulating body involved. For example, within the European Union, crew rest does <u>not</u> include time spent positioning aircrew, travel from home to the reporting location and vice versa, or transfer from the crewmembers place of rest to place of duty. Put simply, any time spent traveling is not considered part of the twelve hours minimum required rest before commencing flight duty time (UK 2004).

The United States and Pakistan also have stipulations about travel built into their crew rest time restrictions. For both of these countries, any non-local travel time either to position the pilot for another flight or to return the pilot to home base is not counted as part of the rest period time. On the other hand, any local travel time to and from the place of rest is included in the designated rest period (CAA 1994; FAA 2007C).

Unfortunately, within the U.S. this inclusion of travel time in the mandatory rest period of ten hours has the potential to reduce a pilot's opportunity to sleep well below the recommended eight hours. For Pakistan, which only requires eight hours of rest or twice the preceding flight time the opportunity for actual sleep could be even less (CAA 1994). Curiously, the other countries examined in this review (Taiwan, Tonga, South Africa, Canada and Australia) do not mention whether or not travel time is included in rest time.

In our review of regulating bodies, it was interesting to see that Australia is the only country to make a distinction between sleep during the circadian trough and sleep at other times of the day. In a progressive move, Australia requires that pilots receive at least nine hours of rest encompassing the hours of 10:00 PM and 6:00 AM or the pilots must receive at least ten hours of rest (CASA 2004). This distinction of when sleep occurs and the amount of sleep needed corresponds to the higher quality of sleep obtained during the circadian trough (see above).

Flight/Duty Time Requirements

Most governing bodies make a distinction between duty time and flight time. Flight time is typically defined as the period of time between when the aircraft makes an initial movement away from a parked position at the point of origin until the aircraft is once again parked at the destination. In contrast, duty time is typically defined as the period of time between when a pilot reports for a flight assignment and when he/she is released from that flight assignment. In other words, duty time includes actual flight time and any administrative work that must be completed either for that assignment or in general.

With regard to flight time, it appears that requirements are fairly standard across the countries examined. Generally speaking, pilots are only permitted to accrue between eight and ten hours during a 24-hour period, with the U.S. limiting pilots to 10-hours. When considering seven consecutive days, flight time limitations range between thirty and forty hours with the U.S. and Australia allowing the least and Canada and Tonga allowing the most. For a one month, all countries examined have a limitation of one hundred hours except Canada which allows one hundred twenty hours. Finally, the maximum flight time in three hundred sixty five days ranges between nine hundred in the EU and Australia and fourteen hundred hours in the United States (CAA 1992; CAA 1994; CAA 2003A; CAA 2003B; CASA 2004; UK 2004; EU 2006; CCAA 2007A; CCAA 2007B; FAA 2007A; FAA 2007B). A summary of crew rest and duty restrictions for the countries examined in this study are provided in Tables 2 and 3 for non-augmented and augmented crews where additional "relief" pilots are included.

NASA Flight Rules

The National Aeronautics and Space Administration (NASA) have established scheduling constraints for onboard crew. Specifically, the limit of a crewmember's time awake during a mission is 16 hours except on days with pre- and post-launch hold time. In these situations, the crew day is limited to 18 hours. NASA has also established a standard sleep period of 8 hours with a minimum sleep period of 6 hours. If a mission is greater than 13 days in duration, all sleep periods must be of at least 8-hours. On shorter missions, NASA does not schedule consecutive days with less than 8-hours of sleep (Lopez 2004).

Table 2. Rest and Duty Time Restrictions for Single or Two Pilot Crews

	United States	European Union	United Kingdom	Taiwan	South Africa	Malaysia	Canada	Australia	Pakistan	Tonga
Max. flight time (hrs) in 24 hours	10	N/A	10	8- domestic 10- int.	8	N/A	8	8	N/A	N/A
Max. duty time (hrs) in 24 hours	14	13	N/A	12-domestic 14- int.	N/A	N/A	14	11	N/A	N/A
Max. flight time (hrs) in 7 days	30	N/A	N/A	32	32	N/A	40	30	35	40
Max. duty time (hrs) in 7 days	N/A	60	N/A	N/A	N/A	N/A	60	N/A	N/A	N/A
Max. flight time (hrs) in 30 (28) days	100	(100)	(100)	(100)	100	(100)	120	100	100	(100)
Max. flight time (hrs) in 365 days	1400	900	900	1000	1000	900	1200	900	1000	1000
Min.rest time (hrs) before duty	10	12 or as long as the preceding flight	12	10- domestic/ int. <8 18- int. > 8	N/A	N/A	8	9 between 10pm and 6am or 10	8 or twice the preceding flight time	N/A
Min. rest time (hrs) after duty	10	N/A	N/A	N/A	N/A	N/A	8	N/A	N/A	N/A

Table 3. Rest and Duty Time Restrictions for Augmented Crews

	United States	Taiwan	South Africa	Canada	Australia
Maximum flight time (hrs) in 24 hours	12 (Max. 8 hours on flight deck)	16 with berths; 12 with resting seats	N/A	12 flight deck time	14 of active duty
Maximum duty time (hrs) in 24 hours	16	18	N/A	14	16
Maximum flight time (hrs) in 7 days	30	32	N/A	40	30
Maximum flight time (hrs) in 30 (28) days	100	(100)	120	120	100
Maximum flight time (hrs) in 365 days	1400	1000	1000	1200	900
Minimum rest time (hrs) before duty	10	10- domestic/ int. <8 18- int. > 8	N/A	8	12
Minimum rest time (hrs) after duty	12 18 for multi-time zone flights	N/A	N/A	10	N/A

RECOMMENDATIONS FOR COMMERCIAL SPACE TRAVEL

As mentioned earlier, the FAA has already established crew rest and duty time restrictions for personnel involved with the operation of reusable launch vehicles (RLV). In general, the current regulations state that:

- No personnel will be scheduled for more than a 12-hour shift during the mission or preceding a reentry mission.
- A minimum of an 8 hour rest period is required after 12-hours of work.
- During the 7 day period prior to the start of the mission, a maximum of 60 hours can be worked.

- No person will work more than 14 consecutive days and after 5 consecutive days of 12 hour shifts, a 48-hour rest period must be given.

While not inherently dangerous, the scientific literature with regard to sleep and fatigue would suggest that modifications in the current crew rest and duty restrictions may be reasonable. This is particularly true when one considers that many critical factors affecting crew rest and fatigue remain largely unknown for the future of commercial space travel (e.g., domicile location, lodging, flight duration, restrictive work environments, workload and stress associated with zero-g flight). As such, we have taken a more conservative stance with regard to crew rest and duty time restrictions for flight crew and ground personnel involved with suborbital and orbital flight.

Suborbital Flight

Vehicle

Given the wide range of possibilities it is difficult to predict what commercial space transportation will look like in 50-100 years. However, in the near term it is anticipated that suborbital vehicles will be launched in either a horizontal or vertical trajectory or may even be launched by a carrier aircraft. Judging from early prototypes it is reasonable to expect that the flight deck of suborbital aircraft will be small – perhaps similar to a small business jet cockpit or the Apollo Command Module. The cabin will likely be equipped for 2-6 for passengers.

While 40-50 years down the road, the actual day-to-day operations may evolve into something more akin to traditional airline operations; it was assumed that launches will resemble NASA and current experimental operations with at least a 24-hour window and actual launches beginning in the early morning with multiple launch possibilities.

Flight crew

It is anticipated that the flight crew compliment initially will be two pilots and one flight engineer/cabin attendant. Preparation for flight is expected to take between 1-5 hours with actual flight lengths of 15-20 minutes in suborbital flight or more. Whether or not multiple missions will be flown by a single crew or multiple crews remains unknown. However, it is anticipated that the crew domicile will resemble current airline domiciles with homes located near the launch site or possibly a long distance away requiring extended commutes and hotel stays near the launch site prior to a mission.

***Crew Rest Recommendations* –** Recall that it is not only the duration of the sleep period but the timing of the sleep that is important. Therefore, to ensure that the flight crew and ground crew are well rested and performing at optimal levels, 8 hours of <u>uninterrupted</u> sleep should be received prior to and after any shift. Furthermore, sleep should not be induced by pharmacological means which are known to disrupt normal sleep architecture. Care should also be taken to ensure that the opportunity to sleep occurs during the circadian trough. If sleep is obtained at places other than an individual's domicile, it is quite possible that sleep will be of lower quality and therefore more sleep may be required when residing in temporary quarters (e.g., hotels and short-term rental properties).

Sleep and crew rest are <u>not</u> the same thing and are treated differently here. The current definition of rest is very general and the time allowed for rest often incorporates personal needs other than sleep. Therefore, any rest restrictions should include time to obtain 8 hours of sleep <u>plus</u> additional time for activities such as meals, personal hygiene, and transit to and from the workplace. With this in mind, a minimum rest period of 12 hours is recommended that allows for 2 hours on either side of required sleep.

Crew Duty Recommendations – Because the literature is arguably limited with regard to crew duty and flight time, we elected to base our recommendations on current restrictions targeting commercial aviation aircrews. Further, because of the largely unknown stressors associated with commercial space travel we chose the most conservative restrictions in place among the governing bodies examined.

It should be noted that within commercial aviation short-haul pilots are typically not augmented and often fly multiple flights per shift. Furthermore, given the nature of multiple legs flown they are exposed more frequently to the most stressful portions of the flight - takeoff and landing. Even if suborbital crews do not fly similar multi-mission days, it is recommended that during any 24-hour period no more than 8 hours involve actual flight time and that no more than 30 hours of flight time be accrued in a 7 day period (Table 4). Arguably however, even this recommendation may be too liberal since the number of suborbital flights that will be flown by a given crew during a shift and the stressors of multiple suborbital spaceflight are largely unknown. With an increase in the number of flights per day, performance may be affected and actual flight time restrictions and accompanying rest periods may need to be adjusted.

With regard to duty time, recall that it includes both flight time and time allotted for other administrative duties. As such, we would recommend that crew duty time not exceed 11 hours in a 24-hour period and no more than 60 hours within a 7-day period. When working for consecutive days, additional care may need to be taken to limit the time per shift worked. After 5 consecutive days of 11 hour shifts, a minimum 48-hour rest period is recommended. A 48-hour rest period should be sufficient to restore most performance deficits incurred.

Ground crew

Like flight crew, ground crew should receive 8 uninterrupted hours of sleep during the circadian trough (when possible) between shifts. Likewise, a minimum of 12 hours off duty should be afforded these personnel to ensure sufficient time exists for sleep, personal activities and transit time to and from the workplace. Using commercial aviation as a model, it is anticipated that most ground crew will not have a problem with poor quality sleep from residing at a temporary domicile since it is anticipated that they will likely live close to the launch site. If that assumption should prove false, provisions similar to flight crews should be enacted.

Shifts should last no longer than 12 hours within a 24-hour period. During any 7-day period, ground crew should not exceed 60 hours of duty time (Table 4). When work involves shifts during the circadian trough it is recommended that all shifts occurring during the circadian trough be followed by at least a single night of sleep during the circadian trough. In other words, two successive night shifts should be avoided.

While the data is lacking in this area, it is recommended that ground crews not be subjected to more than 14 consecutive days of work. When consecutive work days are required, care should be taken to limit time worked per shift. It is further recommended that after 5 consecutive days of 12-hour shifts, a minimum of 48-hours free from all duty should be given.

Orbital Flight

Vehicle

Like suborbital vehicles, it is anticipated that orbital vehicles will be launched in either a horizontal or vertical trajectory or may even be launched by a carrier aircraft. Furthermore it is difficult to predict what all commercial spacecraft will look like and therefore what the flight deck and cabin environment will look like. However, like suborbital vehicles it is reasonable to expect that the flight deck of suborbital aircraft will be small, very close quarters similar to a small business jet cockpit or the Apollo Command Module. The cabin will likely be equipped for 2-6 for passengers.

While the actual day-to-day operations will likely evolve into something more akin to traditional airline operations, it was assumed that launches will resemble NASA and current experimental operations with at least a 24-hour window and actual launches beginning in the early morning. However, unlike suborbital flights only a single launch is anticipated per day.

Flight crew

Like suborbital crews, the crew compliment will likely be two pilots and one flight engineer/cabin attendant. However, there may be an opportunity for augmented crews – particularly when flights in excess of 24 hours take place.

Preparation for flight is expected to take between 1-5 hours with actual flight lengths of 90 minutes to multiple days. It is anticipated that the crew domicile will resemble current airline domiciles with homes located near the launch site or possibly a long distance away requiring extended commutes and hotel stays near the launch site prior to a mission. With longer missions the domicile will likely be the vehicle where rest may be adversely impacted.

***Crew Rest Recommendations* –** Like suborbital flight crews, 8 hours of uninterrupted sleep should be received prior to and after any shift. Furthermore, sleep should not be induced by pharmacological means which are known disrupt normal sleep architecture. Care should also be taken to ensure that the opportunity to sleep occurs during the circadian trough. If sleep is obtained at places other than an individual's domicile (whether that be in space or in a hotel near the launch site), it is quite possible that sleep will be of lower quality and therefore more sleep may be required.

Crew rest restrictions should include time to obtain 8 hours of sleep plus additional time for activities such as meals, personal hygiene, and transit to and from the workplace. Therefore, a minimum rest period of 12-hours is recommended thereby allowing for 2-hours of personal activity on either side of required sleep.

Crew Duty Recommendations – Because of the largely unknown stressors associated with commercial space travel we have chosen the most conservative restrictions in place among the governing bodies examined. However, unlike suborbital crews, missions involving multiple days will likely have augmented crews working around the clock.

With this in mind, it is recommended that during any 24-hour period no more than 8 hours involve actual flight time and that no more than 30 hours of flight time be accrued in a 7 day period (Table 4). Arguably however, even this recommendation may be too liberal since duty time may include operating during the circadian trough when flight crews would otherwise be sleeping. This is one area that warrants further investigation and current recommendations may need to be modified accordingly.

It is recommend that crew duty time not exceed 14 hours in a 24-hour period if the crew is augmented and 12-hours if it is not. In either case, no more than 60-hours should be worked within a 7-day period. When working for consecutive days, care should be taken to limit the time per shift worked. After 5 consecutive days of 12-14 hour shifts, a minimum 48-hour rest period is recommended. A 48-hour rest period should be sufficient to restore most performance deficits incurred.

Ground crew

Like ground crew associated with suborbital flights, those working orbital flights should receive 8 uninterrupted hours of sleep during the circadian trough between shifts (Table 4). Likewise, a minimum of 12 hours off duty should be afforded these personnel to ensure sufficient time exists for sleep, personal activities and transit time to and from the workplace. Using commercial aviation as a model, it is anticipated that most ground crew will not have a problem with poor quality sleep from residing at a temporary domicile since it is anticipated that they will likely live close to the launch site. If that assumption should prove false, provisions similar to those regulating flight crews should be enacted.

Shifts should last no longer than 12-hours within a 24-hour period. During any 7-day period, ground crews should not exceed 60 hours of duty time. When work involves shifts during the circadian trough, it is recommended that all shifts occurring during the circadian trough be followed by at least one night's opportunity to sleep during the circadian trough. Furthermore, it is recommended that ground crews not be subjected to more than 14 consecutive days of work. When consecutive work days are required, care should be taken to limit time worked per shift. Finally, after 5 consecutive days of 12-hour shifts, a minimum of 48-hours free from all duty should be given.

Table 4. Summary of Recommendations

	Suborbital Flights		Orbital Flights	
	Flight crew	Ground crew	Flight crew	Ground crew
Sleep (hrs) in 24 hours	8	8	8	8
Crew rest (hrs) before and after shift	12	12	12	12
Max. flight time (hrs) in 24 hours (non-augmented)	8	N/A	8	N/A
Max. flight time (hrs) in 24 hours (augmented)	N/A	N/A	12	N/A
Max. duty time (hrs) in 24 hours (non-augmented)	11	12	11	12
Max. duty time (hrs) in 24 hours (augmented)	N/A	N/A	14	N/A
Max. flight time (hrs) in 7 days	30	N/A	30	N/A
Max. duty time (hrs) in 7 days	60	60	60	60

CONCLUSIONS

The recommendations presented were derived from current scientific and operational data. With additional research and operational experience in the commercial space environment modifications may need to be made.

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