ESTIMATING CREW READINESS IN DISCRETE EVENT SIMULATIONS

Jon French
Clyde Wetteland
Shane Bowen
Tony Edgin

Micro Analysis and Design
3504 Lake Lynda Drive, Suite 330
Orlando, FL 32708

Abstract

An empirically based mathematical algorithm that predicts operator fatigue was developed for discrete event computer simulations tools. The algorithm estimates fatigue resulting from extended duty days and fragmented or reduced sleep. The algorithm would be useful in many human system integration problems such as predicting which crew duty schedules would produce the least fatigued operators or which crews would be most rested to complete a difficult assignment. It might also be used to degrade computer-generated forces from fatigue to more realistically estimate their effectiveness. During a Micro Saint simulation of two weeks of maritime activity, fragmented and reduced sleep produced by the contemporary US Navy watch schedules resulted in unacceptable fatigue levels over another crew duty schedule.

Biographical Sketches:

JONATHAN FRENCH received a PhD in Physiological Psychology at Colorado State University. He completed postdoctoral training at Cornell University Medical College and worked as a research pharmacologist at the Parke-Davis Co and the University of Michigan. Dr French served for 11 years as a civilian scientist for the US Air Force Research Laboratory at Brooks AFB in the area of sustained operations. He is the author of over 50 research articles on Human Factors issues in military and civilian settings. He is currently a Senior Research Psychologist for Micro Analysis and Design.

CLYDE WETTELAND is a Systems Analyst for Micro Analysis and Design, Inc. and is currently their Project Leader for DD21, the new US Navy destroyer. Prior to joining MA&D Mr. Wetteland was an Instructional Systems Technician at the Naval Air Warfare Center Training Systems Division, where he worked on several advanced training projects including the Shipboard Mobile Aid for Training and Evaluation (ShipMATE) and the Advanced Embedded Training system Advanced Technology Demonstration. Mr. Wetteland is a former Signals Analyst and Cryptologic Officer in the United States Navy and holds master's degree in Instructional Technology from the University of Central Florida.

ESTIMATING CREW READINESS IN DISCRETE EVENT SIMULATIONS

Jon French
Clyde Wetteland
Shane Bowen
Tony Edgin

Micro Analysis and Design
3504 Lake Lynda Drive, Suite 330
Orlando, FL 32708

The punishment [for sleeping on watch the third time] was to be lowered in a basket from the bowsprit with a knife, a beer and a ship's biscuit. He had the choice of staying in the basket until he died from thirst, exposure or hunger, or cutting the rope and drowning.

Log of the MaryRose
http://Maryrose.org/lcity/pilot/bell3.htm

INTRODUCTION

Advanced computer simulations increasingly make use of mathematical algorithms to estimate the impact of a variety of lethal threats to which forces may be exposed. In addition to bullet, blast and shrapnel fatalities for example, synthetic forces are likely to be degraded by thermal, chemical and radiological stressors. These models predict the extent of destruction in military and disaster preparedness simulations and the effectiveness of personnel in varying distances from ground zero. The current prevalence of these models testifies to their accuracy and usefulness in estimating human performance capability under a variety of degrading conditions. Other threats to human capability may be amenable to computer simulations that would further enhance the realism, hence the utility of complex system models. Fatigue induced by sleep deprivation or inadequate sleep has always been an important and persistent threat to operational effectiveness. The impact of fatigue will be increased in future conflicts due to advances in night operations technology; more frequent around the clock operations and reduced manning.

There are many examples from maritime research that warn of the impact of fatigue on physical and mental health of sailors. One study [Sanquist, et al., 1997] of 141 commercial mariners from a variety of ocean ranging vessels over 4 years, found that critical levels of fatigue occur between 8-21 % of the time on duty. Recovery sleep periods were not complete and sleep fragmentation was a serious problem. As well, inconsistent levels of alertness during watch standing periods were substantial during some watches. The authors concluded that there is a serious fatigue problem in the US maritime industry. Other research, from the US Coast Guard, points to the same conclusions. In a recent study [Comperatore, et al., 1999], daytime sleepiness and loss of alertness were found to occur during normal operations and were exacerbated by higher operational tempos. The most important cause of fatigue where 24-hour operations are required is the adequacy of the rest during the sleep phase. Aboard naval and Coast Guard vessels, the opportunity for adequate rest occurs infrequently because of the inconsistent, rotating sleep and shiftwork schedule for the watch section. The watch schedule is the single greatest source of reducible fatigue in maritime operations. This paper describes an algorithm that can estimate the impact of shift schedule on crew effectiveness.

The fatigue algorithm, the FAtigue DEgradation (FADE) tool, was developed for this project that predicts human response capability for tasks over an extended period of sleep wake cycles. The main foci of the algorithm are the interaction of prolonged sleep deprivation or fragmented sleep with circadian disruption on crew performance. In order to demonstrate the utility of the algorithm, it was used to compare a contemporary maritime watch schedule with a less fatiguing one. Finally, the algorithm was used to demonstrate the fatigue levels for one maritime schedule over another in a Micro Saint model of a stressful 14 day mission.

Contemporary Watch Sections

The first record of contemporary 4-hour watch standards can be found in English Navy logs from the 13th century [Campbell, 1956]. The tradition continued throughout the centuries for the Royal Navy and was adopted by the US Navy beginning with the Revolutionary war and continuing on today.

It seems paradoxical that a service, which has always utilized the most advanced technologies for control of its weapons platforms, maintains an ancient tradition to control the alertness of its most valuable resource, the human. The caliber of personnel has been such that those standing watch have, for the most part, gotten through their watch schedules. Crews have, in effect, been punished for their perseverance in getting through the deployment by facing it again on the next, simply because it worked, or seemed to work, well enough last time. There are no regulations guiding the commander in the choice of watch standards. The only regulation referring to the standard (Chapter 10, Article 1002) is quite flexible in theory but not in practice. It requires the commander only to "establish such watches as are necessary for the safety and proper operation of the command" [Stolgitis, 1969]. Typically, the schedule is referred to as a 4/8 cycle in which one's four-hour watch usually occurs after 8 hours of rest or other duty. A version of this 3-day cycle is shown in Table 1.

Table 1. Contemporary USN Watch Schedule

Day 1		Day 2		Day 3	
0800–1200	Watch	0800–1430	Duties	0800–1130	Duties
1300–1630	Duties	1600–1800	Dog	1200 – 1600	Watch
1800–2000	Dog	1900–2330	Rest	1600 – 2000	Break
2030–0330	Rest	0000–0400	Watch	2000 – 2400	Watch
0400–0800	Watch	0400–0800	Break	2400 – 0600	Rest

Watch = On Watch
Duties = Auxiliary Duties, training
Dog = Type of Watch
Break = Personal time
Rest = Time designated sleeping

There are far better schedules that can be generated based not on tradition but on a contemporary and considerably more advanced understanding of human biology than was possible aboard ancient warships. One example is shown in Table 2.

TABLE 2. Non-rotating 4-watch section schedules. Crew are assigned to one of the 4 watch sections and remain on that schedule to develop circadian entrainment around a 24 hour schedule to improve rest and alertness.

WATCH SECTION ONE		WATCH SECTION TWO	
0400 – 0830	FLOAT 3	0800 – 1230	FLOAT 4
0830 – 0930	1 hr break	1230 – 1330	1 hr break
0930 – 1200	2.5 hr DUTY	1330 – 1600	2.5 hr DUTY
1200 – 1630	WATCH 5	1600 – 2030	WATCH 6
1630 – 1730	1 hr break	2030 – 2130	1 hr break
1730 - 1900	1.5 hr DUTY	2130 – 2300	1.5 hr DUTY
1900 – 0400	Rest = 9 hours	2300 – 0800	Rest = 9 hours

WATCH SECTION THREE		WATCH SECTION FOUR	
2000 – 0030	WATCH 1	2400 – 0430	WATCH 2
0030 – 0130	1 hr break	0430 – 0530	1 hour rest
0130 – 0400	2.5 hr DUTY	0530 – 0800	2.5 hr DUTY
0400 – 0830	FLOAT 3	0800 – 1230	FLOAT 4
0830 – 0930	1 hr Break	1230 – 1330	1 hour rest
0930 – 1100	1.5 hr DUTY	1330 – 1500	1.5 hr DUTY
1100 – 2000	Rest= 9 Hours	1500 – 2400	Rest= 9 Hours

NOTE: Float Watch sections occur every other week, that is, the float periods are rotated such that Sections One and Two will have the float watches 3 and 4 respectively on one week. Sections Three and Four will have the float watches 3 and 4 respectively the next week. Time not doing the float watch will be spent on training or other activities.

Watch = On Watch
Duties = Auxiliary Duties, training
Rest = Time designated sleeping
Break = Personnel time

METHODS

The FADE algorithm allows fatigue effects to be anticipated and fatigue-reducing strategies can be tested before exposing real crews to the often-catastrophic consequences of fatigue. FADE is based on data collected at the Air Force Research Laboratory using USAF and USN pilots as subjects during a 52-hour sleep deprivation study. The algorithm is based on one of the fatigue sensitive tasks used, the Maniken task of a divided attention task. This task was selected because it is a complex visual task; it required the subject to pay attention to a signal on the screen while performing one of two tasks, hence to divide their attention to know when to switch to and from one task to the other. It has consistently proven sensitive to fatigue and other stressors in a number of experiments [Benline et al. 1997]. It is similar to the kinds of visual and cognitive performance demands placed on console operators.

The results of the empirical date from the task were modeled and a cosine curve was fitted to the data to unmask the circadian features of performance [Naitoh et al., 1985]. This involved a complex demodulation function that separated the linear aspects of the data. The remainder is the circadian function that allows oscillating performance levels to be predicted for extended periods of time over several days [Redmond et al., 1983]. The circadian component of the equation accounts for time of day effects on performance and the linear component accounts for the hours awake effects. A sleep recovery function was added to permit sleep wake cycles to be evaluated over prolonged periods of time. The model thus is a 3-component model; accounting for time awake and circadian time components and provides a parabolic recovery component as shown in Figure 1.

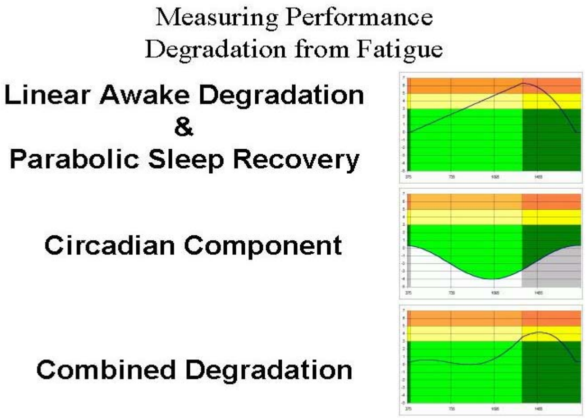


Figure 1. The linear component and the parabolic sleep recovery component. The circadian component is shown separately and then combined in the last panel.

A stylized version of the FADE equation can be written by the following:

FADE = circadian component + linear component + residual fatigue from previous time + recovery estimate if asleep.

The parabolic recovery component of the algorithm takes into account fragmented sleep for short naps and accelerates the recovery for longer sleeps nearer to 8 hours. The equation then combines the circadian component with the linear/parabolic components to predict fatigue based upon hours awake and recovery from fatigue based upon hours slept.

RESULTS

The data from the Maniken task were plotted as shown in Figure 2. The FADE algorithm accounts for a significant ($p < 0.05$) amount of the variance; although most of the variance is linear (0.89%), the cosine fit provides an important oscillating function to estimate performance at different circadian times of day.

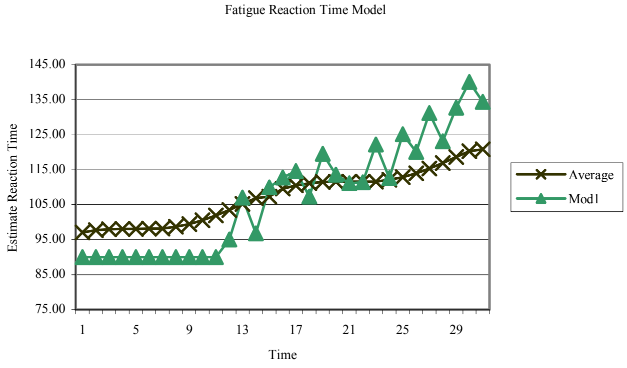


Figure 2. The FADE equation plotted against the Maniken fatigue sensitive test data.

A comparison of the time per day and per week spent on Watch and other duties is shown in Table 3. The contemporary schedule utilizes more Break time and less sleep time than the novel 4 Section schedule.

In order to be operationally useful, the FADE algorithm needed to know where limits to human effectiveness would be. Figure 3 shows the FADE equation predicting fatigue levels for 48 hours of sleep deprivation (in red) and following normal sleep wake cycles (0600-2200 awake; 2200-0600 asleep) for 13 days (in blue) for comparison. As shown in Figure 3, fatigue levels exceed a score of 20 after 48 hours of sleeplessness whereas for a normal sleep wake cycle, fatigue scores never exceed a fatigue score of 4.

Table 3. Estimate of per day (underlined) and per week hours for selected activities on Alternative 4 Section Watch Schedule compared to current USN schedule.

	WATCH	DUTIES	BREAK	REST
4 Section	9	4	2	9
Weekly Estimate	63	28	14	63
Contemporary Schedule	8	4.5	5.6	5.83
Weekly Estimate	56	31.5	39.2	40.81
Difference Per Day	+1	-0.5	-3.6	+3.17

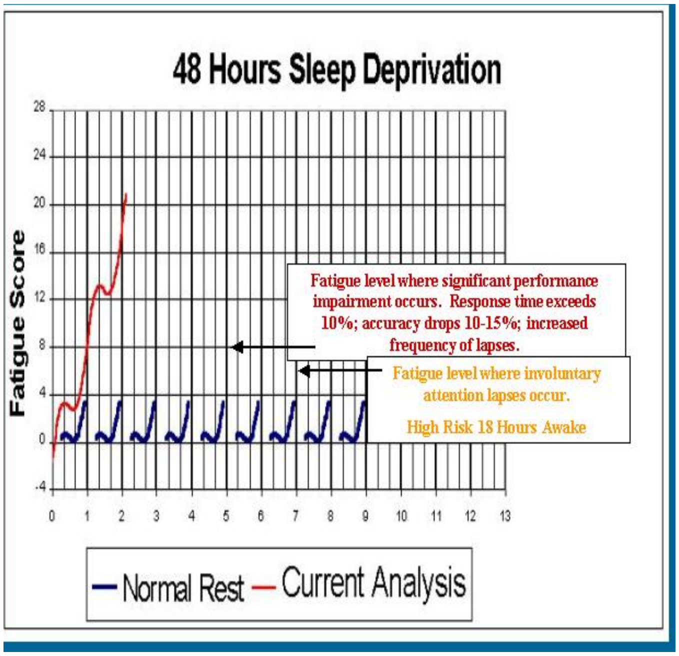
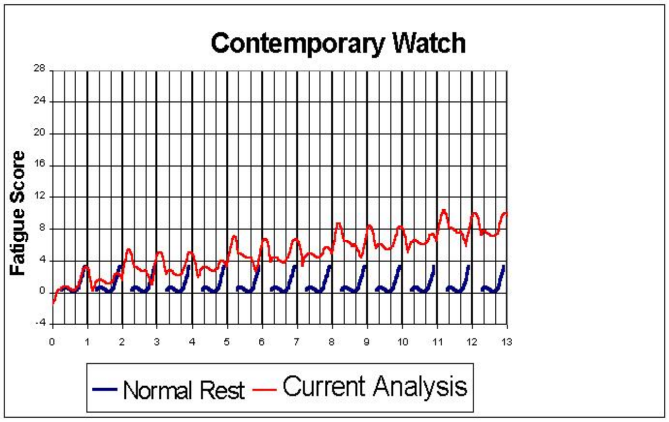


Figure 3. FADE predicted fatigue scores after 48 hours of sleep deprivation (red) and for normal sleep wake cycles (blue) over 13 days. The yellow text points to a marginally effective fatigue score between 6 and 8 corresponding to between 18 and 24 hours awake respectively. The red text points to an unacceptable fatigue score above 8 corresponding to 24 hours awake and beyond.

The area below the arrow associated with the yellow text in Figure 3 indicates where fatigue levels should be considered optimal (below a fatigue score of 4). This is the range –4 to 4 associated with a normal 16 hours awake and 8 hours asleep per day, as indicated in the blue curves in Figure 3. Above this score, between a fatigue score of 4 and 8 should be considered marginally acceptable and corresponds to 18-24 hours of sleep deprivation, respectively. This is a high risk area because involuntary performance lapses frequently occur on fatigue sensitive tests. Lapses are millisecond to seconds-long periods of non-responding due to involuntary inattention, the so-called blank stare. The arrow associated with the red text, above a fatigue score of 8 represents 24 hours awake and borders the zone of unacceptable fatigue. This level of sleep deprivation produces reliable effects on sensitive performance tests. Personnel operating above this level suffer from measurable reductions of response time and frequent errors as well as lapses and microsleeps. They can be dangerous to themselves and others. It is interesting that this level of fatigue is associated with similar levels of performance decrements induced by 0.1 (BAC) blood alcohol concentrations [Dawson et al, 1999]. This is not to say that being extremely tired is the same as being legally intoxicated, simply that the performance consequences are the same. Like people with a 0.1 BAC, fatigued people in this category often fail to realize how impaired their performance is. Nonetheless sensitive cognitive tests and operational measures like driving simulators can quantify the impairment.

The FADE algorithm was used to compare the contemporary schedule (Table 1) and the 4 Section schedule (Table 2) in Figure 4. The contemporary schedule produced fatigue scores that were marginally acceptable (score of 4) on Day 2 of the schedule and continued to be only marginally acceptable until Day 8. The schedule produced scores of unacceptable (score of 8) on Day 8 and throughout the remainder of the 13 days (upper figure). None of the watch positions of the 4 Section schedule produced even marginally acceptable fatigue scores (lower figure). For the contemporary schedule, every opportunity for rest was taken (i.e. during the scheduled breaks and rest periods).

In another study, a Micro Saint model was developed that simulated two weeks of stressful (rescue operations) maritime activity. Two schedules were compared using the FADE algorithm, a contemporary schedule and a less fatiguing recommended schedule. Both utilized a three-section watch schedule although one was based on a contemporary schedule. Each chart shows 3 operators or Sections. The contemporary schedule (upper figure) generated fatigue scores above unacceptable by day 4 and continued to rise. The revised schedule (lower figure) never exceeded a fatigue score of 5. These results are shown in Figure 5. These data are currently competition sensitive and details will be presented more fully in another publication.



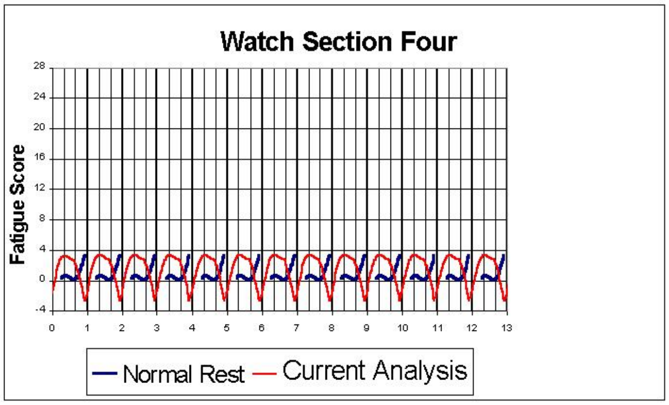
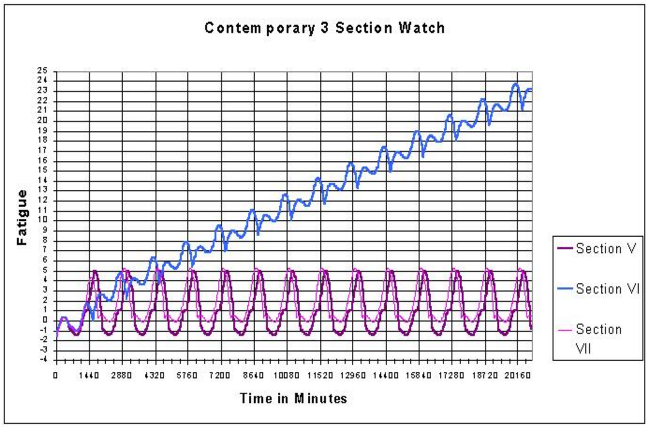


Figure 4. FADE predicted fatigue scores after 13 days on the contemporary watch schedule and the 4 Section watch schedule. Fatigue scores are higher for the contemporary schedule.

DISCUSSION

The fatigue equation is still in development. It is currently robust enough to predict fatigue levels consistent with results found from other studies. It provides a rational, objective means to predict fatigue for managers, planners and individuals. It is hoped that it will improve the safety and effectiveness of crews by comparing shiftwork or watchstander schedules to find the one with the least fatigue. The equation can also be used to gauge the impact of redesigning crew schedules or permitting longer naps or less fragmented naps on crew fatigue. This will certainly lead to an improved quality of life at sea and perhaps increase retention rates.

The consequences of failing to manage fatigue as carefully as possible or from mismanaging fatigue offer a compelling way to address the issue of the potential cost savings and benefits to be derived from applications like the Micro Analysis and Design's FADE equation. Great fatigue-induced catastrophes have occurred and will occur which might have been avoided with adequate fatigue management. The loss of crew or even the loss of a ship is not worth the risk considering the relatively small investment of time the model requires to guide intelligent decisions about crew utilization cycles. Cumulative sleep debt causes immune system disruptions (hence more colds and other illnesses), reduced cognitive and response time capability and significantly reduces workload potential. Optimal workload capacity recovered from avoiding illness, accidents and errors is estimated from our review of the sleep deprivation and maritime operations literature to be at least 10% and as high as 50% with better fatigue management. An additional benefit from considering duty cycles in line with circadian physiology and adequate rest is the positive effects it would have on improving crew quality of life that would have direct benefits on retention rates.



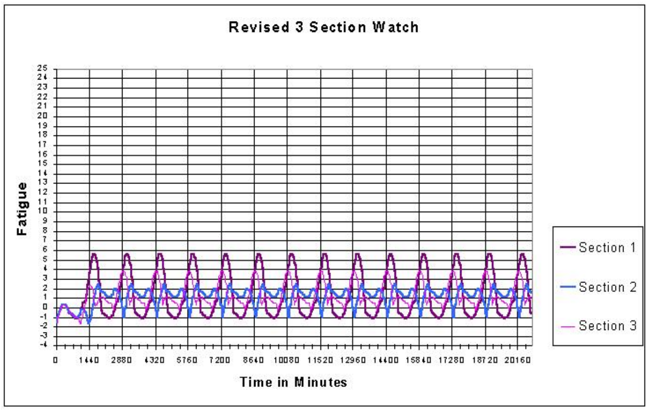


Figure 5. A Micro Saint model incorporating the FADE predictions was used to compare a contemporary 3 section watch (upper figure) and a revised 3 section watch (lower figure). Each figure shows fatigue scores for 4

The response capability of computer generated forces (CGF) that experience sustained or continuous operations could be more reliably estimated by considering fatigue-stress. This is the first application we are aware of that incorporates a fatigue descriptive sleep wake algorithm into a computer simulation. Fatigue may serve as a model for other stressors, heat, cold, intoxication or environmental contamination, for example, which results in response degradation. Incorporating fatigue estimates into discrete event simulation models may provide a cost effective means to estimate the impact of human limitations on military systems and highlight performance areas needing attention.

REFERENCES

Benline, T.A., French, J. and Wing, J. Anti-Emetic drug effects on cognitive performance, Aviation, Space and Environmental Medicine,68(6), pp 504-511**,** 1997.

Campbell, A.B., Customs and traditions of the Royal Navy, Aldershot, Gale and Plden Ltd., 1956, p 70

Comperatore, C., Bloch, C., and Ferry, C., (1999). Incidence of sleep loss and wakefulness degradation on a US Coast Guard Cutter under exemplar crewing limits. Coast Guard Research and Development Center, Groton CT. ID#CK19991228190000935

Dawson, D. and Reid, K., Fatigue, alcohol and performance impairment., Nature, 1997, 388:235.

Naitoh, P, Englund, C.E. and Ryman, D.H. Circadian rhythms determined by cosine curve fitting: Analysis of continuous work and sleep loss data. Behavior Research Methods, Instruments & Computers, 1985, 17 (6), 630-641.

Redmond, D.P., Sing, H.C. and Hegge, F.W. Biological time series analysis using complex demodulation. In Rhythmic Aspects ofBehavior, F.M. Brown and R.C. Graeber, (Eds). Lawrence Erlbaum Associates, Publishers, 1982, 429-457

Sanquist, T.F., Raby, M., Maloney, A.L. and Carvalhais, A.B. Work hours, sleep patterns and fatigue among merchant marine personnel. Journal of Sleep Research, 1997, Dec 6(4): 245-51.

Stolgitis W.C. The effects of sleep loss and demanding work schedules. Naval Postgraduate School, 1969, National Technical Information Service, Springfield, VA 22161