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Are a “can do” attitude and a can of Red Bull enough? Workload and fatigue in high-stakes, high-demand Carrier Sortie operations

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Abstract

The purpose of this investigation was to examine the role of fatigue and crew endurance in human performance of Carrier Sortie requirements; this mission capability involves high-stakes, high-demand, high-tempo operations in a challenging maritime environment. The researchers engaged with a panel of Nimitz crewmembers for a discussion of workload, notional schedules, and endurance risk factors. Workload was examined with models that consider the human capacity for sustaining. The investigation found that more attention is paid to physical fatigue, compared to cognitive or mental fatigue. Crewmembers emphasized that crew has a “can do” attitude to combat fatigue; the crew stated that “pride and adrenaline overpower fatigue…plus coffee and Red Bull.” They indicated that this results in good initiative, but at times bad judgment while trying to accomplish the work. The current research posits that fatigue is likely to reduce the ability of crewmembers to tolerate sustained performance and associated increased physiological and cognitive costs. However, the authors also recognize the limits of fatigue science with regard to predicting human capacity in intense operational and combat conditions. There is much anecdotal information to suggest that sailors are managing fatigue despite the predictions of various fatigue models. As a result, we cannot yet predict with certainty when the accumulated workload and fatigue of the individual sailor will be untenable, or identify critical thresholds of degraded cognitive capacity and decision making. Rather than rely solely on fatigue prediction software, it is recommended that potential mitigations are considered that might provide the crew more tools to manage endurance as a fatigue abatement strategy. The development of a crew endurance program to mitigate the risks posed by fatigue and reduced alertness during carrier sortie operations would identify risks relating to fatigue and alertness, and generate solutions to mitigate these risks by controlling exposure to endurance risk factors during normal operations so that the crew will be better prepared to respond to any operational demand.

*Keywords:*Fatigue; Crew endurance; FAST; MARTHA; Carrier Sortie; Sleep; Human performance; Purpose of the investigation

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1. Purpose

The purpose of this investigation was to examine the role of fatigue and crew endurance in human performance of Nimitz class and CVN 78 Carrier Sortie requirements. A ship's endurance can be described by how long it can support operations at sea without replenishing supplies or requiring in-port maintenance. Similarly, crew endurance can be described as a function of physiological and psychological factors that support the ability of crewmembers to perform their jobs safely and effectively. It has long been recognized that long workdays and reduced sleep produces levels of human fatigue that can compromise the health, safety and performance of operators. This research effort was intended to examine existing and projected levels of fatigue and cumulative sleep debt that may exceed the ability of the crew to replenish the limited cognitive and physiological resources that enable them to endure operations and maintain alertness and performance. This effort sought to determine whether existing and projected schedules and tasking compromise the ability of a selected group of crewmembers to perform their jobs safety and effectively, in light of endurance risk factors and existing research regarding fatigue. Also of interest was an examination of the delta between model predictions and the work successfully sustained by real-world sailors. It is often the case that the shared experience of difficult, sustained work becomes a point of pride that builds crew morale. Such observations are in contrast to the results of models that suggest that the workload associated with the existing Carrier Sortie operations may exceed the human capacity for sustaining work. If we believe that the science of human endurance should play a larger role in the development of ship design requirements, we need to go further in understanding and explaining human experience in the arena of high-stakes, high-demand operations.

2. Overview of fatigue

While a great deal of previous research has examined fatigue both generally and in domains such as aviation or surface transportation, work remains to be done with regard to the role of fatigue in maritime environments. Work at sea poses unique challenges, particularly in the naval context. Work aboard a naval vessel is characterized by longer than normal workdays and work weeks, nonstandard work shifts, extensive night operations and continuous operations, and periods of time that are especially manpower intensive. There are also frequent episodes of intense effort followed by periods of relative inactivity, such as during flight quarters watch when billets are on station in a manpower pool and available if a task needs to be completed but are not necessarily continuously performing tasks. There are additional factors contributing to crew fatigue as well. Sailors experience limited ability to get regular and uninterrupted sleep; the need for 24/7 operations; long work hours; isolation from family; exposure to stressful conditions, both physical and mental; and work shifts and travel across time zones that may result in circadian desynchrony. Circadian rhythm disruption (CRD) may result in fatigue, difficulty completing cognitive tasks, vigilance decrement, increased negative mood, impaired sensory perception, disorientation, impaired decision making, increased reaction time, attentional tunneling, impaired memory, and impaired ability to accurately judge one's own performance [1]. It has been noted in previous research that military personnel are at particular risk for CRD, due in part to mission schedule, travel across time zones, and irregular sleep cycles. Additionally, less than optimal working and sleeping conditions, high operational tempos, extended work shifts, and collateral duties further contribute to sleep debt and fatigue in warfighters [2].

Fatigue can result in sleep debt that can accrue in a variety of ways. Prolonged wakefulness for a single watch or mission can lead to acute sleep deprivation; it is asserted that acute sleep debt frequently arises in continuous military operations [2]. Chronic sleep deprivation can also result in sleep debt; chronic sleep deprivation arises when individuals receive less than eight hours of sleep across multiple nights. Sleep debt may also result from a combination of acute and chronic sleep deprivation. Both acute and chronic cumulative sleep debts result in overall performance degradation.

Extensive research has examined the relationship between sleep deprivation and cognitive performance, repeatedly demonstrating an inverse relationship whereby sleep deprivation degrades performance [3,4]. Both acute and chronic sleep deprivation, resulting in sleep debt, have been associated with degraded cognitive and physical performance, reduced alertness, increased sleepiness, and degraded physical health. Fatigue can degrade performance with regard to reaction time, information processing, and risk perception. Sleep debt and fatigue have also been noted as contributing to degraded decision making under conditions of uncertainty. Previous research has found that individuals subjected to sleep deprivation tended toward altered judgment and riskier decision making [5]. This involves a tendency toward less risk aversion under fatigue; individuals may be more willing to accept the risk involved with a particular decision.

Sleep is an essential commodity for the health and wellbeing of human operators. While many warfighters believe and assert that fatigue can be overcome by motivation, adequate motivation can only moderate the deleterious effects of fatigue to a limited degree [6]. Motivation alone cannot compensate for sleep debt in the maintenance of performance levels, which have been found to decline as much as 30% after the first night of sleep deprivation, and up to 60% during the second night when sleep deprivation was combined with continuous cognitive tasks [7]. Even when overt performance decrements are not observed, the maintenance of a given level of performance under stress requires the recruitment of additional cognitive and physiological resources; these resources involve behavioral and physiological costs, and the expense of increased subjective effort [8]. It has been noted in the discussion of the cognitive-energetic framework that “even where no primary task decrements may be detected, performance may show disruption of subsidiary activities or the use of less efficient strategies, as well as increased psychophysiological activation, strain, and fatigue aftereffects” [9]. Types of latent performance decrements associated with performance under stress, high demand, and fatigue includesubsidiary/secondary task failure, strategic adjustment, compensatory control, and fatigue after-effects.

When the “myth of the warrior” and the role of motivation are viewed in light of the cognitive-energetic framework, it is evident that individual level regulatory activity and coping with regard to fatigue engender significant behavioral and physiological costs and substantial increased effort to maintain performance standards. Overt decrements in performance are precluded by effortful regulation, whereby the individual attempts to maintain a given level of performance and effectiveness under stress, overload, or external distraction by increasing his expenditure of subjective effort; performance output is continuously adjusted to match goal-driven criteria for performance, determined by both short term and long term goals and mission objectives. The upper limit to the computational and functional effort expended toward task performance is primarily motivational in origin; this limit is assumed to be a function of the subjective or perceived value of task goals and mission objectives, as well as individual differences in the capacity for sustained work and tolerance for aversive states that accompany high levels of strain and fatigue [9].

When an individual has depleted his cognitive or physical resources and overall capacity has been compromised, he can no longer engage in effortful regulation and effort expenditure; it is at this point that latent decrements will become overt. An individual with a smaller reserve capacity, due to sleep debt or chronic stress, for example, is more likely to demonstrate overt performance decrements, while an individual with a larger reserve capacity will be more likely to tolerate sustained performance and increased costs. Increasing the crew’s reserve capacity can be supported by the implementation of a crew endurance program, which improves available cognitive and physiological resources and, subsequently, crew performance and morale.

Relying on current and historical data regarding crew workload, sleep scheduling, and environmental conditions such as sea state that impact stress and sleep quality can provide a reliable and sufficiently accurate indicator of crew fatigue, without the need for integration of intrusive, costly, or time-intensive measurements involving biometric monitoring or behavioral assessments. Projected fatigue levels can be combatted through the implementation of an endurance program that supports crew wellbeing as well as sustained performance during high-intensity operations.

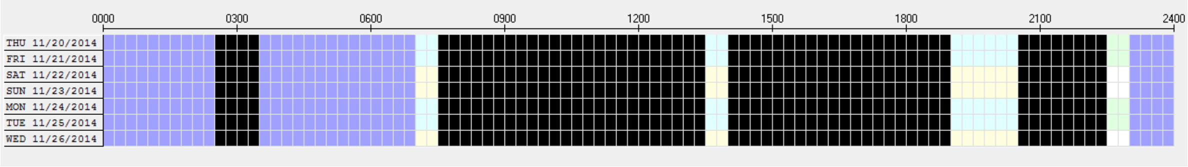

Fig.1. Notional Aircraft Launch and Recovery Officer input.

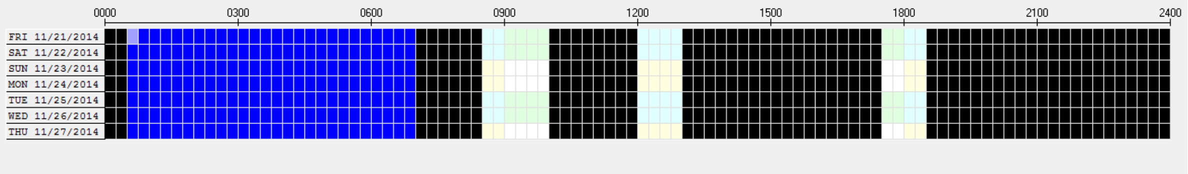

Fig.2. Notional Top Side Petty Officer- Safety input.

3. Model descriptions and outputs

3.1. Model inputs

During the course of the discussion, it was discovered that the panel members could not make detailed projections regarding specific changes in workload and scheduling on CVN 78, beyond noting reduced manning on CVN 78 compared to Nimitz class CVNs. Therefore, notional schedules are limited to typical activities for the identified roles on the Nimitz. This information was used to examine the workload of these sailors with models that consider the human capacity for sustaining work in demanding scenarios. While the current findings do not directly reflect CVN 78 scenarios, the implications regarding fatigue found in this investigation strongly suggest the need for further research regarding fatigue and crew endurance in the CVN 78 Carrier Sortie Model.

Schedules were input for both a notional Aircraft Launch and Recovery Officer and a Top Side Petty Officer-Safety. In the model inputs (see Figure 1 and Figure 2), blue shading indicates periods designated for sleep and black shading indicates periods scheduling for work. No shading reflects personal time without official tasking, but includes such things as mess time, personal hygiene, leisure, and sometimes training.

3.2. Sleep, Activity, Fatigue, and Task Effectiveness- Fatigue Avoidance Scheduling Tool (SAFTE-FAST)

SAFTE-FAST is a biomathematical model of the factors that cause fatigue. It is designed to simulate the underlying physiological system that causes degradations in cognitive performance. The FAST tool implements the SAFTE biomathematical model of performance and fatigue to generate estimates of performance degradation owing to the individual’s level of fatigue. Cognitive effectiveness is dependent upon the current balance of the sleep regulation process, the circadian process, and sleep inertia; sleep regulation is dependent upon hours of sleep, hours of wakefulness, current sleep debt, the circadian process, and sleep fragmentation (awakenings during a sleep period). The primary application of the model is to aid operator scheduling by using work schedule information to estimate fatigue and cognitive effectiveness. FAST can be used to examine specific schedules to determine vulnerabilities, to select optimal schedules, and to plan napping and recovery sleep strategies. The model provides a number of performance metrics (*e.g.*, percent change in cognitive speed, lapse likelihood, reaction time) and sleep-wake metrics (*e.g.*, sleep reservoir, circadian phase). The outputs of the model provide measurements of both duty time and critical time below an adjustable fatigue risk criterion line. A graphic display shows cognitive performance effectiveness (y axis) as a function of time (x axis), and provides an analogous blood alcohol index (BAC) value relative to degree of performance degradation. See Figure 3 for graphical representations of effectiveness and BAC equivalent over time for each notional role.

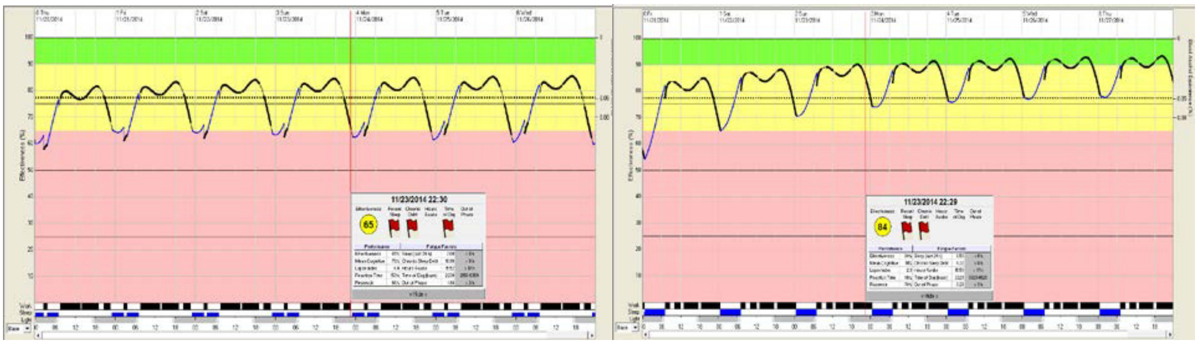

Fig.3. Effectiveness and equivalent BAC for notional Aircraft Launch and Recovery Officer and notional Top Side Petty Officer- Safety.

3.3. MARTHA

MARTHA is a prototype maritime fatigue prediction tool under development as part Project HORIZON, which is employing various realistic seagoing scenarios using bridge, engine room, and cargo simulators, and assessing the impact of fatigue on decision-making performance to minimize risks to both ship and seafarer. The MARTHA model is being tested through the use of high fidelity voyage scenario simulations that provide various watch-keeping patterns that lead to fatigue in watch-keeping officers. This supports the capture of empirical data on the cognitive performance of the watch-keepers undertaking these watch keeping patterns. The outputs of MARTHA include a breakdown of total time, fatigue (amount of time with reduced wakefulness), and risk (of falling asleep) across time spent at work, leisure, awake, and sleep. Work is the time which the Watchkeeper spent in the Bridge or the Engine Room. It does include any paperwork or drills, which watchkeepers may have dealt with in their off-watch time (leisure time). There is a breakdown by day of amount of watch time with reduced wakefulness (Karolinska Sleepiness Scale ≥ 8). Fatigue is the amount of time characterized by reduced wakefulness (Karolinska Sleepiness. Scale KSS ≥ 5). A KSS of ≤ 7 is considered Fit for Duty; it is acceptable for a seafarer to be on watch and he is expected to be capable of doing his work properly. See Figures 4a and 4b for graphical representations of the amount of reduced wakefulness over time for each notional role.

3.4. UK Health and Safety Executive Fatigue Risk Indicator (FRI)

The Fatigue Risk Indicator (FRI) is designed for comparing different work schedules and for examining the potential impact of a change to one feature of a given work schedule (*e.g.*, shift change over time). It can be used to identify the fatigue and risk associated with any particular shift within a given schedule. It is a revised and updated

2 20:30 22:00

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The evaluation includes week:  1, 2, 3, 4, 5, 6

            Total       Fatigue*     Risk**
            ------------------------------
Work        22:18:30    8%           0%
Leisure     7:22:40     45%          0%
Awake       30:17:10    17%          0%
Sleep       11:07:00
```

*) Reduced wakefulness. KSS≥5 **) High risk of falling asleep. KSS≥8

6h 18:30 24:00

Prev. Z 01:00
Next Z 06:30

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The evaluation includes week:  1, 2, 3, 4, 5, 6

            Total       Fatigue*     Risk**
            ------------------------------
Work        24:12:10    61%          0%
Leisure     7:21:10     76%          0%
Awake       32:09:20    65%          0%
Sleep       9:14:50
```
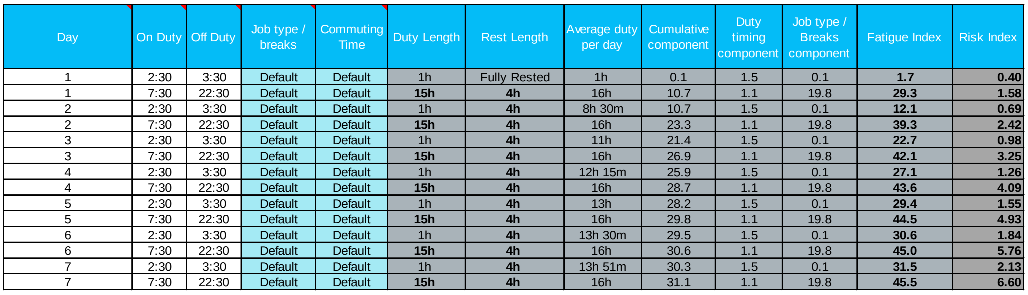

*) Reduced wakefulness. KSS≥5 **) High risk of falling asleep. KSS≥8

Fig.4. (a) Fatigue for notional Aircraft Launch and Recovery Officer; (b) Fatigue for notional Top Side Petty Officer- Safety.



Day	On Duty	Off Duty	Job type / breaks	Commuting Time	Duty Length	Rest Length	Average duty per day	Cumulative component	Duty timing component	Job type / Breaks component	Fatigue Index	Risk Index
1	2:30	3:30	Default	Default	1h	Fully Rested	1h	0.1	1.5	0.1	1.7	0.40
1	7:30	22:30	Default	Default	15h	4h	16h	10.7	1.1	19.8	29.3	1.58
2	2:30	3:30	Default	Default	1h	4h	8h 30m	10.7	1.5	0.1	12.1	0.69
2	7:30	22:30	Default	Default	15h	4h	16h	23.3	1.1	19.8	39.3	2.42
3	2:30	3:30	Default	Default	1h	4h	11h	21.4	1.5	0.1	22.7	0.98
3	7:30	22:30	Default	Default	15h	4h	16h	26.9	1.1	19.8	42.1	3.25
4	2:30	3:30	Default	Default	1h	4h	12h 15m	25.9	1.5	0.1	27.1	1.26
4	7:30	22:30	Default	Default	15h	4h	16h	28.7	1.1	19.8	43.6	4.09
5	2:30	3:30	Default	Default	1h	4h	13h	28.2	1.5	0.1	29.4	1.55
5	7:30	22:30	Default	Default	15h	4h	16h	29.8	1.1	19.8	44.5	4.93
6	2:30	3:30	Default	Default	1h	4h	13h 30m	29.5	1.5	0.1	30.6	1.84
6	7:30	22:30	Default	Default	15h	4h	16h	30.6	1.1	19.8	45.0	5.76
7	2:30	3:30	Default	Default	1h	4h	13h 51m	30.3	1.5	0.1	31.5	2.13
7	7:30	22:30	Default	Default	15h	4h	16h	31.1	1.1	19.8	45.5	6.60

Fig.5. Fatigue and Risk Indices for Fatigue for notional Aircraft Launch and Recovery Officer.

Day	On Duty	Off Duty	Job type / breaks	Commuting Time	Duty Length	Rest Length	Average duty per day	Cumulative component	Duty timing component	Job type / Breaks component	Fatigue Index	Risk Index
1	0:01	0:30	Default	Default	29m	Fully Rested	29m	0.1	1.3	0.0	1.3	0.19
1	7:00	0:00	Default	Default	17h	6h 30m	17h 29m	6.6	1.9	9.3	17.1	1.68
2	0:01	0:30	Default	Default	29m	1m	8h 59m	6.6	1.3	0.0	7.7	0.35
2	7:00	0:00	Default	Default	17h	6h 30m	17h 29m	17.0	1.9	9.3	26.3	2.81
3	0:01	0:30	Default	Default	29m	1m	11h 49m	18.3	1.3	0.0	19.3	0.51
3	7:00	0:00	Default	Default	17h	6h 30m	17h 29m	23.3	1.9	9.3	31.9	3.93
4	0:01	0:30	Default	Default	29m	1m	13h 14m	23.9	1.3	0.0	24.8	0.66
4	7:00	0:00	Default	Default	17h	6h 30m	17h 29m	26.4	1.9	9.3	34.7	5.06
5	0:01	0:30	Default	Default	29m	1m	14h 5m	26.6	1.3	0.0	27.6	0.82
5	7:00	0:00	Default	Default	17h	6h 30m	17h 29m	28.1	1.9	9.3	36.2	6.18
6	0:01	0:30	Default	Default	29m	1m	14h 39m	28.3	1.3	0.0	29.2	0.97
6	7:00	0:00	Default	Default	17h	6h 30m	17h 29m	29.3	1.9	9.3	37.2	7.31
7	0:01	0:30	Default	Default	29m	1m	15h 3m	29.3	1.3	0.0	30.2	1.13
7	7:00	0:00	Default	Default	17h	6h 30m	17h 29m	30.0	1.9	9.3	37.9	8.43

Fig.6. Fatigue and Risk Indices for Fatigue for notional Top Side Petty Officer- Safety.

version of the UK Health and Safety Executive Fatigue Index (FI). This updated model incorporates factors such as cumulative fatigue, time of day, shift length, the effects of breaks, and the recovery from a sequence of shifts. Outputs include both a Fatigue Index (probability of high levels of sleepiness, expressed as a value between 0 and 100) and a Risk Index (the relative risk of an error that might result in an accident/injury). See Figures 5 and 6 for FI and RI values.

Fatigue Index (FI) = 100{1–(1-C) (1-J-T)} where C is the cumulative fatigue component, T is the duty timing component, and J is the job type/breaks component. In the formula, C, J, and T correspond to probabilities and therefore take values between 0 and 1. In the model output, they have been converted to percentages, like the FI itself, by multiplying by 100.

The Risk Index (RI) involves the estimation of the increase in risk on consecutive shifts based on the relative risk data over successive shifts. Risk Index (RI) = C*J*T where C is the cumulative fatigue component, T is the duty timing component, and J is the job type/breaks component.

4. Qualitative findings

The crewmembers interviewed for this research provided an overview of carrier sortie operations. Sortie generation involves significant numbers of crew conducting various challenging cognitive and physical tasks. These tasks involve a high degree of coordination between crewmembers; frequent instances of time critical, high stakes decision making; and maintenance of a highly vigilant state due to job responsibilities and hazards on the flight deck. Despite already high levels of workload on Nimitz Class ships, CVN 78 is designed to increase the sortie generation capability of embarked aircraft to 160 sorties per day (12-hour fly day) and to surge to 270 sorties per day (24-hour fly day) as compared to the CVN 68 Nimitz Class sortie generation rate demonstration of 120 sorties per day/240 sorties for 24-hour surge [10]. The Navy Fact File for CVN 78 notes that “The CVN 78 is designed to operate effectively with nearly 700 fewer crewmembers than a CVN 68-class ship. Improvements in the ship design will allow the embarked air wing to operate with approximately 400 fewer personnel. New technologies and ship design features are expected to reduce watch standing and maintenance workload for the crew” [11]. The crewmembers interviewed anticipate that the increased sortie generation rate and reduced manning will raise the workload of crew, despite the intended reduction in maintenance hours, which is driving the reduce manning.

With regard to maintenance on the Nimitz, the crew noted that there is regularly unscheduled workload for maintenance. Preventative maintenance is scheduled according to times listed on MRCs, but these time allotments do not account for administrative time such as paperwork or ordering supplies. Additionally, corrective maintenance tasks contribute additional workload that is unscheduled. If corrective maintenance must be completed after preventative maintenance, there is no accommodation to subsequent scheduling. Watch hours are extended to support task completion.

It was noted that crew has a “can do” attitude to combat fatigue. This results in good initiative but bad judgment at times while trying to get things done. The crew emphasized that “pride and adrenaline overpower fatigue…plus coffee and Red Bull.” It was noted that crewmembers get bragging rights for how long someone has been awake. Supplements such as Stackers are not condoned because of their dehydrating effects. However, other caffeinated or stimulant-type substances are treated as currency because of their high value to crewmembers. With regard to procedures or oversight for recognizing fatigue, it was noted that during flight ops briefings, supervisors ask if anyone is too tired to safely work. It was reported that no one ever responds in the affirmative. Supervisors try to observe the alertness of the crew during the briefing. It was also noted that there are punitive consequences when a crewmember appears to be overly fatigued. The reasons for the fatigue are investigated, and it was noted that these consequences tend to “roll uphill for a change.” The crew noted that supervisors engage in Operational Risk Management during pre-briefs. Aviators have eight hour crew rest requirements prior to flying. There is no rest requirement after flying. While aviators have crew rest requirements, the maintainers do not. It was noted that more attention is paid to physical fatigue compared to cognitive or mental fatigue. The crew noted that supervisors “don’t really keep an eye on mental fatigue.” It was noted that there is no existing mechanism to support recovery from fatigue. Once fatigue and sleep debt accrue, they will be present for the duration of the deployment, resulting in chronic fatigue.

5. Discussion of model results and panel discussion with crewmembers

The outputs of the FAST, MARTHA, and UK Health and Safety Executive Fatigue Risk Indicator (FRI) models indicate that the notional schedules reflecting typical work for the Aircraft Launch and Recovery Officer and Top Side Petty Officer- Safety are less than ideal with regard to supporting human performance and endurance. The FAST models indicate that the schedules of the notional Aircraft Launch and Recovery Officer and Top Side Petty Officer- Safety would result in individuals frequently operating at levels of fatigue whose effects equivalent to legal intoxication. Crewmembers are operating at moderate levels of effectiveness with reduced reserve capacity. The MARTHA models indicate that the notional Aircraft Launch and Recovery Officer spends approximately 8% of work time with reduced alertness; split-shift night work from 230-330 involves KSS values that approach high risk of falling asleep. The notional Top Side Petty Officer- Safety has high levels of fatigue and reduced alertness for approximately 61% of work time. Work that occurs later at night results in increased KSS values that approach high risk of falling asleep. Risk increases over the course of the deployment as fatigue and chronic sleep debt accumulate. It was noted by the crewmembers interviewed that opportunities to make up lost sleep are infrequent and that fatigue becomes chronic on deployment. Results of the Fatigue Risk Index indicated that the notional Aircraft Launch and Recovery Officer has an average 40.1% probability of a high level of sleepiness, with a range of 1.7% to 45.5%. The average Risk Index is 3.91 and ranges between 0.40 and 6.60. The notional Top Side Petty Officer- Safety has an average 31.3% probability of a high level of sleepiness, with a range of 1.3% to 37.9%. The average Risk Index is 4.93 and ranges between 0.19 and 8.43.

While it was clear from crewmember interviews that work is generally performed in a satisfactory manner despite high levels of fatigue, latent risk exists regarding the detrimental effects of fatigue on processes such as decision making, information processing, and reaction time. Sleep debt and fatigue result in a tendency toward altered judgment and riskier decision making, such that fatigued individuals exhibit less risk aversion. Fatigue and chronic sleep debt also reduce the latent capacity of an individual to respond to unanticipated situations or secondary demands. Types of latent performance decrements associated with performance under stress, high demand, and fatigue include subsidiary/secondary task failure, strategic adjustment, fatigue after-effects, and compensatory control. Compensatory control involves increased mental effort and strain of active control during maintenance of performance levels. Individual level regulatory activity and coping with regard to maintaining performance under fatigue have significant behavioral and physiological costs.

The high levels of crew motivation and “can do” attitude can combat some degree of fatigue, in line with Hockey’s (1997) cognitive-energetic and compensatory control framework. However, this pervasive “myth of the warrior” fails to take into account the strain placed on the individual by heightened regulatory activity. Most overt performance decrements are avoided through effortful regulation. However, when a crewmember has depleted his cognitive or physical resources and overall capacity has been compromised, he can no longer engage in effortful regulation and effort expenditure; it is at this point that latent decrements will become overt. It is also that case that crewmembers will be less well equipped to contend with unscheduled or unanticipated tasking, such as corrective maintenance, high criticality decision making, or other situations. Sleep debt and chronic fatigue reduce the capacity of an individual to sustain performance under fatigue over time, and engenders associated increased physiological and cognitive costs. Increasing the crew’s reserve capacity, through interventions that are part of crew endurance management program, increases available cognitive and physiological resources and, subsequently, crew performance and morale.

Overall, the results of this analysis indicate that current and anticipated crew schedules and tasking exceed the rest requirements of human operators and may pose operational risks that may be unaccounted for. However, while the outputs of the fatigue prediction models indicate that crew members should exhibit remarkable reductions in physical and cognitive performance, examples of such degraded performance are rarely observed by either the crew members interviewed or in the vast operational experience of one of the researchers. This finding highlights the role of compensatory control in crew performance, whereby increased subjective effort is expended by crew members to maintain performance standards under stress, extreme workload, and fatigue.While the results of the models suggest that current tasking may exceed functional human limits, real world sailors continue to sustain these workloads with success, suggesting the need for further scientific research regarding human endurance in high-stakes, high-demand operations involving highly motivated operators.

As such, rather than rely solely on fatigue prediction models, it is recommended that potential mitigations are considered that might provide the crew more tools to manage endurance as a fatigue abatement strategy. The development of a crew endurance program to mitigate the risks posed by fatigue and reduced alertness during carrier sortie operations would support improved crew performance, endurance, reserve capacity, and morale. This type of program would go beyond implementation of fatigue prediction tools to address endurance risk factors that can promote or compromise crew endurance. An endurance program would identify risks relating to fatigue and alertness, and generate solutions to mitigate these risks by controlling exposure to endurance risk factors during normal operations so that the crew will be better prepared to respond to any operational demand including high tempo, high demand scenarios.

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