METHODOLOGY TO QUANTIFY THE BENEFIT ASSOCIATED WITH A REDUCTION IN WORKER FATIGUE AS A RESULT OF ALTERED WORK SCHEDULES IN THE NUCLEAR INDUSTRY

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SUMMARY/ABSTRACT

Worker fatigue is one of many factors that may contribute to human errors in nuclear power plant operation. However, documentation of human errors in licensee event or U.S. Nuclear Regulatory Commission (NRC) inspection reports generally does not identify fatigue as one of these contributing factors. As the impact of fatigue on cognitive functioning is not measured by licensees, worker fatigue is likely under-reported as an event causal factor. Taking this into consideration, the methodology presented in this paper aimed to evaluate the effect of changes in nuclear worker fatigue on the frequency of human performance events without the use of specific historical event data.

Human performance data was extrapolated to replicate work schedule conditions common to power plant operation. The calculated human performance improvement as a result of altered work schedules was assumed to be directly correlated to a change in the human error rate. The human performance change was incorporated into Standardized Plant Analysis Risk (SPAR) models to determine the potential change in a representative plant's calculated core damage frequency (CDF). This change in frequency could then be used to quantify the benefits associated with a reduction in nuclear plant worker fatigue.

The authors implemented this methodology as a supplement to a regulatory analysis for the U.S. Nuclear Regulatory Commission (NRC). It presents a procedure for quantifying fatigue-related human performance and the effects it may have on the nuclear industry and risk to public health. As a result, the methodology advances the ability to address human performance in both Probabilistic Risk Assessment (PRA) and regulatory cost-benefit analyses.

INTRODUCTION

Safe nuclear power plant (NPP) operation is contingent upon many factors, including a low incidence of human errors. For example, nuclear plant worker error was one of the causes of the accident at Three Mile Island Unit 2 in 1979 [1]. As a result of the accident, major changes occurred within the nuclear industry, as well as the U.S. Nuclear Regulatory Commission (NRC). Among these changes was an increased focus on human performance as a critical part of plant safety and the establishment of fitness-for-duty requirements for NPP workers [1]. These changes have led to the identification of fatigue and circadian variations in alertness as important influences on worker cognitive functioning and performance, and potentially, worker fitness-for-duty. Therefore, a need exists to quantify how and to what extent nuclear worker fatigue affects safe plant operation.

The most effective method of evaluating the result of nuclear worker fatigue on safe plant operation would be through the use of historical data, which links worker fatigue to human performance events at a NPP. However, documentation of human errors in plant licensee event reports or NRC inspection reports generally does not provide the level of detail or depth of analysis to identify fatigue as one of the contributing factors. This is likely to be a result of the limitations in the identification of causal factors, as opposed to the lack of fatigue influenced errors. Therefore, the impact of worker fatigue is likely under-reported and warrants further investigation.

The methodology presented in this paper aimed to evaluate the effect of changes in nuclear worker fatigue as a result of altered work schedules on the frequency of human performance events without the use of historical event data. The change in frequency calculated could then be used to quantify the benefits associated with a reduction in NPP worker fatigue. This process, represented in Fig. 1, involved: (1) a fatigue model and available human performance data to calculate the percent net improvement (NI) in human performance (or similarly, the reduction in human error rate) as a result of less worker fatigue, (2) Standardized Plant Analysis Risk (SPAR) models to support the evaluation of the complex interactions between human performance and plant equipment and to enable the calculation of core damage frequency (CDF) values, a metric of plant risk, and (3) the use of the resultant human performance and plant risk metrics to quantify a monetary benefit for the nuclear industry attributed to the lessened worker fatigue.

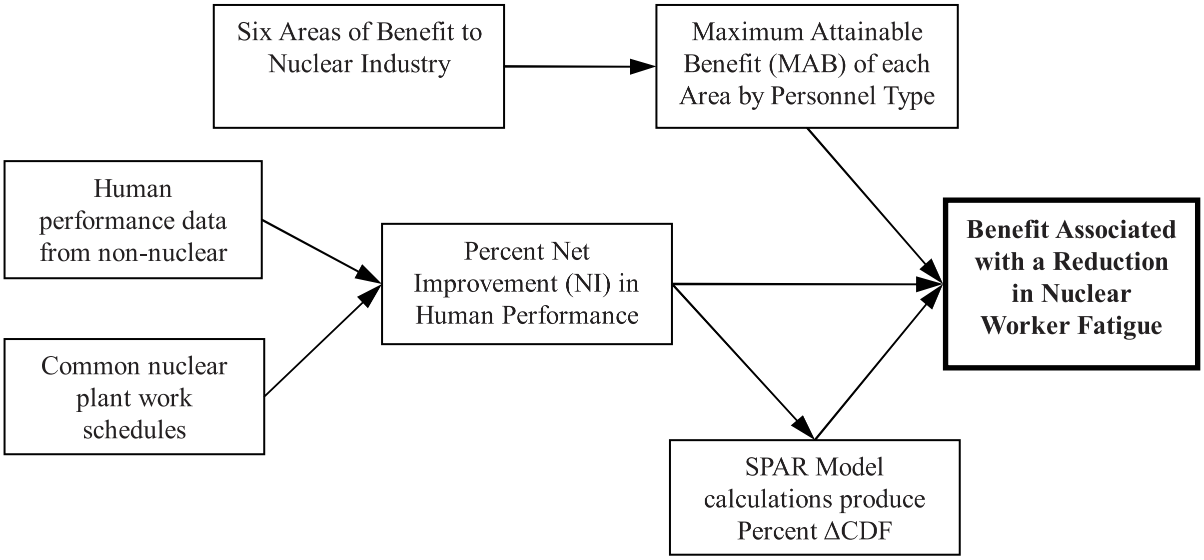

Figure 1 Representation of Methodology to Quantify Benefit Associated with a Reduction in Nuclear Worker Fatigue

HUMAN PERFORMANCE DATA AND MODELING

Human performance studies indicate that worker fatigue varies with work schedules and other individual factors [2, 3]. Longer work schedules may lead to less sleep than is necessary for optimal cognitive functioning and this loss of sleep, even in small amounts, can have cumulative effects that progressively degrade performance [4]. Therefore, the methodology assumed that fatigue and in turn, worker performance, was a function of NPP work schedules. Furthermore, the assumption was made that longer work schedules caused greater lack of sleep in plant personnel [5, 6]. An example of the latter assumption is the direct correlation of a 16-hour work shift with 5 hours of sleep that is used in the model to quantify worker fatigue.

Without historical data to correlate NPP worker fatigue and human performance events reported in Licensee Event Reports (LERs), an alternative method was necessary to depict worker fatigue and its effects during nuclear plant operation. Data from scientific human performance studies that quantified the effects of fatigue, through experiments such as sleep deprivation, was used in conjunction with work schedules normal for nuclear personnel in order to model the effects of a change in sleep duration on nuclear workers.

Two datasets were applied as the foundation for the correlation between sleep (or work-shift duration) and human performance. First, partial sleep deprivation data was used from a study performed by Belenky and colleagues [7], in which subjects received a controlled number of hours of sleep per day for one week and were given a Psychomotor Vigilance Test (PVT) each day to quantify their performance. Second, occupational accident risk data collected by Hanecke and colleagues [8] was used, which correlated work-shift duration to accident risk at the workplace. The metric of human performance for the Belenky study [7] was a ‘lapse’ or when a subject has an unusually slow response time to a stimulus test; while the Hanecke study [8] metric was the relative accident risk or the ratio of worker accident frequency to the exposure data. The Belenky study will be used throughout this paper to represent the methodology’s treatment of both datasets. Both studies demonstrated that, over short periods of time, the degradation of human performance/accident risk increased with increased sleep deprivation/hours at work. This validated the methodology’s central premise that increasing worker fatigue would likely cause an increase in human error.

These datasets were manipulated to analyze how a change in a given work schedule would affect human performance. The short-term data was extrapolated for longer periods of time to model nuclear plant worker fatigue in work schedule conditions common to NPP operation for a time period of up to 180 days. More specifically, the absolute change in lapses (Belenky data [7]) from day to day was calculated for all sleep deprivation scenarios. These change in lapse calculations, ΔL, were treated as a seven-day template for the quantification of cumulative human performance degradation over long time periods. For example, Belenky and colleagues measured the following lapses for subjects limited to 7 hours of sleep per night:

Table 1 Mean Lapse Measurements for Subjects With 7-hour Partial Sleep Restrictions (Adapted from Belenky et al. 2003).

	Base[1]	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Rest [2]
Change in Lapses (ΔL)		0.25	0	0.5	0.5	0	0.75	-0.25
Number of Lapses	1.75	2	2	2.5	3	3	3.75	3.5

[1] *Base case is the measurement taken on the morning of Day 1, all other measurement taken at end of Day n*

[2] *Subjects were under no sleep restrictions on rest days*

The 7-hour partial sleep data presented above was correlated to a 12-hour work shift in the fatigue model. The data was assumed to represent NPP worker fatigue during outage conditions of a 72-hour workweek and a one day break. The number of lapses for each day in week two were found by applying the 3.5 lapses calculated for the end of the first week as the base case for the second week and extrapolating the data using the same ΔL values. This resulted in the following calculations:

Table 2 Model Calculations for 72-hour Workweek

	Base	Day 8	Day 9	Day 10	Day 11	Day 12	Day 13	Rest
Change in Lapses (ΔL)		0.25	0	0.5	0.5	0	0.75	-0.25
Number of Lapses	3.5	3.75	3.75	4.25	4.75	4.75	5.5	5.25

Translating this data to support the long-term concept of cumulative performance degradation required some further assumptions, as well as consideration of normal and extreme work schedules in NPPs. The assumption was made that a worker can fully recover from fatigue accumulated during a 72-hour workweek after a 48-hour break. Personnel who worked less than 72 hours a week were assumed to need proportionally less break time to recover, while receiving a break less than 48 hours each week was assumed to allow personnel to partially recover in a proportional manner. If a worker did not fully recover from fatigue at the end of a week, the "rest debt" would carry over to the next week, essentially compounding the level of fatigue [3]. This "full recovery" from fatigue was modeled by resetting the Number of Lapses to the original baseline lapse measurement. For example, a full recovery of the NPP worker modeled in Tables 1 and 2 would result in the number of lapses decreasing to the initial 1.75 lapses measured as the base case in the Belenky study.

Finally, the fatigue model assumed a level of saturation in fatigue-related performance degradation after a 180-day time period. This saturation was applied to the Belenky data by fitting the ΔL calculations to the exponential function:

$$\Delta L(t) = 1 - e^{\left(\frac{\ln(1-\Delta L_n)}{180}\right)(180-t)} \qquad (1)$$

where ΔL_n is the corresponding ΔL calculated from the Belenky data on day $n = t \bmod(7)$ and t represents the time in days. This equation directs the change in lapses (ΔL) to decrease to zero and the overall number of lapses to saturate after 180 days. These assumptions were based on trends seen in human performance literature [4, 9].

The fatigue model explained above was able to quantify fatigue-related human performance degradation for any work schedule common to an NPP worker (in outage or normal operation). More specifically, baseline work schedules were compared to altered schedules that included more breaks and fewer consecutive hours worked. The applicability of these work schedules to many of the NPP personnel types (e.g., operators, maintenance workers, etc.) was taken into account within model calculations. A cumulative number of lapses (Belenky metric [7]) or cumulative accident risk (Hanecke metric [8]) was then calculated for both work schedules in question. The percent net improvement (NI) in human performance from the baseline or control schedule to the altered work schedule acted as the measure of lessened worker fatigue or human error rate.

INTEGRATION OF HUMAN PERFORMANCE IN SPAR MODELS

Estimated changes in human error rates, as described in the previous section, were used to assess the impact of a change in work schedule (or lessened fatigue) on the plant risk metric of core damage frequency (CDF). Specifically, the risk of severe accidents was modeled in this analysis using the SAPHIRE computer program developed by Idaho National Engineering and Environmental Laboratory (INEEL). This program calculates the frequency of core damage accidents. NRC has developed specific models, or SPAR models, for every plant in the United States. Four plant models were chosen to represent the entire U. S. fleet in this analysis.

SPAR models use many parameters to determine the likelihood that an abnormal condition will lead to damage in the reactor core, including the failure rates of machinery components in the plant and the probabilities of personnel errors in operating the plant, referred to as human actions in SPAR model terminology. A human reliability analysis (HRA) method used for calculating human error probabilities within SPAR is the SPAR-H method. This method is based on an explicit information-processing model of human performance derived from the behavioral sciences literature that was interpreted in light of activities at NPPs [10]. SPAR-H uses eight performance shaping factors (PSFs) deemed most capable of influencing human performance.

This analysis assumed that one SPAR-H parameter, the "Fitness-for-duty" PSF, could change based on the NI percent introduced in the previous section. The Fitness-for-duty PSF, which may be affected by fatigue, refers to whether or not an individual performing a task is physically and mentally fit to perform that task [10]. SPAR-H identifies three levels of fitness associated with this PSF: Nominal, Degraded fitness (includes consideration of fatigue from long duty hours) and Unfit. Unlike some of the PSFs used in SPAR-H, the fitness-for-duty PSF does not address the potential beneficial influences such as those that could result from a well rested individual. Therefore, the simulation used in this analysis employed a modified approach from that used in the SPAR-H method. The fitness-for-duty PSF is changed based on the expected net improvement in performance derived from human performance studies. As these changes are both positive and small relative to the pre-defined SPAR-H levels, the percent net improvement in human performance (NI) is directly applied to the previously calculated SPAR-H human error probabilities.

The modification to the SPAR-H human action was made with consideration as to whether the action being modified was a pre-initiator or post-initiator action. Pre-initiator actions are those actions that occur prior to the event (e.g., maintenance, test and calibration actions). Post-initiator actions are actions that are performed in response to an event. Both action types will affect the calculated CDF, but the translation of the NI percent to error rates specific to a certain action type were treated separately in the methodology. Full weight was given to the calculated NI when translating this percentage to the vigilant response necessary to improve error rates in pre-initiator actions. Yet, the NI percent was only given half-weight when translated into the reactionary response that may improve error rates for post-initiator actions. This differentiation in response types is incorporated into the methodology on the assumption that when workers respond to post-initiator situations, such as an emergency, performance is less likely to be affected by the degradations in alertness and attention normally associated with fatigue. Careful engineering judgment was applied to determine the portion of the SPAR models that were applicable to each of these response types.

Prior to modifying the SPAR models, control runs were completed and baseline CDFs were calculated. Next, the NI percentages corresponding to various altered work schedules were entered into the SPAR models using the methodology presented above and new, improved CDFs were calculated. The average percent change in CDF (ΔCDF) calculated by the four representative SPAR models was judged to be the plant risk improvement that could be attributed to a reduction in NPP worker fatigue. Table 3 displays some example NI calculations (or human error rates) for at-power conditions and the resulting ΔCDF that could be attributed to this improvement in human performance. This 1.1% overall improvement in CDF is the result of human performance and SPAR model runs that compared one baseline NPP work schedule to a schedule with more breaks and fewer consecutive hours worked.

Table 3 Example Human Performance and SPAR Model Results

Job Duty Group and Condition	Response Type	At-Power Net Improvement	Improvement in CDF
On-Shift Operations	vigilant	0.7%	0.04%
On-Shift Operations	reactionary	0.35%	0.80%
Maintenance	vigilant	2.4%	0.26%
Total [3]			1.10%

[3] *Given the previous incorporation of NPP personnel population data, the Total Improvement in CDF is additive*

TRANSLATION OF HUMAN PERFORMANCE AND PLANT RISK METRICS INTO MONETARY BENEFITS

Given a set of altered work schedules that included a combination of more breaks and fewer consecutive hours worked, estimates of the percent NI in human performance and in ΔCDF as a result of lessened fatigue were calculated. These percentages were applied to six areas of benefit for the nuclear industry to quantify the effect of improved performance. These six benefit areas included: (1) Reduction in Frequency of Plant Trips, (2) Reduction in Frequency of Severe Accidents, (3) Reduction in Shutdown Risk, (4) Improved Security, (5) Improved Fire Protection and (6) Reduction in Frequency of Lost and Restricted Work Cases.

The calculation of a monetary benefit, as a result of a reduction in NPP worker fatigue, required two variables: one of the calculated percentages presented in previous sections (NI or ΔCDF) and the maximum attainable benefit (MAB) that could be obtained by the nuclear industry if a specific benefit area in question was eliminated completely. The calculation of MAB was based on the idea that the present cost, for example, of replacing the power to a licensee's customers during a plant trip or of providing worker's compensation for occupational accidents could be eliminated if these events did not occur. Preventing these events, and in turn the payments, was seen as the benefit. MABs were calculated using applicable nuclear industry data and separated by NPP worker type (e.g., operators, maintenance workers, etc.) using nuclear personnel population data.

Given that only a percentage of these events occur as a result of human error caused by fatigue, the NI/ΔCDF percentage was multiplicatively applied to the MAB to obtain the monetary benefit attributed to a reduction in fatigue. While the areas of Plant Trips and Lost and Restricted Work Cases used the NI percentage to quantify the benefit, all other areas used the calculated ΔCDF. The benefits associated with the Improved Fire Protection and Reduction in Shutdown Risk areas were derived from the MAB calculated for the Reduction in Frequency of Severe Accidents. The Improved Security benefit area involved a qualitative analysis as a result of the lack of applicable risk models and the need to protect safeguards information. The resulting monetary benefit calculation could be delineated by NPP personnel types or by benefit area. Summing the benefit for all personnel types and all benefit areas produced the final calculation of the benefit to the nuclear industry of a reduction in worker fatigue as a result of altered NPP work schedules.

CONCLUSION

The methodology presented in this paper described a quantitative procedure to measure fatigue-related human performance and its effects on the nuclear industry. Given the limited availability of detailed historical data relating NPP events to fatigue, the analysis provided an alternative means by creating a relationship between human performance data and risk-significant plant events. The critical assumption that an improvement in human performance could be modeled as a decrease in the human actions base failure probabilities of SPAR models acted as the link between the human performance modeling and NPP risk analysis. This connection created a quantifiable correlation between improved human performance and a decrease in the frequency of risk-significant plant events. Maximum attainable benefit values for specific areas were the means with which these percentages were translated into absolute, measurable monetary quantities.

The authors implemented this methodology as a supplement to the U.S. Nuclear Regulatory Commission (NRC) proposed fatigue management provisions to the Fitness-For-Duty rule. The authors' intent was to use altered work schedules consistent with the proposed provisions and quantify the effect that these provisions would have on the nuclear industry. This analysis can be seen as an advance in the ability to address human performance in Probabilistic Risk Assessment (PRA). Fatigue-related human error affects many other industries in which the maintenance of a certain level of fitness in the workforce has serious risk implications. Therefore, this technique could also be transferable to other industries by addressing how worker fatigue relates to industrial work schedules and how a change in these work schedules may prevent some of this fatigue, and in turn, benefit the industry monetarily.

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