Reliability Engineering and System Safety 96 (2011) 1437–1447

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Inclusion of fatigue effects in human reliability analysis

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ARTICLE INFO

Article history:
Received 5 December 2010
Received in revised form
20 April 2011
Accepted 18 June 2011
Available online 13 July 2011

Keywords:
Human reliability
Human error
Fatigue
Sleep deprivation
Performance shaping factors

ABSTRACT

The effect of fatigue on human performance has been observed to be an important factor in many industrial accidents. However, defining and measuring fatigue is not easily accomplished. This creates difficulties in including fatigue effects in probabilistic risk assessments (PRA) of complex engineering systems that seek to include human reliability analysis (HRA). Thus the objectives of this paper are to discuss (1) the importance of the effects of fatigue on performance, (2) the difficulties associated with defining and measuring fatigue, (3) the current status of inclusion of fatigue in HRA methods, and (4) the future directions and challenges for the inclusion of fatigue, specifically sleep deprivation, in HRA.

1. Introduction

The degree to which fatigue affects human performance can range from slight to catastrophic. In the case of large complex systems, it is possible for the fatigue-related error of a single person working under sleep deprived conditions to cause an industrial accident that can kill thousands of people, cause major environmental damage, and/or cost billions of dollars [1]. Human error has been implicated in 30–90% of all industrial accidents [2]. The U.S. National Safety Council also reported in 1999 that human error was a contributing factor in 80% of all industrial accidents and responsible for $98.5 billion in accident-related costs [3]. The percentage of incidents connecting to human error in several industries and activities is listed in Table 1.

Human error is a major contributor to risk. One way to handle the effect of human error in systems and industry is use human reliability analysis (HRA). HRA is concerned with identifying, modeling, and quantifying the probability of human errors, and can be used as a component of probabilistic risk assessment (PRA) conducted for the entire complex system. This paper discusses three HRA methods (THERP, ATHEANA, and SPAR-H) that are discussed including their limitations with respect to fatigue. Typically, HRA methods use performance shaping factors (PSFs), those factors that influence human performance, to modify a base human error probability. One of the limitations of current HRA methods is reliance on expert opinion in assigning values for the performance shaping factors. A more objective technical basis for assigning performance shaping factor values needs to be developed.

One performance factor that influences human performance and is often a contributing factor in human error is fatigue. Although fatigue is a well known condition, it cannot be defined or measured in a straightforward manner. The effects of fatigue on performance must be measured indirectly through performance metrics, such as reaction time. There are many causes and types of fatigue, and this paper only discusses acute fatigue as the result of sleep deprivation (i.e., continuous hours of wakefulness). In order to demonstrate the effect of sleep deprivation on performance several studies have been conducted equating blood alcohol content (BAC%) to hours of sleep deprivation. Current HRA methods do not explicitly include fatigue. This paper specifically focuses on the inclusion of fatigue effects within the current HRA methods, with the motivation to develop a more objective technical basis for assigning PSF values.

Due to the difficulty defining and measuring fatigue, indirect prescriptive methods have been used in industry to combat fatigue. Fatigue management systems reduce worker fatigue by relating work hours to performance quality. There are two well known fatigue management software programs, FAST™ [9] and SAFTE™ [10], that are used in fatigue management (i.e., shift scheduling), which do include circadian rhythm influence along with other factors. In spite of this and strict shift handover guidelines, predicting how sleep deprived a worker will be during an error event is difficult. During a shut-down, NPP workers have been observed to work shifts that exceed shift-limits (e.g., over 16 h). This combined with the fact that NPP are often located in remote areas and some workers may have long commutes (e.g., in some cases 2 h each way) can produce a sleep deprived worker.

HRA is focused on assessing human performance as part of an overall probabilistic risk assessment (PRA) that encompasses both system hardware and the human operator. Fatigue has repeatedly

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doi:10.1016/j.ress.2011.06.005

been identified as a source of human error. Therefore, fatigue and sleep deprivation need to be included in HRA in a manner that helps quantify human error probability. The inclusion of fatigue will refine HEP and thereby improve risk assessments. These results can also be used to inform and improve fatigue management guidelines.

Four issues need to be addressed before fatigue can be incorporated into HRA. The first is how to define fatigue since there is no single definition of fatigue; the term *fatigue* has many dimensions, and this paper only focuses on sleep deprivation. The next issue is how to measure fatigue; this paper focuses on measurement of hours of continuous wakefulness (i.e., acute fatigue). Thirdly, the effect of fatigue on performance must be indirectly measured through performance metrics, such as reaction time. The fourth issue is how to include fatigue into HRA. This paper reviews the available literature and the state of the art in each of these topics and discusses possible directions and challenges in incorporating fatigue into HRA.

Thus the objectives of this paper are to discuss (1) the importance of the effects of fatigue on performance, (2) the difficulties associated with defining and measuring fatigue, (3) the current status of inclusion of fatigue in HRA methods, and (4) the future directions and challenges for the inclusion of fatigue, specifically sleep deprivation, in HRA. Section 2 highlights fatigue as a contributing factor in several global incidents and as a factor in inattention events at nuclear power plants (NPPs). Section 3 discusses the difficulties in defining and measuring fatigue and its effects, including examples on how fatigue effects on performance are measured. A brief description of HRA methods THERP, ATHEANA, and SPAR-H is given in Section 4, focusing on how they include fatigue effects. Section 5 discusses possible directions for improvement in HRA through the inclusion of fatigue, and Section 6 presents concluding remarks.

2. Fatigue related accidents

Unlike chemical impairment due to alcohol or drugs, which can be detected by biochemical tests, fatigue is more difficult to measure and discern as the cause of accidents. Typically, fatigue must be inferred from the context of the situation. For example, in the case of a single car accident, fatigue or even falling asleep might not be listed as the cause of the accident, instead only the end result, such as driving into a ditch, might be listed even when it is reasonable to assume fatigue as a contributing factor. Despite this limitation, fatigue has increasingly been claimed as the primary cause of many major accidents [11].

Table 1
Human error percentages in various accidents.

Accident	Human error(%)	Reference
Aviation	70–80	[4]
Maritime vessels	80–85	[5]
Chemical industry	63	[6]
NPP (US)	50–70	[7]
Automobile	65	[8]
Heavy truck	80	[8]

Note: NPP refers to nuclear power plants.

2.1. Global incidents with fatigue as a contributing factor

Fatigue has been documented to be at least a contributing factor in many of the major industrial accidents during the last thirty years [11]. Examples of some accidents with global impact that are believed to be related to human fatigue are listed in Table 2. Although fatigue is not the sole cause of the accidents listed in Table 2, it is considered a contributing factor.

A sampling of human error with potentially severe detrimental impacts caused by fatigue can be found when looking at the history of nuclear reactors. The Three Mile Island incident occurred on March 28, 1979, in which nuclear reactor coolant escaped after the pilot-operated relief valve (PORV) failed to close properly. The mechanical failures were compounded by the failure of operators to recognize that the plant was experiencing a loss of coolant. When the situation was noticed, the crew was not able to solve the problem until the relief crew took over for the fatigued crew [2,11,15,16,17]. The incident occurred in the morning between 04:00 am and 06:00 am. On June 9, 1985, at 01:30 am, the Davis-Besse (Oak Harbor, Ohio) nuclear power plant went into automatic shutdown after a partial loss of cooling water and then the total loss of the main feed-water. The incident was compounded when the operator pushed the incorrect button and turned off the auxiliary feed-water system. The operator's error was discovered by workers from the next shift [11,18,19]. On April 26, 1985, at approximately 01:30 am at the Chernobyl nuclear power facility in the Ukraine, workers turned off critical automatic safety systems resulting in the reactor to overheat. The sleep-deprived shift workers turned off the cooling system instead of turning on the automated safety systems. This led to the explosion that released 13 million curies of radioactive gases and less than 20 curies of iodine-131 [2,11,18,20].

Several other non-nuclear incidents related to fatigue have also gained world-wide attention. On February 8, 1986, in Canada, a VIA Rail passenger train collided with a Canadian National Railway freight train near Hinton, Alberta, west of Edmonton. The accident was a result of the crew of the freight train falling asleep [11]. On March 24, 1989, the *Exxon Valdez* oil tanker struck a reef in Prince Island Sound, Alaska, and spilled 11–32 million gallons of crude oil. The accident was caused by the third mate improperly maneuvering the vessel. The third mate had only had 6 h sleep in the previous 48 h, while the first mate had been working for 30 h continuously. The estimated clean-up cost was $2 billion dollars [12,21,22,23]. At 01:55 am on July 18, 1996, the *Peacock*, a cargo vessel carrying 605 ton of heavy fuel oil, ran aground on the Great Barrier Reef at full speed. The inquiry into the accident

Table 2
Incidents which list human fatigue as a contributing factor.

Accident	Date	Country	Time of event	Death toll	Reference
Three Mile Island	28-Mar.-79	USA	4:00	None	[11]
Davis-Besse	9-Jun.-85	USA	1:30	None	[11]
Hinton train disaster	8-Feb.-86	Canada	8:41	23	[11]
Chernobyl	26-Apr.-86	USSR	1:23	50	[11]
Exxon Valdez	24-Mar.-89	USA	0:00	Wildlife & water pollution	[12]
Peacock	18-Jul.-96	Australia	1:55	None	[13]
Am. Airlines Flight 1420	1-Jun.-99	USA	23:50	11 deaths, 110 injured	[14]
Staten Island Ferry	15-Oct.-03	USA	15:21	11 died, 71 injured	[14]