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Journal of Hazardous Materials 142 (2007) 747–753

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Human error and time of occurrence in hazardous material events in mining and manufacturing

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Available online 3 July 2006

Abstract

Human error has played a role in several large-scale hazardous materials events. To assess how human error and time of occurrence may have contributed to acute chemical releases, data from the Hazardous Substances Emergency Events Surveillance (HSEES) system for 1996–2003 were analyzed. Analyses were restricted to events in mining or manufacturing where human error was a contributing factor. The temporal distribution of releases was also evaluated to determine if the night shift impacted releases due to human error. Human error-related events in mining and manufacturing resulted in almost four times as many events with victims and almost three times as many events with evacuations compared with events in these industries where human error was not a contributing factor (10.3% versus 2.7% and 11.8% versus 4.5%, respectively). Time of occurrence of events attributable to human error in mining and manufacturing showed a widespread distribution for number of events, events with victims and evacuations, and hospitalizations and deaths, without apparent increased occurrence during the night shift. Utilizing human factor engineering in both front-end ergonomic design and retrospective incident investigation provides one potential systematic approach that may help minimize human error in workplace-related acute chemical releases and their resulting injuries.
Published by Elsevier B.V.

Keywords: Chemical release; Human error; Night shift operation; Shift work; Public health

1. Introduction

Human errors of commission and omission were at least partially responsible for the Three Mile Island nuclear facility release, the Space Shuttle Challenger explosion, the Bhopal Union Carbide release, the Exxon Valdez oil spill, and the nuclear plant catastrophe at Chernobyl. These events highlight the potential ramifications of human error in the workplace to public health and safety [1,2]. Identifying the overall incidence and significance of human error as a contributing factor in industrial hazardous material events is complicated by the complexity of interactions between systems and organizations, technology, and the final human interface in which the incident actually occurs [3,4]. Also, incident-reporting mechanisms may be designed primarily for external agencies, such as the Occupational Safety and Health Administration (OSHA) or for workers' compensation, in such a way that chemical-related incidents may be underreported [5,6]. Only incidents that result in death, loss of consciousness, days away from work, restricted work activity or job transfer, or medical treatment beyond first aid must be reported on OSHA Form 300, the log of work-related injuries and illness. There is no place on this form to indicate whether human error was a contributing factor [7]. The U.S. Department of Labor, Bureau of Labor Statistics, relies on this OSHA reporting mechanism to compile its detailed statistics on workplace injuries, and hence does not provide contributing factors in its detailed analyses of workplace injuries and illnesses [8].

Some authors report that as many as 90% of all workplace adverse events can be attributed to human error, and that that percentage has increased four-fold between the 1960s and the 1990s [4]. One study from Finland determined that 84–94% of almost 300 hazardous material events in the workplace resulting in fatal and serious injuries were due mainly to human error [9]. A Canadian analysis of 514 industrial incidents of potential major consequence found that human error was the major overall

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0304-3894/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.jhazmat.2006.06.117

cause [6]. These statistics were obtained from a review of the literature on occupational incidents in general and do not specify breakdowns for chemical-related incidents. There is a paucity of literature available reporting such statistics specifically for chemical-related incidents. An analysis of data from the Hazardous Substances Emergency Events Surveillance (HSEES) system maintained by the Agency for Toxic Substances and Disease Registry (ATSDR) provides the opportunity to assess human error in reportable acute releases of chemicals.

The Three Mile Island nuclear release and the Exxon Valdez oil spill both occurred during night shift hours [1,2]. These observations and others regarding the temporal distribution of hazardous material events that threaten public health and safety suggest that there are periods in the 24 h day when human mistakes leading to catastrophes may be more likely to occur. The period from 1:00 a.m. to approximately 8:00 a.m. is a primary period of vulnerability, corresponding to the nadir in the cycle of circadian rhythmicity [1]. We chose to evaluate HSEES data for the manufacturing and mining industries, because companies in these industries often operate for 24 h a day. We were thus able to describe possible associations between human error as a contributing factor of acute chemical releases and the time of occurrence of events.

2. Methods

Since 1990, HSEES has collected data on acute releases of chemicals and their associated injuries and evacuations. HSEES is an active, state-based surveillance system that enables identification of factors related to the public health impact of these acute events and promotion of activities to lessen the impact. Releases are eligible for inclusion in the HSEES system if they are uncontrolled or illegal and require removal, cleanup, or neutralization according to federal, state, or local law. Threatened releases also are included if they result in a public health action, such as an evacuation. Events involving only petroleum are excluded.

State health department personnel used a variety of sources (e.g. records and oral reports of state environmental agencies, police and fire departments, and hospitals) to collect information about the acute hazardous chemical events. Before 2000, participating state health departments entered the data into a computerized data entry system designed by ATSDR, and data were transmitted quarterly to ATSDR for quality-control checks and analyses. Beginning in January 2000, data were entered into a web-based application that enabled ATSDR to instantly access the data. Information collected for each event included the location and industry involved in the event, chemicals released, number of victims, evacuations, and contributing factors for the event. Information on contributing factors was either reported by the notification source or determined by the state HSEES coordinator using various reports; information on contributing factors was not collected until 1996.

The 1990 industrial classification system was used to categorize the industries [10]. A victim is defined as a person experiencing at least one documented adverse health effect (such as respiratory irritation or chemical burns) that was likely associated with the event and occurred within 24 h after the release. The HSEES system does not identify the immediate cause of the adverse health effect other than the event itself. For the analyses, the chemicals released were grouped into 16 categories: acids, ammonia, bases, chlorine, formulations, hetero-organics, hydrocarbons, mixture across categories, oxy-organics, paints and dyes, pesticides, polychlorinated biphenyls, polymers, volatile organic compounds (VOCs), other inorganic substances, and other substances. Mixture across categories consisted of chemicals that were mixed before release, including chemicals from more than one of the other 15 chemical categories used. The category "other inorganic substances" comprised all inorganic substances – except for acids, bases, ammonia, and chlorine – and includes chemicals such as mercury and hydrogen sulfide. The "other" category consisted of chemicals, such as asbestos and carbon dioxide, that could not be classified into any one of the other 15 chemical categories.

The analysis included events captured by HSEES for 1996–2003. Twelve states participated in HSEES during the entire period: Alabama, Colorado, Iowa, Minnesota, Mississippi, Missouri, New York, North Carolina, Oregon, Texas, Washington, and Wisconsin. An additional five states participated during portions of the period: Louisiana (2001–2003), New Hampshire (1996), New Jersey (2000–2003), Rhode Island (1996–2001), and Utah (2000–2003).

Analyses were restricted to events in the mining or manufacturing industries where human error was reported to be a contributing factor in the event. Human error is defined as a mistake made by a person resulting in a release or threatened release of hazardous substances. Examples include leaving a valve open, failure to respond to process alarms, failure to maintain process variables or conditions at the set point, maintenance failures, inappropriate use of equipment, not following appropriate procedures such as lock-out or tag-out, removal of safety devices, misjudgment of conditions, inappropriate action resulting from faulty perception, mishandling accidents (e.g. dropping a vial), or mistakes such as pushing the wrong button, being distracted, and other similar action.

Descriptive statistics are presented that include other contributing factors, chemicals involved in the releases, release type, categories of victims, types of adverse health effects, severity and disposition of the victims, types of personal protective equipment (PPE) worn, decontaminations, evacuations, and time and day of occurrence. HSEES only records what type of PPE was worn; it does not evaluate the appropriateness of the PPE used. Human error-related events in the mining and manufacturing industries were compared with events in the mining and manufacturing industries where human error was not a contributing factor to identify similarities and differences in percentage of victims, deaths, hospitalizations, and evacuations. Time of occurrence of human error-related events in the mining and manufacturing industries was also assessed for events resulting in victims, deaths, hospitalizations, and evacuations. The mining and manufacturing industries were selected for analysis because of their likelihood of having 24 h operations. HSEES does not collect data on hours of operation; therefore, denominator data was unavailable to calculate rates with respect to time of day.

3. Results

A total of 3282 human error-related events occurred in the mining and manufacturing industries during 1996–2003. These events represented 5.7% of all HSEES events and 11.6% of all events in the mining and manufacturing industries in that time-period. The number of human error-related events in the mining and manufacturing industries averaged 410 per year (range: 320–477 events per year). Approximately 94% ($n = 3085$) of the events occurred in fixed facilities.

3.1. Other contributing factors

One or two contributing factors could be reported per event. Of the 3282 events where human error was one of the contributing factors, human error was reported as both the primary and secondary contributing factor for six events. Along with human error, 1181 other contributing factors were reported (Table 1). The most common other contributing factor was improper filling, loading, or packing (349 [29.6%]).

Table 1
Other contributing factors in human error-related events in the mining and manufacturing industries, HSEES 1996–2003

Other contributing factor	Number	%
Equipment failure	250	21.2
Fire	53	4.5
Forklift puncture	24	2.0
Improper filling, loading, or packing	349	29.6
Improper mixing	53	4.5
Performing maintenance	115	9.7
Power failure	18	1.5
System/process upset	112	9.5
System start-up or shutdown	56	4.7
Unauthorized dumping	34	2.9
Vehicle/vessel collision	23	1.9
Other	94	8.0
Total	1181	100.0

3.2. Area of fixed facility where release occurred

For each fixed-facility event, one or two types of area involved in the release could be reported. Of all 3085 human error-related fixed-facility events in the mining and manufacturing industries, 2605 (84.4%) reported one type of area, 439 (14.2%) reported a combination of two area types, and type of area was not reported for 41 (1.3%) events. Among events with one type of area reported, the main area was classified as follows: above-ground storage (558 [21.4%]), process vessel (497 [19.1%]), material handling (387 [14.9%]), piping (372 [14.3%]), ancillary process equipment (330 [12.7%]), transportation within a fixed facility (136 [5.2%]), dump/waste (107 [4.1%]), and the remaining (218 [8.4%]) events involved other areas. Of the events with two areas, 174 (39.6%) involved piping in combination with other types of areas.

3.3. Chemicals

A total of 3506 chemicals were released in the 3282 human error-related events in the mining and manufacturing industries. The number of chemicals released per event ranged from 1 to 14, but in most events only one chemical (3157 [96.2%]) was released. Most releases were spills (55.6%), followed by air releases (37.7%), fires (4.1%), explosions (1.3%), threatened releases (1.0%), and other/unknown (0.7%).

The category of chemicals most frequently released in these events was VOCs (22.1%); however, releases of VOCs were not likely to result in victims (6.2% of all releases in that category) (Table 2). Although not among the most frequently released

Table 2
Distribution of chemicals released in human error-related events in the mining and manufacturing industries, HSEES 1996–2003

Chemical category	Total releases		Releases with victims		
	Number	% of total releases	Number	% of all releases victims	% of releases with victims in chemical category
Acids	334	9.5	66	16.6	19.8
Ammonia	232	6.6	51	12.8	22.0
Bases	178	5.1	24	6.0	13.5
Chlorine	95	2.7	26	6.5	27.3
Hetero-organics	45	1.3	4	1.0	8.9
Hydrocarbons	73	2.1	4	1.0	5.5
Mixture across categories	432	12.3	48	12.1	11.1
Other inorganic substances	507	14.5	42	10.6	8.3
Oxy-organics	228	6.5	26	6.5	11.4
Paints and dyes	96	2.7	4	1.0	4.2
Pesticides	127	3.6	15	3.8	11.8
Polychlorinated biphenyls	13	0.4	0	–	–
Polymers	100	2.9	7	1.8	7.0
Volatile organic compounds	776	22.1	48	12.1	6.2
Other[a]	229	6.5	27	6.8	11.8
Indeterminate	41	1.2	5	1.3	12.2
Total[b]	3506	100.0	397	99.9	11.3

[a] Includes one chemical classified as a formulation.
[b] Percentages do not total 100% because of rounding.

chemical categories, chlorine, ammonia, and acids were the most likely to result in victims (27.3%, 22.0%, and 19.8% of all releases in that category, respectively). Ammonia (217 [6.2%]), sodium hydroxide (117 [3.3%]), and sulfuric acid (110 [3.1%]) were the most frequently released individual chemicals.

3.4. Victims

A total of 1306 victims were injured in 338 events (10.3% of all human error-related events in the mining and manufacturing industries). Of the events with victims, 189 (55.9%) events involved only one victim, and 55 (16.3%) involved two victims. The number of victims per event ranged from 1 to 54. Most victims of human error-related events in the mining and manufacturing industries were employees (1062 [81.3%]). However, members of the general public (187 [14.3%]) and first responders (firefighters, police, employee-responders, and emergency medical technicians) (57 [4.4%]) were also injured in these events. Human error-related events in the mining and manufacturing industries were more likely to result in victims compared with events in the mining and manufacturing industries where human error was not a contributing factor (10.3% versus 2.7%).

Most (705 [54.0%]) victims were treated at a hospital and released, 321 (24.6%) received first aid, 133 (10.2%) were admitted to the hospital, 65 (5.0%) were evaluated by a personal physician within 24 h after the event, 54 (4.1%) were observed at a hospital but did not receive treatment, 8 (0.6%) had their adverse health effects reported by an official within 24 h after the event, and 19 (1.5%) died. The medical outcome was unknown for one victim. More victims were admitted to a hospital in human error-related events in the mining and manufacturing industries compared with events in the mining and manufacturing industries where human error was not a contributing factor (10.2% versus 8.6%); however, a similar percentage of victims died in both types of events (1.5% versus 1.6%).

Eighteen (94.7%) fatalities were employees and one (5.2%) was a member of the general public (Table 3). Three employees died from thermal burns in one event when tetrafluoroethylene exploded at a plastics manufacturing plant. Two other employees suffered thermal burns in this event and were admitted to a hospital. The explosion occurred at 8:55 a.m., and human error was the only contributing factor.

The 1306 victims experienced 2170 adverse health effects. Most victims (81.5%) reported one or two adverse health effects, with five being the maximum number of adverse health effects reported per victim. Respiratory irritation (781 [36.0%]) and dizziness/central nervous system symptoms (295 [13.6%])

Table 3
Profiles of fatalities in human error-related events in the mining and manufacturing industries, HSEES 1996–2003

Event	Time of occurrence	Chemical	Release type	Other factor	Number of deaths	Victim category	Injury
1	5:00 p.m.	Hydrogen sulfide	Air	None	1	Employee	Respiratory
2	8:55 a.m.	Tetrafluoroethylene	Explosion	None	3	Employee	Thermal burns
3	5:30 a.m.	Creosote	Spill	None	1	Employee	Trauma
4	3:20 p.m.	Black powder and pyrotechnic chemicals	Explosion	Explosion	1	Employee	Trauma
5	9:00 p.m.	Sodium hydrosulfide	Spill and air	None	1	Employee	Respiratory
6	3:38 p.m.	Ammonia	Spill and air	None	1	Employee	Respiratory, chemical burns
7	1:40 p.m.	Sodium hydroxide	Spill	None	1	Employee	Chemical and thermal burns
8	1:50 a.m.	Ammonia	Air	None	1	Employee	Respiratory
9	5:45 p.m.	Ditertbutylperoxide	Fire and explosion	None	1	Employee	Thermal burns
10	4:22 a.m.	Phenol	Spill and air	None	1	Employee	Respiratory
11	9:15 a.m.	Anhydrous ammonia	Spill and air	None	1	Employee	Respiratory, chemical burns
12	1:30 p.m.	Antimony pentachloride	Spill	Improper filling, loading or packing	1	Employee	Chemical burns
13	8:30 a.m.	Sulfuric acid and ethyl alcohol	Spill and fire	Explosion	1	Employee	Trauma
14	11:34 a.m.	Fertilizer	Spill	Vehicle collision	1	General public	Trauma
15	11:15 p.m.	Calcium chloride	Spill	Vehicle rollover	1	Employee	Trauma
16	11:10 p.m.	Chlorine	Air	Equipment failure	1	Employee	Respiratory eye irritation, dizziness/CNS[a] symptoms
17	12:01 a.m.	Strontium 90	Radiation	Explosion	1	Employee	Trauma

[a] Central nervous system.

Table 4
Distribution of adverse health effects experienced by victims of human error-related events in the mining and manufacturing industries, HSEES 1996–2003

Adverse health effect	Frequency	Percent
Chemical burns	81	3.7
Dizziness/central nervous system symptoms	295	13.6
Eye irritation	234	10.8
Gastrointestinal problems	169	7.8
Headache	261	12.0
Heart problems	23	1.1
Respiratory irritation	781	36.0
Shortness of breath	24	1.1
Skin irritation	110	5.1
Thermal burns	88	4.1
Trauma	93	4.3
Other	11	0.5
Total[a]	2170	100.1

[a] Percentage does not total 100% because of rounding.

were the most frequently reported adverse health effects (Table 4).

The status of PPE use was reported for 889 (83.7%) employee-victims and for 53 (93.0%) responder-victims. Most (72.7%) of the employee-victims and 41.5% of the responder-victims had not worn any form of PPE. Of the employee-victims who wore PPE, approximately 28% used minimal protection such as a work uniform, gloves, eye protection, hard hat, and/or steel-toed shoes. Among responder-victims who wore PPE, 45.3% wore firefighter turnout gear and 13.2% wore minimal protection.

3.5. Evacuations and decontaminations

Evacuations were ordered in 386 (11.8%) human error-related events in the mining and manufacturing industries. The number of people evacuated per event was known for 351 (90.9%) events and ranged from 0 to 2500 (median: 26 people). The length of the evacuations was known for 355 (92.0%) events and ranged from 0 h to 130.5 days, but the majority (54.7%) of the evacuations lasted 2 h or less. Most (298 [77.2%]) evacuations were of a building or the affected part of a building; 30 (7.8%) were of a defined circular area surrounding the event locations; 23 (6.0%) were of a circular and downwind or downstream area, 20 (5.2%) were of an area downwind or downstream of the event; and the remaining 15 (3.9%) were of no criteria or not known. Evacuations were more frequent in events in the mining and manufacturing industries where human error was a contributing factor compared with events in these industries where human error was not a contributing factor (11.8% versus 4.5%).

Decontamination at a medical facility was done for 91 employees, 16 responders, and 27 members of the general public. Decontamination at the scene was done for 297 employees, 531 responders, and 30 members of the general public.

3.6. Time and day of occurrence

Time of occurrence of human error-related events in the mining and manufacturing industries was analyzed for 2 h increments; this information was missing for 98 (3.0%) events (Fig. 1). Most events occurred in the mid-morning hours

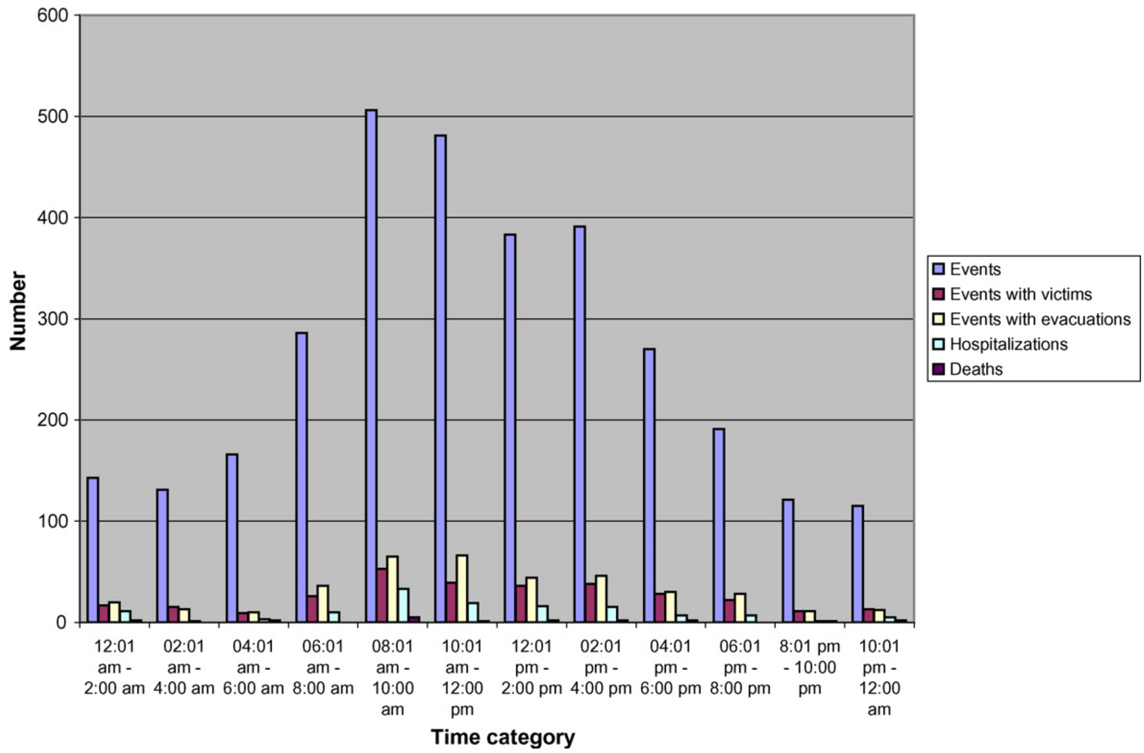

Fig. 1. Distribution of human error-related events, events with victims, events with evacuations, hospitalizations, and deaths in the mining and manufacturing industries, by time of occurrence, HSEES 1996–2003.

of 8:01–10:00 a.m. (506 [15.9%] events) and 10:01 a.m.–12:00 p.m. (481 [15.1%]). The fewest number of events (115 [3.6%]) occurred in the late evening hours of 10:01 p.m.–12:00 a.m. Most events (2781 [84.7%]) occurred on a weekday, with the greatest number of events occurring during Tuesday through Thursday (619 [18.9%], 565 [17.2%], and 587 [17.9%], respectively).

The distribution of human error-related events with victims and evacuations in mining and manufacturing was similar to the distribution of all human error-related events in these industries (Fig. 1). Most events with victims and evacuations occurred in the mid-morning hours of 8:01–10:00 a.m. (53 [17.3%] and 65 [17.1%], respectively) and 10:01 a.m.–12:00 p.m. (39 [12.7%] and 66 [17.3%], respectively). Most hospitalizations and deaths associated with human error-related events in mining and manufacturing also occurred in the mid-morning hours of 8:01–10:00 a.m. (33 [25.8%] and 5 [26.3%], respectively). However, 8.6% of the hospitalizations occurred during 12:01–2:00 a.m., and two or fewer fatalities occurred during the other time categories.

4. Discussion

Although only about 6% of HSEES events during 1996–2003 were human error-related events in the mining and manufacturing industries, 10% of these events resulted in victims (accounting for approximately 8% of all victims). Human error-related events in the mining and manufacturing industries resulted in almost four times as many events with victims and almost three times as many events with evacuations as events in the mining and manufacturing industries where human error was not a contributing factor (10.3% versus 2.7% and 11.8% versus 4.5%, respectively). An analysis of HSEES events in New York similarly found that when human error was a contributing factor, a larger percentage of the events involved injury (24% when human error was involved versus 6% when equipment failure was involved) [11]. In a Canadian study, employee industrial injuries occurred as a result of human error in 55% of critical occupational incidents, as opposed to 22% of incidents involving equipment failures and 26% involving structural failures [6].

The percentage of events related to human error in this analysis (11.6% of all HSEES events in the mining and manufacturing industry) is much lower than the generally accepted rate of 80–90% attributable to human error [9]. It is also lower than the New York HSEES analysis indicating that 33% of the chemical release incidents across all industries, not just those in manufacturing and mining, were attributable to human error [11]. Another HSEES analysis of hazardous ammonia releases, which lead to evacuation and injury more often than releases of other chemicals, found that 12% involved human error [12]. In a Canadian study of occupational incidents in general, 54% resulted from identifiable human error [6]. These differences in percentages could be attributed to many factors, including the data collector's understanding of what constitutes human error. Additionally, HSEES data are restricted to hazardous material incidents, while other reports in the literature are not similarly restricted. The more important finding from the public health perspective is that those acute chemical releases where human error was a contributing factor are more likely to involve victims and evacuations.

The time of occurrence of events in mining and manufacturing where human error was a contributing factor showed a widespread distribution for number of events, events with victims and evacuations, and hospitalizations and deaths, without an apparent increased occurrence during the night shift. These findings are not consistent with other reports suggesting that human error is more likely to occur during the vulnerable period corresponding to decreased alertness and increased fatigue during the circadian lows of the night shift [1,2]. However, a limitation of this analysis is that data collection does not indicate the hours of operation or the relative work capacity during different hours of operation of the industries where releases occurred. If industries were included that do not have 24 h operation, or which have restricted nighttime capacity, there is a potential underestimation of the impact of night shift work on human error contribution. Further studies on the temporal distribution of acute chemical releases precipitated by human error which use data only from industries with 24 h full operation would be useful in exploring possible connections between circadian lows of night shift work and human error.

Because humans are fallible, it is not possible to totally eliminate human error as a contributing factor in hazardous material events in the workplace. In fact, the contribution of human error to incidents in hazardous technologies has reportedly increased four-fold during the 1960s–1990s and has now become the most common contributing factor in incidents in complex and potentially hazardous systems. This increase is more likely due to advances in safety engineering and increasing system complexity than to an increase in accident proneness of individuals [4]. From a public health perspective, searching for explanations of contributing factors of hazardous material events with a mindset on future prevention is more useful than establishing blame.

5. Conclusions

The finding that acute hazardous material events where human error is a contributing factor are more likely to result in injury and evacuation makes determining the underlying cause for these errors, with a focus on future prevention, an important public health intervention. To do so requires an understanding that human factors are a product of individual psychological factors, such as momentary inattention and forgetfulness, as well as organizational and system dynamics. The use of human factor engineering in both front-end ergonomic design and retrospective incident investigation provides one potential systematic approach that can be used to minimize human error in workplace-related chemical releases and their resulting injuries. A human factors engineering approach examines potential contributors to hazardous material event sequences including equipment design, facility design, procedures, training, communication, workload, job design, personal and psychological factors, and determinant interactions (e.g. fatigue and task complexity/low workload and vigilance) [13]. Such a holistic, systems-based approach to determining why human error occurs may suggest interventions that could lessen the likelihood of acute chemical releases and resultant injuries attributed to human error.

Acknowledgments

Our grateful appreciation goes to our partners in the participating state health departments who, with diligence and dedication, researched and gathered much of the data for this publication. Without their assistance, ideas, and comments, this work would not have been possible.

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