Using Fault Tree Analysis to Identify Contributing Factors to Engulfment in Flowing Grain in On-Farm Grain Bins

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ABSTRACT. Findings reported by researchers at Illinois State University and Purdue University indicated that since 1980, an average of eight individuals per year have become engulfed and died in farm grain bins in the U.S. and Canada and that all these deaths are significant because they are believed to be preventable. During a recent effort to develop intervention strategies and recommendations for an ASAE farm grain bin safety standard, fault tree analysis (FTA) was utilized to identify contributing factors to engulfments in grain stored in on-farm grain bins. FTA diagrams provided a spatial perspective of the circumstances that occurred prior to engulfment incidents, a perspective never before presented in other hazard analyses. The FTA also demonstrated relationships and interrelationships of the contributing factors. FTA is a useful tool that should be applied more often in agricultural incident investigations to assist in the more complete understanding of the problem studied.

Keywords. Engulfment, Fault tree analysis, Flowing grain, Hazard, Suffocation.

Since 1978, Purdue University has maintained a national database of agriculture-related engulfment cases that have occurred in loose agricultural materials in both commercial and on-farm facilities. The database presently contains over 500 documented cases of fatal and non-fatal engulfments in the U.S. and Canada. A study of cases that occurred between 1966 and 1999 revealed that approximately five individuals per year in the U.S. and Canada suffocated in on-farm metal grain bins due to engulfment in grain (Kingman et al., 2001). A follow-up study was conducted by collaborating researchers at Illinois State University and Purdue University that reviewed more recent cases that occurred from 1980 through 2001. It was believed that a review of cases that occurred after 1980 would include more complete information, represent contributing factors of present-day engulfment incidents, and provide a better sense of whether or not the engulfment problem was continuing. Results from the study of the more recent cases indicated that the average number of deaths was approximately eight per year and that the engulfment problem was continuing (Kingman and Field, 2003). Although the findings reported by these studies and in the literature were helpful in identifying potential contributing factors to engulfment, a comprehensive investigation into the basic causes of engulfment was not completed.
During a recent effort to develop intervention strategies and recommendations for an ASAE farm grain bin safety standard, a systems approach was used to identify the contributing factors to engulfment. As part of the systems approach, contributing factors to engulfment in grain were identified by conducting several activities. A fault tree analysis (FTA) was constructed, and agricultural safety literature related to engulfment and the prevention of out-of-condition grain was reviewed. In addition, a summary of Purdue University’s database of engulfments was completed, and several investigations of engulfment incidents were conducted. Finally, an expert panel was convened to review and prioritize the list of identified contributing factors.

A review of the literature revealed that FTA has been utilized as a post-incident tool to identify contributing factors in well-known incidents such as the Three Mile Island nuclear power plant mishap, the space shuttle Discovery explosion, and the Titanic sinking. In addition, FTA has been used to identify the potential factors that could lead to failure in the nuclear power industry, intercontinental missile guidance systems, and airliners such as the Boeing 757.

FTA diagrams provided a spatial perspective of the circumstances that occurred prior to engulfment incidents, a perspective never before presented by other hazard analyses. The FTA also demonstrated interrelationships of the contributing factors and offered insights for researchers and the expert panel regarding the engulfment problem. An increase in the application of FTA to agricultural scenarios may be beneficial to researchers and safety curriculum writers. The authors hope that the use of FTA to address the engulfment problem will inspire others to utilize this technique.

Review of the Literature

A broad range of techniques was found in the literature that addressed the identification of hazards in industrial settings. These included methods such as cause and effect diagrams, fault tree analysis (FTA), the success likelihood index method, hazard analysis and critical control point, job safety analysis, hazard and operability studies, failure modes and effects analysis, and what-if analysis. It was determined that cause and effect and FTA diagramming would be beneficial to the identification of hazards related to engulfments in grain.

Cause and Effect and FTA Diagrams

The usefulness of diagrams to represent complex systems and interrelationships of causes of incidents has been demonstrated by numerous researchers (Ishikawa, 1986; Jones and McBride, 1990; Fortune and Peters, 1995). Ishikawa (1986) of the University of Tokyo organized complicated processes more efficiently by developing a cause and effect analysis that included the use of diagrams. The diagrams, which became known as Ishikawa fishbone diagrams, were developed to illustrate multiple causes, which were grouped into major categories and directly related to a single outcome or problem (Jones and McBride, 1990). Figure 1 is an example of a fishbone diagram with four categories of causes: A, B, C, and D.

Jones and McBride (1990) touted the ability of fishbone diagrams to represent meaningful relationships between causes and effects during structured problem-solving techniques and applications, especially when situations were so complex that explanations using words alone were difficult. They provided a case study of the use of a fishbone diagram that was developed by an expert panel to address the problem of out-of-weight specification of products by identifying contributing factors and their interrelationships. In this example, the panel first reviewed the problem and determined the main categories
of causes, which were man, material, method, and machine (fig. 2). The group then identified and categorized the intermediate and indirect causes or factors, placing them in the diagram under the appropriate heading. Following this procedure, a comprehensive list of the contributing factors to the problem was identified. Jones and McBride (1990) reported that the fishbone diagram facilitated the portrayal of interrelated causes and contributing factors to each event category.

FTA diagrams, like fishbone diagrams, have also been used to identify cause and effect relationships. In our research, FTA was chosen as a means to identify contributing factors to engulfments based on the wide acceptance and benefits of FTA.

FTA was conceived by H. A. Watson of Bell Laboratories in 1961 to perform reliability and safety analysis of the Minuteman launch-control system (Brown, 1976; Ericson, 1999). Hammer (1972) described FTA as an effective modeling technique for safety analysis, one that included the identification of contributing factors that might not otherwise be realized. Brown (1976) documented the benefits of using FTA to qualitatively analyze the safety of a system and reported that the technique was invaluable to managers for understanding of the safety of a system and focusing on the most critical areas.
Researchers contracting with the U.S. Nuclear Regulatory Commission (NRC) developed the Fault Tree Handbook, NUREG-0492 (NRC, 1981), in order to promote the use of FTA and present standard FTA symbols and methodologies. NUREG-0492 was found to be referenced in most FTA-related literature published since 1981.

Roland and Moriarty (1983) reported that a benefit of incorporating FTA into safety and reliability analyses was to distinguish critical control points that were essential for safe system operation. Embrey et al. (1984) reported that NRC researchers were the most substantial users of FTA during the 1970s and 1980s. The NRC used FTA to predict the reliability of nuclear power generation systems and evaluate incidents including the mishap at the Three Mile Island facility. Dhillon (1986) stated that FTA was especially beneficial for analyzing human and machine error in a system. McCormick and Sanders (1987) described FTA as an analysis of a system or operation based on deductive logic that depicts graphically the interrelationship of combinations of events that can result in accidents or injuries.

FTA diagrams show the cause and effect relationship between the undesired event and all the contributing causes (Stephenson, 1991; Redmill et al., 1999). The lowest level of each group of events, or branch, is a failure or error-initiating event and identifies the initial contributing factors (Murphy, 1992). An FTA was developed by Anderson and Smith (1988) for tractor runovers due to bypass starting (fig. 3) (Murphy, 1992). Interdependent events and circumstances related to this type of incident are also depicted.

Brauer (1994) suggested that FTA is a useful method to use when addressing a complex situation. Plog (1996) described FTA as a method in which an undesired event is selected and all possible occurrences that can contribute to the event are diagrammed in the form of a tree, with branches that indicate intermediate and basic event causes, as shown in figure 4. Independent and dependent relationships of events are indicated by logic gates (Bahr, 1997). Ericson (1999) described FTA as a tool for analyzing, visually displaying, and evaluating failure paths in a system.

Figure 3. FTA applied to tractor runovers during bypass starting (Murphy, 1992).
Ericson (1999) and McManus (1999) reported that FTA continued to be used as a substantial tool in industrial safety system applications in the 1990s. Schweitzer et al. (2000) published FTA diagrams to illustrate the probability of component failures in high-voltage transmission lines. Ericson (2000) introduced a new symbol, an “evidence date,” to assist in his application of FTA to circumstances prior to incidents, such as crashes involving aircraft. Modifications to FTA symbols and additional symbols were also reported by Bobbio et al. (2000), Huang et al. (2000), Wu and Gu (2000), and others.

FTA Symbols

The following FTA symbols (fig. 5) were adapted from the Fault Tree Handbook, NUREG-0492 (NRC, 1981), where a more complete reference of these and other traditional FTA symbols can be found.

The OR gate is a type of logic gate. In FTA, it shows that the output event occurs only if one or more of the input events occurs (fig. 6). Output event causality reflects the independent actions within or related to the input events. In a quantitative analysis, the probabilities of an output event occurring are calculated by adding the probabilities of the input events.

AND gates show that the output fault occurs only if all of the input faults occur; this is referred to as a dependent event. Figure 7, an example FTA representation of DC power failure, shows that all DC power failed because all power sources, even the battery backup, failed. In a quantitative analysis, the probability of complete power failure would be determined by multiplying the probabilities of each of the input failures.
FTA symbols have been used to illustrate relationships and interrelationships between primary and secondary contributing factors in incidents involving aircraft, ships, and other major disasters. In addition, FTA has been utilized to identify problem areas of missile guidance systems and the management of crucial industry processes, such as nuclear power generation. Because of the documented benefits of using the FTA method, it was determined that it could be successfully used to identify contributing factors of engulfment in flowing grain and illustrate the associations between factors.

FTA Applied to Engulfment in On-Farm Grain Bins

The resulting FTA diagram of engulfment in on-farm grain bins is shown in figures 8 and 9. Because of the size and complexity of the original diagram, it was reconfigured for this publication in order to improve the reader’s ability to review the figures.

The top, or the undesired event, chosen for the analysis was the full or partial engulfment of a victim in flowing grain in an on-farm grain bin (fig. 8). The FTA diagram was divided into three branches that correlated with the common types of engulfments:

**Figure 6.** Example OR gate used with output and input events (NRC, 1981).

**Figure 7.** Example AND gate with multiple DC power failures (Brauer, 1994).
Victim is fully or partially engulfed in flowing grain in an on-farm grain bin

Victim is on grain mass in a dangerous situation

Victim attempts to clear plugged auger

Victim falls into bin

Auger operating

Auger purposely switched on

Auger inadvertently switched on

Plugged auger

Moldy grain plugs auger

Victim falls into bin

Victim enters grain bin to clear plugged auger

Victim covered during avalanche of crusted grain

Victim covered during avalanche of moldy grain

Substantial crusting

Moldy grain

Victim falls through horizontally crusted grain

Victim is on grain mass in a dangerous situation

Void present under grain surface

Substantial crusting

Moldy grain

Victim is adjacent to vertically crusted grain

Grain mass becomes dislodged

Moldy grain

Figure 8. FTA diagram of top, or undesired, event.

(1) victim falls through horizontally crusted grain, (2) victim sinks into grain mass with auger operating, and (3) victim covered during avalanche of crusted grain. These three
instances of engulfment were chosen based on previously reported categories of engulfment by Kelley (1995) and findings of engulfment investigations (Freeman et al., 1998).

The event of a victim falling through horizontally crusted grain was preceded by two intermediate events: (1) victim is on crusted grain surface, and (2) void present under the grain surface. The event of a victim being on the surface of a crusted grain mass was determined to be the result of any of three initial events, including victim unaware of danger, victim disregards danger, or victim unaware of void. The cause of the void was attributed to the initial event of unloading grain in conjunction with substantial crusting caused by out-of-condition grain.
The second branch of the FTA represents the event of a victim sinking into the grain mass with the auger operating. This event was preceded by two dependent events: (1) victim on grain surface in a dangerous situation, and (2) auger operating. Victims were located on the grain because they had fallen into the bin or were attempting to unplug a plugged auger inlet. In order for this intermediate event to have occurred, the victim must have fallen into or entered the bin and the auger must have been plugged. The victim entered the bin because he disregarded the danger or was unaware of the danger associated with flowing grain, both of which have been shown as initial events. The plugged auger was found to be related to the event of substantial crusting in conjunction with the action of moldy grain blocking the unloading auger inlet.

The other dependent event under the top event in figure 8 involved the operation of the auger. Two independent events were found to relate to the operation of the auger: the auger was switched on either purposely or inadvertently. When the auger was purposely operated, it was found that either of two initial events occurred: (1) the operator was unaware of the danger, or (2) the operator disregarded the danger. When the auger was inadvertently switched on, it was blamed on miscommunication between the operator and victim, or the wrong switch was activated.

The third branch of the FTA, representing the event of a victim covered during an avalanche of crusted grain (fig. 8), was preceded by three intermediate events: (1) substantial crusting, (2) victim adjacent to vertically crusted grain mass, and (3) grain mass becomes dislodged. Two independent events were identified that could have led a victim to be adjacent to vertically crusted grain. This exposure was associated with the victim not being aware of the danger or disregarding the danger. The dislodgement of the crusted grain mass was found to be caused directly or indirectly by the victim or by a co-worker.

Situations involving substantial crusting of grain (fig. 9) were found to be caused by moisture entering the bin or because the moisture content at the time of storage was too high. Moisture that inadvertently entered the bin was attributed to the combination of an available moisture source and a pathway for moisture to enter the bin. Sources of moisture were identified as precipitation, primarily snow or rain, and humidity. The pathway of moisture was found to be one of four initial events: (1) hole in the roof, (2) open roof hatch, (3) ventilation fan not covered, and (4) roof vents or existing openings around the eaves of the bin.

The situation of the storage moisture content being too high was attributed to the intermediate causes of improperly dried grain and improper storage management. Improperly dried grain, with respect to high moisture content, had five antecedent causes: three initial events, and two intermediate events. The initial events were identified as utilizing an inadequate or improperly set-up drier, or drying grain in extremely cold weather. The intermediate events were related to a high percentage of fines and BCFM (broken kernels and foreign material) and high harvest moisture content. The fines were attributed to harvesting grain at less than 25% moisture content (refers to corn), the combine not being set up correctly, and grain not being cleaned prior to storage. The high harvest moisture content was blamed on moisture content not being checked, poor field drying conditions, grain variety, or harvesting before maturity. The storage problems arose from two initial events: (1) not cooling the grain after drying, and (2) not regularly inspecting or monitoring the grain during the storage interval.

Conclusion

Besides identifying and categorizing contributing factors to engulfment, the FTA also illustrated initial events that might seem initially unimportant, but combined with other
factors, can lead to engulfment of an individual. The following factors were identified through the use of FTA as especially important contributors to engulfment and suffocation:

- Out-of-condition grain leading to hazardous situations, such as crusting and auger plugging.
- Operation of unloading equipment in conjunction with a worker on the grain surface.
- Moisture entering the bin and causing grain spoilage.
- Knowledge of engulfment hazards by individuals working in and around grain bins.
- Inadvertent operation of unloading equipment.
- Grain dried improperly prior to long-term storage.
- Miscommunication or absence of communication between workers.
- Victim disregarding engulfment hazards when recognized.
- Victim not recognizing hazardous situations, i.e., not recognizing out-of-condition grain.
- Not covering or sealing the fan.
- Excessive presence of fines and BCFM in grain mass.

Safety specialists who are engaged in devising curriculum and intervention strategies dealing with the prevention of on-farm engulfment incidents should consider at least the contributing factors identified in this study. By addressing and eliminating these initial factors, individuals involved in the handling and storage of grain in on-farm grain bins may lower their risk of engulfment. In addition, engineering solutions to the engulfment problem and the development of an ASAE grain bin safety standard could be based on these factors.

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