7-2015

A review on the environmental impact and physiological conditions on the human body during an engulfment, entrapment and extrication

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Abstract
Grain entrapments and engulfments are one of most common hazards associated with grain storage facilities. Since 1970's over 1000 grain entrapments and engulfments incidents have been documented. However, there have been very few attempts to understand the forces and physiological conditions on the victims involved in these incidents, and understand why and how injuries are caused. This research will contribute to a better understanding of the conditions a body faces when entrapped/engulfed in grain. This is critical to understand to be able to address the low survival rate (12%) of engulfments. Based on literature review, the human body can be impacted by two sources. First there are environmental conditions such as grain pressure, oxygen levels that can determine the survivorship of a victim. Second there are physiological conditions such as asphyxiation, suspension trauma and heart rate that also have an impact on the human body. In conclusion the human body is impacted by multiple conditions and forces both internally and externally that impact the likelihood for survival. To be able to have an impact it is critical that studies are conducted on the impact of lateral pressure on lung expansion and if suspension trauma might be a contributing factor in the deaths.

Keywords
Grain entrapment, grain engulfment, grain extrication, suspension trauma, lateral grain pressure, fatality prevention

Disciplines
Agriculture | Bioresource and Agricultural Engineering

Comments
This proceeding is from 2015 ASABE Annual International Meeting, Paper No. 152189336, pages 1-10 (doi: 10.13031/aim.20152189336). St. Joseph, Mich.: ASABE. Posted with permission.

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An ASABE Meeting Presentation

Paper Number: 152189336

A review on the environmental impact and physiological conditions on the human body during an engulfment, entrapment and extrication.

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Written for presentation at the

2015 ASABE Annual International Meeting

Sponsored by ASABE

New Orleans, Louisiana

July 26 – 29, 2015

(The ASABE disclaimer is in a table which will print at the bottom of this page.)

Abstract. *Grain entrapments and engulfments are one of most common hazards associated with grain storage facilities. Since 1970's over 1000 grain entrapments and engulfments incidents have been documented. However, there have been very few attempts to understand the forces and physiological conditions on the victims involved in these incidents, and understand why and how injuries are caused. This research will contribute to a better understanding of the conditions a body faces when entrapped/engulfed in grain. This is critical to understand to be able to address the low survival rate (12%) of engulfments. Based on literature review, the human body can be impacted by two sources. First there are environmental conditions such as grain pressure, oxygen levels that can determine the survivorship of a victim. Second there are physiological conditions such as asphyxiation, suspension trauma and heart rate that also have an impact on the human body. In conclusion the human body is impacted by multiple conditions and forces both internally and externally that impact the likelihood for survival. To be able to have an impact it is critical that studies are conducted on the impact of lateral pressure on lung expansion and if suspension trauma might be a contributing factor in the deaths.*

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Although agriculture has long been recognized as one of the nation's most high-risk industries (in terms of fatal/non-fatal injuries per employment), the number of nationally documented fatal incidents has remained fairly stable since the 1980s. For instance, between 1980 and 1995, the number of recorded fatalities per year averaged 831 (NIOSH, 2001); in 2002 (the latest reporting year), that number was 840, close to the previous 15-year average (NIOSH, 2004). This 'stability,' however, has not been the case when it comes to agricultural confined spaces incidents. Over that same 35-year period, the number of fatalities and injuries occurring in confined spaces has increased. For instance, in the decade of the 1980s, fatalities per year averaged 21, whereas over the last 10 years (2004 to 2014) that average had increased to 35, with 2010 recording 54 fatal confined space cases (Issa et al., 2014; Issa et al., 2015).

An agricultural confined space is defined as any space (not used as a regular workstation) that has a restricted entrance/exit and is associated with physical or toxic hazards to anyone who might enter it (Pettit & Braddee, 1994). Examples of agricultural confined spaces include (but are not limited to) grain wagons, grain bins, silos, manure pits, and fertilizer tanks. Among the associated hazards would be grain entrapment, grain engulfment, grain-dust explosion, a fall in or around confined spaces, asphyxiation, poisoning, entanglement with equipment (e.g., auger), and drowning. One of the most dangerous hazards associated with confined spaces is grain entrapment and engulfment. An entrapment is defined as any situation in which the victim's head is above the grain mass but the victim is incapable of getting out without some form of assistance. (Commonly, an entrapped person is buried up to chest level, but one could be 'buried' only up to the knees and still not be able to get free). An engulfment means that the victim is entirely covered by the grain and is no longer visible. Grain entrapments and engulfments represent about 50% of all agricultural confined spaces incidents (Issa et al., 2014; Issa et al., 2015); and the number of grain entrapment and engulfment cases (fatal and non-fatal) per year continues to increase—the latest 5-year average being around 40, with 59 reported in 2010 (Issa et al., 2015). While grain entrapments and engulfment represents a significant hazard in agricultural confined spaces there has been no significant attempt at reviewing all the potential environmental and physiological conditions the human body experiences while entrapped, engulfed and during extrication. The aim of this paper is to review current literature to gain a deeper understanding of the conditions, pressures and forces that the body experiences during entrapment and engulfment and then summarize these results.

Literature Review

Research Efforts

Schmecta and Matz (1971) carried out some of the earliest research studies about grain entrapments where they studied the speed in which a person can get entrapped in grain and their ability to self-extricate themselves at various depths. They also found that when a person was entrapped up to their chest breathing became more difficult for the individual. This was followed by the work of Schwab et al. (1985) on the amount of force required to vertically pull (extricate using a body harness) a human mannequin entrapped and engulfed in various levels of grain. In 1977, the Purdue University Agricultural Safety and Health Program (PUASHP) created—and continues to manage—a database on grain entrapment and engulfment injuries and fatalities. This on-going effort has stimulated subsequent researches on such topics as: entrapments in grain transport vehicles (Kelley et al., 1996), entrapments in commercial grain facilities (Freeman et al., 1998), on-farm fatalities (Kingman et al., 2001), contributing factors to grain entrapments (Kingman et al., 2003), safety of grain vacuums (Field et al., 2014) and impact of grain rescue tubes on the forces needed to extricate a victim (Roberts et al., 2015). In addition, since 2010, PUASHP has published annual summaries of U.S. grain-related entrapments/engulfments (Roberts & Field, 2010; Riedel & Field, 2011; Roberts et al., 2012; Issa et al., 2013; Issa et al., 2014; Issa et al., 2015).

Educational Efforts

Besides research, extensive educational efforts have been made to raise awareness of grain entrapment causes, consequences, and prevention. One of the earliest of such efforts was a Purdue Extension publication by McKenzie (1969) that included specific warnings of the risks to children exposed to free-flowing grain plus a slide presentation on the hazards of flowing grain, this latter resource revised in 1978 and distributed nationally (Field & McKenzie, 1978). In the mid-1980s, an Extension outreach project (conducted by PUASHP in conjunction with the Indiana Prairie Farmer magazine, Brock Manufacturing, Meridian Insurance Company, and the Indiana Rural Safety and Health Council) involved (1) placement of up to 18,000 flowing-grain warning decals on grain storages and transport vehicles throughout the state and (2) development of a grain handling safety curriculum that was distributed to all secondary agricultural education teachers in Indiana, Ohio, Michigan, and Kentucky. Among other notable grain-safety educational efforts were these:

- A training module, including slide set with script, produced by Aherin and Schultz (1981) at the University of Minnesota and distributed throughout the U.S. and Canada.

- A teaching curriculum on grain safety (in particular, entrapments) produced by Schwab, Miller, and Goering (1997) of Iowa State University that was incorporated into high school science and math lessons.
- Safety decals for grain transport vehicles (GTVs) plus related educational materials for distribution throughout North America, developed and funded by Farm Safety 4 Just Kids, an organization whose founder's son had died by suffocation in a GTV (Adams, 1997).
- A basic training curriculum for local first responders (commonly firefighters) on how to handle incidents involving grain storage facilities (Field et al., 2014a).
- A basic training curriculum for young and beginning workers on the dangers of grain entrapments and other confined space incidents. (Field et al., 2014b)

Regulatory Efforts

In addition to research and education, there have been regulatory efforts by the federal government beginning in the late 1980s to try to reduce the risk of confined spaces hazards. Perhaps the most relevant regulations in this area are set forth in two of OSHA's workplace safety and health standards—29 CFR 1910.146, Permit-Required Confined Spaces, and 29 CFR 1910.272, Grain Handling Facilities. However, the OSHA regulations generally do not apply to 'exempt' venues, including many farms, feedlots, and small seed processing operations, where the greatest amount of grain is stored and where about 70% of documented confined spaces-related entrapments occur (Issa et al., 2014).

Current Grain Entrapment Rescue Strategies

In general, three rescue strategies have been most commonly employed in attempting to extricate those entrapped or engulfed primarily in grain bins. The first involves removing grain from around a victim so he can be freed, which can be done by (1) cutting holes in a grain bin to lower the grain level until a rescue attempt is possible; (2) placing retaining walls around the victim then removing the grain from the enclosed area, again until he can be freed; or (3) a combination of procedures 1 and 2. (Note: with regard to the retaining walls, they can be 3 or 4 plywood sheets, a 55-gallon drum with both top and bottom cut out, a professionally made grain rescue tube, or anything else that can isolate the victim from the grain mass [Roberts 2008]). The second strategy, which is more apt to be used for entrapments or engulfments inside a grain wagon and other GTV, involves opening the outlet door(s) or tipping the GTV in hopes that the victim will flow out with the grain. The third strategy involves pulling a victim up and out of the grain mass using a harness and/or rope attached to some type of mechanical wench or driver (Roberts el al., 2015; Schwab et al., 1985).

In general, attempting to pull someone from a grain mass has been considered a highly dangerous maneuver as the following three studies illustrate. Schwab (1985) found out that about 400 pounds of force are needed to pull out an adult mannequin entrapped at waist level and 900 pounds of force needed if entrapped up to the neck. Roberts et al. (2015) found that extricating a victim—in this case, a mannequin—after placement of a grain rescue tube around it actually increased the amount of force required to free the victim. And one case study was reported in which a farmer used a rope and truck to pull someone out of a grain mass, resulting in fatality (Roberts, 2008).

Methodology

A comprehensive literature review was conducted using google scholar and Purdue University article database on any study that might be related to grain entrapment and engulfment. This includes terms such as suspension trauma, asphyxiation, grain pressure, grain entrapment, grain engulfment, extraction, vertical pull force, grain lateral pressure and any term that might be useful in understanding the impact of grain entrapment and engulfment on the human body. A review on current regulations and curriculum for grain entrapment and engulfment was also conducted.

In addition, the Purdue University Agricultural Confined Space Incident Database (PACSID), the most comprehensive database on confined space incidents (Issa et al., 2015) was analyzed to understand trends in confined space incidents and rates of survival in grain entrapment and engulfment incidents.

Results and Discussion

Currently the PACSID database contains 1765 confined space incidents and of those 1096 are grain entrapment and engulfment cases. The majority of the grain entrapment and engulfment cases in the database are fatalities (68%). In the last five years (2010-2014), the fatality rate of grain entrapment and engulfment cases decreased to 44% due to increased reporting of non-fatal cases. The increased reporting is likely due to multiple factors including, better surveillance efforts, and more awareness on this issue. Of the 1096 cases, 570 are grain engulfments with only 68 incidents in which the victims survives. Thus means that grain engulfments have only 12% survival rate (88% fatality rate). The low survival rate for grain engulfments coupled with the fact that these incidents continue to occur despite educational and regulatory efforts highlights the importance of understanding environmental and physiological factors that impact the survival rates. The incidents of grain entrapment and engulfment are in sharp contrast to grain-dust explosions injuries and fatalities which have declined steadily since the 1980s even though both type of incidents were included in the same regulation effort (Figure 1). This is most likely due to the fact that the majority of grain explosions occur in non-exempt facilities which are regulated by OSHA, while historically 70% of grain entrapment and engulfment occurred in exempt farms and facilities (Issa et al., 2013).

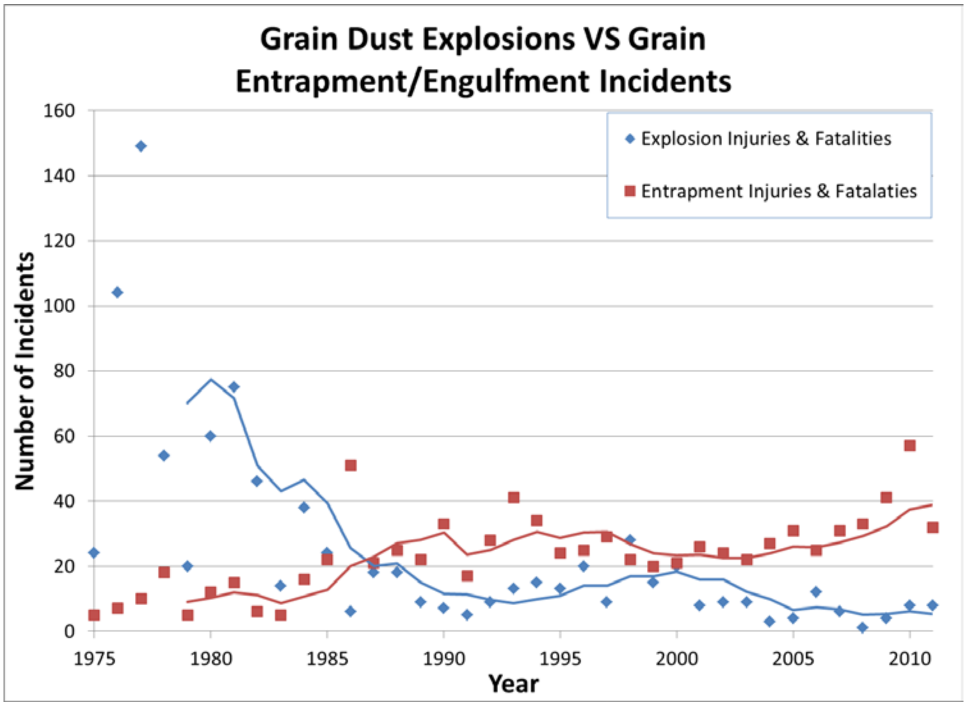

Figure 1. Annual number of injuries and fatalities for grain-dust explosions (OSHA, 2012) vs. grain entrapments and engulfments. The squares/diamonds represent actual year values, and the lines represent 5-year averages.

The conditions that the human body experiences in grain entrapments and engulfments can be split into two major categories environmental and physiological. Environmental factors include friction, lateral pressure of grain, weight of grain, availability of oxygen in the grain mass and diffusion rate of oxygen. Physiological conditions include physical asphyxiation (breathing passages blocked), lack of oxygen, blood flow, heart rate and chest expansion capacity. Research on each of these factors and their relation to grain engulfment will be reviewed.

Environmental Factors: Lateral Pressure

If the person is entrapped in an upright position, the grain's lateral force would likely compress his chest, although it's unclear at which depth to where he could no longer breathe. A study by Thompson et al., (1997) found that the lateral pressure against the grain bin wall at a depth of 5 feet was 5-7 kPa (kilo Pascal), at 40 feet was between 20-30 kPa, and did not increase beyond that depth. Compared to what a scuba diver facer underwater (i.e., 15 kPa at 5 feet and 121 kPa at 40 feet), the pressures experienced in grain are relatively low. However, it is important to note that the load cells used to measure lateral pressures might not correctly measure & estimate the actual pressure on the human chest because, as one breathes, the victim creates micro-voids that get filled with grain. The chest might not be able to expand against the grain mass to allow for breathing. This might be in contrast to water where the chest at low depth can easily displace water molecules.

Environmental Factors: Grain pressure

If a person happens to be engulfed in a horizontal position, he will experience substantially more pressure—about 30 kPa at 5 feet and about 90 kPa at 40 feet (Thompson et al., 1997). Even when entrapped in a vertical position the grain mass above the person act as a barrier to pulling a person out.

Environmental Factors: Friction

While friction not a major force during the process of entrapment or at steady-state condition, the force of friction can be significant when the victim is being pulled up and out of the grain. The total force on the body when being extricated from grain can be calculated by summing the force of friction and weight of grain above the person (Thompson, 1987). Schwab et al., (1985) demonstrated that a person buried under grain would experience about 7,000 N (newton) of force if pulled directly out of the grain and about 3,000 N of force if entrapped to his shoulders. Similarly, Thompson (1987) found that basic temperature cables in the grain mass could experience up to two times as much force when grain is flowing than when it is in a steady-state condition. Another avenue in which a person might experience friction is while wearing a harness. If the person is wearing a harness when he gets entrapped he will experience friction forces as he is being pulled into the grain. Depending on how deep the victim sinks before there in no slack in his lifeline, the force generated could be sufficient enough to yank out a ladder attached to the grain bin wall or cause structure deformity or collapse of the roof beams (depending on where the rope was attached).

Environmental Factors: Oxygen availability and diffusion rate

Sweet corn seed has a porosity values from 57%-61% (Coskun et al., 2006). This means that about 60% of a grain mass is filled with air. While in theory this might mean that a person can breathe under grain this is highly dependent on the local conditions. Factors that might limit the ability for one to breathe include low initial oxygen levels in the grain mass (due to mold or insect activity), actual porosity of the grain mass, the diffusion rate of oxygen in the grain mass, and amount of dust/fines in the grain mass. Less than 16% oxygen in the grain is considered an immediate danger to life, while between 16-19% is considered dangerous but not life threatening (Pettit & Braddee, 1994)

Physiological Factors: Lack of oxygen

A person engulfed in grain will likely struggle to get enough oxygen to his lungs from the surrounding grain mass. Physiological factors that might exasperate the situation include one’s age, health, and smoking habits.

Also, a person who panics will use up most of the available oxygen in a relatively short time versus one who remains calm, thus reducing his chances for survival.

Physiological Factors: Asphyxiation

There are multiple ways in which a victim can experience asphyxiation in grain. One of the most common ways is that with no barrier between his face and the grain (e.g., a mask) and the victim responding to being pulled in grain by opening his mouth (to shout or breath), the flowability of grain may be enough to fill the victims mouth, nose, and lungs with grain, leading to asphyxiation. The inability for chest expansion because of the passive grain pressure could also cause asphyxia. Other incidents that might exasperate asphyxia are having the arms and hands behind the back or above the head (reduces ability for chest expansion). Lastly fear or stress associated with asphyxia can in of itself cause death by cardiac arrest (Beynon, 2012)

Physiological Factors: Blood flow and heart rate

When a person is entrapped or engulfed in grain they lose the ability to move their legs and torso and that might lead to similar physiological conditions as one experiences while suspended in a harness. Weems & Bishop (2003) reported that a healthy adult suspended in a vertical position for as few as 5 minutes with no body movement can lose consciousness and, if not placed in a horizontal position, can die. The reason is that blood quickly starts pooling in the legs due to lack of muscle movement, reducing the supply to the heart; straps around the thighs further cuts off blood flow. This physiological condition was subsequently confirmed by Pasquier et al., (2011). Bahlmann et al., (2002) reported on a case study in which the victim was buried up to his armpits in grain and experienced chest pain until he was fully extricated. If the pain was caused solely by the pressure of the grain on his chest he should have experienced pain relief as soon as the grain level was below his chest. His symptoms closely align to what one experiences during suspension trauma and might indicate how the body is responding physiologically due to grain entrapment and engulfment.

Summary

While extensive research has been conducted on various aspects of the grain entrapment and engulfment issue, one area where a lack of empirical data still exists is the impact of grain mass and extrication pull forces on the human body. Investigations should be conducted to understand the environmental and physiological conditions impacting survival rate in grain entrapments and enguflments. Future research should include 1) evaluating the ability for the chest to expand under various depth of grain 2) oxygen availability and diffusion rate in the grain mass and 3) the blood flow and heart rate for victims entrapped in grain. Each of these research topics should help provide insight how to increase survival rate for victims especially in engulfments.

Acknowledgements

Partial support for this material was provided under grant number SH24885SH3 from the Occupational Safety and Health Administration, U.S. Department of Labor. It does not necessarily reflect the views or policies of the U.S. Department of Labor, nor does mention of trade names, commercial products, or organizations imply endorsements by the U.S. Government.

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