Grain Entrapment Pressure on the Torso: Can You Breathe while Buried in Grain?

K. G. Moore, C. L. Jones

ABSTRACT. *The pressure applied to the chest and back of a simulated grain entrapment victim was measured. Pressure sensors were attached to the chest and back of a manikin that was buried in grain in the vertical position. Measurements were made in four grain types at four grain depths ranging from the top of the manikin's shoulders to 0.61 m (24 in.) over the head. The pressure ranged from 1.6 to 4.0 kPa (0.23 to 0.57 psi). Based on available physiological information, this amount of pressure is unlikely to limit the respiration of an otherwise healthy adult male victim. However, other factors, such as the victim's age, gender, and body position in the grain, may influence respiration. The aspiration of grain appears to be the most likely asphyxiation risk during grain bin entrapment. Entering a grain storage bin is inherently dangerous, and Occupational Safety and Health Administration (OSHA) guidelines for permit-required confined spaces and grain handling facilities must be followed. Due to the risk of grain aspiration during engulfment, the development of safety equipment that could help protect the airway of a victim should be investigated.*

Keywords. *Asphyxia, Engulfment, Entrapment, Grain, Safety, Suffocation.*

Agriculture is consistently recognized as one of the most dangerous working environments. Fatalities in the industry sector of agriculture, forestry, fishing, and hunting rose by 14% in 2014 (BLS, 2015). One area of risk that has received significant attention recently is grain handling and storage. There were at least 38 grain entrapments in 2014, 17 of which resulted in death. Reported grain entrapments and deaths have risen during the past three years (Issa et al., 2015a). The term "entrapment" is often used to describe any event in which victims are trapped by a flowable agricultural material and unable to free themselves. However, the grain handling industry makes a distinction between grain entrapment and engulfment. An entrapment victim is still partially above the grain surface, while an engulfment victim is fully submerged in grain. This can result in a considerable difference in the final outcome for the victim. A review of grain rescue strategies in 2011 determined that of the cases where the depth of submersion was known, the survival rate of entrapment was 90% versus 18% for engulfment (Roberts et al., 2011). That study also identified suffocation as the most commonly reported cause of death.

Previous efforts to understand the impact of grain entrapment on a victim have involved measuring the force required to pull a victim from the grain. The earliest known study was completed by Schmechta and Matz (1971) in Germany. They investigated the ability of a

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human subject to extricate himself from grain when buried to the knees, waist, and top of the shoulders. When the grain reached the victim's waist, he could only escape with the assistance of others. When he was buried to the shoulders, he experienced difficulty breathing and could not escape without the removal of grain (Schmechta and Matz, 1971). Schwab et al. (1985) later measured the force required to extract a manikin from static and flowing grain. The vertical force required to extract the manikin from the grain ranged from 2000 to 8000 N (450 to 1800 lbf). This information has been used extensively in Extension publications and training materials, especially concerning the need to remove grain from around victims before attempting to pull them out. This has led to the common use of rescue tubes and cofferdams by first responders to a grain entrapment. In addition to blocking the inflow of additional grain around the victim, these devices were also believed to reduce the force experienced by the victim. This hypothesis was tested by Roberts et al. (2015) by placing a manikin in grain and measuring the force needed to pull it out of the grain with and without a rescue tube. The researchers found that the process of inserting the grain tube actually increased the required pull force by 22% to 26% depending on the grain depth. This was attributed to an increase in the bulk density of the grain during insertion of the rescue tube. However, the force decreased by 31% to 38% when the tube was installed and grain was removed to knee level inside the tube.

Although many anecdotal reports indicate that entrapment victims experience increased chest pressure and difficulty breathing, no published data could be identified concerning the magnitude of this pressure. This information would be valuable to first responders and medical personnel. It could also provide insight into recommended safety equipment for bin entry. The goal of this project was to estimate the pressure on the chest and back of a victim buried in grain.

Materials and Methods

Testing was performed in a 1.83 m (6 ft) diameter corrugated steel bin with a hopper bottom (fig. 1) at Oklahoma State University's Stored Product Research and Education Center (SPREC) in Stillwater, Oklahoma. Four grain types were evaluated: corn, soybeans, wheat, and canola. Table 1 lists the measured physical properties of each grain tested. These properties are consistent with the range of values published by Boac et al. (2010).

Each grain was tested at four depths above the shoulders of the manikin: 0 m, 0.28 m (11 in., head covered), 0.58 m (23 in.), and 0.89 m (35 in.). Three replications were tested for each grain and depth combination.

Pressure measurements were made using a pressure mapping system (CONFORMat, Tekscan, Inc., Boston, Mass.). This system consists of two thin, flexible panels measuring 0.471 m (18.5 in.) on each side with a total of 2,048 sensing elements. The sensor mats were covered with ripstop material for protection from the grain and affixed to the chest and back of a rescue manikin during testing (fig. 2). The top of the sensor mat was located at the middle of the shoulder such that the first row of sensing elements was located near the collarbone. The manikin was dressed in work clothes and boots and measured 1.85 m (73 in.) tall with a weight of 90.7 kg (200 lb). The sensor mats were equilibrated and calibrated prior to testing for each grain per the manufacturer's instructions. A universal testing machine (model 5966, Instron, Norwood, Mass.) was used to apply a uniform force to the sensor mat through a thin layer of the grain to be tested during calibration (fig. 3).

The manikin was placed in the grain bin in the vertical position. Grain was loaded into

Figure 1. The 1.83 m (6 ft) diameter steel bin used during measurement of entrapment pressures.

Table 1. Measured physical properties of tested grains.

Grain	Moisture Content (%)	Bulk Density (kg m^{-3})	Dimensions length / width / thickness (mm)	Static Angle of Repose (°)
Corn	12.6	798	11.6 / 8.5 / 4.6	30.5
Soybeans	13.0	696	7.2 / 5.8 / 4.8	32.9
Wheat	10.6	862	5.5 / 2.9 / 2.5	33.2
Canola	7.4	675	1.7	29.6

the top of the bin from a discharge spout until the specified fill height was reached. Marks were placed on the inside of the bin to facilitate consistent filling between measurements. Special care was taken to direct the discharge spout around the perimeter of the bin so that the grain filled evenly around the manikin. Pressure data were collected at a frequency of 3.3 Hz for 1 min under static conditions. There was minimal variation during this time, so the mean contact pressure on the front and back sensor mats was calculated at the middle set of data points (time = 30 s). Following each measurement, the grain was removed from the bin with a grain vacuum and refilled prior to the next measurement. Data were analyzed by analysis of variance and tested for interactions using SAS (ver. 9.3, SAS Institute Inc., Cary, N.C.). Trends were evaluated based on grain depths. All measures of significance were evaluated for $\alpha = 0.05$.

Figure 2. Rescue manikin outfitted with sensor mats prior to testing in soybeans.

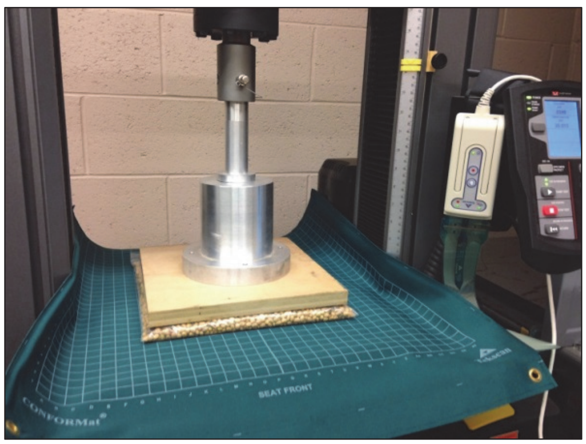

Figure 3. Calibration of sensor mat with universal testing machine prior to testing. Force is applied through a layer of grain to approximate testing conditions.

Results and Discussion

Mean contact pressures for each grain and depth combination are presented in table 2. There was a positive correlation between grain depth and pressure for all grains. There was no significant difference between corn and soybeans at any depth. There was a significant difference between canola, wheat, and corn/soybeans at all depths with the exception of

Table 2. Comparison of mean contact pressure (kPa) by depth for each grain.[a]

	Grain Depth above Shoulders (m)			
Grain	0	0.28	0.58	0.89
Canola	1.6	2.3	2.5	2.6
Wheat	1.9	2.8 b	3.2	3.7 e
Corn	2.8 a	2.9 bc	3.7 d	4.0 e
Soybeans	2.6 a	3.0 c	3.6 d	3.9 e

[a] Contact pressure values followed by different letters are significantly different.

wheat and corn at 0.28 m and 0.89 m. Wheat and corn/soybeans exhibited significant linear trends with depth, while canola exhibited a linear and quadratic trend (fig. 4).

The behavior of canola was unexpected and may be attributed to the size and shape of the seeds. Considerable effort has been directed toward understanding the behavior of granular material. Early work by Janssen (1895) recognized that the force exerted by water at the bottom of a storage vessel increases linearly, while granular material such as grain approaches an upper limit. This is due to interactions between the particles, which translate a portion of the vertical stress horizontally to the wall of the vessel. These small-scale grain-to-grain interactions influence the macroscopic behavior of grains (Clement, 1999). Granular material can be placed in many stable configurations, with loosely packed material behaving more like a liquid, and tightly packed material behaving more like a solid. When a force is applied to granular material, it is distributed through contact points where particles touch one another. This leads to the formation of force chains, a branching network of high-stress particle interactions that carry the majority of the load while other particles experience little or no loading. Therefore, the force distribution in granular material is heterogeneous and will vary based on the loading history of the material (Hidalgo et al., 2004). An unexpected result of this phenomenon is illustrated by the “sand pile” problem, in which the vertical stress in a pile of sand reaches a minimum under the peak. Particle shape has been shown to impact the behavior of these force chains, with elongated particles resulting in longer force chains that involve fewer particles and have a higher concentration of force (Azéma and Radjaï, 2012; Estrada et al., 2008; Zuriguel et al., 2007). Canola seeds

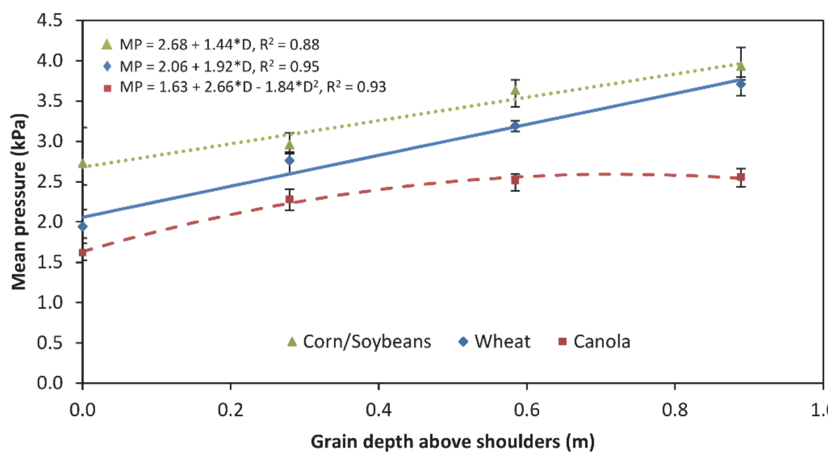

Figure 4. Mean contact pressure (MP) on the torso of a manikin at varying grain depths (D). Corn and soybeans were not significantly different and have been pooled. Wheat and corn/soybeans exhibit a linear trend with depth. Canola exhibits a linear and quadratic trend with depth.

are essentially spherical, while corn, soybeans, and wheat are oblong. Canola seeds are also much smaller than the other three grains (table 1). It may be that this difference in the shape and size of the canola particles led to the non-linear trend. Additional study is needed to fully understand this phenomenon.

The Purdue Agricultural Confined Space Incident Database (PACSID) contains data on reported grain entrapments in the U.S. from 1962 to the present. Of the 1,028 documented entrapment cases, 70% were fatalities (Issa et al., 2015a). While information concerning the cause of death is not always available, suffocation is most commonly reported. Freeman et al. (1998) investigated 71 entrapment cases at commercial grain facilities and found that 86% were engulfments and 92% of these were fatalities. In contrast, of the ten cases that were partial entrapments, there was only one fatality. Death from asphyxiation can be caused in two ways: (1) aspiration of grain or (2) traumatic asphyxiation due to restriction of chest movement by grain.

Several cases of grain aspiration have been documented in the literature (Arneson et al., 2005; Bahlmann et al., 2002; Jurek et al., 2009; Slinger et al., 1997). During engulfment, grain can fill the mouth and throat and even enter the bronchi of the lungs. Protecting the airway during engulfment would prevent this type of asphyxiation. A fairly recent case of this was documented by a television program concerning the engulfment of Arick Baker in 2013 (Awes, 2015). Arick was working alone on the family farm and entered a grain storage bin to clear a blockage while the auger was still energized. This was clearly unsafe behavior and in violation of Occupational Safety and Health Administration (OSHA) guidelines for permit-required confined spaces (OSHA, 2016b) and grain handling facilities (OSHA, 2016a). He quickly became engulfed in grain and was unable to free himself. Fortunately, he did not become entangled in the auger or asphyxiate from grain inhalation. Arick typically wore an air circulating mask when entering the grain bin to help with his asthma. This mask covered his face and appears to have protected his airway during engulfment, allowing him to survive until he could be freed from the grain.

Traumatic asphyxia is caused when respiratory motion is limited by a heavy weight on the torso while the airway remains open. This can occur when an individual is pinned under an automobile or tractor, trampled or pressed against a door or wall by a large crowd, or buried during an avalanche or earthquake (Byard et al., 2006; Campbell-Hewson et al., 1997; Stalsberg et al., 1989; Williams et al., 1968). Expansion of the chest and abdomen is required for respiration. This motion increases the volume of the lungs, which lowers the pressure in the alveoli, allowing air at atmospheric pressure to enter. In one case study, the head of an avalanche victim was uncovered, and mouth-to-mouth resuscitation was attempted while the body was still buried in snow. This proved to be impossible until the torso was uncovered so the chest could expand (Gray, 1987). Issa et al. (2015b) postulated that the chest expansion and contraction of a grain entrapment victim packs grain particles around the chest and might eventually stop respiration.

The literature is unclear concerning the amount of pressure that a human can withstand on the chest before breathing becomes impossible. However, research on the human respiratory system indicates that maximum inspiration pressures range from 9.5 to 14.7 kPa (1.4 to 2.1 psi) for men. Two studies included data on females and reported values approximately 30% lower than for male subjects. Additional variation is expected based on the size, age, and physical condition of the victim (Agostoni and Rahn, 1960; Lausted et al., 2006; Milic-Emili et al., 1964; Wilson et al., 1984). The influence of age on respiratory strength may also be important in understanding the potential risk during engulfment, as

28% of reported grain entrapment victims were ages 1 to 20, and 20% were over the age of 60 (Issa et al., 2016). Wilson et al. (1984) measured the maximum inspiration pressures of children ages 7 to 17 as 7.4 kPa (1.1 psi) for boys and 6.2 kPa (0.9 psi) for girls. They also found a significant negative correlation between age and maximum respiratory pressures in adult males. Respiratory studies of guinea pigs and dogs applied a mass equal to 2, 3, 4, and 5 times the body weight of the animal to the chest. In these studies, the animal survived for over an hour with a mass of two times the body weight applied to the chest, while no animal survived longer than 10 min with a mass of five times the body weight (Furuya, 1981). Assuming similar results for a human, an otherwise healthy male should be able to withstand a pressure on the torso of 14 kPa (2 psi) for at least an hour. An individual trapped near the surface of grain will experience a much smaller pressure, roughly 2 to 4 kPa (0.3 to 0.6 psi). If the corn/soybean data from our study are extrapolated in a linear fashion, a pressure of 14 kPa would occur at a depth of 7 to 8 m (23 to 26 ft). However, the age, gender, and overall health of the victim should be considered when applying these results. Additionally, the stress of entrapment and asphyxia alone can lead to cardiac arrhythmias or cardiac arrest (Beynon, 2011). Body position during entrapment may also impair breathing. The pressure experienced by a victim in the horizontal position is expected to be higher than for a victim in the vertical position. In addition, when the arms are positioned above the shoulders, there is a small decrease in total lung capacity, which may be due to restriction of chest wall expansion (McKeough et al., 2003). Other factors, such as the distribution of grain around the victim (flat, peaked, inverted cone) and the weight of rescue personnel standing on the grain, may increase the pressure experienced by the victim.

Conclusion

The amount of pressure applied to the torso of a simulated grain entrapment victim in the vertical position was measured at static grain depths of 0 to 0.89 m (0 to 35 in.) above the shoulders for corn, soybeans, wheat, and canola. The pressure increased linearly with depth for all grains except canola, which exhibited a linear and quadratic trend. Pressures ranged from 1.6 to 4.0 kPa (0.23 to 0.57 psi).

The measured pressure on the torso does not appear to be high enough to limit respiration for an otherwise healthy adult male unless the entrapment depth is quite deep (over 7 m) or the duration of entrapment is long enough to cause respiratory fatigue. However, other factors, such as the victim's age, gender, and body position in the grain, may influence respiration. Based on this information, preventing the aspiration of grain during engulfment warrants further study. The use of a full-face respirator during bin entry has the potential to help protect the airway during engulfment. Future research should evaluate the ability of commercially available respirators to stay in place and prevent grain aspiration during engulfment. An appropriately designed respirator could be an important addition to grain bin entry safety equipment.

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