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Mortar Separations in Troughs and Drums

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ABSTRACT

Rarely is there only one mitigation strategy to reduce the level of hazard posed by a problem. This concept is explored in the context of alternate strategies for limiting the potential problem posed by fireworks mortar bursts within troughs and drums. This begins with a discussion of the nature of the mortar burst problem and the current National Fire Protection Association (NFPA) requirements for using mortar troughs. This is followed by a discussion of a series of alternate mitigation strategies that are thought to provide equivalent spectator protection.

Prolog

Since drafting this article, the referenced National Fire Protection Association (NFPA) code has been modified. One of the stated requirements has been dropped for electrically fired displays, and one of the mitigating strategies has been substituted. Since the hazard analysis presented in this article is generally relevant (and hopefully instructive), the article is preserved in its original form. However an epilog has been added to clarify the current code requirement.

Introduction

The 1995 edition of the National Fire Protection Association's *Code for Fireworks Display* (NFPA-1123) provided some requirements for the placement of mortars in troughs or drums for electrically discharged displays. One requirement was that there must be at least a 50-mm (2-in.) separation between individual mortars and between any mortar and the wall of the trough or drum[2,3] (see Figure 1). However, in a general recognition that alternate methods might be employed that provide an equivalent (or even superior) level of protection, the NFPA code includes an equivalency statement.[4] This allows consideration of alternate methods and

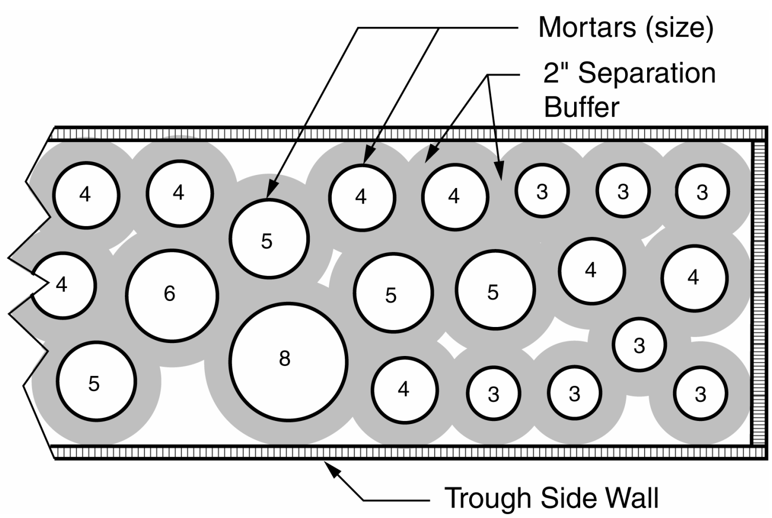

Figure 1. Illustration of mortar placement in a trough using the NFPA 50-mm (2-in.) separation. (Overhead view.)

equipment that provide equivalent levels of protection. This article presents a limited discussion of the rationale for the 50-mm (2-in.) separation and suggests some ways in which equivalent levels of spectator protection might be accomplished.

For electrically discharged displays, when mortars are in close proximity to one another, one area of major concern involves a possible aerial shell malfunction within its mortar, wherein the mortar is violently destroyed (a so-called "aerial shell detonation"). For star shells, this type of malfunction is quite rare. On those occasions when a star shell functions within its mortar, usually the result is a milder explosion. One where the mortar survives undamaged and the contents of the aerial shell are projected upward, out of the mortar in a mostly harmless display (a so-called "flowerpot").

A violent in mortar explosion (VIME) can be powerful enough to damage an adjacent mortar still containing an aerial shell. This could render the adjacent damaged mortar incapable of properly launching its shell. However, a greater potential problem is that adjacent mortars, still containing aerial shells, will become dangerously misaligned by the mortar explosion. Serious misalignment is of greater concern than mortar damage because the probability of this happening is greater, and the possible consequences are more severe.[5] (Why this is the case is discussed in the next few sections of this article and is followed by a discussion of some strategies to mitigate this hazard.)

There are a large number of ways in which a mortar explosion accident might proceed, as well as a large array of possible mitigation strategies. Thus, as a matter of practicality, only some of the most likely and consequential scenarios will be discussed in this article. For example, the discussion will be limited almost entirely to a discussion of mortar troughs, when many of the same points apply equally to mortars buried in the ground or in drums and even to mortars in racks. Also, it must be acknowledged that very little direct research has been done on mortar explosions and their consequences. Thus, for the most part, the information presented in this article is based on accident investigations and general scientific principles.

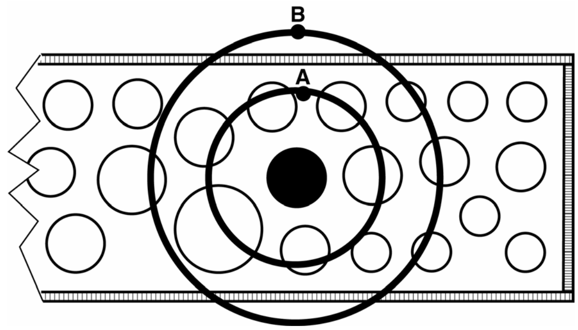

Figure 2. Zones of decreasing blast effect around a mortar explosion (overhead view).

Consideration of the Hazards from a Mortar Explosion

The energy transferred from an explosion to nearby objects decreases with distance. In large part, this is a manifestation of blast pressures dropping roughly in proportion to the area over which they are acting.[6] For example, in Figure 2, if there were a powerful explosion of the "black" mortar, and if there were no intervening materials, the blast pressure at point B would be approximately 1/4 that at point A. However, there is also a loss of energy to materials in the area of the explosion. In this case, some energy may be consumed in damaging adjacent mortars and in ejecting sand from the trough (sometimes called a "sandbox").

Generally much more force is required to dent or crush a mortar than is required to reposition it. Accordingly, for mortars to be damaged they must be relatively close to the exploding mortar. Because relatively few mortars will be close enough to be damaged, as compared with the number of mortars that are close enough to be repositioned, mortar repositioning is more likely to occur than is mortar damage.

For spectators, the potential consequences of a mortar explosion damaging or repositioning surrounding mortars is zero, unless one of those mortars contains an aerial shell that is subsequently discharged.[7] There are two ways in which such a post-mortar-explosion shell firing might occur. One is a direct result of the initial mortar exploding; such as the fire and firebrands produced in the initial explosion causing an ignition of another shell. The other way in which a shell might be discharged is that a firing signal might be sent to the electric match of that shell.

For spectators, an aerial shell firing after a mortar explosion is only a problem if the shell is discharged from a misaligned mortar that propels it into or over a spectator area. Given the speed and mass of aerial shells, a collision with a spectator could prove fatal. There is also a potential for serious injury from the pyrotechnic output of the shell, should it burst among or immediately over spectators. In this case there is actually a little less potential hazard from a damaged mortar (dented or crushed), than from an undamaged mortar. This is because, if the mortar were seriously damaged, the likely course of events would be that the discharging aerial shell would also explode in the mortar. In that event, the aerial shell would never reach the spectator area to threaten their safety.

Accordingly the major spectator hazard from a violent in mortar explosion (wherein a shell fires from an adjacent mortar) is from repositioned mortars, not from damaged mortars. As discussed above, this is because: (1) there will be many more repositioned mortars than damaged mortars; (2) the severity of consequences will tend to be less for damaged mortars because they are less likely to allow an intact shell to exit; and (3) a damaged mortar that is not also repositioned, presents relatively little spectator hazard.

Ballistic Considerations for Repositioned Mortars

To better evaluate various hazard mitigation strategies for mortar explosions, it is useful to consider what degree of mortar repositioning poses a problem. Figure 3 illustrates the trajectory of aerial shells fired from tilted mortars. These are computer-modeled data[8] for 150-mm (6-in.) spherical shells. (Note that the general accuracy of the computer model has been confirmed experimentally.) In this analysis, it has been assumed that the aerial shell bursts 5 seconds after leaving the mortar, and that it disperses its contents with a spread typical of a hard breaking spherical shell.[9]

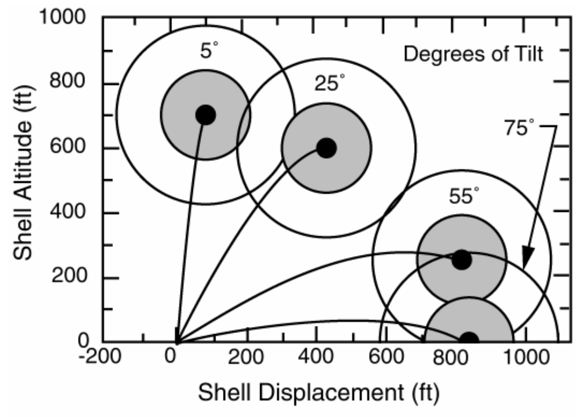

Figure 3. An illustration of the trajectory and functioning diameter of 150-mm (6-in.) aerial shells fired from tilted mortars. [To convert from ft to m divide by 3.28.]

In Figure 3, the location of the shell at the time of its functioning is shown as a large solid dot. At the scale of the drawing, the diameter of the dot is 15 m (50 ft) and is intended to correspond roughly to the zone of maximum injury potential. In each case the dot is surrounded by a shaded area, corresponding to a diameter of 76 m (250 ft), through which there is a much less, but still significant, potential for injury. The still larger circle, corresponding to the diameter of 152 m (500 ft), is the approximate maximum extent of burning material from the shell burst. It is intended to represent the approximate extent of even minimal injury potential.[10]

For normally functioning aerial shells, it is apparent from Figure 3 that it is not minor repositioning of mortars that poses a hazard to spectators. Of course this is because the aerial shells fired from those mortars will function far enough above the ground. It is only when the tilt angle (measured from vertical) exceeds approximately 60 degrees that much burning debris is expected to reach the ground.[11]

Mortar Explosion Hazard Mitigation

Before considering alternate hazard mitigation strategies, it is appropriate to first consider the level of protection provided by the NFPA's 50-mm (2-in.) separation requirement. Because the forces associated with an explosion fall off with distance, the 50-mm (2-in.) separation does provide a certain level of protection in the event of a mortar explosion. It is true that, as a consequence of the 50-mm (2-in.) separation, there will be slightly less blast pressure on adjacent mortars. However, this 50-mm (2-in.) clearance is very much less than is necessary to significantly reduce the chance of the adjacent mortars being repositioned. The greater benefit from the 50-mm (2-in.) separation is that potentially fewer mortars are affected. This is illustrated in Figure 4, in which the same number and sizes of mortars as in Figure 2 have been grouped more closely. Note that the mortars now occupy only about half the space as in Figure 2. This increased concentration of mortars means that a greater number of mortars could be dangerously repositioned in the event of a violent in mortar explosion. Accordingly, while the 50-mm (2-in.) separations do not eliminate the potential for spectator injury, they are of benefit in reducing the level of hazard.

The present NFPA code provides essentially no minimum requirements for the construction, orientation, barricading or operating procedures for troughs. All of this is left to the good judgment of the fireworks display company, along with that of the local enforcing authority. Obviously, not all methods of construction, orientation, barricading, and operating procedures are equivalent in terms of spectator safety. Accordingly, it may be possible to achieve equal (or even superior) levels of spectator safety without using the 50-mm (2-in.) separation. For example, consider the following two scenarios. In one case, the 50-mm (2-in.) mortar separations are used, along with equipment and procedures that are typical of those in the industry. In another case, mortars are placed with less than the 50-mm (2-in.) separations, but superior equipment and procedures are used. It is possible that the use of superior equipment and procedures will fully compensate for the lack of the 50-mm (2-in.) mortar separations. (It may even provide an increased level of spectator safety.)

When there is a violent in mortar explosion in a trough, it is likely that at least one wall of the trough will be broken. This generally allows many of the mortars contained in that section of trough to tip, with some reaching potentially dangerous orientations. Obviously, details of the construction of the trough can be an important mitigating factor, with heavy construction and numerous securing cross members being a benefit. Heavy construction [e.g., 19-mm (¾-in.) plywood walls reinforced with nominal 2 × 4-in. (37 × 87 mm) lumber] makes it less likely that a trough wall will fail. In turn this makes it less likely that mortars will be repositioned. Numerous securing cross members (e.g., threaded rods between the trough side walls), in addition to strengthening the trough walls, also act to shorten the length of sidewall that may fail. The added strength again makes it less likely that mortars will be repositioned because a trough wall breaks. However, when a trough wall does fail, it tends to fail between pairs of securing cross members. Thus, if there are numerous sidewall-securing cross members, the number of mortars within the length of trough between cross members will be less, and the hazard is reduced because the number of mortars that might be repositioned will be less.

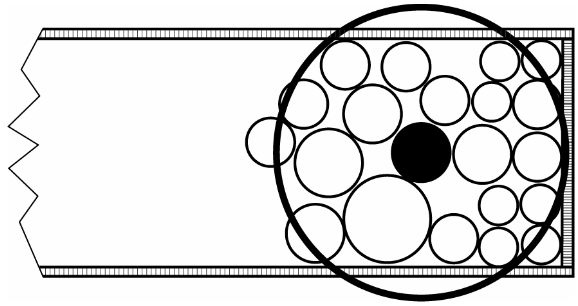

Figure 4. Mortars placed without the NFPA 50-mm (2-in.) separation.

The orientation of the trough is also important. When a mortar explosion breaches the walls of the trough, mortars will be repositioned, and that repositioning will tend to be in directions away from the exploding mortar. This is illustrated in Figure 5, in which the large arrows are pointing in the approximate directions in which repositioned mortars would tend to be aimed. However, it is only those mortars that still contain aerial shells that have any potential for launching a shell. In Figure 5, it is assumed that the firing of the display is from the bottom of the drawing to the top. Thus those mortars toward the bottom of the drawing are likely to be empty, those mortars aimed toward the sides might have a 50% chance of still containing an aerial shell, and those mortars aimed towards

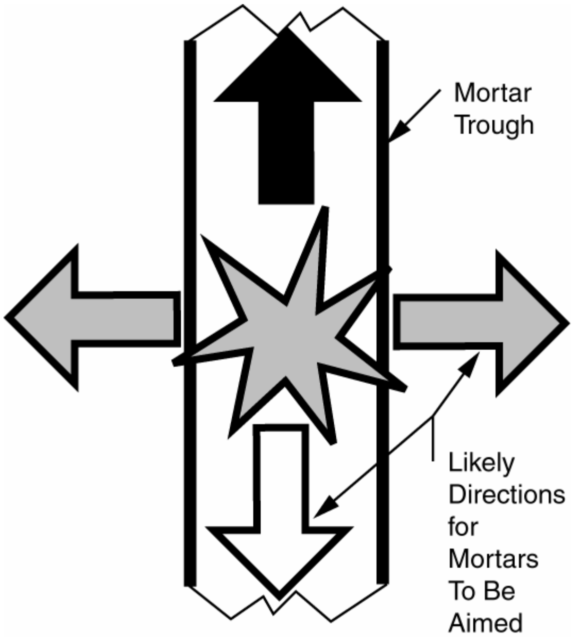

Figure 5. Illustration of likely mortar orientations after a mortar explosion in a trough. (Overhead view.)

the top (black arrow) most likely will contain live shells. An important conclusion can be drawn from this: the preferred orientation of a trough is in a line away from the main spectator area, with the firing beginning on the end nearest the main spectator area and proceeding away from the main spectator area.

A strong barricade of some sort between the trough and spectators, extending several feet above and to the sides of a trough, can be effective in helping to stop or destroy any fireworks shells that are propelled toward spectators. These barricades could be specifically erected for this purpose, but this is likely to be expensive and time consuming. Thus this strategy is most practical when natural features, (like dense woods) or man-made features (like a structure or retaining wall) can be used as a barricade.

Prudent operating procedures can also help mitigate the hazard of mortar explosions leading to shells firing into spectator areas during electrically discharged fireworks displays. One such practice (sometimes called "short wiring") is to secure the electric match wires to the mortar, leaving only the minimum length needed to reach the point of attachment to the firing system (sometimes called a "rail" or "slat"). In this way, if there is a mortar explosion that seriously repositions mortars still containing aerial shells, it is likely that the electric match wires will be torn apart or will be pulled loose from the firing system. When this happens, there is no possibility of the firing current reaching one of these shells. (However, they might still fire from sparks or firebrands igniting the shells.)

Another critically important mitigation strategy is to formally train the firing crew members to be alert to the possibility of mortar explosions and to carefully and explicitly instruct the crew how to deal with them. One example of an effective procedure, whenever there is any possibility that a mortar explosion has occurred, is to insist that the firing crew automatically cease firing from the potentially affected mortars, until an inspection determines that it is safe to proceed with the display. (With advance planning for this possibility, this inspection could be accomplished in as little as 15 or 20 seconds.) Another useful procedure, in the event of a possible mortar explosion, is to have the firing crew automatically skip all firing cues for mortars that could have been repositioned, at least until it can be confirmed that it is safe to fire those mortars. (To be most effective, training needs to be very specific as to the actual procedures to be followed, and that needs to be explicit company policy.)

Trough status indicators might be used to report on the condition of the troughs. This could be something as simple as a wire looped tightly around then zigzagging across a trough. With this properly installed, a mortar explosion that seriously damages the trough will cause this sensing wire to be severed. Then, if this wire were used to power a safe status light at the firing console, that light would serve to indicate whether the trough had been seriously damaged.

The other way that an aerial shell in a repositioned mortar can be discharged is from flame or burning debris from the mortar explosion itself. In this case, the use of tight fitting mortar coverings, such as the polyethylene pipe covers manufactured by Cap Plug®, can help reduce the possibility of such aerial shell ignitions. Further, if the electric match has been installed into the lift charge and the shell leader removed, there is less chance of fire or firebrands causing an ignition.

Another procedure to limit the potential hazard to spectators is to control where and how salutes are discharged during a fireworks display. The potential for a salute producing a mortar explosion is much greater than that for a typical star shell. This is because salutes function by exploding powerfully. If they function within a mortar, there is a much greater chance that the mortar will be destroyed than if it had contained a star shell. (For HDPE and paper mortars it is essentially certain that an exploding salute will burst the mortar.) Examples of mitigation—regarding the firing of salutes—are to use relatively few salutes, limit their size to 75 mm (3 in.), and to fire them from individual mortars each placed in their own widely separated small containers (e.g., 5 gal. pails).

There are also situations when no possible malfunction at the discharge site will present a hazard to spectators. Specifically, this would be when there is a great distance [at least 1 km (1/2 mile)] separating the nearest spectator and the firing site, such as with some barge displays. In that case, no other spectator hazard mitigation is needed.

Conclusion

All human activities involve some risk; everyday people slip in the shower to receive serious injuries, while others choke to death eating food. Yet showering and eating are generally considered safe. This is because the risks associated with those activities are low enough that we readily accept them as part of life. Similarly, there will always be some risk associated with the entertainment provided by fireworks displays. The NFPA code states that its purpose "is to provide requirements for the reasonably safe conduct of outdoor fireworks displays"[12]. Accordingly, the code sets this "reasonable" level of safety as the standard for judging the acceptability of alternate procedures and equipment.

Recall that, for electrically fired displays with the mortars buried in the ground, drums or troughs, the use of a 50-mm (2-in.) buffer space, by itself, does not provide complete spectator safety in the event of a violent in mortar explosion. By the same token, using less than the 50-mm (2-in.) separation does not preclude achieving the same level (or even a greater level) of protection, providing that some additional mitigation strategies such as suggested above are utilized.

Acknowledgement

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Epilog

In the 2000 edition of the NFPA code, the requirement for a 50-mm (2-in.) separation between the mortars in a trough and the wall of the trough when firing electrically remains.[13] However, while it remains a good practice to do so, for mortars no larger than 150 mm (6 in.) in diameter and providing the shells are not chain fused, the requirement for a 50-mm (2-in.) separation between individual mortars was dropped.[14] Instead, the code adopted two of the other possible mitigating factors suggested in this article. Specifically, there is now a requirement to orient the trough such that its narrow side is toward the area with the greatest number of spectators.[15] Further, there is now a requirement that the sides of the troughs be braced or reinforced in two places at least every 1.2 m (4 ft).[16]

Notes and References

1) While the authors are members of the National Fire Protection Association (NFPA) Technical Committee on Pyrotechnics, the thoughts and opinions expressed in this article are only those of the authors.

2) NFPA-1123 (1995) "2-3.3.3* Mortars that are buried in the ground, in troughs, or in drums shall be separated from adjacent mortars by a distance at least equal to the diameter of the mortar. Exception: Where electrical firing is used, all mortars buried in earth or placed in drums or troughs shall

be spaced at least 2 in. (50 mm) nominally apart."

3) NFPA-1123 (1995) "2-3.3.3.2 There shall be a separation distance of at least 2 in. (50 mm) or 1/2 the diameter of the mortar, whichever is greater, between the mortar and the trough or drum. Exception: When electrical ignition is used, all mortars placed in drums or troughs shall be spaced at least 2 in. (50 mm) from the wall of the drum or trough."

4) NFPA-1123 (1995) "1-3 Equivalency. This code is not intended to prevent the use of systems, methods, or devices that provide protection equivalent to the provisions of this code, provided equivalency can be demonstrated to the authority having jurisdiction."

5) For more information on performing hazard assessments, see
(a) K. L. and B. J. Kosanke and C. Jennings-White, "Basics of Hazard Management", *Fireworks Business*, No. 129 (1994). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 3 (1993 and 1994)*, Journal of Pyrotechnics, 2002.
(b) K. L. and B. J. Kosanke, "Dud Shell Hazard Assessment: NFPA Distances", *Fireworks Business*, No. 178 (1998). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 5 (1998 through 2000)*, Journal of Pyrotechnics, 2002.
(c) K. L. and B. J. Kosanke, "Dud Shell Hazard Assessment: Mortar Angling", *Fireworks Business*, No. 179 (1999). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 5 (1998 through 2000)*, Journal of Pyrotechnics, 2002.

6) For more information on the general subject of attenuation of blast waves, see G. F. Kinney and K. J. Graham, *Explosive Shocks in Air*, Springer-Verlag, 1985.

7) For the purposes of this article, no consideration is given to the possibility of debris from a mortar explosion reaching spectator areas. For the most part, when using the NFPA distances, this can only occur for steel mortars, and then the 50-mm (2-in.) separation will make essentially no difference in limiting the range of those fragments.

8) K. L. and B. J. Kosanke, "Computer Modeling of Aerial Shell Ballistics", *Pyrotechnica XIV* (1992). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 2 (1990 to 1992)*, Journal of Pyrotechnics, 1995.

9) K. L. and B. J. Kosanke, "Japanese Shell Break Radii," *Pyrotechnics Guild International Bulletin*, No. 59 (1988). Also in *Selected Publications of K. L. and B. J. Kosanke, Part 1 (1981 to 1989)*, Journal of Pyrotechnics, 1995.

10) The burst spreads of the aerial shells in Figure 3 are shown as being spherical, where actually those fired from the more angled mortars would be distorted somewhat because of the motion of the shell at the time of its explosion.

11) When mortars are tilted nearly horizontal, often they will be free to recoil along the ground if a shell fires from it. This has the potential for reducing the distance to which the shell can be propelled; however, that has not been considered in Figure 3.

12) NFPA-1123 *Code Fireworks Display* (1995) 1-2.1.

13) NFPA-1123 *Code Fireworks Display* (2000) 2.4.4.1.

14) NFPA-1123 *Code Fireworks Display* (2000) 2.4.4.0.

15) NFPA-1123 *Code Fireworks Display* (2000) 2.4.5.2.

16) NFPA-1123 *Code Fireworks Display* (2000) 2.4.5.1.