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Dud Shell Risk Assessment: NFPA Distances

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There are potential hazards and some level of risk resulting from those hazards associated with all human activities. When the risks are below an acceptable level, those activities are generally considered safe. The hard part is not the estimation of risks; there are relatively simple methods to estimate risk. Rather, the hard part is determining what is an *acceptable level* of risk for an activity. For the most part, this article only addresses the easy part, discussing the relative risks of dud shells falling into spectator areas for different scenarios. The reader is left with the hard part, deciding what level of risk is acceptable and what (if anything) to do about those risks for their displays.

Spectators at a fireworks display may be exposed to a range of potential hazards, only one of which is the possibility of a dud shell falling in their midst. However, while an analysis and discussion of this one risk is intrinsically useful, it can also serve a broader purpose. Namely, to demonstrate how risk assessments are performed and how such information can be used to evaluate and select appropriate risk management strategies for any hazard.

Some fireworks display operators may believe the separation distance requirements of the National Fire Protection Association, in NFPA 1123 (1990 and 1995 editions), are sufficient to assure that dud aerial shells will never fall into spectator areas. Unfortunately, the chance of this happening is not zero; however, the current separation distances do greatly reduce the risk when compared to that for the distances in earlier versions of the code. This article begins the discussion by quantifying and then comparing the spectator risk for displays performed with both the earlier and current NFPA separation distances. (A subsequent article will consider the merits of various mortar placements and tilt angle, and the use of even greater separation distances.)

Drift Distance

For a number of reasons, aerial shells follow a trajectory somewhat different from that predicted by the alignment of the mortar from which it is fired. For example, if an aerial shell is fired from a mortar aligned perfectly vertical and with absolutely no wind, one might predict that it would rise straight up into the air. Further, if the shell failed to burst, that it would eventually fall straight down, landing quite near the mortar from which it left. However, this essentially never happens. One cause for the divergence is the sideways force produced by the tumbling of the shell as it moves through the air. (This is the same force used by a baseball pitcher in throwing a curve ball.) For a dud shell, "drift distance" can be defined as the difference between where the shell is predicted to land, based on simple ballistics, and where it actually falls to the ground, see Figure 1.

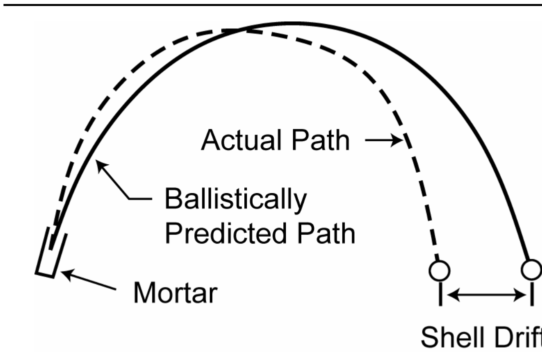

Figure 1. Illustration of drift distance for a dud aerial shell.

A number of years ago, results from a series of aerial shell drift studies were reported.[1] (While more than 400 test shells were fired in that effort, and while it seems to be the most complete study reported in the literature, the study was not so extensive that the results should be taken as absolutely correct.) In those studies, it was found that dud spherical shells have an average drift distance of approximately 32 feet per inch of shell size. (For example, for three-inch spherical shells, the average dud drift distance is 3 times 32 feet, or approximately 96 feet.) Further, it was found that approximately nine percent of the dud shells fall at more than twice the average drift distance, and that approximately one percent of the dud shells may fall at more than three times the average drift distance.

NFPA Separation Distances

Prior to the 1990 edition of the NFPA code, the minimum separation distances (distance from the spectators to the mortars) were relatively short, see Table 1. With the 1990 edition of the code, the separation distances were increased substantially. For vertically placed mortars the separation distance became 70 feet per shell inch (also shown in Table 1). Obviously, one effect of the increased separation distances is a reduction in the potential risk of dud shells falling into spectator areas. Not obvious, however, is just how significant is that reduction in risk. Much of the remainder of this article will be devoted to estimating the magnitude of this reduction.

Risk Assessment

In performing a risk assessment, consideration is given to both the likelihood (probability) of an event happening and the consequences (level of hazard) of that event, should it occur. [For a more information about performing risk assessments, see reference 2.] To illustrate how a risk assessment is performed, and to provide data for the discussion of separation distances, two scenarios will be considered for a somewhat typical fireworks display. In both cases, for simplicity, it is assumed that: spectators are located in one small area immediately adjacent to the display site, the mortars are placed vertically, there is no wind blowing during the display, and only spherical shells of typical construction are used. In both scenarios each size of mortar is grouped together and placed at the minimum distances from spectators as listed in Table 1. In scenario one, the distances are those from before 1990. Thus the three-inch mortars are all at 50 feet from spectators, the four-inch mortars are at 75 feet, the five-inch mortars are at 100 feet, etc. (see Figure 2). In scenario ttwo, the distances are those from after 1990. Thus, in this scenario all the three-inch mortars are at 210 feet from the spectators, all the four-inch mortars are at 280 feet, all the five-inch mortars are at 350 feet, etc. The number and size of shells in these hypothetical displays were chosen to be fairly typical for a modest size fireworks display, and are given in Table 2.

Table 1. NFPA Minimum Separation Distances.

Shell Size (in.)	Pre-1990 Distance (ft)	Post-1990 Distance (ft)
3	50	210
4	75	280
5	100	350
6	150	420
8	150	560
10	150	700
12	150	840

The consequences of a dud shell falling into spectator areas arise from two potential hazards, from direct impact of a dud with a spectator and from the pyrotechnic output of a shell if it ignites upon impact with the ground. Calculations and measurements suggest the impact velocity of dud shells range from about 90 to perhaps as much as 150 miles per hour, depending on shell size and shape.[3–4] With shells weights ranging from 0.3 to more than 15 pounds, the potential

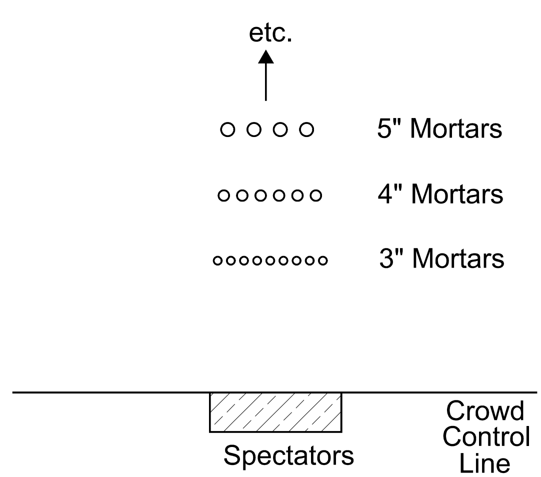

Figure 2. Example of mortar placements for the two scenarios.

Table 2. Dud Shell Risk Assessments for Two Display Scenarios.

Shell Size (in.)	Quantity in Body / Finale	Hazard Scale	Scenario No. 1		Scenario No. 2	
			Probability	Risk	Probability	Risk
3	130 / 100	1	0.81	187	0.06	13.8
4	65 / 0	2	0.73	95	0.06	7.8
5	30 / 0	3	0.71	64	0.06	5.4
6	15 / 6	5	0.60	63	0.06	6.3
8	8 / 0	9	0.73	53	0.06	4.3
10	4 / 0	13	0.79	41	0.06	3.1
12	2 / 1	17	0.85	43	0.06	3.1
			Cumul. Risk	546	Cumul. Risk	39.5

for serious injury or death from the impact of a falling shell is significant.

During measurements to determine spherical aerial shell drift, it was observed that aerial shells smaller than five inches rarely ignite on impact although many shell casings were noticeably damaged (had cracked). For six-inch shells it was found that roughly 10 percent ignited on impact and essentially all shell casings had cracked. For shells larger than eight inches, at least 60 percent of shells ignited on impact and all had seriously damaged casings. However, none of the ignitions observed produced a typically powerful shell burst. In each case, upon ignition, only a fireball was produced with the projection of a few relatively low velocity stars. Nonetheless, for large caliber shells the fire ball dimensions were substantial. Apparently, it was the damage to the shell casings on impact that was the reason for the lack of a typically powerful explosion.

The accident hazard values of Table 2 are relative values, such that values of 2 or 17 are intended to correspond to accidents whose consequences are 2 times or 17 times as severe, respectively, as an accident with a hazard value of 1. In part, the relative hazard scale in Table 2 is a rough estimate based on the information described in the previous paragraphs. However, information from actual accidents, where dud shells have fallen into spectator areas, was also considered in assigning relative severity values. Nonetheless, relatively little time was spent trying to develop a highly accurate hazard severity scale for this example. (Similarly, not much time was devoted to assigning precise probability values, also listed in Table 2.) However, the values in Table 2 are reasonably correct and are adequate for use in contrasting the relative risks of the two display scenarios.

There is no published data to suggest that the probability for any size shell being a dud is different than that for any other size shell. Thus for the purpose of this analysis, it will be assumed that dud probability is independent of shell size. As with hazard values, the probabilities in Table 2 are also relative values. The relative probability values used are just the probabilities for dud shells falling anywhere in a 360 degree circle, beyond the distances being considered. Obviously, because the spectators are assumed to all be in a small area in front of the display and because relatively few shells become duds, these individual probabilities are a gross over estimate. However, since it is only the relative risk between the two scenarios that is of interest, using these relative probabilities is acceptable.

Since the hazard severities listed in Table 2 are relative hazards, and the probabilities are relative probabilities, the resulting risks are only relative risks. For simplicity, in Table 2 and in the remainder of this article, generally the adjective “relative” will not be used but is meant to be implied.

To arrive at the risk for a single shell of any given size, the hazard rating for that size dud shell is multiplied by the probability of a dud shell of that size reaching the spectator area. The combined risk for firing a number of shells of that size is the number of shells times the risk for firing a single shell. Thus the combined risk from firing the 65 four-inch spherical aerial shells at a distance of 75 feet is: 65 shells, times 2 for the hazard, times 0.73 as the probability. This equals 94.9, which is rounded up to 95 in Table 2. Finally, the cumulative risk for each scenario is just the sum of the risks, for firing the numbers of each size shell.

Results

From Table 2, the relative spectator risk from dud shells using the minimum pre-1990 NFPA separation distances (scenario one) is approximately 550, while that using the minimum current NFPA distances (scenario two) is approximately 40. Accordingly, within the context of these two scenarios, using the current NFPA distances should account for more than a 90 percent reduction in the risk from dud shells falling into spectator areas. (Note that large risk reductions are also found when comparing the old and new separation distances in other more realistic scenarios, such as when the spectators are more spread out around the display site.)

Within the scenarios of this article (aerial shells fired vertically at the minimum allowed separation distances), note that it is not the firing of the largest shells that pose the greatest potential hazard to spectators. This is because, for the relative severity scale used, the greater number of small shells fired turns out to be a more significant risk than that posed by the few large shells.

Discussion

When the NFPA Pyrotechnics committee decided to increase the appropriate size of fireworks display sites to 70 feet per shell inch, frankly that was just a good guess, based on the general experience of the committee. At the time, there was no known published data on drift distances for shells, or typical shell burst diameters, or how far down range a shell might be propelled from a misaligned mortar. By the time the code was revised for the 1995 edition, some data had become available that could be used to evaluate the adequacy of the 1990 separation distances. However, more importantly, experience with the new distances was beginning to demonstrate that they were probably sufficient to provide for the "reasonably safe conduct of outdoor fireworks displays". Based on that data and experience, the NFPA Technical Committee on Pyrotechnics chose not to make further changes to the separation distance requirements for the 1995 edition.

The NFPA Committee is now (in 1998) working on the next edition of the code (NFPA-1123). At a recent meeting of the committee's Fireworks Task Group, consideration was given to a proposal (from outside the NFPA committee) to increase the separation distance requirements to 100 feet per shell inch. At that meeting, it was tentatively decided that no increase was needed. In a second article on the risks from dud shells falling into spectator areas, estimates will be made for the effect of such an increase of separation distance. In addition, estimates will be produced and used to investigate the effect of alternate mortar placements and tilt angle.

References

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