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Air Blast TNT Equivalency for Rolls of Paper Toy Caps

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ABSTRACT

A study of the explosive output of rolls of paper toy caps, in variously sized assemblages, was conducted. The testing has shown that toy cap rolls are clearly capable of producing a powerful explosive effect if initiated with a sufficiently energetic event. TNT equivalencies based on toy cap composition mass ranged from approximately 10 to 80% for different sized configurations, with the largest equivalences being produced by the largest assemblages of toy caps tested. The results of this study are disturbing, considering that the toy caps (even in bulk packaging) have a UN classification of Explosive1.4S, which by definition should not produce significant blast or fireball effects when initiated. Thus perhaps it is appropriate to consider whether the UN test protocol is adequate for this product.

Keywords: air blast, TNT equivalence, toy caps, Armstrong's mixture, UN test

Introduction

A few years ago, an accident occurred in a toy factory in California. Several workers were killed and others were injured when a number of bulk cases of rolls of paper toy caps exploded with great violence, sufficient to produce traumatic amputations of worker's limbs. The workers involved were repacking the bulk cases of toy caps at a workstation using a blister pack machine. A number of enforcement and regulatory agencies were involved in the accident investigation and reconstruction. However, while it seemed quite clear that the toy caps were the cause of the accident, this was hard to reconcile with the fact that the bulk cases of toy caps were classed as Explosive 1.4 S.

No quantitative information had been produced by the primary investigating agencies regarding the expected explosive output of bulk quantities of toy caps, and a literature search was unsuccessful in locating such data. As part of the continuing accident reconstruction effort, an estimate of the effective amount of energetic material involved in the explosion was sought. The technique used was to determine the TNT equivalence of various quantities of the toy paper cap rolls. As with any condensed phase explosion, a number of effects are produced, including the production of an air blast wave, fireball, ground shock and projectiles. To estimate the yield of such an explosion, the most useful measure is the air blast wave. This paper reports on that study.

Paper Toy Cap Materials

Toy cap composition is typically composed of Armstrong's mixture, generally consisting of approximately 67% potassium chlorate, 27% red phosphorus, 3% sulfur and 3% calcium carbonate by weight.[1] To form the toy caps, the composition is prepared wet and extruded onto a strip of paper as a series of tiny dots, which are then laminated over with another thinner layer of paper and wound into rolls. The dry mixture is extremely sensitive to accidental ignition[1–2] and, even in small quantities (1 gram), is reported to have significant explosive strength (approximately 23% TNT air blast equivalent when initiated using an electric match).[3]

Careful weight audits of sample cap materials in this case were conducted to determine the average mass of toy cap composition per cap. This was determined through a comparison of: 1) the mass of a collection of blank paper dots, taken from the rolls of caps from the areas between the individual caps using a paper punch; and 2) the mass of a collection of individual toy caps harvested using the same paper punch that was used to produce the blank paper dots. The result was an average energetic material content of approximately 1.85 milligrams per cap.

The bulk quantities of this particular brand of cap were packaged 100 caps per roll, 12 rolls per thin-walled plastic tube, 12 tubes per paper package, and 100 packages per corrugated cardboard case. Thus a case contained 1.44 million individual toy caps, estimated to contain a total mass of 2.66 kg (5.86 lb) of energetic material.

TNT Equivalence Concept

A blast wave from an explosion can damage structures and injure personnel in the area. From an analysis of this damage an estimate of the charge size involved in an explosion can be calculated. While complicating factors must be considered, such as reflections off structures in the area, the geometry of the charge, etc., the technique is viable and quite useful.[4] However, when practical, the direct measurement of explosive output is preferred. Since in this case there was a sufficient (but not abundant) supply of the paper toy caps, the direct measurement approach was taken.

The information to follow is based on reference 5; however, much the same information can be found in other standard reference texts.[6,7] The ability of explosives to cause damage is often stated in terms of its TNT equivalence (*E),* which can be defined as the ratio of the mass of TNT (trinitrotoluene) to the mass of a test explosive that produces the same explosive output under the same conditions, specifically

$$E_{Test} = \frac{M_{TNT}}{M_{Test}} \qquad (1)$$

where M is charge mass, E is usually expressed in terms of percent, and a common measure of explosive output is peak air blast overpressure.

Using this technique typically begins with measuring the peak overpressure, p^o, produced at a measured distance from a test explosive charge of known mass. Then the amount of TNT that would be needed to produce the same peak overpressure is determined using accepted "standard" data for a charge of TNT under similar test geometry.

The comparison between the measured output of a test explosive charge and that from TNT is accomplished using a so-called mass-scaled distance, Z, defined as

$$Z = f_d \cdot \frac{R}{M^{1/3}} \qquad (2)$$

where R is the distance between the center of the explosive charge and the point of measurement of its output, and f_d (called the atmospheric transmission factor for distance) corrects for the effect of differing air densities. This atmospheric transmission factor is

$$f_d = \left(\frac{P_a \cdot T_o}{P_o \cdot T_a} \right)^{1/3} \qquad (3)$$

where P and T are the absolute atmospheric pressure and temperature. The subscript a denotes ambient conditions at the time of the measurement, and o denotes the standard conditions of the TNT blast data, specifically 1.013 bars and 288 K (15 ºC).

Procedurally, after one determines the peak air blast overpressure for the test explosive charge, it is converted to a relative peak overpressure, p^o/P_a. Then using the data and method of reference 5, the scaled distance, Z, is determined for which a standard charge of TNT (i.e., a spherical 1 kg charge of TNT exploded at 1.013 bars pressure and a temperature of 15 ºC) is known to produce the same relative overpressure as did the test explosive charge. Then, using the value of Z just determined, and the values of R, T and P that existed for the overpressure measurement of the test explosive charge, equation 2 can be rearranged to solve for the mass of TNT, M_{TNT}, which would produce the same peak overpressure under the same conditions as did the test charge. At that point, knowing both the masses in equation 1, the TNT equivalence can be calculated for the test explosive.

In cases where a booster (or initiating charge) is used, the output from that charge may contribute a significant portion of the overall explosive output. When that is the case, it is necessary to account for the booster's contribution. This can be done by measuring the explosive output of the booster exploding alone and calculating its TNT equivalence. Knowing the explosive mass of the booster, M_B, equation 1 can be used to calculate the booster's equivalent mass of TNT, $M_{(TNT)B}$.

$$M_{(TNT)B} = Z_B \cdot M_B \qquad (4)$$

Then in calculating the TNT equivalence for the test charge (less the contribution of the booster), the booster's equivalent TNT mass, $M_{(TNT)B}$, must be subtracted, and equation 1 becomes

$$E_{Test} = \frac{M_{TNT} - M_{(TNT)B}}{M_{Test}} \qquad (5)$$

Paper Toy Cap Testing Program

First, a relatively soft initiator was devised for testing the cap materials. The intent was to provide a relatively strong shock without producing much in the way of high density fragments that could act as flyer plates. The first configuration tried was simply to insert an electric match (Daveyfire A/N 28 B) inside one of the tubes of toy cap rolls. This initiator would have been preferred because the explosive charge would be a single electric match with virtually zero explosive output; however, in three tests this initiator was unsuccessful in initiating a reaction of the toy caps.

The next igniter tried was a small acrylic tube filled to capacity with a large number of individual toy caps (obtained from a roll of caps using a paper punch) and carefully stacked on top of one another. After installing an electric match (Daveyfire A/N 28 B) in the tube, which rested against the bottom of the stack of toy caps, the tube was sealed on both ends with a small amount of hot-melt glue. The tube's dimensions (75 mm long, 6 mm ID and 9 mm OD) were chosen because it would fit snugly into the central hole in the rolls of paper toy caps. This initiator had the desirable characteristic of being solely composed toy caps; however, this initiator also failed to function.

A third initiator configuration was tried, in which the stack of toy caps mentioned above was replaced with a 1 gram charge of firework flash powder (70% potassium perchlorate and 30% pyro aluminum). The flash powder configuration performed quite nicely and was chosen as the initiator for subsequent testing. The construction of the initiator is shown in Figure 1.

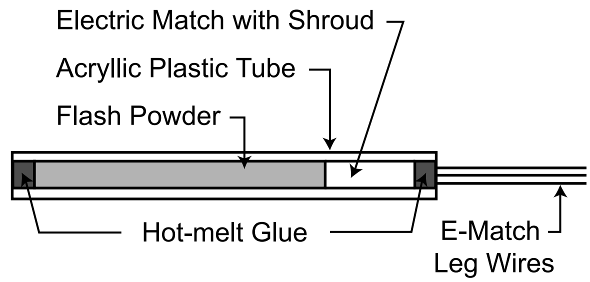

Figure 1. Sketch of the initiator chosen for use in the testing.

This initiator and a number of toy cap configurations were tested in a steel blast chamber (2.5 m in diameter and 5 m long). In each case the test explosive charge was suspended in the chamber approximately on its center axis. Two free-field piezoelectric pressure gauges (PCB model 137A12) were used to measure the side-on pressure from the test devices. The distances to the gauges were chosen to be commensurate with the size of the charges being tested; however, in each case the far gauge was at twice the distance of the near gauge, see Table 1. Digital oscilloscope records were made of the pressure-time history of each explosion.

A series of tests were conducted using increasingly larger assemblages of tubes of toy cap rolls. These configurations were constructed to approximate a right circular cylinder (actually having a hexagonal cross-section) with a height to diameter ratio reasonably close to one. The initiator was always inserted into the middle of one of the tubes of 12 rolls of paper toy caps, and that tube of toy caps was placed at the approximate geometric center of the test charge. Tests were conducted using 7, 28.5, 74, 183, and 676 tubes of toy cap rolls. Figure 2 is a photo of two of the configurations tested, those with 28.5 and 74 tubes. Because there were a limited number of toy caps available, only the test configuration with 7 tubes of toy caps was conducted more than once. Most of the explosion testing was conducted inside the blast chamber described above. The blast chamber tests were conducted at an air temperature of approximately 5 ºC and at a pressure of 0.87 bar (at an elevation of 4600 feet, in western Colorado). Testing of the configuration using 676 tubes of toy cap rolls had to be moved outdoors because, based on the previous testing, it was thought it might exceed the safe capacity of the blast chamber. In addition, one final test was performed that used a full case of the bulk toy caps, which consisted of 1200 tubes of toy caps, for a total of 1.44 million individual caps (100 packages of 12 tubes of 12 rolls of 100 toy caps). This test also needed to be conducted outdoors because of the large size

Table 1. Raw Data from the Paper Toy Cap Testing Program.

Number of Tubes of Toy Caps [a]	Composition Mass [b] (kg)	Total Charge Mass [c] (kg)	Near Blast Gauge		Far Blast Gauge	
			Distance (ft) [d]	Pressure (psi) [e]	Distance (ft) [d]	Pressure (psi) [e]
0	0.001 [f]	n/a	2	1.71	4	0.71
				1.52		0.79
				1.82		0.87
0 [g]	0.001 [f]	n/a	2	1.57	4	0.72
7	0.016	0.10	2	4.84	4	1.81
				4.15		1.59
				4.22		1.86
7 [h]	0.016	0.10	2	3.07	4	1.38
28.5	0.063	0.41	3	3.19	6	1.38
74	0.164	1.06	3	6.53	6	2.76
183	0.406	2.16	3	10.2	6	4.11
676	1.50	9.67	6	17.3	12	8.84
1200 [i]	2.66	17.2	10	15.9	20	5.26

a) Each tube of caps had 12 rolls of 100 toy caps for a total of 1200 individual toy caps.

b) This is only the mass of toy cap composition, exclusive of their inert components and initiator. The amount of composition per cap averaged approximately 1.85 milligrams.

c) Total mass of toy caps, including paper and packaging, but exclusive of the initiator. The total mass of a tube of toy caps averaged approximately 14.3 grams.

d) To convert feet to meters, divide by 3.28.

e) This is peak air blast pressure to three significant figures. To convert psi to kPa, multiply by 6.89.

f) No toy caps were used; this was an initiator only, and it used 1.0 gram of a flash powder.

g) No toy caps were used; this was an initiator only, but it was wrapped with paper approximating the confinement provided by the rolls of toy caps

h) This was the same as the other 7 tube tests, but used an initiator with only 0.5 gram of flash powder.

i) This was one case of toy caps in an unaltered condition, with the exception of placing an initiator in a tube of toy caps in the approximate center of the case. The case consisted of 100 packages of 12 tubes of toy caps.

of the test charge. The outdoor testing was conducted with the test charges and free field blast gauges at approximately 3 feet above the ground, and at an air temperature of approximately 27 ºC and a pressure of 0.86 bar.

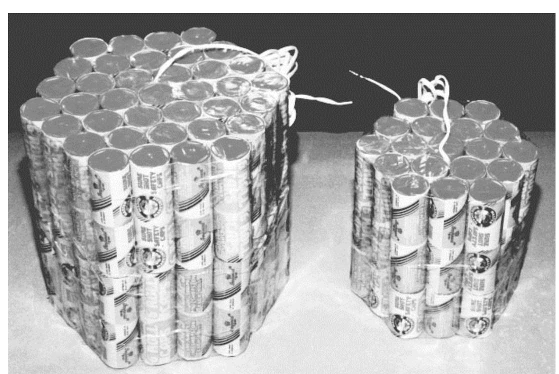

Figure 2. A photograph showing two of the toy cap test configurations, those containing 74 (left) and 28.5 (right) tubes.

Results

The three tests conducted using the chosen initiator in the absence of any toy caps produced an average overpressure TNT equivalency of 47%, see Tables 1 and 2. Given the construction of the initiator, the result is reasonable. With a mass of 1.0 gram of flash powder, the booster weight contribution ($M_{(TNT)B}$ in equation 5) used in subsequent testing was 0.47 grams TNT equivalent. One test was performed to determine whether the stronger confinements produced by insertion of the initiator into a roll of paper toy caps would result in a significant difference in its performance (see Table 1). While the peak air blast overpressures were less than the average from the three previous tests of the initiator, the overpressures were within the range of the three previous measurements. Thus it was concluded that the effect of wrapping the initiator with paper (or rolls of toy caps) was negligible.

The results of testing the assemblages of toy caps are presented in Tables 1 and 2, including the calculated TNT equivalencies—based on the mass of toy cap composition alone and on the total mass of the rolls of caps—for the variously sized configurations. After three tests of the smallest test charge (7 tubes of toy cap rolls), an additional test again using 7 tubes of caps was conducted; however, in this case the flash powder charge in the initiator was reduced to only 0.5 gram. The result was a significant drop in the explosive output of the toy caps. This suggests that the 1.0 gram initiator, at best, may only be marginally sufficient for the purpose. However, there was not enough space inside the rolls of toy caps to have used an initiator with a larger charge of flash powder, and the use of a non-pyrotechnic (high explosive) initiator was thought to be excessive for the purposes of these output tests.

Table 2. TNT Equivalence Results for Paper Toy Caps.

Number of Tubes of Toy Caps (j)	Equivalent TNT Mass (kg) (k)	TNT Equivalence (%) (l)	
		Composition Only (m)	Total Toy Cap Mass (n)
0 (o)	0.00047	47	n/a
7	0.0024	15	2.4
7 (p)	0.0012	9	1.4
28.5	0.0057	9	1.4
74	0.020	12	1.9
183	0.056	14	2.6
676	0.81	54	8.4
1200 (q)	1.9	81	12.5

j) Each tube of caps had 12 rolls of 100 toy caps for a total of 1200 individual toy caps.

k) Based on peak air blast overpressure and correcting for the contribution of the initiator. This is the average of the results from the near and far blast gauges. When multiple tests were performed, this is the overall average of the results. The results are reported to two significant figures.

l) Calculated using the average of the near and far equivalent TNT masses.

m) Calculated based only on the mass of toy cap composition, but correcting for the initiator. The results are reported to the nearest 1%.

n) Calculated based on the total mass of toy caps, including paper and packaging, but correcting for the initiator. The results are reported to the nearest 0.1%.

o) No toy caps were used; this was an initiator only.

p) This was the same as the other 7 tube tests, but used an initiator with only 0.5 g of flash powder.

q) This was one case of toy caps in an unaltered condition, with the exception of placing an initiator in a tube of toy caps in the approximate center of the case. The case consisted of 100 packages of 12 tubes of toy caps.

The output from the smaller assemblages of paper toy caps (those comprised of 7 to 183 tubes and using the 1.0 gram initiator) ranged from 9 to 15% TNT equivalence based on composition mass, and there was no obvious trend in the data. This is in significant contrast with the results from the two larger assemblages (those comprised of 676 and 1200 tubes), which produced TNT equivalences of 54 and 82%, respectively, based on composition mass.

The physical debris produced in the tests of the smaller assemblages of paper toy caps consisted of a moderate amount of cap paper and unexpended caps, indicating the non-homogeneous nature of the rolls of toy caps and the incomplete propagation throughout the test charges. However, the amount of visible paper and unexpended caps present after the largest two test configurations (676 and 1200 tubes) was substantially less than in the smaller test configurations. This is consistent with a more complete propagation of the explosive reaction through the assemblages and accounts for the significantly higher TNT equivalencies obtained for these larger assemblages of toy caps.

The propagation mechanism involving the rolls of paper toy caps is not fully understood but is assumed to be one of sympathetic explosion, where the initiation of one cap may on average initiate one or more caps as a result. Given the construction of the cap rolls, the transfer mechanism may be one of impact through the thin paper separating the individual caps. Tube-to-tube transfer may be similar, through the plastic tube separations which are much thicker. To some extent, the efficiency of propagation was evidenced by the amount and nature of the debris left after each test. As described above, larger charges were shown to be more efficient in their ability to propagate.

Differences in the shape of the overpressure decay curve (the portion of the air blast positive phase after reaching peak overpressure) change the efficiency with which the blast wave propagates in air. Thus the air blast TNT equivalences found at various distances from a non-TNT test charge depend on details of the shape of the blast wave produced by that explosive, as compared with a blast wave from TNT.[8] This is certainly true for this study, due to the non-ideal explosive involved and to a lesser extent the non-spherical geometries. A comparison of the air blast results in this toy cap study reveals that the far gauge consistently resulted in significantly higher TNT equivalences. (It was verified that this was not a calibration or other problem with the instrumentation.) Accordingly, in Table 2, the TNT equivalences reported are the average of the near and far gauge results. While this is a reasonable approach, it must be realized that had the gauges been placed at other distances than those in this study, the TNT equivalences would be somewhat different as well.

Both high and low speed video cameras were setup to record the two test explosions produced outdoors. However, in the first test (that using 676 tubes of caps) the unexpectedly large air blast shock cause a circuit breaker to trip-off, which caused the high speed video record to be lost. Other than that, the recorded results of both tests were quite similar although somewhat different in scale. Figure 3 is a series of 1/60 second video fields, with a shutter speed of 1/60 second, recorded using the low speed video camera. (The low speed video images are reproduced here because they were captured with a more appropriate *f*-stop setting and the images are more distinct.) The numbers on these images are the number of video fields elapsing after the first image, which was the last image recorded prior to the explosion. The field of view in the images, at the location of the explosion, is approximately 18 feet high by 26 feet wide (5.5 by 8 m). In image number zero, the full carton of paper toy caps and the near blast gauge have been highlighted with circles.

It is of interest to note that in the first image of the explosion (#1) that, while some of the debris from the explosion (appearing dark in the image) has been propelled to a diameter of approximately 16 feet (4.9 m), essentially no flash of light is discernable. In the next image (#2) the debris has expanded to approximately 21 feet (6.4 m), and a fireball has started to develop. In the next image (#4) the fireball has developed fully and thereafter decays. It is thought that the fireball is not part of the explosive reaction, but rather the burning in air of the finely shredded paper debris from the toy caps. This is consistent with the observation of a near total lack of paper debris after the explosion, including remnants of the heavy cardboard carton. The lack of a significant flash during the initial stages of the explosion and the subsequent development of a fireball was confirmed in the high frame rate video record.

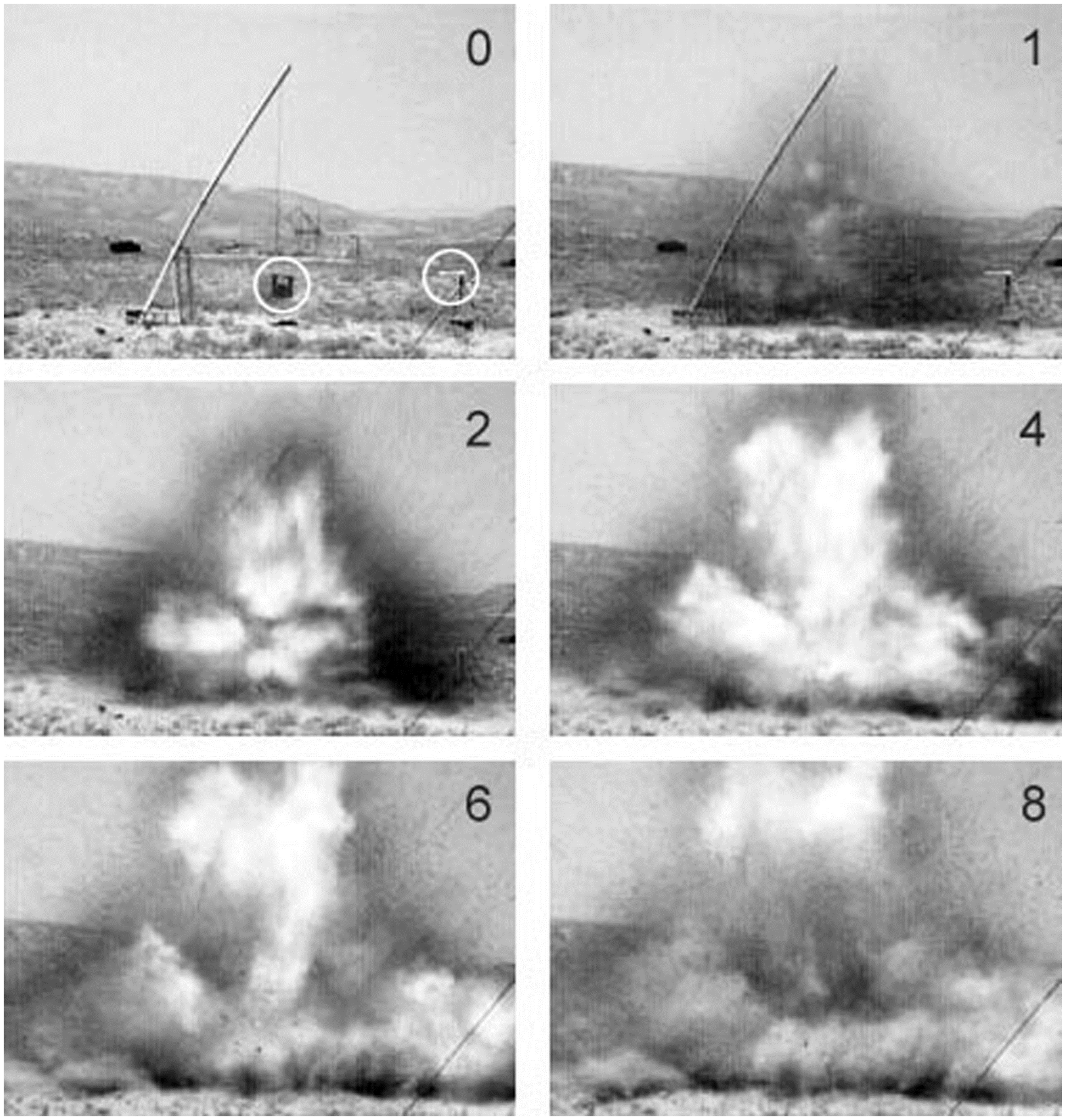

Figure 3. Video images just before and during the test involving a full case of paper toy caps. The field of view at the approximate distance of the explosion is 18 by 26 feet (5.5 by 8 m), and the numbers on the images are the number of 1/60 second video fields elapsing after the first image.

Conclusion

Had greater quantities of toy caps been available for study, more tests could have been performed. This would have produced greater certainty in the results and other aspects of the case could have been investigated, such as identifying possible causes for the initiation of the caps in the accident. Nonetheless, the testing has shown that bulk quantities of paper toy cap rolls are clearly capable of producing a powerful explosive effect if initiated with a sufficiently energetic event. TNT equivalencies, based on toy cap composition mass, ranged from approximately 10 to 80% in different sized configurations, with the largest equivalences being produced by the largest assemblages of toy caps tested. This was unexpected, as the authors had thought that the opposite would likely have been the case, with very large assemblages tending to fail to efficiently propagate the explosion.

The results of this study are disturbing, considering that paper toy caps (even in bulk packaging) have a UN classification of Explosive 1.4S, which by definition should not produce significant blast or fireball effects when initiated. In the UN test protocol it is only required to initiate one item near the center of one case used in the testing. As part of this study of TNT equivalence, some very limited testing was performed in an attempt to learn how the accident might possibly have come to occur. During that testing, it seemed clear that a single toy cap functioning, or even a significant fraction of a single roll of caps functioning, was unlikely to have been sufficient to propagate well enough to produce the massive explosion that caused the fatalities or those explosions observed in the TNT equivalencies tests. Thus, it is understandable that the current UN test would conclude that the proper classification for the toy caps was Explosive 1.4S. Nonetheless, massive explosions certainly are possible (and have accidentally occurred at least once) for bulk cases of paper toy caps. This would generally not have been thought to be possible for items with an Explosive 1.4S classification. Accordingly, perhaps some consideration should be given to changes in the UN test protocol or the classification of paper toy caps.

Acknowledgments

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