WINDBORNE DRUM MISSILES

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ABSTRACT

Accident analyses performed for nuclear facilities typically consider windborne missiles impacting drums and other storage containers. In contrast, the analysis presented here considers the converse problem, namely that of drums becoming missiles and rupturing on impact with a stationary object. This was of special interest for a new type of container, called the Pipe Overpack Container (POC), which consists of a heavy-gauge pipe component packed in a 55-gallon drum. The POC is being used for the packaging of transuranic waste and transport to the Waste Isolation Pilot Plant. It is shown in this report that for Rocky Flats Environmental Technology Site (RFETS), the credible wind speeds (straight line and tornado) are not great enough for this to be a significant issue. However, for DOE sites subject to severe tornadoes and hurricanes, this issue needs to be considered.

Symmetrical objects, such as 55-gallon drums, cannot be lifted by the horizontal component of the wind, except momentarily if the orientation of the drum relative to the wind is advantageous. Heavy drums can remain suspended in the air only if the vertical component of the wind is substantial. For a 450-lb drum, for example, the vertical component of the wind speed must be on the order of 200 mph for the air density at RFETS; at sea level, the vertical component of the wind would not have to be quite as great. The horizontal velocity of a windborne drum depends upon the horizontal wind speed and upon drum weight. A 200-lb drum, for example, could attain a speed of about 110-mph (at RFETS) for a horizontal wind speed of 350 mph. An 800-lb drum, on the other hand, couldn't attain a speed of 60 mph for such a wind.

The damage done to a windborne drum when it impacts a stationary object depends upon the kinetic energy of the drum, how the drum strikes the object, the shape of the object, and how unyielding the object is. In the case of the POC, if it struck a building end-on or side-on it would not be breached even for wind speeds as high as 350 mph. However, it could be breached if it impacted side-on an unyielding object that was narrow, such as the horizontal timber of a rigid telephone pole; the wind speed would have to be on the order of 150 mph or greater for such a rupture of a POC. For other types of drums, the wind speed required for a rupture can be calculated if the energies to cause rupture for the various types of impact are known.

The occurrence probability of a rupture of a windborne drum missile depends on many factors. What is the probability of attaining the needed wind velocity (horizontal and vertical components)? If the drum is banded with others, what is the probability of the banding breaking? What is the probability of the drum being moved by the wind to an unshielded location so that it can be lofted? What is the probability of the drum striking a "sharp" object that is sufficiently unyielding to cause the rupture? What is the probability of the orientation of the drum being such that the impact causes a rupture (as opposed to a glancing impact)? In the case of the POC, when all these factors are considered it is found that a rupture is less probable than 1E-6/yr, even using very conservative estimates of the factors entering the calculation. For other types of drums and other DOE sites, however, this may not be case.

1 INTRODUCTION

Accident analyses for authorization-basis documents have traditionally considered accidents involving the impact of windborne missiles, such as wooden timbers and pipes, on packages of wastes. In this report, the converse problem is addressed, namely, packages of wastes becoming windborne missiles and the subsequent damage they could suffer upon impact. In particular, the effects on 55-gallon drums are investigated. A subset of especial interest is the Pipe Overpack Container (POC) (Peterson, 2000). The POC consists of a sealed pipe component (Schedule 40 pipe with 6-inch diameter or Schedule 20 pipe with 12-inch diameter), contained within a Type 17C 55-gallon drum; the pipe component is separated from the drum by fiberboard packing material and a plastic liner. Although this report often refers to POCs at the Rocky Flats Environmental Technology Site (RFETS), the methodology can be applied to other types of drums at other DOE sites.

High winds are capable of lifting certain objects into the air and accelerating them to speeds great enough that they can become missiles. Such winds will either be (1) "straight-line" or (2) tornadoes. (Hurricane winds can be considered "straight line" in this context, as can winds from thunderstorms.) For a package as small as a 55-gallon drum, only the wind velocity (horizontal and vertical components) is important, not the source of the wind. The rotational aspect of a tornado controls the direction a 55-gallon drum travels and the tornado's larger vertical velocity will give rise to a greater lift compared to straight-line winds. However, the shear forces and atmospheric pressure changes associated with a tornado are not important for an object as small as a drum.

When a 55-gallon drum is exposed to a high wind, it initially rolls and tumbles along the ground. As it tumbles, it may momentarily bounce high enough to be carried by the wind a short distance. The horizontal component of the wind, however, is not capable of lifting a symmetrical object, such as a 55-gallon drum, except briefly if the angle of attack happens to be advantageous; as the drum tumbles, the angle of attack would soon become disadvantageous and the drum would be driven back toward the ground. This is confirmed by experiments and numerical modeling. An Electric Power Research Institute study (EPRI, 1983) included a number of experiments in which various objects (12-inch pipes, automobiles) were fastened to a platform mounted on a railcar. The platform was accelerated to speeds up to 300 mph, at which point the object was released. The report concluded: "*None of the test objects (two tests with 12-inch pipes and three tests with automobiles in a variety of positions) rose more than 2.5-m (8-ft) above the 12-m (40-ft) long ground plane. A horizontal pipe simply rolled/slid off the platform. Results of calculations with the 6-DOF*[1] *model were in reasonable agreement with the measured initial trajectories. These results support the conclusion that the 12-inch steel pipe and automobile do not have sufficient lift to be injected from ground level to a height greater than about 3-m in a 300-mph wind. They also cast doubt on the reasonableness of an assumption that these objects could be suddenly driven vertically 40-m upward into a tornado windfield as assumed in the NBS*[2] *study*." Only a strong vertical wind component is capable of lifting a drum any distance. Vertical winds this strong are very unlikely, as will become evident in Section 2.

The following treatment considers drums that have already become airborne. It calculates the speeds and energies of these drums as a function of wind speed and the likelihood of POCs being breached upon impact. It does not calculate the wind speed needed to lift an object, as this would require more sophisticated models than employed here. However, this report does estimate these lift-off speeds

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[1] DOF stands for Degrees-Of-Freedom.

[2] NBS stands for the National Bureau of Standards, now called the National Institute of Standards and Technology. DOE-STD-1020-94 (DOE, 1994) indicates that this NBS study is similar to the McDonald (1975) study that formed the basis for that standard.

by comparison with results from earlier studies on other types of missiles and calculations of vertical wind speeds needed to keep a missile aloft. It is extremely improbable that a POC would become an airborne missile that is breached on impact. Not only is it very difficult for wind to lift a symmetrical object, such as a drum, to any significant height, as evident from the above quote from the EPRI study, other factors also lessen the likelihood of a drum becoming an airborne missile. This will be discussed more fully in Section 4. The U.S. Department of Energy (DOE) standard DOE-STD-1020-94 (DOE, 1994) indicates that for straight-line winds, 2”×4” timber planks are the only missiles of concern for any wind speed; even these planks are not of concern for winds of less than Performance Category 3 (PC-3), for which the exceedance probability is 1E-3/yr. The average PC-3 straight-line wind speed for the 13 DOE sites listed in DOE-STD-1020-94 is 98 mph. The implication is that timber planks do not become airborne for lesser wind speeds. Furthermore, this DOE standard indicates that for tornadoes, no missiles need be considered for tornadoes less than PC-3, for which the exceedance probability is 2E-5/yr. The average PC-3 tornado wind speed for the 12 DOE sites listed is 124 mph. (RFETS was not given a tornado wind speed in this DOE standard.) For PC-3 tornadoes, only the timber planks and 3-inch steel pipes were missiles of concern. The POC would require an even greater wind speed than planks or pipes, based on the analysis in Section 2. In the following analysis, missile speeds are calculated for winds as low as 100 mph. This should not be interpreted to mean, however, that a 100-mph wind is capable of initially lofting a 55-gallon drum. Indeed, as will be shown, wind speeds that low can be discounted for POCs.

2 CALCULATIONAL METHOD

The treatment of windborne missiles is sufficiently complex that many simplifying assumptions must be made to make the problem tractable. Even computer models that have been used employ many simplifications. For this report, wind effects on 55-gallon drums are based on a scaling of results from previous modeling results, which were computer based. The results presented here must therefore be considered as approximate.

The speeds of various windborne missiles (timber planks, pipes, utility poles, and automobiles) are given in Table 1. These data were taken from Coats and Murray (1985), who in turn were quoting results (with one exception) from a computer model developed at Texas Tech University (McDonald, 1975). The exception taken by Coats and Murray concerned only the automobile results, which they decreased to account for the rolling and tumbling motion of the automobile. Note that in that study, the utility pole and automobile did not become airborne for wind speeds of 200 mph or less. The missile speeds given in Table 1 appear to be conservative for RFETS, as sustained winds exceeding 100 mph have been achieved a number of times at RFETS without timber planks or pipes becoming missiles, although during these winds such potential missiles were lying outdoors in abundance.

Of these four missile types, only the 3-inch pipe and the utility pole will be compared to the 55-gallon drum. These three objects are all cylindrical, and therefore would be expected to respond in a similar way to the wind.

The force (F) of the wind on an object depends upon the wind velocity (V_a), air density (r), cross-sectional area (A), and the coefficient of drag (C_d). For low wind speeds, the flow of air around the object is laminar and the force varies linearly with wind speed. However, as the wind speed increases the flow becomes turbulent. The turbulent force varies as the square of the wind speed. For the wind speeds considered here, the contribution from laminar flow is trivial and only the turbulent contribution need be considered. The force of the wind on an object is thus

$$F = \frac{1}{2}\, r\, C_d\, A\, V_a^2 \qquad (1)$$

For cylindrical objects, C_d is about one, the exact value depending somewhat upon the smoothness of the surface. At sea level, $r = 1.29$ kg/m^3 but at RFETS the average value is about 0.88 kg/m^3. Table 1 is based on sea-level air density, so $\rho = 1.29$ kg/m^3 is used when calculating the wind forces on those objects. However, for potential windborne missiles at RFETS, the value of 0.88 kg/m^3 is used. For a given wind speed, the force of the wind would be 32% less at RFETS than at sea level, because of this difference in air density. Greater wind speeds are therefore required at RFETS to achieve the same missile speeds as at sea level.

Table 1 Windborne Missile Velocities (mph)

WIND SPEED (mph)	**MISSILE TYPE**			
	4”×12”×12’ Timber Plank	**3"×10’ Pipe**	**13.5”×35’ Utility Pole**	**Automobile**
100	60	40	0	0
150	72	50	0	0
200	90	65	0	0
250	100	85	80	25
300	125	110	100	45
350	175	140	130	70

The weights and cross-sectional areas of the pipe and utility pole, and those of 55-gallon drums, are shown in Table 2. (The 55-gallon drums are slightly less than two feet in diameter and slightly less than three feet high. The cross-sectional area has been rounded up to 6 ft^2 to account for the extra area presented by the drum chimes and lid locking mechanism.) The weights of the 55-gallon drums are shown as a range, to encompass those expected at RFETS. The lightest gross weight likely to be encountered is 200 lb and the maximum weight (gross) allowed for a 55-gallon drum is 800 lb. The maximum allowed weights (gross) for the two types of POCs are 328 lb for the POC with the 6-inch pipe component and 547 lb for the POC with the 12-inch component (NRC, 1997).

Table 2 Weights and Cross-Sectional Areas of Missiles

Missile Type	**Weight (lb)**	**Mass (kg)**	**Area (ft^2)**	**Area (m^2)**
3-Inch Steel Pipe	75.8	34.4	2.5	0.232
Utility Pole	1,490	676	39.4	3.66
55-Gallon Drum	200 - 800	91 - 363	6.0	0.557

Equation (1) can be inverted to determine the vertical wind speed required to maintain a missile in the air once it has become airborne, by setting the force, F, equal to its weight, mg, where g (= 9.81 m/s^2) is the acceleration due to gravity. This vertical wind speed is the same as the terminal speed of the object if it falls from a great height in calm air. Table 3 shows these speeds for the 3-inch pipe, the utility pole, and the two POCs. (The vertical wind speeds shown are for the orientation of the object that gives the greatest lift. For any other orientation, even greater vertical wind speeds are required.) These vertical wind speeds are very large and are not likely to ever be achieved in a straight-line wind. They obviously can be attained in tornadoes, as heavy objects are lifted in very strong tornadoes. The horizontal winds speeds are greater than the vertical in a tornado; for example, the McDonald (1975) model uses the rule-of-thumb that the vertical component is ${}^{2}/_{3}$ that of the horizontal. (This assumption would imply, for example, that in a tornado the horizontal wind speed required to suspend a 6-inch POC in the air would be about 259 mph.) Tornadoes this strong (class F4 or greater for the POCs) are considered *incredible* at RFETS (McDonald, 1995).

Table 3 Vertical Wind Speeds Required to Suspend an Object in the Air

Missile Type	Vertical Wind Speed (m/s)	Vertical Wind Speed (mph)
3-Inch Steel Pipe	57.5	128.5
Utility Pole	64.2	143.5
6-inch POC	77.1	172.6
12-inch POC	99.6	222.8

The kinetic energy of a missile ($KE = ½\, mV_m^2$) is equal to the work (W) done by the wind in bringing a missile of mass m up to velocity V_m. The work done is the integral of the force of the wind over the distance (X) required to achieve velocity V_m.

$$W = \int F(x)\, dx \tag{2}$$

where x varies from 0 to X. The force of the wind on an object depends upon the relative speed on the wind and the object and therefore decreases as the speed of the object increases. The work done is thus $\langle F \rangle X$, where $\langle F \rangle$ is the average force over the distance X. To a first approximation, the average force will be set equal to the initial force, so that $W = F_i X$, where F_i is the initial force. The effects of this approximation largely cancel out in the following calculations of drum-missile speed, which are based on scaling the missile speeds of the 3-inch pipe and utility pole. The ratio, R, of the kinetic energy of the missile to the work required to bring it up to velocity V_m, is thus,

$$R = (m/r\ C_d\ A\ X)\ (V_m/V_a)^2 \tag{3}$$

Ideally, this ratio should be equal to one but it will be allowed to be greater or less than one to account for the approximate nature of this evaluation. The distance X is unknown, as is the exact value of C_d, although the latter is known to be approximately one. This evaluation is based on the assumption that the product RC_dX should be about the same for the 3-inch pipe, utility pole, and the 55-gallon drum. Values of RC_dX for the 3-inch pipe and utility pole, based on equation (3) and data taken from the Table 1 and Table 2, are shown in Table 4.

The values of RC_dX in this table are all of the same magnitude, as expected, with the ratio of the largest to smallest values being about 1.6. In the following calculations, the RC_dX values for the 3-inch steel pipe are used for wind speeds of 200 mph or less, and the average of the pipe and utility pole values are used for greater wind speeds.

Table 4 RC_dX (meters) for 3-Inch Pipe and Utility Pole for Various Wind Speeds (mph)

Missile Type	**Wind Speed (mph)**					
	100	**150**	**200**	**250**	**300**	**350**
3-Inch Steel Pipe	18.36	12.75	12.12	13.27	15.43	18.36
Utility Pole				14.66	15.90	19.75

Equation (3) can now be solved for V_m for the various values of V_a. The results are shown in Table 5 for winds speeds from 100 to 350 mph. Recall that the utility pole couldn't be lifted by winds of 200 mph or less, and that the vertical wind speed required to keep a POC suspended is even greater than for the utility pole. Therefore, missile speeds are not shown in this table for wind speeds less than the vertical speed required to keep the object aloft (Table 3). The cut-off is 223 mph for weights greater than or equal to that of a 12-inch POC, and 173 mph for weights greater than or equal to that of a 6-inch POC. This is a conservative assumption.

Table 5 Missile Speeds (mph) of 55-Gallon Drum of Various Weights vs. Wind Speed

Drum Gross Weight (lb)	**Wind Speed (mph)**					
	100	**150**	**200**	**250**	**300**	**350**
200	31.51	39.39	51.20	68.69	87.31	112.34
300	25.73	32.16	41.81	56.08	71.29	91.73
328	**-**	**-**	**39.98**	**53.64**	**68.18**	**87.72**
400	-	-	36.20	48.57	61.74	79.44
500	-	-	32.38	43.44	55.22	71.05
547	**-**	**-**	**-**	**41.53**	**52.80**	**67.93**
600	-	-	-	39.66	50.41	64.86
700	-	-	-	36.72	46.67	60.05
800	-	-	-	34.34	43.66	56.17

The missile speeds for the 6-inch and 12-inch POCs are shown in this table in **bold** type.

The horizontal distance traveled by a drum, once it becomes airborne, depends primarily upon how long it is subjected to the forces of the high-wind or tornado. This would vary, of course, from one event to the next. However, once the drum escapes from the control of the high wind or tornado, its horizontal travel distance can be calculated, if its height is known. The time (T) it takes for an object to strike the ground in falling from a height h, ignoring air friction, is

$$T = (2\,h / g)^{1/2} \tag{4}$$

A POC with a 6-inch pipe component, for example, traveling 88 mph in a 350 mph wind, at a height of 3 m, would take $(2 \times 3 \text{ m} / 9.8 \text{ m/s}^2)^{1/2} = 0.8$ s to fall to the ground. In this time it would travel (0.8 s × 88 mph × 5,280 ft/mile / 3,600 s/hr) = 103 feet. The distance traveled would be even less for more realistic wind speeds. This distance is small compared to the distance it might travel while under the influence of the high wind or tornado.

3 RESULTS

The missile speeds given in Table 5 as are shown in Figure 1. As mentioned above, the variety of weights of 55-gallon drums shown are expected to cover the range of weights that may be found at RFETS. The two heavy lines in the figure (one solid, the other dashed) are for the two types of POCs, those with 6-inch and 12-inch pipe components. The curves for the heavier drums are truncated at the lower wind speeds, as they couldn't be lofted for these wind speeds.

Straight-line wind speeds for RFETS for various annual exceedance probabilities (McDonald, 1995) are given in Table 6. Both sustained (fastest-mile) speeds and peak gust speeds are shown. [The sustained winds shown have been calculated from the peak gusts using the equation given in McDonald (1995) of V(fastest mile) = 0.958 V(peak gust) – 11.34 mph.] The corresponding tornado wind speeds are also shown for comparison. Comparisons between Table 5 (or Figure 1) and Table 6 shows that a POC wouldn't be lofted for the 1E-3/yr exceedance probability event (139 mph sustained wind, 157 mph peak gust). It would require at least an event with 1E-4/yr exceedance probability to loft a POC with a 6-inch pipe component, and an event with 1E-6/yr exceedance probability to loft a POC with a 12-inch pipe component. Other DOE sites will have to generate similar tables.

Table 6 Expected Straight-Line and Tornado Wind Speeds at RFETS (McDonald, 1995)

Annual Exceedance Probability	Sustained Winds (mph)	Peak Gusts (mph)	Tornadoes (mph)
2E-2	109	126	-
1E-2	117	134	-
1E-3	139	157	-
1E-4	161	180	77
1E-5	183	203	145
1E-6	205	226	201
1E-7	225	247	253

The damage that could be suffered by a POC upon impact depends upon the energy of the impact, the orientation of the POC, and the type of object it impacts. Table 7 (Peterson, 2000) gives the kinetic energies required to rupture a POC. "Top (flat)" refers to an impact to one end of the POC, such as the POC impacting a building end-on. "Side (flat)" refers to a side impact by a flat object, such as the POC impacting a building side-on. "Side (edge)" refers to a side impact by a relatively narrow object, such as the end of a horizontal timber at the top of a telephone pole. Figure 2 shows the variation of kinetic energy with wind speed. The kinetic energy of a drum for a given wind speed is the same for all drum weights because the speed attained by a drum varies inversely as the square root of its weight (for these calculations).

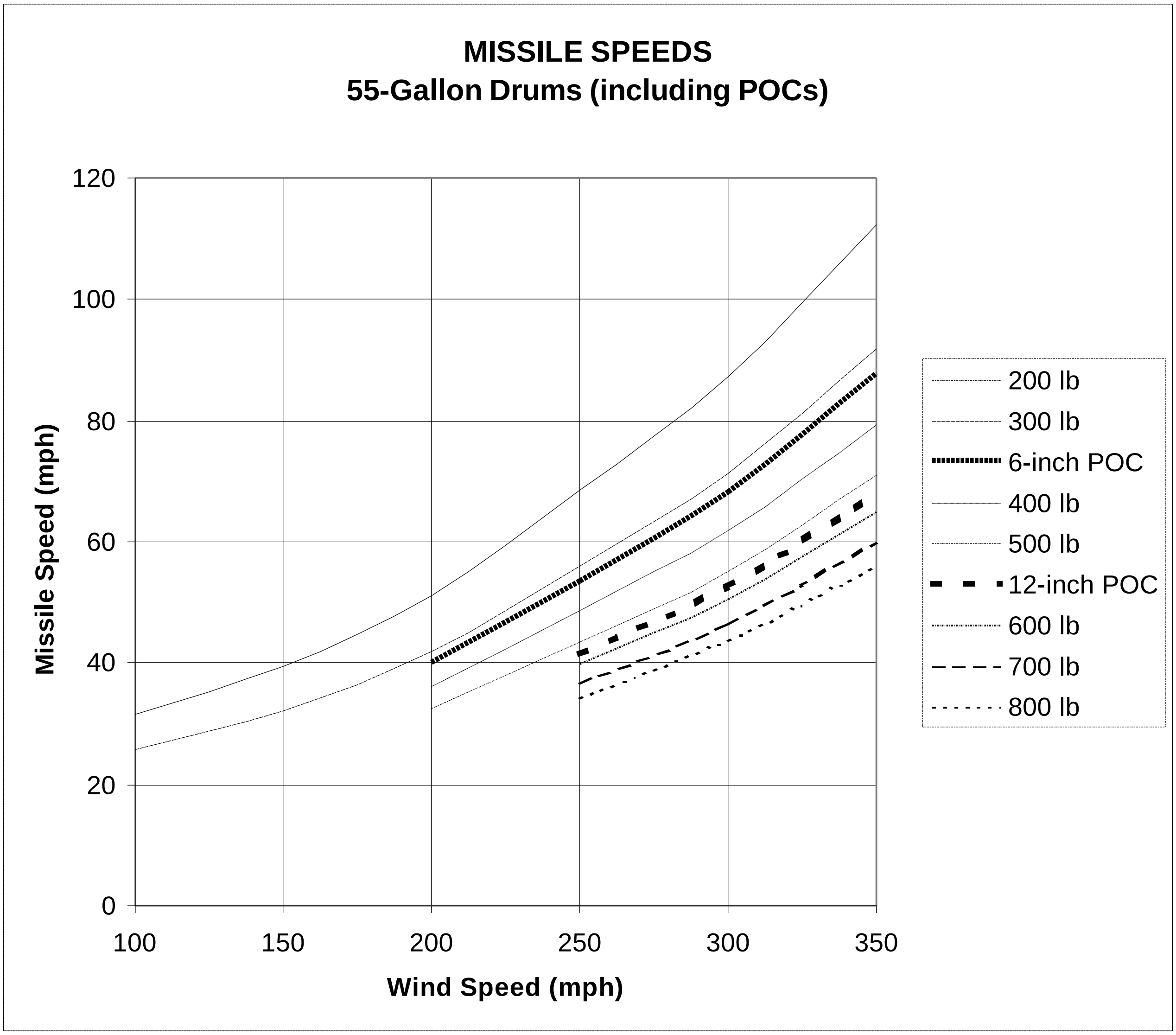

Figure 1 Air Speeds of 55-Gallon Drums of Various Weights

Table 7 Energies (Joules) Required to Rupture POCs

Impact Type	6" POC	12" POC
Top (flat)	1.6E+05	1.75E+05
Side (flat)	9.0E+04	1.7E+05
Side (edge)	2.0E+04	1.6E+04

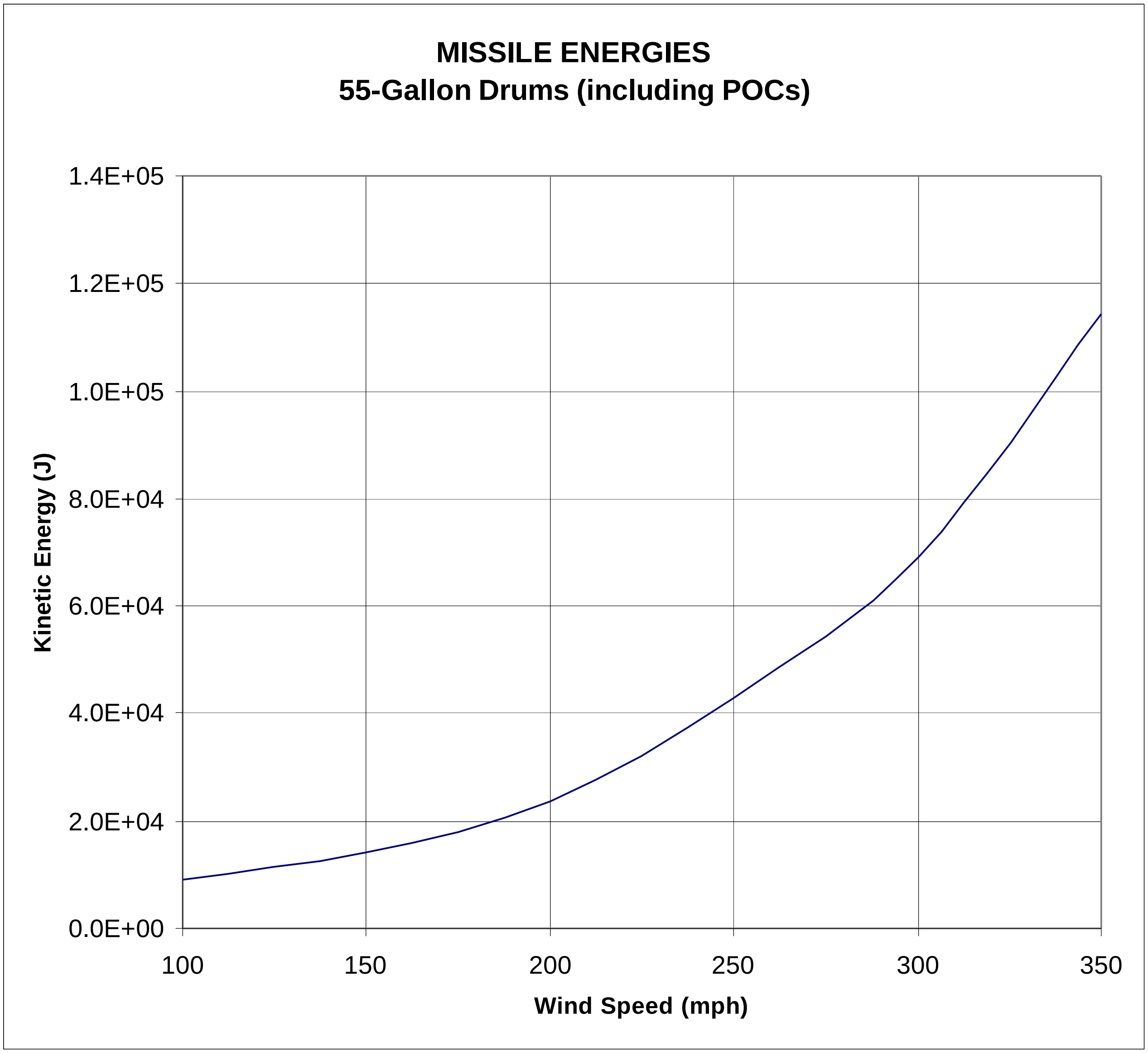

Figure 2 Kinetic Energy of Drum Missiles as a Function of Wind Speed

Comparison of Table 7 with Figure 2 shows that for wind speeds less than 350 mph the POC would not be ruptured by a flat impact, such as against a building or the ground. For an impact to the side of the POC by the edge of an object, such as the horizontal timber at the top of a telephone pole, a wind speed high enough to loft a POC would also be enough to rupture it. The wind speeds for rupture correspond to about 165 mph, for a 6-inch POC, and 148 mph for a 12-inch POC. In contrast, the lofting speeds have to be at least 173 mph and 223 mph, respectively, as shown earlier. This type of POC breach assumes the object impacted is unyielding. In the case of a telephone pole, it is likely that the impact would break off the cross-member or possibly topple the telephone pole, but not rupture the POC. There are other objects that would be relatively unyielding, of course, such the steel supports for the steam pipes. Considering the total available cross-sectional area of such targets, compared to the total cross-sectional area of the space through which POC missiles would fly, it is clear that the probability of such an impact must be small. This is discussed further in the next section.

Similar damage evaluations can be made for POCs that do not become missiles but are struck by windborne missiles, such as those in Table 1. The kinetic energies, based on the missile speeds of Table 1, are shown in Table 8 for the 3-inch steel pipe and the utility pole.

Table 8 Kinetic Energies (Joules) of Windborne Missiles for Various Wind Speeds (mph)

Missile Type	Wind Speed (mph)					
	100	150	200	250	300	350
3-Inch Steel Pipe	5.50E+03	8.59E+03	1.45E+04	2.48E+04	4.16E+04	6.73E+04
Utility Pole				4.32E+05	6.75E+05	1.14E+06

Comparison of Table 7 with Table 8 shows that the utility pole could rupture a POC for any wind speed of 250 mph or greater. The 3-inch pipe, on the other hand, could rupture a POC only if it hit the side of a POC with wind speeds greater than 200 mph. Even then, the impact would have to be one in which the POC is against a rigid barrier that doesn’t allow it to move.

4 OCCURRENCE PROBABILITIES

In the preceding discussion, it has been argued that the probability of a POC being breached during a high wind event or tornado is very small. This section provides a rough estimate of this annual exceedance probability. The probabilities of the following succession of events must be multiplied together to derive the overall probability of a rupture. This discussion is specifically for the damage to a POC if it becomes a missile and subsequently impacts some object. A similar argument can be made for other objects striking fixed POCs.

The exceedance probability of a wind strong enough to cause a breach of a POC is less than 1E-4/yr, based on the discussion above. This is for a side impact on a 12-inch POC by the edge of some unyielding object.

Banding of the POCs (four to a pallet, every pallet) and shielding by other drums/POCs and the remaining building structure will lessen the probability that a drum/POC will be become a missile. The POC would have to break loose from the other POCs on the pallet, roll free into an area in which it is not obstructed by another object, and not be shielded from the wind by other objects. This reduction in probability is estimated to be a factor of 100.

Assuming the wind is strong enough and the POC is in the open, the probability of a drum being lofted by the high-wind or tornado is estimated to be less than 1%.

The POC-missile has to strike an unyielding object. In the case of the cross-member of a telephone pole, the cross-sectional area would be about 50 in^2, for a 4”×12” timber. Assuming such support structures are placed 100 feet apart and are 20 feet high, and each provides two such objects that could penetrate the POC, these objects present an area of about 100 in^2 within a total cross-sectional area of about 2,000 ft^2, or 2E5 in^2. The probability of striking an object that could penetrate the POC is thus about 5E-4. In addition, the POC could strike the edges of other unyielding objects. To be conservative, this probability is therefore increased to 1E-3 per POC.

The axis of the POC has to be oriented approximately perpendicular to its direction of motion so that the impact is direct, rather than glancing. Probability estimated as 10%.

The overall frequency of occurrence for a POC breach in a high-wind event or tornado is thus estimated to be about 1E-11/yr for a single POC. This then has to be multiplied by the number of POCs that could be involved in the high-wind event or tornado, say 10,000 to be conservative. Although the above probabilities are only estimates, they do show that the probability of a POC rupture in a high-wind event or tornado should be considered *incredible*, that is, less than 1E-6/yr.

5 SUMMARY

Straight-line winds cannot loft POCs to heights greater than a few meters, and then only briefly for the strongest of winds. It is conceivable that tornadoes could turn 55-gallon drums into airborne missiles but the likelihood of a POC being ruptured during a tornado is considered *incredible*. Wind speeds as high as 350 mph, should they cause a POC to become airborne, will not result in a breach for a side-on (flat) or top/bottom impact into an unyielding object such as a building. For RFETS, such wind speeds are *incredible*, according to McDonald (1995) and DOE-STD-1020 (DOE, 1994). Although a breach of a POC from an impact to its side by the edge of an unyielding object could occur at lower wind speeds – but at least 173 mph – the sequence of events needed to cause the breach is *incredible*.

In summary, the chances of even one POC becoming a missile and rupturing upon impact during a high wind event or tornado is considered *incredible*.

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