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DETONATION PROBABILITIES OF HIGH EXPLOSIVES

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ABSTRACT

The probability of a high explosive violent reaction (HEVR) following various events is an extremely important aspect of estimating accident-sequence frequency for nuclear weapons dismantlement. In this paper, we describe the development of response curves for insults to PBX 9404, a conventional high-performance explosive used in US weapons. The insults during dismantlement include drops of high explosive (HE), strikes of tools and components on HE, and abrasion of the explosive. In the case of drops, we combine available test data on HEVRs and the results of flooring certification tests to estimate the HEVR probability. For other insults, it was necessary to use expert opinion. We describe the expert solicitation process and the methods used to consolidate the responses. The HEVR probabilities obtained from both approaches are compared.

INTRODUCTION

Nuclear weapon dismantlement processes are currently of great importance to the US Department of Energy (DOE) because of nuclear weapon arsenal downsizing in both the US and former Soviet Union nations. Nuclear weapons contain high explosives (HE) and radioactive and toxic materials, providing the necessary conditions for the energetic release of these materials to the environment in accident conditions. The DOE is working to reduce the likelihood of accidents during weapon dismantlement through an integrated program of tooling, procedural, and training upgrades. A key part of this program is a concurrent and iterative hazard analysis of the dismantlement process. Insights gained from this analysis are available for the tooling and procedural designers to help minimize the likelihood of dismantlement accidents. Here we describe the development of probability estimates for the response of HE to possible insults during weapons disassembly. These estimates are used in the hazards analysis described in a companion paper (Bott and Eisenhawer, 1995).

The probability of a high explosive violent reaction (HEVR) for various insults is critically important to an analysis of weapon dismantlement safety. Many events can be postulated during dismantlement that can result in HE being dropped, abraded, or struck by another object. Without some idea of the probability of HEVR from such insults, the analyst must be overly conservative in his estimates of the frequency of accident conditions. This paper describes the development of probabilities of HEVR for relatively low-energy insults such as drops from moderate heights and strikes by relatively low-energy objects. The materials considered are the plastic-bonded explosives PBX 9404 and LX10 (Dobratz, 1981). They are similar high-performance conventional HEs used in US nuclear weapons. Here we specifically consider billets of explosives that have been machined into hemispheres.

A number of incidents resulting in an HEVR have occurred in the nuclear weapons complex. These incidents illustrate the relatively uncertain nature of the hazard posed by the PBX-based HE used in some nuclear weapons. An HEVR occurred in a weapons assembly plant in the United Kingdom when a billet being moved by forklift fell from the pallet onto a concrete floor. The height of the drop was only a few inches—much less than the median height for an PBX 9404 HEVR as the result of a 90° drop on a hard surface. It was realized that the critical factor was the frictional heat generated as the billet slid across the floor. This incident led to the inception of skid testing for HE. A similar HEVR also occurred at a burn pit at Los Alamos. It is speculated that the HEVR was a result of billets being dragged across a pickup bed or HE billets being thrown onto other billets with an HE-on-HE skid.

Except under very specific conditions associated with high-energy insults, it is not possible to estimate the probability of an HEVR directly from physical models. Two empirical

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED approaches to estimating HEVR probabilities were used. Our approach to estimating the probability of an HEVR is to favor the use of experimental data. Test data, when available, are a source of HE response data that is superior to expert opinion because the latter is subject to many biases. The manner in which the question is asked and any feedback that the questioners may have can bias experts in their opinion. In addition, the experts' opinion is based almost entirely on observations of HE tests tempered with some operational experience with HE. Often the probabilities that the analysts seek are beyond the direct experience of the expert and require difficult extrapolations or reliance on intuition, both notoriously unreliable sources of probability estimates (Reason, 1990). For this reason, the analysts have sought to extract as much data as can be obtained from what testing has occurred. However, the tests are not directly applicable to the scenarios of interest in most cases. One exception is the case where a billet falls onto *NIS* flooring—a specific floor used in areas where explosives are handled. The methodology used in this case is developed below. It was necessary to use expert opinion for the remaining scenarios.

ANALYSIS OF HIGH EXPLOSIVES TEST DATA

The data sources used in this study to estimate the probabilities of weapon responses include testing and experimentation, along with some operational experience. These data were taken from the raw data sources and from published summaries (Stull, 1986). A great deal of explosives safety testing has been conducted over the years as part of the nuclear weapons program. However, much of the data is not useful for the purposes of dismantlement hazards assessment for several reasons.

The insults to the HE encountered in weapon dismantlement are low compared with the energies at which the bulk of the testing has occurred. Safety testing has been concerned with establishing the relative sensitivities of different explosives, so the testing methods have concentrated on establishing the median drop heights for reaction. In addition, tests are often performed with high-friction materials, whereas actual conditions encountered in weapon dismantlement include floor coverings specifically designed to reduce friction heating of the HE.

Dismantlement drops typically occur from heights far below the median drop height for the HE-flooring pair of interest. Thus, a large numbers of drops would be needed to achieve reasonable confidence for the reaction probabilities at these heights. Such tests are expensive and cannot be performed in the numbers required to generate reaction probabilities at drop heights much below the median drop height. The different types of tests examined and their applicability to accident scenarios are discussed below. The tests deemed most appropriate for the analysis of insults during dismantlement were the skid, flooring certification, and spigot tests.

Skid tests are performed at both Los Alamos National Laboratory and at the Pantex facility near Amarillo, Texas, where US nuclear weapons are disassembled. The skid tests are designed to address the effect of friction when dropping HE billets. The tests are performed by lifting the HE billet and allowing it to free fall onto a surface typically covered with a silvered sandpaper. The velocity vector of the billet makes an angle of 45° or 14° with the normal to the strike surface. For a given height, sensitivity to detonation is usually greater at 14°. For PBX 9404, the median heights at 14° and 45° are 1.8 and 4.8 ft, respectively. The Los Alamos tests use a vertical drop and can be performed at heights up to 150 ft (45.7 m). The Pantex apparatus is a pendulum, and heights above 14.2 ft (4.3 m) pose problems, although a maximum of 28 ft (8.5 m) is possible. Skid tests can result in a variety of responses from no apparent effect to full-scale detonation. Several factors, such as sandpaper grit, substrate on which the sandpaper is attached, impact angle, drop method, HE configuration, and HE surface finish vary from one test series to the next. If any reaction occurs in PBX 9404 or LX10, it generally will be an HEVR, so we consider any test where a reaction was observed to be a positive. Also, for our purposes, nonresponses include tests in which the HE billet cracks or shatters on impact.[1]

Skid tests have been run on many HE formulations and on many surfaces, including the *NIS* flooring used in the cells and bays at Pantex. Most of the data have been collected using Brewston or Langlie test procedures (Mills, 1980). The purpose of these tests is to establish the median heights for an HEVR so data are sparse in the tails of the probability distribution function.

A special type of skid test is a flooring certification test. A Los Alamos certification test consist of dropping six specimens of HE from 20 ft (6.1 m) on flooring specimens that are oriented at an 45° angle. If none of the drops results in HEVR, the flooring passes the certification test. Pantex uses a similar certification procedure where 10 specimens are each dropped from 14 ft (4.3 m). In general, it is the case that if a flooring material is in use, it has passed one of these tests. However, there are cases in which a subsequent test of a certified flooring has resulted in an HEVR.

Spigot tests are performed by dropping an HE billet onto a large-diameter (~1-1/2 in.) projecting object. This test is intended to approximate dropping an HE hemisphere onto relatively sharp tooling. Strikes on very sharp objects are not addressed by these tests and may represent a more severe insult than the cases tested. This perspective is based on anecdotal experience where a skid test went awry and a billet struck a protruding nail on the pendulum support. Such sharp targets for HE strikes were not identified in the analysis of the dismantlement process. The spigot test data for 9404 were very limited and were not adequate for estimating HEVR probabilities for strikes by tooling and drops on tooling.

APPLICATION OF SKID TEST DATA TO HIGH EXPLOSIVE DROPS ONTO NIS FLOORING

A combination of skid test data on high-friction surfaces and NIS flooring certification data were used to construct a drop sensitivity curve for PBX 9404. The drop sensitivity curve is a function of drop height that specifies the probability that a specifically configured HE specimen will experience an HEVR

[1] Billets that fail on impact are not observed to undergo an HEVR.

when dropped from a given height. The basic approach used in this analysis involved two steps. The first step was to develop a baseline drop sensitivity curve for the high explosive striking sandpaper in a skid test. This type of test represents the bulk of the testing data at varying heights. This curve then was modified to account for the mitigating effects of the NIS flooring by assuming constant variance and determining the probability of reaction for drops on the flooring that would lead to the observed test data with a given level of confidence. The implications of these assumptions will be discussed below.

Although our primary interest was in the sensitivity of PBX9404, LX10 drop test data also were analyzed to obtain sensitivity curves for drops on flooring because of the similarity in median drop height for the two explosives.[2] This aggregation of data enlarges the database on which the estimates were based. The drop sensitivity curves were estimated based on the assumption that each test billet of HE has a threshold drop height (i.e., the minimum height from which a specimen of HE must be dropped to obtain an HEVR). These threshold drop heights are assumed to be distributed according to a two-parameter lognormal random distribution with parameters μ and σ. The parameters μ and σ are the mean and standard deviation, respectively, of the natural-log-transformed heights. These parameters are sometimes called the geometric mean and geometric standard deviation of the distribution. The antilog of μ is the median drop height, δ_{50}. A discussion of the lognormal distribution is given in Aitchinson (1963) and an early application of this distribution to HE sensitivity testing is described in the Statistical Research Group report (1944).

The drop sensitivity curve is the cumulative distribution function (CDF) of the random variable just described; i.e., the CDF gives the probability that a drop from a given height or less will result in HEVR. Thus, determination of a sensitivity curve is equivalent to estimating the values of μ and σ in a lognormal distribution.

The skid test data are assumed to be right- or left-censored observations from a lognormal distribution, depending on whether or not the test results in a violent reaction. The maximum likelihood (ML) procedure (Winkler and Hays, 1975) then is used to obtain estimates of μ and σ. A test series may or may not be useful for estimating μ and σ, depending on the outcomes of the tests and the range of drop heights used. If there are inadequate data to characterize the nonresponse and violent-reaction tails of the distribution, the ML procedure may not converge to a solution, or the estimates of μ and σ may have unacceptably high standard errors.

Data from standard skid tests using 10.4-kg hemispherical billets (Dobratz, 1981) at Los Alamos and Pantex with both PBX9404 and LX10 were used to develop the baseline drop sensitivity curve. By standard tests, we mean that standard weights of specimens, configurations, drop methods, and surfaces were used. For some of the data sets, special conditions were noted in the data sources—density of the HE (normal, high, and low), the surface condition of the HE (normal vs as pressed), the impact angle (45° for Los Alamos and 14° or 45° for Pantex), and other special conditions

As mentioned above, not all data sets proved to be useful for estimating μ and σ. However, data sets were not combined unless specific information from HE experts indicated that such combining would be proper. Combining data obtained under different conditions can result in invalid estimates of μ and σ and in general leads to higher estimates of HEVR for small drop heights. A summary of the skid test analysis is given in Table 1. Expert opinion concerning these data were supplied by Expert A, whose qualifications are discussed below.

The data sets above from which reasonable ML estimators could be derived were analyzed, and the results are shown in Table 2. Included are ML estimates of μ, σ and δ_{50} and the estimated standard error of the ML estimates of σ. Five data sets were deemed to be suitable for analysis based on the ML fit to the data and the standard error of the estimate of σ. The five selected data sets were used to fit a lognormal model with a different μ and a common σ for each set. The ML estimate of σ provided by this analysis is 0.515. The upper 95% confidence bound on σ also was calculated for use in determining a more conservative set of flooring sensitivity curves. The standard error associated with the combined estimate of σ is 0.095. The approximate 95% upper confidence bound on σ is $0.515 + 1.645 \times 0.095 = 0.671$. Note that we have used both 45° and 14° degree data to estimate σ.

An approximate likelihood ratio test was performed to test the null hypothesis that all five data sets came from populations with equal values of σ. The test failed to reject the null hypothesis ($p > 0.7$), so within these data, there is no evidence to contradict the assumption of a common σ.

The individual Los Alamos data sets listed in Table 1 are too small to provide good fits, so they were not used to provide estimates of σ. However, the Los Alamos high-, low-, and normal-density data sets were combined on the advice of HE experts and provided an estimate of $\sigma = 1.11$. Because this estimate is based on three sets of HE with different characteristics, the value of σ is believed to be conservatively large. This estimate, 1.11, is used to develop another third set of flooring sensitivity curves below.

METHODOLOGY FOR ESTIMATING FLOOR SENSITIVITY CURVES

As mentioned above, data do not exist to estimate flooring curves directly. That is, the tests were performed strictly for certification purposes and were never intended to provide estimates for μ and σ on flooring. Therefore, an indirect estimating method must be used. Such a method requires some important assumptions. First, as in the case of the other drop tests, we assume that a two-parameter lognormal model is appropriate. Second, it is assumed that the geometric standard

[2] PBX 9404 and LX10 show very similar sensitivity in all of the standard sensitivity tests.

TABLE 1
PBX9404 AND LX10 DROP SENSITIVITY SUMMARY

ID	Tests in Series	Material	Density	Specimen Wt.	Impact Angle	Surface	Comments
LANL-Nor	10	9404	Normal	N/A	45	Sand	From Expert A
LANL-Hi	10	9404	High	N/A	45	Sand	From Expert A
LANL-Lo	9	9404	Low	N/A	45	Sand	From Expert A
LANL-50	10	9404	N/A	N/A	45	Sand, 50-80	From Expert A
LANL-60	9	9404	N/A	N/A	45	Sand, 60-80	From Expert A
Combine	29	9404			45		Combined per Expert A
LLL45HB	49	9404	N/A	25 lb	45	Sand	LLNL Explosives Handbook Table 9.2
LLL14HB	41	9404	N/A	25 lb	14	Sand	LLNL Explosives Handbook Table 9.2
LLL45DB	57	9404	N/A	25 lb	45	Sand	Normal HE Surface
LLL45DB-33	11	9404	N/A	25 lb	45	Sand	Normal HE Surface, 33 Tilt
LLL45DB-AP	36	9404	N/A	25 lb	45	Sand	As-Pressed HE Surface
LLL14DB	37	9404	N/A	25 lb	14	Sand	Normal HE Surface
LLL14DB-AP	18	9404	N/A	25 lb	14	Sand	As-Pressed HE Surface
LLL14DB-AP33	18	9404	N/A	25 lb	14	Sand	As-Pressed HE Surface, 33 Tilt
LLL14DB-APBO	7	9404	N/A	25 lb	14	Sand	As-Pressed HE Surface, Boss Offset
LX45DB-Lo	10	LX101	Low	25 lb	45	Sand	
LX45DB	28	LX101	N/A	25 lb	45	Sand	
LX14DB	36	LX101	N/A	25 lb	14	Sand	

TABLE 2
STATISTICAL SUMMARY OF SKID TEST DATA

ID	Material	Impact Angle	μ	σ	δ_{50} (ft)	$E(\sigma)$	μ^*	δ_{50}^* (ft)
LLL45DB	9404	45	1.94	0.618	6.95	0.197	1.88	6.55
LLL45DB-33	9404	45	0.425	0.286	1.53	0.151	0.542	1.72
LLL14DB	9404	14	0.669	0.535	1.95	0.187	0.661	1.93
LLL14DB-AP33	9404	14	0.545	0.531	1.72	0.263	-0.556	1.74
LX45DB	LX101	45	1.37	0.303	3.93	0.147	1.54	4.66

Nomenclature: δ_{50} = median height for HEVR, $E(\sigma)$ = standard error of σ, μ^* = geometric mean with $\sigma = 0.515$, δ_{50}^* is the corresponding median height

deviations for all test surfaces are the same and that any test series provides an estimate of σ. The assumption that σ remains constant for various surfaces is equivalent to assuming that the ratios of pairs of quantiles remain constant. For example, the assumption would imply that the ratio of the 95th percentile to the median is the same for drops on sandpaper as it is for drops on flooring.[3] With this assumption, the skid test series for the sandpaper surface can be used to provide an estimate of σ. Third, we use an appropriately conservative upper bound on HEVR probability for 20-ft (6.1-m) (Los Alamos) or 14-ft (4.3-m) (Pantex) drops to establish a quantile of the flooring sensitivity curve.

Although we know that the flooring passed the certification test, we do not know the median drop height associated with the flooring. However, we can independently specify the probability that the observed result (i.e., no HEVRs) occurred. These probability values then are used to determine what quantile should be associated with 20 ft or 14 ft. For example, if the 50% bound is used (the probability that no HEVRs occurs during the certification series, $p_p = 0.5$) then, in the case of Los Alamos method, 20 ft is the 0.11 quantile, or the 11th percentile of the distribution [i.e., $(1 - 0.11)^6 = 0.5$]. Because σ is known (estimated), we can solve for an estimate of μ and thus define a lognormal distribution where we have specified σ and a confidence estimate, p_p, associated with passing the certification test. For $\sigma = 0.51$ and the 50% bound, μ is approximately 3.5 and the implied median drop height associated with the certification tests is 33 ft (10 m). Table 3 shows HEVR probabilities for a 3-ft (0.9 m) drop as a function of σ and p_p. A Bayes estimate of the HEVR probability, based on a uniform prior distribution, is also provided for each case. Subject to the assumptions described above, the curves based

[3] Although a reasonable statistical hypothesis, it was not possible to verify it independently from the available data nor were we able to construct a strong argument based upon physical models for its validity.

on the 50% bound and the Bayes uniform prior can be considered to be best guesses. The curves based on the 95% and 99% bounds are conservative. It is important to note that all flooring materials certified by a given laboratory will have identical sensitivity curves because they undergo identical certification procedures with identical results.

The results above are based strictly on a value of p_p with no additional information concerning a possible subsequent HEVR during recertification. However, as noted earlier, an HEVR during recertification was observed.[4] We specifically consider two exceptions. For the first, the study assumes that 10 drops from 14 ft (4.3 m) resulted in successful certification, with no HEVRs, and that at a later time an 11th drop results in an HEVR. The second exception assumes that 6 drops from 20 ft (6.1 m) resulted in successful certification, with no HEVRs, and that a subsequent 7th drop results in an HEVR. Table 4 gives the HEVR probabilities for these cases with the same values of σ and as in Table 3. The effect of the HEVR is, as expected, to increase the probability of an HEVR at 3 ft.

For a 14-ft drop-height certification, the HEVR probability, p_r, associated with a 3-ft drop ranges from 3.5×10^{-6} to 0.07, depending on the combination of values for σ, the value of p_p, and the presence or absence of an observed HEVR after certification. The range for a 20-ft drop-height certification is $4 \times 10^{-7} < p_r < 0.09$. The wide ranges result mainly from the uncertainties that exist because of the lack of suitable data for determining flooring sensitivity curves directly. The best estimate for σ and one detonation gives a 3-ft probability of $p_r = 2 \times 10^{-4}$ for $p_p = 0.05$. This large interval was unacceptable for use in a hazard assessment, and we chose to specify a conservative set of parameters to obtain a point estimate. To begin, only the case where a post-certification HEVR was observed was used (Table 4). In addition it was felt that the confidence in passing the certification should be high, say 95%, so $p_p = 0.05$ was considered appropriate. We also chose to use a value of $\sigma = 0.67$, using a 95% confidence interval. Finally, the value of μ is the average for both drop test methods. With these choices, the estimate for the probability of an HEVR resulting from a 3-ft drop onto *NIS* is $p_r = 3 \times 10^{-3}$. Figure 1 shows the HEVR probability as a function of height for these parameters for no detonation and for one detonation with the best estimate value of $\sigma = 0.51$. Figure 1 indicates that, for explicit choices of σ and p_p, we can reasonably estimate p_r for a given drop height within an order of magnitude.

EXPERT ELICITATION ESTIMATES OF HE SENSITIVITY CURVES

For other insults of interest, the data were inadequate to use a statistical analysis, and we turned to elicitation of expert opinion. Originally, we planned to interview the selected experts all at one time; however, because of logistical problems, it was necessary to interview them separately. The thought processes used by the experts were widely different, but the results had a consistency that surprised us. Each expert's estimate is discussed individually in the following sections. The complete set of questions posed to the HE experts was long. A sample set of the questions asked is presented in Table 5. This set is representative of the classes of HE insults in the accident scenarios encountered in the nuclear weapon dismantlement HA. Note that Question 1.1 is the case considered in the previous section. The questions were discussed in detail with the experts. In some instances a particular expert was familiar with the accident scenario associated with a particular insult. In this case we tried to ensure that only the HE response probability, not the probability associated with the chain of events culminating in the HE insult, was being estimated.

One of the vagaries of expert elicitation is the wide variability among experts arising from their personalities and experiences. Each of the experts consulted in constructing the drop sensitivity curve for PBX 9404 is discussed separately so that the reader may gain some appreciation for their varying expertise and viewpoints. All the experts were familiar with the testing methods and knew the median drop heights for normal and skidding impacts.

Expert A. Expert A has years of experience in testing and working with PBX-based HE such as 9404. Expert A has conducted and reviewed many tests conducted for sensitivity of HE including skid test, drop-weight tests, and spigot tests among others. Expert A has participated in expert elicitation for previous nuclear weapon HAs and was familiar with the requirements of the analysts. Expert A answered all questions without hesitation once the question was understood.

Expert A expressed estimates for the standard set of HE insults as a band of probabilities that either covered 2 orders of magnitude or was stated as a probability of "less than 10^{-6} (per occurrence)." We thoroughly explored the meaning in Expert A's mind of the two endpoints of the probability band. The

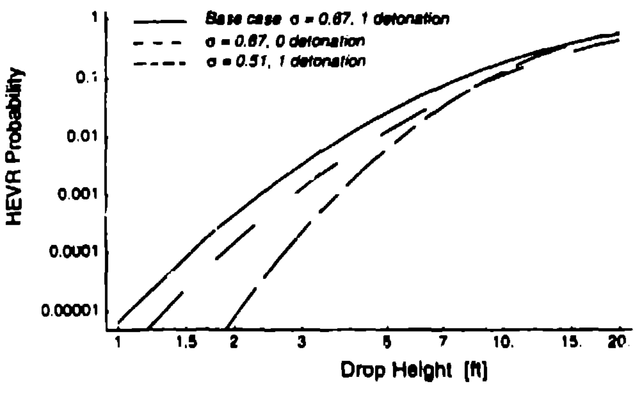

FIG. 1. PROBABILITY OF AN HEVR AS A FUNCTION OF DROP HEIGHT ON *NIS* FLOORING. CURVES ARE BASED UPON 95% CONFIDENCE LEVEL FOR CERTIFICATION TEST, $p_p = 0.05$ AND USE AN AVERAGE μ DERIVED FROM THE TWO DROP TEST PROCEDURES.

[4] The circumstances surrounding this result are not totally understood because of changes made in the composition of the flooring in question.

TABLE 3
PROBABILITY OF HEVR ON NIS FLOORING

σ	Method	$P_p = 0.5$		$P_p = 0.05$		$P_p = 0.01$		Bayes	
		μ	P_r(3 ft)	μ	P_r(3 ft)	μ	P_r(3 ft)	μ	P_r(3 ft)
0.51	LANL	3.62	3.8E3	3.14	3.[illegible]E-5	3.05	6.5E-5	3.58	5.7E-7
0.51	Pantex	3.39	3.5E-6	2.97	1.2E-4	2.81	4.0E-4	3.36	4.6E-6
0.67	LANL	3.82	2.4E-5	3.18	9.5E-4	3.06	1.7E-3	3.77	3.3E-5
0.67	Pantex	3.63	7.9E-5	3.07	1.6E-3	2.86	4.3E-3	3.58	1.1E-4
1.11	LANL	4.36	1.6E-3	3.31	2.3E-3	3.11	3.5E-2	4.27	2.1E-3
1.11	Pantex	4.28	2.1E-2	3.35	2.1E-2	3.01	4.2E-2	4.20	2.6E-3

TABLE 4
PROBABILITY OF HEVR ON NIS FLOORING WITH RE-CERTIFICATION HEVR

σ	Method	$P_p = 0.5$		$P_p = 0.05$		$P_p = 0.01$		Bayes	
		μ	P_r(3 ft)	μ	P_r(3 ft)	μ	P_r(3 ft)	μ	P_r(3 ft)
0.51	LANL	3.38	3.8E-6	2.97	1.2E-4	2.81	4.0E-4	3.34	5.4E-6
0.51	Pantex	3.17	2.4E-5	2.82	3.7E-4	2.68	9.6E-4	3.13	3.4E-5
0.67	LANL	3.50	1.7E-4	2.96	2.7E-3	2.75	6.7E-3	3.45	2.2E-4
0.67	Pantex	3.34	4.1E-3	2.87	4.1E-3	2.69	8.8E-3	3.29	1.21E-3
1.11	LANL	3.82	7.1E-3	2.94	4.85E-2	2.59	8.9E-2	3.74	8.7E-3
1.11	Pantex	3.80	7.5E-3	3.03	4.1E-2	2.72	7.2E-2	3.71	9.3E-3

TABLE 5
WEAPONS RESPONSE SAMPLE QUESTIONS

1. High Explosive Drops

1.1. A bare hemisphere falls 3 ft on *NIS* with a skidding impact

1.2. A bare hemisphere in nylon mesh bag falls 3 ft onto *NIS* with a skidding impact

2. High Explosive Strikes

2.1. A clamp weighing 1/4 lb. falling 2 ft strikes sharp edge on a bare hemisphere

3. High Explosive Abrasion

3.1. A 1/4 lb adiprene-coated clamp is slided by hand with no forcing across the equatorial surface of the hemisphere.

higher probability was clearly a high-confidence upper bound, probably between 90% and 99%. The lower number was less certain. It seemed to represent a value somewhat below the median but clearly well above a lower 1% or 10% bound. We chose to express this lower value as between a 30th and 40th percentile. The estimated lower bound often lies closer to the median in expert elicitation. This phenomenon has been encountered by other workers in eliciting quantitative estimates of probabilities (Reason 1990). It seemed in this case to be connected with a strong desire to make sure the upper bound was not too optimistic. Expert A compensated for his upper-bound conservatism by raising the lower bound to a slightly optimistic best estimate.

Expert B. Expert B has many years of experience in testing and working with PBX-based HE such as 9404. Expert B had not participated in expert elicitation for previous HAs and was initially unfamiliar with the requirements of the hazards analysis. He was reluctant to express his opinions in terms of probability ranges and preferred to provide estimates in terms of a median drop height. Expert B stated that the probability distribution was lognormal and estimated σ. We explored the meaning in Expert B's mind of σ. It seemed to represent the relative variability of the data normalized for the value of the mean. Following a discussion of variance in various experiments he had performed, a log variance of 0.5 was used for all of Expert B's estimates. This value is somewhat greater than that generally observed in a single series of skid tests but is reasonable when similar groups of tests are grouped together. Note that this is quite close to the ML value for σ found in the previous section. From this information, the analysts were able to convert his estimates into probabilities of HEVR for the various scenarios. Expert B did not attempt to answer questions relating to strikes on HE.

Expert C. Expert C has years of experience in the chemistry of PBX-based HE such as 9404 and has conducted a large number of HE sensitivity tests including skid tests. Expert C had not participated in expert elicitation for previous hazards assessments and was initially unfamiliar with the requirements of the hazards analysts. Expert C expressed estimates for the standard set of questions in a qualitative manner. Expert C's estimates covered only a small subset of the standard questions and served as mainly a relative ranking. In addition, Expert C's answers helped identify questions for which there was agreement or disagreement among the experts. Expert C's responses were not in a form that could be used to calculate probability estimates.

Expert D. Expert D is a colleague of Expert A and has similar, albeit somewhat less extensive, expertise relating to sensitivity of PBX-based explosives. He has participated in expert solicitation for previous hazards assessments and is familiar with the process. Expert D provided responses to all of the questions. His responses were given in terms of probability ranges, and confidence estimates were provided. The probability bands were relative probability bands of 10, 15, and 100. Some estimates were also given as " less than 10^{-6}." Expert D stated that the lower end of the band represented the 0.25 quantile and the upper bound was at 0.75. These could be fit exactly to a two-parameter lognormal distribution. For his less than 10^{-6} estimates, Expert D declared a confidence of 0.70.

Combined Estimates from Expert Opinion

In this section we discuss our approach to obtaining combined probability estimates from the expert solicitation. To be useful in an HA, it is necessary to have not just a point estimate of p_r for each insult but also some description of the uncertainty associated with it. We begin by considering the probability estimates of Experts A and D because these were expressed in a similar manner. From the confidence estimates provided, we constructed a set of cumulative distribution functions (CDFs) assuming that the underlying probability distribution was log normal. This distribution seemed consistent with the experts' orders-of-magnitude probability range. In any case, it was determined that the results were relatively insensitive to the choice of underlying distribution function. The CDFs shown in Fig. 2 represent the experts' confidence that the probability of an occurrence of a particular event is less than or equal to a certain value. The abscissa is normalized in terms of relative probability, p_{rel}. Relative probabilities were used because both experts used probability intervals. For Expert D, two CDFs are shown corresponding to p_r intervals of 1 and 2 orders of magnitude. The CDF for Expert D's relative probability, p_{rel} = 10 case, (his most frequent estimate) is very close to Expert A's p_{rel} = 100 case. That is, μ and σ are quite close—the medians of these two distributions are approximately 3 (relative probability), σ is about 1.5, and the mean is approximately 8. The agreement on the relative ranking of the various hazards (in the complete list of questions) was very strongly correlated. In this case, the two experts discussed the various questions after Expert A had provided his estimates but before Expert D's responses. Thus, it is not clear whether these estimates are actually independent or represent some intermediate consensus. We have chosen to disregard this issue here. For the cases where the probability was estimated as less than 10^{-6}, we fit this to a lognormal with the 0.7 quantile corresponding to this probability and with

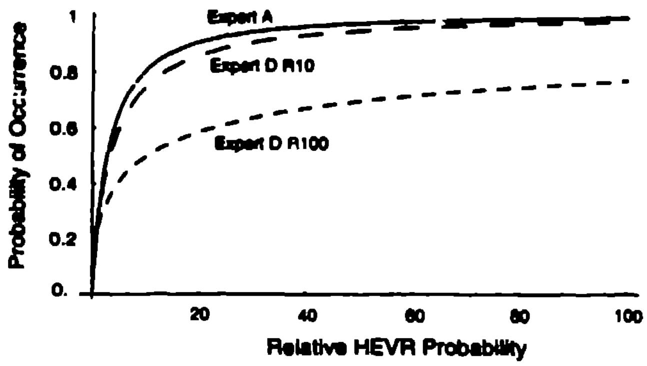

FIG. 2. CUMULATIVE DISTRIBUTION FUNCTION (CDF) FOR HEVR FOR EXPERTS A AND D. ORDINATE REPRESENTS THE CUMULATIVE CONFIDENCE IN THE HEVR PROBABILITY ON THE ABSCISSA.

the geometric standard deviation for Expert D's 1-order-of-magnitude probability band (σ = 1.76). This results in a mean of 2×10^{-6} and a median of 4×10^{-7}. Note that although we have considerable information about these experts' confidence in their probability estimates, we actually cannot construct a sensitivity curve for any of the insults. Rather we know only what quantile from four separate probability distributions (two for each expert) corresponds to a particular value of the specified insult.

As noted above, Expert B took a different approach. He defined a separate response curve for each insult by using a constant σ and varying the value of the median drop height. The problem here is that we have no estimate for the uncertainty associated with this specification for the median. To combine these estimates with the others, it was necessary to establish some confidence measure. We chose to use a CDF for the confidence in the probability estimate assuming that Expert B's values corresponded to a best estimate (median) and with a value of σ that was the average of Experts A and D's.

Table 6 gives the results of the expert solicitation for the three questions given in Table 5. For Experts A and D, we list the upper probability estimate for HEVR and the range in orders of magnitude between it and the lower estimate. For Expert B, the median height and the associated 0.5 quantile probability are given. The qualitative comments from Expert C also are included. The final columns show the combined mean and median probabilities. The relative ranking by all of the experts is the same here; this was also true for the complete set of questions with only a couple of exceptions. Only in the cases of skidding drops of a bare hemisphere or of one in a nylon bag were the probabilities of an HEVR significant. The large spread between the mean and median for Question 1.1 results from the fact that Expert D increased his confidence interval by an order of magnitude with a corresponding increase in the variance.

TABLE 6
SUMMARY OF EXPERT OPINION RESPONSES FOR HEVR SCENARIOS

HE Insult	Expert A		Expert B		Expert C	Expert D		Final Probabilities	
	Range	Pmax	Median height ft	Pr		Range	Pmax	Mean	Median
1. HE Drops									
1.1. Bare HE drops to 3 ft onto NIS	2	1.E-01	20	8.E-05	*Concerned about shock or heat build-up—would require friction heating for reaction*	2	5.E-02	0.2	6E-03
1.2. Bare HE in mesh dropped onto NIS 3 ft.	2	1.E-02	40	1.E-07		1	1.E-03	7E-04	3E-04
2. HE Strikes									
2.1. Bare HE: Clamp of 1/4 lb falling 2 ft. sharp edge.		<1.E-06			*Concerned about impacts on bare HE, i.e., tool drops*		<1.E-06	2E-06	4E-07
3. HE abrasion									
3.1. Bare HE, hand sliding 1/4 lb adiprene-coated clamp across HE surface with no forcing.		<1.E-06			*Low level of concern with clamp insertion. <1.E-06*			2E-06	4E-07

Comparison of HEVR Probabilities for a Drop on Flooring

As noted earlier, two different methods were used to estimate the probability of an HEVR for the case of a hemisphere falling onto NIS flooring. Recall that when the skid test data are used directly, it is necessary to assume that σ is a constant and to specify p_p. From Fig. 1, we estimate the probability of an HEVR for a 3-ft drop as $10^{-4} < pr < 5 \times 10^{-3}$. The upper end of this range is based on a value of $p_p = 0.05$ and includes the HEVR during recertification. The corresponding value based on expert opinion is 6×10^{-3}; this is the median. We note also that Expert B's estimate of the median for a reaction is exactly the standard Los Alamos test height. This would imply that the probability of the flooring passing the Los Alamos test was only $p_p = 0.015$. Although we cannot quantify it, the relatively high probabilities estimates from Experts A and D also must correspond to a low probability that the flooring would pass the certification test. Each of these experts was familiar with the HEVR during recertification. In this one case where our two separate approaches can be compared, the results are very similar.

CONCLUSIONS

Probabilities of reaction for low-energy mechanical insults to PBX 9404 were developed using a combination of test data and expert opinion. In constructing a sensitivity curve for drops on flooring, it was necessary to use skid test data for sensitivity on a high-friction surface to estimate the variance of underlying lognormal distribution. We assume that this variance is also applicable to drops on flooring. This assumption is critical to the analysis. Then for a specified *a priori* probability that the flooring passes the certification test series, a lognormal probability distribution can be constructed. This distribution is consistent with the available test data and addresses explicitly the problem of a later HEVR during recertification testing. For other insults, it was necessary to use expert opinion. Probabilities from the experts are combined using CDFs that represent the confidence that the individual experts have in their estimates. The probability estimates for an HEVR for a 3-ft drop on NIS flooring obtained using both methods are similar. The methods used in this analysis are applicable to other types of explosives and the data are usable for other weapons that use PBX 9404 or LX 10 explosives.

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