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ON THE USE OF CONFIDENCE LEVELS IN RISK MANAGEMENT

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Summary

A framework for incorporating uncertainty in risk management is developed and applied to two aspects of decision making: meeting standards or safety goals, and cost—benefit criteria. The framework is applied to several case studies including toxic chemicals in water, failure of civil engineering structures and nuclear power plants. The framework proposes that decisions be based on a level of confidence, in addition to comparing best estimate or point values with standards and goals.

Introduction

At the present time, there is heightened interest in developing quantitative standards for technologies which pose a hazard to the public. As an example, the Nuclear Regulatory Commission (NRC) has published a proposed policy statement on safety goals for nuclear power plants [1]. Other U.S. governmental agencies such as the Environmental Protection Agency (EPA) and the Food and Drug Administration (FDA) must regulate against quantitative standards set forth in such legislation as the Clean Air Act, the Clean Water Act and the Delaney Clause.

Because of the statistical nature of technological risk, probabilistic risk assessment (PRA) plays an increasingly important role in risk management. PRA is, however, limited by uncertainty inherent in the underlying data, uncertainties in understanding various physical phenomena, and uncertainties in the methodology itself. As a result of uncertainty as well as the statistical nature of risk, the results of PRAs vary in their quality of information. The results of some PRAs are given as mean or median values, while others are given as statistical distributions. Some propagate uncertainties, while some perform sensitivity studies to obtain limiting cases. As a result, it is difficult to determine the appropriate quantity for comparison with a standard or for use in a cost—benefit consideration.

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In this paper, two aspects of risk management are considered: meeting standards or safety goals and cost—benefit criteria. The framework developed here aims to provide the risk manager with information on uncertainty in addition to the use of point or best-estimate values in decision making. In particular, quantitative levels of confidence with which estimated risks meet standards or goals is examined. The framework is also extended to cost—benefit considerations in an effort to determine levels of confidence at which benefit exceeds cost as a prelude to regulatory action.

Framework

Risk and uncertainty

The concept of risk involves a mathematical combination of two components: the consequences resulting from an undesirable event and its frequency of occurrence. Such consequences may include the number of injuries, an amount of money lost, acute deaths, latent cancer deaths, and property damage (e.g., occurrence of system failure, amount of land contaminated, etc.). Frequency can be given as the number of undesired events per year or exposure per year. For some events, such as those described by actuarial data, the risk may be obtained by simply multiplying the consequences and the frequency. It can be expressed as individual or societal risk. For others, the risk may be estimated and represented by either a mean value or a statistical distribution. These estimates are usually based on models and supported by empirical data.

Inherent in any probabilistic risk assessment (PRA) are various uncertainties. These uncertainties may be due to (a) the statistical nature of data, (b) insufficient understanding of physical and biological phenomena, and (c) unpredictable events (e.g., natural, biological and human behavior). The statistical distributions that represent the risks of hazardous material usually, but not extensively, include (a) and (b) above. The unpredictable events, such as sabotage, etc., are not easily quantified and represent "unquantified residuals" [2]. When statistical distributions are derived, mean and median values can be estimated.

The relationship between mean value risk (best-estimate), degree of confidence and a safety goal can be described as follows. Consider a hypothetical PRA leading to a statistical distribution for some measure of risk given by $p(x)\mathrm{d}x$. For example, if x represented the number of latent cancer deaths per year,

$$\overline{X} = \int_0^\infty p(x)\mathrm{d}x \qquad (1)$$

would be the mean value of the risk of latent cancer death. If a safety goal for latent cancer death were given by X_g, then the probability of meeting this goal would be

$$P_r(x < X_g) = \int_0^{X_g} p(x)\mathrm{d}x \tag{2}$$

This integral is the probability that the risk is less than the goal and is defined as the "degree of confidence" with which the risk in question meets the goal, when expressed as a percentile. Mathematically, it defines a point on a cumulative distribution function, and is determined by integration of the statistical distribution. The median value, X_m, is defined by

$$0.5 = \int_0^{X_m} p(x)\mathrm{d}x \tag{3}$$

Before proceeding however, it is important to mention the following. If $p(x)\mathrm{d}x$ were determined with great precision, eqn. (2) would, in fact, define the confidence level. Since $p(x)\mathrm{d}x$ is determined from models which are uncertain, eqn. (2) represents an estimate of confidence. As mentioned in the Introduction, it is usually $\overline{X}$ or X_m that is compared with a standard or goal. When these values differ greatly from X_g, the risk manager's decision may be obvious; when they are close to X_g, and in the presence of uncertainty, eqn. (2) provides additional information upon which to base a decision.

Cost—benefit and confidence levels

A second consideration facing the risk manager is the question of whether or not the risks posed by the presence of a hazardous material should be reduced. Such considerations are usually dealt with using cost—benefit trade-offs. Within the context of PRA, costs are usually characterized in monetary terms and include both the direct cost of the change (e.g., equipment and labor) as well as indirect costs (e.g., increased operating costs, increased occupational health risks, etc.).

If benefits (in terms of reduced risks) are to be compared directly with costs, they must be expressed in equivalent monetary terms. Since equivalency is often controversial (e.g., placing a dollar value on a human life saved), surrogate benefits are often considered. An example is the use of population dose averted (with respect to radioactive material), valued at $1000 per person-rem averted. The population dose is used as a surrogate for all health effects, and sometimes property damage. In either case, the formalism outlined above can be extended to cost—benefit trade-offs as follows.

The risk, R_i, corresponding to the ith consequence of interest (e.g., acute fatalities, acres of land contaminated, etc.), and reported at the Cth confidence level is defined as R_i^c, and is given by

$$C \equiv P_r(R_i < R_i^c) = \int_0^{R_i^c} p(R_i)\mathrm{d}R_i \tag{4}$$

When changes are made to avert risk, the benefit, ΔR_i can also be expressed at a given confidence level [3]

$$C \equiv P_r(\Delta R_i < \Delta R_i^c) = \int_0^{\Delta R_i^c} p(\Delta R_i^c)\mathrm{d}R_i \tag{5}$$

If the total cost of a given risk reduction strategy is C_0 (costs usually have much less uncertainty than risk, and hence can be considered point values), and L is the time span of the change, then the given strategy is "cost-effective" when $\Delta R_i > C_0/L$. The degree of confidence that the strategy is cost-effective is just

$$P_r(\Delta R_i > C_0/L) = \int_{C_0/L}^{\infty} p(\Delta R_i)\mathrm{d}R_i \tag{6}$$

The annualized cost, C_0/L, can account for the "time value" of money as well as other effects (e.g., escalation during construction, etc.) and can be discounted according to accepted accounting procedures. The benefit is assumed to be expressed in equivalent dollars as noted in the discussion above. When uncertainty in cost becomes important, it can also be accommodated by defining the "net benefit" as $NB \equiv \Delta R_i - C_0/L$. The risk reduction strategy will then be cost effective when

$$P_r(NB > 0) = \int_0^{\infty} P(NB)\mathrm{d}NB \tag{7}$$

Inferring levels of confidence

To ascertain the practicality of using levels of confidence to augment the risk management of hazardous materials, two questions should be considered: (1) to what extent can acceptable confidence levels be inferred over a variety of risk situations? and (2) how might these values be applied to decisions regarding the management of hazardous materials?

Examples

Structural design standards

In the design and analysis of civil engineering structures, "factors of safety" are provided to account for the uncertain nature of the loads, the structural properties, and the models used. Traditionally, safety or load factors (numbers greater than one) were applied to the design load and resistance factors (numbers less than one) were applied to structural properties to insure conservatism. These factors were based on engineering judgments: experience, perception, and intuition.

More recently, probabilistic distributions have been used to characterize uncertainties in loads and structural properties. As an illustration, consider a single structural component acted upon by a random load. The load induces a stress, S, which has a statistical distribution. The yield stress of the material is also considered a random variable, denoted by R, and a new random variable $F = R - S$ can be defined. When $F < 0$, failure of the structural component occurs. Note that if S and R were deterministic, i.e., always had the same value because of certainty, failure would be defined by the deterministic variable $F = R - S < 0$.

In practice, R and S are usually defined by normal distributions with parameters

$$\overline{F} \equiv \overline{R} - \overline{S} \tag{8}$$

and

$$\sigma_F^2 = \sigma_R^2 + \sigma_S^2 \tag{9}$$

where the bar denotes expected value (mean or best-estimate) and σ is the standard deviation. Hence, the probability of failure is just

$$P_{\mathrm{f}} = P_{\mathrm{r}}[F \leqslant 0] = \int_{\infty}^{0} p(f)\mathrm{d}f \tag{10}$$

where $p(f)$ is a normal distribution whose parameters are $\overline{F}$ and σ_F.

Before discussing values of P_{f} or $1 - P_{\mathrm{f}}$, which is called the reliability, it is convenient to introduce three other useful parameters. The central safety factor, C_0, is defined by

$$C_0 \equiv \overline{R}/\overline{S} \tag{11}$$

and measures the ratio of mean strength to mean load. The coefficients of variation are defined by

$$\zeta_R \equiv \sigma_R/\overline{R} \qquad \zeta_S \equiv \sigma_S/\overline{S} \tag{12}$$

and measure the spread in the distributions. Note that as any σ approaches zero, the load or resistance becomes deterministic.

Lastly, the reliability index, β, is defined by the number of standard deviations $\overline{F}$ is from $F = 0$

$$F = 0 = \overline{F} - \beta\sigma_F$$

or (13)

$$\beta = \frac{\overline{R} - \overline{S}}{\sqrt{\sigma_R^2 + \sigma_S^2}} = \frac{\overline{F}}{\sigma_F}$$

The reliability index, β, is useful in that it accounts for the relative difference between $\overline{R}$ and $\overline{S}$ (as does the safety factor), as well as the narrowness of the distribution (as does the coefficients of variation). High values of β can be attributed to conservatism in design ($\overline{R} \gg \overline{S}$) or good statistical data (small σs).

Hart [4] gives plots of P_f, the failure probability, for various coefficients of variation as a function of the central safety factor. The question of acceptable values of P_f (and of β) is resolved by examining current civil engineering practice. Hart [4] gives the following commonly accepted values:

strength failures: $P_f = 10^{-4}$, $\beta \simeq 3.5$
serviceability failures: $P_f = 10^{-2}$, $\beta \simeq 2.0$

For a number of different probability distribution functions, P_f values of the order of 10^{-2} correspond to safety factors of 1.4—2.2 and P_f values of the order of 10^{-4} to safety factors of 2.4—3.0 and above.

Ellingwood and Galambos [5] give a range for the reliability index, β, based on current criteria for the design of reinforced concrete and steel beams. Values of β range between 2.3 and 4.0 for a wide variety of conditions. (Coefficients of variation range from 0.10 to 0.30 for most cases.)

For example, in geotechnical engineering, Meyerhoff [6] lists the following minimum safety factors:

Category	Item	Safety factor
Loads	Dead loads	0.9—1.2
	Live loads	1.0—1.5
	Static water pressure	1.0—1.2
	Environmental loads	1.2—1.4

These values correspond to a 90% reliability; i.e., to have a confidence level of 0.9, the best-estimate load should be less than its limiting value by 20% and 50% for dead loads and live loads, respectively. For stability of earthen structures and foundations, safety factors of 1.9—3.3 were found to yield a reliability of 99%. Here, the goal is set at factors of 2—3 above the median value to achieve a confidence level of 0.99. These values can be used in one of two ways. In the first, one can say that the current practice of using safety factors (ratio of standard or goal to mean value of risk) of 1.0—1.5 and 1.9—3.3 yields confidence levels 0.90 and 0.99, respectively. In the second, one can make a statement concerning the narrowness of the distribution, namely, for a confidence level of 0.90, the standard and mean should be less than 50% apart. For a confidence level of 0.99, they should be less than a factor of 3 apart.

Toxic chemicals

A recent study by Solomon et al. [7] compared the risks posed by several selected chemical carcinogens with two standards. The comparisons were as follows. For each comparison, two measures were considered: some actual risk (defined as operational risk), determined empirically or assumed to occur at the regulated standard value and some specific or generic safety standard.

TABLE 1

Inferred confidence levels for selected toxic chemicals

Chemical	Annual risk	$P_r(R_i < R_g)$	
		EPA goal (1.4×10^{-8}/yr)	NRC goal (1.9×10^{-6}/yr)
DDT	1.5×10^{-7}/yr	0.02	0.98
Dieldrin	7.1×10^{-10}/yr	0.95	0.99
Vinyl chloride	1.8×10^{-9}/yr	0.76	0.99

Of particular interest here are the risks of selected carcinogens in drinking water and their comparison with EPA guidelines, as well as the NRC's proposed guideline for latent cancer deaths. For waterborne chemicals, the EPA guidelines designate a mean lifetime risk of 1.0×10^{-6} or 1.4×10^{-8} per year, assuming a 70-year lifetime. The NRC, on the other hand, has suggested a goal for latent cancer as 0.1% of the background cancer risk or 1.9×10^{-6} cancer deaths per year. Drinking water samples were obtained from an eleven-city sample, and a statistical study was performed to convert these to lifetime risks using the Safe Drinking Water cancer risk estimates [8]. These risks were then converted to annual figures and, using a normal distribution, levels of confidence were inferred with respect to the EPA (1.4×10^{-8} per year) and NRC (1.9×10^{-6} per year) guidelines. These results are shown in Table 1.

Examination of Table 1 shows that, for the selected chemicals, the estimated level of confidence in meeting the proposed NRC goal is quite high (0.98 or greater) for each case. As expected, the level of confidence in meeting the EPA goal is smaller, because the goal is more stringent. The confidence level for DDT is very small because the mean annual risk is greater than the EPA goal. However, it meets the NRC goal.

Levels of confidence in nuclear reactor safety

The assessment of nuclear reactor accident risks is carried out within the framework of probabilistic risk assessment. In general, probabilistic risk assessment (PRA) is a quantitative estimate of the consequences and frequency (probability) of a set of accident sequences, including an estimate of their uncertainty given as a statistical distribution. Although WASH-1400 [9] attempted to estimate the accident risk at nuclear power plants by calculating the frequencies of various accident sequences for two typical reactors (a PWR and a BWR) and their attendant consequences (at a composite site), the treatment of uncertainty was not emphasized.

In the Zion [10] and Indian Point [11] PRAs, an attempt is made to quantify uncertainty. Results are presented for various measures of risk (including core-melt frequency) and uncertainty given in terms of upper (90%) and lower (10%) confidence bounds. This uncertainty analysis includes both internal and external initiators, but not such things as sabotage. Because the results of these PRAs are well documented, they are used extensively in this paper for illustrative purposes. It should be emphasized that no attempt was made to evaluate the methodology used in obtaining these results, their confidence limits, or their completeness.

The NRC safety goals

The policy statement and proposed numerical guidelines proposed by the NRC for nuclear power plants are composed of four basic parts [1]:

(1) A criterion for the frequency of core-melt.
(2) Limits on individual and societal risk of prompt (acute) death.
(3) Limits on individual and societal risk of latent (cancer) death.
(4) A cost-effectiveness criterion in terms of cost per person-rem averted beyond compliance with the goals above.

In this section, the core-melt criterion and the limits on societal risk for both prompt and latent deaths are examined. Societal risk is chosen over individual risk because the available PRAs specify risks for the population in the 50-mile radius surrounding the site.

The safety goals used in this analysis are:

(1) The frequency of core-melt should not exceed 1.0×10^{-4} per year.
(2) The risk to the population in the vicinity of a nuclear power plant site of prompt fatalities that might result from reactor accidents should not exceed 0.1% of the sum of prompt fatility risks resulting from other accidents to which members of the U.S. population are generally exposed.
(3) The risk to the population in the area near a nuclear power plant site of cancer fatalities that might result from reactor accidents should not exceed 0.1% of the sum of cancer fatality risks resulting from all other causes.
(4) Further risk reduction should be undertaken if the cost is less than $1,000 per person-rem averted (out to 50 miles).

In applying this guideline, the Commission proposes that, for societal risk of prompt death, the area within one mile of the plant site boundary be used. For latent (cancer) deaths, a 50-mile radius should be used to determine the latent risk limits, as follows:

The individual risk of prompt fatality in the U.S., regardless of cause, is about 5.0×10^{-4} per year [1]. Hence, the goal requires that the societal risk be less than 0.001×10^{-4} per year $\times$ population within one mile of the site.

The population within one mile of the 111 U.S. nuclear power plant sites ranges between 0 and 1400 persons, with 168 as an average. Using 168,500 and 1000 gives the limit for prompt (acute) risk as

$168 \sim 1.0 \times 10^{-4}$ d/yr
$500 \sim 3.0 \times 10^{-4}$ d/yr
$1000 \sim 5.0 \times 10^{-4}$ d/yr

Since the Zion and Indian Point sites are in densely populated areas of the country, 5.0×10^{-4} deaths per year is chosen as the limit for prompt (acute) death.

Roughly 19 persons per 10,000 U.S. population die of cancer each year [1]. Hence, the goal requires that the societal risk of latent death be less than $0.001 \times 19 \times 10^{-4}$ per year $\times$ population within 50 miles of the site. The population within 50 miles of a nuclear plant ranges between 7700 and 17.5 million. Because the Zion and Indian Point sites are the most populated in the country, 17.5 million is used here, yielding a risk limit of 33 cancer deaths per year.

These numerical guidelines can be summarized as follows for the Zion and Indian Point sites:

Limit on core-melt frequency:	1.0×10^{-4} events per year
Limit on societal risk of prompt (acute) death:	5.0×10^{-4} deaths per year
Limit on societal risk of latent (cancer) death:	33 deaths per year
Limit on cost effective risk reduction:	1000 per person-rem averted

The Zion/Indian point PRAs

In order to illustrate the use of the level of confidence concept in risk management for nuclear power plants, estimates for core-melt frequency and the societal risk of early (acute) and latent (cancer) death are derived from the PRAs for Zion and Indian Point.

For Indian Point Units 2 and 3, the median, mean and upper 90% confidence values of core-melt frequency are given. For the Zion plant, only the mean value is given for total core-melt frequency. Hence the median and upper 90% confidence limit are estimated from the probability distribution function given for externally induced core-melt frequency. These are shown in Table 2.

For the Zion and Indian Point sites, the societal risk for five damage indices are given in the PRAs as a set of complementary cumulative distribution functions (CCDF). Moreover, for each damage index, the CCDF is shown at the 10th, median (50th) and 90th percentile confidence limits. The mean risk at each percentile can be obtained by calculating the area under the CCDF curve. These results are shown in Table 3.

TABLE 2

Core melt frequency for three plants

Core-melt frequency (per year)	Indian Point		Zion
	Unit 2	Unit 3	
Median	4.0×10^{-4}	9.0×10^{-5}	2.2×10^{-5}
Mean	4.7×10^{-4}	1.9×10^{-4}	6.7×10^{-5}
Upper 90%	1.0×10^{-3}	5.5×10^{-4}	2.0×10^{-4}

TABLE 3

Societal risks for three plants

Confidence level	Risk of acute death (deaths per year)		
	Indian Point 2	Indian Point 3	Zion
0.1	5×10^{-7}	5×10^{-8}	–
0.5	2×10^{-6}	7×10^{-6}	5×10^{-7}
0.9	5×10^{-4}	4×10^{-5}	5×10^{-5}
Confidence level	Risk of latent death (deaths per year)		
	Indian Point 2	Indian Point 3	Zion
0.1	3×10^{-3}	1×10^{-3}	1×10^{-3}
0.5	1.5	8×10^{-2}	5×10^{-2}
0.9	10	1	5×10^{-1}

Estimate of level of confidence

To determine the confidence, the various measures (core-melt frequency, risk) should be specified probabilistically. Since statistical distributions are not given, it is assumed for illustrative purposes that the various risk measures are log-normally distributed. Moreover, to test the sensitivity to an assumed distribution, the Weibull distribution is also used.

It should be noted that the log-normal and Weibull distributions used are two-parameter distributions and only two data points are necessary for curve fitting. For acute and latent deaths, three data points are given. Since the high confidence end is of interest, the median (50%) and 90% values are used. If the distributions were truly log-normal (or Weibull), the 10% values would be close to the curve. Since this closeness only occurs in one case, the true distribution is not log-normally distributed.

The log-normal distribution function has the useful property that, when the cumulative distribution function is plotted against the logarithm of the argument on "normal curve" graph paper, a straight line results. Moreover, the point where the (complementary) cumulative distribution function equals 0.5 occurs where its argument is the median value. Similarly, if a variable conforms to a Weibull distribution, it becomes a straight line when plotted on "extreme value" probability paper. The degree of confidence is the ordinate of the intersection of the cumulative distribution function with the NRC numerical guidelines (safety goals) calculated for this study. Table 4 demonstrates the level of confidence for the three risk measures obtained in this manner.

TABLE 4

Level of confidence for Zion and Indian Point

Reactor	Median risk	Log-normal	Weibull
Core-melt frequency (Safety goal: 1×10^{-4} per year)			
IP No. 2	4×10^{-4} per year	0.03	0.10
IP No. 3	9×10^{-5} per year	0.52	0.53
Zion	4×10^{-5} per year	0.72	0.75
Societal risk — acute deaths (Safety goal: 5×10^{-4} deaths per year)			
IP No. 2	2×10^{-6} deaths per year	0.900	0.9000
IP No. 3	7×10^{-6} deaths per year	0.999	0.9999
Zion	5×10^{-7} deaths per year	0.970	0.970
Societal risk — latent deaths (Safety goal: 32 deaths per year)			
IP No. 2	1.5 deaths per year	0.980	0.98
IP No. 3	0.08 deaths per year	0.999	0.9999
Zion	0.05 deaths per year	0.9998	0.99999

Results

If the risk estimates were, in fact, described by the log normal or Weibull distributions, the level of confidence would be the confidence with which the safety goal were met. For core-melt frequency, this level of confidence is small for Indian Point 2 (3—10%), because neither the mean nor median value meet the goal. For Indian Point 3, the confidence level is approximately 52% because the median and mean are on both sides of the goal (0.9×10^{-4} and 1.9×10^{-4}, respectively). For Zion, the confidence in meeting the core-melt frequency goal level is between 72 and 75% depending upon the distribution.

For the societal risk goals, one would be 90% confident that Indian Point 2 met the safety goal for acute (early) deaths; for Indian Point 3 and Zion, one would be 97% confident or greater. For latent (cancer) death, one would be 98% confident or greater that the safety goal would be met for all three plants.

The above results also demonstrate a property of these distributions: as the confidence range gets greater (above 50%), the difference in the two distributions becomes negligible. At the low end, they tend to differ. The above analysis demonstrates that, in addition to comparing a mean or median value (point estimate) with a safety goal, one can determine a level of confidence if a distribution is available.

At this point, it is of interest to compare these results with the results presented for the civil engineering structures and the toxic chemicals. For the societal risk measures (both acute and latent), the high degree of confidence compares favorably with the risks due to a range of toxic chemical species. For core-melt frequency, the results are less comparable. In addition to examining the level of confidence, it is useful to examine other aspects of the statistical distribution of core-melt.

For civil engineering structures, the use of the safety factor and reliability index as other measures for including uncertainty was discussed. Recall that the safety factor was defined as the ratio of the mean strength to the mean load, and the reliability index as the distance in standard deviations from failure. In this case, the safety goal can be considered as the mean strength and is deterministic with no deviation. The load is core-melt frequency with mean deviation.

One can construct the following table for core-melt frequency from the data available.

Reactor	Median	One sigma value (84%)	Safety goal
IP No. 2	4.0×10^{-4}	8.0×10^{-4}	1.0×10^{-4}
IP No. 3	9.0×10^{-5}	3.7×10^{-4}	1.0×10^{-4}
Zion	2.2×10^{-5}	1.7×10^{-4}	1.0×10^{-4}

In every case, the value at one standard deviation (σ) is greater than the safety goal. Hence β, the reliability index, will always be less than one, illustrating the relatively large degree of uncertainty in the distributions for core-melt frequency. This result is in contrast to commonly accepted values found in the civil structures literature, where the median plus 2σ values are less than the limiting condition.

One can examine the ratio of the upper 90% confidence bound to the mean to quantify the narrowness of the distribution. In addition, the ratio of the upper 90% confidence bound to the goal measures the closeness of the distribution to the goal. For the estimates of core-melt frequency there obtains the following table.

Reactor	90% value/mean	90% value/goal
IP No. 2	2.1	10
IP No. 3	2.9	5.5
Zion	2.9	2.4

The first column is similar to the coefficient of variation, which for civil structures is usually less than unity (0.1—0.6).

As an alternative, the safety factor concept can be applied. If the frequency specified by the safety goal (1.0×10^{-4} per reactor year) is divided by the mean value (best-estimate) for core-melt frequence, an analogous "safety factor" can be defined. This is shown in the following table.

Confidence	Type	Safety factor (Goal/mean)
0.03—0.01	I.P. 2[a]	0.25
0.52—0.53	I.P. 3[a]	1.1
0.72—0.75	Zion[a]	2.5
—0.90	Soil load	1.0—1.9
—0.99	Soil stability	1.9—3.3

[a]Ratio of safety goal to median core-melt frequency.

By comparing these two results, it would appear that a safety factor of ~ 3 corresponds to a confidence in risk estimate of 0.9 for core-melt frequency. Hence, in the absence of a distribution function, a risk manager might employ a safety factor to insure some degree of confidence, or account for uncertainty that is not quantified.

Cost—benefit considerations

Cost—benefit trade-offs are used by decision managers as an aid in determining whether or not action should be undertaken. In most cases, costs have much less uncertainty then benefits when the latter is expressed in terms of risk averted. As an example of the framework developed in this paper, a risk reduction option (a filtered vented containment system) is considered for the boiling water reactor (BWR) considered in the Reactor Safety Study [9]. Such a system is assumed to perfectly eliminate containment failures due to overpressurization following a core melt accident.

The Reactor Safety Study gives the frequency of each possible radioactive release category at the 5th, 50th and 95th percent confidence levels. These are shown in Table 5. The consequences corresponding to each radioactive release category are given in Table 6. If the risk reduction option is implemented, it will remove the BWR 2, BWR 3 and BWR 4 release categories.

TABLE 5

BWR release categories reflecting uncertainty in frequency with no FVC[a]

Release category	Frequency		
	5%	50%	95%
BWR 1	1×10^{-7}	1×10^{-6}	8×10^{-6}
BWR 2	1×10^{-6}	6×10^{-6}	3×10^{-5}
BWR 3	5×10^{-6}	2×10^{-5}	8×10^{-5}
BWR 4	5×10^{-7}	2×10^{-6}	1×10^{-5}
BWR 5	1×10^{-5}	1×10^{-4}	1×10^{-3}

[a]Taken from Draft WASH-1400 [9].

TABLE 6

Consequences of individual release categories (composite site)

Type	Average[a]		
	Man-rem ($\times 10^6$)	Acute fatalities	Damage (\$ $\times 10^9$)
BWR 1	2.2	1.7	1.2
BWR 2	1.8	48	1.2
BWR 3	0.89	3.0	0.61
BWR 4	0.42	3.9	0.28
BWR 5	0.19	1.1	0.10

[a]Average over population and meterological conditions, assuming accident occurs with unit probability, i.e., given the accident.

TABLE 7

Risk reduction (benefit) for peachbottom using a filtered vented containment

Risk averted	Confidence level		
	5%	50%	95%
Acute deaths per year	65×10^{-6}	355×10^{-6}	172×10^{-5}
Latent deaths per year	13×10^{-4}	59×10^{-4}	26×10^{-3}
Man-rem per year[a]	6.5	13.4	129.0
Man-rem per year[b]	60	140	1300
Off-site property damage per year	\$4.4 $\times 10^3$	\$20. $\times 10^3$	\$8.8 $\times 10^4$

[a]Draft, WASH-1400, Table VI-21. Average site.
[b]High population site.

TABLE 8

Probability that the benefit is greater than the cost

Risk averted	$P_r(\Delta R > C_0/L)$
Man-rem (draft WASH-1400, using \$1000/man-rem averted)	0.40
Man-rem (high population site using \$1000/man-rem averted)	0.95
Property damage (draft WASH-1400)	0.45
Total costs averted (health effects and property damage)[a]	0.55

[a]Draft WASH-1400 values.

The reduction in risk can then be determined as shown in Table 7.

The results shown in Table 7 indicate that the dominant contributors to benefit are man-rem averted and off-site property damage averted. The costs for simple low and high volume vents (using the suppression pool as a scrubber) have been estimated at \$0.9 × 10^6 and \$1.2 × 10^6, respectively, by Benjamin [12]. Using a thirty year effective life and the higher cost, C_0/L is \$40,000 per year. Using a log-normal distribution, eqn. (6) can be evaluated for each risk averted. The results are shown in Table 8.

Table 8 indicates that, using the original RSS data, the probability that the total benefit is greater than the cost is 0.55. For the high population site, the probability is 0.95 when only man-rem is considered at the high population site.

Summary and conclusions

Most policy statements specifying standards or goals for hazardous material contain both qualitative goals and numerical guidelines. The numerical guidelines are singular values; limits on individual and societal risk of acute and latent death, limits on concentration of material, limits on core-melt frequency; and, possibly, limits on cost—benefit.

Rather than trying to meet a goal or standard with a median or mean value, a more appropriate question might be: *How confident should one be that this guideline is met?*

In order to establish a quantitative response to this question, PRAs should specify statistical distributions for each measure of risk (or at a minimum upper and lower confidence limits) so that a measure of confidence can be determined. If a quantitative level of confidence is to be determined, uncertainties which are quantifiable should be propagated through PRAs and the risk should be presented as statistical distributions rather than as median values.

In an effort to address the practicality of using levels of confidence, various risks were examined. Based on a limited survey, it appears that a high level of confidence (90% or more) would reflect conservatism to account for uncertainties which are not easily quantified or may be unquantifiable.

One may wish to consider other parameters, such as a reliability index or a safety factor, which are related to the width of the statistical risk distribution. The data presented in this paper were limited, and can provide only a limited basis for making a quantitative recommendation. The reliability index is a useful quantity because it includes both the relative width of the distribution and the separation between a goal and mean. For the nuclear cases examined, the reliability index was always less than unity, while current civil engineering practice yields values of the order of 2—4 for various structures. The safety factor, however, gives a relationship between a goal and the mean value independent of the spread of variance. As such, one would expect, for safety situations whose variance in outcome is similar to structural failures following soil load and soil stability mishaps, that a safety factor of about

2.0—3.0 might be reasonable. However, because the variance associated with the frequency of a core-melt accident is higher*, a larger safety factor is expected. While a precise value for this safety factor for core-melt cannot be selected at present, values between 2.5 and 5 appear to be comparable to 90—99% confidence. Supportively, it turns out that the data on core-melt frequency indicates that the core-melt risk as the 90th percent confidence level is always within a factor of 10 of the goal and within a factor of 3 of the mean.

In the absence of a statistical distribution, uncertainty can be included by a safety factor (roughly defined as the ratio of the safety goal to the best-estimate or mean risk). At this point, sufficient information is lacking to support a firm quantitative value for all measures of risk. However, a safety factor of 2.5—5.0 appears to be appropriate for core-melt frequency.

In summary, an alternative approach for the consideration of a goal or standard has been presented. It is based on requiring that a goal be met at a certain level of confidence. By examining some nonnuclear and nuclear risks, it appears that such an approach is practical providing sufficient information is given. Moreover, there appears to be a basis for requiring that goals be met at a high degree of confidence.

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*That is to say, the uncertainty distribution for the core-melt situation is likely to be wider (flatter) than the corresponding distribution in the soil load and soil distribution cases.