EFFECT OF COMPLIANCE PERIOD ON PERFORMANCE ASSESSMENT RISK METRICS: PEAK-OF-THE-MEAN, MEAN-OF-THE-PEAKS, AND CUMULATIVE RELEASE

R. W. Rice
SRT, Inc.
P.O. Box 13208
El Paso, Texas 79913-3208

J. C. Walton
Environmental Science and Engineering
University of Texas at El Paso
El Paso, Texas 79968

ABSTRACT

The behavior of a disposal system site with hazardous and radioactive wastes is quantitatively evaluated in a risk assessment using the risk metrics of peak-of-the-mean, mean-of-the-peaks, and cumulative release. These metrics are commonly used to estimate risk and demonstrate compliance allowing the site to obtain an operating license. Compliance may be determined according to satisfying a regulatory standard that includes a time period of interest such as a compliance period. This paper evaluates the effect of the compliance period on risk metrics of peak-of-the-mean, mean-of-the-peaks, and cumulative release using a simplified model. The model includes the following parameters: waste container failure, release from a disposal site, and transport of the release with retardation to a receptor. Monte Carlo sampling is used to investigate the impacts of uncertainty on the risk predictions. The sampling accounts for uncertainty within the disposal system and utilizes probability distribution functions for the modeled parameters. Risk predictions are determined for a range of compliance periods and the effect of the compliance period on these performance assessment risk metrics is quantitatively demonstrated. The results are normalized with respect to a containment time that is characterized as spanning conditions from poorly contained to well-contained. The results from the analysis indicate that the compliance period should be greater than the containment time for the disposal system Risk predictions for each metric are stable and accurate when the compliance period is greater than the containment time for the disposal system. If the compliance period is less than the containment period, risk predictions using these metrics can be unstable and inaccurate.

INTRODUCTION

The predictions from a risk assessment must meet regulatory requirements for the type of contamination at a site and are typically made based upon one or more performance metrics. Common risk metrics, which are determined from an assessment of exposure of a receptor to contamination, include peak-of-the-mean, mean-of-the-peaks, or cumulative release. Performance metrics can be classified as related to maximally exposed individual risk or to long-term population risk. Individual risk is determined by peak exposure/peak concentration, whereas population risk is related to the total or cumulative release of contaminants from a site.

There has not been a general quantitative analysis of risk predictions and factors that impact those risk predictions, such as compliance period, reported in the literature. The risk guidance and policy of the U.S. Environmental Protection Agency (EPA) states the importance of evaluating uncertainty in PRAs (1,2). Codell et al. (3) present a discussion of the sensitivity of risk predictions for the peak-of-the-mean metric. A number of studies discuss the importance of separating uncertainty and variability. These studies also offer examples of approaches to separate uncertainty and variability (4,5,6,7,8,9).

This paper offers a perspective that quantitatively assesses how risk predictions for a metric are affected by the compliance given uncertainty in the behavior of the disposal system. Furthermore, the analysis investigates the behavior of risk metrics by determining the most stable and accurate metric at predicting risk. Stability of the risk metric relates to its behavior over a range of factors such as uncertainty and containment time. Accuracy of the risk metric is its ability to predict the “true” risk.

The primary purpose of this work is to better understand the behavior and limitations of risk assessment projections and how they relate to the structure of regulations. In setting a risk-based regulatory standard, many choices are available. What metric will be codified in the regulation? Will a regulatory time period (i.e., a compliance period) be specified or must models be run for indefinite time periods? This work represents an initial attempt to address these issues.

DESCRIPTION OF RISK METRICS

Three performance metrics are chosen for investigation in this work: peak-of-the-mean, mean-of-the-peaks, and cumulative release. There are other possible performance metrics (10,11), but these three metrics are common and consequently investigated in this work. In this work, the peak-of-the-mean and the mean-of-the-peaks metrics are determined using release rates. However, these two metrics could also be considered as measures of the dose rate since release rates can be converted to dose rates using a multiplicative factor that takes the ultimate use of the contaminated water into account (i.e., a dose model). Therefore, the results presented in this work for the performance metrics, which are determined from release rates, can be interpreted as risks.

The peak-of-the-mean is determined by calculating the mean release rate at each time step from all realizations and then determining the peak value of that mean release rate. The peak-of-the-mean metric factors into the estimate of risk both the probability that a particular individual will be exposed and the extent the individual is exposed.

The mean-of-the-peaks is calculated by averaging the peak release rates from all Monte Carlo realizations. This metric is useful for regulations written in terms of the risk to any individual exposed to releases from the disposal system, regardless of the time at which the individual is exposed.

The cumulative release metric is determined by integrating the release from each realization over the time period of interest (e.g., the compliance period). This metric is most useful for calculating risk to populations over the compliance period.

MODELING APPROACH

For the purposes of this paper, a highly simplified model was developed to assess the performance of a disposal system. The simplicity of the model demonstrates the behavior of risk predictions for the three metrics without confounding effects from a more complicated model. The conceptual model considers releases from the disposal system to the receptor and consists of near-field and transport factors.

A FORTRAN program was developed and tested to simulate this conceptual model using Monte Carlo sampling of probability distributions for these near-field and transport factors. The near-field factors are the time of container failure and the first-order release rate constant. Transport factors are the groundwater travel time and retardation coefficient. These four factors are general and, because the factors are modeled stochastically, may be considered "lumped" parameters whose probability distributions encompass detailed processes.

Releases to the receptor are calculated assuming that once a container fails, the contaminant release is directly proportional to the amount of the contaminant remaining in the container (i.e., a first-order release rate model). The released material is then transported to the exposed individual assuming plug flow of the contaminant, a retardation factor for the contaminant, steady state flow, and a first-order reaction that could represent hydrolysis, biodegradation, or radioactive decay.

The general equation used to compute the release rate to the receptor, $R\,(t)_{receptor}$, accounts for the near-field factors (k and t_{fail}) and transport factors (t_{gwtt} and r_d):

$$R(t)_{receptor} = 0 \qquad for \quad t < t_{fail} + t_{gwtt} r_d \qquad \text{(Eq. 1)}$$

$$R(t)_{receptor} = k\, e^{-k\left[t - \left(t_{fail} + t_{gwtt} r_d\right)\right]}\, e^{-\lambda t} \qquad for \quad t \geq t_{fail} + t_{gwtt} r_d \qquad \text{(Eq. 2)}$$

where,

t	=	time [T]
k	=	release rate constant [1/T]
λ	=	decay constant (= ln(2)/$t_{1/2}$) [1/T]
$t_{1/2}$	=	half-life [T]
t_{fail}	=	time of container failure [T]
t_{gwtt}	=	groundwater travel time [T]
r_d	=	retardation factor [ ]

The release rate constant, container failure time, groundwater travel time, and retardation factor are sampled stochastically and used in Eqs. 1 and 2 to calculate $R\,(t)_{receptor}$. The means and the associated variances of these four parameters and model variables are assigned values in units based on a containment time. The containment time is defined as the sum of the mean time required for a container to fail and the mean time for the release to arrive at the receptor using the mean values for each parameter. The variables and parameters in Eqs. 1 and 2 are defined with respect to the containment time [T] to make them non-dimensional. This approach allows the results to be interpreted in the useful context of the protection afforded by natural barriers and engineered barriers of the disposal system.

The contaminant half-life is defined as a fraction of the containment time. Releases are calculated for three contaminants differentiated by half-life, but with the same retardation. The values of the three half-lives are 0.1, 0.5, and 2.5 of the containment time. The half-life of 0.1 represents a "well contained" contaminant, because basically all of the contaminant decays or biodegrades (i.e., 10 half-lives) prior to being released into the environment. The contaminant with a half-life of 2.5 is classified as "poorly contained", because there is little decay or biodegradation prior to being released into the environment.

Values of the four near-field and transport factors are also defined with respect to the containment time. Both near-field and transport factors are assumed to contribute equally and each delays the release by one-half of the containment time. Therefore, the mean container failure time is set at one-half of the containment time, while the mean groundwater travel time is specified as 0.05 of the containment time with a mean retardation factor of 10. Consequently, using mean values, the transport factors account for one-half of the containment time, since the transport travel time is the product of the groundwater travel time and the retardation factor.

Similarly, the mean value for the release rate constant is set at a value that results in 50% release at 0.25 of the containment time for a conservative (i.e., nondecaying) contaminant. Furthermore, this mean value of the release rate constant also yields 75% and 94% releases at 0.50 and 1.0 of the containment time, respectively.

UNCERTAINTY

The implications of not having perfect knowledge for the parameters are quantitatively evaluated in this paper with "uncertainty," and compared to the nominal case. The nominal risk is defined, for the purposes of this paper, as the deterministic peak impact calculated using mean values for all parameters and is intended to represent the actual or true risk from the site.

"Uncertainty" is a lack of complete information for a parameter and is modeled as an increase in the variance. As more information becomes available (e.g., experiments are conducted), the uncertainty decreases and the variance of the parameter would also decrease. In this analysis, the "uncertainty" in a parameter is modified using a factor that is multiplied by its variance. A factor of zero corresponds to zero uncertainty. In a risk analysis, it is common to identify parameters that have the greatest impact on the performance measure (i.e., are the most sensitive) and devote resources to decrease their uncertainty in order to move the analyses closer to the actual behavior of the disposal system. However, there are instances when decreasing the uncertainty can yield a higher estimate of risk, depending on the metric. These instances are counter-intuitive and result in what is known as "risk dilution".

COMPLIANCE PERIOD

A compliance period is the time span over which the regulatory criteria are in effect. This work evaluates the performance of a disposal system over a range of compliance periods using the peak-of-the-mean, the mean-of-the peaks, or cumulative release metrics. The approach examines the effects of zero-to-low-to-medium-to high uncertainties on performance for well-contained to poorly-contained contaminants.

The reference compliance period is specified to be equal to one containment period. This value is used since the compliance period and containment time should be approximately the same order of magnitude. That is, good engineering practices dictate that the repository would be designed for substantial containment of the waste during the regulatory period. The calculations determine the three performance metrics for eleven different compliance periods that range from 0.1 to 2 times the reference compliance period.

SIMULATIONS

The distributions provided in Table I are input values for Eqs. 1 and 2. Monte Carlo simulations with 4,000 realizations were conducted and yield release rates at times from 0 to the maximum simulation time at time steps equal to 0.002 of the containment time. Convergence testing suggested 4,000 realizations were a reasonable number for convergence of these Monte Carlo results.

The maximum simulation time equals 10 times the longest half-life, which is 2.5 times the nominal containment time. The nominal containment time consists of equal contributions from nominal values for the container failure time and the contaminant transport time (i.e., the product of the groundwater transport time and the contaminant retardation factor).

The performance metrics for the peak-of-the-mean, mean-of-the-peaks, and cumulative release are calculated at different levels of uncertainties. Values specified for "uncertainty" in the simulations using eleven uncertainty factors are multiplied by the variances in Table I. These values are 1.00, 1.25, 1.55, 1.93, 2.41, 3.00, 3.74, 4.66, 5.80, 7.22, and 9.00. The eleven compliance periods are 0.1, 0.28, 0.46, 0.64, 0.82, 1.0, 1.2, 1.4, 1.6, 1.8, and 2.0 times the reference compliance period which is equal to the containment time.

Output from simulations includes 121 sets of values for each of the three performance metrics representing all possible combinations of the 11 uncertainties and 11 compliance periods. Each value is the performance metric calculated over the simulation time for a particular uncertainty and compliance period is the logarithm (base 10) of the ratio of the performance metric with respect to its nominal value calculated over the simulation time for the reference compliance period. Thus, a value of 1.0 is interpreted as a one order-of-magnitude overestimation of the nominal value for that performance metric. Similarly, a value of -3.0 is interpreted as a three order-of-magnitude underestimation of the performance metric with respect to the nominal risk.

Table I. Sampled parameter means and variances specified as a fraction of the compliance time, T.

Sampled Parameter (mean units)	mean*	base variance**
Release rate constant [1/T]	2.75	0.002
Container failure time [T]	0.5	0.002
groundwater travel time [T]	0.05	0.002
retardation factor [ ]	10.0	0.002

* arithmetic mean value of the sampled distribution
** variance of logtransformed values of the sampled distribution

EXPLANATION OF RISK METRIC RESULTS

Figs. 1 and 2 show the release rates for a subset of the first 50 of the 4,000 realizations and represent Points A and B, respectively. As discussed in the previous section, these points are one of the 121 sets of values that are output from simulations. The difference between Point A and Point B is the uncertainty. Point A models “zero” uncertainty, whereas Point B models a “high” uncertainty with a factor of 7.22 applied to the parameter variances.

The release rates are plotted as a function of the number of containment times ranging from 0.3 to 25. The mean release rate and the peak-of-the-mean, mean-of-the-peaks, and cumulative release rate performance metrics for those 50 realizations are also presented. These figures illustrate the relationship between release rates for each realization, the mean release rate, and the performance metrics. The relationship among the performance metrics is also shown. Figs. 1 and 2 utilize the same scales for the horizontal and vertical axes, which facilitates a comparison of the results. Figure 3 is the same as Figure 1 except the “Number Containment Time” axis is expanded to show individual release rates.

In both figures, although it is more apparent in Figure 1, releases begin at about two containment times. Releases rates are significantly more variable for Point B, where uncertainty is high, than for Point A, where there is zero uncertainty, as evidenced by the saw-tooth pattern for the Point B mean release rate. The peak-of-the-mean for Point B is entirely determined by one realization with an early release rate. Although it is difficult to observe in Figure 1, because of the relatively narrow ranges of release rates, but clearer in Figure 3, a number of realizations contribute to the peak-of-the-mean for Point A. Comparing Figure 1 with 2 indicates how increasing uncertainty increases the separation between individual peak releases. This increased separation yields a lower peak-of-the-mean release rate that is mostly determined by the peak for the largest individual realization since the other peaks are not superimposed. This example shows how increased uncertainty, which is often characterized as a “conservative” assumption, leads to a decrease in the predicted risk or “risk dilution”.

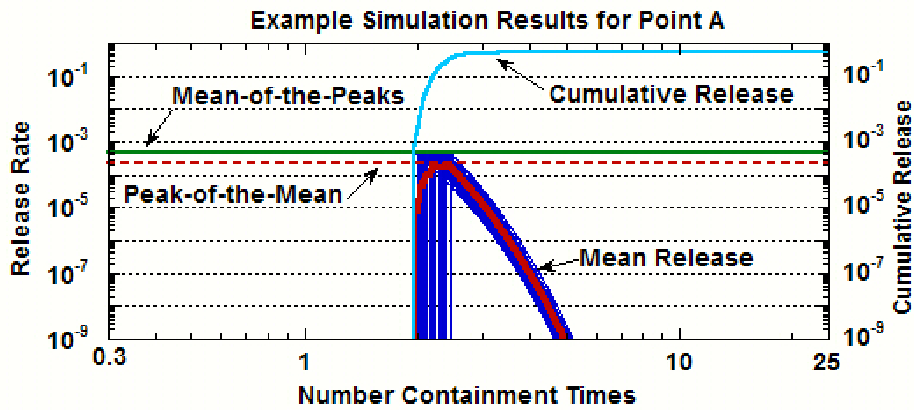

Fig. 1. Release rates from 50 realizations showing the peak-of-the-mean, mean-of-the-peaks, and cumulative release for Point A with "zero" uncertainty.

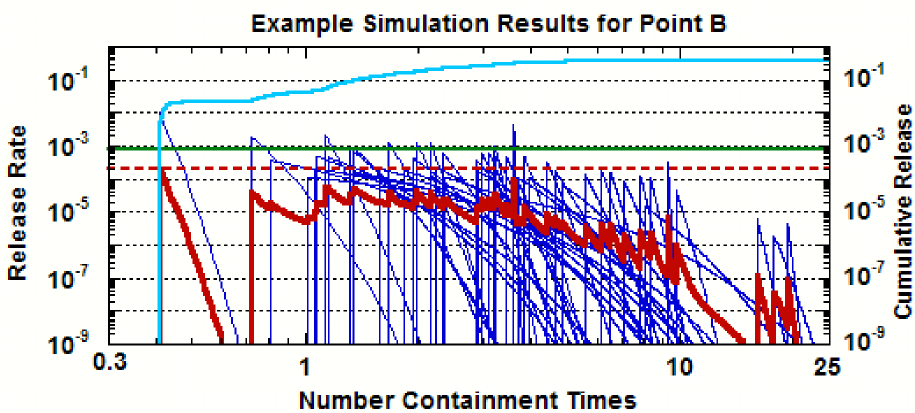

Fig. 2. Release rates from 50 realizations showing the peak-of-the-mean, mean-of-the-peaks, and cumulative release for Point B with "high" uncertainty (i.e., a factor of 7.22 is applied to parameter variances).

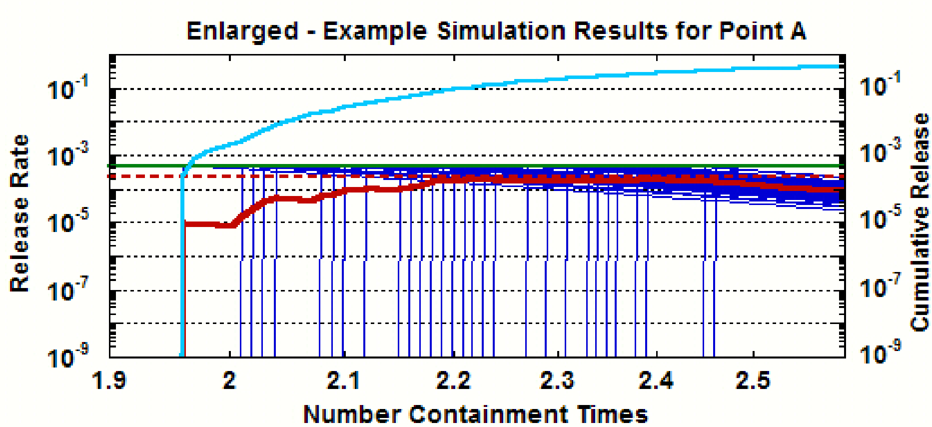

Fig. 3. Enlargement of the "Number Containment Time" axis for Fig. 1.

The mean-of-the-peaks in Figures 1 and 2 is greater than the peak-of-the-mean because the time that the peak occurs is irrelevant for this metric. The difference between the mean-of-the-peaks and the peak-of-the-mean is greater for Point B than for Point A because the former metric is insensitive to the time of the peaks, while the latter is sensitive. Note that if the peak releases all occurred at the same time, the mean-of-the-peaks and the peak-of-the-mean would be equal.

The cumulative release utilizes the same scale as the release rates. Comparing the cumulative release metrics in Figures 1, 2, and 3 reveals a stability that is not dominated by release rates from individual realizations (i.e., there is no saw-tooth pattern in the individual release rates) even though the uncertainty changes from "zero" to "high". This is in contrast to the peak-of-the-mean metric which is dominated in this case by a single realization and to some extent to the mean-of-the-peaks metric shown in Figure 2 that appears to be determined by about five relatively large realizations. These results suggest that the cumulative release metric is the most stable of these performance metrics.

RESULTS AND DISCUSSION

Simulation output is plotted and contoured in figures. The effects of a particular value for the compliance period is provided in Figure 4 for the peak-of-the-mean, mean-of-the-peaks, and cumulative release performance metrics. The regulatory compliance time period is set equal to multiples of the nominal containment time period.

The results show changes in the risk predictions with increasing uncertainty. The most significant observations from the results in this figure are in regard to the risk predictions for compliance periods greater than and less than the containment time. When the compliance period is less than the containment time, each of the three performance metrics underestimates the predicted risk with respect to the nominal risk, which in some instances can vary significantly with increasing uncertainty. When the compliance period is greater than the containment time, the risk prediction is approximately equal to the nominal risk and risk predictions show less sensitivity as uncertainty increases. If the compliance period is greater than the containment period, the risk prediction is more stable and closer to the nominal risk. Additionally, all three-performance metrics behave similarly when the compliance period is greater than the containment time showing a much smaller dependence upon the ratio of the contaminant decay rate relative to the containment time.

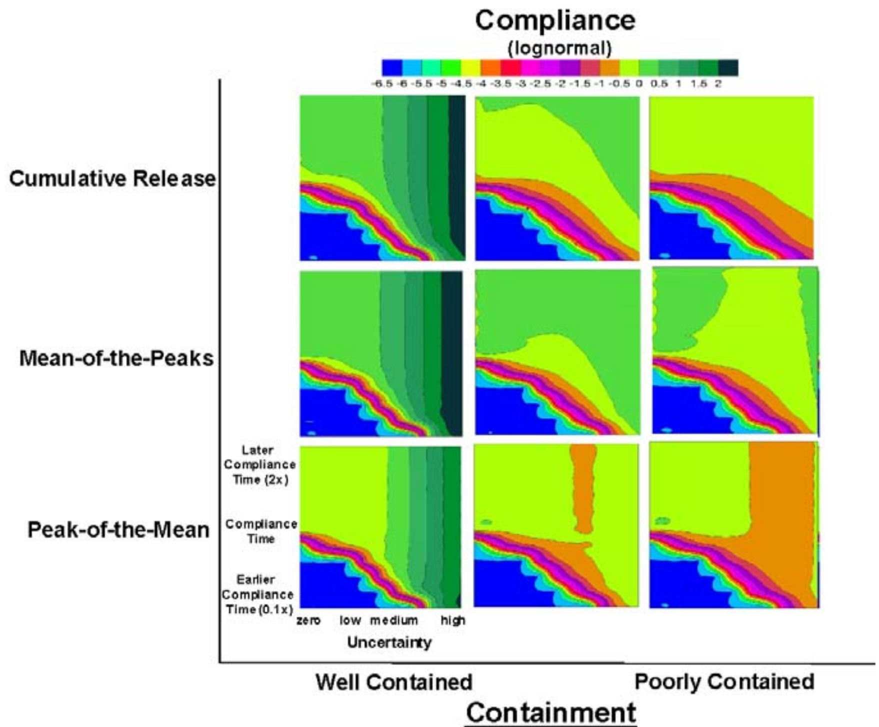

Fig. 4. Simulation results for the peak-of-the-mean, mean-of-the-peaks, and cumulative release performance metrics considering a range of compliance periods.

CONCLUSIONS

Most regulations include a compliance period, which is the regulatory time limit for how long the performance assessment model must be run. Because models may be run for different times and risk predictions may be affected that time, it is desirable to have a better understanding how the chosen time frame influences the risk predictions.

This paper presented the impacts of the compliance period on risk predictions for the three risk metrics of peak-of-the-mean, mean-of-the-peak, and cumulative release. Details of the modeling methodology and observations for other aspects of risk prediction are presented in Rice (12). In this paper, risks were estimated with a simplified performance assessment model. The model used lumped parameters for each of the major components of confinement, release, and transport. The following observations can be drawn from this work.

- Compliance period that is greater than the containment time is less sensitive to modeling assumptions
- Compliance period that is greater than the containment time will more closely predict risk for all three performance metrics examined in this paper

- Generally, whenever the compliance period is greater than the containment time, lower uncertainties yield better risk predictions

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