METHODOLOGY OF ENVIRONMENTAL DOSE ASSESSMENT

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INTRODUCTION

It has often been said that risk assessment is more an art than a science. In the early days of risk assessment, this may have been a true statement. Indeed, the components that comprise a risk assessment evolved as individual sciences, considering transport of radionuclides in the environment, dosimetry, and risk, once exposure has occurred. These individual sciences gradually and more frequently were merged together into comprehensive dose and risk assessment models. Risk assessment is a process that is rapidly becoming very sophisticated in its techniques, and through extensive efforts in validation of models, it is gaining credibility as a reliable scientific approach to understanding risk and making decisions about risk. Today, risk assessment is indeed a science that will become more important in the future of radiological health.

Risk assessment can be either prospective or retrospective. Risks can be estimated for possible future releases of materials (prospective), or they can be estimated for releases that occurred in the past (retrospective). Prospective risk assessments are carried out in conjunction with new facilities that are being constructed or perhaps to demonstrate that compliance will be met for an operating facility. An excellent example of retrospective risk assessments are the dose reconstruction studies being conducted on the weapons complex facilities in the US and studies of populations exposed following the Chernobyl reactor accident. Although the two types of risk assessment may be undertaken somewhat differently in their methods, there are many similarities in the techniques applied to both.

In explaining the process of risk assessment to my colleagues and to the public, I have often used this illustrative equation to express the interdisciplinary nature of this research and how these disciplines are inherently linked together.

$$\text{Risk} = (S \bullet T \bullet U \bullet D \bullet R)_{uvcp}$$

where,

S = source term (characterization of the quantity and type of material released),
T = environmental transport and fate of the material released,
U = usage factors (characteristics of individuals exposed),
D = conversion to dose,
R = conversion to risk,
u = uncertainty analysis,
v = validation,
c = communication of results, and
p = public participation.

This presentation will briefly review the state-of-the-art of each of these basic elements of risk assessment and describe what, in my judgment, the future holds and where the focus of our efforts should be for improving this science. Since our research has recently focused on dose reconstruction in the US, I will use examples from these studies throughout this paper.

SOURCE TERM (S)

The source term is the characterization and quantification of the material released to the environment. It is the heart of a risk assessment. We frequently give too little attention to the derivation of the source term, and yet this step of risk assessment is where the greatest potential lies for losing scientific and public credibility. Therefore, it is important that development of the source term be given highest priority and that the source term be carefully checked before making risk calculations.

Two key points are offered about how source terms should be derived for risk assessments. First, uncertainties must be included with the estimates of releases. This aspect of the source term has frequently been overlooked in the past, with release estimates being reported as single values, when in reality we know there is a range of possible values that exist. The uncertainty estimates should account for all possible sources of uncertainty in the calculation.

Second, the source term should be derived from as many different independent approaches as possible. The Fernald Feed Materials Production Center (FMPC), near Cincinnati, Ohio in the US is a part of the US nuclear weapons complex that processed uranium ore. We estimated the release of uranium from the FMPC using two methods. The first method considered the amounts of material being processed at the site and estimated the fractional release of uranium to atmosphere through the various offgas treatment systems (primarily scrubbers and dust collectors). Using this approach, it was determined that the "best estimate" of uranium released to atmosphere was 170,000 kg with the 5th and 95th percentiles ranging between 270,000 kg and 360,000 kg (Table 1). An alternative calculation was performed (1), looking at the amount of uranium deposited on soil within 7.5 km of the site based on soil samples that had been collected over time. Taking into account environmental removal of some of the uranium, and the amount of uranium that would have been deposited from the atmosphere, it was estimated that the source term for uranium released from the site to the atmosphere would lie between 78,000—90,000 kg with a median value of 212,000 kg. This alternative calculation, although the uncertainties are large, gives us additional confidence that our estimate of the source term for uranium is reasonable.

The Fernald site included several concrete silos in which ore containing high concentrations of radium was stored. Between 1952 and 1979 these silos (known as K-65 silos because of the radium bearing material stored inside) were vented to the atmosphere, thus creating a strong source of radon and radon daughter products, that exposed nearby residents (Figure 1). After 1979 several remedial measures were taken to reduce the emissions of radon, and in more recent years, a number of measurements were made to estimate radon releases. Unfortunately during the period prior to 1979, few measurements were made to quantify the release of radon, at a time when the releases would have been the greatest.

Table 1. Uranium and Radon Source Terms for the FMPC for 1951-1988[a] (1)

Source	Median release estimate	5th percentile	95th percentile
U to Atmosphere			
Primary estimate	310,000	270,000	360,000
(Alternative calculation)	212,000	78,000	390,000
U to Surface Water	99,000	85,000	120,000
Radon to Atmosphere			
Primary estimate	6,300 TBq	4,100 TBq	8,500 TBq
(Alternative calculation)	3,200 TBq	540 TBq	11,000 TBq
Radon-222 daughters[b]	4,800 TBq	3,200 TBq	7,000 TBq

[a] Values are in kg of uranium, except releases from the K-65 silos which are reported in TBq.

[b] The release quantities for decay products are quantities of each of the short-lived decay products, polonium-218, lead-214, bismuth-214, and polonium-214.

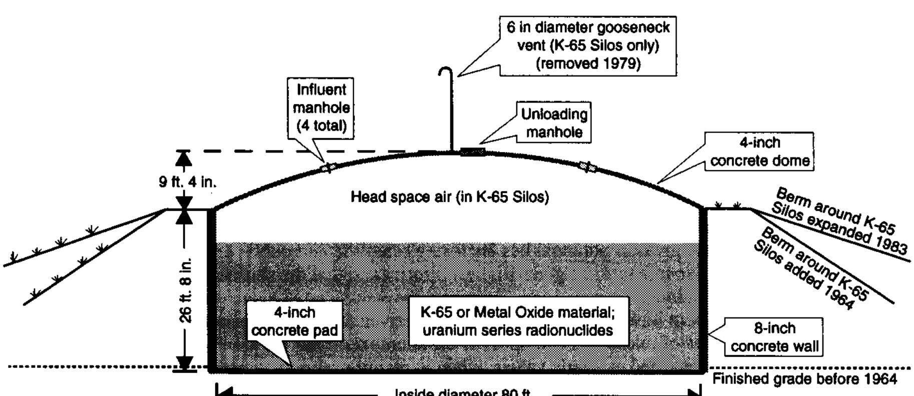

Figure 1. Schematic diagram of the K-65 silos located on the Fernald site.

The radon source term for Fernald was particularly challenging to derive. As with uranium, we estimated radon emissions and uncertainties for the silos using two different techniques. One method used measurements that were made prior to and after the sealing of the silos in 1979, along with information we had about the history of the silos and characteristics of the material stored. The second technique was a strictly theoretical approach that calculated the amount of radium in the silos, estimated the radon production and diffusion into the head space and out of the silo vents. The theoretical technique resulted in a greater uncertainty because more parameters with wide distributions were involved in the calculation. However, as can be seen in Table 1, there is overlap in the two estimated source terms, giving us confidence that our estimates for radon are plausible.

Environmental Transport (T)

With regard to environmental transport, one important recommendation stands out — always apply site specific data when they are available. The more data that exist characterizing the environment around a site, the more defensible the risk assessment. In fact, where measurements of environmental concentrations can be used in place of models, this is always preferable.

One example of a case where we have applied environmental measurements to assist in risk assessment is for the dispersion of releases to the atmosphere at the Fernald site. As with many dose reconstruction studies, detailed information on atmospheric conditions (wind speed and direction, stability categories, precipitation) at the site were not available until the late 1980s. In our search of the historical records, we located two sets of measurements of radon at different distances downwind from the silos, collected during the 1980s. A diffusion coefficient was developed based on a Gaussian area source model for a circular area of radius 50 m (representing the area of the two silos from which the radon emerged). The curve was fit to the radon measurement data. The uncertainties account for factors such as parameters used in converting concentrations to diffusion values and uncertainties in release rates of radon from the silos as well as measurement error.

We applied this empirical dispersion model to the releases of both uranium and radon released to the atmosphere at Fernald (Figure 2). Obviously, many other factors had to be accounted for in the overall model such multiple release points at the site, different chemical forms of uranium, particle size, deposition and resuspension among others. However, the air concentration as a function of distance downwind was based on measurements taken near the site. This approach resulted in less overall uncertainty in the environmental transport calculations. Therefore, it is always a smart investment in resources to carefully characterize environmental properties at the site for which the risk assessment will be performed. In the end, a more defensible calculation can be made and in addition, less uncertainty is likely to be introduced into the calculation.

USAGE FACTORS (U)

The importance of usage factors is often overlooked in risk assessment. The term, usage factor, refers to diet, lifestyle, and residence history data for individuals who live near the site, and other information that characterize the region around the facility being studied such as land use and agricultural practices. Typically we put little effort into developing usage factors in risk assessment and opt instead to insert values taken from the literature which often have little relevance to the particular region being studied. Although this tactic may not introduce large uncertainty into the overall estimation of risk, it can result in a loss of credibility with the public who are the object of the study.

In almost every risk assessment there are special population groups who do not fit the usage factors for the general public. One example of this occurred in the dose reconstruction project for the Hanford Site, another facility within the US nuclear weapons complex, located in south-central Washington state in the US. The Hanford facility released large amounts of radionuclides, and I-131 in particular to the atmosphere (3), however significant quantities of materials were also released directly into the Columbia River which was used for cooling the production reactors at the site (4). Pathways of exposure from the river were investigated thoroughly. Members of the general public who lived near the river received relatively small doses (estimated to be 15 mSv over about 40 years) from consumption of river water, consumption of fish from the river (150 kg of fish per year), and activities in and around the river. However, special attention had to be given to Native Americans who relied on the river for a major component of their food, fish. Therefore, the types of fish consumed, the quantities of fish eaten, and other uses of the river had to be determined specifically for Native American tribes near the site. Such information is not available in the literature and had to be collected by surveying elders of the tribes to develop a typical diet and to determine where the principal fishing locations existed. These data are currently being collected and analyzed, however, it is evident that the Native Americans who lived near and downstream of the site are likely to have received significantly higher doses from this pathway than the general public. Such an analysis could not be made without the cooperation of the Native American tribes in the Hanford study.

Surveys of individuals being studied to obtain person-specific usage factors were also carried out in the Utah Thyroid Cohort Study (5). In that research, surveys were conducted on the parents (or another living relative) of approximately 3,500 individuals who were children at the time of exposure to iodine from fallout resulting from the

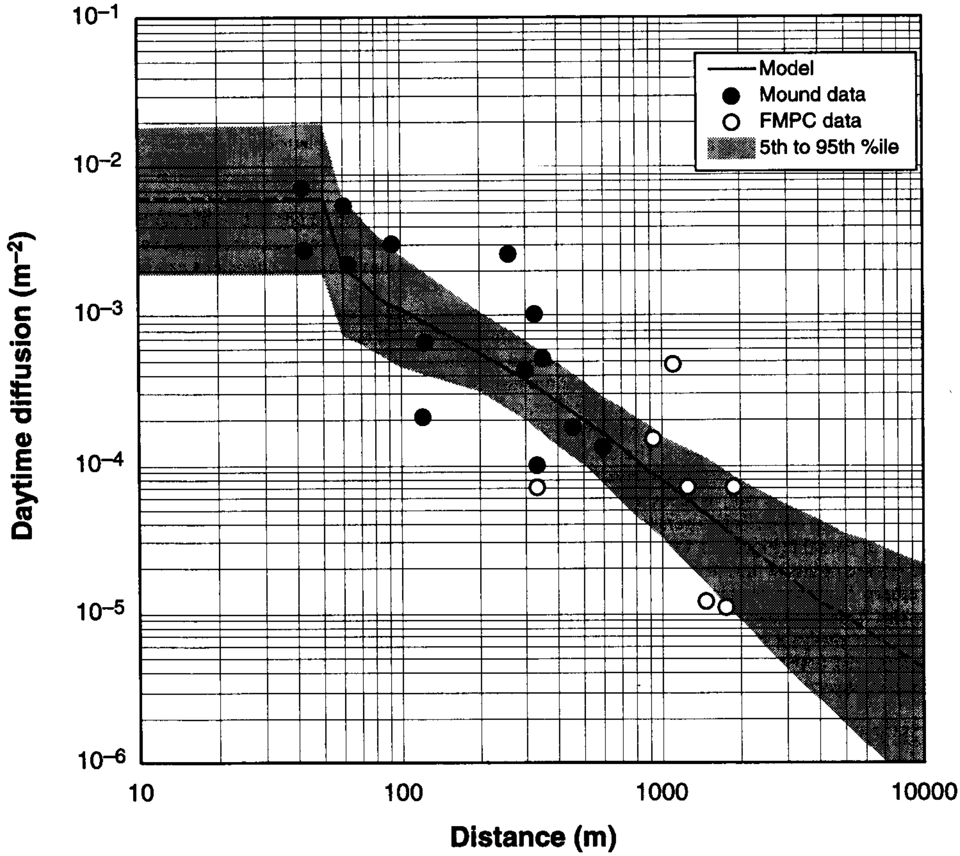

Figure 2. Atmospheric diffusion model fitted to local radon monitoring data for the Fernald site (2).

atmospheric nuclear weapons tests in the US. These data allowed individual doses and uncertainties to be estimated for each member of the cohort. The doses and uncertainties were used to determine if a higher incidence of thyroid disease existed in the group and could it be attributed to the fallout.

These two examples illustrate the importance of usage factors in risk assessment and the fact that the collection of such site-specific data cannot be underestimated.

DOSE CONVERSION FACTORS (D)

The conversion of intake of radionuclides or external exposure to dose has become a simple process because of effort put into deriving and publishing dose conversion factors using metabolic models. However, these factors typically do not include uncertainties and therefore a key component in the overall risk calculation is often not addressed.

In the Hanford Environmental Dose Reconstruction project (3-4), it was determined that one of the two most important contributors to overall uncertainty was the dose conversion factor for I-131 (the other key component of uncertainty was the feed-to-milk transfer coefficient.) In this analysis, it was pointed out that the uncertainty in the iodine dose conversion factor was due primarily to variability in the mass of the thyroid, uptake of iodine in the gastrointestinal tract, transfer of iodine to the thyroid, and the biological half-time of iodine.

Estimating uncertainties for dose conversion factors is a fertile and important area for research in the future. Although work in this area is underway, it will be a considerable time before dose conversion factors and their uncertainties can be established for all radionuclides. Indeed, this is an area where priorities must be set, in order to establish the methods to be used and to be sure we are focusing first on radionuclides of greatest importance in risk assessment.

CONVERSION TO RISK (R)

Two key issues are important to note with regard to risk conversion. The first issue deals with inclusion of uncertainties in estimates of dose in epidemiological studies to analyze incidence of disease and resulting risk. Kerber et al. (5) incorporated individual doses and uncertainties (6) into their analysis of thyroid disease in a cohort exposed to fallout from the Nevada test site. They concluded that there was a statistically significant excess of thyroid neoplasms, with an increase in excess relative risk of 0.7% per mGy. This approach to incorporating uncertainties associated with doses into the epidemiological analysis will be used more commonly in the future and is a relatively new technique for deriving estimates of risk in studies of large populations where individual doses have been assigned.

The second issue related to conversion to risk is that of quantifying uncertainty in the risk factors being applied. As with conversion of intake or external exposure to dose, conversion of dose to risk is a straight forward process with the publication of risk factors by a number of different groups (7-9). Little is known about uncertainties associated with the risk factors in use today. The current risk estimates of cancer following exposure to ionizing radiation are based primarily upon analyses of Japanese survivors of the atomic bombings at Hiroshima and Nagasaki. These risk estimates essentially relate to uniform whole-body low LET radiation exposures to doses ranging from 0.01 Gy to 4 Gy delivered at high dose rate.

Uncertainty in the risk factors for radiation was described by Sinclair (10) as having five primary components: (1) epidemiological uncertainties; (2) dosimetrical uncertainties (3) projection to lifetime; (4) transfer between populations; and, (5) extrapolation to low dose and dose rate. Epidemiological uncertainties include statistical uncertainties associated with quantifying the relatively small number of excess cancers attributable to ionizing radiation from the background cancers resulting from all causes. Also included in epidemiological uncertainties are uncertainties from underreporting of cancers per unit population and non-representativeness of populations used to determine risk. Dosimetrical uncertainties include those from random errors in individual dose estimates arising from errors in the input parameters used to compute doses and systematic errors due to the presence of more thermal neutrons at Hiroshima than originally estimated. Risk projection includes uncertainties associated with extrapolating beyond the time period covered by the observed population. Transfer of estimates of risk from one population (Japanese) to another introduces an additional source of uncertainty that must be considered. Finally, since the exposures for the A-bomb population was at relatively high dose rate, uncertainty is introduced when we extrapolate estimates of risk to low dose, low dose rate situations, common in most risk assessments. This area of risk assessment research is very important for the future and the ideas introduced by Sinclair (10) must be pursued. Indeed, it is very possible we may find that the risk factors themselves introduce more uncertainty into the overall estimate of risk than any other single component.

UNCERTAINTY ANALYSIS (*u*)

Uncertainty analysis is an essential element of risk assessment. Methods for quantification of uncertainty have been well established. Today, it is expected that when one carries out a risk assessment, the best estimate of risk is reported along with associated uncertainties. Although we commonly see uncertainties associated with doses, it is not likely to see uncertainties calculated in overall risk, primarily because as mentioned above, uncertainties in the risk factors are still being developed.

The most common method for uncertainty analysis uses Monte Carlo statistical techniques incorporating a random sampling of distributions of the various models and parameters involved (Figure 3). In this simplified illustration, A is an input parameter to the model, and Y is the result, or output, corresponding to A. For each specific value of A, the model produces a unique output Y. Such an application of the model is deterministic, because A determines Y. But A may not be known with certainty. If uncertainty about A is represented by a distribution, such as the triangular one in the figure, repeatedly sampling the distribution at random and applying the model to each of the sample input values A_1, A_2... gives a set of outputs Y_1, Y_2,..., which can be arranged into a distribution for Y. The distribution of Y is then the estimate of the uncertainty in Y that is attributable to uncertainty in A. This is a stochastic, or Monte Carlo application of the model.

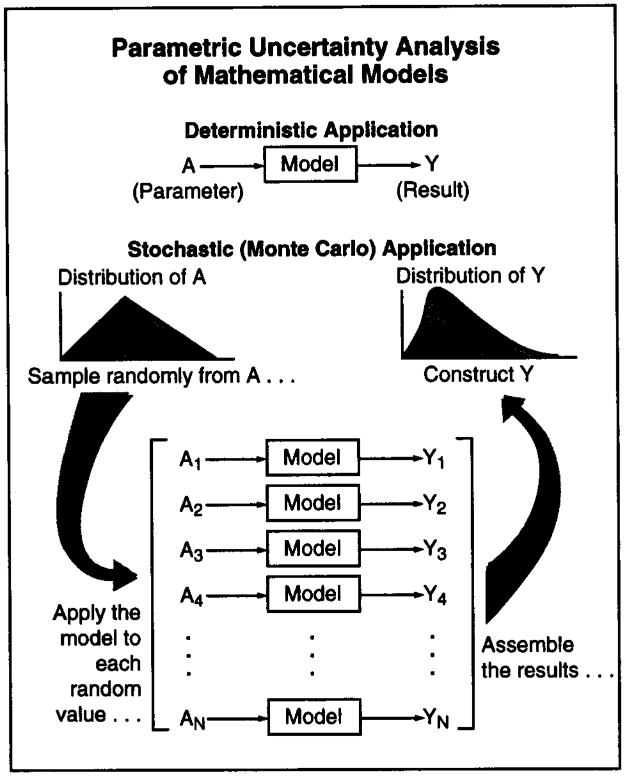

Figure 3. Schematic presentation of Monte Carlo methods for propagating a parametric uncertainty distribution through a model to its results.

The goal to estimate uncertainties in risk assessment demands that powerful computers be available for such a calculation. Until recently, limitations in computer hardware were the primary reason why uncertainties were not propagated throughout the entire calculation. Today, however, computer memory and speed of calculations have advanced to the point where relative inexpensive computers are required to undertake such a complex calculation.

VALIDATION (*v*)

Retrospective risk assessments in dose reconstruction are providing a unique opportunity to validate environmental transport models. The historical records contain a vast resource of measurement data, much of it collected many years ago, that can be used as the basis for comparisons between estimated environmental concentrations and values that were measured. These comparisons are providing us with some of the best indicators of reliability to date for the mathematical models being developed and applied by scientists in risk assessment.

In the Fernald Dosimetry Reconstruction Project, we have examined all available monitoring data from several different sources, and calculated predicted to observed ratios for a number of different pathways. As expected, it is rare that perfect agreement exists; however, overall confidence in our methodology is boosted by the strong agreement between historical data and estimated concentrations, suggesting that neither the source term nor the environmental transport calculations are seriously off the mark.

For example, Killough et al. (11) have made extensive use of historical monitoring data to confirm that estimates of releases of uranium in air and surface water are reasonable. Figure 4 shows one example of comparisons of predicted uranium concentrations in the Great Miami River near Fernald to those measured for the same period. Good agreement exists between predicted to observed values (mean P/O value of 1.3), enhancing confidence that the source term and environmental concentrations predicted reasonably reflect conditions that actually existed at the time.

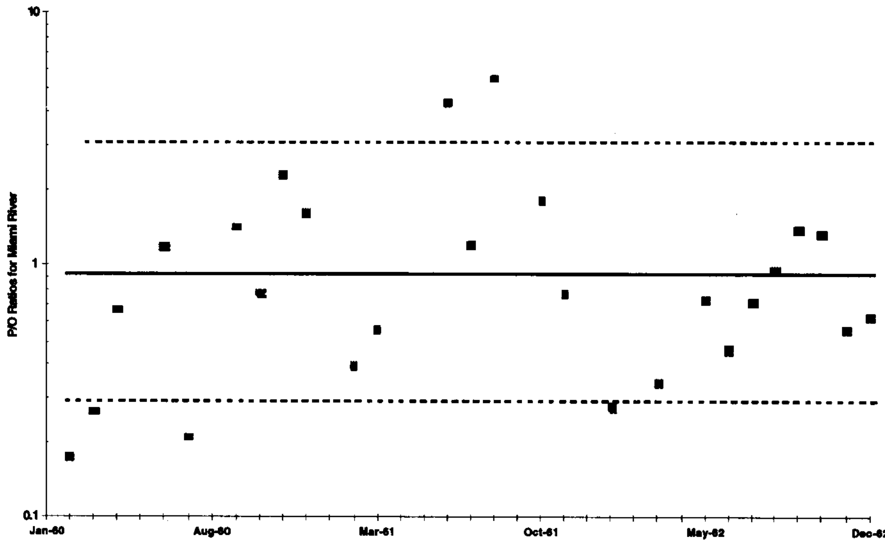

Figure 4. Comparison of predicted to observed concentrations of uranium in the Great Miami River downstream of the Fernald site (11).

Validation of our methods must continue to receive strong attention in the future. We must be certain that every opportunity is taken to make comparisons between predicted and observed estimates of concentrations in the environment.

COMMUNICATION OF RESULTS AND PUBLIC PARTICIPATION (*c,p*)

I include the remaining two elements of risk assessment into this final section because they are inherently linked together. Risk assessment is a public process. In almost all situations, we are required to estimate risk to members of the public who have been or who may be exposed to releases of contaminants to the environment. In the end, we must achieve both public and scientific credibility (12). As scientists we have come a long way in establishing the technical methods described in the sections above. On the whole, however, we are quite inept in communicating our results with the public and working with the public in conducting risk assessments. This is an area where the most progress could be made with the least investment of resources.

Risk communication has become a branch of risk assessment in itself. Many techniques have been devised to explain to the public the meaning risks resulting estimated doses. Many comparisons have been proposed between risks from exposure to radiation and risks from other sources common in life. We may be able to help people understand the potential importance of risks by referring to the overall risks posed by natural background, fallout, and other involuntary exposures and comparing these to our own estimates of risk for the particular situation. Although these comparisons help, there is no replacement for scientists personally conveying the results of their calculations to the public who are at risk. We would all like to think that society is ready to agree on a common set of risk levels for decision-making. Indeed it would make life simpler, but we are not at that point with either the technology to compute risks or the public's understanding and acceptance of risk. Trying to impose a level of risk as being "significant" or "insignificant" leads to a serious loss of credibility. During my past decade of work on dose reconstruction projects, I have learned that the best way to respond in communicating the significance of a level of risk is to respond personally. What I mean by this is that we as scientists can tell people how we feel about the significance of a level of risk, but we cannot tell the public what they should feel or think.

Public involvement in risk assessment is not common to us. I have found, however, that including the public in as many ways as possible in the risk assessment process builds credibility. Further, including the public who are being addressed in the risk assessment can lead to the inclusion of valuable site-specific information as described in the discussions above about usage factors.

CONCLUSIONS

Risk assessment is a science that will gain momentum and recognition in the future. It began as many individual sciences addressing the release of radionuclides to the environment, their transport in environmental media, their ingestion by humans, the resulting dose to organs of the body, and the correlation between these doses and the incidence of disease in the population exposed. Slowly and methodically, the individual sciences were melded into the discipline we call risk assessment. Today, this science is rapidly advancing on both the radiological and chemical fronts. There is no question that in the future, risk assessment will be the major tool for making decisions about building new facilities that are yet to release contaminants, and for understanding the importance of contaminants that have been released in the past.

To say we have come a long way in the advance of this science is an understatement. To say we have much work yet to do is a fact.

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