Air Emission Risk Assessment Sensitivity Analysis for a Coal-Fired Power Plant

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ABSTRACT

The Electric Power Research Institute's Air Emissions Risk Assessment Model (AERAM), which assesses the risk of toxic air emissions from coal-fired power plants, was used to study the excess cancer risk due to inhalation of airborne emissions from the Mt. Tom Power Plant in Holyoke, Massachusetts, and the key sensitivities of the risk assessment process were investigated as a guide for future analyses. With arsenic used as the pollutant, source-term descriptions, air-dispersion parameters, population exposure parameters, and dose-response models were varied to assess the effect on the risk result. It was found that eliminating pollutant enrichment on fly-ash particles reduced the risk by 50%. Changing from complete ground reflection to no reflection in the air-dispersion model reduced the risk by 57%; changing the settling velocity had no effect on the risk. Using the urban mode 2 stability pattern increased the risk by 124%, while using different stability array data changed the risk by about ±30%. The effect of using age-specific breathing rates in the exposure module was small (an 11% decrease in the risk), as was the impact of considering only respirable particles (a 4% decrease). The largest variation in the risk was observed when the Environmental Protection Agency's unit risk factor was replaced with one of four different low-dose extrapolation models utilized with three dose-response data sets; variations of up to 10 orders of magnitude were found. These results show that careful selection of dose-response data and low-dose extrapolation models should be a fundamental concern in risk assessment.

KEY WORDS: Air toxic risk assessment, coal-fired power plant, air emission cancer risk

INTRODUCTION

Generation of electricity by coal-fired power plants causes the emission of a variety of air pollutants, some of which are carcinogens. Although control technology can be used

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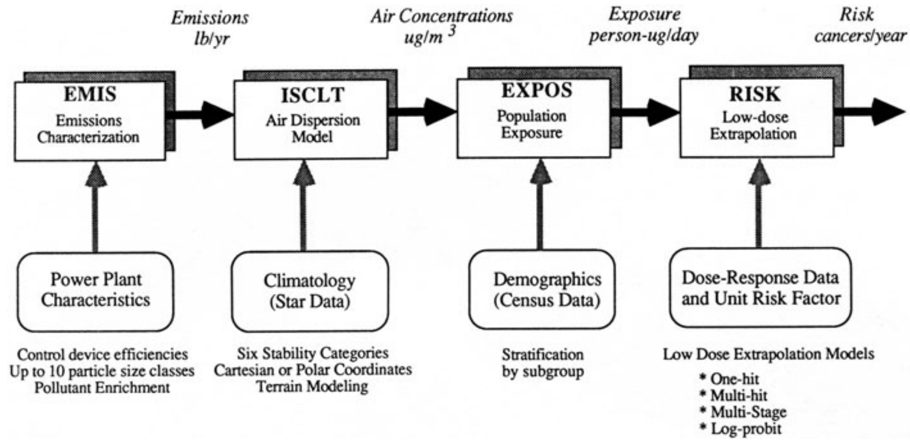

Fig. 1. Air Emissions Risk Assessment Model (AERAM) Methodology.

to reduce these emissions, some pollutants will be released into the atmosphere. It is difficult to determine the exposed population's actual cancer risk due to the pollutants; however, risk analysis can be used to estimate the health risks and to evaluate the risk reduction associated with various control strategies. In the process, addressing the uncertainty of risk estimates is an important step, since the results are sensitive to both model options and data selection. A proper understanding of these sensitivities will aid in the estimation of risk uncertainty and the decision-making processes involving health risks.

This paper describes a risk assessment sensitivity study which used the Electric Power Research Institute's Air Emissions Risk Assessment Model (AERAM) to revise and extend an earlier analysis of cancer risks due to arsenic emissions from Northeast Utilities' (NU) Mt. Tom Power Plant in Holyoke, Massachusetts. The sensitivity of cancer risk due to variations in data input values and program options were examined. The resulting sensitivities can be used to focus attention on the most important data needs for risk analysis.

BACKGROUND

The development of AERAM, a computerized model for estimating human cancer risk associated with toxic air pollutants emitted from coal-fired power plants[1,2] was sponsored by the Electric Power Research Institute (EPRI) to aid utility decision makers in the evaluation of power plant control strategies. AERAM is an integrated four-module FORTRAN computer code with each module addressing one of the four components of the risk analysis process: pollutant emission, atmospheric dispersion, population exposure, and health risk estimation. A flow-chart of these modules with an overview of the AERAM methodology is shown in Fig. 1. The recently developed AERAM manager was used as an aid for handling and modifying the extensive input and output data files for the sensitivity analysis. The AERAM manager is a top-level, menu-driven program which performs file handling, allows editing of AERAM data sets, checks input data prior to execution, executes the four AERAM modules, allows browsing of output, and provides context-specific help.[3]

The emission module (EMIS) uses coal properties, power-plant operating parameters, and removal efficiency of the pollution control devices to calculate the stack pollutant emission rate for the pollutant of interest. The program can account for the pollutant's enrichment on the fly ash as a function of particle size.

The air-dispersion module, which uses EPA's Industrial Source Complex – Long Term (ISCLT) disperson model, determines ambient air concentrations of the pollutant from the plant. The primary input data required for this module are meteorological data in the form of a stability array (STAR) summary, which is a tabulation of the joint frequency of occurrence of wind speed and direction stratified according to Pasquill atmospheric stability categories. The program can model terrain, dry deposition, and surface reflection of particles. This module calculates the ambient air pollutant concentration at each receptor in a user-defined exposure grid.

The exposure module, EXPOS, estimates population exposure using the modeled pollutant concentrations, demographic data, and breathing rates. Exposure is calculated for each receptor in the exposure grid. The module has the capability to account for population subgroups.

The risk module, RISK, calculates cancer risks based on a unit risk factor or dose-response data from human exposure or animal studies. It extrapolates risk from high to low doses and, when necessary, from animal species to humans. AERAM currently includes four low-dose extrapolation models: the one-hit, the multihit, the multistage, and the log-probit models. The results include an estimate of the excess human lifetime cancer risk for the total study population.

NU was the first utility to apply AERAM to one of its facilities, using it to evaluate the lung cancer risk associated with exposure to two carcinogens, benzo(a)pyrene (BaP) and arsenic, from its Mt. Tom Power Plant.[4] Mt. Tom was built in 1960 as a coal-fired electrical power generating facility, but in 1970, it was converted to burn oil and, except for about six months during the oil embargo in 1974, remained on oil until December 1981, when it began burning coal again. This generating station has one front-fired boiler designed to burn pulverized bituminous coal. The station has a peak capacity of 155 mW(e) normal gross output.

NU's calculations with AERAM showed that the excess cancer risk for arsenic emissions to the surrounding population in a 20 by 20 km study area was a very small percentage of the risk from the background arsenic level. Details of the calculation, including the fuel pollutant concentrations and stack emissions, are described elsewhere.[4,5]

METHODS

AERAM needs diverse data to perform risk calculations, some of which can be based on measurements while others must be estimated. Since modeling with AERAM involves selection of input data and various model options, the results are very dependent on these choices, although some may affect the results more than others. The following procedure was used to investigate the effect of input data selection and model options on the results of the baseline risk analysis of arsenic emissions from the Mt. Tom Power Plant.

Ten AERAM options/parameters were chosen for the sensitivity analysis: particle enrichment, ground reflection, settling velocity, adjustment of stability for surface type, modeling surface terrain, the STAR data, the breathing rate of subpopulations, respirable particles, the low-dose extrapolation model, and the dose-response data. Figure 2 presents these parameters as a branching tree of possible choices.

The baseline Mt. Tom Power Plant analysis is shown in Fig. 2 as a dashed line taking one route at each branch of the tree. The sensitivity of the risk estimate to changes in

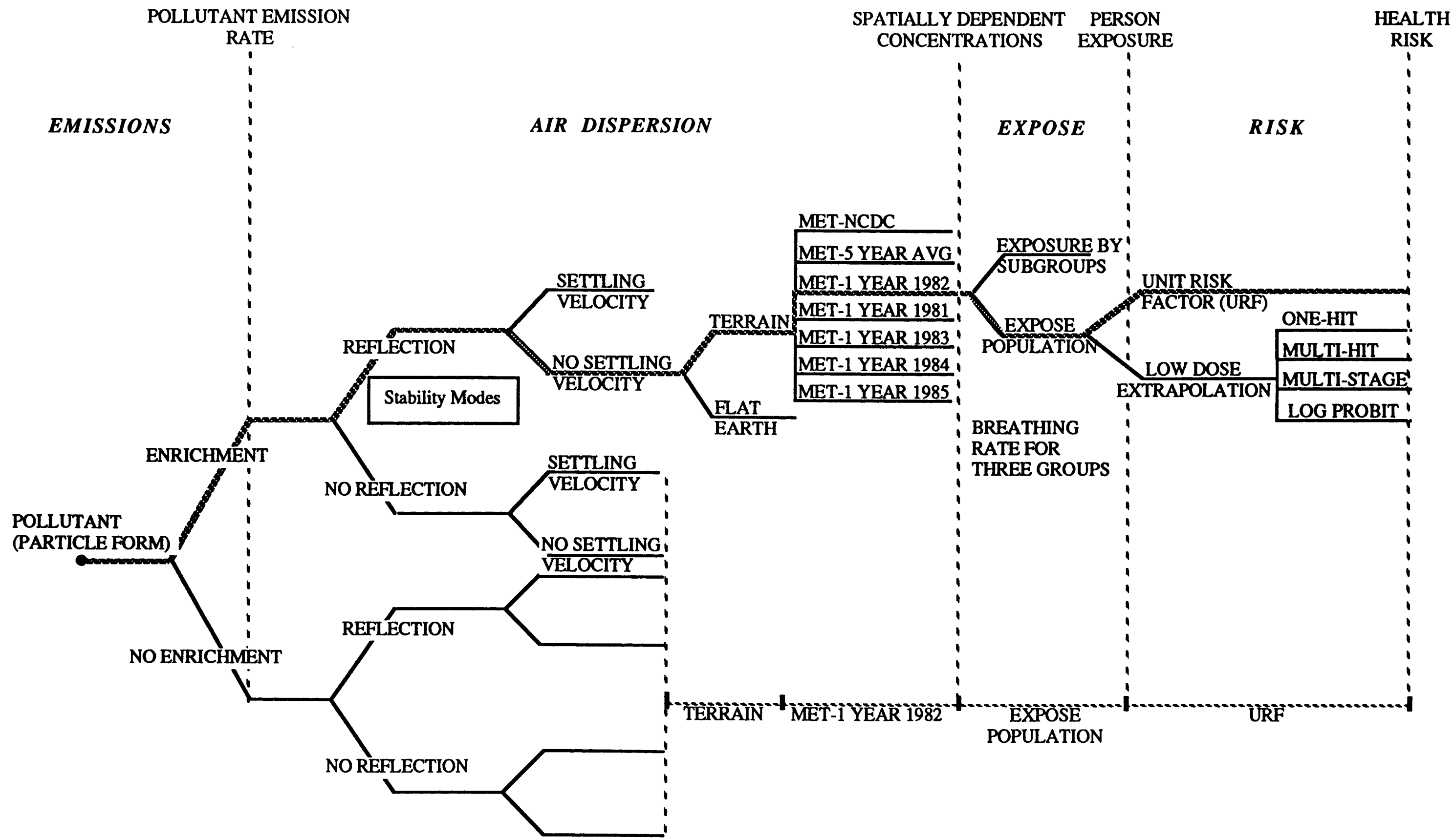

Fig. 2. Basic Risk Calculation Options and Variations for Sensitivity Study.

parameter values was investigated relative to this baseline case. The baseline calculation is a reasonable best-estimate except for the use of the unit risk factor, which is a plausible upper bound. When the unit risk factor is used, as in the baseline case, changes in the risk estimate are proportional to the changes in exposure.

In the sensitivity study, values were selected for each parameter to represent a range. In some cases, the values were simply a dichotomous choice to use or not use an option. Other parameters involved discrete options such as the stability data adjustment, which has three possible modes: rural mode, urban mode 1, and urban mode 2. In the rural mode, rural mixing heights and the Pasquill-Gifford (PG) standard deviations for the indicated stability category are used. In the urban modes, urban mixing heights are used. In urban mode 1, the stable E and F categories are redefined as neutral (D) stability, and the PG standard deviations are used. In urban mode 2, the E and F stability categories are combined and the PG deviations for the stability category one step more unstable than the indicated category are used. Appropriate values were used for other parameters to represent the analysis variations. For example, three different dose-response data sets obtained from the literature were used for the calculation of risk. This analysis involved 20 separate runs of AERAM.

RESULTS

The settings or values for each of the ten options/parameters and the corresponding risk sensitivities are summarized in Table 1. The sensitivity is expressed as the ratio of the risk with the given test input over the risk in the baseline case. By examining these risk ratios, the relative sensitivity of the different parameters is found.

The sensitivity of the risk result to source-term parameters in the emission module considered pollutant enrichment, which occurs as a function of particle size. The emission rate for the study pollutant, arsenic, is based on its concentration of 8.8 μg/g in the coal. Particulate arsenic was modeled with lower particle diameter bounds of 0.1, 0.5, 2.0 and 10 μm, with associated control efficiencies[6] of 98.5, 95.0, 99.1, and 99.7%, respectively. The choice of particle enrichment or nonenrichment impacts the resulting emission by a factor of 0.5, with a similar change in the risk. Enrichment refers to the change in trace element concentration from the bulk material to the fly ash as a function of particle size. Arsenic has been shown to undergo significant enrichment with decreasing particle size. Enrichment factors for arsenic were based on in-stack samples collected at a coal-fired power plant.[7]

Additional model choices can impact the risk concern options that affect the pollutant concentration at the receptor sites. These include the ground reflection and settling velocity of the pollutant, dispersion coefficients, terrain elevation, and meteorology.

The removal of airborne emissions by dry deposition is included to improve the dispersion model accuracy.[8] Larger particulates can be brought to the surface by the combined process of atmospheric turbulence and gravitational settling. Smaller particulates and gases tend to be reflected from the surface. ISCLT allows for both gravitational settling and dry deposition using a settling velocity. Reflection can be accounted for by an input parameter that specifies the fraction of material reaching the ground surface by the combined process that is reflected from the surface. The sensitivity to both the reflection coefficient and the settling velocity can be important.[9] The results in Table 1 indicate that removal of ground reflection decreased the concentrations and risk by 57%. The use of 100% reflection is an upper bound, as some particles are trapped at the surface. The effect of using the calculated settling velocites was nil. On the other hand, the addition of settling velocities at an extreme value of 0.01 m/sec increased the concentrations and risk by 53%.

Table 1. Summary of Air Emissions Risk Assessment Model Sensitivity Results

AERAM Module	Description of Variant	Baseline[a]	Variation from Baseline	Risk Ratio
EMIS	Particle Enhancement	Enrichment[b]	No Enrichment	0.51
ISCLT	Ground Reflection	100%	0%	0.43
	Settling Velocity	0	Calculated Velocities[c]	1.00
	Dispersion Coefficients	Rural Mode	Urban Mode 1	1.19
			Urban Mode 2	2.24
	Receptor Terrain	Elevations	Flat-earth	0.68
	Stability Array (STAR) data	1982 Measured	5-year Ave. Measured	0.91
			1981 Measured	0.94
			1983 Measured	0.98
			1984 Measured	0.81
			1985 Measured	0.83
			NCDC STAR[d]	1.30
EXPOSE	Exposure Groups	One Group	Three Age Groups	0.89
	Respirable Particles	All sizes	0.1 to 10 um only	0.96
RISK	Dose-Response Data Set	Unit Risk Factor	Tseng[13,14]	
	Low-Dose Extrapolation Model		One-Hit	2.4
			Multi-Hit	6E-03
			Multi-Stage	1.49
			Log-Probit	2E-05
	Dose-Response Data Set	Unit Risk Factor	Mabuchi[15]	
	Low-Dose Extrapolation Model		One-Hit	1.59
			Multi-Hit	1.17
			Multi-Stage	0.26
			Log-Probit	5E-06
	Dose-Response Data Set	Unit Risk Factor	Ishinishi[16]	
	Low-Dose Extrapolation Model		One-Hit	0.18
			Multi-Hit	3E-10
			Multi-Stage	3E-09
			Log-Probit	6E-09

a. Based on an annual excess lifetime per capita cancer risk of 3.87E-8 calculated for a population of 129,082 using a unit risk factor of 4.3E-3 lifetime cancers per microgram of arsenic per cubic meter.
b. Based on enrichment factors of 5, 5.3, 2.2 and 1 for the particle size groups, respectively.
c. Based on settling velocities of 3.4E-6, 5.7E-5, 1.4E-3, and 8.3E-2 m/sec for the respective particle size groups using equations for the aerodynamic mean diameter and settling velocity from reference 8. If an upper bound settling velocity of 1E-2 m/sec is used for all groups, the relative risk is 153%.
d. Based on National Climatic Data Center data for Chicopee Falls, Mass. locted 16.8 km from Mt. Tom.

Meteorological data used in the dispersion module were obtained from a tower located on site. This tower is equipped with instruments that provide real-time wind speed and direction, ambient temperature and stability class data. The base year chosen was 1982, which turned out to give the highest health risk of a five-year set of measurements. Results indicative of changes in the exposure and risk under different meteorological conditions are shown in Table 1. With respect to the base year, the five-year average produces a risk which is about 10% less. On the other hand, if National Climatic Data Center (NCDC) data are used for the closest site to Mt. Tom, the risks are 30% higher. This site, Chicopee Falls, is about 17 km south of Mt. Tom and, although those data may not be representative of the site topography, this study indicates that use of best available STAR data should not cause major discrepancies in the results.

The impact of assuming an elevated terrain versus the "flat-earth" approximation normally used to simplify risk analyses was considered in the sensitivity study. Receptor elevations were taken from a topographic map. The results shown in Table 1 indicate that the flat-earth approximation can result in an underestimation of the unit-risk-factor estimated risk by about one third, which is consistent with previous results.[10]

The population in each receptor zone was estimated using 1980 census data. A key assumption of the exposure module and risk assessment is that the entire population in the study area is continuously exposed for a 70-year lifetime at a constant exposure level. This is a static approach because the population in the study area is assumed to be fixed. Sensitivity of the risk results to the addition of age-specific breathing rates in the exposure analysis was investigated by stratifying the baseline population data into three age groups: under 5; 5 to 17; and 18 years and older. The age distributions from the 1980 census[11] for Northampton and Holyoke were assigned to the northwestern and southeastern halves of the population grid, respectively. The Northampton age distribution was 4.3%, 15.7%, and 80.0%, while the Holyoke age distribution was 7.1%, 20.5%, and 72.4% for the under 5, 5 to 17, and 18 and older age groups, respectively. The under 5 age group exposure calculation assumed a breathing rate of 7 m^3/day,[12] the 5 to 17 age group a rate of 15.0 m^3/day, and the 18 and older group a rate of 22.4 m^3/day breathing rate.[12] The resulting risk was 89% of the baseline risk; the refinement of population age distribution apparently has relatively little effect on the risk.

The health hazard from the inhalation of particles depends on the concentration of deposits in regions of the human lung. The size of the particles largely determines their fate in the respiratory system. The majority of particles with an aerodynamic diameter larger than 10 μm are trapped in the nasal passages and thus prevented from entering the lung. Finer particles (about 1 μm) easily penetrate to all parts of the respiratory system. Very fine particles (less than 0.1 μm) are exhaled if not chemically reacted in the lung. The respirable particles were considered to be in the range of 0.1 to 10 μm for investigating the effect of expected health risk by considering all particles versus only respirable particles. Because of arsenic's high enrichment on small particles, the mass of arsenic in particulates is primarily in the respirable range (96%), so the risk is reduced by only 4% when only respirable particles are considered.

Arsenic has been implicated as a human carcinogen. The uncertainty of the carcinogenic response to arsenic exposure was considered in the sensitivity analysis. The EPA unit risk factor was chosen for the basic risk estimate. Low-dose extrapolation models with different dose-response data sets were a key part of the sensitivity study. Dose-response data used in the risk module for arsenic were obtained from the literature. The first data set is based on epidemiological studies by Tseng *et al.* of arsenic ingestion in drinking water.[13,14] Tseng *et al.* found increased incidence of skin cancer in Taiwanese villagers exposed to arsenic-contaminated drinking water. Within a population of 40,421 individuals, the overall prevalence rate of skin cancer was 10.6 per 1000. The second and third data sets for arsenic are more directly applicable, being based on inhalation exposures.

Ishinishi *et al.* studied the tumorigenicity of arsenic trioxide to the lung in Syrian golden hamsters by intermittent installations.[15] The third arsenic data set is based on the investigation of cancer mortality by Mabuchi *et al.* among 1,393 workers exposed to high concentrations of inorganic arsenicals for varying lengths of time during the manufacture of pesticides at a plant in Baltimore, Maryland.[16] Dose-response data were derived using the tabulated data for the observed and expected number of deaths from lung cancer and other causes, and from Standardized Mortality Ratios by high exposure duration to arsenicals and nonarsenicals among male production workers first employed before 1955. The use of three dose-response data sets and four low-dose extrapolation models were compared to the use of the unit risk factor for arsenic as part of the sensitivity study and the results are shown in Table 1.

Results for the health risks based on the three data sets for arsenic differ by a factor of 13 for the one-hit model, a factor of 10 million for the multihit model, a factor of 1 billion for the multistage model, and a factor of 10 thousand for the log-probit model. The variation from the unit risk factor baseline case ranges from a factor of 5 for the one-hit model to 16 or 17 orders of magnitude for the other models. Results for the health risks are based on point risk estimates from each of the four dose-response functions. The range of results is indicative of the large uncertainty in dose-response modeling. The results for the different dose-response data sets indicate that the model choice between unit risk and low-dose extrapolation presents the greatest variability in the results. If the low-dose extrapolation scheme is selected, the greatest variability in the results appears to be due to the choice of data sets.[17]

Since many assumptions were made in the air emission risk estimation process, it is instructive to look at overall sensitivities to understand the uncertainty in risk estimates. The results in Table 1 show that an analyst could compute excess risks that vary from a factor of 10 higher than the baseline results to at least 10 orders of magnitude lower. In general, the lower uncertainty end point is zero; that is, there is no induced cancer from the expected levels of exposure to the pollutant. The upper uncertainty end point given by a unit risk factor is likely to yield a conservative estimate. It should be understood that the use of an upper bound at any point in the analysis does not allow for a best estimate of the risk with its associated uncertainty bounds.

Another issue is the impact of including the background level of the pollutant in risk calculations because the nonlinearity of the low-dose extrapolation models means that the total exposure is needed for an accurate estimate of risk. The background levels of arsenic in the Mt. Tom area are very high relative to the calculated concentrations from plant emissions. The sensitivity results reported herein have not included background and the reported risks are for excess cases from Mt. Tom emissions only.

CONCLUSIONS AND RECOMMENDATIONS

The AERAM code provides a useful and convenient means to analyze the sensitivity analysis of health risk related to toxic air emissions from coal-fired power plants. The development of a user-friendly interface for AERAM has allowed for flexibility and efficiency in performing air emission risk assessment sensitivity studies.

This sensitivity analysis was performed to examine the effects of changing some of the analysis options. Changes in the source term usually result in proportionate changes in the risk. The effects of changes in model options and data that impact the source and dispersion calculations are all relatively small, being of the order of less than a factor of 3. However, the risk results were very sensitive to the choice of dose-response data and, as had been observed in an earlier study,[17] to the choice of low-dose extrapolation model.

This means that careful consideration of dose-response data and model selection are paramount in the calculation of risk.

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