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Sensitivity analysis for power industry radionuclide air stack emissions leukemia incidence risk comparison models*

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Abstract

The authors developed mathematical models to quantify the impact of accidents on the U.S. nuclear power industry radionuclide air emissions incidence risk. Additionally, sensitivity analysis was performed on the terms in those models. The number of accidents of a given size needed to equilibrate the nuclear power industry leukemia incidence risk with the coal power industry leukemia incidence risk under normal operating conditions was calculated. We evaluated an accident's impact on the total leukemia incidence risk comparison done using all of the six types of postulated dose response curves. An overlapping plot of the number of nuclear accidents required to equilibrate industry risks versus accident magnitude enabled the comparisons of models. Sensitivity analysis on the developed models for the current mix of U.S. coal and nuclear power plants was used to verify model limitations. Sensitivity analysis also showed that the models with cell killing terms gave meaningless numbers for large dose accidents and that when both the linear and quadratic terms are present in the dose-response curves, the linear term dominates the quadratic term by a factor of 10 until the dose exceeds 110,000 mrem (1.10 Sv). Air emission leukemia incidence risk projections to the year 2000 were obtained by including plants due to go online by 2000. The application of these models provided an approach toward developing a methodology for identification of the relative risk from power generation alternatives.

Introduction

Models for power industry radionuclide air stack emissions leukemia incidence risk comparison are developed and explored in this work. Verification of critical assumptions and the determination of model limitations have been

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accomplished by performing sensitivity analyses on these risk comparison models.

Previous work developed (Prybutok and Gold [1]) risk comparison models of leukemia incidence associated with radionuclide air stack emissions from a specified number of coal plants versus an equal number of nuclear plants. Those models used emission values for a single coal and a single nuclear plant that provided the nuclear plant with an advantage under normal operating conditions. The converse was true with the inclusion of a significant accident for the nuclear power plant. Prybutok and Gold's [1] accident unit for a nuclear plant was defined as a multiple of a dose equivalent to the 1979 Three Mile Island accident (TMI) (U.S. Nuclear Regulatory Commission [2]), and multiples from 0.05 to 25 times TMI were considered.

Goals of the present work included improvement of the total industry risk models, the use of a generic accident termed the "Standard Incident", sensitivity analysis on the improved models and projection to the year 1995 and beyond. The generic accident or "Standard Incident" (SI) has been defined by us as the bone dose to the individual in the fence post area which occurs as a result of the output of a current day (mid 1980's) normally operating nuclear plant for an entire year. The accident sizes ran from 0.1 SI to 300 SI per person. Furthermore, there was no attempt to favor either the coal power or the nuclear power industry. There was also no desire to argue the health physics validity and applicability of the dose incidence equations except in a mathematical sense.

The leukemia incidence risk due to radionuclide air emissions of an entire industry, where industry is defined as a specified number of coal power plants or a specified number of nuclear power plants, cannot be determined by either normal operating conditions or accident conditions alone. Determining the difference between the coal power industry under normal operating conditions and the nuclear power industry under a combination of normal operation and accidents yields relative risk or a ratio of risks. We quantify the risk by determining the number and size of nuclear accidents for equilibration of leukemia incidence from both industries that were evaluated. This work further developed the models from Prybutok and Gold [1] to enable comparison of the leukemia incidence for the current U.S. coal power and nuclear power industries.

Prybutok and Gold [1] developed models to compare leukemia incidence risk for a 1000 MWe plant nuclear industry (either 1000 MWe boiling water reactors (BWRs) or 1000 MWe pressurized water reactors (PWRs)). The number and size of accidents required to equilibrate the coal and nuclear power industry risk under each assumed dose response relationship were quantified. The present work develops models which allow for a mix of nuclear power plants and explores these models using the actual 1985 mix of nuclear and coal power plants. Examination of the models developed by Prybutok and Gold indicates that the cell killing term makes a negligible contribution to the dose response curves when these curves are used in evaluation of an entire industry response with accidents less than 25 times the magnitude of Three Mile Island (TMI). This work also examined the impact of the cell killing term when accident magnitude goes beyond 25 times TMI in multiples of SI and demonstrates that the cell killing term makes models for large accidents meaningless. Furthermore, Prybutok and Gold found that when both linear and quadratic terms are present in the dose response curves, the linear term is always dominant This finding is also examined for accidents beyond 25 times TMI in multiples of SI and is again of little impact.

In the present work we consider factors impacting on the risk quantification for the current U.S. (year 1985) and projected (year 2000) coal and nuclear power industries. The relationship between the number of accidents and the size of the accidents required to put the nuclear power industry risk at the same level as that for the coal power industry is examined. This examination enables definition of the limitations of the risk comparison models and results in improved risk quantifications.

Background

Several methods have been employed to compute relative risk associated with power generation. Below, we review only those studies that are concerned with the radionuclide air stack emissions risk. Terrill et al. [3] examined quantities of discharge of the major pollutants from each type of plant per megawatt-year. Using these values and the standards for conventional agents, they calculated a yearly volume of air required for the dilution of the pollutants discharged. The results showed larger volumes were required for the dilution of the radioactivity and conventional pollutants from fossil-fuel power plants than for dilution of the radioactivity from pressurized water reactors (PWRs). Hull [4,5] updated this study with the inclusion of boiling water reactors (BWRs) and lower air quality emission standards for sulphur dioxide. Hull found greater dilution volumes are required by coal power plants.

Eisenbud and Petrow [6] compared only the radionuclide effluents and found coal and oil plants had relatively greater quantities of atmospheric pollutants. In 1978 McBride et al. [7] compared coal and nuclear plants assuming the new "As Low As Reasonably Achievable" or "ALARA" criteria, Code of Federal Regulations, for nuclear power plants and 99% flyash collection for coal power plants. McBride's data (see footnote to Table 4) for maximum potential exposures will be assumed for this work. We term this the fence post exposure for coal and nuclear.

Ilyin et al. [8] examined the radiation risk due to all primary natural radionuclides from fossil-fuel powered stations and compared this to the radiation risk of nuclear power stations. These risks were compared based on increased mortality due to malignant neoplasms resulting from the radionuclide exposures. Ilyin et al's work did not consider the possibility of an accident (release of emissions due to a mishap at a nuclear site), or make the comparison between single plants and the total industry. Finally, Ilyin et al.'s work used linear extrapolation and linear dose–response curves, which is questionable in light of BEIR-80 [9], e.g. see Brown [10,11] and Land [12].

Land's work provides human dose–response curve data specific to leukemia and breast cancer. Calculation of expected leukemia incidences is dependent on the dose–response curve. Land's work indicates that six dose–response curves must be examined and that none of the proposed curves can be rejected based on a Chi-Square goodness of fit for curves developed from a fit to present human data. Land's proposed curves (curves are also available from BEIR [9]) are linear, pure-quadratic, linear-quadratic and each of these with a cell killing term.

Land's age-adjusted leukemia curves were used to calculate the leukemia incidence $I(D)$ for a specified dose D given in rems(rads).

Linear:

$$I(D) = (2.5 \pm 0.6)D$$

Pure quadratic:

$$I(D) = (0.016 \pm 0.004)D^2$$

Linear quadratic:

$$I(D) = (1.0 \pm 1.2)D + (0.01 \pm 0.008)D^2$$

Linear with cell killing:

$$I(D) = (2.5 \pm 1.0)D(\exp[-(0 \pm 8.4)D^2])$$

Pure quadratic with cell killing:

$$I(D) = (0.026 \pm 0.01)D^2(\exp[-(11 \pm 7.0)D^2])$$

Linear quadratic with cell killing:

$$I(D) = [(0 \pm 1.8)D + (0.026 \pm 0.028)D^2](\exp[-(11 \pm 11)D^2])$$

The values used in this work are McBride's [7] maximum individual radionuclide doses to bone marrow for single 1000 MWe coal power and nuclear power plants. The use of McBride's calculations is supported by Pacyna's [13] work which contains values of the same order of magnitude. McBride's maximum individual doses in 10^{-5} Sv from airborne releases of 1000 MWe plants are summarized below in Table 1.

The bone marrow dose was chosen because Land's leukemia dose–response curves are for bone marrow dose. The relationship between bone marrow dose and leukemia is supported by Gofman [15] and Linos et al. [16]. The dose

TABLE 1

Maximum individual doses in 10^{-5} Sv from airborne releases of 1000 MWe plants [7]

Type of plant	Whole body	Bone
Coal	1.9	18.2
BWR[a]	4.6	5.9
PWR[b]	1.8	2.7
CFR Guide [14]	5.0	0.5

[a]BWR is boiling water reactor.
[b]PWR is pressurized water reactor.

data varied with the type of power plant (coal versus nuclear) and within nuclear (PWR or BWR).

Total U.S. industry exposure was estimated for a hypothetical total industry by Prybutok and Gold [1]. The total industry for each power generation source was defined as 1000 plants, with 1000 coal power plants contrasted to an equal number of nuclear plants. Each plant was of a 1000 MWe size and each individual about the plant received McBride's maximum bone dose (the fence post dose). The population about TMI for a 50 mile radius (80 km) is 2.166 million people and is used to calculate a maximum individual dose, D_{TMI}, in a fashion similar to McBride, Prybutok and Gold [1] showed that the linear-quadratic model is linearly dominated and the cell killing term is not operative for accidents less than 25 times TMI. Using these findings, Prybutok and Gold [1] showed that the following two relationships may be deduced directly from the format of the equations:

$$M_{\mathrm{if}} = [N/\alpha][(D_{\mathrm{c}} - D_{\mathrm{n}})/(D_{\mathrm{TMI}})]$$

for the linear and

$$M_{\mathrm{if}} = [N/\alpha^2]([(D_{\mathrm{c}})^2 - (D_{\mathrm{n}})^2]/(D_{\mathrm{TMI}})^2)$$

for the quadratic model where M_{if} denotes the number of accidents of a particular TMI fraction that will equilibrate the nuclear and coal power industries, N is the number of plants, and α is a fractional or whole multiple.

Prybutok and Gold [1] showed that plots of M_{if} versus α for the assumptions of the linear and quadratic curves indicate that there is a crossover point at which the number of accidents is equal for linear and quadratic. Below this crossover point, the linear yields more conservative values (a worse condition requiring fewer accidents to equilibrate the industries) and the quadratic is more conservative above the crossover. The more conservative quadratic form for M_{if} was used to determine the magnitude of a single critical accident which will equilibrate the industries.

Prybutok and Gold [1] performed their calculations for a 1000 MWe coal power plant industry versus a 1000 MWe BWR power plant nuclear industry, as well as for a 1000 MWe coal power plant industry versus a 1000 MWe average nuclear power plant (NAVE) industry. The NAVE plant is the average in effect (maximum individual doses) for a PWR and BWR.

Prybutok and Gold's derived models are easily calculated and the number of nuclear accidents required for equivalent leukemia incidence risk due to radionuclide air emissions for a given multiple of TMI can be computed on a hand calculator. Therefore, Prybutok and Gold suggested that the easier to work with models, M_{if} for linear and M_{if} for quadratic, be used to estimate risk comparison values. The need exists to investigate whether the linear term still dominates the linear-quadratic model, and whether the cell-killing term remains inoperative as the magnitude of the nuclear accident becomes large (i.e. beyond 25 times TMI). Also, Prybutok and Gold's models require modification to allow for a mixture of nuclear plants (BWRs and PWRs) rather than assuming a single type of nuclear plant and permitting more realistic applications.

Methodology

Analysis

The general form of the dose–response curves may be written as:

$$f_i(D) = (a_{0i}D + a_{1i}D^2)(\exp[-a_{2i}D^2])$$

where D is the dose, $f_i(D)$ is the corresponding leukemia incidence and the i subscript indicates that $f(D)$ is dose–response curve dependent (i represents 1 through 6).

The coefficients for Land's fitted curves with values of plus minus one standard deviation are given in Table 2 below for doses given in rads (rems). To utilize sieverts for the units in the dose–response equations multiply the linear coefficient by 10^2 and the quadratic and cell killing coefficients by 10^4.

To denote coal and nuclear during normal operation a subscript 'c' and a subscript 'n' are used respectively. We can write the dose–response relationship for each as:

TABLE 2

Dose–response curve coefficients

Dose–response curve from	i	a_{0i}	a_{1i}	a_{2i}
Linear	1	2.5 ± 0.6	0	0
Linear with cell killing (/CK)	2	2.5 ± 1.0	0	0 ± 8.4
Pure quadratic	3	0	0.016 ± 0.004	0
Pure quadratic /CK	4	0	0.026 ± 0.01	11 ± 7.0
Linear-quadratic	5	1.0 ± 1.2	0.01 ± 0.008	0
Linear-quadratic /CK	6	0 ± 1.8	0.026 ± 0.028	11 ± 11

$$f_i(D_c) = D_c(a_{0i} + a_{1i}D_c)(\exp[-a_{2i}(D_c)^2]$$

and

$$f_i(D_c) = D_n(a_{0i} + a_{1i}D_n)(\exp[-a_{2i}(D_n)^2]$$

For an accident corresponding to a dose D_f,

$$f_i(D_f) = D_f(a_{0i} + a_{1i}D_f)(\exp[-a_{2i}(D_f)^2]$$

Prybutok and Gold's [1] general form of the leukemia incidence risk model can then be written as:

$$M_{if} = N[f_i(D_c) - f_i(D_n)]/[f_i(D_f)]$$

where N is the number of plants. After simplification, the following model equations were derived [1]:

$$M_{if} = [N/\alpha][(D_c - D_n)/(D_{TMI})]$$

for the linear model, and

$$M_{if} = [N/\alpha^2][((D_c)^2 - (D_n)^2)/(D_{TMI})^2]$$

for the quadratic model, where M_{if} is the number of accidents for a specified accident fraction which will equilibrate the nuclear and coal power industries; N is the number of plants; α is some multiple (fractional or whole); D_c is the dose for a coal power plant; D_n is the dose for a nuclear power plant, and D_{TMI} is the Three Mile Island accident dose equivalent.

Prybutok and Gold's [1] models were for nuclear and coal power industries which contained equal numbers of equal sized power plants. To relate to real industries, the products N_iD_i or $N_iD_i^2$ represent the real contributions of segments of the power industries, where N_i is the total number of the ith type of power plant and D_i is the average dose from the ith type of power plant.

Before any further development of the models, another look at linear-quadratic models and models with cell killing is called for. Prybutok and Gold [1] showed $a_{1i}D_f^2 \ll a_{0i}D_f$ for all cases where D_f is $\leq 25\ D_{TMI}$, where $D_{TMI} = 1.524$ mrem. This means that the linear term is always dominant in this dose range. Let

$$a_{0i} + a_{1i}D = a_{0i}(1 + \delta)$$

Now, if $D_f = 25\ D_{TMI}$, then for the nominal value of the coefficients,

$$\delta = 0.01524 \ll 1$$

This means that the quadratic term in the linear-quadratic equation is about 1.5% of the linear term. For the value of δ to reach 0.1, or for the quadratic term to reach 10% of the linear term, requires that the dose reaches 10 rem (10,000 mrem or 0.1 Sv).

We can algebraically rearrange Prybutok and Gold's 1987 model equation:

$$M_{if} = [1/\alpha][(N_c D_c - N_n D_n)/(D_{TMI})]$$

for the linear model, and

$$M_{if} = [1/\alpha^2][(N_c (D_c)^2 - N_n (D_n)^2)/(D_{TMI})^2]$$

for the quadratic model.

In order not to dwell on Three Mile Island and to have the convenience of a reference level of dose, an incidence D_{if} was defined as a multiple β of a dose (D_{SI}) from a standard incident (SI) which is defined later.

$$D_{if} = \beta D_{SI}$$

This will replace αD_{TMI}. The linear case becomes:

$$M_{if} D_{if} = N_c D_c - N_n D_n$$

and the quadratic case becomes:

$$M_{if}(D_{if})^2 = N_c (D_c)^2 - N_n (D_n)^2$$

We chose to follow Table 4 of McBride [7] and use the single model for the coal plant and the BWRs and PWRs for the nuclear plants. We also decided to include High Temperature Gas Reactor power plants to allow for future changes in the mix of plants. Let

$$N_n D_n = \Sigma N_{nt} D_{nt}$$

and

$$\Sigma N_{nt} D_{nt} = N_P D_P + N_B D_B + N_H D_H$$

where P stands for PWR, B for BWR, and H for high temperature gas reactor (HTGR). Similarly, for the quadratic case:

$$\Sigma N_{nt}(D_{nt})^2 = N_P (D_P)^2 + N_B (D_B)^2 + N_H (D_H)^2$$

Assuming McBride's (1978) maximum individual doses to bone marrow for 1000 MWe plant emissions yields:

$$D_H = D_B = 5.9 \times 10^{-5}\ \text{Sv}, \quad D_P = 2.7 \times 10^{-5}\ \text{Sv} \quad \text{and} \quad D_c = 18.2 \times 10^{-5}\ \text{Sv}$$

The distribution of the current industries (1985) and the average sized plants are available from the Nuclear Regulatory Commission (NRC 1985 [2]) and the Energy Information Administration (E.I.A. 1985 [17]):

$N_P = 60$ @ 881.4 MWe $\quad N_c = 1283$ @ 222.75 MWe

$N_B = 34$ @ 817.5 MWe $\quad N_H = 1$ @ 330 MWe

The doses for the actual average plants are scaled 1000 MWe plant doses. Recalling that 10^{-5} Sv = 1 mrem, then

$$\text{PWR}(881.4/1000)\times(2.7\times10^{-5}\text{Sv}) = 2.38\times10^{-5}\text{Sv}$$
$$\text{BWR}(817.5/1000)\times(5.9\times10^{-5}\text{Sv}) = 4.82\times10^{-5}\text{Sv}$$
$$\text{HTGR}(330/1000)\times(5.9\times10^{-5}\text{Sv}) = 1.95\times10^{-5}\text{Sv}$$
$$\text{Coal}(222.75/1000)\times(18.2\times10^{-5}\text{Sv}) = 4.05\times10^{-5}\text{Sv}$$

Substitution in the linear model yields:

$$\Sigma N_{\text{nt}} D_{\text{nt}} = 60(2.38\times10^{-5}\text{Sv}) + 34(4.82\times10^{-5}\text{Sv}) + 1(1.95\times10^{-5}\text{Sv})$$

$$\Sigma N_{\text{nt}} D_{\text{nt}} = 308.63\times10^{-5}\text{Sv}$$

$$N_{\text{c}} D_{\text{c}} = 1283(4.05\times10^{-5}\text{Sv}) = 5196.16\times10^{-5}\text{Sv}$$

$$M_{\text{if}} D_{\text{if}} = (5196.16 - 308.63)\times10^{-5}\text{Sv}$$

$$M_{\text{if}} D_{\text{if}} = 4887.52\times10^{-5}\text{Sv}$$

Substitution in the quadratic model shows:

$$\Sigma N_{\text{nt}}(D_{\text{nt}})^2 = 60(2.38\times10^{-5}\text{Sv})^2 + 34(4.82\times10^{-5}\text{Sv})^2 + 1(1.95\times10^{-5}\text{Sv})^2$$

$$\Sigma N_{\text{nt}}(D_{\text{nt}})^2 = 1.13336\times10^{-7}\text{Sv}^2$$

$$N_{\text{c}}(D_{\text{c}})^2 = 1283(4.05\times10^{-5}\text{Sv})^2 = 0.210444075\times10^{-5}\text{Sv}^2$$

$$M_{\text{if}}(D_{\text{if}})^2 = 1.99108\times10^{-6}\text{Sv}^2$$

Standard incident (SI)

Both as a matter of convenience and further to remove references to Three Mile Island, a standard incident (SI) is defined as a single accident with acute bone dose size per person equivalent to the cumulative dose from a normal nuclear plant for a year (Basis 1985). Then

$$\text{Linear SI} = \Sigma N_{\text{nt}} D_{\text{nt}} / \Sigma N_{\text{nt}} = 3.249\times10^{-5}\text{Sv}$$

$$\text{Quadratic SI} = \{\Sigma N_{\text{nt}}(D_{\text{nt}})^2 / \Sigma N_{\text{nt}}\}^{1/2} = 3.454\times10^{-5}\text{Sv}$$

The average of these values is

$$\text{Linear-Quadratic average} = 3.351\times10^{-5}\text{Sv}$$

We will call the dose from a standard incident D_{SI} and define it as

$$D_{\text{SI}} = 3.35\times10^{-5}\text{Sv}$$

We will also define a quantity β as a multiple, fractional or whole, of the standard incident. Therefore,

$$D_{\text{if}} = \beta D_{\text{SI}}$$

and M_{if} is now the number of accidents of size βD_{SI} required to equilibrate the nuclear and coal power industries.

At this point it is desirable to continue the examination of the equations and the effects of the cell killing terms.
For the linear model with cell killing:

$$M_{\mathrm{if}}=\{N_{\mathrm{c}}D_{\mathrm{c}}\exp[-a_{2i}(D_{\mathrm{c}})^2]-\Sigma N_{\mathrm{nt}}D_{\mathrm{nt}}\exp[-a_{2i}(D_{\mathrm{nt}})^2]\}/\{\beta D_{\mathrm{SI}}\exp[-a_{2i}(\beta D_{\mathrm{SI}})^2]\} \quad (1)$$

Similarly, for the quadratic model with cell killing:

$$M_{\mathrm{if}}=\{N_{\mathrm{c}}D_{\mathrm{c}}^2\exp[-a_{2i}(D_{\mathrm{c}})^2]-\Sigma N_{\mathrm{nt}}D_{\mathrm{nt}}^2\exp[-a_{2i}(D_{\mathrm{nt}})^2]\}/\{\beta^2D_{\mathrm{SI}}^2\exp[-a_{2i}(\beta D_{\mathrm{SI}})^2]\} \quad (2)$$

Projection for the year 2000 is achieved by including plants due to go on line by the year 2000 [2,17], i.e.:

83 PWRs	60 w/avg of 881.4 MWe (1985)
	23 w/avg of 1112.6 MWe (New)
42 BWRs	34 w/avg of 817.5 MWe (1985)
	8 w/avg of 1076.5 MWe (New)
1 HTGR	1 w/avg of 330 MWe (1985)
1346 Coal	1283 w/avg of 222.75 MWe (1985)
	63 w/avg of 482.76 MWe (New)

Using McBride's [7] information, the average doses for the plants to come on line between 1985 and 2000 are:

PWRs	$(1112.6/1000)(2.7\times10^{-5}\mathrm{Sv})=3.004\times10^{-5}\mathrm{Sv}$
BWRs	$(1076.5/1000)(5.9\times10^{-5}\mathrm{Sv})=6.35\times10^{-5}\mathrm{Sv}$
Coal	$(482.76/1000)(18.2\times10^{-5}\mathrm{Sv})=8.79\times10^{-5}\mathrm{Sv}$

Both linear and quadratic models with cell killing can be upgraded from 1985 to the year 2000 by using the same form of the equations and adding the new plants projected to come on line. Therefore,

$$M_{\mathrm{if}}|_{2000}=M_{\mathrm{if}}|_{1985}+M_{\mathrm{if}}|_{\mathrm{new}} \quad (3)$$

The full forms of the equations for the year 2000 are given below. For the linear model with cell killing:

$$M_{\mathrm{if}}=\{N_{\mathrm{c}}D_{\mathrm{c}}\exp[-a_{2i}(D_{\mathrm{c}})^2]-\Sigma N_{\mathrm{nt}}D_{\mathrm{nt}}\exp[-a_{2i}(D_{\mathrm{nt}})^2]\}/\{\beta D_{\mathrm{SI}}\exp[-a_{2i}(\beta D_{\mathrm{SI}})^2]\}|_{1985}+\{N_{\mathrm{c}}D_{\mathrm{c}}\exp[-a_{2i}(D_{\mathrm{c}})^2]-\Sigma N_{\mathrm{nt}}D_{\mathrm{nt}}\exp[-a_{2i}(D_{\mathrm{nt}})^2]\}/\{\beta D_{\mathrm{Si}}\exp[-a_{2i}(\beta D_{\mathrm{SI}})^2]\}|_{\mathrm{new}} \quad (4)$$

For the quadratic model with cell killing:

$$M_{\mathrm{if}}=\{N_{\mathrm{c}}D_{\mathrm{c}}^2\exp[-a_{2i}(D_{\mathrm{c}})^2]-\Sigma N_{\mathrm{nt}}D_{\mathrm{nt}}^2\exp[-a_{2i}(D_{\mathrm{nt}})^2]\}/\{(\beta D_{\mathrm{SI}})^2\exp[-a_{2i}(\beta D_{\mathrm{SI}})^2]\{|_{1985}+\{N_{\mathrm{c}}D_{\mathrm{c}}^2\exp[-a_{2i}(D_{\mathrm{c}})^2]-\Sigma N_{\mathrm{nt}}$$

$$\times D_{\mathrm{nt}}^2 \exp[-a_{2i}(D_{\mathrm{nt}})^2]\}/\{(\beta D_{\mathrm{SI}})^2 \exp[-a_{2i}(\beta D_{\mathrm{SI}})^2]\}|_{\mathrm{new}} \quad (5)$$

Results

Since all dose–response curve coefficients with the exception of the cell killing exponential term cancel, then the concern in a sensitivity analysis deals with the values of this coefficient (a_{2i}). As was shown in previous work [1], inclusion of the cell-killing term had no effect on the leukemia incidence risk for accidents less than 25 times the size of TMI or approximately 15 standard incidents. The sensitivity to the size of the incident for large scale concerns was the impetus to carry these numbers to as much as 300 times the standard incident. Figure 1 shows the plot of the linear modeling with cell killing for the mean, the mean ± 1 S.D. and the mean ± 2 S.D. (where S.D. is the standard deviation in the mean value of the coefficient) values of the a_{2i} term. It is interesting to note that this plot does not vary from previous work, as long as the mean value of a_{2i} is used. When the $+1$ S.D. and $+2$ S.D. values of a_{2i} are used, the values of the equations increase in a manner which says that the number of accidents increases with an increase in accident size. Logic would dictate that as the size of the accident increases, it would take fewer accidents to equilibrate the nuclear power industry with the coal power industry. This anomaly begins to occur at approximately 25 times a standard incident and is a result of the $+1$, $+2$ S.D. values of a_{2i} and the mathematical behavior of the

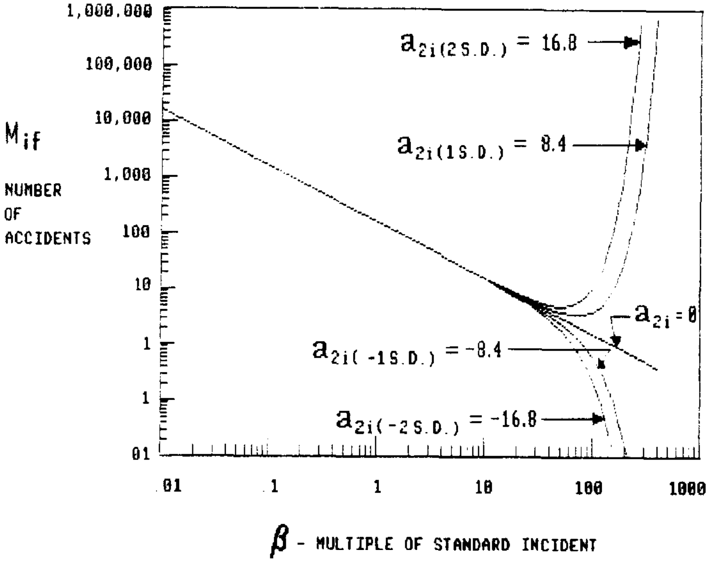

Fig. 1. Plot of M_{if} versus β in the year 2000 for the linear with cell killing model.

exponential term. At this same point, the −1 S.D. and −2 S.D. cause the values of the equations for more M_{if} rapidly to approach zero.

Figure 2 is a plot of the quadratic case with cell-killing term. Again the curves go unstable for large-scale accidents. In the quadratic case, the mean, negative one S.D., the plus one S.D., and the plus two S.D. terms diverge at approxi-

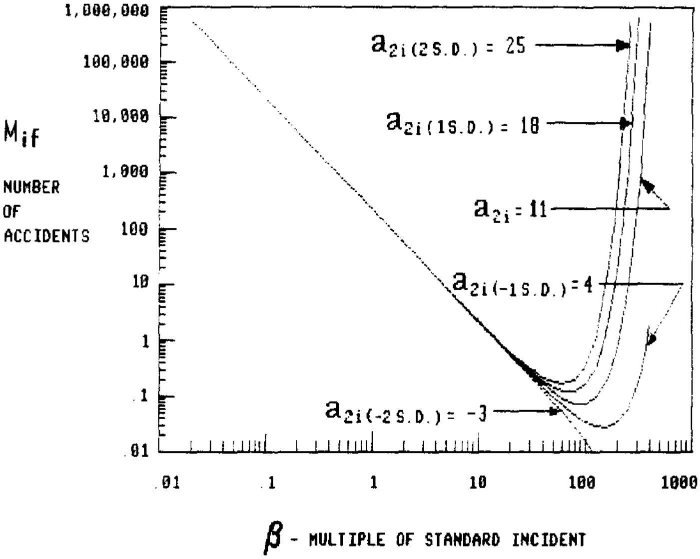

Fig. 2. Plot of M_{if} versus β in the year 2000 for the quadratic with cell killing model.

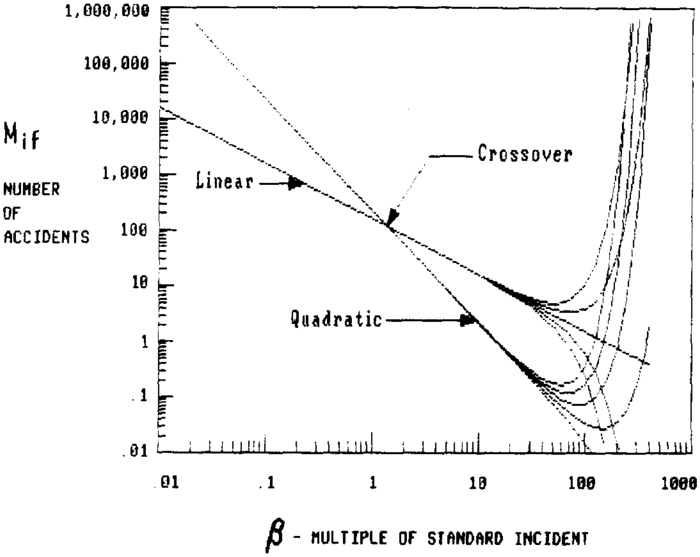

Fig. 3. Plot of M_{if} versus β in the year 2000 for the linear and quadratic with cell killing models.

mately 25 times the standard incidence size. The only term to yield a stable result is the negative two S.D. term.

Figure 3 shows the superimposed linear and quadratic with cell killing cases. It can be seen that for smaller accidents, the linear model gives fewer accidents to equilibrate the industries. The quadratic model indicates fewer accidents to equilibrate the industries when the accident sizes are larger.

Conclusions

It is clear from Fig. 3 that for smaller accidents sizes, fewer accidents are required to equilibrate the industries (worst case) when using the linear model with cell killing. After the crossover point, the quadratic model with cell killing gives the worst case. It is unrealistic to discuss any non-integer number of accidents of any size. Therefore, one accident, independent of size, is the minimum which leads to a meaningful discussion. Zero accidents eliminates all discussion. Regardless of the exponential coefficients used for the cell killing term, the crossover (point where linear and quadratic yield the same value) and the single accident (quadratic) of approximately 42 times the defined standard incident necessary to equilibrate the industries does not change as a result of including the exponential forms. Another way of interpreting these results is that if one assumes a non-accident scenario, the addition of 42 average size nuclear power plants to the year 2000 inventory will equilibrate the nuclear and coal power industries. This is an increase of almost 50% in the size of the nuclear power industry assuming no growth in the coal power industry.

These findings show that it is reasonable to use the simplified linear and quadratic models (for M_{if}) with the included modifications that allow for a mix of plants to bound the radionuclide emissions leukemia incidence risk comparison. The large number and sizes of nuclear accidents required to equilibrate the nuclear power industry with the coal power industry in the year 2000 is due in part to the larger number of coal plants which will be online in the year 2000 and the use of McBride's [7] maximum individual dose values. Changes in these assumptions would modify the resulting risk quantifications but not the techniques. Although the findings in this work are limited by the assumptions and specific to air stack emissions leukemia incidence risk, the techniques provide a step in the quantification of risk comparisons between coal and nuclear power industries.

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