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A PROBABILISTIC EVALUATION OF FALLOUT EFFECTS ASSOCIATED WITH NUCLEAR AIR BURSTS

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ABSTRACT

Several effects of fallout from air bursts of small and nominal yield nuclear weapons under circumstances which include probability of precipitation are modeled. Calculations of the distributions of the effects, and evaluations of the probability of exceeding given values of the effects are included. The model incorporates inherent uncertainties about meteorological conditions and the stochastic nature of mass transport phenomena under turbulent conditions. Effects measurements from tests of weapons suspended from balloons over Nevada have been used to evaluate input parameters and demonstrate the accuracy of prediction of the model under dry circumstances.

GENERAL CONCEPTS

Introduction

Over the past quarter of a century, models dealing with atmopheric dispersive effects in general, and fallout in particular, have periodically been developed, tested, found to be inaccurate, modified, retested, etc., until most were forgotten. This author is of the opinion that the reason most were unsuccessful is that most of them failed to take cognizance of the fact that meteorological and geophysical phenomena are inherently stochastic in nature. The model described in this paper does utilize explicit recognition of the inherent variability of these natural phenomena, and this is perhaps the major significant difference between it and many others of the past. Fallout from the air burst of a nuclear weapon was chosen as the subject of this study because it is of continuing interest in some circles, and upon reflection, it is among the simpler problems in atmospheric dispersion studies.

The model is based on the principle that in making a prediction of the amount of fallout to be deposited, and other associated effects resulting from the detonation of a nuclear weapon at some future time, one has only an estimate as to how fast the wind might blow, how turbulent the atmosphere might be, etc., and therefore any prediction based on calculations utilizing specific values of those phenomena is pertinent to only a very rare combination of events. However, if a very large number of such calculations are made, with the individual parameter values for each appropriately chosen from the observed distributions of values descriptive of the natural phenomena, then a tabulation of the results of all those calculations should give one a good idea of what values of effects are likely, and additionally, how likely they are.

Some Definitions of Terms

Some terms in this paper are used in a somewhat more restricted or different sense than is common in the English language. This section is intended to clarify their meaning in the context of their usage in this paper.

"Cloud" is used with reference to the atmospheric suspension of radioactive debris resulting from a nuclear detonation, or the suspension of tracer material during conduct of an atmospheric dispersion study.

"Storm" is used with reference to areas of active precipitation, or to cells of precipitation systems. What is commonly called a "rain cloud" will be called a "rain storm" (regardless of intensity) or "precipitation system" or "precipitation cell", etc.

"Problem" refers to the entire set of calculations performed in order to examine all the modeled effects resulting from the detonation of a nuclear weapon under a given set of deployment circumstances.

"Case" refers to the limited set of calculations performed in order to obtain one value of an effect (or one value of each of several effects), at one or more distances of interest, using a single combination of elemental parameter values.

"Element" is a parameter value, or functional relation of parameter values, which is a necessary ingredient of a desired computation. A "primary element" is essentially a model input parameter, (such as wind speed, or a particular conversion factor) which is not further decomposed in the model. "Secondary" or "derived elements" are functional relationships of primary elements. In this program, "primary elements" are functionally combined to produce "derived elements" which are combined during the computations of "cases", and all case results are combined to obtain the solution of a "problem".

A "stochastic element", or "random element" is one which has associated with it some degree of uncertainty concerning its precise value. This uncertainty, however, always has well defined statistical parameters associated with it, and any particular value used for this element will come from a distribution of numbers which possess the same statistical parameters. To emphasize this feature, the set of random numbers is usually referred to as the "appropriate distribution", or the random numbers are "appropriately distributed", or "appropriately chosen".

A "totally stochastic" element is one for which a different appropriate random variable is utilized every time the element enters into a calculation.

A "partially stochastic" element is one for which the random variable is appropriately chosen the first time the element is used in a case calculation, but thereafter that same value is used whenever the element enters into the case calculations. Different values are used for each case in the problem, although the same value is used throughout a case.

"Cell" refers to a segment of distance along the path the cloud takes from burst point to a distance of observational interest.

"Cloud inventory" refers to the amount of radioactive material contained within the entire cloud at a time of interest.

Program Organization

The functional relationships between the parameters used to calculate case effects at a particular distance in the model are shown in Fig. 1. The box at the top of any of the tree structures shown in the figure represents an element which is to be calculated. The boxes below it contain elements which are essential to the calculation. This decomposition continues to proceed down the branches of the tree until primary elements, i.e., those which are basic input parameters, are reached. The elements which are in boxes connected together on the same horizontal line are combined together by a proper functional relationship such as by simple multiplication or division or perhaps by more complicated functions, to produce the element in the box above from which they stem. If more than one sequence stems from a box, such as where "Deposition" sprouts two elements, "Dry Deposition" and "West Deposition", a decision process is indicated, such that either one or the other of the branches may be proper, but not both. At the time of execution the branch to be utilized is chosen by an appropriate random process.

Some boxes are not perfectly rectangular. This notation is merely to alert the reader that the remainder of that branch is diagrammed elsewhere, or the element is otherwise described. A pendant hanging from a box is also a notation, frequently redundant, that the remainder of the branch is described elsewhere.

Some of the boxes have an "*" next to them. This symbol indicates that values of that element are specifically extracted as outputs from the program.

The symbols $\in$ and $\ni$ are included in some boxes to indicate that they are stochastic elements. The symbol $\in$ indicates that the element is totally stochastic during the execution of the problem. On the other hand, the symbol $\ni$ indicates a partially stochastic element.

During execution of course, actual computation proceeds from the bottom of the structure up. The structural diagram helps to visualize the elements essential to any calculation, and also, to easily determine which higher elements may be affected by a change in any branch.

Polynomial Representation of Frequency Distributions

If the cumulative distribution function of a variate quantity x is defined by the relation

$$F(x) = r \quad , \quad 0 \leq r \leq 1.0 \qquad [1]$$

then the inverse transformation function of $x^{(1)}$ is usually defined as

$$F^{-1}(r) = x \qquad [2]$$

On occasion it has been found useful to approximate $F^{-1}(r)$ with a polynomial, or a "transformed" polynomial, such that

$$P(r) \approx F^{-1}(r) = x \qquad [3]$$

or

$$P(r) \approx F^{-1}(r) = \log x \qquad [4]$$

where P(r) is a polynomial in r.

Polynomials are fairly easy to fit to most naturally occurring distributions, and such fits up to order 4 or more can readily be done even with some desk calculators.

Other useful extensions of the inverse transformation which this author has found useful, but not seen discussed elsewhere, are the forms

$$P(\upsilon) \approx x \qquad [5]$$

and

$$P(\upsilon) \approx \log x \qquad [6]$$

where υ is a normally distributed random variate.

Equation [3] through Eq. [6] are especially useful where data are available to plot a cumulative distribution, but it is difficult or inconvenient to find a standard distribution function to satisfactorily fit the data distribution.

To use Eq. [5] and Eq. [6] the percentiles of x are converted to their normal deviates, i.e. the 10th percentile corresponds to a normal, (0, 1) deviate of -1.2817 and the 95th percentile to a normal (0, 1) deviate of 1.645. Of course, in using these polynomial approximations a bit of judgment must be exercised. Relations Eq. [3] and Eq. [4] under these circumstances limit the possible range of x. Relations Eq. [5] and Eq. [6] allow for essentially unlimited range of x, but one must be sure that sensibly acceptable values of x are returned corresponding to a range of υ over approximately $-4 \leq \upsilon \leq 4$. Obviously, if in utilizing relations Eq. [5] or Eq. [6], a first order (straight line) fit results, one has a simple normal or log normal distribution, respectively.

Modeling Stochastic Elements

In relating many secondary elements, y to other elements, x, plots of y vs x were constructed to help gain insight into which might be the most appropriate functional relationship such that

$$y = f(x) \qquad [7]$$

As part of this discussion, it should be understood that transforms of y and x might be examined such that

$$g(y') = f(j(x')) \qquad [8]$$

where g and or j may be transforms such as

$$g(y') = \log y' \qquad [9]$$

$$j(x') = x'$$

etc.

Even after transformation and the use of regression analysis for the selection of the best function f, there frequently remains a considerable degree of scatter of the data points of y vs x about the fitted relational line. Well reasoned arguments can be made that the transformations and functional relation should be chosen so that this scatter is not only as small as possible, but further that the degree of scatter should be as uniform as possible over the entire range of x.[2] Throughout the course of this study, every effort was made to satisfy these last conditions while obtaining regression estimates of the functional relationships between elements. In recognition of the unexplainable remaining scatter, the functional relationships between y and x were redefined by

$$y_i = \widehat{y}_i + \epsilon_{yi} \qquad [10]$$

where

$$\widehat{y}_i = f(x_i) \qquad [11]$$

A measure of the remaining scatter is denoted by S_y, which is rigorously defined as the standard deviation of the residuals about the fitted line, or the standard error of the estimate of the regression fit.

In using Eq. [10] and Eq. [11] to predict the value of y resulting from a particular value of x, we are faced with two uncertainties[2]. The first is the uncertainty in $\widehat{y}$, the location of the line itself. The second is the inherent uncertainty due to the scatter of the results of each individual observation about the fitted line, even if it were perfectly known. The magnitude of the first uncertainty is inversely proportional to the number of data points used to obtain the equation, and directly proportional to S_y and the distance one is from the mean of the range of the independent variable. It is always smaller than the second uncertainty, of which S_y is an estimate, and is frequently very much smaller than S_y. The current version of the model ignores the existence of the first uncertainty, assumes perfect knowledge of the fitted equation, and only considers the second uncertainty, equating it to S_y.

Throughout this program, effort has been made to express functional relationships as simply as is possible without sacrificing accuracy or physical significance. One might make the argument that some relations are overly simplified - for example, cloud rise is here a function only of yield. Such considerations as atmospheric stability, temperature, humidity, wind speed, turbulance, etc. have not been included. Aside from the fact that data relating to other parameters is often very difficult if not impossible to obtain, there is one important consideration to include before other parameters are incorporated into the analysis. The a priori uncertainty of all other parameters is implicit in the chosen relation, assuming that the data set from whence it was derived is a representative sample of situations to be modeled. (The latter question is also often difficult to assess). Were one able to reduce the variance associated with the chosen relation by including other parameters, one would have to be able to predict the values, or range of values, of the other parameters expected to be encountered during the modeled situation. At present, this frequently appears quite difficult, and thus all the combined uncertainty inherent in those elements of the problem is contained in S_y.

Limitations of space permit only the briefest descriptions here of the various elements in the calculation. Arguments concerning the appropriatness of selection can be found in a report in preparation, which is a more comprehensive description of the model.

CLOUD DYNAMICS

The model utilizes the simplest of concepts with respect to cloud description. It is assumed that the cloud is a right circular cylinder with a vertical axis of revolution. The top surface is determined by the height at which the cloud top stabilized several minutes after detonation. The bottom surface is chosen as the height of detonation. Cloud radius is a function of weapons yield and travel distance from ground zero. The distribution of concentration within the cloud is assumed to a uniform step function.

Concentration Distributions

The concept of uniform concentration of radioactive material within the main cloud resulting from a nuclear explosion is utilized because of its overwhelming simplicity. Additionally it can be argued and demonstrated that it is also a good description of concentrations within turbulent clouds.

The most popular functional description of concentration distributions within atmospheric clouds is the Gaussian distribution. However, instantaneous concentrations in clouds or plumes display fairly discreet edges and a lumpy and irregular nature associated with concentration throughout the cloud. This character correlates rather well with theories of turbulence which claim that eddies of magnitude equivalent to cloud size will be most responsible for cloud growth, while those of magnitudes appreciably different will be of considerably less importance. In such a situation, where sizable lumps of the cloud are moved hither and yon by turbulence, the approximation of concentration distribution by a uniform distribution appears to be a reasonable assumption.

In discussing matters relating to concentration, one other important consideration must be addressed, namely, the existence of tails. Rigorously, there are no tails associated with a step function. The existence of tails, or regions of measurable concentrations which are orders of magnitude below concentrations within the body of the cloud is well documented. This is a nasty problem which at present is handled by an artificiality called an "exchange coefficient". If one assumed a cloud model as described, but with the lower surface of the cylindrical cloud at ground level, predicted concentrations and associated effects would be orders of magnitude higher than those actually measured on an event being modeled. The model at present is designed to describe the effects of low and nominal yield nuclear weapons. The visible clouds of such devices are almost always confined to the troposphere. Their dimensions are at most about 10 kilometers in extreme height at stabilization, and they are usually several kilometers from top to bottom. If vertical dispersion were as effective as horizontal dispersion, one would expect the base of the cloud to reach ground level within a few tens of kilometers. Such behavior would result in modeled air concentrations and associated effects several orders of magnitude higher than were actually observed on about two dozen air bursts conducted in Nevada. It is well established that vertical dispersion is much smaller than horizontal growth. Effectively the bulk of the cloud material remains at an invariant altitude throughout the modeled period of interest--but a small amount of material is slowly transferred through the layer of atmosphere between the cloud bottom and the ground. In order to obtain values of air concentration near the ground, the concentration in the main cloud is multiplied by a mass transfer coefficient, referred to herein as the "exchange coefficient". Since concentrations elsewhere outside the perimeter of the cloud are not of interest in this model, other "tails" are at present not dealt with.

Cloud Elevation

Cloud top elevation, H is described in this model as a function of yield, y, by the equation(3)

$$\widehat{H} = B_o + B_1 \text{ Log } y + B_2(\text{Log } Y)^2 + B_3(\text{Log } Y)^3 + B_4(\text{Log } Y)^4 \quad [12]$$

H is considered to be normally distributed about $\widehat{H}$. To overcome absurd and rare possibilities such as H being less than burst height because of its random element, H is tested, and if lower than burst height, it is reset equal to twice burst height.

After a great deal of investigation, it was decided that at present the best value for the cloud bottom is at burst height.

Cloud Diameter

Cloud diameter, D, is modeled as a function of distance[4], x, and yield[3], y, by the relation

$$D_x = \epsilon_\sigma B_o x^{B_1} + \epsilon_d b_o y^{b_1} \qquad [13]$$

This relation reflects an initial cloud diameter dependent upon weapon yield, and a growth term dependent upon travel distance. The ϵ_σ and ϵ_d are partially stochastic elements in the relationship, both log normally distributed. ϵ_σ is essentially a measure of the atmospheric turbulence. It is only partially stochastic to model the phenomena that the degree of turbulence remains constant throughout a case history. That is, a cloud which begins its history growing faster than average retains that characteristic. Changes in degree of turbulence, which are occasionally observed, are ignored. A large amount of experimental data, in addition to weapons tests, is available to relate the growth of cloud diameter to distance. The relation between initial cloud diameter and yield is only poorly documented.

METEOROLOGICAL CONSIDERATIONS

Wind Speeds

Climatological data for wind speeds at various altitudes are readily available for much of the world.[9] It has been found useful to describe wind speed distributions obtained from these climatologies by Eq. [6].

Precipitation Scavenging Effects

Precipitation scavenging effects at present are not very well understood. However, a fair body of experimental data exists to indicate that scavenging effects are most highly correlated with total precipitation amounts, and much less so with other storm features.[10]

This model utilizes a concept referred to as the portion of the vertical integral scavenged, (FVI), which is defined as the fraction of the integral of cloud concentration with respect to height which is deposited as the result of precipitation mechanisms.

It can be argued that a useful description of FVI scavenged, F, is given with respect to total precipitation P_t by

$$\log \widehat{F} = B_o + B_1 \log P_t \qquad [14]$$

F is a fully stochastic element, log normally distributed about $\widehat{F}$. P_t is also a fully stochastic element, dependent upon the time interval of interest, t. In the model, this chaining effect is combined in a relation between F and t which is usually of the form

$$\text{Log } \widehat{F} = B_o + B_1 \text{ Log } t + B_2(\text{Log } t)^2 + B_3(\text{Log } t)^3 + B_4(\text{Log } t)^4. \quad [15]$$

Precipitation Probabilities and Amounts

Precipitation statistics are at present a troublesome element in this model. The time scales involved in the model are of the order of minutes or hours, whereas most precipitation information is available at best on a daily basis. Hourly data are very scarce. To overcome this paucity of actual data, some auxiliary simulators were constructed to attempt to simulate hourly time sequences of wet and dry periods, and hourly precipitation amounts, from special observational data and climatological summaries. These sequences of hourly data are very useful for determining probabilities of precipitation, and distributions of precipitation amounts to be observed during periods of arbitrary duration. Data available to verify the accuracy of these simulators is indicating contradictory results, depending upon data source. Further experiments to determine the validity of the precipitation time series simulators is being undertaken.

Storm Sizes

Recent inventigations in precipitation system behavior have begun to document the fact that precipitation is not generally uniform throughout a synoptic system, but is distributed over space and time with respect to amount and intensity over a scale of subsystems, reaching down to identifiable cells of only a few square kilometers of affected area.(5) Additionally, it can be readily verified that precipitation cells identified as such do not generally move with the mean wind, but because of their dynamics move in other ways. To model these effects, it is assumed that storms are circular in area and they have diameters which are fully stochastic, being log normally distributed with geometric mean of approximately 10 km diameter, and geometric standard deviation of approximately 2.5, resulting in a range of storm diameters of about 1 km to 100 km. Also, within any computational cell along a cloud path, the distance separating the centers of cloud and storm is fully stochastic, should the cloud and storm be deemed to interact.

Cloud Storm Interactions

Precipitation scavenging effects enter into the model in two ways. They may deplete the inventory of radioactive material in the cloud before it reaches an observer, and they may affect the deposition of radioactive material upon the environs of an observer once the cloud is overhead.

The cloud path is divided up into computational cells during the execution of a problem. For purposes of inventory depletion, the cloud is considered to reside in each cell for a length of time dependent upon the case wind speed and cell size. The probability of the cloud encountering precipitation while in each cell is computed as a function of residence time, conditioned by whether or not precipitation was encountered earlier along the track. If precipitation is deemed to occur, through selection of a fully stochastic uniform random number, then a storm diameter and center separation distance are also stochastically selected. The intersecting area is calculated, and expressed as a fraction of cloud horizontal area. A FVI is selected as a function of the residence time in the cell. The FVI times the fraction of cloud area interacting with the storm is the fraction of the cloud inventory removed by scavenging in that cell.

For purposes of scavenging effects at a point of observation, the length of time the cloud will be overhead is calculated as a function of cloud diameter, wind speed, and distance the observer is stochastically chosen to be off the cloud diameter. If it is deemed that precipitation will occur, a FVI is chosen on the basis of this length of time, and the FVI is applied to the product of cloud concentration and cloud depth, to obtain the value of wet deposition.

MASS TRANSFER COEFFICIENTS AND CONVERSION FACTORS

The elements of the model which fall into the category of mass transfer coefficients and conversion factors are all fully stochastic elements. Usually they are elsewhere treated as constants, but a great deal of evidence can be presented to show that the assumption of constancy is poor. Additionally, their stochastic parameters can encompass a great deal of uncertainty of problem circumstances, i.e. turbulence, terrain roughness, surface chemistry effects, etc.

Exchange Coefficient

It was mentioned earlier that this mass transfer coefficient was necessary to reconcile differences in concentrations observed aloft and at ground level. A stepwise, linear regression analysis, performed on the logarithms of pertinent weapons test data, indicates that this element is most strongly a function of burst height. A measure of turbulence expressed by the ratio of cloud diameter to travel distance is also important, as is travel distance itself. These factors reduce to a function of burst height, cloud diameter, and travel distance. The exchange coefficient is considered to be log normally distributed about its median functional value.

Deposition Velocity

Deposition velocities used for this model were derived from weapons test data which allowed deposition, as measured by dose rate surveys, to be combined with air sampler data obtained at similar locations, to obtain the statistical parameters for this element's distribution. Deposition velocities are apparently uncorrelated with other elements, and are considered to be log normally distributed.

Deposition to Dose Rate Conversion Factors

The median value for this conversion factor was interpreted from a simulation study by Cohen(6), and from a great deal of fallout monitoring data.(7,8) The variance of its log normal distribution was obtained by examining distributions of redundant fallout monitoring data.(8)

Radioactive Decay

The decay of radioactive fission products is modeled by approximating the actual decay vs. time relation, which has been rigorously obtained by summing the decay relations for the numerous individual fission product isotopes, by a series of power function approximations fitted over many short time intervals. Decay computations are thus performed by essentially a table entry and interpolation routine.

Determination of Computational Cell Sizes

In solving problems treated by this model it is convenient to obtain solutions at a variety of distances from the burst point. For the present model, distances of interest lie between a few and a few hundred kilometers. Experience has shown that the sequence of distances employed in most atmospheric dispersion problems is most economically displayed on a logarithmic scale. However, in this problem cloud and storm interactions appear to be most reasonably treated on a linear distance scale. A compromise was effected whereby the distance of interest was first divided into a relatively large number of equal basic segments on a logarithmic scale. For the first fourth of this number, the cells were eight basic segments long. For the second fourth, four basic segments, two basic segments for the third fourth, and cells were left equal to the basic segments in the last fourth. This division allows cells to vary from a few kilometers near burst point, to a few tens of kilometers at maximum distance. Readjustments are then made to cell boundaries so that observational points fall at the geometric centers of the cells. Cell locations are invariant throughout the problem once they have been established.

SUMMARIZATION OF COMPUTATIONAL RESULTS

The complete solution to a problem consists of calculating the desired effects using several thousands of cases, each employing a distinct combination of parameters, and examining the distributions of results. During the course of the evaluation, effects are calculated for each distance of observational interest, beginning at distances closest to burst point. Values of partially stochastic elements are saved for use in further computation. The values of effects to be displayed are bin sorted, and selected percentile values are obtained by interpolation after the bin sort, and printed out. These selected effects values are also saved to be graphically presented at the end of the problem computations. Graphical displays, a sample of which is shown in Fig. 2, are then prepared, in which equal percentiles of effects vs. distance are plotted. Because the problem is solved by a Monte Carlo technique, the equal-percentile lines, especially those depicting small and large percentiles, tend to be quite irregular and ragged. These irregularities are smoothed out by employing a least squares fit to a fourth order polynomial through the points interpolated for any given percentile curve.

VERIFICATION EXPERIMENTS

Unclassified reports of fallout monitoring activities are available for the Plumbob series[7], and Hardtack II[8] series of weapons tests, conducted in Nevada in 1957 and 1958 respectively. Although the weapons tested as air bursts were suspended from balloons, rather than being air drops, the data were nevertheless considered useful for parameter evaluation and verification for this model. Data from twelve tests in the Plumbob series were used for parameter determination, and simulations were made to compare predicted effects with observed effects for eight tests in the Hardtack II series. Additionally, data from other weapons tests were used for parameter evaluation if considered appropriate. Figure 2 shows a comparison of predicted effects with data points obtained for fallout arrival time dose rates as measured on the Lea and Santa Fe tests. This figure also allows one an idea of the range of effects values to be expected, and the graphic display of effects produced by the computer program. Other verification exercises for dry cases produced results similar to Fig. 2, in that the observed effects fall nicely within the range of effects predicted by the model. Data do not exist to verify accuracy of predictions for precipitation effects.

The present configuration of the model has been coded in FORTRAN for execution on a CDC 7600 computer. All verification exercises and the example of program output in this paper were run using 5000 cases in the Monte Carlo portions of the program. Execution time for each complete problem is approximately 50 seconds under these conditions. One of the objectives during coding was to produce a program which would execute quickly, hence several system features and fast subroutines unique to the CDC 7600 computers at Los Alamos were incorporated. The program can, however, be readily modified to execute in a standard FORTRAN environment, with some loss in speed of execution to be expected.

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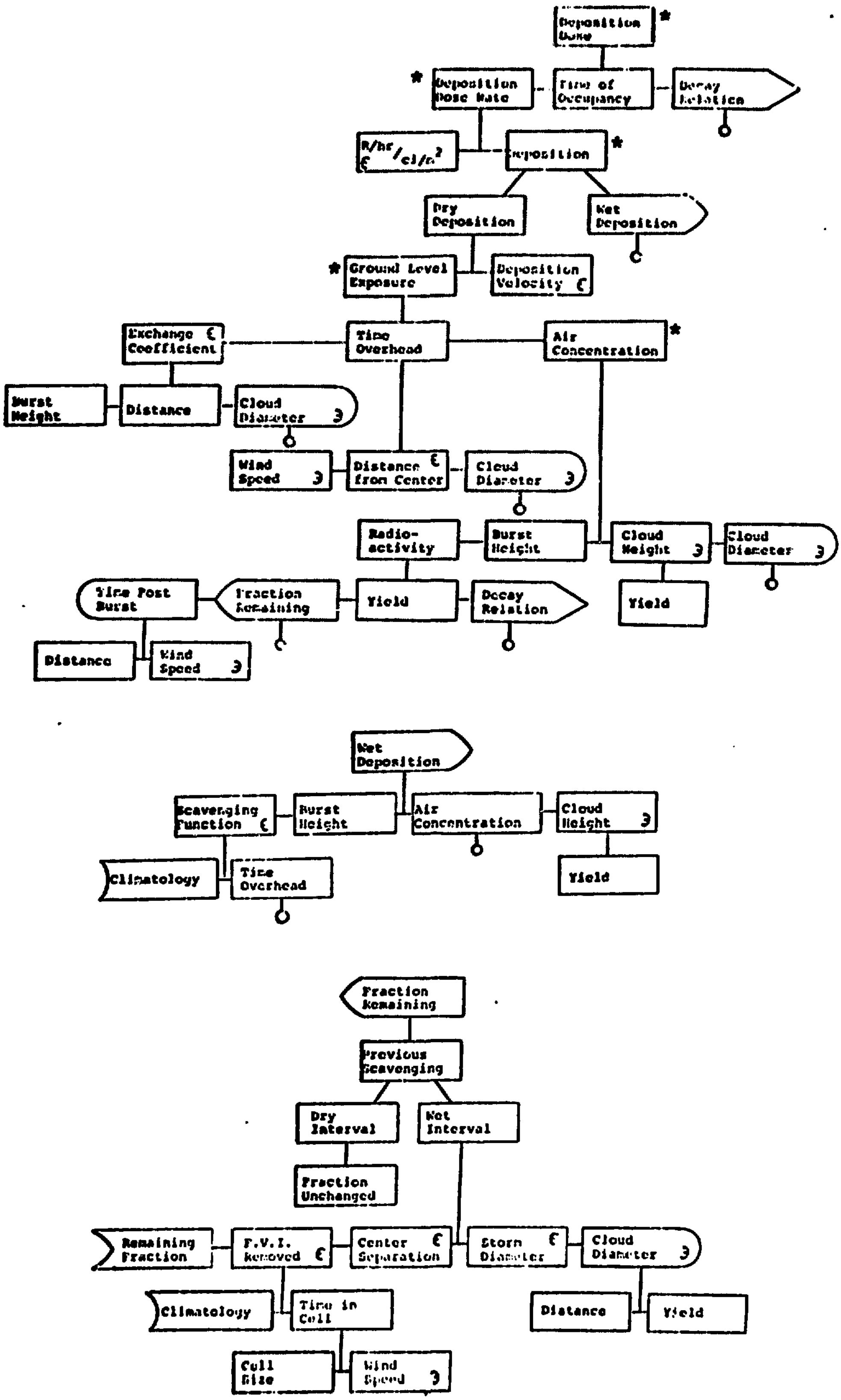
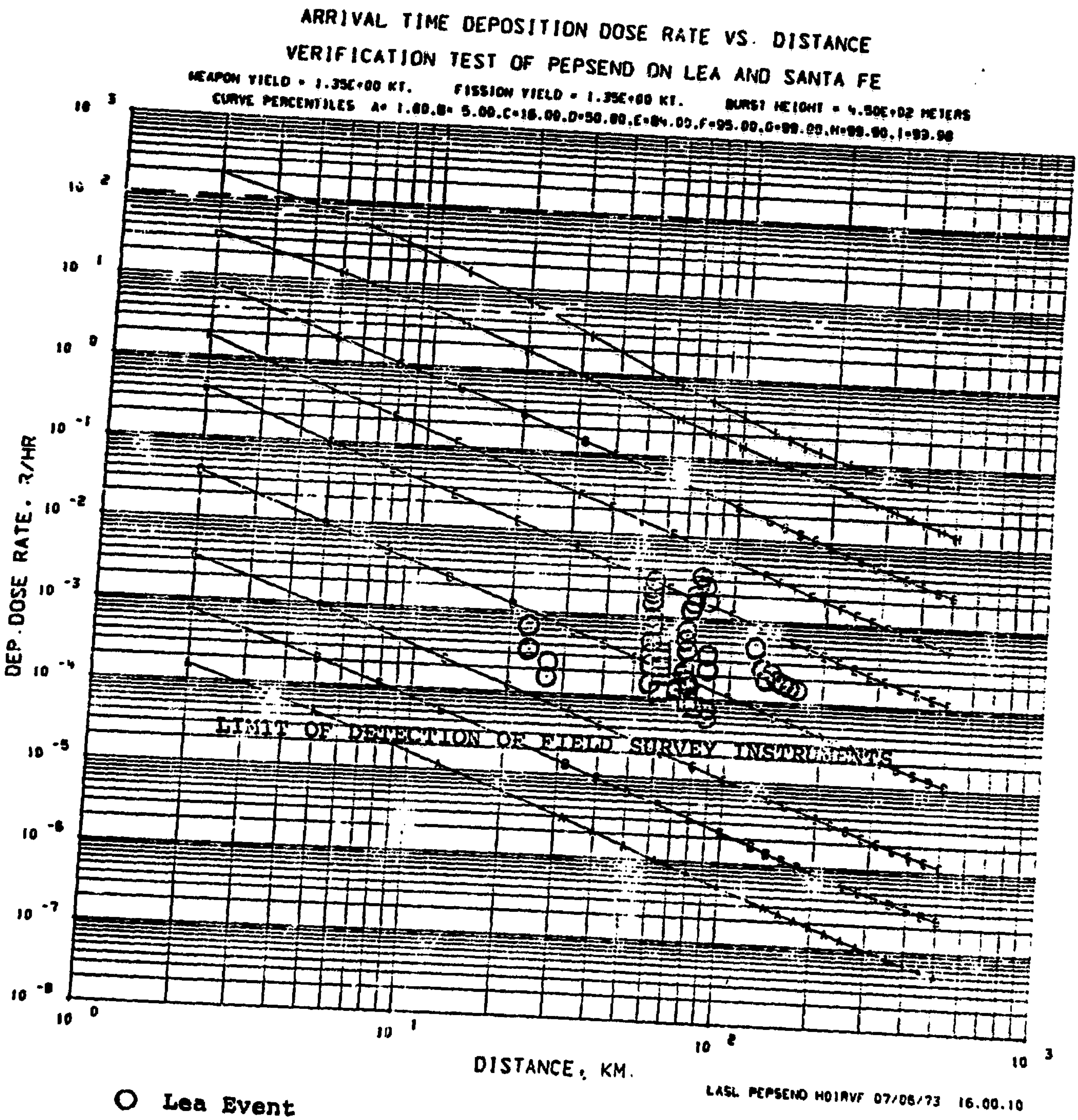


Figure 1. Structural Relations Between Model Elements



○ Lea Event

□ Santa Fe Event

Figure 2. Example of Program Output, With Verification Points