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FALLOUT MODELS AND
RADIOLOGICAL COUNTERMEASURE EVALUATIONS

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INTRODUCTION

The design of a fallout model, or any other model, for application in investigations of specific types of problems, generally requires recognition and definition of the end-point measures associated with the purpose of the application. In the case of civil defense applications where the evaluation of radiological countermeasures is involved, the focal point of interest in the modeling is to make objective representations of radiological environments resulting from a nuclear war. Within this scope of application, the end-point outputs of a fallout model must be designed to yield estimates of the two measures of radiological hazard: (1) the exposure dose from external radiation and (2) the absorbed dose due to radiation from radionuclides that have entered the body.

The designation of these two measures of radiological hazard as model outputs at the outset determines, to a large degree, the conclusion that the design of the fallout model involves the consideration of all pertinent processes that may occur between the time the first detonation occurs in a nuclear war to any specified later time of interest.

Radiological countermeasures may be defined as including all positive actions taken to reduce either the exposure dose or the absorbed dose. To evaluate the relative usefulness of these countermeasures, information is required both on the effectiveness of each in reducing the exposure dose or the absorbed dose and on the major operational and technical parameters that influence the countermeasure effectiveness (including representations of the dependence of the countermeasure effectiveness on these parameters). Biological effects, in terms of maximum allowed doses, are utilized in the evaluations as boundary conditions, or constraints, in the determination of the feasibility characteristics of a countermeasure. These dosage constraints are necessary, both from a mathematical and practical standpoint, to establish an appropriate relationship between the output from a fallout model and performance parameters of the countermeasures. They are also necessary for the determination of numerical evaluations of the adequacy of the countermeasures. The form of the constraint is always associated with a judgment regarding the biological effects from a given radiation dosage level.

In the following sections, the fallout models that either have been or are being developed for civil defense applications are outlined. The fallout model output parameters that serve as inputs to contamination-decontamination models for use in countermeasures are summarized in the discussion of the contamination-decontamination model.

THE FALLOUT MODEL

Models for the deposition patterns from both world-wide and local fallout have been developed and reported.^{1, 2} Both models are based on theoretical concepts of fallout formation and distribution processes that were deduced from the analysis and correlation of a large variety of data on fallout. To facilitate the application of the models in damage assessment and other studies of interest, the models are expressed in the form of fallout deposition scaling systems. In both models the scaling parameters are evaluated from carefully selected sets of analyzed data. In the following discussion, the world-wide fallout model is described first.

The assumptions and parameters considered in the world-wide fallout model are as follows:

1. The types of detonation considered include air bursts and land-surface bursts; all the radioactivity (fission products plus induced activity) produced in an air detonation is assumed to be world-wide fallout; about 20 percent of the radioactivity produced in a surface detonation (mainly the decay products of the rare gases) is assumed to form world-wide fallout.
2. For the air detonation, the radionuclide composition is assumed to be unfractionated, and all nuclides are assumed to be potentially soluble in water (i.e., in raindrops).
3. The fraction of the debris initially injected into each of three altitude compartments is given, as derived from cloud heights and dimensions, as a function of total weapon yield.
4. The residence half-life for the debris initially injected into each of three altitude compartments as evaluated from a variety of reported data on world-wide fallout, is specified for estimating the relative yearly and accumulated deposit levels.
5. A standardized monthly deposit rate distribution, with a peak in the month of April, as evaluated from reported data on

world-wide fallout, is utilized for estimating the relative monthly deposit rates.

6. A standardized total deposit distribution as a function of latitude with a peak at 37 degrees, as evaluated from reported data on world-wide fallout, is utilized to estimate the fraction of each nuclide that is eventually deposited in each of a series of latitude bands.
7. The latitude of injection into the atmosphere from each detonation and weapon yield determines the fraction of the debris that is eventually deposited in the northern and southern hemispheres.
8. Ten percent of each nuclide produced in each detonation is assumed to be deposited as dry fallout.
9. Ninety percent of each nuclide produced in each detonation is assumed to be deposited along with rain as wet fallout.
10. The fraction of each nuclide deposited with rain in each latitude band is taken to be proportional to the average yearly rainfall at each location within the latitude band.
11. The outputs of the model include the current monthly deposit and the total deposit at any given date; the unit of measure of these quantities is atoms per square foot at zero time (i.e., time of detonation) for any nuclide of interest.
12. The computer program is arranged to accumulate the world-wide fallout deposits for any radionuclide from any number of detonations that may be assumed for a global nuclear war.
13. The models for the contamination of water and food crops (both foliar contamination and root uptake) are based on reported data on the contamination levels of these items from past weapon tests.

The manner in which these assumptions and parameters are used in the world-wide fallout model and the numerical values of the major parameters, where applicable, are given in Reference 1.

The local fallout model considers only land-surface detonations and consists of the following fallout model elements, as submodels:

1. Weapon models
2. Condensation models
3. Particle cloud models
4. Distribution models
5. Contamination models
6. Dose models
7. Resource models
8. Transport system models

The weapon model was developed to provide estimates of the contribution of induced radionuclides to the gross mixture of radionuclides that might be found in fallout, in addition to the fission product nuclides. Considerations include the fraction of the fission yield of a weapon, the weapon type and total yield, soil composition (including water content) and its variation over the continental United States, and the chemical composition of various urban structures. The model is based on empirical scaling relationships that were derived from reported data. A preliminary report on the weapon model has been prepared and is in the process of editing and review. The output from the model is in the number of radioactive atoms produced in a detonation at zero time.

The currently used condensation model is similar to that reported in Reference 2. In this model, it is assumed that the radioactive nuclides (fission products plus induced activities) are initially all vaporized along with large amounts of soil and that these vaporized species begin to condense and form small liquid particles as the fireball cools to 3000 or 4000 degrees K; at lower temperatures, where larger particles can exist in the fireball either in a completely or partially melted condition, most of the small particles coalesce with the larger ones, and the still vaporized material condenses into these larger liquid particles. At later times, when the fireball or cloud has cooled further, the surface of the entering particles is no longer melted; when this occurs, the remaining volatile elements (or their decay products) condense on the surface of these unaltered crystalline particles as well as on the surface of the cooled glassy, previously liquid, particles.

The condensation model is based on the thermodynamic functions for ideal gases, ideal solutions, and an ideal soil which has a defined melting point at 1400 degrees C. The ideal thermodynamic system was assumed because of lack of available pertinent thermodynamic data. Kinetic theory and diffusion effects are not expressly utilized in the mathematical formulation of the model. However, in the development stages of the model, application of kinetic theory was utilized to estimate such quantities as collision rates and atomic velocities as a function of the rate of change of temperature in the fireball; these

estimates provided some guidance on the rapidity at which gas condensation processes could occur. In the current model, the diffusion effects are idealized for the so-called two periods of condensation; thus, effectively, a high degree of diffusion is assumed for the liquid particles, and a low degree of diffusion is assumed for the unaltered solid particles. A sharp discontinuity in the diffusion of the radionuclides into particles is assumed to occur at 1400 degrees C.

The amount of soil initially vaporized and the total amount of soil melted and in the fireball when it has cooled to 1400 degrees C is estimated from thermal data on soil minerals and fireball energy balance considerations. These estimates, for certain weapon yields, are correlated, for verification, with reported data on the specific activity of collected fallout samples.

The first output of the calculation is given as the fraction of an element that has condensed (this fraction is called an "r" factor) between zero time and any later time after detonation, or to any temperature between 3000 and about 300 degrees K as a function of weapon yield and particle diameter. The estimates of the diameters of the particles that are present in the fireball at a given time after detonation are based on empirical scaling functions derived from adjusting the model output to reported fractionation data (given as a function of particle diameter) on fallout from weapons in the megaton yield range. Part of one of the cloud models was utilized to assist in the derivation of the functions.

Two final outputs are provided by the condensation model: (1) an air ionization rate decay curve as a function of particle diameter (or terminal falling velocity) for three feet over an ideal infinite plane contaminated uniformly with the equivalent activity from one fission event per square foot and (2) the ratio of the number of potentially soluble atoms of a nuclide at zero time to the ionization rate at one hour after detonation as a function of particle size (or terminal falling velocity). In use, the number of potentially soluble atoms is arbitrarily taken to be those that are computed to have condensed on the exterior surfaces of the fallout particles at fireball temperatures lower than 1400 degrees C. The model calculations of both outputs are currently based on individual nuclide disintegration rates as a function of time after fission for normal (unfractionated) fission products from slow neutron fission of U-235. These disintegration rates are adjusted (1) for differences in fission yields for other modes of fission and for other fissile materials, (2) to air ionization rates by use of multipliers derived from analysis of individual nuclide decay schemes, and (3) to air ionization rates from fractionated radionuclide mixtures by use of

the "r" factors. An example calculation of the ionization rate decay curves from use of the weapon and condensation models is shown in Figure 1.

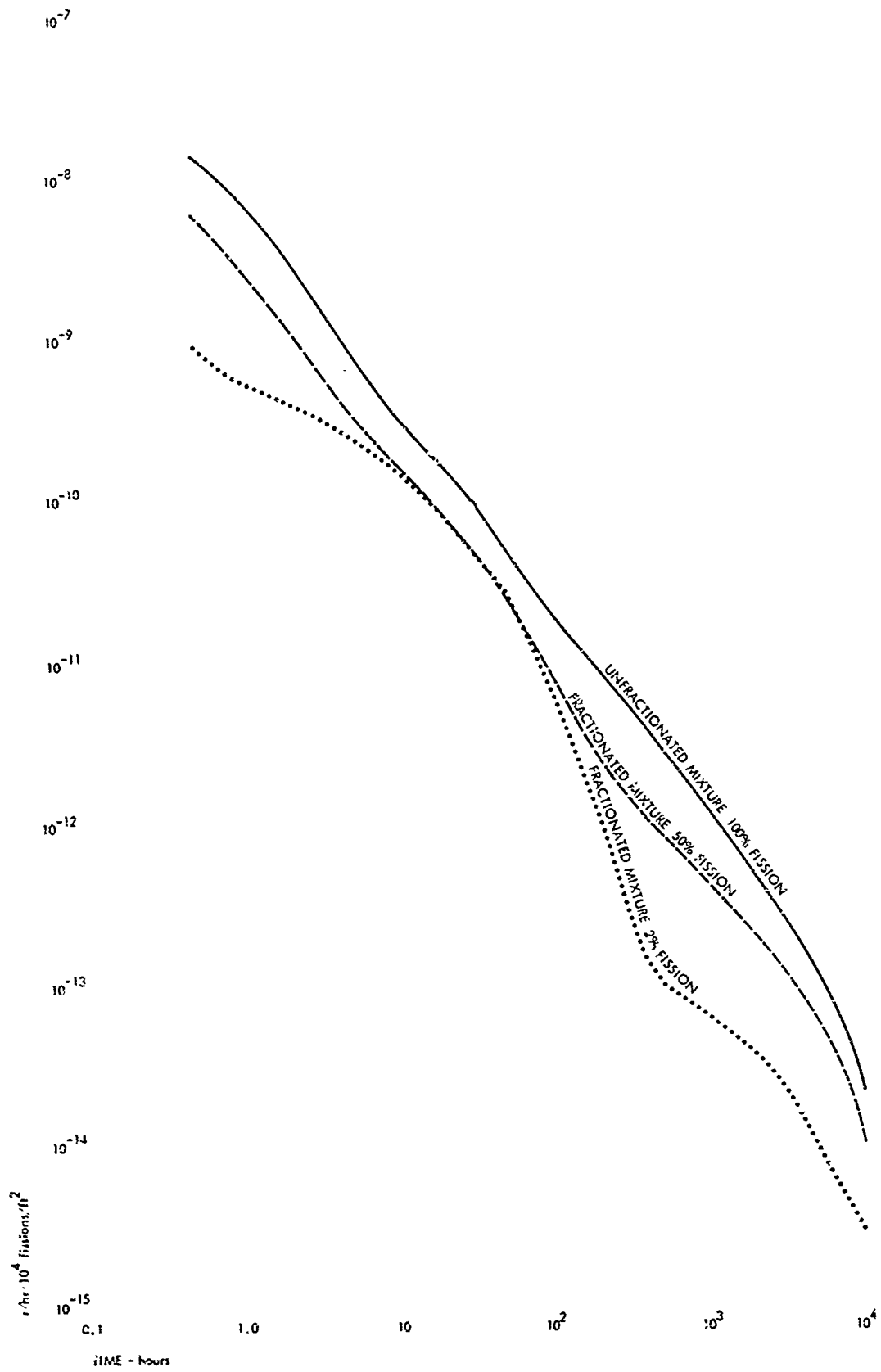
The only available information for improving the currently used condensation model is the vapor pressure and diffusion measurements of Norman *et al.*³ Present and future model improvement work involves the incorporation of the new thermodynamic and kinetic data, with special emphasis on the development of appropriate functions for the diffusion effects.

The current particle cloud models consist of a stem particle cloud and the visible stabilized mushroom cloud as the initial volumes for the fallout particles. The visible, stabilized mushroom cloud, as a source volume of particles, is assumed to have the shape of an ellipsoid of revolution; the variation of the cloud dimensions and height with weapon yield is derived from observed data. The radioactive elements carried by fallout particles with a given diameter are assumed to be uniformly distributed throughout the stabilized cloud volume. The stem particle cloud consists essentially of a series of circular particle discs whose radii increase exponentially with height from a minimum height (depending on weapon yield) up to the mid-height of the visible cloud, with the largest particles in the disc at the minimum height and with the particle diameters decreasing with height. The time after detonation at which each disc starts falling to earth is a logarithmic function of the height of the rising cloud, depending on weapon yield. The stem particle cloud model is thus designed to reproduce, in a crude way, the resultant effect of internal coroidal circulations on the times after detonation and the altitude at which particles of a given diameter are ejected from the rising cloud and begin to fall back to earth.

Adjustment of the cloud model parameters to reported or observed times of arrival of fallout particles of a given size permitted the derivation of scaling functions (i.e., the functional dependence on weapon yield) of the average time that the particles circulate around the periphery of the rising cloud before they fall towards the earth under gravitational forces only. The circulation time scaling function is used to (1) estimate the time of arrival on the ground of particles of a given diameter (or terminal fall velocity), (2) compute the variation of the air ionization rate with time after detonation for very close-in fallout, and (3) compute the variation with particle diameter of the "r" factor for each radionuclide (see condensation model). However, because of the empirical form of the derivations for these models, the times of arrival from the stem altitudes are limited to locations downwind from ground zero.

Figure 1

COMPUTED IONIZATION RATE CURVES FOR THE RADIONUCLIDE COMPOSITIONS
IN FALLOUT PARTICLES OF A GIVEN SIZE GROUP FROM AN ASSUMED 10 MEGATON
YIELD SURFACE DETONATION ON AVERAGE SOIL



The particle cloud model associated with the stabilized visible cloud is also designed to provide estimates of the fallout arrival times and the variation of the air ionization rate at 3 feet above a flat plane with time after detonation during the fallout arrival period. The estimates include contributions to the ionization rate from both the airborne particles and the deposited particles. Empirically derived distributions of the activity as a function of the terminal fall velocity of particle groups and of the weapon yield are used to estimate the deposition rate of the fallout as a function of the time after detonation.

The currently used fallout distribution model¹ is actually a fallout pattern scaling system. The computed fallout patterns are in two parts: (1) a stem fallout pattern and (2) a cloud fallout pattern. The fallout pattern contours are expressed in terms of the standard intensity (i.e. the air ionization rate at 3 feet above a flat plane in roentgens per hour decay-corrected to one hour after detonation) including nominal corrections for terrain roughness and instrument response. In other words, the standard intensities are referred to observed or measured ionization rates at three feet above an open area with terrain features and land surface roughness similar to that of a coral island or of the Nevada desert.

The basic scaling system considers the dependence on weapon yield and on average or effective wind speed of the coordinate locations and the standard intensities for nine different selected locations in the fallout area. These selected location-standard intensity combinations are defined as fallout pattern features. Four of the pattern features are used to generate the contours of the stem fallout pattern and five are used to construct the cloud fallout pattern. The scaling functions for the coordinates and standard intensities associated with each of the pattern features were derived from the respective particle cloud model parameters. Characteristic terminal fall velocity scaling functions were derived for each of the nine pattern features from selected fallout patterns that were constructed from evaluated weapon test data. These terminal fall velocity scaling functions, in turn, provide the means for computing the variation of the coordinates of each of the nine pattern features with weapon yield and effective wind speed. Functions describing the variation of the standard intensity for each of the pattern features with weapon yield and with effective wind speed are similarly based on the terminal fall velocity scaling functions; the latter are utilized as limit values for evaluating activity integral approximations for the standard intensities which are derived from the two particle cloud models.

The shapes of the contours for the stem fallout pattern are idealized and, in the upwind and crosswind directions, they consist of concentric circles which are joined to half ellipses in the downwind direction from ground zero. The shapes of the contours for the cloud fallout pattern, also idealized, are in the form of two half ellipses. The width of the pattern is derived from pattern integrations for conservation of a given fraction of the total radioactivity produced in the detonation (in terms of the r/hr at 1 hour). The dimensions of the circles and ellipses for specified contours are determined from a systematic combination of the locations and intensities of the nine pattern features. The theoretical upper limit of the total activity within the total fallout pattern is about 80 percent of the activity produced (20 percent is allocated for world-wide fallout). The activity integrals, evaluated for the fractions of the total activity originally produced in the detonation that is contained within the 1 r/hr at 1 hour contour, are adjusted to range from 40 percent for a yield of one kiloton to 75 percent for a yield of 100 megatons. The contour levels are adjusted to the yield equivalent of 100 percent fission.

The fallout pattern scaling system, as derived from the observed fallout patterns, contains the effects of lateral wind shear that were in the original fallout patterns. Because this feature did not permit the calculation of fallout arrival times at all locations in the derived fallout patterns from the particle cloud models, a standard lateral wind shear submodel was designed for which calculations have been made to provide a means for distorting the idealized pattern shapes to a degree depending on the assumed gradient in the crosswinds from the top to the bottom of the cloud.

In addition to the standard intensity, the output of the model for describing the radiological situation at any coordinate location of interest includes a value of the median diameter (or terminal fall velocity); the mass contour ratio (milligrams of fallout particles deposited per square foot of horizontal surface divided by the standard intensity), the minimum and maximum terminal fall velocities of the deposited particles; and the total mass of the deposited particles per square foot of horizontal surface.

Current and future work on the distribution models consists in a re-evaluation of the activity-size distributions for the fallout produced in past nuclear test detonations. This work includes the use of all observed standard intensities, times of fallout arrival, particle size distributions, wind data, and other such quantities (where available) at each location in the fallout area to derive the original particle source altitudes and the activity-size distribution for the fallout.

The derived distributions are used to back-compute the observed parameters at each data point. In each case, this analysis procedure permits the evaluation of the degree of fit of the derived model to the available data, point-by-point, as observed. Once satisfactory agreement with the data points is achieved, the fallout pattern is computed in sufficient detail for the reconstruction of the contours for the detonation in question and then another pattern is computed for the case of no lateral wind shear and selected values of effective wind speed. When these computations are completed, the latter group of patterns will be utilized to re-evaluate the scaling functions for the distribution model.

In addition, fallout patterns from detonations at various heights above ground surface and below ground surface have been analyzed with respect to the areas within contours and the fraction of the activity contained within the fallout pattern. Correlations from these analyses are being utilized to develop fallout pattern scaling functions for other than land-surface detonations. When these correlations are completed, the fallout scaling system parameters will be expressed in terms of the scaled height (or depth) of burst as well as in terms of weapon yield.

The external contamination models, either in current use or in process of revision and development, include the following:

1. Contamination of paved areas and roofs in urban complexes
2. Contamination of exposed water sources and distribution systems
3. Retention of particles by the aboveground parts of plants
4. Contamination of exposed animals and fowl
5. Personnel contamination
6. Ingress of fallout particles into structures.

The basic independent parameters common to most of these models include (1) particle diameters, (2) micrometeorology (wind speed and direction at near-surface locations), (3) humidity, and (4) rainfall. The weather factors, as applied, lead to redistribution of the particles with time after the initial contamination takes place.

The internal contamination models, either in current use or in process of revision and development, include the following:

1. Uptake of radionuclides by food crop plants through their root systems

2. Assimilation of radionuclides by food crop plants through their foliage or fruits
3. Assimilation of radionuclides by animals and their subsequent presence in foods (i.e. in meats)
4. Milk contamination
5. Contamination of fowl (meat) and eggs
6. Assimilation of radionuclides by insects
7. Internal contamination of aquatic species
8. Assimilation of radionuclides by human organs.

The internal contamination models basically consider (1) the behavior of single (soluble) radionuclides from fallout in food chains, (2) the growth cycles and growth patterns over time of all species considered, and (3) the likely diets of the species under consideration.

The dose models in current use for plants, animals, fowl, insects, and aquatic species consider only external gamma radiation and the radiosensitivity of these species to external radiation. In most cases, the radiosensitivity (in terms of LD₅₀ or LD₁₀₀) to a brief exposure is utilized in the models. A model for estimating the dose from external beta radiation sources for plants and other species is being developed.

The dose models for humans include methods for estimating both the exposure dose from gamma radiation and the absorbed dose to body organs from assimilated radionuclides (the latter as a follow-up to the internal contamination model for humans). In civil defense applications involving the evaluation of a radiological countermeasure or the determination of performance requirements, the following exposure dose categories, as criteria, are utilized:

1. The maximum dose from which recovery is virtually certain is 200 r, ERD; this ERD is not exceeded if the exposure dose does not exceed 190 r in one week, 270 r in one month, or 700 r in one year.
2. The exposure dose for which death is virtually certain is 600 r in four days or 1,000 r in one month.
3. The consequences of intermediate exposure dosages are uncertain or unknown.

In applications to the radiological consequences following a nuclear attack, the dose models and radiosensitivity of each of the biological species are used to estimate the number of fatalities, the number of casualties, and the number of noncasualties among humans and the number

or amounts of other biological resources that survive (as well as the number and amounts of each that may be recovered by the humans without additional casualties).

The resource models currently in use include all items that serve as the data base for application of the models. These include, on a national basis (1) target lists, (2) attack patterns, (3) population distributions by location, (4) processing plant distributions, (5) food crop and pasture land distributions, average crop yields, planting times, and harvest times, (6) domestic animal distributions, (7) forest land distributions, (8) shelter distributions, (9) water source distributions, and drainage systems, (10) soil characteristics and composition distributions, (11) annual rainfall distributions, and (12) any other resource of interest (public utilities, petroleum industry, etc.).

The available processing, transportation, and local distribution system models for estimating the times and amounts of produce that go from producer (i.e., farms) to the processor, from the processor to local distribution centers, and from the latter to the consumer are as yet too few in number for direct model use. The format of such a model for wheat and milk has been recently developed.⁴ These models are needed to establish the possible composition of postattack diets and the appropriate time scale for application of the absorbed dose models.

CONTAMINATION-DECONTAMINATION MODELS

The outputs from the dose models generally provide the means by which radiological countermeasures are evaluated with respect either to feasibility of application or to design requirements. This evaluation involves a limiting case determination based on the first category of the exposure dose criteria discussed above (see dose models).

For a countermeasure such as decontamination that involves the removal of the fallout particles from various surfaces and the disposal of these particles, the evaluation includes at least two factors: (1) the effectiveness of the method in removing the particles from the surfaces and (2) the average rate at which the particles can be or would be removed and disposed of by application of a specific amount of work. Once these factors are evaluated experimentally, radiological recovery operations can be modeled and applied to civil defense systems evaluations in nuclear war situations. The fallout model outputs that are pertinent to the specification of fallout conditions for radiological recovery operations include the following:

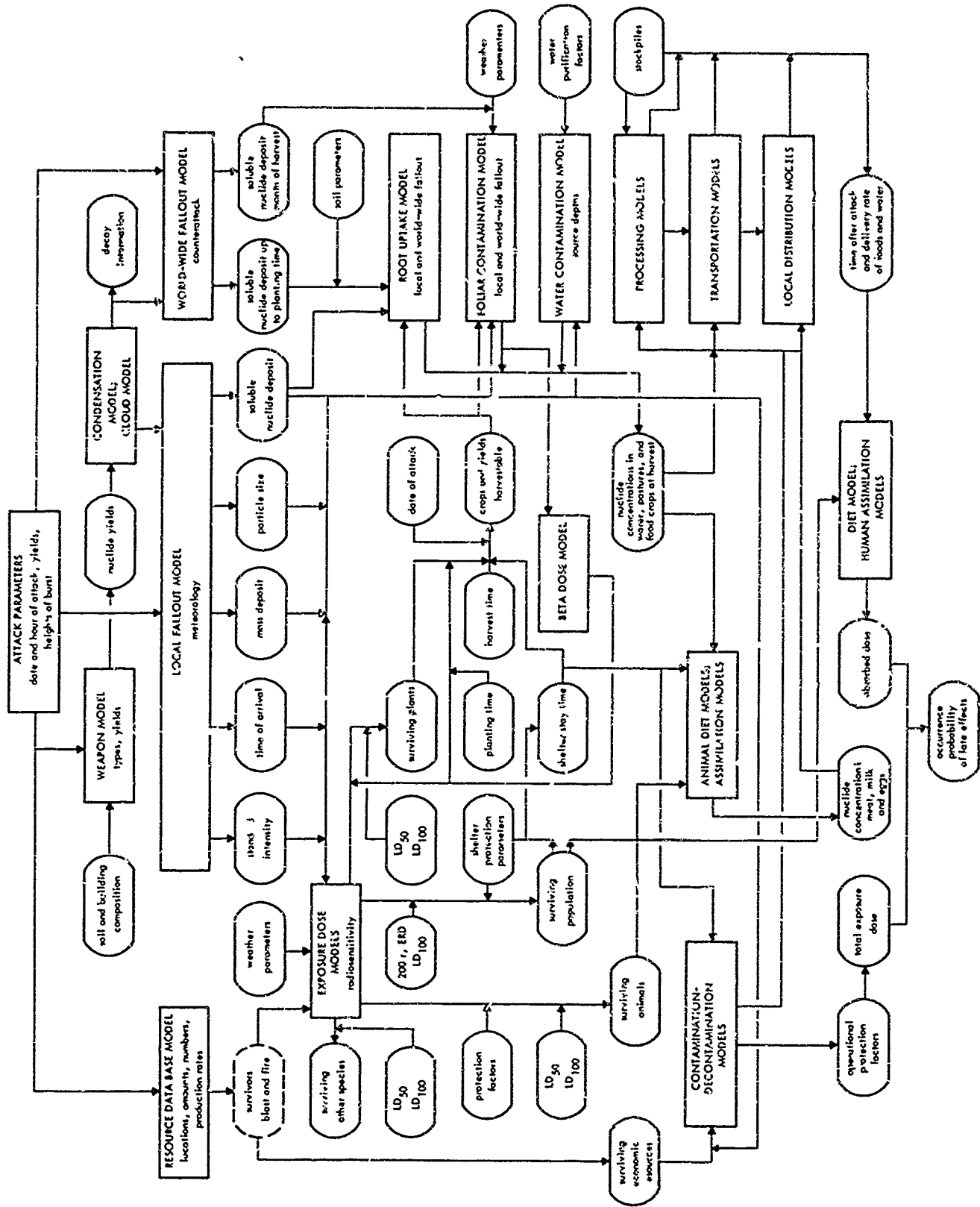
1. Range in standard intensities for which the method may be useful
2. Surface density of particles associated with the range of standard intensities
3. Range in particle diameters
4. Likely solubility of important radionuclides
5. Time (or times) after contamination when application of the method is feasible because of exposure dose limits to the crews.

In addition to the decontamination effectiveness information, the contamination-decontamination models must include representations for "operational" crew doses, accounting for equipment shielding and the effect of the cleaning operation on the exposure doses of the crews. Additional information important to the description of the operator includes setup times, rate of fuel consumption, rate of use of other supplies (water, etc.), crew organization and size, and other factors that may influence the effectiveness of the method or its use as a radiological countermeasure for any postattack situation. The numerical specification of these various parameters provides the basic information needed in the modeling of all radiological defense system components for system evaluation, in conjunction with described fallout models, under hypothetical nuclear war situations.

The currently available contamination-decontamination models include the fire-hosing of paved areas and roofs, motorized flushing and motorized sweeping of paved areas for simple urban area configurations and for staging areas. In addition, input information on the recovery of land areas by use of motorized scrapers, motorized graders, and bulldozers is available. Standard civil defense routines, including postattack evacuation, are being modeled so that the feasibility of a variety of alternate postattack countermeasures (as contamination-decontamination models) can be quickly determined within the scope of the combined model system. Current work involves the extension of the models to include more complex urban area configurations.

A schematic diagram of the combined models for use in estimating radiological effects from postulated nuclear wars is shown in Figure 2.

Figure 2
 SCHEMATIC OUTLINE OF MODEL SYSTEMS FOR ESTIMATING RADIOLOGICAL EFFECTS



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