

(e) Using standard statistical methods, verify from the distribution of film badge readings whether the badged sample adequately represents the intended group.

(f) Calculate the mean external gamma dose, with variance and confidence limits, for each unbadged population. Assign a dose equal to 95% probability that actual exposure did not exceed the assigned dose.

(g) If badge data is not available for a statistical calculation, conduct a dose reconstruction.

(h) For dose reconstruction, define radiation environment through use of all available scientific data, e.g., measurements of radiation intensity, decay, radioisotopic composition.

(i) Quantitatively relate activities shielding, position, and other factors to radiation environment as a function of time. Integrate dose throughout period of exposure.

(j) Where possible, calculate mean dose with confidence limits; otherwise calculate best estimate dose or, if data are too sparse, upper limit dose.

(k) Compare calculations with available film badge records to verify the calculated doses. Whether or not film badge data is available, calculate initial and internal doses where identified as a meaningful contribution to the total dose.

#### §218.3 Dose reconstruction methodology.

(a) *Concept.* The specific methodology consists of the characterization of the radiation environments to which participants through all relevant activities, were exposed. The environments, both initial and residual radiation are corrected with the activities of participants to determine accrued doses due to initial radiation, residual radiation and/or inhaled/ingested radioactive material, as warranted by the radiation environment and the specific personnel activities. Due to the range of activities, times, geometries, shielding, and weapon characteristics, as well as the normal spread in the available data pertaining to the radiation environment, an uncertainty analysis is performed. This analysis quantifies the uncertainties due to time/space variations, group size, and available data.

Due to the large amounts of data, an automated (computer-assisted) procedure is often used to facilitate the data-handling and the dose integration, and to investigate the sensitivity to variations in the parameters used. The results of the gamma data calculations are then compared with film badge data as they apply to the specific period of the film badges and to the comparable activities of the exposed personnel, in order to validate the procedure and to identify personnel activities that could have led to atypical doses. Radiation dose from neutrons and dose commitments due to inhaled or ingested radioactive material are not detected by film badges. Where required, these values are calculated and recorded separately.

(b) *Characterization of the radiological environment.* (1) This step describes and defines the radiological conditions as a function of time for all locations of concern, that is, where personnel were positioned or where personnel activities took place. The radiation environment is divided into two standard categories—initial radiation and residual radiation.

(2) The initial radiation environment results from several types of gamma and neutron emissions. Prompt neutron and gamma radiation are emitted at the time of detonation, while delayed neutrons and fission-product gamma, from the decay of radioactive products in the fireball, continue to be emitted as the fireball rises. In contrast to these essentially point sources of radiation, there is gamma radiation from neutron interactions with air and soil, generated within a fraction of a second. Because of the complexity of these radiation sources and their varied interaction properties with air and soil, it is necessary to obtain solutions of the Boltzmann radiation transport equation. The radiation environment thus derived includes the effects of shot-specific parameters such as weapon type and yield, neutron and gamma output, source and target geometry, and atmospheric conditions. The calculated neutron and gamma radiation environments are checked for consistency with existing measured data as available. In those few cases displaying significant discrepancies that cannot

be resolved, an environment based on extrapolation of the data is used if it leads to a larger calculated dose.

(3) In determining the residual radiation environment, all possible sources are considered including radioactive clouds, radiation that may have been encountered from other tests, and radioactive debris that may have been deposited in water during oceanic tests. The residual radiation environment is divided into two general components—neutron-activated material that subsequently emits, over a period of time, beta and gamma radiation; and radioactive debris from the fission reaction or from unfissioned materials that emit alpha, beta, and gamma radiation. Because residual radiation decays, the characterization of the residual environment is defined by the radiation intensity as a function of type and time. Radiological survey data are used to determine specific intensities at times of personnel exposure. Interpolation and extrapolation are based on known decay characteristics of the individual materials that comprise the residual contamination. In those rare cases where insufficient radiation data exist to adequately define the residual environment, source data are obtained from the appropriate weapon design laboratory and applied in standard radiation transport codes to determine the initial radiation at specific distances from the burst. This radiation, together with material composition and characteristics, leads to description of the neutron-activated field for each location and time of interest. In all cases observed data, as obtained at the time of the operation, are used to calibrate the calculations.

(c) *Activities of participants.* This step uses all official records, augmented by personnel interviews where gaps exist, to depict a scenario of activities for each individual or definable group. When a dose reconstruction is performed for a specific individual, information available from the individual is accepted unless demonstrably inaccurate. For military units, whose operations were closely controlled and further constrained by radiological safety monitors, the scenario is usually well defined. The same is true for observers, who were restricted to specific loca-

tions both during and after the nuclear burst. Ships' locations and activities are usually known with a high degree of precision from deck logs. Aircraft tracks and altitudes are also usually well defined. Personnel engaged in scientific experiments often kept logs of their activities; moreover, the locations of their experiments are usually a matter of record. Where the records are insufficiently complete for the degree of precision required to determine radiation exposure, participants' comments are used and reasonable judgements are made to further the analysis. Possible variations in the activities, as well as possible individual deviations from group activities, with respect to both time and location, are considered in the uncertainty analysis of the radiation dose calculations.

(d) *Calculation of dose.* (1) The initial radiation doses to close-in personnel (who were normally positioned in trenches at the time of detonation) are calculated from the above-ground environment by simulating the radiation transport into the trenches. Various calculational approaches, standard in health physics, are employed to relate in-trench to above-trench doses for each source of radiation. Detailed modeling of the human body, in appropriate postures in the trench, is performed to calculate the gamma dose that would have been recorded on a film badge and the maximum neutron dose. The neutron, neutron-generated gamma, and prompt gamma doses are accrued during such a short time interval that the posture in a trench could not be altered significantly during this exposure. The fission-product gamma dose, however, is delivered over a period of many seconds. Therefore, the possibility of individual reorientation (e.g., standing up) in the trench is considered.

(2) The calculation of the dose from residual radiation follows from the characterized radiation environment and personnel activities. Because radiation intensities are calculated for a field (i.e., in two spatial dimensions) and in time, the radiation intensity is determinable for each increment of personnel activity regardless of direction or at what time. The dose from exposure to a radiation field is obtained

by summing the contribution (product of intensity and time) to dose at each step. The dose calculated from the radiation field does not reflect the shielding of the film badge afforded by the human body. This shielding has been determined for pertinent body positions by the solution of radiation transport equations as applied to a radiation field. Conversion factors are used to arrive at a calculated film badge dose, which not only facilitates comparison with film badge data, but serves as a substitute for an unavailable film badge reading.

(3) The calculation of the dose from inhaled or ingested radioactivity primarily involves the determination of what radionuclides entered the body in what quantity. Published conversion factors are then applied to these data to arrive at the radiation dose and future dose commitments to internal organs. Inhalation or ingestion of radioactive material is calculated from the radioactive environment and the processes of making these materials inhalable or ingestible. Activities and processes that cause material to become airborne (such as wind, decontamination or traffic) are used with empirical data on particle lofting to determine airborne concentrations under specific circumstances. Volumetric breathing rates and durations of exposure are used to calculate the total material intake. Data on time-dependent weapon debris isotopic composition and the above-mentioned conversion factors are used to calculate the dose commitment to the body and to specific body organs.

(e) *Uncertainty analysis.* Because of the uncertainties associated with the radiological data or calculations used in the absence of data, as well as the uncertainties with respect to personnel activities, confidence limits are determined where possible for group dose calculations. The uncertainty analysis quantifies the errors in available data or in the model used in the absence of data. Confidence limits are based on the uncertainty of all relevant input parameters, and thus vary with the quality of the input data. They also consider the possible range of doses due to the size of the exposure group being examined. Typical sources of error in-

clude orientation of the weapons, specific weapon yields, instrument error, fallout intensity data, time(s) at which data were obtained, fallout decay rate, route of personnel movements, and arrival/stay times for specific activities.

(f) *Comparison with film badge records.*

(1) Calculations of gamma dose were compared with film badge records for two military units at Operation PLUMBBOB to initially validate this methodology. Where all parameters relating to radiation exposure were identified, direct comparison of gamma dose calculations with actual film badge readings was possible. Resultant correlations provided high confidence in the methodology.

(2) Film badge data may, in some cases, be unrepresentative of the total exposure of a given individual or group; nevertheless, they are extremely useful for direct comparison of incremental doses for specific periods, e.g., validating the calculations for the remaining, unbadged period of exposure. Moreover, a wide distribution of film badge data often leads to more definitive personnel grouping for dose calculations and to further investigation of the reason(s) for such distribution. In all cases, personnel film badge data are not used in the dose calculations, but rather are used solely for comparison with and validation of the calculations. For dose reconstructions accomplished to date, comparison has been favorable and within the confidence limits of the calculations.

#### **§218.4 Dose estimate reporting standards.**

The following minimum standards for reporting dose estimates shall be uniformly applied by the Military Services when preparing information in response to an inquiry by the Veterans Administration, in connection with a claim for compensation, or by a veteran or his or her representative. The information shall include all material aspects of the radiation environment to which the veteran was exposed and shall include inhaled, ingested, and neutron doses, when applicable. In determining the veteran's dose, initial neutron, initial gamma, residual gamma, and internal (inhaled and ingested) alpha, beta, and gamma shall