Environmental Consequences of Nuclear War Volume I:
Physical and Atmospheric Effects
A. B. Pittock, T. P. Ackerman, P. J. Crutzen,
M. C. MacCracken, C. S. Shapiro and R. P. Turco

CHAPTER 7
Radiological Dose Assessments

7.1 INTRODUCTION

Nuclear explosions create highly radioactive fission products; the emitted neutrons may also induce radioactivity in initially inert material near the explosion. In this chapter the potential doses associated with these radionuclides are assessed. Our focus is on the consequences outside the zone of the initial blast and fires. Prompt initial ionizing radiation within the first minute after the explosion is not considered here, because the physical range for biological damage from this source is generally smaller than the ranges for blast and thermal effects (see Chapter 1).

In this assessment of the potential radiological dose from a major nuclear conflict, the contributions from "local" (first 24 hours) and more widely distributed, or "global" fallout will be considered separately. Global fallout will be further subdivided into an intermediate time scale, sometimes called tropospheric, of 1 to 30 days; and a long-term (beyond 30 days) stratospheric component. Mainly the dose from gamma-ray emitters external to the body is considered. Contributions from external beta emitters are not estimated because of the limited penetration ability of beta radiation, but there is the possibility that in areas of local fallout, beta radiation can have a significant impact on certain biota directly exposed to the emitters by surface deposition (Svirezhev, 1985; see also Volume II). Potential internal doses from ingestion and inhalation of gamma and beta emitters are estimated in only an approximate manner as these are much more difficult to quantify (see also Volume II, Chapter 3).

The total amount of gamma-ray radioactivity dispersed in a nuclear exchange is dominated by the weapon fission products, whose production is proportional to the total fission yield of the exchange. Exposure to local fallout, which has the greatest potential for producing casualties, is very sensitive to assumptions about height of burst, winds, time of exposure, protection factor, and other variables. For global fallout, the dose commitments are sensitive to how these fission products are injected into various regions of the atmosphere, which depends on individual warhead yield as well as burst location. The distribution of fallout in time and space from the atmospheric weapons testing programs of the 1950s and early 1960s has been studied extensively as a basis for developing a methodology for treating these many dependencies (see, for example, Glasstone and Dolan, 1977; UNSCEAR, 1982).

Despite this dependence of potential radiological dose on the details of an exchange, a scenario-independent methodology is presented—if you will, "user's guides"—to allow interested researchers to estimate doses for the scenarios of their choice. In this chapter, these methods are applied to scenarios typical of those that have been reported in the literature. For local fallout, aspects of the baseline scenario outlined in Chapter 2 are considered. For global fallout, both the 5300 megaton baseline scenario reported by Knox (1983), and the TTAPS 5000 megaton reference nuclear war scenario (Turco et al., 1983a) are considered.

Some previous assessments of radiological fallout have relied on assumptions that are no longer valid. For example, the 1975 study by the U.S. National Academy of Sciences (NAS, 1975) predicted global dose levels significantly lower than those reported here. The NAS study was devoted to the assessment of long range effects and specifically excluded local and short term effects derived from the deposition of radioactive fallout, even though they were acknowledged to be of significance. The total yield of the NAS scenario was 10,000 Mt consisting principally of weapons having a 1 or 5 Mt yield. This contrasts markedly with current scenarios that generally assume use of weapons having yields of 0.5 Mt or less. These lower yield weapons inject most of their radioactivity into the troposphere, where it is more rapidly deposited at the surface. Such injections can, therefore, deliver higher radiation doses than stratospheric injections. In the study by Shapiro (1974), lower doses were also found because its dose assessments were based on scaling from past atmospheric tests. Again, the mix of yield, burst locations, and meteorology in these tests were very different from present weapons arsenals and scenarios.

Previous studies have not considered the potential effects on radiological estimates of the possible climatic perturbations described in Chapter 5. By considering the possible effects of perturbed conditions here, earlier assessments have therefore been extended. These efforts have only begun; thus, the present results must be viewed only as indicative of what may happen, given current understanding and relatively simple assumptions.

7.2 LOCAL FALLOUT

Local fallout is the early deposition of relatively large radioactive particles that are lofted by a nuclear explosion occurring near the surface in which large quantities of debris are drawn into the fireball. For nuclear weapons, the primary early danger from local fallout is due to gamma radiation.

Fresh fission products are highly radioactive and most decay by simultaneous emission of electrons and gamma-rays. The most intense radiation occurs immediately after a nuclear explosion. Elements that are less radioactive, however, linger for long periods of time. An approximate and conservative rule-of-thumb for the first six months following a weapon detonation is that the gamma radiation will decay by an order-of-magnitude for every factor of seven in time (Glasstone and Dolan, 1977). Thus, if gamma activity at 1-hour after detonation produces a radiation level of 1000 rad/h, then at 7-hours the dose rate would be 100 rad/h. In two weeks it would be ~ 1 rad/h. For the sake of comparison, a lethal whole-body radiation dose would be about 450 rads delivered within 48 hours or 600 rads received over several weeks. The lethal dose level also depends on the presence of other trauma as well as on the amount of medical attention available (i.e., a lower dose could prove fatal if untreated).

If the implausible assumption is made that all of the radioactivity in the fresh nuclear debris from a 1 Mt, all-fission weapon arrives on the ground 1-hour after detonation and is uniformly spread over grassy ground such that it would just give a 48-hour unshielded lethal dose (i.e., 450 rad) then approximately 50,000 km^2 could be covered. Given such a "uniform deposition" model, it would require only about 100 such weapons to completely cover Europe with lethal radiation. In reality, because of a variety of physical processes, the actual areas affected are much smaller. Most of the radioactivity is airborne for much longer than an hour, thus allowing substantial decay to occur before reaching the ground. Also, the deposition pattern of the radioactivity is uneven, with the heaviest fallout near the detonation point where extremely high radiation levels occur. When realistic depositional processes are considered, the approximate area covered by a 48-hour unshielded lethal dose is about 1300 km^2, i.e., nearly a factor of 40 smaller than the area predicted using the simplistic model above. This large factor is partially explained because only about one-half of the radioactivity from ground bursts is on fallout-sized particles (DCPA, 1973). The other portion of the radioactivity is found on smaller particles that have very low settling velocities and therefore contribute to global fallout over longer times. Portions of this radioactivity can remain airborne for years. For airbursts of strategic-sized weapons, virtually no fallout-sized particles are created, and all of the radioactivity contributes to global fallout.

Calculating the physical processes governing the amount, time, and location of the deposition of the radioactive particles is an exceedingly complex and difficult task requiring computer simulation, but it is extremely important to do this properly because of the large variations that can occur (as indicated above). If less accurate information is sufficient, then semi-quantitative approaches which have been derived from sophisticated models are available. These models are based largely on nuclear test observations.

A semi-quantitative model that has been widely used for impact analysis and planning purposes has been presented by Glasstone and Dolan (1977). Semi-quantitative models are useful where scenarios are neither too complex nor wind shears too different from those used to derive the model. However, if solutions are needed that require consideration of complex wind systems, time-of-arrival of radioactivity, or overlay of doses from many fallout patterns, then more sophisticated models should be used. In this study, to facilitate analysis of yet undefined scenarios, a simple graphical method is presented that can be used to generate rough estimates of gamma radiation patterns from multiple nuclear weapon scenarios. Based on a complex computer simulation, this graphical model was chosen for its ease of usage. Time-of-arrival of radioactivity has been accounted for in its development. Overlap from multiple bursts is considered in Section 7.2.3.

7.2.1 Phenomenology

Lofted radioactive fallout particles that have radii exceeding 5 to 10 μm have sufficient fall velocities to contribute to local fallout. Most of these local fallout particles can be seen by the unaided eye. Particles can be as large as several millimeters in radius. These paticles have settling velocities that range from a few centimeters per second to many tens of meters per second. They are lofted by the rising nuclear debris cloud and are detrained anywhere from ground level to the top of the stabilized cloud.

Horizontal wind speeds usually increase with height up to the tropopause and, frequently, wind directions have large angular shears. Nuclear clouds disperse due to atmospheric shears and turbulence. The larger the debris cloud, the faster its radius grows since the rate of eddy mixing increases as the size of the cloud increases (for a discussion of scale-dependent eddy mixing see Walton, 1973). The arrival of radioactivity at a given location can occur over many hours, with large particles from high in the cloud usually arriving first at a downwind location.

Rainout effects have been suggested as being potentially significant contributors to local fallout effects from strategic nuclear war (Glasstone and Dolan, 1977). However, the inclusion of rainout processes would probably not significantly affect the answers to generic questions pertaining to large-scale nuclear war phenomena (for example, "What percent of Western Europe would suffer lethal levels of gamma radiation from local fallout in a large-scale nuclear exchange?"), especially if a substantial portion of the weapons are surface-burst. This is particularly true for strategic weapon yields of greater than 30 kt, because the radioactivity on the small particles most affected by rainout rises above all but the largest convective rain cells. Thus lethal doses from rainout should occur only from large convective rain cells, and this should occur only over relatively small areas (i.e., beneath moving convective cells). However, for any given radioactive air parcel, the overall probability of rainout the first day from a convective cell is quite low for yields greater than 30 kt. Rainout may also occur over large areas associated with frontal systems, but in the case of strategic yields, the radioactivity on small particles must diffuse downward from levels that are often above the top of the precipitation system in order to produce rainout. As a result, radiological doses from debris in precipitation would be substantially lower than early-time doses associated with local fallout. In either case (frontal or convective rainout), for a large-scale multi-burst exchange, the size of the expected lethal-dose rainout areas should typically be small (i.e., well within the range of modeling uncertainty) compared to the size of the fallout areas created by particles with large settling velocities. Thus, first order rainout areas can be ignored in calculating the radiological hazard from a large-scale nuclear war scenario. However, for lower yield (≤ 30 kt) tactical war scenarios, or at specific locations, rainout could lead to important and dominant radiological effects.

Fallout of radionuclides from commercial nuclear reactors has been suggested as a potentially significant contributor to local fallout doses. Calculations indicate that fallout from a reactor and nearby stored nuclear waste facilities can exceed fallout from a single nuclear explosion, if the reactor core can be fragmented and its stored nuclear waste is lofted in the same manner as occurs for weapon radioactivity. However, in a large scale nuclear exchange, if the most dangerous early time impact (that is, gamma radiation deposited by local fallout) is considered, then, in the critical time period during the first week after detonation, the gamma radiation from the reactors will contribute a relatively small portion of the gamma radiation generated by the weapons used in the attack, even if all the radioactivity from all reactors is lofted. In the longer term (i.e., one year or longer), the reactors' radioactivity has the potential to be more important than the weapons' radioactivity. However, the dose rates would be orders of magnitude lower than during the first 48 hours from weapons radiation. (See Appendix 7A for further discussion of the potential radiological dose from an attack on nuclear fuel cycle facilities).

7.2.2 Single-Weapon Fallout Model

To calculate the time of arrival of radioactivity at a location with reasonable accuracy, all significant processes must be taken into consideration. Once the duration and amount of radioactivity arriving at a particular point have been calculated, the dose is obtained by an integration over time, taking into account the decay of the radionuclides. For this work the KDFOC2 computer model (Harvey and Serduke, 1979) was used to calculate fallout fields for single bursts, which in turn were used to develop a semi-quantitative model for preparing rough estimates of fallout areas for typical strategic weapons. A wind profile (including shear) characteristic of mid-continental Northern Hemisphere summer conditions was selected from observations and baseline fallout calculations were performed for several explosion yields assuming all-fission weapons. (A procedure is given below to scale from all-fission to various fusion-fission weapon configurations.) As an example of the results, a one-megaton fallout pattern is shown in Figure 7.1. Figure 7.2 gives the area versus minimum dose relationship for several different yields. Fallout areas are shown rather than maximum downwind extents for various doses since areas are less sensitive to variations in wind direction and speed shears, and should be more useful for analysis. For example, numbers of people or hectares of land can more easily be determined from estimates of area covered than of downwind extent. These areas correspond to doses associated with external gamma-ray emissions. All of the local fallout estimates given below are based on the KDFOC2 model and the wind pattern leading to Fig. 7.1.

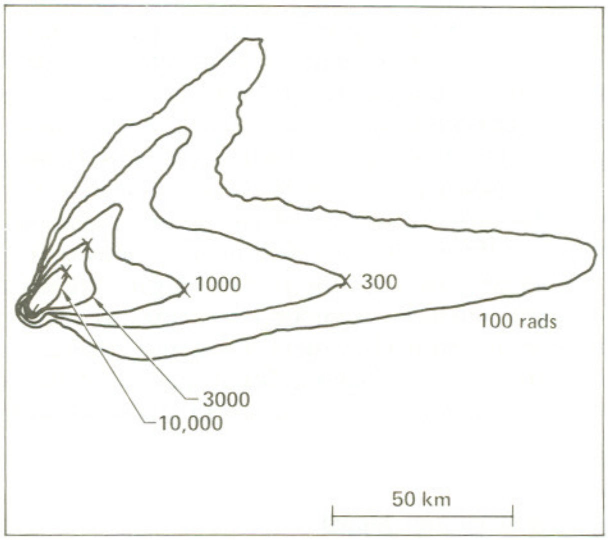

Figure 7.1. 48-hour dose predictions for a 1-Mt all-fission weapon detonated at the surface. A mid-continental Northern Hemisphere summer wind profile was used. The double-lobed pattern is due to a strong directional wind shear that is typical during this season. For a 1-Mt weapon, the lofting of radioactivity is so high that topographic features are not expected to play a large role in pattern development; thus, a flat surface has been used. The protection factor is 1. The local terrain is assumed to be a rolling grassy plain

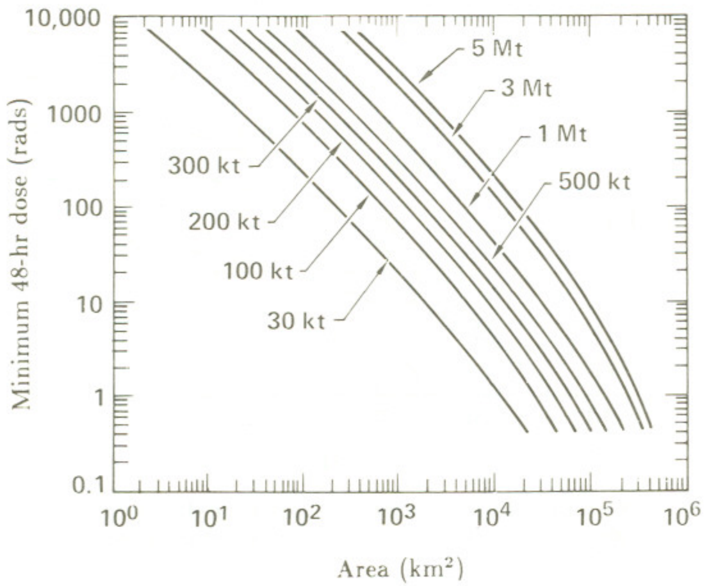

Figure 7.2. Fallout areas versus minimum 48-hour doses for selected yields from 30 kt to 5 Mt. The weapons were surface-burst and all-fission. The wind was that used in the calculation to produce Figure 7.1. These curves include an instrument shielding factor of 25% (Glasstone and Dolan, 1977). Doses within the area defined would exceed the minimum dose

To convert from areas for the 48-hour curves shown in Figure 7.2 to areas for minimum doses over longer times, an "area multiplication factor", AMF, is given in Figure 7.3. For example, if the 2-week, 300-rad area is needed, first the 48-hour, 300-rad area is found from Figure 7.2, then the appropriate AMF is read from Figure 7.3. The 2-week, 300-rad area is the product of the 300-rad, 48-hour area and the 2-week, 300-rad AMF. For example, a 1-Mt, all fission weapon, has a 2-week, 300-rad area of

$$\sim 2000\ \text{km}^2 \times 1.30 \simeq 2600\ \text{km}^2.$$

There are two scaling laws that allow weapons design and various sheltering to be factored into dose calculations. The first scaling law permits consideration of weapons that are not all fission. Most large yield weapons (>100 kt) are combined fission-fusion explosives with approximately equal amounts of fusion and fission (Fetter and Tsipis, 1981). The fission fraction (ρ) is the ratio

$$\rho = \frac{\text{fission yield}}{\text{total yield}} \quad .$$

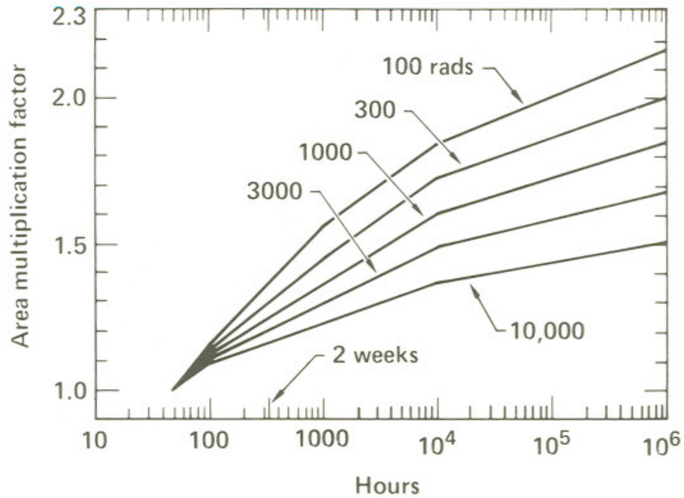

Figure 7.3. Area multiplication factors to extend the dose integration time from 48 hours to longer times. These factors must be used in conjunction with the areas given in Figure 7.2

To find a 48-hour minimum dose area for a particular fission fraction using Figures 7.2 and 7.3, the dose of interest, D, should be multiplied by $1/\rho$ before reading the values of the area and the area multiplication factor. For example, to obtain the 450 rad, 48-hour dose area for a 50% fission weapon, the area for the scaled dose of 900 rad would be obtained from Figure 7.2. For a 1-Mt, 50% fission weapon, the estimated 450-rad dose area is found to be 720 km^2. The rationale for this scaling law is that the thermodynamics and hydrodynamics of fallout development are insensitive to fission fraction because particle characteristics and lofting altitudes are determined predominantly by total energy yield. For yields that are only part fission, each particle has a fraction of the gamma radioactivity that it would otherwise have if the weapon were an all-fission weapon. This scaling law is appropriate for fission fraction ratios above ~ 0.3; smaller ratios can lead to situations where neutron induced radioactivity becomes a significant factor. For such cases, careful consideration of surrounding materials may be necessary to produce accurate fallout estimates.

The second scaling law accounts for "protection factors" (K) against ionizing radiation that would be provided by sheltering. The 48-hour minimum dose areas given in Figure 7.2 are appropriate for a person or other organism located on a rolling grassy plain. In other configurations, radiation exposure varies according to how much shielding is obtained while remaining in the area. For example, a person leading a normal lifestyle is likely to achieve an average K of 2 to 3 for gamma radiation from time spent inside buildings and other structures. Basements can provide K's of 10 to 20. Specially constructed shelters can provide K's of 10 to 10,000 (Glasstone and Dolan, 1977).

To determine the radiation area for a dose of D when shielding with a protection factor K is available, the scaled dose KD from Figure 7.2 should be used. For example, for those in an undamaged basement with $K = 10$ for the first 48-hours, Figure 7.2 indicates that the 450 or more rad effective dose area from a 1-Mt, all-fission weapon is about 130 km^2. This is obtained by using a scaled dose of 4500 rads. For comparison, the 450-rad minimum dose area is about 1300 km^2 for people with no shelter, greater by a factor of 10 than the area for those with a K of 10.

Other factors that could reduce the effects of fallout on the population over long time periods ($\geq$1 month) include weathering (runoff and soil penetration), cleanup measures, relocation, and the ability of the body to repair itself when dose is spread over time or occurs at lower rates. These consideratons can be taken into account with existing computer models, but are not treated here. Several factors that could enhance the effects of fallout are mentioned below.

7.2.3 Dose Estimation From Multiple Explosions

In a major nuclear exchange, there could be thousands of nuclear warheads detonated. For such an exchange, realistic wind patterns and targeting scenarios could cause individual weapon fallout patterns to overlap in complicated ways that are difficult to predict and calculate. Even though acute doses are additive, a *single* dose pattern calculated for a weapon cannot be used directly to sum up doses in a multi-weapon scenario, except under limited conditions. For example, if the wind speed and direction are not approximately the same for the detonation of each weapon, then different patterns should be used. Thus, only under limited conditions may a single dose pattern be moved around a dose accumulation grid to sum total doses from many weapons.

The number of possible fallout scenarios far exceeds the number of targeting scenarios. This is because, for each targeting scenario that exists, the possible meteorological situations are numerous, complex, and varying. Probabilistic analysis, however, may be used to obtain probability distribution functions which could be analyzed to answer questions of planning and impact analysis.

Two relatively simple multi-burst models can be developed for use in conjunction with the semi-quantitative model presented here. These cases can provide rough estimates of fallout areas from multiple weapons scenarios; however, their results have an uncertainty of no better than a factor of several, for reasons explained below, and are neither upper nor lower case limits. The no-overlap (NO) case is considered first; this could occur when targets are dispersed, there is one warhead per target and the fallout areas essentially do not overlap. Second, the total-overlap (TO) case is examined; this approximation would arise when targets are densely packed and the same size warhead is used against each. A large number of warheads used against, say, a hardened missile field site would be more closely modeled by the TO model than the NO model. Possible incoming warhead fratricide should also be considered in developing any credible scenario for closely packed targets.

As an example of the use of the NO and TO approximations, a case with 100 1-Mt, 50% fission, surface-detonated explosions is considered and estimates are developed for the 450-rad, 48-hour dose areas for both cases. For the NO case the fallout area can be obtained by determining the area for a single 1-Mt weapon (900-rad scaled dose from Figure 7.2) and multiplying by 100. This gives 7.2×10^4 km^2 for the 450-rad, 48-hour dose contour. For the TO model, the area is obtained for a single 1-Mt weapon, 9-rad scaled dose from Figure 7.2. One hundred of these, laid on top of each other, would give 450 rads for 50% fission weapons. The area in this case is 3.3×10^4 km^2. These results differ by about a factor of two, with the NO case giving a larger area.

Although these models are extremes in terms of fallout pattern *overlap,* neither can be taken as a bounding calculation of the extremes in fallout *areas* for specified doses. It is very possible that a more realistic calculation of overlap would produce a greater area for 100 weapons than either of these models. Such a result is demonstrated by a more sophisticated model prediction that explicitly takes overlap into account (Harvey, 1982). In this study, a scenario was developed for a severe case of fallout in a countervalue attack on the U.S. where population centers were targeted with surface bursts. Figure 7.4 shows the contours of a 500-rad minimum 1-week dose where overlap was considered. The 500-rad area is about three times greater than that predicted by the NO model, and six times that of the TO model. Note also that the distribution of radioactivity is extremely uneven. About 20% of the U.S. is covered with 500-rad contours, including nearly 100% of the northeast, approximately 50% of the area east of the Mississippi, 10% of the area west of the Mississippi, and only a small percentage of the area in the Great Plains.

Results of this scenario, as well as those postulated by others, clearly show that such estimates are very scenario-dependent and that detailed estimates should be made with care. For example, the regional results shown in Figure 7.4 could be significantly different if military targets (e.g. , ICBM silos) were included as well. Although the NO and TO cases presented in this chapter are simple to apply, they must be used only to develop rough estimates of total area coverage within regions with relatively uniformly dispersed targets.

When the density of targets of one area is as large as in the northeastern U.S. and another is as dispersed as in the western U.S., regional models should be used to develop specific regional estimates. Even then, multiple weapon fallout estimates should be considered to have uncertainties no smaller than a factor of several, with the uncertainty factor increasing as the model sophistication decreases.

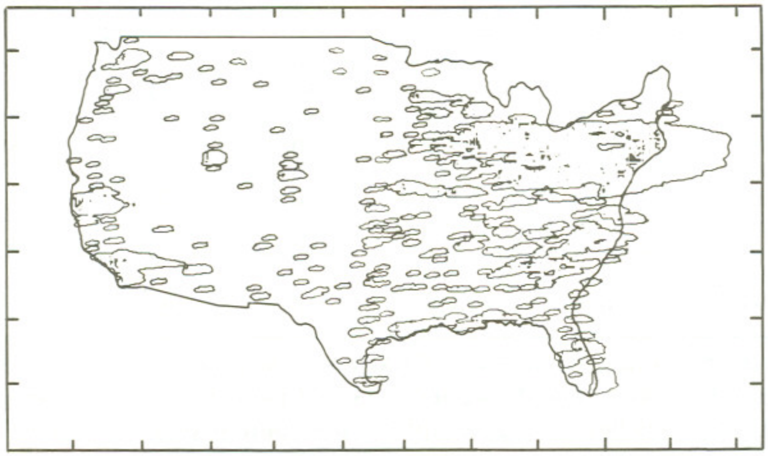

Figure 7.4. A fallout assessment that explicitly takes fallout pattern overlap into account. Shown are 500-rad, 1-week minimum isodose contours. This scenario was intended to emphasize population dose. Approximately 1000 population centers in the U.S. were targeted, each with a 1-Mt, 50%-fission weapon. The assumed winds were westerly with small vertical shear and were nearly constant over the continent (taken from Harvey, 1982)

7.2.4 Sample Calculation of Multiple-Weapon Fallout

To illustrate the fallout prediction method presented here, an escalating nuclear exchange scenario, which is consistent with that developed in Chapter 2, is used to estimate fallout areas. In this scenario there are four sequential phases of attack against five different regions. The five regions are: Europe (both east and west), western U.S.S.R. (west of the Urals), eastern U.S.S.R., western U.S. (west of 96° west longitude), and eastern U.S. The four phases of attack are: initial counterforce, extended counterforce, industrial countervalue, and a final phase of mixed military and countervalue targeting. The weapon yields and the number of warheads that are employed for just the surface bursts during each phase are shown in Table 7.1. Airbursts are omitted since they do not produce appreciable local fallout.

TABLE 7.1.
SURFACE-BURST WARHEADS IN A PHASED NUCLEAR EXCHANGE. ALL WEAPONS ARE ASSUMED TO HAVE A 50% FISSION YIELD

	Number of warheads				
Weapon yield (Mt)	Initial counter-force phase	Extended counter-force phase	Industrial counter-value phase	Final phase	Full baseline exchange
0.05	0	300	0	250	550
0.1	975	150	50	8	1183
0.2	0	250	50	121	421
0.3	500	250	0	125	875
0.5	1000	200	0	25	1225
1.0	250	495	160	125	1030
5.0	0	50	15	8	73
Total surface-burst yield	~1000	~1000	~250	~250	~2500

In the first phase, land-based ICBM's are the primary targets. These are assumed to be located in the western U.S. and the U.S.S.R. at sites containing 125 to 275 missiles. The geographical distribution of missile silos in the U.S.S.R. is assumed to be fifty percent east and fifty percent west of the Urals. Each missile silo is attacked with a surface-burst and an air-burst weapon. For a given site, the TO model is used to calculate the fallout pattern. All U.S. ICBM sites are attacked with 0.5 Mt weapons. Each of five U.S. ICBM complexes are presumed to have 200 missile silos, while each of 6 U.S.S.R. complexes are presumed to have between 125 and 275 missile silos, with a total of 1300. The Soviet sites are attacked with 1, 0.3, and 0.1 Mt weapons. During this phase, each side employs a total of about 1000 Mt. Besides the attack on Soviet missile silos, 425 0.1-Mt weapons are assumed to be surface-burst against other Soviet military targets, with approximately 28 Mt west of the Urals and 14 Mt to the east. The 425 fallout patterns from these weapons have been modeled with the NO model.

In the second phase of the attack, there are an additional 1000 Mt of surface-burst weapons employed. These are employed against each region with 20, 40, and 40% of the weapons being used against targets in Europe, the U.S. and the U.S.S.R., respectively. Here, Europe includes both the NATO and Warsaw Pact countries. To roughly account for population distribution, the weapons employed against the U.S. are divided up as two-thirds in the eastern U.S. and one-third in the western U.S.; for Soviet targets it is assumed that two-thirds are detonated west and one-third east of the Urals.

TABLE 7.2.
PERCENT OF LAND MASS COVERED BY A MINIMUM 450 RAD, 48-HOUR DOSE

	Initial counter-force phase	Extended counter-force phase	Industrial counter-value phase	Final phase	Full baseline exchange
Europe	0	2.9	0.6	0.8	4.3
Eastern U.S.S.R.	0.5	0.5	0.1	0.2	1.3
Western U.S.S.R.	1.6	2.3	0.7	1.7	6.3
Eastern U.S.	0	4.7	1.0	1.4	7.1
Western U.S.	4.4	2.3	0.7	6.6	8.0

For all the weapons employed in the second, third and fourth phases, the fallout pattern is calculated using the NO model. The results, in terms of percent of land covered by at least a 450 rad, 48-hour dose, are shown in Table 7.2. No shielding has been assumed in calculating these percentages. Similar areas were found for 600 rad over two weeks.

Care must be taken in interpreting these results. To begin with, there is an uncertainty factor of several in the NO and TO modeling schemes, as discussed earlier. Another substantial bias is introduced by neglecting the radioactivity that is blown into or out of a region. For example, the western U.S.S.R. would likely receive substantial amounts of radiation from weapons detonated in eastern Europe because the wind usually blows from Europe toward the Soviet Union. Thus, the area percentages shown in Table 7.2 for Europe would be expected to decrease since some of the area credited to Europe would actually be in the Soviet sector. Similarly, the percentage of the western U.S. is probably overestimated, assuming typical wind conditions. For the eastern U.S., the area covered would be increased by radioactivity originating in the central U.S. and decreased as a result of radioactivity blowing out over the Atlantic Ocean.

There are a number of factors that could change these local fallout assessments.

- Shielding is probably the most sensitive parameter in reducing the effective dose to a population. This effect has been ignored in these calculations. Protective measures could substantially reduce the human impact of fallout.
- Choosing a scenario that exacerbates local fallout (e.g., surface bursting of cities) could increase lethal areas by factors of several.

- Large differences in doses could arise because of irregularities in fallout patterns in the local fallout zones that could range over orders of magnitude. Relocation could substantially reduce a population's dose.
- Debilitating, but not lethal, radiation doses ($\sim$200 rad or more) would be received over much larger areas than areas receiving lethal doses.
- Fission fractions of smaller modern weapons could be twice the baseline assumption of 0.5. Adding these to the scenario mix could increase lethal fallout areas by up to 20% of the baseline calculation.
- Tactical weapons, ignored in the baseline scenario, could increase lethal local fallout areas in certain geographical regions; particularly within Europe, by about 20% of the baseline calculations.
- Internal radiation exposure could increase the average total doses to humans by about 20% of the external dose.
- External beta exposure, not treated here, could add significantly to plant and animal exposures in local fallout areas.
- Targeting of nuclear fuel cycle facilities could contribute to radiation doses (see Appendix 7A).

7.3 GLOBAL FALLOUT

Global fallout consists of the radioactivity carried by fine particulate matter and gaseous compounds that are lofted into the atmosphere by nuclear explosions. One may distinguish two components to global fallout—intermediate time scale and long-term. Intermediate time scale fallout consists of material that is initially injected into the troposphere and is removed principally by precipitation within the first month. The fractional contribution to intermediate time scale fallout decreases as the total weapon yield increases above 100 kt. The importance of intermediate time scale fallout has grown with reductions in warhead yields. Long-term fallout occurs as a result of deposition of very fine particles that are initially injected into the stratosphere. Because the stratosphere is so stable against vertical mixing and the fine particulate matter has negligible fall velocities, the primary deposition mechanism involves transport of the radioactivity to the troposphere through seasonal changes in stratospheric circulation. Once within the troposphere, these particles would normally be removed within a month by precipitation scavenging.

7.3.1 Methodology

Given a specific nuclear war scenario, it is possible to use experience gained from atmospheric nuclear tests to estimate the fate of both intermediate time scale and long-term fallout particles if the atmosphere is not perturbed by smoke. GLODEP2 (Edwards et al., 1984), an empirical code that was designed to match measurements from atmospheric testing has been used. The model contains two tropospheric and six stratospheric injection compartments. By following unique tracer material from several atmospheric nuclear tests in the late 1950s, combined with subsequent balloon and aircraft measurements in the stratosphere and upper troposphere and many surface air and precipitation observations, it was possible to estimate the residence time of radioactivity in the various stratospheric compartments and the interhemispheric exchange rate in the stratosphere. Radioactive material that is placed initially into the troposphere is also handled by the GLODEP2 model (Edwards et al., 1984). From this information, surface deposition tables were prepared. The GLODEP2 model has never been tested against atmospheric nuclear tests in middle latitudes since no extensive series of explosions have occurred in this region. As a result, there is some uncertainty in the results of explosions centered around the Northern Hemisphere middle latitudes, but little uncertainty in the Northern Hemisphere sub-polar latitude calculations since the stratospheric fallout there would deposit much the same as the global fallout from the polar bursts used to generate the polar deposition tables in the model.

In this section, a simple table, based on GLODEP2 calculations is prepared that enables readers to obtain dose estimates for their own scenarios. Table 7.3 presents the 50-year external gamma-ray dose commitment, in rads, for single nuclear explosions of 0.1 to 20 Mt yield. All bursts are assumed to occur at the surface, and to be all fission. For an airburst (where the fireball does not touch the ground), the tabular values must be doubled since about twice as much radioactivity is available for global fallout for an airburst as compared to a surface burst. Recall that about half the radioactivity dispersed in a surface burst is deposited within 24 hours as local fallout. Two burst latitudes, 40° N and 55° N, were selected as median latitudes for strikes against the U.S., Europe, and the U.S.S.R., respectively.

Table 7.3 should be used only (a) for surface bursts or (b) for airbursts whose height is below 3 km but above the height where the fireball touches the surface. The height of an airburst may be defined by the relation $H \geq 870Y^{0.4}$, where Y is the total yield of the explosion in megatons and H is in meters (Glasstone and Dolan, 1977).

As an example of how Table 7.3 can be used, average dose estimates are derived at 30-50° N latitude for an arbitrary, illustrative, simplified nuclear exchange during the Northern Hemisphere winter season. Table 7.4 presents the results of this example. The doses per weapon in column 7 were obtained from Table 7.3, interpolating between yield columns where necessary.

Using the Table 7.3 on this illustrative scenario gives a total 30–50° N dose of 8.8 rads, while the computer version of GLODEP2 gives 8.1 rads. The small difference is due principally to interpolation between total yield categories and the fact that tabular values are given to only one significant

TABLE 7.3.

GLOBAL EXTERNAL GAMMA-RAY DOSE (IN RADS) FROM A SINGLE NUCLEAR WEAPON EXPLODED AT THE SURFACE AS CALCULATED BY GLODEP2. DOSES ARE DUE TO THE RADIOACTIVITY DEPOSITED AT THE SURFACE AND ARE INTEGRATED OVER 50 YEARS, ASSUMING NO WEATHERING. ALL WEAPONS ARE ASSUMED TO BE 100% FISSION. FOR AIRBURSTS MULTIPLY TABULAR VALUE BY TWO

NORTHERN HEMISPHERE WINTER												
Latitude	Bursts at ~40° N Total Yield (Mt)						Bursts at ~55° N Total Yield (Mt)					
	0.1	0.3	1	3	10	20	0.1	0.3	1	3	10	20
70–90N	4×10^{-5}	2×10^{-4}	1×10^{-3}	2×10^{-3}	4×10^{-3}	8×10^{-3}	2×10^{-3}	4×10^{-3}	1×10^{-3}	2×10^{-3}	4×10^{-3}	8×10^{-3}
50–70N	1×10^{-3}	3×10^{-3}	4×10^{-3}	8×10^{-3}	2×10^{-2}	3×10^{-2}	5×10^{-3}	1×10^{-2}	4×10^{-3}	8×10^{-3}	2×10^{-2}	3×10^{-2}
30–50N	4×10^{-3}	9×10^{-3}	6×10^{-3}	1×10^{-2}	2×10^{-2}	4×10^{-2}	2×10^{-3}	4×10^{-3}	5×10^{-3}	1×10^{-2}	2×10^{-2}	4×10^{-2}
10–30N	8×10^{-4}	2×10^{-3}	2×10^{-3}	3×10^{-3}	6×10^{-3}	1×10^{-2}	5×10^{-5}	3×10^{-4}	2×10^{-3}	3×10^{-3}	6×10^{-3}	1×10^{-2}
10S–10N	1×10^{-5}	5×10^{-5}	3×10^{-4}	5×10^{-4}	6×10^{-4}	1×10^{-3}	6×10^{-6}	4×10^{-5}	3×10^{-4}	5×10^{-4}	6×10^{-4}	1×10^{-3}
10–30S	3×10^{-6}	2×10^{-5}	2×10^{-4}	4×10^{-4}	1×10^{-3}	3×10^{-3}	3×10^{-6}	2×10^{-5}	2×10^{-4}	4×10^{-4}	1×10^{-3}	3×10^{-3}
30–50S	3×10^{-6}	2×10^{-5}	1×10^{-4}	8×10^{-4}	4×10^{-3}	8×10^{-3}	3×10^{-6}	2×10^{-5}	1×10^{-4}	8×10^{-4}	4×10^{-3}	8×10^{-3}
50–70S	1×10^{-6}	8×10^{-6}	6×10^{-5}	5×10^{-4}	3×10^{-3}	6×10^{-3}	1×10^{-6}	8×10^{-6}	6×10^{-5}	5×10^{-4}	3×10^{-3}	6×10^{-3}
70–90S	7×10^{-8}	4×10^{-7}	3×10^{-6}	1×10^{-4}	7×10^{-4}	1×10^{-3}	7×10^{-8}	4×10^{-7}	3×10^{-6}	1×10^{-4}	7×10^{-4}	1×10^{-3}
NORTHERN HEMISPHERE SUMMER												
70–90N	3×10^{-5}	1×10^{-4}	5×10^{-4}	1×10^{-3}	3×10^{-3}	6×10^{-3}	1×10^{-3}	3×10^{-3}	7×10^{-4}	1×10^{-3}	3×10^{-3}	6×10^{-3}
50–70N	1×10^{-3}	3×10^{-3}	3×10^{-3}	6×10^{-3}	2×10^{-2}	3×10^{-2}	4×10^{-3}	9×10^{-3}	3×10^{-3}	6×10^{-3}	2×10^{-2}	3×10^{-2}
30–50N	3×10^{-3}	7×10^{-3}	4×10^{-3}	1×10^{-2}	2×10^{-2}	5×10^{-2}	1×10^{-3}	3×10^{-3}	4×10^{-3}	1×10^{-2}	2×10^{-2}	5×10^{-2}
10–30N	6×10^{-4}	1×10^{-3}	1×10^{-3}	3×10^{-3}	7×10^{-3}	1×10^{-2}	4×10^{-5}	2×10^{-4}	1×10^{-3}	3×10^{-3}	7×10^{-3}	1×10^{-2}
10S–10N	7×10^{-6}	3×10^{-5}	2×10^{-4}	3×10^{-4}	5×10^{-4}	9×10^{-4}	3×10^{-6}	2×10^{-5}	2×10^{-4}	3×10^{-4}	5×10^{-4}	9×10^{-4}
10–30S	2×10^{-6}	1×10^{-5}	1×10^{-4}	3×10^{-4}	1×10^{-3}	2×10^{-3}	2×10^{-6}	1×10^{-5}	1×10^{-4}	3×10^{-4}	1×10^{-3}	2×10^{-3}
30–50S	2×10^{-6}	1×10^{-5}	9×10^{-5}	7×10^{-4}	4×10^{-3}	7×10^{-3}	2×10^{-6}	1×10^{-5}	9×10^{-5}	7×10^{-4}	4×10^{-3}	7×10^{-3}
50–70S	9×10^{-7}	6×10^{-6}	4×10^{-5}	6×10^{-4}	3×10^{-3}	7×10^{-3}	9×10^{-7}	6×10^{-6}	4×10^{-5}	6×10^{-4}	3×10^{-3}	7×10^{-3}
70–90S	1×10^{-7}	7×10^{-7}	6×10^{-6}	2×10^{-4}	1×10^{-3}	2×10^{-3}	1×10^{-7}	7×10^{-7}	6×10^{-6}	2×10^{-4}	1×10^{-3}	2×10^{-3}

figure. This close comparison suggests that increasing the number of yield columns the number of significant figures in the body of the table is not warranted.

TABLE 7.4.
DOSES (IN RADS) AT 30–50° N FOR AN ILLUSTRATIVE NUCLEAR WAR SCENARIO

No. of weapons	Yield (Mt)	Total fission fraction	Burst height (m)	Burst height factor[a]	Burst latitude	Doses from Table 7.3 (rads)	Total dose[b] (rads)
1000	1.0	0.5	1500	2	40° N	6×10^{-3}	6.0
55	20.0	0.5	0	1	40° N	4×10^{-2}	1.1
135	1.5	0.5	0	1	55° N	7×10^{-3}	0.7
52	9.0	0.5	2500	2	55° N	2×10^{-2}	1.0
						Total	8.8 rads

[a] Factor = 1 for surface bursts, 2 for airbursts.
[b] Total dose is the product of columns 1, 3, 5 and 7.

7.3.2 Global Dose in an Unperturbed Atmosphere Using Specific Scenarios

A variety of scenario studies have been performed using GLODEP2 (Knox, 1983; Edwards et al., 1984) Dose calculations for scenarios (A) and (B), which are described in Table 7.5, are presented in detail in Table 7.6. The atmospheric compartments in Table 7.5 refer to those used in the GLODEP2 model. The Ambio reference nuclear war containing 5700 Mt and 14,700 warheads has not been considered here. Its preponderance of low-yield warheads would produce even higher dose estimates than scenarios (A) or (B).

As indicated in the illustrative example, dose assessment is sensitive to yield, and so a somewhat larger dose is expected from (B) than from (A) because of its lower average yield per warhead. From a comparison of GLODEP2 results for the (A) and (B) scenarios for a Northern Hemisphere winter injection (Table 7.6, columns A_1 and B_1), it is seen that the Northern Hemisphere averages for (A) and (B) are about 16 and 19 rads respectively, while Southern Hemisphere averages are more than a factor of 20 smaller. The maximum appears in the 30–50° N latitude band, where scenarios (A) and (B) yield 33 and 42 rads, respectively. All the doses reported here for global fallout are integrated external gamma-ray exposure over 50 years and assume no sheltering, no weathering, and a smooth plane surface.

TABLE 7.5.
NUCLEAR WAR SCENARIO

Scenario A Knox (1983) 5300 Mt baseline nuclear war		Scenario B TTAPS (Turco et al., 1983a) 5000 Mt reference nuclear war	
Total yield/warhead (Mt)	Total fission yield injected (Mt)	Total yield/warhead (Mt)	Total fission yield injected (Mt)
20.0	305	10.0	125
9.0	235	5.0	125
1.0–2.0	355	1.0	213
0.9	675	1.0	319
0.75	15	1.0	2 5
0.55	220	0.5	187
0.3–0.4	115	0.5	125
0.1–0.2	110	0.3	113
<0.1	1	0.3	7 5
		0.2	5 0
		0.2	7 5
		0.1	7 5
		0.1	1 2

Mt of fission products injected into atmosphere	Scenario A	Scenario B
Polar troposphere	226	369
Lower polar stratosphere	1234	898
Upper polar stratosphere	571	226
High polar atmosphere	0	25
TOTAL	2031	1520
Fraction of yield in surface bursts	0.47	0.57
Fission fraction	0.5	0.5
Total number of explosions	6235	10400

For scenario (A), 55% of the dose emanates from the tropospheric injections. The corresponding value for (B) is 75%. This emphasizes the sensitivity of dose to the yield mix of the scenario. As individual warhead yields decrease, the fractional injections into the troposphere increase, resulting in much larger doses on the ground due to more rapid deposition. Tropospheric radioactivity injections per megaton of fission can produce doses on the ground about a factor of 10 greater than those resulting from lower stratospheric injections, which in turn contribute about 3 to 5 times higher dose compared to upper stratospheric injections (Shapiro, 1984). Injections of radioactivity above the stratosphere as a gas or as extremely fine particles would produce relatively negligible doses at the ground.

TABLE 7.6.
GLOBAL FALLOUT DOSE ASSESSMENTS (RADS) FOR AN UNPERTURBED ATMOSPHERE WITH NO SMOKE

A = 5300 Mt baseline nuclear war (Knox, 1983)
B = 5000 Mt reference nuclear war (Turco et al., 1983a)

Latitude band	A_1	B_1	A_2	B_2	A_3	B_3
70–90N	4.5	3.7	2.9	2.5	7.8	8.2
50–70N	27.3	28.8	21.7	22.7	21.3	24.6
30–50N	32.9	41.7	27.4	33.7	22.3	23.9
10–30N	6.9	8.3	5.6	6.6	7.6	7.2
10S–10N	0.8	0.6	0.5	0.3	1.3	1.0
10–30S	0.6	0.4	0.4	0.2	0.6	0.4
30–50S	0.8	0.4	0.6	0.4	0.7	0.4
50–70S	0.5	0.3	0.5	0.3	0.5	0.3
70–90S	0.1	0.0	0.2	0.1	0.2	0.1
Area averaged—N.H.	16.2	19.1	13.1	15.2	12.8	13.7
Area averaged—S.H.	0.6	0.4	0.5	0.3	0.7	0.4
Area averaged—Global	8.4	9.8	6.8	7.8	6.8	7.1
Global population dose ($\times 10^{10}$) person-rads	6.7	8.2	5.5	6.6	5.3	5.5

A_1 = Winter injection using GLODEP2
B_1 = Winter injection using GLODEP2
A_2 = Summer injection using GLODEP2
B_2 = Summer injection using GLODEP2
A_3 = Summer injection using GRANTOUR with stratospheric contributions from GLODEP2
B_3 = Summer injection using GRANTOUR with stratospheric contributions from GLODEP2

Table 7.6 includes calculated values for the global population dose. This quantity is calculated by multiplying the dose in each 20° wide latitude band by the population of that latitude band, and then summing over all latitudes. For a given scenario, this number is one measure of the potential global biological impact. The global population dose as calculated by GLODEP2 for (A) and (B) are 7 and 8×10^{10} person-rads, respectively. Essentially all of this dose occurs in the Northern Hemisphere because 90% of the world's population and higher doses prevail there.

Figure 7.5 illustrates the time behavior of the buildup of the dose to the 50-year lifetime value as a function of latitude for scenario (A). The bulk of the dose is caused by deposition (mainly from the troposphere) and exposure during the first season after the war, followed by a gradual rise to the 50-year value.

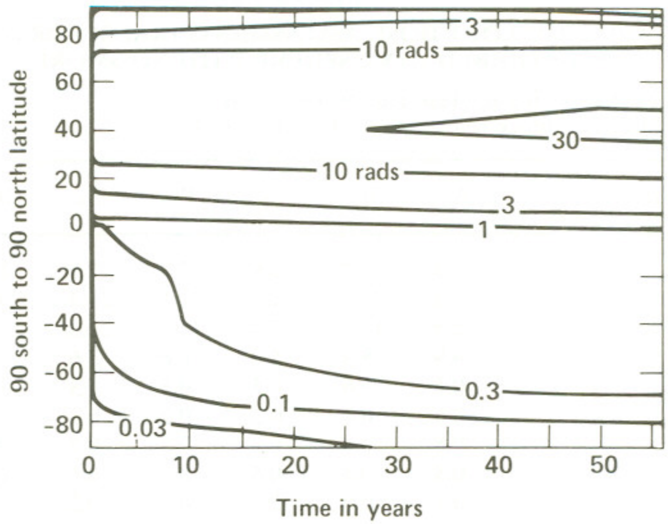

Figure 7.5. Global fallout: accumulated whole body gamma dose (rads) from 6235 explosions totaling 2031 Mt of fission products (scenario A). An 8 day tropospheric deposition decay constant, characteristic of a winter injection, is assumed

A comparison of the GLODEP2 results for the TTAPS scenario (B) and Turco et al. (1983a) results (using an entirely different methodology) reveals that GLODEP2 doses are 19 rads for the Northern Hemisphere average and 42 rads for the 30–50° N latitude band, while Turco et al.'s estimates give corresponding doses of 20 rads and about 40 to 60 rads.

Other studies that have been undertaken using GLODEP2 and the 5300 Mt scenario (A) have led to the conclusions:

Winter vs Summer Injection: GLODEP2 contains an exponential tropospheric deposition model with a variable time constant τ that depends on the season. Values used for τ are 8.2 days for the Northern Hemisphere winter and 18.2 days for summer. For the 30–50° N latitude band, comparison of two runs for scenario (A) yields 27 rads for summer injections compared to 33 rads for winter injections. The corresponding figures for the global population dose are about 6×10^{10} person-rads (summer) and 7×10^{10} person-rads (winter). The population averaged dose per person is 12 rads (summer) and 15 rads (winter). Because of a decrease in the frequency and intensity of large scale precipitation systems in summer, the doses from the troposphere and lower polar stratosphere are reduced somewhat in comparison to winter, while the upper stratospheric contribution is increased. These results indicate that the predicted differences between summer and winter are not large, the dose commitments are not very sensitive to τ, and that other sources of uncertainty would predominate.

Scenarios with Smaller-Yield Devices. The long-term consequences of the shift in the nuclear arsenals from larger to smaller yield devices has been assessed. This shift in average yield has been going on for about the past two decades as targeting accuracy improved, although the trend appears to have halted (see Chapter 2). Table 7.7 presents results comparing the 5300 Mt baseline scenario with two variations. In scenario (Aa), the number of devices in the baseline scenario (A) is increased from 6235 to 13250 while the total yield is held at 5300 Mt. In scenario (Ab), smaller yields have been used, but the number of devices is constant at 6235 (the total yield consequently is reduced by 25% from 5300 to 4000 Mt). The figures presented are for the 50 year gamma-ray dose. For the same total yield, it is seen that a shift to smaller weapons in the baseline scenario has approximately doubled the dose (scenario Aa). For case (Ab), the dose remains about the same even with a 25% drop in the total yield.

TABLE 7.7.
GLOBAL FALLOUT: SENSITIVITY OF DOSE TO WARHEAD YIELD. THE SAME FISSION FRACTION AND GROUND BURST FRACTION AS ASSUMED AS IN SCENARIO A

Scenario	Total yield (Mt)	Number of explosions	Avg. Yield per warhead	30°–50° N dose (rads)	Global avg. dose per person (rads)	Global pop. dose (10^{10} person-rads)
A	5300	6235	0.85	33	15	6.7
Aa	5300	13250	0.40	64	27	12.5
Ab	4000	6235	0.64	33	14	6.5

7.3.3 Global Fallout in a Perturbed Atmosphere

Following a large scale nuclear exchange, the large quantities of smoke and soot lofted to high altitudes could decrease the incoming solar radiation, resulting in tropospheric and stratospheric circulation changes (see Chapter 5). Over land in the Northern Hemisphere, the presence of smoke and soot would probably result in less precipitation and a lowering of the tropopause; these changes could decrease the intermediate time scale (tropospheric) fallout and, depending on changes in stratospheric circulation, could alter the stratospheric contribution to fallout in the Northern Hemisphere. However, before the stratospheric burden is carried into the troposphere, a sizeable fraction would be transported to the Southern Hemisphere by the accelerated interhemispheric transport, resulting in doses there that are likely to be increased over those calculated for an unperturbed atmosphere.

Both the GLODEP2 and the Turco et al. (1983a) models assumed fission product depositions from a normal atmosphere in calculating global fallout. Preliminary studies have been conducted with radionuclides in a perturbed atmosphere using a three-dimensional version of the GRANTOUR model (see MacCracken and Walton, 1984). GRANTOUR is a three-dimensional transport model driven by meteorological data generated by the Oregon State University (OSU) general circulation model (Schlesinger and Gates, 1980). Particulate matter appearing as an initial distribution or generated by sources is advected by wind fields, locally diffused in the horizontal and vertical, moved vertically by convective fluxes and the re-evaporation of precipitation, and removed by precipitation scavenging and dry deposition. Information, in the form of mixing ratios of curies per kg of air, is carried by Lagrangian parcels that move with the prescribed winds. It is assumed that the fission products are in the form of particulate material in two size ranges, greater than and less than one micrometer in diameter. The significance of the two size ranges lies in the assumption that the large particles are scavenged by precipitation with greater efficiency than the small ones. Thus, the surface dose will depend upon the assumed division of the radioactivity between the two size ranges. Coagulation from small to large particles is not treated in the version of the model used here. All meteorological information is specified on a fixed spatial grid and is interpolated to the parcel locations. In turn, when mixing ratios are needed on the fixed grid, they are obtained from weighted averages of the parcel values. The removal processes cause material to be accumulated on the ground and this information is saved in a history file that can be used for post-processing. The radioactive decay of the fission products is not calculated in GRANTOUR, but rather in a post-processor. Knowing the time of injection and the amount and time of arrival at a grid point, it is possible to compute the dose for any time interval.

Studies focused on comparisons of radiation dose assessments with smoke in the atmosphere (interactive atmosphere) and without smoke (noninteractive); other relevant parameters were also explored, including consideration of particle size distribution, source location, different initial meteorology, and averaging doses over land areas only. All of the GRANTOUR simulations reported here are for the Northern Hemisphere summer season and use five radioactivity and smoke source locations of equal strength. The locations include two in the U.S., two in the U.S.S.R., and one in western Europe. This division of sources is similar to that assumed in our earlier discussion on local fallout. Sources were initially injected with a Gaussian distribution whose amplitude was 10% of the maximum at a radius of 15° along a great circle. The total amount of smoke injected was 150 teragrams (equivalent to the urban smoke contributions used by Turco et al. (1983a) and NRC (1985)). MacCracken and Walton (1984) describe the induced climatic perturbations (also see Chapter 5). The vertical distribution of the radioactivity injections were distributed, as was the smoke, with the same vertical distribution as the source term injections calculated using the GLODEP2 injection algorithm. Most of the calculations assumed the radionuclides were attached to particles of two diameter sizes; ($> 1\,\mu$m and $< 1\,\mu$m), with an initial distribution of 43% of the radioactivity attached to the larger particles and 57% to the smaller particles. Deposition was followed for 30 days in most calculations. A single 60 day run indicated that 30 days is sufficient to account for 90% of the deposition. Results are compared for a 50 year unsheltered, unweathered, external gamma-ray dose.

GRANTOUR treats only the troposphere and splits it into three vertical layers extending from 800–1000, 400–800 and 200–400 mbar. In a normal atmosphere, these layers reach up to 2.0, 7.1 and 11.8 km. In the comparisons, GLODEP2 was used to estimate the dose contributions from the stratospheric injections, which were added to the doses calculated by GRANTOUR assuming altered climatic conditions. The results for GRANTOUR's $10° \times 10°$ (latitude-longitude) grid size were then suitably averaged to obtain results for the nine 20° wide latitude bands in order to facilitate comparison with GLODEP2. Average doses were also calculated for only the land masses.

Scenarios A and B were used in the calculations. Columns A_2 and B_2 in Table 7.6 display a comparison of the predictions of GLODEP2 for these two scenarios. Column A_3 and B_3 list the results from GRANTOUR, assuming an unperturbed atmosphere (no smoke; no climatic perturbation) for the same two scenarios. There is reasonable agreement (i.e., generally within about 50%) between the GLODEP2 only and GRANTOUR/GLODEP2 methodologies for an unperturbed atmosphere (cases 1 and 3), providing some confidence that the results of GLODEP2 and GRANTOUR can be combined for simulations with a perturbed atmosphere, although the initial accelerated interhemispheric mixing of radionuclides in the stratosphere has not yet been considered. This may lead to a small underestimate of the long term Southern Hemisphere dose.

Table 7.8 compares calculations for a perturbed atmosphere (interactive smoke) with estimates for normal July conditions. These results are also shown in Figures 7.6 and 7.7. and indicate that the perturbed atmosphere lowers the average dose in the Northern Hemisphere by about 15%. Because the principal mechanism for radionuclide removal from the troposphere is precipitation, the GRANTOUR calculations are roughly consistent with the thesis that precipitation is inhibited when large amounts of smoke are introduced. The transfer of fission product radionuclides to the Southern Hemisphere is somewhat enhanced by the perturbed climate, resulting in higher doses than for the unperturbed case. The increases in Southern Hemisphere dose, however, are not large, and the resulting doses are still about a factor

TABLE 7.8.
GLOBAL FALLOUT DOSE USING THE THREE-DIMENSIONAL GRANTOUR MODEL (SUMMER SCENARIO) COMPARISON OF PERTURBED ATMOSPHERE (SMOKE) AND UNPERTURBED ATMOSPHERE (NO SMOKE) EXTERNAL GAMMA-RAY DOSES ARE IN RADS. BECAUSE GRANTOUR ONLY CALCULATES THE TROPOSPHERIC CONTRIBUTION, THE DOSES HERE INCLUDE THE CONTRIBUTIONS FROM THE STRATOSPHERE AS CALCULATED BY GLODEP2

Latitude band	A_3 (no smoke)	A_4 (smoke)	B_3 (no smoke)	B_4 (smoke)
90–70N	7.8	6.4	8.2	5.8
70–50N	21.3	17.2	24.6	18.0
50–30N	22.3	20.1	23.9	20.4
30–10N	7.6	7.5	7.2	7.2
10N–10S	1.3	1.6	1.0	1.4
10–30S	0.6	0.8	0.4	0.6
30–50S	0.7	0.8	0.4	0.5
50–70S	0.5	0.5	0.3	0.3
70–90S	0.2	0.2	0.1	0.1
Area averaged—N.H.	12.8	11.5	13.7	11.5
Area averaged—S.H.	0.7	0.8	0.4	0.6
Area averaged—Global	6.8	6.1	7.1	6.1
Population average—Global	11.5	10.7	12.0	10.7
Global population dose ($\times 10^{10}$) person-rads	5.3	4.9	5.5	4.9

A_3 = 5300 Mt (Knox, 1983), unperturbed atmosphere (no smoke)
A_4 = 5300 Mt (Knox, 1983), perturbed atmosphere (smoke)
B_3 = 5000 Mt (Turco et al., 1983a), unperturbed atmosphere (no smoke)
B_4 = 5000 Mt (Turco et al., 1983a), perturbed atmosphere (smoke)

of 20 lower than in the Northern Hemisphere. This is because the increased transfer to the Southern Hemisphere is mitigated by the decay in activity during the time before the radionuclides are deposited on the ground.

Preliminary conclusions from other parameter studies include:

Land area averages: For each GRANTOUR calculation reported above, dose calculations were repeated, averaging only over the land areas. Since the source locations are centered over land masses, one would expect land average values to be higher than average values that include both land and ocean areas. Averaging doses over only the Northern Hemisphere land areas increased the calculated tropospheric dose by about 30% above the combined average for land and oceans in all of the cases presented. Considering the total dose, including the contribution from the stratosphere, the percentage increase was smaller, ranging from 10 to 20%.

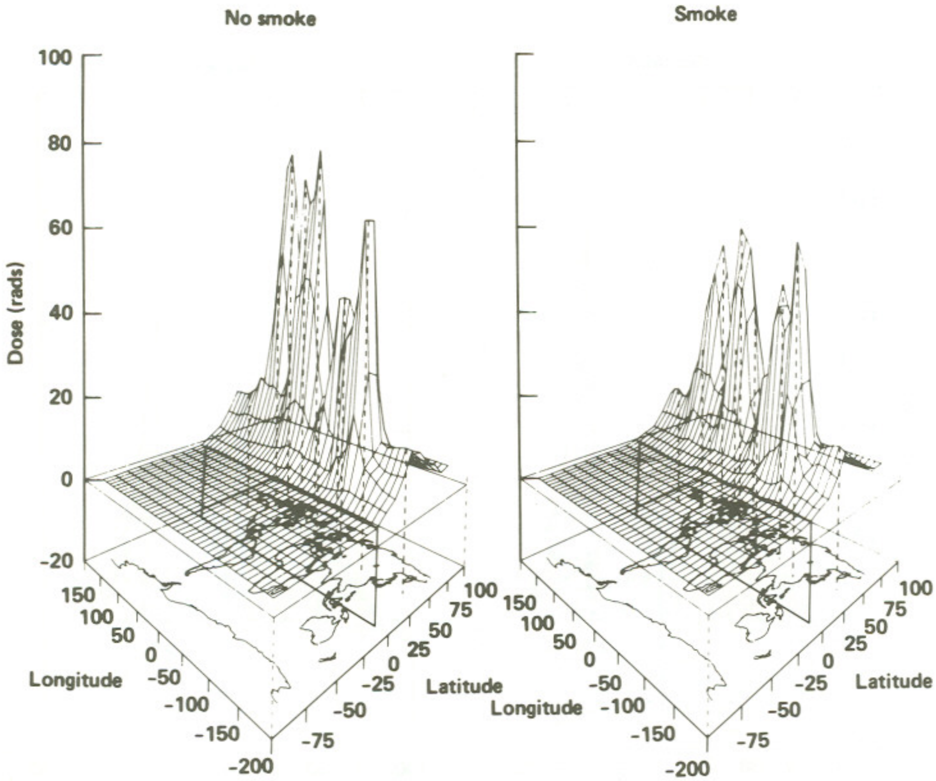

Figure 7.6. Comparison of radionuclide global dose distribution for cases with unperturbed and smoke-perturbed climates (tropospheric contributions only)

Hotspots: Figures 7.6 and 7.7 reveal longitudinal, as well as latitudinal, details that are not apparent in the averages of Table 7.8. Scenario B is illustrated here since the changes due to smoke-induced effects are more apparent. The five original sources have produced four discernible peaks in the tropospheric dose distribution, and the two U.S. sources have merged in the 30 day dose distribution. The tabulated values presented in Table 7.8 are averages over 20° latitude bands. The dose in "hotspots" can be examined by looking at peaks on the 10° × 10° grid. Typically the highest value for a grid square ($\sim 5 \times 10^5$ km^2) is about a factor of 6 to 8 higher than the Northern Hemisphere average dose. There will also be local areas much smaller than the 10° × 10° grid size where the peak doses would be considerably higher.

Particle size. By changing the initial assumed distribution of radioactivity on large and small particles from 43 and 57% to 70 and 30%, respectively, the average dose in the Northern Hemisphere increases about 25%. This is due to more rapid deposition of the larger particles.

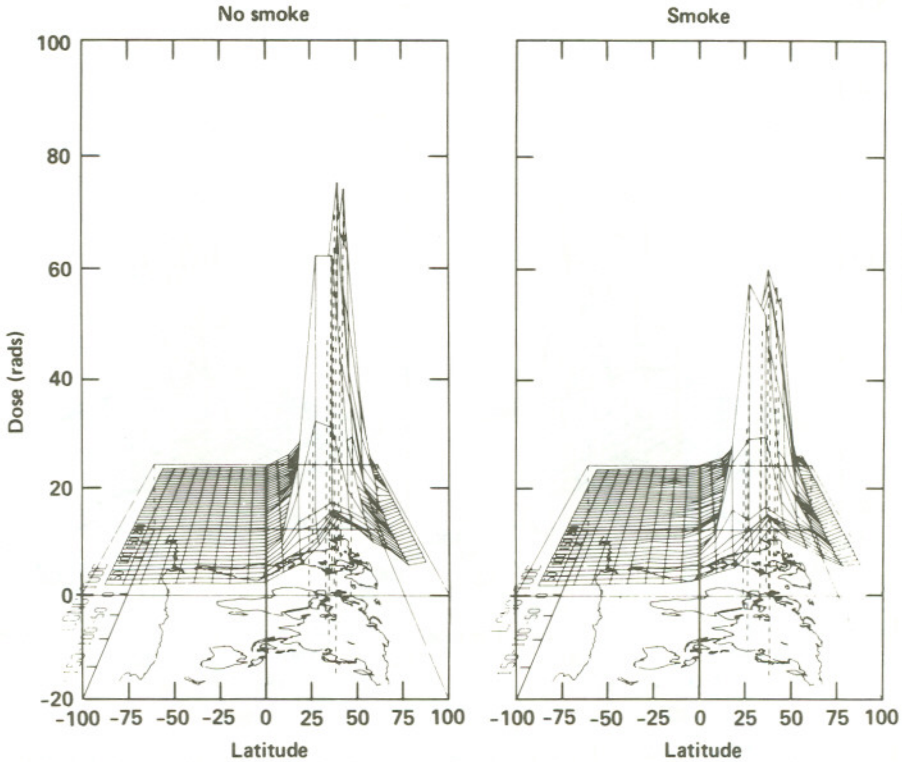

Figure 7.7. Same as Figure 7.6, but a different viewing angle

Source locations. By shifting the source about 5° on a great circle, zonal changes in dose of 10–20% are observed, but the hemispheric averages do not change significantly. The zonal changes are primarily due to the source strength shifts, but variations in local weather on the first day of the OSU meteorological input to GRANTOUR also play a role.

Initial weather conditions. By starting on day 10 of the Oregon State University July climate (rather than day 1), dose estimates for the northern midlatitude bands change significantly (about 30%), but the Northern Hemispheric average is unchanged. This indicates that initial weather conditions may produce significant variations in local dose, but that these may average out over hemispheric areas.

As GRANTOUR treats only the troposphere and GLODEP2 has been used for the stratospheric contributions (which assumes an unperturbed stratosphere), additional calculations using a computer model that includes the perturbed stratosphere should be undertaken.

7.4 INTERNAL DOSE DUE TO INHALATION AND THE FOOD CHAIN

One serious problem following a large-scale nuclear exchange is radioactive contamination of drinking water. Those cities that are damaged would undoubtedly lose their water system due to power loss and ruptured supply pipes. Suburban residents within the local fallout pattern would encounter heavily contaminated water supplies and would have to rely on stored water. Surface water supplies would be directly contaminated by fission products.

During the first few months in areas extending several hundred kilometers downwind of an explosion, the dust, smoke, and radioactivity could cause severe water pollution in surface waters. The dominant fission product during this time would be ^{131}I (iodine-131). Beyond a few months, the dominant fission product in solution would be ^{90}Sr (strontium-90) (Naidu, 1984). Many of the fission products would remain fixed in fallout dust, river and lake sediments and soils. In rural areas, intermediate and long-term fallout would pollute water supplies to a lesser extent than the city and suburban supplies. In the absence of additional contamination from runoff, lakes, reservoirs and rivers would gradually become less contaminated as water flowed through the system.

Initially groundwater supplies would remain unpolluted but they may be difficult to tap. Eventually, however, some groundwater could become contaminated, and remain so for some tens of years after a nuclear war. It would take hundreds or thousands of years for an aquifier to become pure (or nearly so) (van der Heijde, 1985). Doses from drinking this water would be small, but, nonetheless, possibly above current water quality standards. In the long term, ^{90}Sr and ^{137}Cs (cesium-137) would be the major radionuclides affecting fresh water supplies.

The GLODEP2 fractional deposition rates have been used to calculate ^{90}Sr surface concentrations. The results are given in Table 7.9 for the Northern Hemisphere winter and summer seasons. The values are based on the Knox (1983) 5300 Mt baseline scenario A, and are expressed in mCi/km^2 for a 6-year period over 20° latitude bands. The maximum deposition occurs between 30–70° N. The concurrent deposition values for ^{137}Cs can be obtained by multiplying the ^{90}Sr values by 1.6. These values assume an unperturbed atmosphere. As stated earlier, introducing smoke and soot into the troposphere and stratosphere would probably slightly reduce Northern Hemisphere values and slightly increase ^{90}Sr deposition in the Southern Hemisphere.

Significant doses to individual human organs can also arise from specific radionuclides via food pathways. Such doses are caused by consumption of radioactively contaminated milk, meat, fish, vegetables, grains, and other foods. For a normal atmosphere, various researchers (ICRP30, 1979; Kocher,

TABLE 7.9.
AVERAGE ACCUMULATED STRONTIUM-90 DEPOSITION (MCI/KM^2) AFTER SIX YEARS AS A FUNCTION OF LATITUDE

	Latitude band								
Season	70–90N	50–70N	30–50N	10–30N	10S–10N	10–30S	30–50S	50–70S	70–90S
Winter	271	937	862	234	39	25	47	26	3
Summer	226	946	978	237	26	19	39	30	10

1979; Ng, 1977; Lee and Strope, 1974) have provided means to calculate organ doses for a number of radionuclides and food pathways. However, in a post-nuclear war atmosphere perturbed by large quantities of smoke, the results of the above studies may not be valid since the dose in rads/Ci from soil to animal feed to humans are highly variable geographically and depend upon the degree of perturbation of weather and ecosystems.

However, the internal total body dose (the sum of the dose to each organ weighted by the risk factor due to consumption of various foods) has been very roughly estimated by J. Rotblat (private communication)to be about 20% of the external dose from local fallout, about equivalent for intermediate time scale fallout, and somewhat greater than the external dose from long-term fallout. These estimates are very uncertain. Further consideration of the pathways of fission products into the food chain is given in Volume II.

7.5 SUMMARY

Methods for estimating doses from radionuclides have been studied for more than thirty years. During this period, a better recognition of the effects that may be most important has developed, although there are no assurances that all of the crucial issues have been investigated.

For radionuclides, the most important short-term consequence is the downwind fallout during the first few days of relatively large radioactive particles lofted by surface explosions. The deposition of fresh radioactive material in natural and induced precipitation events could also contribute to enhanced surface dose rates over very limited areas (hotspots) both near to and far away from detonation sites. For both local fallout and distant hotspots, dose rates can be high enough to induce major short- and long-term biological and ecological consequences (see Volume II).

Calculations of local fallout fields were performed using the KDFOC2 model and an escalating nuclear exchange scenario (described in Chapter 2). In this illustrative example where simple assumptions are made about the overlap of fallout plumes, these estimates indicate that about 7% of the land surface in the U.S., Europe, and the U.S.S.R. would be covered by lethal external gamma-ray doses exceeding 450 rads in 48-hrs, assuming a protection factor of 1 (i.e., no protective action is taken). A similar area estimate is obtained for lethal doses exceeding 600 rads in 2-weeks. More realistic overlap calculations would suggest that these areas could be greater (by a factor of 3 in one specific case). For those survivors protected from radiation by structures, these areas would be considerably reduced. Areas of sub-lethal debilitating exposure ($\geq$200 rads in 48 hrs) would, however, be larger. A good approximation is that these areas are inversely proportional to the 48 hr dose. In local fallout fields of limited area, the dose from beta rays could be high enough to significantly affect surviving biota. Variations in fallout patterns in the local fallout zones could range over orders of magnitude. If large populations could be mobilized to move from highly radioactive zones or take substantial protective measures, the human impact of fallout could be greatly reduced.

The uncertainties in these calculations of local fallout could be several factors. In addition, using different scenarios (e.g., all surface bursting or little surface bursting of weapons) could modify the calculated lethal areas by several factors. There are a number of other factors that could change these local fallout assessments. Fission fractions of smaller modern weapons could be twice the baseline assumption of 0.5. Adding these to the scenario mix could increase lethal fallout areas by about 20% of the baseline calculation. Tactical weapons, ignored in the baseline scenario, could increase lethal local fallout areas in certain geographical regions, particularly within western Europe, by up to 20% of the baseline scenario. Internal radiation exposure could increase the average total doses to humans by up to 20% of the external dose. Targeting of nuclear fuel cycle facilities could contribute to radiation doses (see Appendix 7A).

For global fallout, different computer models and scenarios have been intercompared. The calculations predict that the 50 year unsheltered, unweathered average external total body gamma-ray dose levels in the Northern Hemisphere would be about 10 to 20 rads, and about 0.5 to 1 rad in the Southern Hemisphere. The peak doses of 20 to 60 rads appear in the 30° to 50° north latitude band. Values predicted for the global population dose using the assumptions made in this study are typically about 6×10^{10} person-rads. The doses in the maxima grid points using a $10° \times 10°$ latitude and longitude mesh size, are a factor of 6 to 8 higher than the Northern Hemisphere averages. Fifty to seventy five percent of the global fallout dose would be due to the tropospheric injection of radionuclides that are deposited in the first month. These results were obtained assuming a normal (unperturbed) atmosphere, and have an estimated confidence level of a factor of 2 for a given scenario. The most sensitive parameter that affects global fallout levels is the scenario (e.g. total yield, yield mix, surface or airburst, burst locations).

Additional calculations involving a perturbed atmosphere indicate that the above dose assessments would be about 15% lower in the Northern Hemisphere, and marginally higher (approximately 1 rad) in the Southern Hemisphere compared to predictions for the unperturbed atmosphere. These results are consistent with the projection that smoke injections can increase vertical stability, inhibit precipitation, and increase interhemispheric transport.

Estimates of dose contributions from food pathways are much more tenuous. Rotblat (private communication) has roughly estimated that internal doses would be about 20% of the external dose from local fallout, about equivalent for intermediate fallout, and somewhat greater than the external dose from long-term global fallout.

APPENDIX 7A

Radioactivity from Nuclear Fuel Cycle Facilities

Three potential effects of radioactivity from nuclear fuel cycle facilities are considered in this report, although there is considerable controversy over the subject of the possible targeting with nuclear warheads of nuclear fuel cycle facilities. There is general agreement that enormous reservoirs of long-lived radionuclides exist in reactor cores, spent fuel rods, fuel reprocessing plants and radioactive waste storage facilities. Disagreement arises when the feasibility and extent of such a targeting strategy are considered. Even if one adopts the view that "what if" questions must be considered, there is still disagreement over the quantitative treatment of the potential dispersal of the radioactivity contained in these sources. In the present treatment, some of the assumptions regarding radioactivity release are considered highly improbable by a number of researchers. The results, therefore, should not be separated from the assumptions and large uncertainties associated with them.

7A.1 INTRODUCTION

A gigawatt nuclear power plant may be a valuable industrial target in a nuclear war. If a targeting rationale is proposed that the largest possible amount of Gross National Product be destroyed in an attack on a nation's industry (one measure of the worth of a target to a nation), then large ($\sim$1000 MW(e)) nuclear power plants could become priority targets for relatively small ($\leq$125 kt) strategic weapons (Chester and Chester, 1976). In the U.S. there are about 100 such targets, and worldwide about 300. There are also military reactors and weapons facilities that could be targeted. Since these facilities may be targeted, reactor-generated radioactivity should be considered as part of the potential post-attack radiological problem.

Whether the radioactivity contained in a reactor vessel can be dispersed in a manner similar to a weapon's radioactivity is debatable. Nuclear reactor cores are typically surrounded by a meter-thick reinforced concrete building that has about a 1 cm thick inner steel lining, many heavy steel structural elements inside the containment building, and an approximately 10 cm thick reactor vessel. Inside the reactor vessel are fuel rods and cladding capable of withstanding high temperatures and pressures. For the core radioactivity to be dispersed in the same way as the weapons radioactivity, all of these barriers must be breached. The core itself must be at least fragmented and possibly vaporized, and then entrained into the rising nuclear cloud column along with possibly hundreds of kilotons of fragmented and vaporized dirt and other materials from the crater and nearby structures, including the thick concrete slab that supports the reactor building. Under certain conditions of damage, there is a possibility of a reactor core meltdown resulting in the release of some of the more volatile radionuclides to the local environment. If this were to occur, however, the area of contamination would be relatively small compared to the contamination by a reactor core if it were to be pulverized and lofted by a nuclear explosion.

Some believe that if the reactor is within the weapon's crater radius that the core could potentially contribute to global and local fallout. Others believe that it cannot be fragmented and lofted in a manner similar to the weapon's residual radioactivity. Considering potential future terminal guidance technology, it is likely that the containment building would be within both a weapon's crater and fireball radius, *if* the containment structure were targeted with a surface-burst weapon.

Even if these barriers were secure, the primary contributor to the long-term dose at a nuclear power plant would not be the core. The most hazardous radioactivity, when assessing long-term effects (≥ 1 yr after attack), is that held in the spent-fuel ponds, if the reactor has been operating at full power for a few years. Since the spent-fuel storage usually has no containment building nor reactor vessel to be breached, it is much more vulnerable to being lofted by a nuclear weapon than the core materials. Unless spent-fuel is located at sufficient distance from a reactor, it could potentially become part of the local fallout problem.

Other nuclear fuel cycle radioactivity may also be significant. Reprocessing plants, although not as immediately important economically as power plants contain a great deal of radioactivity that could significantly contribute to the long-term doses. Also, military reactors developing fissile material and their reprocessing plants might be important wartime targets. They also hold significant amounts of radioactivity in their waste ponds and reactor cores.

Military ships fueled by nuclear power could be prime targets as well. Ships' reactors typically produce less power ($\sim$60–250 MW(t)) than commercial reactors (Ambio Advisors, 1982). They could, however, have substantially radioactive cores, depending on the megawatt-hours of service a shipboard reactor has produced since refueling. A large nuclear powered ship with more than one reactor, designed for years of service without refueling, can have nearly as much long-lived radioactivity (e.g., ^{90}Sr) on board as an operating commercial reactor (Rickover, 1980). Such shipboard reactors may also be more vulnerable to vaporization than commercial reactors.

Figure 7A.1 shows the gamma radiation dose rate-area integrals from a 1-Mt, all-fission nuclear weapon and from possible commercial fuel cycle facilities. In the first few days, the higher activity of the nuclear weapon debris dominates over the gamma radiation of the reactor. Likewise, gamma radiation levels from a light water reactor (LWR) is greater than that of 10 years worth of stored spent fuel for about one year after the detonation. Subsequently, the spent fuel would be relatively more radioactive. Similarly, the gamma radiation from 10 years of spent fuel is greater than the radioactivity of a 1 Mt fission weapon after about two months because of the greater abundance of long-lived gamma emitters in the spent fuel.

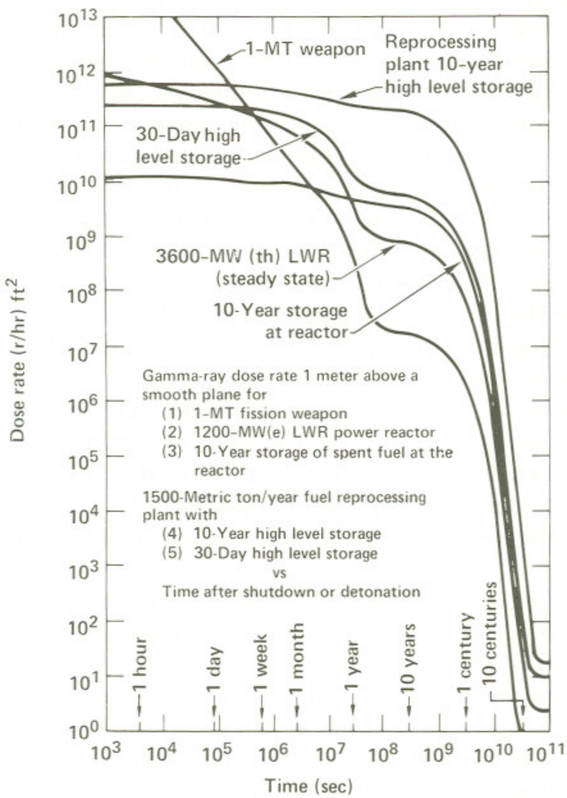

Figure 7A.1. Gamma-ray dose rate area integral versus time after shutdown or detonation (Chester and Chester, 1976)

Thus, for doses from a 1 Mt all-fission weapon detonated on a reactor, the core gamma radiation would be comparable to the weapon's radiation at about five days. By two months the gamma radioactivity from the weapon would have decayed by a factor of over 1000 from its value at 1 hour. Beyond about one year the gamma radiation from the weapon is insignificant compared to a reactor's radiation; however, the dose levels are no longer acutely life threatening.

7A.2 LOCAL FALLOUT

For dose estimates from local fallout, two timeframes are considered—the short-term, where there is acute lethal radiation, and the long term, when chronic doses become important. In the short-term, the gamma radiation is the main hazard. Later, specific radionuclides become important concerns for doses via food pathways.

For doses received within the first 48-hours, the nuclear weapon gamma radiation pathway for a high-yield (~ 1 Mt) warhead dominates the fuel-cycle gamma radioactivity, even if one assumes a worst case assumption in which all the radioactivity from the attacked nuclear fuel cycle facility is lofted with the weapon products. For lower yields and thermonuclear weapons, the core gamma radiation becomes more important, and could potentially dominate the dose, even at very early times. However, since there are now only approximately 100 nuclear power plants available for targeting in the U.S., and possibly a few hundred shipboard reactor targets which are dispersed over the globe (Ambio Advisors, 1982), and because there are typically more than a thousand other U.S. targets in major nuclear exchange scenarios, the impact of fuel cycle radiation to the total U.S. 48-hour external gamma-ray dose would likely be less than 10%.

In the long-term, the radioactivity from the core and spent-fuel ponds could have a dominant effect, both around the reactor and at substantial distances downwind. Because of the long-lived nature of the core radioactivity, civil defense measures (e.g., using expedient shelters) might also require modification when reactor radioactivity is contributing to the local fallout effects.

After about one year, the products from the nuclear fuel cycle could make a substantial contribution to the total gamma-ray dose fallout patterns over the U.S. Certainly, if released, fallout gamma radiation from a large reactor would dominate the dose of a 1 Mt weapon over the long-term (see Figure 7A.2).

In terms of radiological effects, individual radionuclides (e.g., ^{90}Sr) become more important over the longer time-frame than the whole-body gamma radiation. Assuming 50% fission weapons, it is possible to have more ^{90}Sr in a single reactor and its spent fuel pond than that produced in a

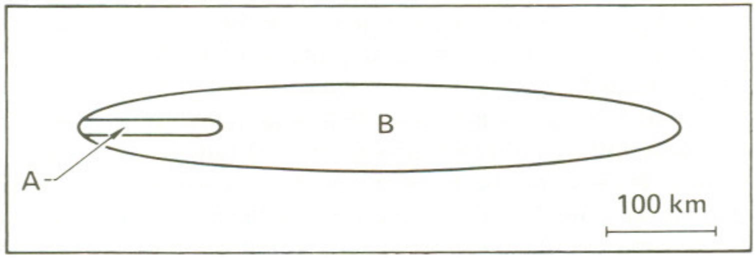

Figure 7A.2. Contours of 100 rad fallout dose during one year's exposure, starting one month after the detonation of (A) a 1 Mt bomb, and (B) a 1 Mt bomb on a 1 GW(e) nuclear reactor (Rothlat, 1981)

1000 Mt attack. Most of the ^{90}Sr is in the spent fuel pond and thus could be more easily lofted as fallout than the ^{90}Sr in the heavily shielded reactor core. Accordingly, in the long term, the fuel-cycle ^{90}Sr contribution can dominate over the weapon contribution. For example, Chester and Chester (1976) calculated levels of ^{90}Sr much higher than the current maximum permissible concentration (MPC) over much of the U.S. farmland one year after an attack on the projected nuclear power industry of the year 2000. Scaling down their results to an attack on a 100 MW(e) nuclear power industry, they calculated that about 60% of the U.S. grain-growing capacity would be in areas that exceed current ^{90}Sr MPC levels.

The previous discussion emphasizes the effects on U.S. targets since past studies have focused on these. The conclusions, however, are more general.

7A.3 GLOBAL FALLOUT

In calculation of the potential global fallout, assumptions have been made that facilitated calculations and allowed estimation of expected dose. For example, it was assumed that each nuclear facility would be surface targeted by a high yield, accurately delivered warhead that would completely pulverize and vaporize all of the nuclear materials, and that these materials would then follow the same pathways as the weapon materials (a worst case assumption). It was assumed further that the major nuclear facilities in a 100 GW(e) civilian nuclear power industry would also be attacked. The results should be viewed as providing estimates that approach maximum global fallout for an attack on a commercial nuclear power industry of 100 Gw(e). Higher estimates would be obtained, however, using the same assumptions by including military facilities and a larger civilian industry.

This hypothetical reactor attack scenario assumed that, as part of the 5300 Mt exchange of Knox (1983), some of the warheads would be targeted on nuclear power facilities. Specifically 0.9 Mt weapons would be surface burst on 100 light water reactors (LWR's), 100 10-year spent fuel storage (SFS) facilities, and one fuel reprocessing plant (FRP). With a 0.9 Mt surface burst on each facility, 2% of the radioactive fission products would be injected into the troposphere and 48% into the stratosphere. The remaining activity (50%) would contribute to local fallout. Such large yields were assumed because of the hardness of the nuclear reactor. If smaller yield weapons were used to target the nuclear facilities, the relative injections of radioactivity into the troposphere would be much greater. While the weapons radioactivity would result in higher doses on the ground, this would not be true for the nuclear facility radioactivity. This is because of the relatively slow decay of the facilities' radioactivity. Hence, a faster deposition time would not significantly affect the 50 year dose. The patterns and local concentrations of fallout deposition would, however, be affected.

Using GLODEP2 and a Northern Hemisphere winter scenario, the resulting unsheltered, unweathered doses are shown in Table 7A.1. The largest value of 95 rads for the total of weapons plus the nuclear power industry occurred in the 30–50° N latitude band. The doses obtained for the Southern Hemisphere were about a factor of 30 smaller than in the Northern Hemisphere. The majority of the dose contributions came from the spent fuel storage facilities and the high level waste in the reprocessing plant.

TABLE 7A.1.
FIFTY-YEAR EXTERNAL GAMMA-RAY GLOBAL FALLOUT DOSE IN RADS FOR NINE LATITUDE BANDS ASSUMING A FULL NUCLEAR ATTACK, INCLUDING A FULL-SCALE, TOTALLY EFFECTIVE ATTACK ON A 100 GW(E) NUCLEAR POWER INDUSTRY. THESE VALUES DO NOT ACCOUNT FOR WEATHERING, SHELTERING OR RAINOUT

	Latitude bands								
Source	70–90N	50–70N	30–50N	10–30N	10N–10S	10–30S	30–50S	50–70S	70–90S
Weapons	4.5	27.3	32.9	6.9	0.8	0.6	0.8	0.5	0.09
LWR[a]	1.8	6.3	9.1	3.0	0.6	0.3	0.3	0.1	0.01
SFS[b]	6.7	23.8	32.7	11.3	2.3	1.0	1.0	0.4	0.03
FRP[c]	4.1	14.6	20.1	7.0	1.4	0.6	0.6	0.2	0.02
Total	17.1	72.0	94.8	28.2	5.1	2.5	2.7	1.2	0.15

[a] LWR = 100 light water reactors
[b] SFS = 100 spent fuel storage facilities
[c] FRP = fuel reprocessing plant

Figure 7A.3 is a plot of accumulated dose in the 30°–50° N latitude band as a function of time out to 50 years (200 quarter years) for the 5300 Mt scenario (Northern Hemisphere winter injection) with and without the targeting of nuclear power facilities. The bulk of the dose from the weapons alone for this scenario resulted from deposition in the first year. The relative contributions of the nuclear facilities were minimal in the first year, but became larger with time. At 50 years, the contribution of the nuclear facilities would be approximately double that of the weapons alone. In addition, while the weapons-only curve at 50 years is almost flat, the nuclear facilities curve has a positive slope with the radioactivity continuing to directly affect future generations.

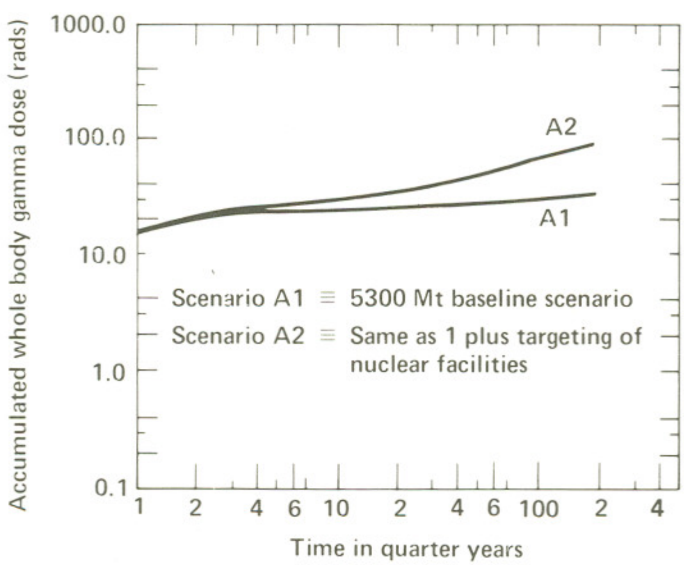

Figure 7A.3. Accumulated dose at 30°–50° N vs time for scenario A, with (A2) and without (A1) an attack on U.S. nuclear facilities

An attack on all of the world's civilian nuclear fuel cycle facilities (approximately 300 GW(e)) would scale the above results up by about a factor of three, although this scenario is even less likely. The potential effect is growing in time; the world's nuclear capacity has been projected to grow to 500 GW(e) by 1995. A significant contribution could also come from targeting military nuclear facilities, with results qualitatively similar to those obtained from attacking power plants.

In summary, using some "worst case" assumptions for a speculative nuclear war scenario wherein 100 GW(e) of the nuclear power industry is included in the target list, the 50 year global fallout dose is estimated to increase by a factor of 3 over similar estimates wherein nuclear power facilities are not attacked.

Accounting for possible moderate to heavy attacks on civilian and military nuclear facilities, for the internal doses necessarily accompanying the external doses (perhaps doubling or tripling these) over generations, the formation of localized hotspots with up to ten times the average radioactivity—in combination with all the other sources of radioactivity—it seems that reactor debris could result in significant long-term radiological problems for humans and ecosystems. Many of these problems involving the radiological assessments associated with nuclear facilities are unresolved and uncertain, but deserve more thorough attention.