NUCLEAR ACCIDENT ABOARD A NAVAL VESSEL HOMEPORTED AT STATEN ISLAND, NEW YORK

Quantitative Analysis of a Hypothetical Accident Scenario

by

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This paper describes a quantitative, site-specific analysis of a hypothetical nuclear accident scenario aboard a military vessel homeported at the Stapleton-Fort Wadsworth Complex, Staten Island, New York. Conventional methodology used by the U. S. Nuclear Regulatory Commission (NRC) to regulate the U. S. civilian nuclear industry is applied to evaluate the consequences of an accident involving incineration of a single nuclear weapon containing 5 kg of plutonium-239 in a three-hour shipboard fire. Bracketing assumptions (i. e., assumptions that lead to accident consequences that are likely to encompass those of a real accident) are used to assess the impact of the accident on the environment, human health and on the economy of New York City. Conclusions and Recommendations of this report are contained in section VII (pp. 57 to 61). The reader is encouraged to review this section in particular.

Such an accident would produce a radioactive cloud containing particulate and aerosolized plutonium-239. The commonest wind direction at the site (Figure 1) would carry the radioactive cloud northeast in the form of a plume, directly over downtown Manhattan (Figure 2). First landfall would occur 9 km (approximately 5.5 miles) from the accident site, at the southern tip of Manhattan. The centerline of the plume would pass through the financial district (Wall Street), and bisect the World Trade Center. The path of the plume would then coincide approximately with the Avenue of the Americas, pass adjacent to the Empire State Building, through the Rockefeller Center, and into Central Park. The centerline of the radioactive plume would continue northward through Harlem, into the Bronx, and beyond.

The lateral boundaries of the plume were calculated for the two boundary conditions, namely the most stable (narrowest plume) and the least stable (widest plume) atmosphere. In the former case the plume would encompass Broadway, Park Ave. and Madison Ave. on its eastern edge, and Eighth Ave. and Central Park West on its western edge. Thus, the narrowest possible plume would nonetheless engulf the major section of downtown Manhattan, assuming the most common wind direction. The widest possible plume would engulf all of Manhattan, cross the Hudson on the west, the western portion of Queens, and most of the Bronx on the east (Figures 2 and 3).

As the hypothetical radioactive plume travels northward from the Bronx, its centerline would pass through Yonkers and Mt. Vernon, Eastchester, White Plains, past the western corner of Connecticut and directly across the Kensico reservoir, a major water supply for New York City. The centerline would then pass through the western portion of Connecticut and into the western sector of Massachusetts. Lateral boundaries of the plume would extend into New Jersey on the west, and nearly to Long Island Sound on the east (Figures 4 and 5). As will be summarized below, significant radiological impact would occur up to approximately 200 km (122 miles) from the site of the accident at Staten Island, i.e, well into Massachusetts.

The concentration of plutonium-239 in the plume was calculated for two extremes of accident conditions: no initial thermal loft, and 100 m (328 feet) of thermal loft by the heat of the fire (Figures 8 and 9). Calculations were carried out both for the most stable atmosphere (Pasquill category F) and the least stable atmosphere (Pasquill category A). These calculations indicate that the plutonium concentration in the plume would exceed existing federal limits by up to ten thousand times near the scene of the accident. Under the worst conditions (stable atmosphere and 100 m thermal loft), plutonium concentration in the air would exceed federal limits by approximately five-hundred times throughout Manhattan and into Yonkers. The air concentration would under these conditions remain above federal limits out to approximately 100 km (61 miles) from the accident site—well beyond New York City and into rural regions to the north.

As the hypothetical radioactive cloud is transported downwind, plutonium contained within it would deposit on all exposed surfaces in the form of "fallout". The calculated deposition would exceed federal limits by as much as one million times near the scene of the accident. Surface deposition would exceed federal limits by nearly ten thousand times throughout Manhattan for the case of 100 m (328 feet) of thermal loft and the most stable atmospheric conditions (Figure 10 and 11).

Persons in the path of the radioactive cloud would be exposed to the plutonium-239 primarily by inhalation. Exposure by other pathways has been ignored in the present analysis, under the conservative assumption that persons in the path of the cloud will evacuate shortly after the accident and food and water will be quarantined immediately. For the worst conditions (thermal loft of 100 m combined with the most stable atmospheric conditions), inhalation exposure from breathing plutonium is approximately one thousand times higher than federal guidelines and two hundred thousand times above background levels up to approximately 20 km (12.2 miles) from the accident site, i. e., for most of Manhattan (Figures 12 and 13). Exposure levels remain above federal guidelines up to 105 km (approximately 63 miles) from the scene of the accident—the farthest distance included in this analysis.

Casualties from the above inhalation exposure include latent cancer fatalities (LCFs; i. e., cancers that are induced by the accident, but occur from a few to several years later) and severe genetic defects. The latter are not calculated in the present analysis. Casualties are calculated for the workforce population in addition to the residential population. For the most stable atmospheric conditions and the highest dose-conversion factors (Figures 15 - 18), latent cancer fatalities may be expected for up to 30,442 people.

The commonest wind direction would carry the radioactive plume over the Croton watershed that supplies much of New York City's water supply and over the Kensico Reservoir. Significant short-term and long-term contamination of the water supply with plutonium would be expected for the least favorable accident conditions.

Economic impacts from such an accident include those associated with evacuation and decontamination, as well as "indirect" losses from the interruption of the New York City economy and the resultant ripple effects on the national economy. Although these costs are difficult to estimate accurately, U. S. government studies suggest that the cost of decontamination alone, assuming it were feasible, could run into several tens of billions of dollars.

The risk of such an accident is the product of the consequences (described above) and the probability of occurrence. Although some consequences, such as LCFs, can be estimated with some precision, calculating the probability of such an accident requires information that the military has been unwilling to provide. In the absence of this information, the risks (probability × consequences) associated with the hypothetical accident modeled cannot be calculated. The military itself has contingency plans to deal with an accident of this type (although not of this scope), suggesting that it views the risk as finite.

The following recommendations stem from the results of this study.

- RECOMMENDATION # 1: *The environmental impacts of possible nuclear accidents consequent to homeporting nuclear capable vessels in New York Harbor should be analyzed in detail. Included in such analyses should be the impacts of such accidents on the terrestrial and aquatic environments, and on the water supply to New York City.*

- RECOMMENDATION # 2: *The full resources of the City of New York and the U. S. Navy should be brought to bear in producing an exhaustive analysis of nuclear accident scenarios and their medical consequences before further consideration of homeporting nuclear capable vessels in New York Harbor.*

• RECOMMENDATION # 3: *The City of New York, together with State and Federal Agencies that are responsible, should determine whether an effective emergency evacuation plan can be developed for the city in the event of a severe nuclear accident aboard a homeported naval vessel.*

• RECOMMENDATION # 4: *Any such emergency evacuation plan should be rehearsed periodically to demonstrate and develop its effectiveness.*

• RECOMMENDATION # 5: *City, State and Federal officials and agencies should work with the military to develop a realistic plutonium decontamination plan. Included in such plan should be assignment of responsibilities, cost and duration, and answers to questions of legal liability and indemnity.*

• RECOMMENDATION # 6: *Economic analyses of the possible impacts of nuclear accidents in New York Harbor should be undertaken in connection with the homeporting proposal. Linkages with the national and international economy should be taken into account in this analysis.*

• RECOMMENDATION # 7: *City and State authorities should insist on obtaining from the military sufficient data to assess accurately the probability of an accident like the one modeled here. Such accidents should be taken into account in arriving at an informed policy regarding homeporting nuclear capable vessels in densely populated urban centers such as New York City.*

IV. INTRODUCTION AND OVERVIEW

A. Statement of the Problem

As part of its strategic policy for dispersal of the fleet, the United States Navy has proposed to homeport several nuclear-capable warships in various ports in U. S. coastal cities. Included in this proposal is the stationing of the refitted battleship *Iowa* at the Stapleton-Fort Wadsworth Complex, Staten Island, New York. The *Iowa* is designed to carry up to 32 nuclear-tipped Tomahawk Sea-Launched Cruise Missiles (SLCMs) (Cochran et al., 1984). The policy question of whether to homeport the *Iowa* in New York harbor is therefore a question of whether to station nuclear weapons in the midst of a densely-populated urban region.

Any rational policy-making procedure examines the costs of a particular action and weighs them against the benefits. If the costs outweigh the benefits, then by definition the policy is non-utilitarian. A significant component of the costs of a homeporting policy is the risk associated with nuclear accidents aboard the homeported vessel while in port. Such analyses have not been performed by the Navy in its Environmental Impact Statements on the homeporting question. Indeed, the broader policy question has been largely sidesteped by the Navy, on the basis that it neither confirms nor denys the presence of nuclear weapons aboard any of its ships. The Navy's Draft Environmental Impact Statement (DEIS) on the homeporting of the battleship *Iowa* at the Stapleton-Fort Wadsworth Complex, for example, states:

> "Because the information is classified for national security reasons, the Navy's regulations forbid it either to admit or deny the presence of nuclear weapons aboard any station, ship, or aircraft;" (DEIS, p. 4-142)

The DEIS explains this policy as follows:

> "These regulations deny a potential enemy the opportunity to count weapons, determine distribution of weapons or assess employment (sic) doctrine. Additionally, by not knowing if a weapon is actually present, the policy denies information to a potential soboteur (sic) who might have as an objective a plan intended to damage, destroy or capture a weapon." (DEIS, p. 4-142).

The history of the "neither deny nor confirm" policy suggests, however, a different mission. Paul Warnke has testified before the U. S. Senate that the policy originated not for security reasons, but for public relations—to avoid provoking the fears of local populations (Warnke, 1974). And, in any case, the Navy would not contravene this policy by performing a dispersion/consequence analysis of a plausible accident scenario involving a nuclear weapon.

B. Purpose and Background

Policy-makers need to know the risks associated with possible nuclear accidents so that socially utilitarian policy decisions can be reached with the full benefit of complete scientific and technical information. The purpose of this analysis is to provide such an analysis of a nuclear accident scenario aboard a military vessel stationed at Staten Island, New York.

There are several possible accident scenarios by which nuclear materials contained within a weapon could be dispersed into the environment, ranging from accidental explosion of the device (considered highly improbable) to explosion of the chemical initiator and resultant disintegration of the nuclear material (considered possible, but unlikely) to incineration by a shipboard fire (perhaps the most plausible accident sequence). Plutonium is pyrophoric, i. e., it combusts in air to form plutonium oxide at temperatures below those of a typical hydrocarbon fire (1,475 - 2,000°F; Dennis et al., 1978). The U. S. military has recognized this possibility, and indeed such accidents have occurred in the past.

> "The United States has never had an accident with a nuclear weapon which resulted in a nuclear yield. Accidents have occurred, however, which released radioactive contamination because of fire or high explosive detonations." (Defense Nuclear Agency, 1984, p. i.)

Nuclear weapons accidents are unique in that they are capable of contaminating regions that are remote from the accident site itself.

> "...a nuclear weapons accident is uniquely different from most accidents because of the very real possibility of radioactive contamination at the accident site and many miles downwind." (ibid.).

The nature and consequences of such accidents are outlined in another official U. S. document as follows:

> "Most nuclear weapons in the stockpile and all presently in development contain plutonium. An accidental or terrorist attack that caused the high explosive in these weapons to detonate would result in significant radioactive contamination of the surrounding area through plutonium scattering alone. This would require costly cleanup operations and could cause extremely adverse political consequences." (DOD/DOE, 1984, p. I-6).

and

> "Even if an accident does not cause the high explosive to detonate, the weapon may be engulfed in a fire that has the potential to result in plutonium dispersal." (ibid., page unnumbered)

Given the possibility of such accidents, the military has specific contingency plans to deal with them, at least on a small scale. These plans are outlined as follows in an official U. S. Navy document as follows:

> "Contaminated human remains must be monitored before transfer from the ship or activity. Human remains, which after decontamination show measurable contamination, will be wrapped and sealed in sheet polyethylene and stored in a properly labeled human remains case. Such human remains will be stored in a posted locked storage area until transfer." (CINPACFLT, 1981).

C. Qualitative Description of Accident Scenario

The above information suggests that the U. S. military considers nuclear accidents plausible and has specific contingency plans for dealing with them. The plausibility of such accidents is further underscored by the 3 October 1986 Yankee-II Soviet submarine fire and explosion in the Atlantic Ocean near Bermuda, and the accompanying destruction of at least one SS-N-6 nuclear-armed missile and its warhead(s). It seems appropriate to analyze the possible consequences of such accidents in port, and to assess their probabilities as carefully as possible as part of the decision-making process surrounding the homeporting policy.

The accident scenario that is modeled in this paper is a shipboard fire that incinerates one or more nuclear weapons. In the event of such an accident aboard a ship homeported at Staten Island, plutonium oxide in aerosol and particulate form would be carried aloft in a radioactive cloud. The cloud would then be transported by prevailing winds in the form of a radioactive plume. The plutonium originally contained in the weapon and now oxidized by the fire would be dispersed initially in the atmosphere and respired by persons engulfed by the plume downwind. Plutonium particles contained within the cloud would settle out onto exposed surfaces in the form of "fallout", causing radioactive contamination of property and potentially exposing people to medically significant levels of radiation. Food and water supplies would be contaminated, and the impacted area of the city would require evacuation and decontamination prior to rehabitation. It is this accident sequence that is analyzed quantitatively in the remainder of this paper.

V. METHODOLOGY

A. Quantitative Approach of This Analysis

The methodology used to analyze the above accident sequence is similar to that promulgated by the U. S. Nuclear Regulatory Commission (NRC) to regulate the commercial nuclear industry. This methodology evolved, in part, from the literature on the dispersal of airborne fossil fuel pollutants, and was first elaborated for purposes of nuclear regulation in the "Reactor Safety Study", also known as the Rasmussen Report, or document WASH-1400 (NRC, 1975). Aspects of the methodology have been criticized for understating the impact of a nuclear accident, but the approach is the best available, and remains the official basis for regulating the U. S. civilian nuclear industry. The same methodology can be applied to any accident involving dispersion in the atmosphere of nuclear materials, including an accident involving nuclear weapons.

The details of this methodology are presented in Appendix I of the present report, and illustrated by sample calculations in Appendix II. Briefly, it is first necessary to establish the inventory of dispersible radioactive material. The fraction of this inventory that is released in an accident is then decided. The resulting quantity of material released is called the source term.

Having established the source term, its dispersion in the atmosphere is calculated under specific, idealized, release assumptions, using established mathematical equations for turbulent diffusion in the atmosphere. These equations are based on a Gaussian distribution of radionuclides in the horizontal and vertical dimensions within the radioactive plume. The dimensions of the plume are computed for different atmospheric stability conditions (Pasquill categories), at increasing incremental distances from the accident site. Plume width is calculated as three standard deviations of crosswind radionuclide concentration, in accord with WASH-1400 (NRC, 1975).

On the basis of the equations for turbulent diffusion, the downwind concentrations of radionuclides in the air can be determined under specific release assumptions. Fallout from the cloud, based on the air concentration, can then be determined using established source-depletion parameters. Once the air and ground concentrations of radionuclides (in the present case, plutonium) are determined, as above, these values can be compared with various contamination standards. If these standards are exceeded, evacuation and/or decontamination may be appropriate.

Following the above calculations of the dispersion of radionuclides, the medical significance of the resultant radiation doses to people is evaluated for five pathways: 1) exposure to gamma radiation in the passing radioactive cloud (also termed "cloudshine"); 2) inhalation of the radioactivity dispersed in the air; 3) exposure to radioactivity on deposited surfaces ("groundshine"); 4) exposure to radionuclides that were deposited in the initial fallout and subsequently resuspended in the atmosphere ("resuspension"); and 5) ingestion of radionuclides deposited in food and water supplies ("ingestion"). On the basis of published radiation dose conversion factors, the medical impact of these exposures can be expressed in terms of prompt and delayed casualties. The latter take the form of latent (delayed) cancer fatalities (LCFs), as well as non-fatal cancers and genetic damage. For a broad mix of fission products, LCFs are usually taken as equal in number to fatalities from severe genetic defects. In the case of plutonium, genetic impact will depend on the form of the plutonium (specifically the solubility), but is generally likely to be less (by a factor of 10 to 100) than casualties from LCFs.

This general approach of the NRC has been followed in the present analysis, with several modifications. First, ingestion, resuspension, cloudshine and groundshine pathways are omitted from consideration here. Omission of the ingestion pathway is based on the assumption that the population will be evacuated immediately and all food and water supplies will be immediately quarantined. Omission of the resuspension pathway is based on the assumption that the affected regions of the city will be evacuated and remain uninhabited until decontaminated. Omission of the cloudshine and groundshine pathways are based on the fact that plutonium is a weak gamma emitter and therefore will not produce a large radiation exposure from these pathways. As a consequence of these omissions, only a single pathway is considered, namely inhalation. This renders the present analysis conservative in this respect.

The second modification from the basic NRC methodology is that consequences are calculated for a single, most probable wind direction, rather than integrated probabilistically over all 360° of the compass. This modification is justifiable owing to the relatively short duration of the accident that is assumed (3 hours).

The third modification of the basic NRC approach is the estimation of the amount of initial thermal lofting of the radioactive cloud at the accident site, rather than its calculation from available but complex equations (see Appendix I). The effect of this assumption is minimized by performing all calculations for a minimum and (potentially) maximum thermal loft, namely zero and 100 m (328 feet). A larger thermal loft—which is possible—would result in a larger number of casualties and greater contamination further from the accident, and hence the effect of this modification is also probably to understate the impact of the accident.

The fourth modification from NRC methodology is the omission of credit for shielding and evacuation. This modification is based on the fact that gamma radiation from cloudshine and groundshine (the primary form of radiation that is mitigated by shielding) is absent in the special case of plutonium. Shielding from inhalation is not likely to be effective because most structures in the path of the radioactive cloud are fitted with forced air circulation systems that replace internal air rapidly (frequently several times per hour), and hence indoor concentrations of plutonium may not be significantly different from those outdoors.

It should be noted that the methodology developed originally in WASH-1400 is now applied most frequently in the form of complex computer codes (CRAC1, CRAC2, CRACIT, and more recently, MACCS1 and MACCS2). These codes are based on the same methodology and equations as used here. The most recent codes (MACCS) yield casualty figures that are two to three times higher than the older codes based on unmodified WASH-1400 methodology such as that applied here. It seems likely, therefore, that the present analysis understates the casualties in comparison with the most recent computer codes, but a direct comparison has not been made.

Complete details of the methodology used here are given in Appendix I. Sample calculations illustrating the application of this methodology, in the present case, are presented in Appendix II.

B. Assumptions of the Present Analysis

In order to apply the NRC methodology outlined briefly above and detailed more completely in Appendices I and II, it is of course necessary to define explicitly the assumptions of the hypothetical accident modeled. For purposes of the present study, it is assumed that a vessel bearing nuclear weapons is stationed at the Stapleton-Fort Wadsworth Complex, Staten Island, New York—the proposed homeporting site of the battleship *Iowa* and its surface action group of several additional military ships. It is assumed that a three-hour fire aboard the vessel incinerates and disperses a total of 5 kg of plutonium-239, probably equivalent to a single warhead (total source term, or amount released, 311.50 Curies).* The fraction of solid (metallic) plutonium-239 released by a fire is generally considered to be less than one percent of the available inventory (e. g., Selby et al., 1973; Walker, 1978), and hence this scenario would probably require a combination of explosion of the high-explosive chemical initiator, consequent fragmentation of the plutonium within the warhead, and subsequent fire. Further details of the

*62.3 Curies/kg of plutonium-239.

accident need not be specified for purposes of the ensuing analysis.

It is assumed that the explosion/fire breaches the containment provided by the hull of the vessel and creates a hole 10 m (approximately 32.8 feet) wide. The consequence analysis is not sensitive to this assumption, although it does require a breach of containment.

Assumptions about thermal lofting are, to an extent, avoided by performing all calculations for zero and 100 m of thermal loft. This procedure may bracket the actual amount of thermal rise of the cloud, although as noted above, greater thermal loft will probably generate more total casualties and downwind impact.

It is generally acknowledged that the greatest casualties and consequences are associated with the most stable atmospheric conditions (Slade, 1968; Turner, 1969). This is because less stable atmospheres are associated with greater wind flux and hence the area is cleared more rapidly of atmospheric contaminants by rapid dilution and transport. Assumptions about atmospheric stability are avoided here, however, by performing all calculations for the two extremes (most stable, or Pasquill category F; and least stable, or Pasquill category A). The actual impact probably lies somewhere between these extremes, depending on the actual distribution of atmospheric stabilities in the New York region. Atmospheric inversions that would entrap the radioactive cloud are assumed not to occur, an assumption that is conservative since such entrapment would enhance local impact.

A windspeed of 1 meter per second is assumed (2.24 mph). This is on the low end of the range of actual windspeeds in the New York region, and low windspeeds tend to maximize impact. This assumption is justified on the basis of 95% meteorology (see Appendix I). In any case, impact is inversely proportional to windspeed. In other words, a windspeed of 10 m/sec (on the medium scale of those recorded in the New York region) would result in one-tenth the downwind impact. As will be shown, the downwind impact of the accident modeled is so great that even a one-tenth reduction does not fundamentally alter the conclusions of this study. The direction of the wind is assumed to be from the most common compass quadrant, namely from the south-south-west toward the north-north-east (FIGURE 1 AND TABLE 1).* Dry weather is assumed, i. e., no wet deposition is taken into account, which represents an additional conservatism. A dry deposition velocity of 1 cm per second is assumed, the average value suggested in WASH-1400 (NRC, 1975), and a reasonable average for the likely diameter of plutonium particles under the accident conditions modeled (approximately 80% of which are expected to be 20 micrometers and below; Vogt, 1983, Fig. E-1, p. E-6).

TABLE 1
FREQUENCY OF WINDSPEED OBSERVATIONS FROM DIFFERENT COMPASS DIRECTIONS, JFK AIRPORT, NEW YORK
(DATA TABULATED FROM FIGURE 1)

COMPASS DIRECTION	PERCENT OBSERVATIONS
S	11.3
SSE	3.9
SE	2.7
ESE	2.5
E	4.4
ENE	4.0
NE	4.8
NNE	5.0
N	6.9
NNW	5.0
NW	8.3
WNW	6.8
W	7.2
WSW	7.5
SW	6.9
SSW	7.2

The population at risk in this hypothetical accident is assumed to be the residential and workforce population in the direct path of the radioactive cloud. It is assumed that the

*It will be noted from TABLE 1 that the commonest wind direction is from the south, but that the third, fourth and fifth most common directions are from the south west sector. This is the basis of assigning an average wind direction from the SSW.

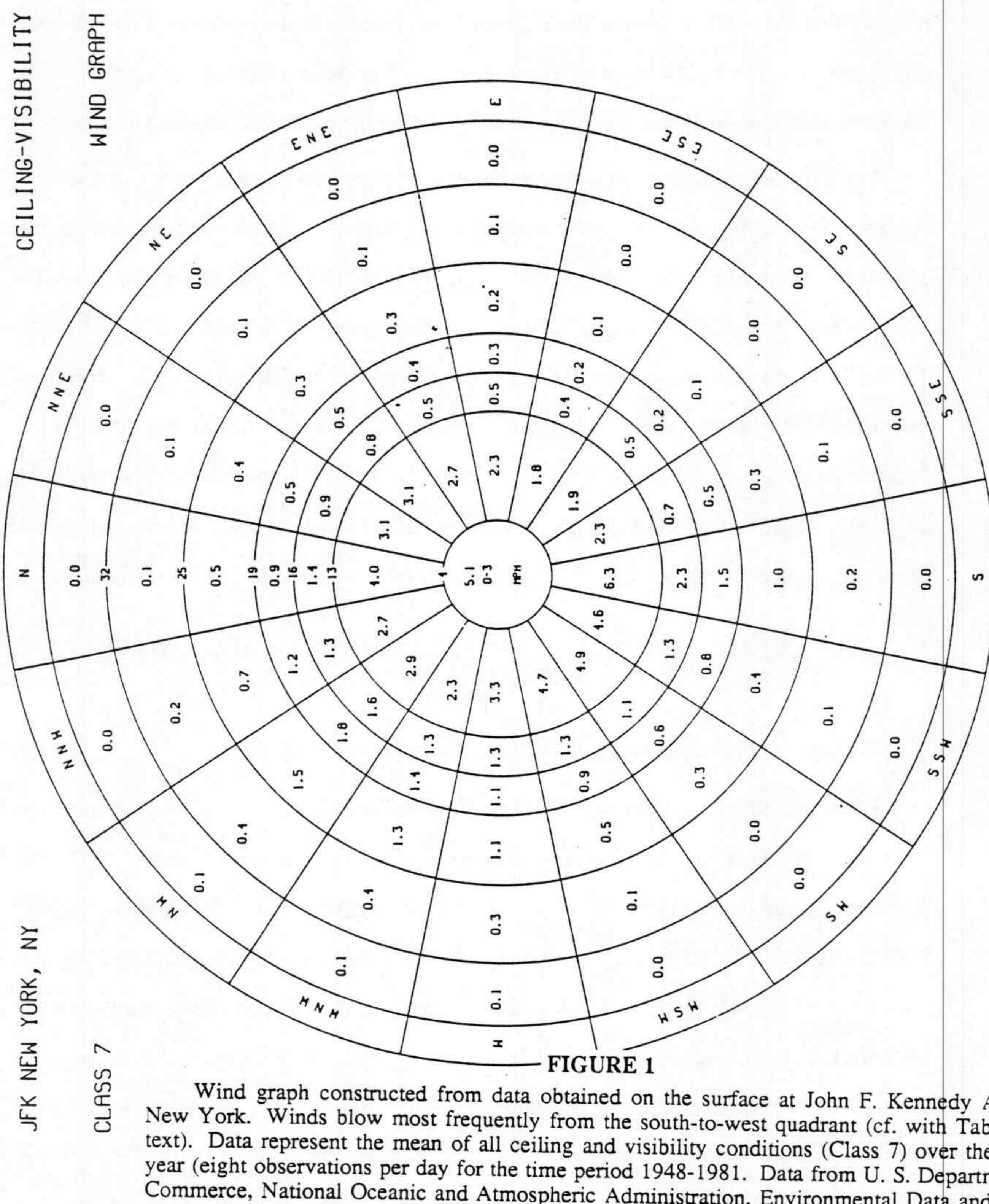

FIGURE 1

Wind graph constructed from data obtained on the surface at John F. Kennedy Airport, New York. Winds blow most frequently from the south-to-west quadrant (cf. with Table 1 in text). Data represent the mean of all ceiling and visibility conditions (Class 7) over the entire year (eight observations per day for the time period 1948-1981. Data from U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data and Information Service, National Climatic Center, Asheville, North Carolina, and prepared for the Office of Aviation Policy and Plans, Federal Aviation Administration, under Interagency Agreement DOT-FA79WAI-057, January 1981.

workforce population is the same as the residential population, and hence the total population at risk is twice the residential population. Residential population densities are obtained from census tract data. All affected persons are assumed to be adults, a conservative assumption inasmuch as children and infants are more susceptible to radiation effects than are adults.

Casualties are calculated using the same bracketing procedure as employed for atmospheric stability. That is, low and high risk factors from the scientific literature are utilized, in the expectation of bracketing the projected radiological impact. The low risk factor used is 10,000 person-rem per latent cancer fatality (LCF), which is lower than that assumed in BEIR-III (NAS, 1980), The high risk factor used is 235 person-rem per LCF (Gofman, 1981). Recent re-evaluation of the Hiroshima data suggests that existing radiation risk factors may be low by a factor of three to eight or ten; hence the high risk factor may be closer to the correct value. In any event, the calculated casualties are expected to encompass the actual casualties that would result from such an accident.

VI. CONSEQUENCES OF A HYPOTHETICAL NUCLEAR ACCIDENT AT STATEN ISLAND

A. *Geographical Parameters of the Hypothetical Accident*

Given the commonest average direction of prevailing winds in the New York area, the radioactive plume from a burning ship at Staten Island would be carried toward the North-Northeast, directly over Manhattan. The centerline of the plume, shown by the dashed line in FIGURE 2 and FIGURE 3, would travel over the lower portion of Manhattan, reaching first landfall approximately 9 km (5.5 miles) from the burning ship. On reaching Manhattan, the centerline of the radioactive plume would pass through the financial district and Broadway, the World Trade Center, and then approximately bisect the Avenue of the Americas. The centerline would pass adjacent to the Empire State Building, and intersect the Rockefeller Center before entering Central Park and crossing the Croton Reservoir. Continuing on its trajectory at the

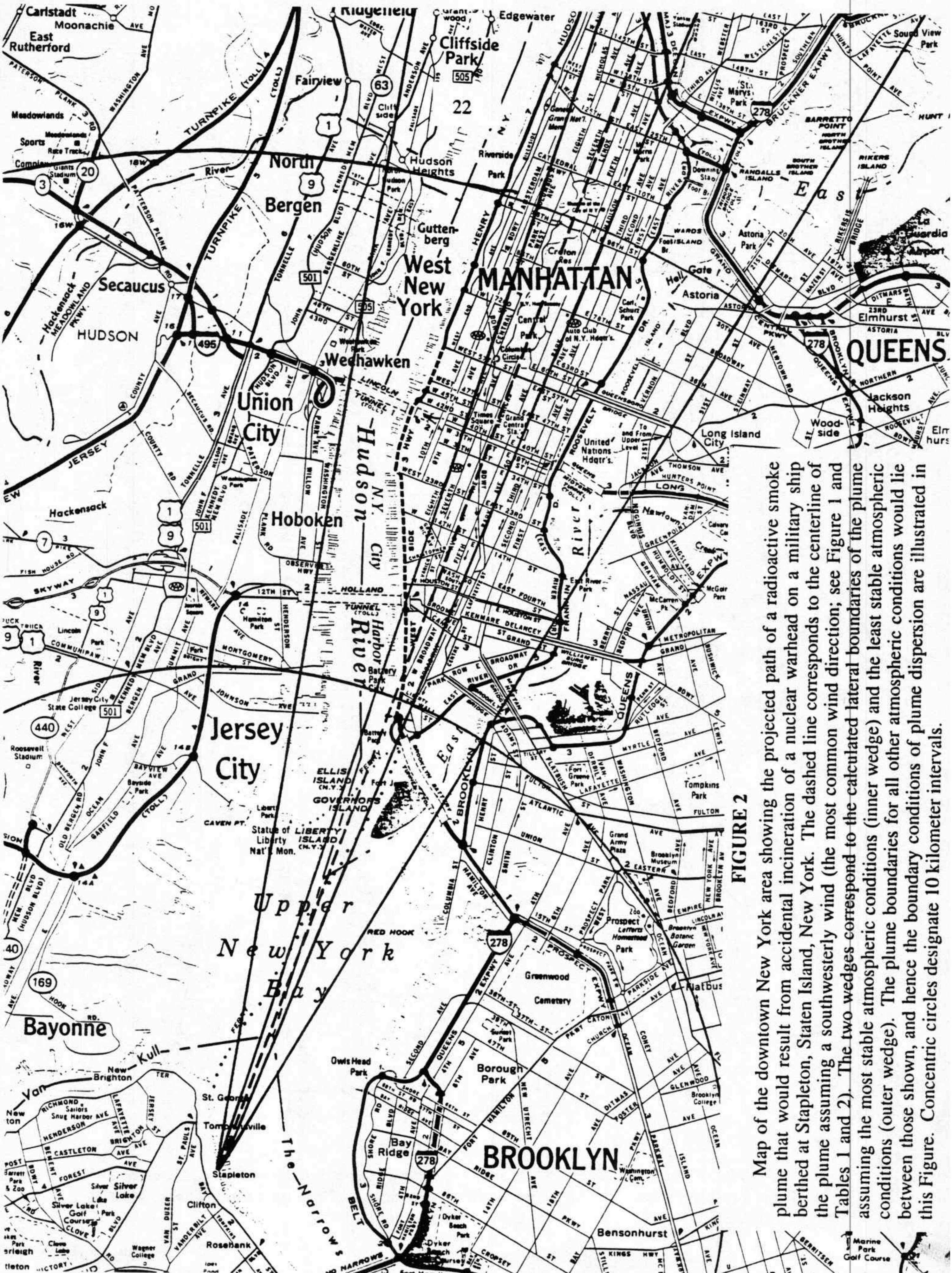

FIGURE 2

Map of the downtown New York area showing the projected path of a radioactive smoke plume that would result from accidental incineration of a nuclear warhead on a military ship berthed at Stapleton, Staten Island, New York. The dashed line corresponds to the centerline of the plume assuming a southwesterly wind (the most common wind direction; see Figure 1 and Tables 1 and 2). The two wedges correspond to the calculated lateral boundaries of the plume assuming the most stable atmospheric conditions (inner wedge) and the least stable atmospheric conditions (outer wedge). The plume boundaries for all other atmospheric conditions would lie between those shown, and hence the boundary conditions of plume dispersion are illustrated in this Figure. Concentric circles designate 10 kilometer intervals.

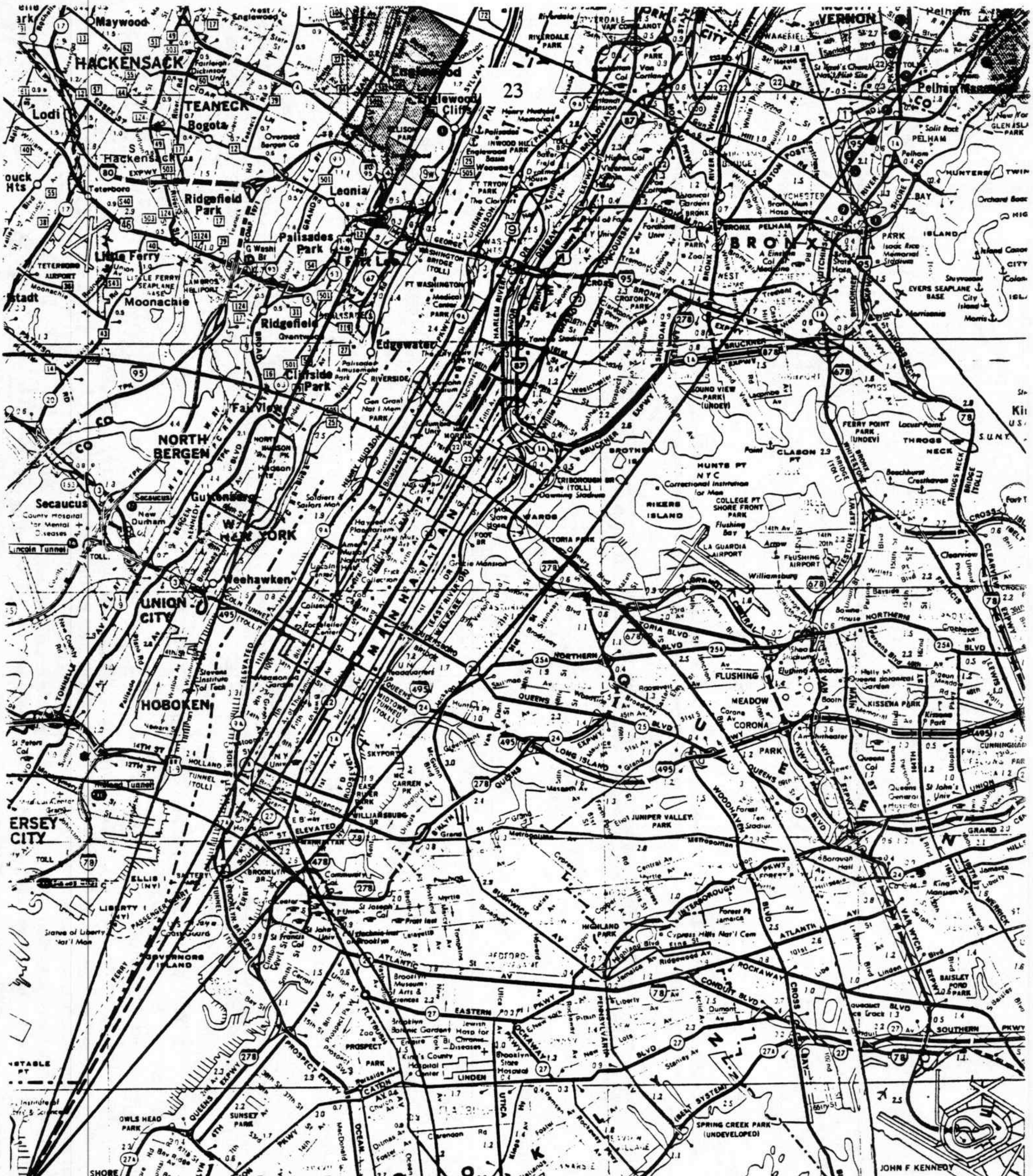

FIGURE 3

Map of the New York area showing the projected path of a radioactive smoke plume that would result from accidental incineration of a nuclear warhead on a military ship berthed at Stapleton, Staten Island, New York. Conventions as in Figure 2.

speed of the prevailing wind, the radioactive plume would drift through Harlem into the Bronx and beyond, into the Yonkers and Mt. Vernon areas (FIGURE 4).

On a larger scale (FIGURES 4, 5), the centerline of the plutonium-bearing plume would pass through Eastchester, White Plains, Valhalla, across the Kensico Reservoir and past the southwestern corner of Connecticut. Approximately 90 km from the site of the accident, the centerline of the radioactive plume would pass into the state of Connecticut, continue adjacent to Danbury and New Milford, past Torrington and directly through the city of Winsted before entering Massachusetts, approximately 180 km (110 miles) from the burning ship. The centerline of the plume would then pass through the western sector of Massachusetts and into the Vermont/New Hampshire regions (FIGURE 5). As will be documented below, significant radiological impact could, under the most unfavorable accident conditions, occur up to approximately 200 km (122 miles) from the accident site, i. e., well into Massachusetts.

The above description of the path of the radioactive plume is highly idealized, in that it assumes a constant wind blowing in the most common average direction for the full three-hour duration of the accident. The above description does not take into account micro-geographical differences in wind direction, vertical winds, etc. Such simplification is convenient, and indeed necessary, for purposes of quantitative modeling, but real nuclear accidents are much more variable and less predictable, as illustrated by the erratic behavior of the radioactive plume emanating from the Chernobyl nuclear power plant accident in the USSR following the explosion and fire there. In a real accident, horizontal wind shifts, inversion layers, vertical wind shear, and other variables, could be expected to generate a more random pattern of plutonium distribution than the one portrayed above. The idealized accident scenario depicted above must be qualified, therefore, with at least two caveats.

First, the wind graph of FIGURE 1, and the corresponding data in TABLE 1, show that while there is an approximately 33% chance that the wind will blow from the south or southwest

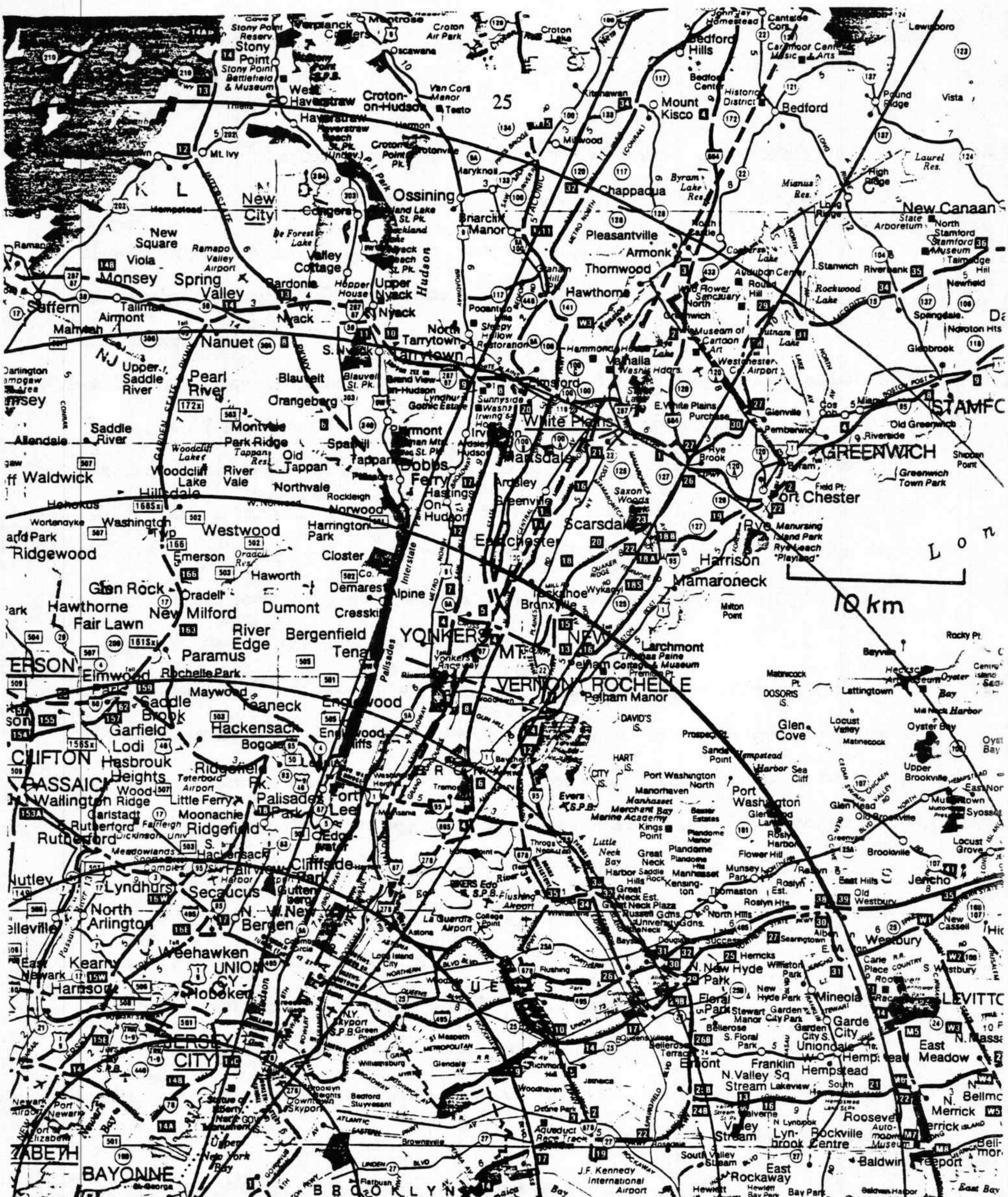

FIGURE 4

Map of the New York area showing the projected path of a radioactive smoke plume that would result from accidental incineration of a nuclear warhead on a military ship berthed at Stapleton, Staten Island, New York. Conventions as in Figure 2.

FIGURE 5

Map of the New York area showing the projected path of a radioactive smoke plume that would result from accidental incineration of a nuclear warhead on a military ship berthed at Stapleton, Staten Island, New York. The wedge corresponds to the plume boundaries assuming the least stable atmosphere (with the centerline indicated by the solid line), while the circle has a radius of 100 km (the approximate limit of radioactive contamination calculated in this analysis).

compass sectors, there is an 8.3% chance that the wind will blow from the northwest; a 13.8% chance that it will blow from a north east sector; etc. The actual area of possible impact of a nuclear accident of the kind modeled here is therefore more accurately portrayed by a series of concentric circles, with the source of radiation at the center. Such concentric circles are shown in FIGURES 2 - 4 as 10 km (6.1 miles) circles; and in FIGURE 5 as a 100 km (61 mile) circle. These circles denote the areas of progressively greater impact with increasing proximity to the source, as developed below. Any area within these circles—not just the areas subtended by the idealized, wedge-shaped plumes of FIGURES 2 - 5—is subject to the radiological impact calculated and graphed below. The wedges shown in the figures simply denote the most probable impact zones given the assumptions of the idealized accident.

As a second caveat, wind patterns are known to vary substantially from one location to another in such geographically broad areas as can be affected by a nuclear accident. Therefore, it is likely that the path of the radioactive cloud would not be linear over its full course, as portrayed in FIGURES 2 - 5. Instead, the plume may meander according to local wind conditions. These qualitative possibilities are raised simply to highlight the idealizations in the accident model that is employed in the present quantitative analysis.

The calculated geographical parameters of the idealized radioactive smoke plume are shown quantitatively in FIGURE 6 (width of plume) and FIGURE 7 (ground area subtended by the plume in each downwind spatial interval). Downwind spatial intervals 1 - 20 in these and subsequent similar figures correspond to 1 km increments from the source of the accident. Spatial intervals 21 and 22 correspond respectively to additional 5 km increments from the source, while intervals 23 - 30 correspond to 10 km increments from the source. Thus, interval 30 corresponds to 105 km (approximately 63 miles) from the accident site, the farthest distance for which calculations were made in the present study. The apparent discontinuities in the curves of FIGURES 6 and 7 (and in subsequent figures) are caused by the increase in distance represented

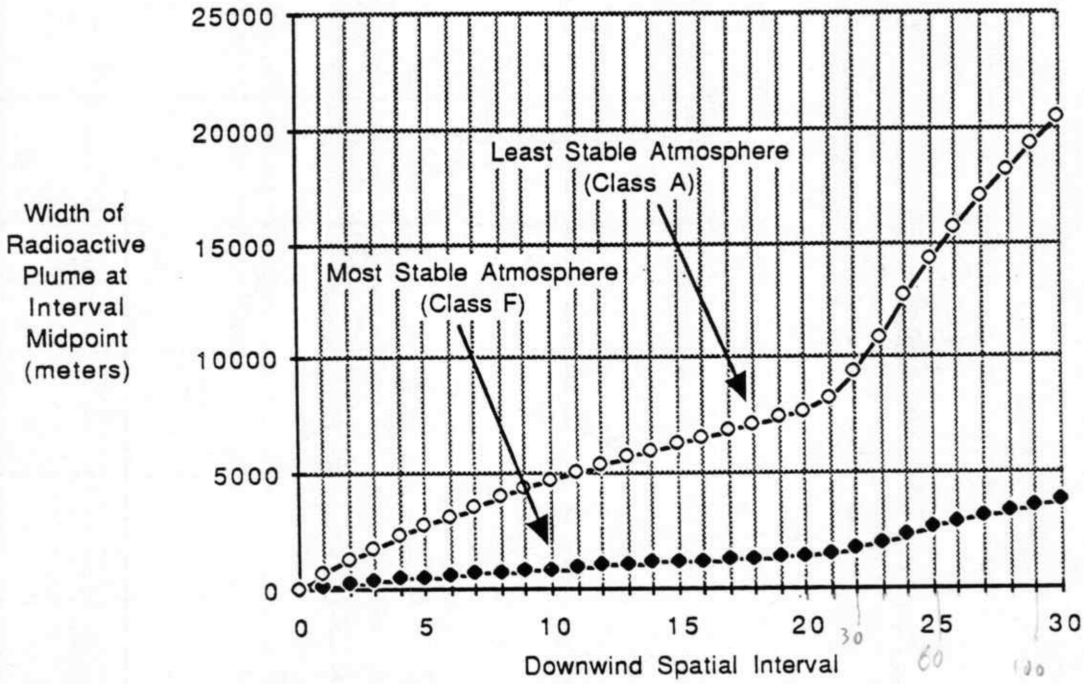

FIGURE 6

Calculated width of the radioactive plume emanating from a ship homeported at Stapleton, Staten Island, New York, *versus* downwind spatial interval. the downwind spatial intervals represent increasing distances from the fire in increments of 1 km through interval 20. Intervals 21 and 22 correspond to 5 km increments, while intervals 23-30 correspond to 10 km increments. The two curves correspond to the most stable (lower curve) and least stable (upper curve) atmospheric stability conditions (Pasquill categories F and A, respectively). In this and subsequent graphs, the discontinuities in intervals 21-30 are caused by the larger increments in downwind distance for these intervals.

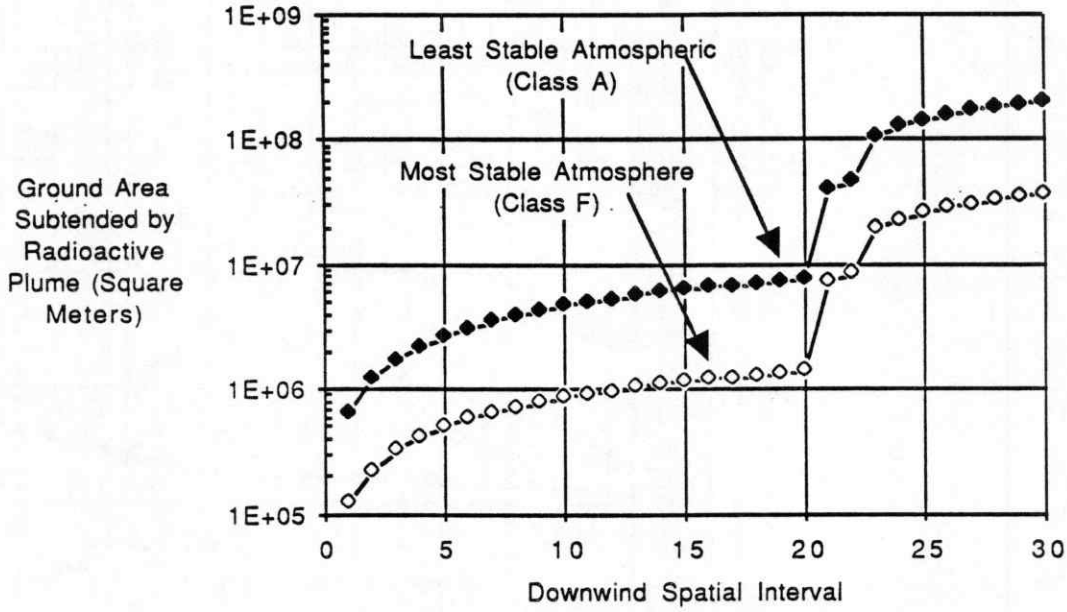

FIGURE 7

Calculated ground area subtended by a radioactive smoke plume originating from a fire aboard a military vessel homeported at Stapleton, Staten Island, New York, *versus* downwind spatial interval (see legend to Figure 6 for the relation between downwind spatial interval and distance).

by spatial intervals 21 - 30.

B. Air Concentration of Plutonium in New York City and Beyond

As the radioactive cloud is carried downwind from the source (in this case a ship fire), the plutonium-239 that is contained within it will be inhaled by people, and will settle to earth and deposit on all external surfaces. In addition, ventilation systems of buildings will draw the contaminated air into skyscrapers, office buildings, schools and hospitals. Conventional filter systems are not capable of removing particles of plutonium (20 micrometers and below; Vogt, 1983). Therefore, given the rapid turnover of air inside ventilated structures, their interiors will become contaminated with plutonium also, although with delay time and perhaps to a lower level than the ambient external atmosphere. In order to assess the possible medical consequences of the resultant radiation exposures, it is essential to know the concentration of plutonium-239 in the air downwind from the accident site.

The air concentration of plutonium can be calculated using equations for turbulent diffusion in the atmosphere, as recommended by the U. S. NRC (1975) and as detailed in Appendices I and II. The results of these calculations are illustrated here in FIGURES 8 and 9. Calculations have been undertaken for two different conditions at the site of the accident. In the first condition, the radioactive plume is assumed to originate at sea level and begin to expand immediately in the horizontal and vertical dimensions (thermal loft = 0). In the second condition, the thermal energy released by the fire is assumed to loft the radioactive cloud to a height of 100 m (328 feet) above the accident site, where plume expansion and dispersion begins.

Calculations are also presented for two different atmospheric stability classes: very stable (Pasquill category F), and very unstable (Pasquill category A). These categories represent the two extremes of atmospheric stability conditions, and parameters for the other four atmospheric stability classes lie between them. By performing calculations for the two extremes of atmospheric stability, the boundary conditions for the consequences of this accident are established.

FIGURE 8 A illustrates calculated air concentrations of plutonium-239 for the condition of no thermal loft. Also shown is the maximum permissible concentration (MPC) in air of the soluble form of this radionuclide for unrestricted use by the public, as established by the U. S. NRC (horizontal line labeled NRC MPC).* The air concentration of plutonium is greatest nearest the site of the accident, and declines exponentially with increasing distance. The air concentration is 1,000 to 10,000 times above the NRC limit near the accident site, and remains above the NRC limit out to spatial interval 23, corresponding to a downwind distance of up to 40 km. As expected, the concentration is greater (by a factor of about 7) for the least stable atmospheric conditions, since under these conditions less incoming air is available per unit time to dilute and disperse the released plutonium.

FIGURE 8 B shows comparable calculations for the condition of 100 m thermal loft. For the least stable atmospheric conditions (class A), the concentration profile with distance is not changed significantly from the 0 m thermal loft shown in FIGURE A. This is illustrated more directly in FIGURE 9, which compares the two conditions of thermal loft (0 m and 100 m) for the least stable (FIGURE 9 A) and most stable (FIGURE 9 B) atmospheric conditions. As shown in FIGURE 9 A, the concentration profiles for the two conditions of thermal loft are nearly identical for least stable atmospheric conditions. This is because the dilution of the cloud by incoming air is so dominant under these atmospheric conditions that lofting has little impact on the downwind concentration profile.

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*The limit given by the NRC is for 1 year of continuous exposure. This limit has been compressed into the 3 hour release duration the present accident, as illustrated in Appendix I.

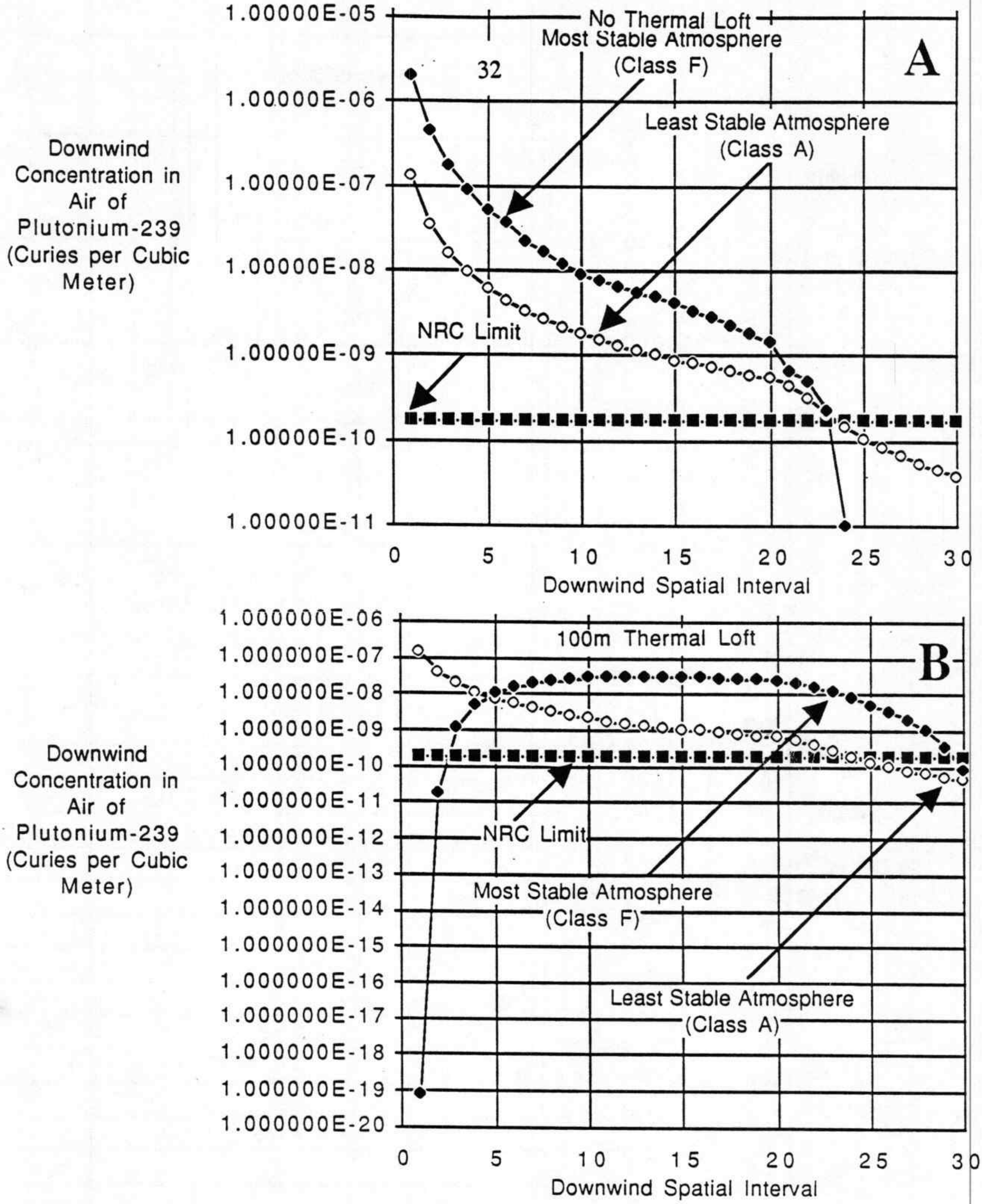


FIGURE 8

Calculated downwind air concentrations of plutonium-239 over New York following destruction by fire and dispersal of a single nuclear warhead containing 5 kg of plutonium aboard a military vessel homeported at Stapleton, Staten Island. Air concentration is graphed against downwind spatial interval (equivalent to distance from the fire in km for intervals 1-20; see legend to Figure 6). The concentrations were calculated assuming no thermal loft (Part A) and a 100 meter thermal loft (Part B), for the two extremes of atmospheric stability (Pasquill Class A and Class F). Air concentrations for all other atmospheric stability conditions lie between these extremes. Included for comparison is the maximum permitted concentration (MPC) of plutonium-239 in air, as promulgated by the U. S. Nuclear Regulatory Commission (NRC). The calculated air concentrations exceed the federal limit by up to approximately one thousand (Class A) to ten thousand (class F) times (note logarithmic concentration scale on ordinate).

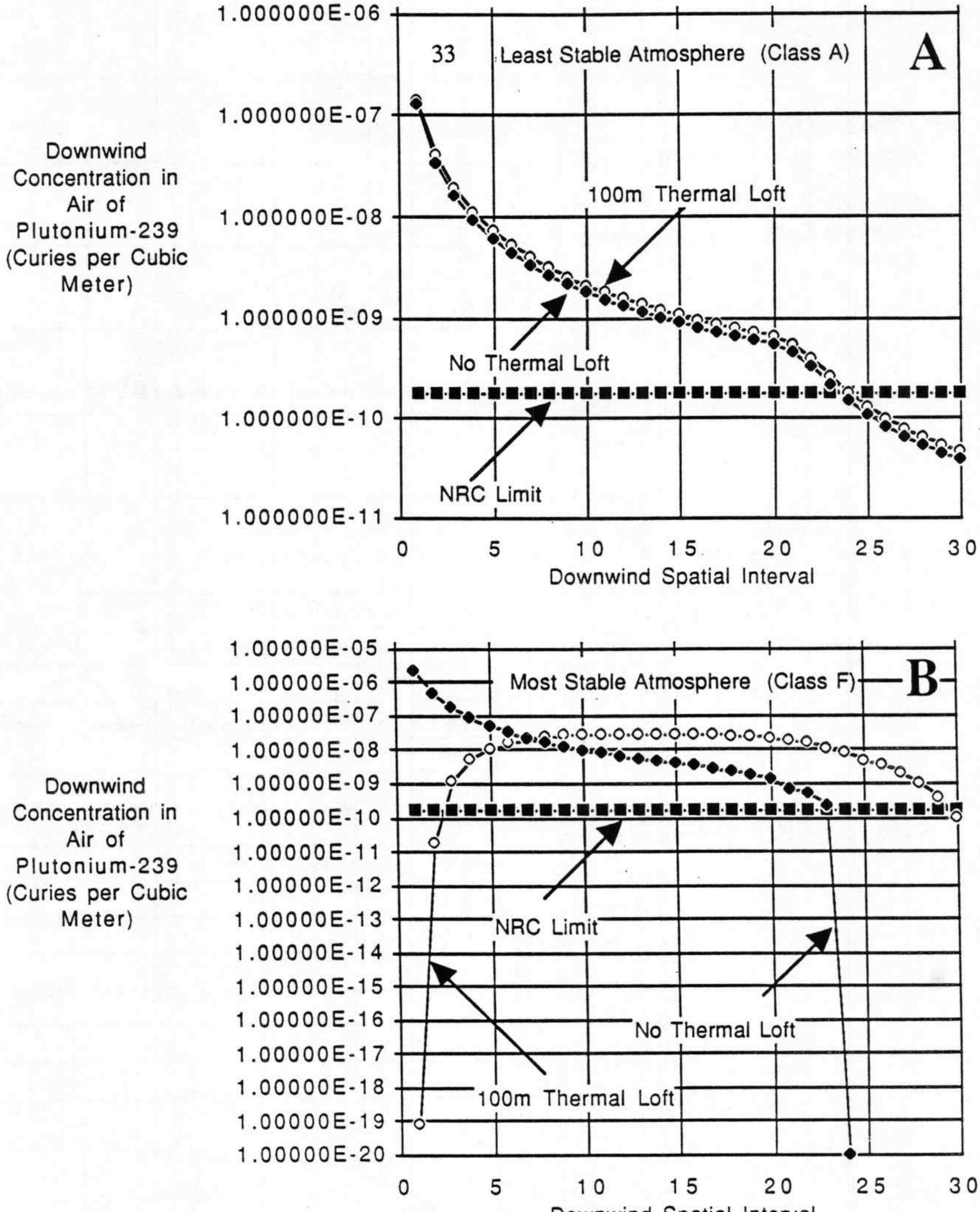


FIGURE 9

Calculated downwind air concentrations of plutonium-239 over New York following destruction by fire and dispersal of a single nuclear warhead containing 5 kg of plutonium aboard a military vessel homeported at Stapleton, Staten Island. Air concentration is graphed against downwind spatial interval (equivalent to distance from the fire in km for intervals 1-20; see legend to Figure 6). Same data as in Figure 8, but here grouped to compare the effects of thermal lofting. For the least stable atmospheric conditions (Part A), thermal lofting has little effect on calculated downwind concentration values. For the most stable atmospheric conditions (Part B), in contrast, thermal lofting reduces the air concentration near the site of the accident (spatial intervals 1-6), with a corresponding increase further away (remaining spatial intervals).

In contrast, the impact of thermal loft on the concentration profile for the most stable atmospheric conditions is significant (FIGURE 9 B). The concentration nearest the site of the accident is substantially less than in the case of no thermal lofting. This is because thermal lofting wafts the cloud up over nearby observers, where it is then carried downwind by prevailing winds. As a consequence of the decreased air concentration near the site of the accident, however, the concentration in downwind spatial intervals is correspondingly greater. This increase manifests already in spatial interval 2 , and continues in downwind spatial intervals, as indicated by the greater separation between the curves in FIGURE 9 B than in FIGURE 9 A. This effect of thermal lofting is especially significant in the case of the present accident, where the first landfall—Manhattan—is reached between 9 and 10 km from the burning ship. As is clear from FIGURE 9 B, the effect of thermal loft is to maintain the plutonium concentration in the plume at higher levels than would occur in the absence of thermal loft, thereby maximizing the radiological impact on the distant city.

Thermal lofting also increases the radiological impact for distant urban locations. Spatial interval 20 in Figure 9 B, for example, corresponds to mid-town Manhattan (FIGURE 3), while spatial interval 23 corresponds approximately to Yonkers. As shown clearly in FIGURE 9, air concentrations of plutonium in these locations shows little diminution in comparison with the first landfall at southern Manhattan. The exponential decline seen with no thermal lofting is absent, increasing the radiological impact at a distance.

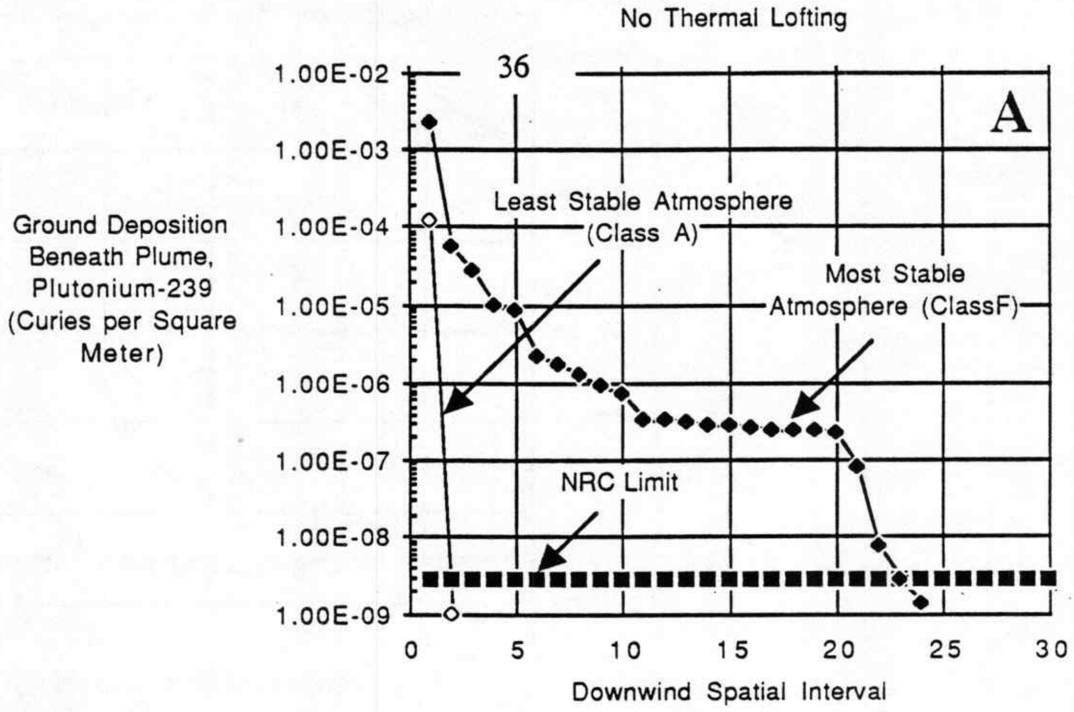
These data illustrate that the decrease in air concentration initially associated with thermal lofting is compensated by an increase in air concentration for the remainder of the downwind impact area. Whereas thermal lofting spares nearby observers from the full impact of the accident, it worsens the impact for persons located further from the scene. In the case of large, densely populated urban areas extending over many kilometers (as is the case for New York City), and especially in the case of locations in which the accident site is separated from the urban population by a stretch of low-lying, unpopulated area such as water (as is also the case for New York City), thermal lofting of the radioactive cloud increases the net radiological detriment of the accident. This increase manifests clearly in the casualty analysis described below.

C. Ground Deposition of Plutonium in New York City and Beyond

As the radioactive plume is transported downwind, radioactive particles settle out onto the ground, attaching to all exposed surfaces. The deposited radioactivity effects people by resuspension in the air (induced by wind and traffic) and subsequent inhalation (the most hazardous pathway for plutonium), and ingestion (associated with contamination of food and water). Especially in the case of long-lived radionuclides, such as plutonium-239 (half life nearly 25,000 years), ground contamination can represent the most important radiological detriment of the accident.

Plutonium surface contamination calculated for the incineration of a single nuclear warhead on a ship berthed at the Stapleton-Fort Wadsworth Complex is illustrated in FIGURES 10 and 11. FIGURE 10 compares directly the two atmospheric stability classes for the condition of 0 m (FIGURE 10 A) and 100 m (FIGURE 10 B) thermal lofting, while FIGURE 11 uses the same calculations to compare the two thermal lofting conditions for the least stable (FIGURE 11 A) and most stable (FIGURE 11 B) atmospheric conditions.

As shown in FIGURE 10, atmospheric stability greatly influences ground deposition of released radionuclides. For the most stable atmospheric conditions (class F), deposition is highest near the scene of the accident and declines exponentially with increasing distance. The surface concentration near the scene of the accident is one million times the NRC maximum permissible concentration for unrestricted use by the public (Appendix I), and remains elevated above the NRC's MPC out to a distance of 40 km (24.4 miles) for the condition of 0 m thermal lofting. In contrast, under the least stable atmospheric conditions (class A), no deposition occurs



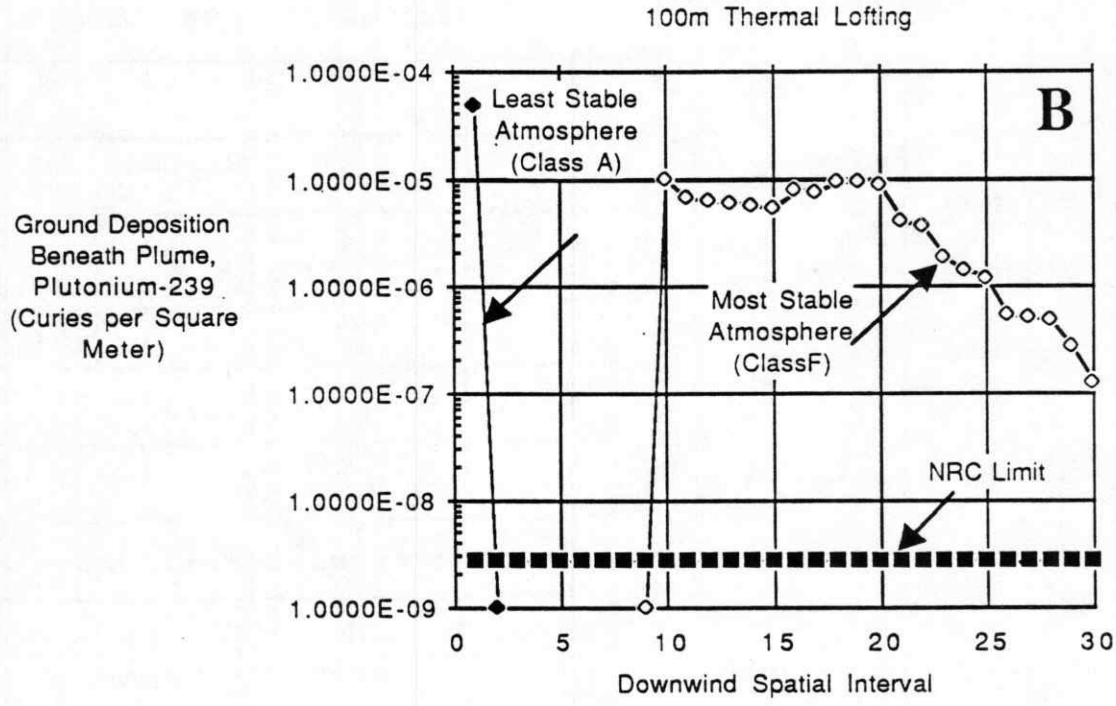


FIGURE 10

Calculated surface deposition of plutonium-239 in New York following destruction by fire and dispersal of a single nuclear warhead containing 5 kg of plutonium aboard a military vessel homeported at Stapleton, Staten Island. Surface deposition is graphed against downwind spatial interval (equivalent to distance from the fire in km for intervals 1-20; see legend to Figure 6). The surface depositions were calculated assuming no thermal loft (Part A) and a 100 meter thermal loft (Part B), for the two extremes of atmospheric stability (Pasquill Class A and Class F). Surface depositions for all other atmospheric stability conditions lie between these extremes. Included for comparison is the maximum permitted surface concentration (MPC) of plutonium-239 for unrestricted use by the public, as promulgated by the U. S. Nuclear Regulatory Commission (NRC). The calculated surface concentrations exceed the federal limit by up to approximately one hundred thousand (Class A) to one million (class F) times (note logarithmic concentration scale on ordinate).

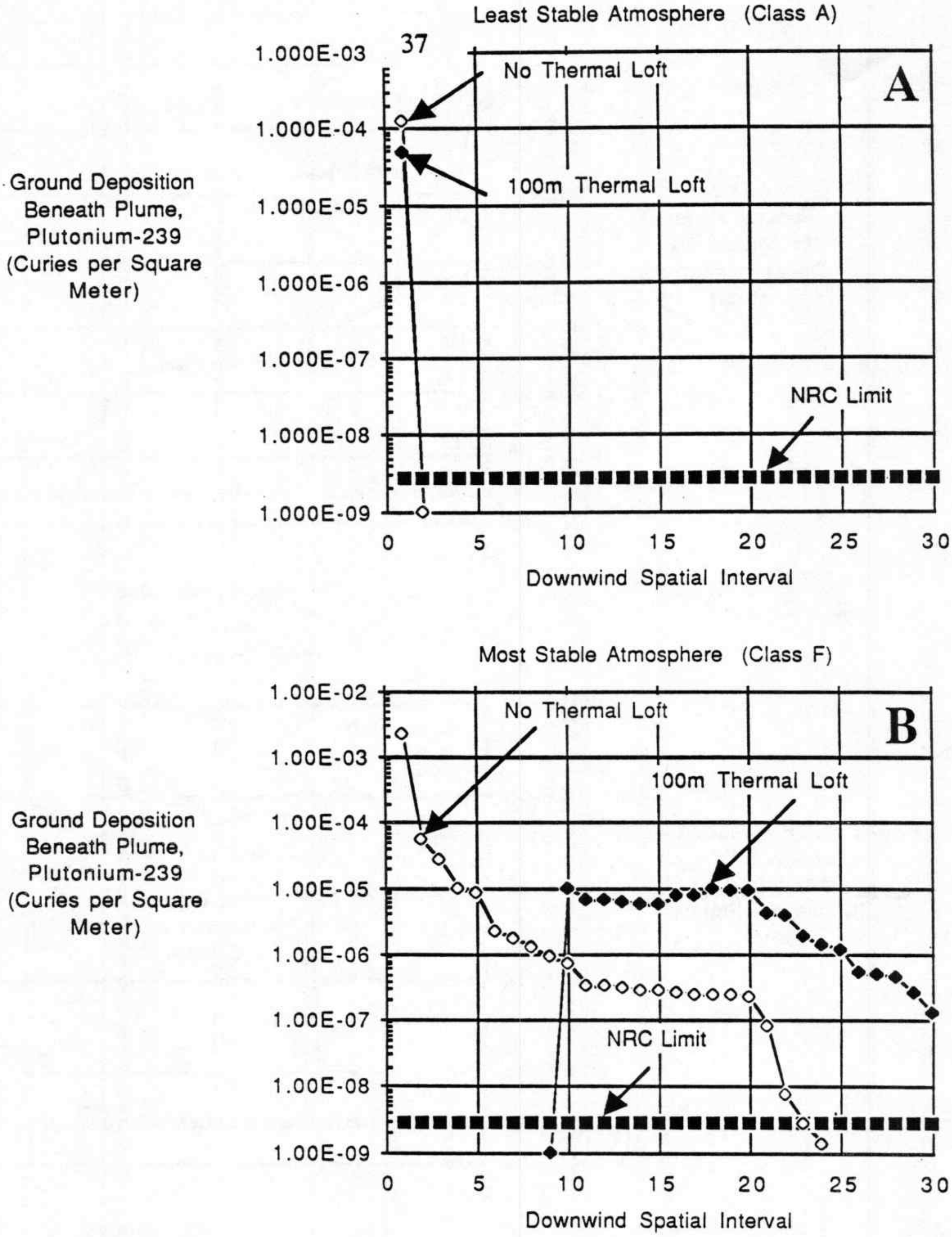


FIGURE 11

Calculated surface deposition of plutonium-239 in New York following destruction by fire and dispersal of a single nuclear warhead containing 5 kg of plutonium aboard a military vessel homeported at Stapleton, Staten Island. Surface deposition is graphed against downwind spatial interval (equivalent to distance from the fire in km for intervals 1-20; see legend to Figure 6). Same data as in Figure 10, but here grouped to compare the effects of thermal lofting. There is virtually no local deposition for the least stable atmosphere (Class A), because incoming wind mixes the plutonium into the atmosphere and carries it away for deposition in remote locations as "fallout". For the most stable atmospheric conditions (Part B), in contrast, thermal lofting reduces the air concentration near the site of the accident (spatial intervals 1-9), with a corresponding increase further away (remaining spatial intervals). The boundary of Manhattan begins at approximately spatial interval 9.

after the initial downwind interval (1 km from the accident site). This is because the greater volume of incoming wind carries the radioactivity away, without allowing sufficient time for deposition.

FIGURE 11 directly compares the two thermal lofting conditions modeled. As in the case of plutonium air concentration (FIGURES 8 and 9), the effects of thermal lofting on ground deposition are much less for least stable atmospheric conditions (FIGURE 11 A) than for the most stable atmospheric conditions (FIGURE 11 B). In the latter case (Pasquill Class F), ground deposition throughout most of the affected area is much greater under conditions of thermal lofting.

It is most significant that for the condition of greater thermal lofting (FIGURE 11 B, 100 m thermal loft), the ground deposition of plutonium is still elevated nearly 100 times above the NRC limit 105 km (63 mi) from the scene of the accident (spatial interval 30). Although calculations for greater distances have not been performed, extrapolation of the curve indicates that ground deposition of plutonium would exceed the maximum permissible concentration out to more than 200 km (122 mi) from the accident scene at Staten Island. As shown in FIGURE 5, this corresponds to sites in the western portion of Massachusetts. Under conditions of greater thermal lofting, the affected distance would be even greater. It is obvious, therefore, that a nuclear weapon accident of the kind modeled here has the potential of contaminating areas hundreds of miles away—as in fact occurred in the case of the nuclear power plant accident at Chernobyl.

D. *Radiation Exposure and Casualties in New York and Beyond*

1. *Inhalation Exposure from Plutonium.* Plutonium-239 is primarily an alpha emitter, and hence does not deliver a significant dose from "cloudshine" nor "groundshine". The primary exposure pathway is through inhalation of the radionuclide suspended in air. For this pathway, however, plutonium-239 is extremely toxic—indeed only two radionuclides (plutonium-240 and americium-241) are more toxic for the inhalation pathway. The radiation dose that would be received by adult individuals downwind from the accident site for each hour of respiration in the radioactive cloud is shown in FIGURES 12 and 13, following the format established in previous figures. That is, FIGURE 12 contrasts atmospheric conditions, while FIGURE 13 contrasts thermal lofting conditions. In both figures, the NRC limit of radiation exposure of the general public for short periods of time (2 mrem per hour), is shown for comparison (horizontal line labeled NRC limit).

As shown in FIGURE 12 A, the inhalation dose from incineration of a single nuclear warhead exceeds the NRC's limit by up to approximately 10,000 to 100,000 times near the scene of the accident. It should be noted that this limit is already orders of magnitude above the level of background radiation from natural causes and atmospheric weapons testing. The corresponding background level is approximately 0.0114 mrem per hour (horizontal lines in FIGURES 12 and 13 labeled "Background"). The inhalation exposure from incineration of a single warhead is up to more than one hundred million times this background level near the scene of the accident. As in the case of downwind air concentration (FIGURES 8 and 9) and ground deposition (FIGURES 10 and 11), the greatest detriment is associated with the most stable atmospheric conditions (FIGURE 12) and the greatest thermal lofting (FIGURE 13).

2. *Population at Risk.* In order to calculate the medical consequences of the above radiation doses, it is necessary to know the number of persons at risk, i. e., the population of the impact area. To determine the persons at risk from the modeled accident, the number of persons

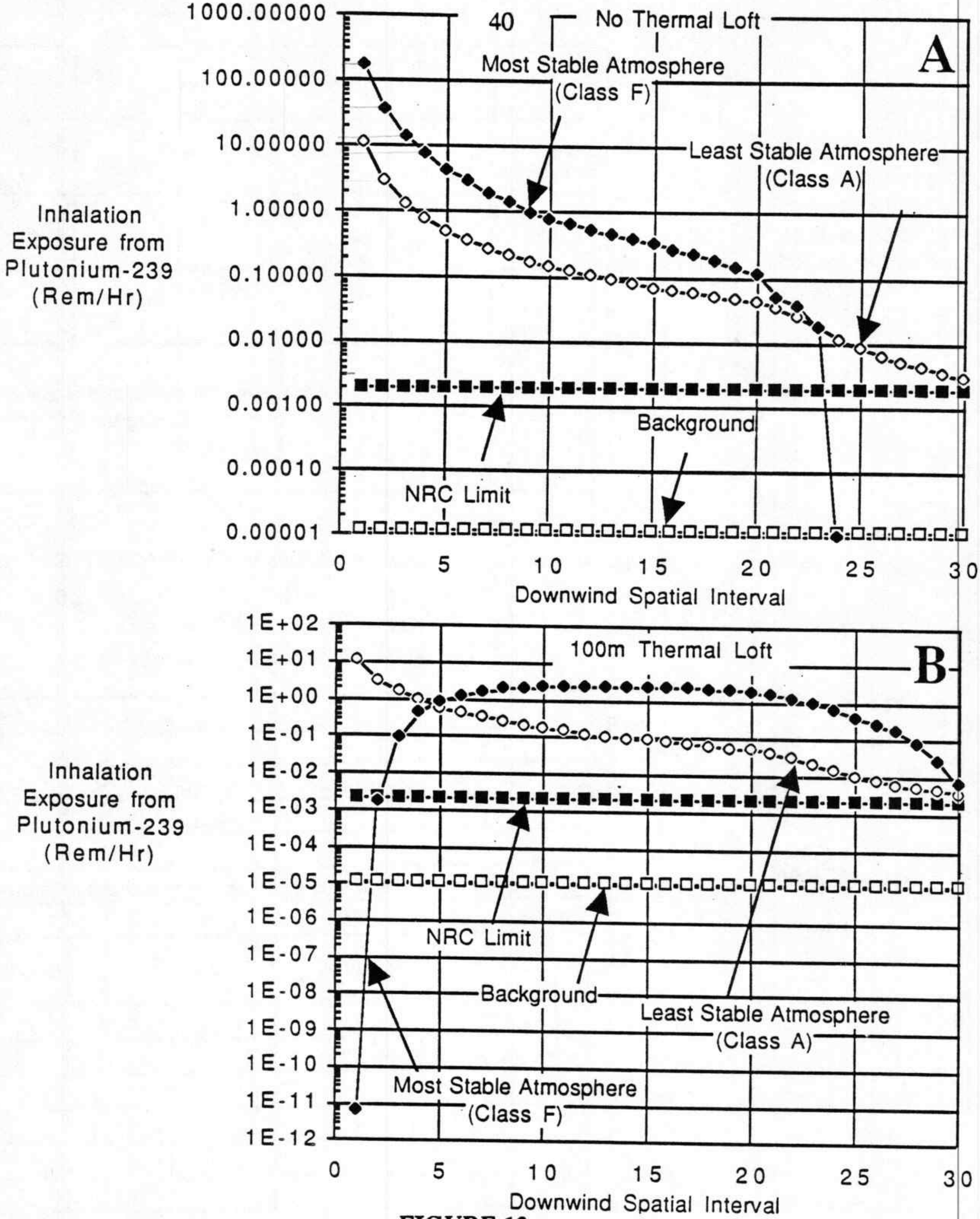


FIGURE 12

Calculated inhalation exposure from respiration of air containing plutonium-239 downwind from a fire that incinerates a single nuclear warhead containing 5 kg of plutonium aboard a military vessel homeported at Stapleton, Staten Island, New York. Inhalation exposure is graphed against downwind spatial interval (equivalent to distance from the fire in km for intervals 1-20; see legend to Figure 6). The exposures were calculated assuming no thermal lofting of the radioactive cloud (Part A) and a 100 m thermal lofting (Part B) for the two extremes of atmospheric stability (Pasquil Class A and Class F). Exposures for other atmospheric stability classes lie between these extremes. Included for comparison is the maximum permitted exposure to members of the general public, as promulgated by the U. S. Nuclear Regulatory Commission (NRC limit), as well as background exposure from natural sources and fallout from weapons testing (Background). The calculated exposures exceed the federal limit by up to approximately ten thousand (Class A) to one hundred thousand (Class F) times (note logarithmic exposure scale).

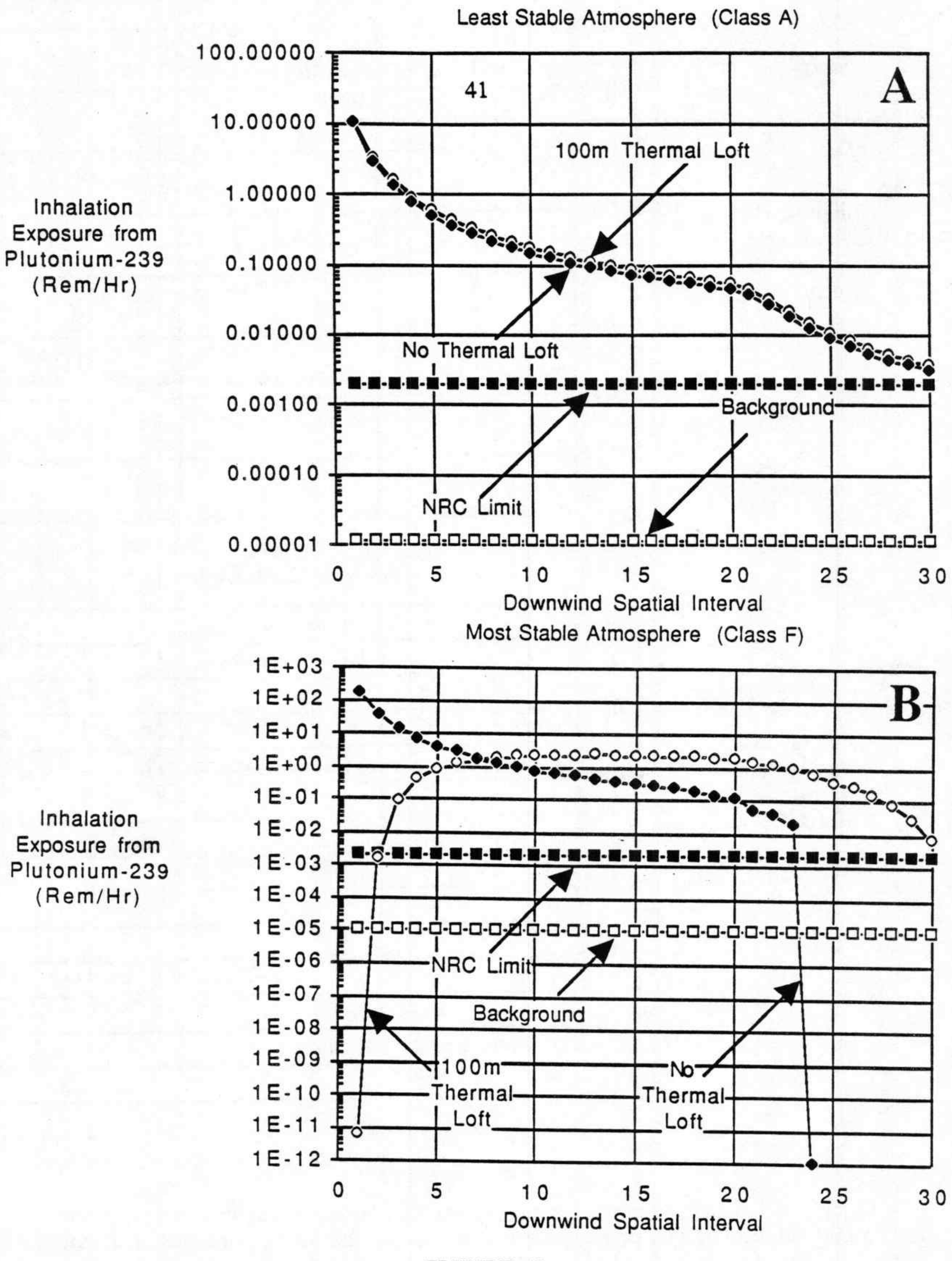


FIGURE 13

Calculated inhalation exposure from respiration of air containing plutonium-239 downwind from a fire that incinerates a single nuclear warhead containing 5 kg of plutonium aboard a military vessel homeported at Stapleton, Staten Island, New York. Inhalation exposure is graphed against downwind spatial interval (equivalent to distance from the fire in km for intervals 1-20; see legend to Figure 6). Same data as in Figure 12, but here grouped to compare the effects of thermal lofting. For the least stable atmospheric conditions (Part A), thermal lofting has little effect on calculated inhalation exposure values. For the most stable atmospheric conditions (Part B), in contrast, thermal lofting reduces the inhalation exposure near the site of the accident (spatial intervals 1-6), with a corresponding increase further away (remaining spatial intervals).

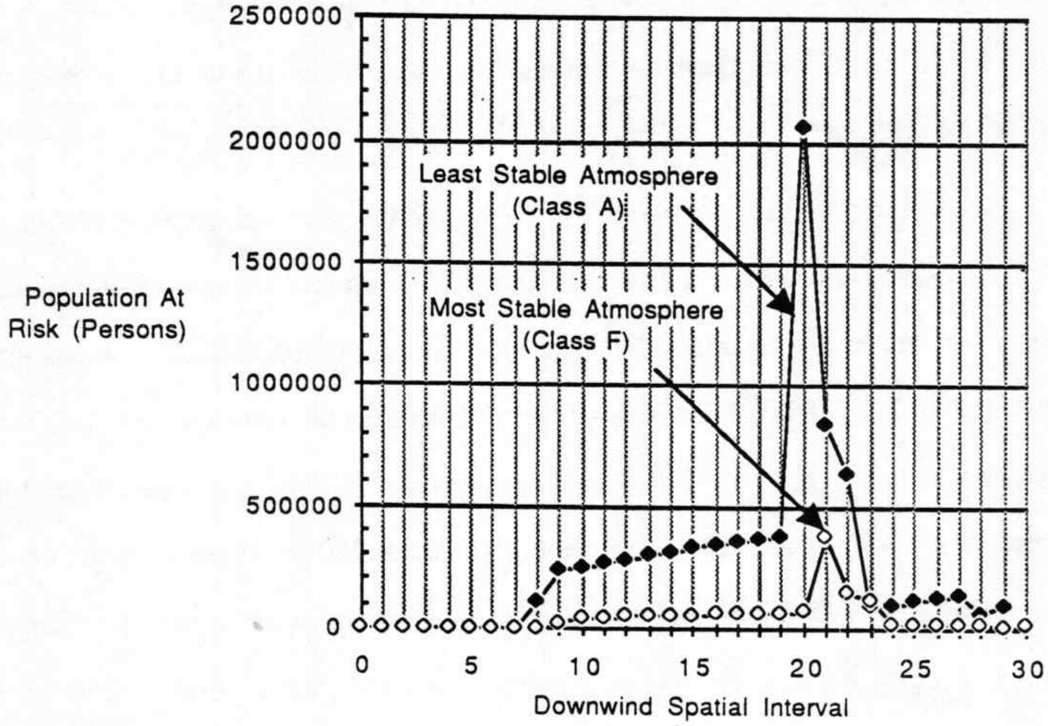


FIGURE 14

Persons subject to exposure to radiation from a cloud emanating from a burning military vessel homeported at Stapleton, Staten Island, New York, *versus* downwind spatial interval (equivalent to distance from the fire in km for spatial intervals 1-20; see legend to Figure 6). Points calculated from data presented in Figure 7 in combination with population density determined from U. S. Bureau of Census data.

in the path of the radioactive cloud is calculated from population density (taken from official U. S. census tracts) and from the ground area subtended by the plume (FIGURE 7). The resulting number of persons at risk in each downwind spatial interval is shown in FIGURE 14. Casualties can then be calculated from these data, in combination with inhalation exposures presented earlier (FIGURES 12 AND 13).

3. *Casualties*. Inasmuch as plutonium-239 is primarily an alpha emitter and therefore does not deliver a significant radiation dose from cloudshine nor groundshine, only inhalation of contaminated air within the passing radioactive cloud is considered here. The inhalation exposure levels shown in FIGURES 12 and 13 approach 200 rem per hour of exposure, for spatial interval 1 under conditions of thermal loft and a stable atmosphere. This dose is calculated for a 50 year commitment, however, and does not represent an actual 200 rem dose of radiation in a 1 hour period, but rather a whole-body commitment to such a dose over the next 50 years per hour of exposure. Specific organ doses and whole-body doses for shorter commitments have not been calculated here, and hence the possibility of prompt fatalities from the accident is not considered. All casualties described below are latent cancer fatalities (LCFs), i. e., fatalities from cancers induced from a few to several years following the accident.

The number of LCFs under different assumptions of atmospheric stability, thermal lofting and dose conversion factors, are shown in FIGURES 15 - 18 (see Appendices for methodology). The graphs contained in these figures are arranged from the least to the most projected casualties.

FIGURE 15 A shows cancer mortality for the least stable atmosphere, no thermal loft, and a dose conversion factor that is well below the level of BEIR-III. The total number of casualties from LCFs under the minimizing assumptions of this histogram is 117. Casualties are greatest in downtown Manhattan (intervals 10 - 20); the peak in interval 21 is caused by the greater increment in distance (5 km rather than 1 km) represented by interval 21. Under the same accident

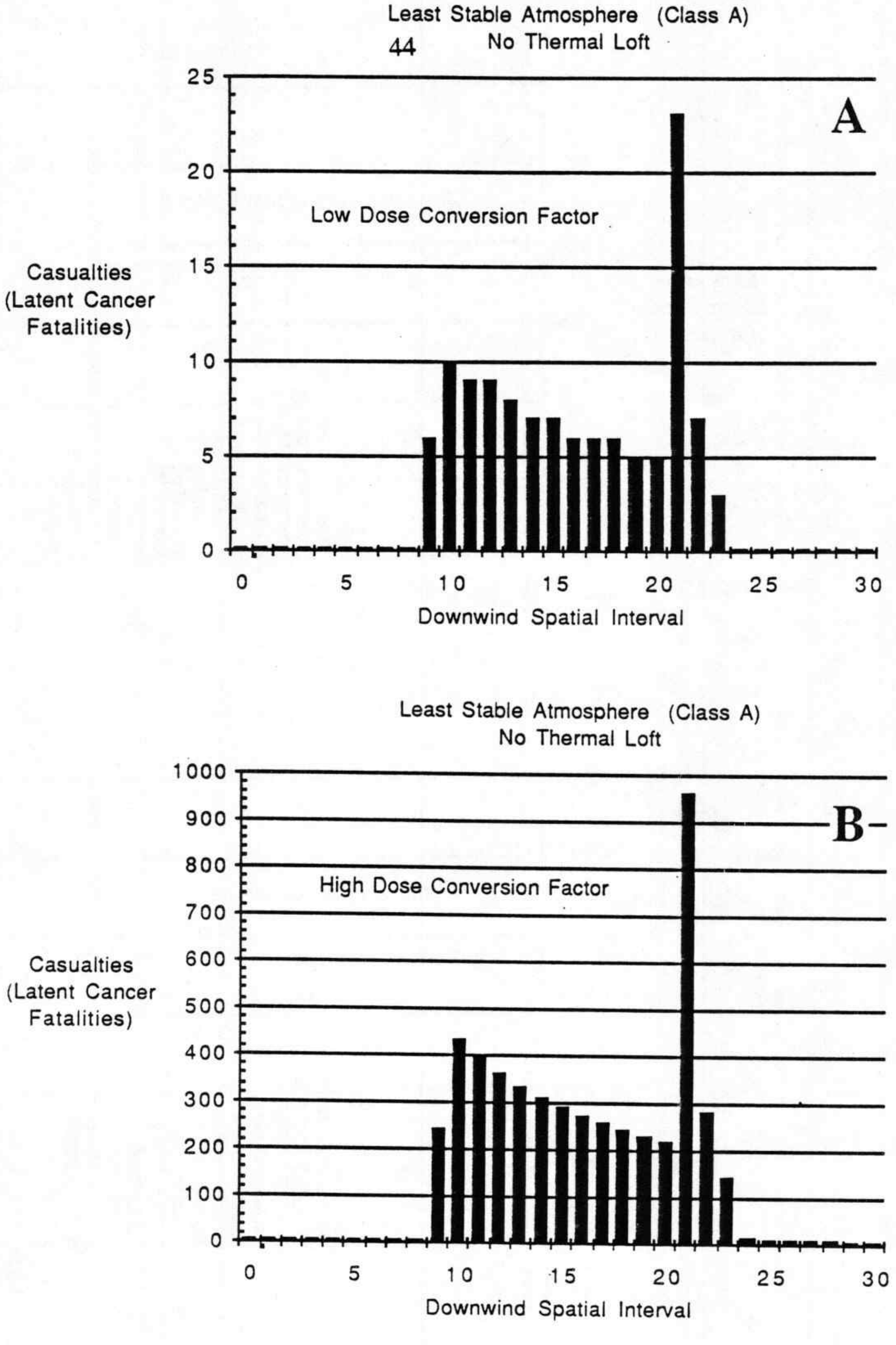


FIGURE 15

Casualties (from fatal latent cancers) caused by accidental incineration of a single nuclear warhead containing 5 kg of plutonium-239 in a fire aboard a military vessel homeported at Stapleton, Staten Island, New York. The casualties shown here were calculated for the least stable atmospheric conditions (Pasquill Class A) and assume no thermal lofting. Part A is based on a low radiation risk factor (one fatality per 10,000 person-rem), while Part B is based on a high radiation risk factor (one fatality per 235 person-rem). The former value is likely to be unrealistically low.

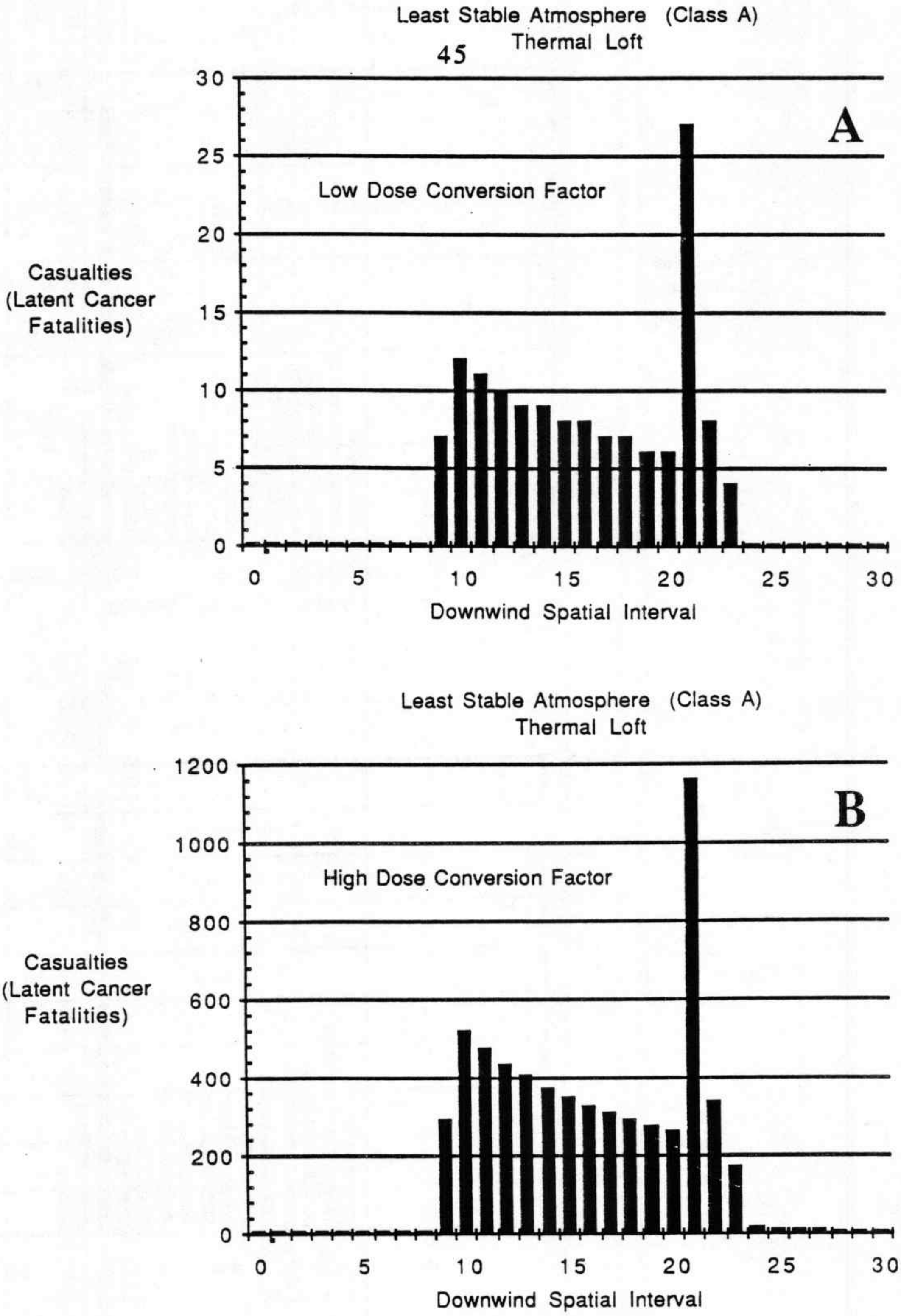
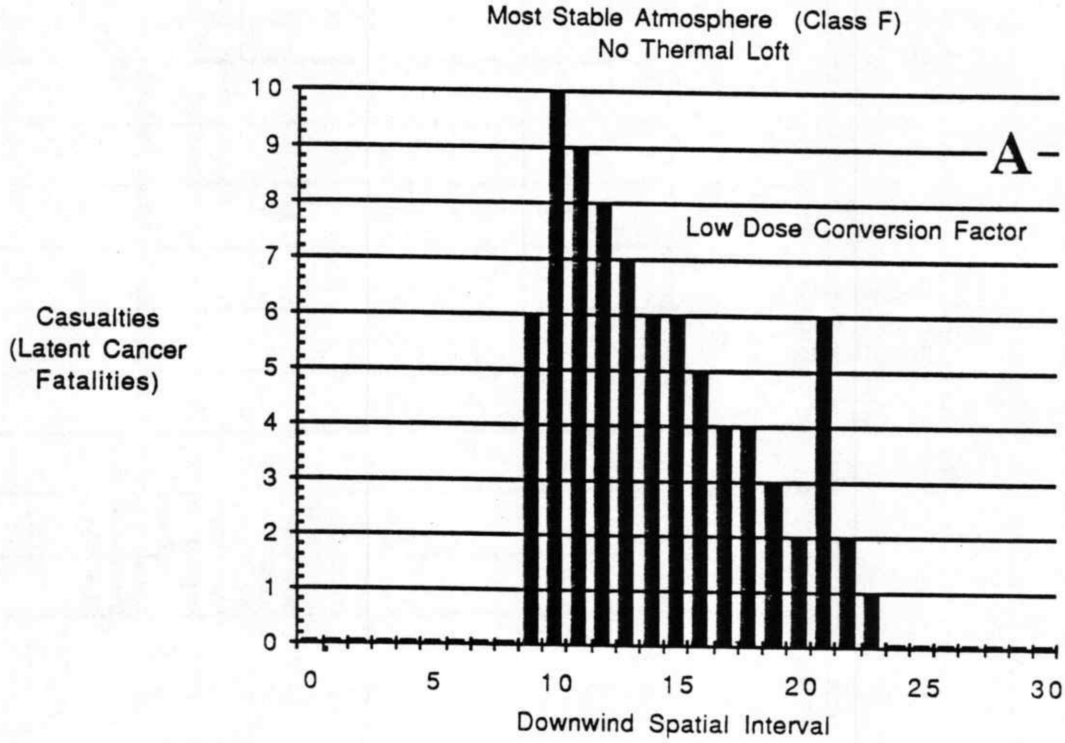


FIGURE 16

Casualties (from fatal latent cancers) caused by accidental incineration of a single nuclear warhead containing 5 kg of plutonium-239 in a fire aboard a military vessel homeported at Stapleton, Staten Island, New York. The casualties shown here were calculated for the least stable atmospheric conditions (Pasquill Class A) and assume thermal lofting of the radioactive cloud to 100 m. Part A is based on a low radiation risk factor (one fatality per 10,000 person-rem), while Part B is based on a high radiation risk factor (one fatality per 235 person-rem). The former value is likely to be unrealistically low. Note the greater casualties associated with greater thermal lofting (cf. with Figure 15).



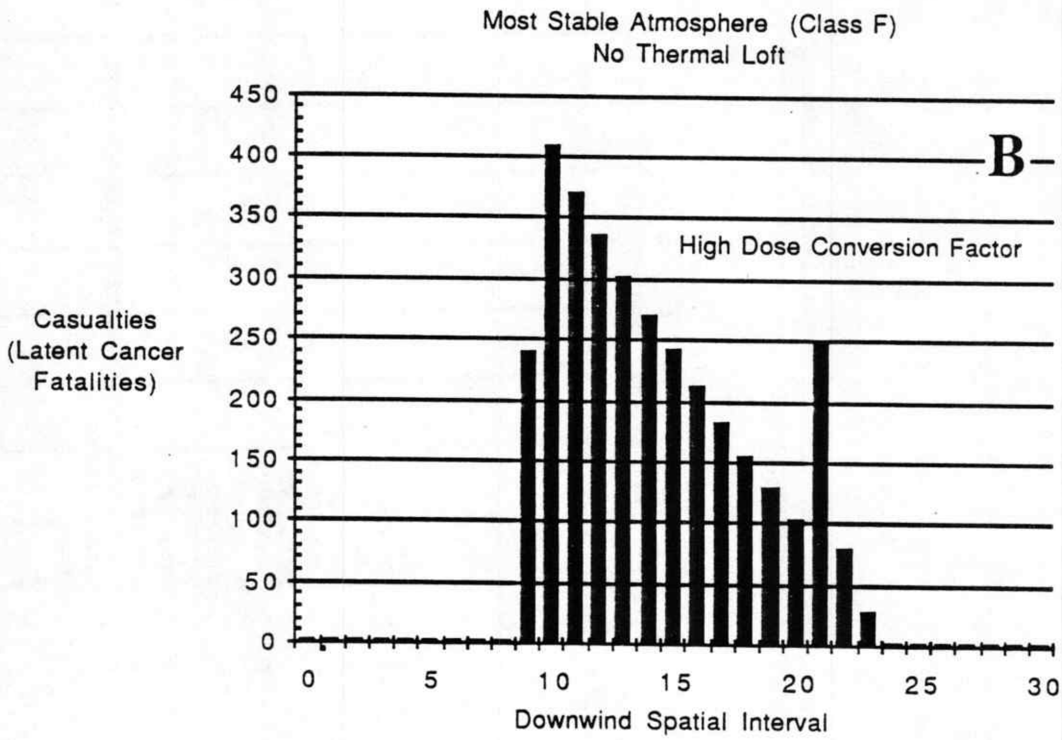


FIGURE 17

Casualties (from fatal latent cancers) caused by accidental incineration of a single nuclear warhead containing 5 kg of plutonium-239 in a fire aboard a military vessel homeported at Stapleton, Staten Island, New York. The casualties shown here were calculated for the most stable atmospheric conditions (Pasquill Class F) and assume no thermal lofting. Part A is based on a low radiation risk factor (one fatality per 10,000 person-rem), while Part B is based on a high radiation risk factor (one fatality per 235 person-rem). The former value is likely to be unrealistically low.

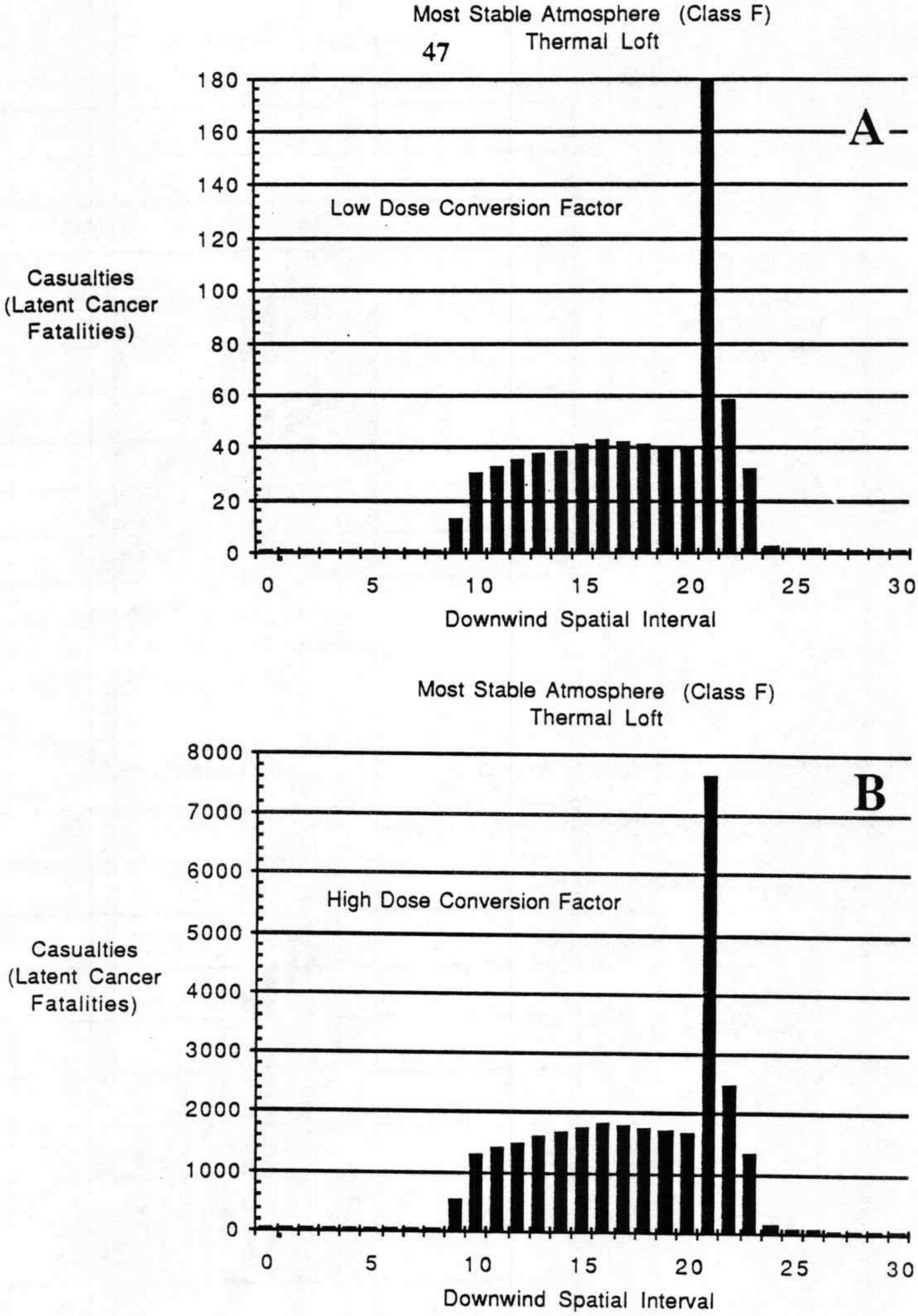


FIGURE 18

Casualties (from fatal latent cancers) caused by accidental incineration of a single nuclear warhead containing 5 kg of plutonium-239 in a fire aboard a military vessel homeported at Stapleton, Staten Island, New York. The casualties shown here were calculated for the most stable atmospheric conditions (Pasquill Class F) and assume thermal lofting of the radioactive cloud to 100 m. Part A is based on a low radiation risk factor (one fatality per 10,000 person-rem), while Part B is based on a high radiation risk factor (one fatality per 235 person-rem). The former value is likely to be unrealistically low. Note the greater casualties associated with greater thermal lofting (cf. with Figure 17).

conditions, but assuming a dose conversion factor that is probably more realistic (Gofman, 1981), but high (FIGURE 15 B), the number of casualties from LCFs is greater (total of 5,021), with a comparable spatial distribution. These figures represent the minimal casualties incurred under the assumptions of this analysis, and assuming the destruction of a single nuclear warhead. Incineration of each additional warhead would incur a comparable number of additional casualties.

FIGURE 16 shows cancer mortality for the least stable atmosphere, but under conditions of initial thermal lofting to 100 m. Casualties are slightly higher than those incurred in a similarly unstable atmosphere in the absence of thermal lofting (cf. FIGURE 16 with FIGURE 15).

In FIGURE 17, latent cancer fatalities are shown for the most stable atmosphere under conditions of no thermal lofting. These range from 79 (low dose conversion factor; FIGURE 17 A) to 3,304 (high dose conversion factor; FIGURE 17 B). Compared with the same accident under the least stable atmospheric conditions (FIGURE 15), these casualties are somewhat less. This is because the smaller radiation exposures associated with a less stable atmosphere (FIGURE 12 A) are more than compensated by the broader swath of the plume under unstable atmospheric conditions.

FIGURE 18 shows the casualties associated with the most stable atmospheric conditions under the assumption of an initial thermal lofting of the radioactive cloud to an altitude of 100 m. Casualties from LCFs range from 713 (FIGURE 18 A; low dose conversion factor) to 30,442 (FIGURE 18 B; high dose conversion factor). These represent the maximum projected casualties from latent cancer fatalities, under the assumption that only one warhead is incinerated by the shipboard fire. For each additional warhead incinerated, a comparable number of additional casualties would be incurred.

A number of general conclusions emerge from this casualty analysis (FIGURES 15 - 18). First, and as expected, casualties are generally greatest closest to the scene of the accident, and decline approximately exponentially with distance. Second, total casualties in the form of latent cancer fatalities range widely, from 79 to 30,442. This wide range reflects uncertainty in the scientific literature regarding radiation risk factors. Third, and as expected (Slade, 1968; Turner, 1969), the most casualties generally (but not always) occur during the most stable atmospheric conditions (Class F). This occurs because under these conditions the radioactive cloud is diluted least by incoming air. Fourth, and contrary to conventional wisdom, thermal lofting does *not* yield fewer total casualties. Casualties near the accident site are fewer, because the radioactive cloud is wafted up and over the heads of nearby people; but the result is disproportionately greater casualties further from the scene, since the cloud is less depleted when it reaches the ground. Especially when the accident site is separated from high-density populations by a sparsely populated area (such as the New York Harbor), this effect is magnified.

It should be emphasized that these casualties are computed under conservative assumptions, and omit consideration of fatalities from severe genetic damage and non-fatal cancers. These calculations also omit casualties that could involve persons on the water downwind from the accident site. It should be noted further that the above casualty estimates represent those associated with complete destruction of a single warhead containing 5 kg of plutonium. For each additional warhead completely incinerated, a comparable number of additional casualties would be incurred. Finally, the above casualties represent only those that would be incurred during the 3 hour accident modeled. Additional casualties would be incurred mainly from inhalation of plutonium that is deposited on the ground and then resuspended in the atmosphere by atmospheric agitation. These casualties have been omitted here because of the many uncertainties in calculating radiation exposure via the resuspension pathway.

E. Economic and Environmental Impact of the Hypothetical Accident

1. *Economic Implications.* The half-life of plutonium-239, the primary radionuclide that would be distributed in the event of a nuclear weapon accident, is 24,500 years. Therefore, before rehabitation of the contaminated area could be permitted following a nuclear weapon or reactor accident, decontamination would be required. An issue in need of careful consideration, therefore, is the practicality, time required, cost and liability for decontamination.

Procedures for decontaminating a large urban area have not been developed. They would have to be pioneered. Brief reflection on the nature of the accident emphasizes the difficulties that would be faced. Every ventilated structure, including skyscrapers, office buildings, high-rise buildings, hospitals and schools, would draw contaminated air through the ventilation systems. Conventional filters could not remove the tiny (less than 20 micrometers) radioactive particles, which would therefore be distributed throughout the ventilation ducts and internally within each ventilated structure. Every ventilated building would have to be decontaminated, inside and out. Streets, automobiles, vegetation, clothing, indeed all surfaces that come in contact with air, would have to be cleaned and monitored with radiation-detecting equipment. Such procedures would have to be applied to urban areas extending to tens of square kilometers—conceivably all of Manhattan, much of the Bronx and Yonkers.

The cost of such decontamination procedures is completely unknown, since no country has had experience decontaminating a densely-populated urban environment. Decontamination expenses at Three Mile Island, where radioactivity released by the accident was largely confined to the containment structure, are now projected to reach several billion U. S. dollars. The U. S. NRC estimates that even a relatively minor accident could cost $1.7 billion to clean up (NRC, 1980). A recent U. S. GAO report (1986) indicates that the cost of cleaning up after a catastrophic nuclear power reactor accident would range from 0.3 to 15 billion dollars. The report notes that the actual costs of decontamination, under worst-case conditions, could range to ten times this amount, i. e., to 150 billion U. S. dollars—an amount that exceeds the national budget of most nations. These estimates excluded the costs of investigating, settling and defending claims. Nor did the GAO estimates address on-site costs and "indirect economic losses." Such losses are defined as those resulting from the impairment of the local economy, as would occur until the contaminated portion of the city were cleaned up and reinhabited.

Inasmuch as the accident depicted here would render Manhattan uninhabitable pending effective decontamination, the economy of the city would come to a standstill until cleanup were completed. To the extent that the economy of the city is coupled with the economy of the nation, the national economy and indeed the world economy would be impacted as well. Wall Street and the financial centers of south Manhattan would be terminated pending decontamination and rehabitation. The duration of the decontamination effort therefore becomes paramount for estimates of the daily indirect losses. According to the NARP manual cited earlier:

> "Actions to decontaminate the area [contaminated by a nuclear accident], and return the area to normal use, require coordination with civil authorities and may take several months to complete." (DNA, 1984, p. ii)

Termination of activity of Wall Street for several months could throw the entire U. S. economy into chaos.

The magnitude of the potential decontamination costs raises the issue of who would pay. In the U. S., the industry's liability for any commercial nuclear accident is limited by the recently-renewed Price-Anderson Act to approximately seven billion dollars. Provisions in the act confer responsibility on the federal government for paying additional claims that are "legitimate." But the U. S. government declines responsibility for many types of nuclear accidents (e. g., those entailing transportation of spent nuclear fuel) unless it agrees in writing to assume such responsibility (Peach, 1984). It is unclear whether a different standard would be applied in the case of a naval nuclear accident in New York.

A detailed analysis of the economic impacts of the accident modeled here is beyond the scope of this report. But even the cursory treatment offered above suggests that these impacts could be beyond any accident that has ever befallen any city, or for that matter any country.

2. *Environmental Impacts.* A nuclear accident of the magnitude of the one modeled here could have significant impacts on the terrestrial and aquatic environment of the New York area. Dispersed plutonium would eventually wash into estuaries, rivers, sounds and the oceans, with unknown impacts on animal and plant life. A detailed analysis of these effects is beyond the scope of this report.

The environment of more distant regions could also be impacted by the modeled accident. As shown in FIGURES 10 and 11, significant surface deposition from fallout could occur as far away as 200 km (122 miles). As illustrated in FIGURE 19, the three major watersheds supplying New York City —the Delaware, the Catskill and the Croton—are all within the radius of impact. Indeed, the most probable prevailing winds would carry the idealized radioactive plume through the eastern half of the Croton watershed, and the centerline would pass directly through the Kensico Reservoir—the most immediate water supply for New York. Plutonium surface contamination at the Kensico Reservoir would be approximately 900 times the NRC's Maximum Permissible Concentration, raising the possibility of significant plutonium contamination of the New York water supply.

The Kensico Reservoir can be bypassed by the New Croton Aqueduct (FIGURE 19). But a slight shift in the wind would carry the radioactive plume directly over the New Croton Reservoir, which feeds the New Croton Aqueduct. Indeed, as shown by the wind graph in FIGURE 1, the *commonest* wind direction in the New York area is directly from the south—which would carry a radioactive plume, originating at Staten Island, directly over the New Croton Reservoir and impact maximally on the Croton watershed. In this case the New York water supply could be permanently and perhaps fatally impaired.

FIGURE 19

The New York City water supply system, showing the impact of an accident involving incineration of a nuclear weapon aboard a ship homeported at Stapleton, Staten Island, New York. The path of the cloud assuming wind from the southwest is shown by the wedge, with the plume centerline designated by a dashed line. The concentric circles correspond to 50 km increments. Note that the cloud would encroach upon the Croton Watershed and, in particular, that the Kensico Reservoir (the terminal storage area for normal operations) lies exactly on the centerline of the cloud. Implications for the contamination of the New York water supply with plutonium are elaborated in the text.

It is astonishing that this contingency has not been considered more thoroughly, not only in the case of homeporting, but also in the case of nuclear power facilities located in the region. A detailed analysis of the implications of nuclear accidents for the New York water supply is beyond the scope of this paper; but the data reported here suggest that such an analysis would be advisable.

F. Probability of a Nuclear Weapon Accident

The analysis presented above deals exclusively with the *consequences* of a hypothetical nuclear weapon accident in New York Harbor. The *risk* of such an accident, however, is the product of consequence and the *probability* that such an accident will take place. In order to assess the risk posed by such an accident to New York City and its people, it is essential to determine the probability of the accident. And given the enormous consequences of such an accident, it would seem prudent to do so.

As noted in the Introduction to this paper, the U. S. military acknowledges that such accidents have occurred in the past, and contingency plans for future accidents of a limited scope exist. The Nuclear Weapons Surety report of 1984 (DOD/DOE, 1984), states that problems have been identified with respect to the physical security of nuclear weapons, including conflicts between Department of Defense manuals and the directives of the implementing military services (ibid., p. I-18). The document notes that:

> "Review of the 1984 Defense Nuclear Agency inspection program shows that the unit unsatisfactory rate is remaining at an almost static level. *Security and technical operations continue to be the areas of most frequent failing deficiencies.*" (ibid., p. I-19; emphasis added).

The quotations cited earlier from various official U. S. government documents demonstrate that the U. S. military considers the accident scenario modeled here a plausible one. Determining the exact probability of such an accident, however, is more problematical. There are two independent approaches to probability analysis for nuclear accidents (see Appendix I). By the first, the probability of the accident is calculated theoretically from first principles. By the second, the probability is determined empirically from the history of similar or related accidents. Unfortunately, the military has not been willing to release information that would enable either approach to be implemented in the case of a nuclear weapon accident.

With respect to the theoretical approach, calculation of the probability of accidental incineration of a nuclear warhead would require access to data on the warhead itself—its contents, construction, ability to withstand thermal and mechanical stress, etc. The calculation would also require knowledge of the missile, as well as the vessel that carries the warhead, including the proximity of missile or ship fuel to the warhead, the construction of the ship with respect to fire retardation, the nature and amount of other flamable material with respect to the warhead, etc. Some warships are constructed in part of relatively flamable aluminum, increasing the probability of circumstances that could lead to the kind of accident modeled here.

As noted earlier, the U. S. military refuses even to confirm or deny that nuclear warheads are aboard any ship. As a consequence of this secrecy, it is impossible to calculate the probability that a nuclear weapon will be accidentally incinerated aboard a military vessel.

With respect to the empirical approach, calculation of the probability of accidental incineration of a nuclear warhead would require access to information on the history of similar past accidents. It is known that numerous accidents have occurred aboard military vessels, many of which involved nuclear weapons. These are catalogued by Kaplan (1983 a, b) and Stirling (1986) and in U. S. government documents cited above. These amount to one accident and scores of incidents per year, at least some of which have entailed accidental destruction by fire or explosion of one or more nuclear warheads. As far as is known from the public record, very few accidents involving widespread dispersal of plutonium from a nuclear weapon have occurred. It is not certain, however, that the public record would contain evidence of such an accident even if it occurred, given the military propensity for secrecy regarding nuclear weapons.

To apply this empirical probability approach to the incineration of a nuclear warhead, it would also be necessary to know the frequency of fires aboard military ships, the proportion of fires that occur in port, and the location, duration and intensity of all such fires. Data would also be required on the fire-resistance of ships and of nuclear warheads. None of these data have been made publically available by the military of any country.

In the absence of data on military ships, recourse is made to the accident history of civilian (commercial) vessels, which is available to the public. Analysis of all fire casualty reports submitted to the International Maritime Organization (IMO) pertaining to commercial vessels (IMO, 1986) demonstrates that shipboard fires are frequent. Moreover, fires occur in port as often as underway, even though commercial ships spend most of their time at sea. The mean duration of commercial shipboard fires reported to the IMO over the past two decades is 20.36 hours for ships in port (standard deviation, or s. d., 68.25 hours), and 23.36 hours for ships underway (s. d., 44.23 hours). Data published in Lloyd's Register of Shipping, *Casualty Return for 1985*, indicate that the probability of total constructive loss by fire for commercial vessels during the calendar year 1985 was 0.00407 per year per vessel—more than ten times higher than the calculated probability of a commercial nuclear power reactor accident (0.0003 per reactor year of operation).

According to the U. S. Department of Commerce's treatise on maritime firefighting (U. S. Department of Commerce, 1977), there is no effective means of combating a fire that involves a combination of fossil fuels and flammable, radioactive metal. Indeed, such a class of fire is not even recognized in the six categories of ship fires identified in this "bible" of maritime fire safety.

Data on commercial vessels are, of course, of limited relevance to military vessels, which are engineered and built for a much different mission. But the civilian data do suggest that the necessary and sufficient conditions for the type of accident modeled here, involving incineration of a single nuclear warhead in a hydrocarbon fire lasting 3 hr., are plausible. Until the military divulges more information than it has been willing to provide to date, the probability of such an accident will remain unknown. And in this case, the risk to New York City and its public of homeporting nuclear-capable ships will remain incalculable.

VII. CONCLUSIONS AND RECOMMENDATIONS

The present analysis raises a number of considerations that could be usefully considered in weighing the policy of homeporting nuclear-capable warships in densely populated urban regions. These considerations are summarized here, followed by the policy recommendations that they imply.

A. *Levels of Radioactive Contamination Resulting from Naval Accidents*

Application of conventional NRC methodology demonstrates that air and ground concentrations of plutonium-239 following accidental incineration of a single nuclear warhead on a ship berthed in New York Harbor would exceed maximum permissible levels by thousands to millions of times. Because the radioactive contamination is directly proportional to the quantity of radioactivity dispersed, even a fractional release (< 1%) would cause contamination in excess of U. S. federal limits. Environmental impacts have not been analyzed carefully here, but they could be significant.

• RECOMMENDATION # 1: *The environmental impacts of possible nuclear accidents consequent to homeporting nuclear capable vessels in New York Harbor should be analyzed in detail. Included in such analyses should be the impacts of such accidents on the terrestrial and aquatic environments, and on the water supply to New York City.*

B. Resultant Casualties

As shown by the above analysis, latent cancer fatalities from a nuclear weapon accident would range from 79 to 30,442, depending on the accident conditions and radiation risk factor used. Plutonium contamination would exceed federal limits by up to one million times near the scene of the accident, and by ten thousand times throughout greater Manhattan and into the Bronx. Such levels of contamination would require evacuation and decontamination of the affected area prior to rehabitation.

- RECOMMENDATION # 2: *The full resources of the City of New York and the U. S. Navy should be brought to bear in producing an exhaustive analysis of nuclear accident scenarios and their medical consequences before further consideration of homeporting nuclear capable vessels in New York Harbor.*

C. Emergency Evacuation

The number of casualties and degree of contamination of the city would, according to the present limited analysis, require immediate evacuation of the population, and decontamination prior to rehabitation. Even in the event of a comparatively small accident, unacceptable casualties could ensue and rapid evacuation of the impacted region could be required. The affected area could include all of downtown Manhattan and the beyond, up to several tens of kilometers from the accident site. Such findings highlight the need for detailed, effective evacuation plans.

Such emergency preparedness plans exist for military facilities and surrounding urban areas in England (Clyde Area Monitoring Organization, 1968), Australia (WASES, 1986), and in the United States: including Pearl Harbor (U. S. Navy, 1981), Puget Sound Naval Shipyard (USN, 1977), and Mare Island Naval Shipyard (City of Vallejo, 1978). The Pearl Harbor emergency plan entails evacuation of as many as 350,000 persons (not all at the same time). The City of Vallejo, California, anticipates evacuation for areas up to 5 miles from the site, and planning for the most extreme emergencies extends to 50 miles from the site.

As shown by the present analysis, radioactive contamination of downtown Manhattan could begin within a few minutes of an accident at the Esquimalt berth, and would incur significant casualties within a few hours. Therefore, an effective evacuation plan must be capable of clearing Manhattan within 1-2 hrs. Because such an accident could occur during working hours, any evacuation plan would have to address the maximum workforce population, which for New York is approximately double the residential population.

According the the U. S. federal government, the mere existence of an evacuation plan is insufficient; the plan must also be tested periodically in order to be useful in times of emergency. A comprehensive report to the U. S. Congress by the U. S. Government Accounting Office (GAO, 1979) on the subject of emergency evacuation plans, in the vicinity of nuclear facilities, concluded that: "Problems found with plans that were tested indicate that an untested plan would probably be ineffective in an emergency situation." The GAO report recommends that "local emergency preparedness should be periodically tested in concert with the nearby nuclear facility" (p. 27), in this case, the military authorities in command of the homeported vessel.

• RECOMMENDATION # 3: *The City of New York, together with State and Federal Agencies that are responsible, should determine whether an effective emergency evacuation plan can be developed for the city in the event of a severe nuclear accident aboard a homeported naval vessel.*

• RECOMMENDATION # 4: *Any such emergency evacuation Vplan should be rehearsed periodically to demonstrate and develop its effectiveness.*

D. Decontamination

As demonstrated in preceding sections, a nuclear accident of the magnitude studied here would require decontamination of the city prior to rehabitation. The cost of any such decontamination would have to be less than the real property value of the contaminated area to make decontamination a viable economic decision. Costs of decontamination for a moderate accident would be up to 15 billion U.S. dollars. Costs could reach up to 150 billion in extreme circumstances.

• RECOMMENDATION # 5: *City, State and Federal officials and agencies should work with the military to develop a realistic decontamination plan. Included in such plan should be assignment of responsibilities, cost and duration, and address questions of legal liability and indemnity.*

As noted above, indirect economic losses would attend such an accident, in that the economy of the city would be terminated pending decontamination and rehabitation. Inasmuch as the affected area is also the heart of the national economy, it would seem prudent to assess in advance the possible economic impacts of an accident of the kind modeled here on the city and national economy. Limiting the indirect economic losses would require clear division of responsibilities for cleanup in advance of any accident, including allocation of costs.

• RECOMMENDATION # 6: *Economic analyses of the possible impacts of nuclear accidents in New York Harbor should be undertaken in connection with the homeporting proposal. Linkages with the national and international economy should be taken into account in this analysis.*

E. Policy Formulation

Rational policy decisions require assessing accurately both the costs and the benefits of any action, and weighing one against the other. To date both the military and city officials have concentrated on the benefits of homeporting, without considering prospective costs associated with nuclear accidents. Obviously, the relevance of such an analysis depends upon the probability of such an accident. It is imperative, given the consequences of a nuclear accident in New York Harbor, that the probabilities be clearly understood.

- RECOMMENDATION # 7: *City and State authorities should insist on obtaining from the military sufficient data to assess the probability of an accident like the one modeled here. Such accidents should be taken into account correspondingly in arriving at an informed policy regarding homeporting nuclear capable vessels in densely populated urban centers such as New York City.*

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X. APPENDIX I: METHODOLOGY of ACCIDENT ANALYSIS

A. General Approach

The consequences of an accidental release of radioactivity from a reactor accident can be ascertained using established methodology of the U.S. Nuclear Regulatory Commission (NRC), as published in document WASH-1400 (the "Rasmussen Report"; NRC, 1975). WASH-1400 has been criticized as understating the actual impacts of any such accident (e.g., Wilson et al., 1986), and the criticisms receive support from the recent history of the nuclear industry (e.g., Three Mile Island, Cherbonyl). The WASH-1400 methodology nonetheless represents the official U.S. government basis for undertaking nuclear accident analyses, and it probably represents the best available synthesis of concept and application. In this report the assumption is made that the same WASH-1400 methodology applies to the accidental release to the atmosphere of radioactivity from any anthropogenic source.

The general steps used to determine the consequences of any hypothetical nuclear accident, based on WASH-1400 methodology, are as follows. First, determine the total inventory of radionuclides available for release. Second, define and justify assumptions about the fraction of this inventory released under the specific accident scenario considered. Third, establish the meteorological conditions at the site of the hypothetical accident. Fourth, calculate the dispersion of radionuclides in the atmosphere downwind from the accident site. Fifth, calculate the deposition of released radionuclides on the ground downwind from the accident. Sixth, obtain population data for the site of the hypothetical accident. Seventh, calculate the radiation doses to people delivered by the calculated releases and associated health impacts. Eighth, calculate the costs of decontaminating the regions in which radioactivity has been deposited. And ninth, assess the probability of the accident scenario modeled. Details of each of these nine steps that are relevant to this study are described next briefly in subsequent sections of this appendix, followed by sample calculations from the present study.

B. Details of the Methodology

1. *Inventory of Radionuclides Available for Release*

The inventory of radionuclides available for release depends entirely on the type of accident modeled. Possible scenarios include, in approximate order of decreasing severity, nuclear war, a nuclear power reactor meltdown, a mishap involving a production reactor or a reprocessing plant, a naval propulsion reactor accident, a non-explosive nuclear weapons accident, an accident involving plutonium transport, a research reactor accident, and an accident involving spent nuclear fuel in transport.

The first step in each case is to determine the inventory of radionuclides present in the initial source. In the case of nuclear war, the task is to determine the inventory of radionuclides resulting from the detonation of the assumed inventory of nuclear weapons. For nuclear reactors (and potentially other sources), the inventory can be computed using the ORIGEN computer code (developed by the Oak Ridge National Laboratory, or ORNL, Tennessee), which calculates the mix and quantity of fission products available in the core of a nuclear reactor under different fuel, loading and operating conditions.* A core inventory of radionuclides for a 3,200 megawatt PWR power reactor, calculated with the computer code ORIGEN, is presented in WASH-1400. For a reprocessing plant, establishing the source term requires technical knowledge of the process and the type and total quantity of radionuclides present. For plutonium transport and nuclear weapons accidents, the most significant source term is plutonium-239 (62.3 Curies per kilogram). The exact quantity of plutonium used in any particular weapon is classified information, but may be assumed to range between 1 and 10 kg. For an accident involving a military

ORIGEN has now been replaced with ORIGEN2, available (with documentation) from ORNL.

reactor or spent nuclear fuel, the inventory term is again calculated using ORIGEN or based on published accounts of the radionuclide inventory in one or more spent fuel assemblies, combined as appropriate with knowledge of spent nuclear fuel transportation cask capacities.

2. *Fraction of Inventory Available for Release (Source Term)*

One of the key assumptions of any analysis is the fraction of the total inventory that is plausibly available for release, or the "source term," defined as the product of the inventory and the release fraction. For a nuclear reactor accident, release of radionuclides occurs in three steps. In the first step, heat up and melting of the reactor core releases radionuclides from the fuel elements to the interior of the reactor vessel. In a severe accident it is generally assumed that in this step more than 80% of the most volatile elements are released (xenon, krypton, cesium, rubidium, iodine, bromide, antimony, tellurium and silver) (Wilson et al., 1986). The moderately volatile elements are assumed to be partially released, including barium, strontium, ruthenium and molybdenum (*ibid.*).

In the second step of a severe reactor accident, these materials are released from the reactor vessel to the containment structure. A significant fraction of the volatiles will "stick" to the surfaces of the reactor vessel and never reach the containment structure ("plate out"); and an additional fraction will plate out within the containment structure.

In the third step, radionuclides are released from the containment structure into the environment. This step depends strongly on the nature of containment and on the integrity of the containment structure. Realistic values for release fractions cannot be calculated from models based on first principles, and hence reliance must be made on experimental measurements and analysis of actual accident sequences. The data for many relevant nuclides are scarce or absent (Wilson et al., 1986). Qualitative estimates become inevitable.

Release fractions to the environment for a severe reaction accident (type PWR-1) are estimated in WASH-1400 (NRC, 1975) as follows: noble gases (xenon, krypton), 90%; iodines, 70%; cesiums and rubidiums, 40%; telluriums and antimony, 40%; barium and strontium, 5%; volatile oxides (cobalt, molybdenum, rutheniums), 40%; and non-volatile oxides (lanthanum, cerium, zirconium, transuranics), 0.3%.

Even with the best technical information available, therefore, the assumption of source term is subject to wide uncertainty and is somewhat arbitrary. One response to this uncertainty is to perform a "sensitivity analysis" on release fraction, i.e., to explore the impact of several different assumed release fractions. This approach is generally simple to apply, since impact is linearly proportional to release fraction. Therefore, once the consequence of releasing a particular fraction of the source term is calculated, the impact of other release fractions can be readily scaled accordingly. A second approach to the uncertainty regarding source term is to assume a 100% release fraction for the noble gases, a 10% release for the volatile oxides, iodines, cesiums and telluriums (which are relatively volatile), and a 1% release for all other nuclides. These release fractions are conservative in comparison with a PWR-1 accident as given in WASH-1400. A combination of these two approaches is used in the present study.

Actual release fractions from the Chernobyl accident, as reported by the U.S.S.R (SCUAE/USSR, 1986; INFAG, 1986), are as follows: noble gases, 100%; iodine, 20%; cesiums, 10-13%; telluriums, 15%; strontium, 4%; whole core, 2.3 - 3.2%. The release fractions assumed in the present study are conservative also with respect to these Chernobyl release fractions.

For other (non-reactor) nuclear accidents, the release fraction is subject to several influences, including the physical form of the nuclear material, the physical setting in which the material is contained, its proximity to forms of potential dispersive energy, the probability of disruptive events capable of inducing release, etc. Spent commercial nuclear fuel, for example, generally takes the form of uranium dioxide, which is not as readily oxidized further, although volatile fission products are subject to easier release. Spent research reactor fuel sometimes is in the form of relatively combustible uranium metal, however, which makes it more dispersible and hence increases plausible release fractions. Knowledge of the physical properties of the source term and its containment is clearly essential in arriving at an informed judgement of plausible source terms.

3. *Meteorological Conditions at the Accident Site*

Weather conditions at the site of the hypothesized accident determine the dispersion pattern of the released radionuclides. Critical meteorological parameters include the wind direction and velocity, as deduced from "wind roses," atmospheric stability, as deduced from "stability wind roses," atmospheric inversion altitude and frequency, and precipitation patterns.

These data are generally readily obtainable from climatic records, published in numerous sources. Once the existing data are collected, there are at least five alternative conventions for their use. By the first convention, the "typical" weather pattern (i.e., the most frequently obtained) is employed. By the second, "95% meteorology" is assumed, i.e., weather conditions resulting in consequences that would be exceeded only 5% of the time. This approach is recommended by the NRC. By the third convention, boundary conditions are used to estimate a range of possible impacts (e.g., the best and worse case conditions). By the fourth convention, the worst case conditions are assumed. The fifth convention is probabilistic; it integrates the consequences of all weather conditions and assigns weighted probabilities to each. This last convention is the most satisfying, but it is also the most difficult to apply. This convention is integrated into the most developed computer codes for consequence analysis, such as MACCS.

In practice some combination of the first (typical conditions) and second (95% meteorological conditions) generally represents a practical and satisfactory compromise. The third convention is perhaps the most satisfactory mix of completeness and practicality. With respect to wind direction, this entails choosing either the most frequent (convention 1) or the most damaging (convention 2) wind direction.

With respect to atmospheric stability, meteorologists recognize six categories, ranging from "extremely unstable" (Pasquill category A) to "extremely stable" (Pasquill category F). It is generally accepted that the greatest radiological detriment is associated with the most stable atmospheric conditions (Slade, 1968; Turner, 1969), since dilution by incoming winds is least under these conditions, resulting in the highest local air concentration of radionuclides and the greatest ground deposition. It may be difficult, however, to obtain data on atmospheric stability for some locations. One solution to this problem is to establish boundary conditions for the accident modeled (the equivalent of the third convention discussed above). The way in which atmospheric stability is incorporated into the analysis is described in the next section.

Inversion patterns are important because they can entrap air (and radionuclides suspended within air) in one location, resulting in prolonged exposure in one location rather than dilution and dispersion. Precipitation is likewise important because it increases the quantity of radionuclides deposited on the ground, although it also accelerates subsequent "weathering" and run off of the radionuclides. The ways in which inversions and precipitation are incorporated into dispersion analyses are also treated in the next section. Vertical wind patterns would be important to include but they are seldom known and only poorly understood and therefore represent a major uncertainty in dispersion analysis.

4. *Equations for Atmospheric Dispersion of Released Radionuclides*

Radionuclides that are released accidentally into the atmosphere will be transported in the form of a radioactive cloud in the horizontal direction of the prevailing wind. The next step is the analysis is to combine the assumptions about source term with local, site-specific meteorological conditions to determine the dispersion of the radionuclides in the atmosphere, using equations for turbulent diffusion as developed in WASH-1400. This aspect of the WASH-1400 document is probably the soundest from a scientific viewpoint, inasmuch as the quantitative methodology for turbulent diffusion in the atmosphere has evolved over several decades from the literature on dispersion of non-radioactive materials (fossil fuel pollutants) and has a reasonably sound theoretical and empirical basis (see for example Slade, 1968). A helpful practical guide to this methodology for first-time users is Turner's *Workbook of Atmospheric Dispersion Estimates* (Turner, 1969), which includes numerous sample problems and their solutions. Also included are several mathematical tables specifically crafted for the kinds of applications encountered in this type of analysis.

The basic model utilized to calculate the downwind concentration of a specific radionuclide from a source of known magnitude is a Gaussian diffusion model. According to this model, radionuclides released from a point source diffuse in three dimensions, termed x (downwind), y (crosswind) and z (vertical). In the event of a prevailing wind, mass transport in the downwind direction far exceeds simple diffusion. This condition may be assumed when release is continuous or when the duration of release is equal to or greater than the travel time from the source to the downwind location of interest. In this case diffusion expands the radioactive plume only in the horizontal or crosswind direction (y) and in the vertical direction (z). To calculate the resultant concentration in air (χ, in Curies per cubic meter) of any specific radionuclide, equation 1 that follows can be used.

Equation 1

$$\chi_{(x,y,z;H)} = \left\{ \frac{Q}{2\pi\sigma_y\sigma_z u} \right\} \left\{ e^{\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]} \right\} \left\{ e^{\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]} + e^{\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]} \right\}$$

where π = 3.1416 (dimensionless); Q = the rate of release at the point source in Curies per second (i.e., the source term divided by the release duration); σ_y and σ_z are the horizontal and vertical diffusion parameters (meters), calculated as described below according to the atmospheric stability category as functions of downwind distance; u = the wind velocity (meters per second); e = the base of the natural logarithm, approximately 2.7283 (dimensionless); y = the crosswind distance from the plume centerline (meters); z = the vertical distance from the plume centerline (meters); and H = the height of the point source above the ground (meters).

For the majority of applications, one or more of several simplifying assumptions can be made to reduce the complexity of the calculations. First, it is frequently appropriate to assume that the "receptor" of the radionuclides (i.e., an exposed person) is located at ground level. In this case $z = 0$, and equation 1 above reduces to equation 2 below.

Equation 2

$$\chi_{(x,y,0;H)} = \left\{ \frac{Q}{\pi \sigma_y \sigma_z u} \right\} \left\{ e^{\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]} \right\} \left\{ e^{\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]} \right\}$$

A second useful simplification can be realized by assuming that the receptor is located at the centerline of the plume. In this case $y = 0$, and equation 2 above reduces to equation 3 below.

Equation 3

$$\chi_{(x,0,0;H)} = \left\{ \frac{Q}{\pi \sigma_y \sigma_z u} \right\} \left\{ e^{\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]} \right\}$$

A third simplification can be realized by assuming that the radionuclides are released from a ground level source with no effective plume rise. This assumption may be valid, for example, for a sea level release near an urban area that is significantly elevated above sea level. Suppose, for example, that the mean elevation of a city is 50 m. A sea level release followed by a 50 m plume rise from thermal lofting will then result in an effective source elevation of 0. Assuming that the assumption of $H = 0$ is justifiable, equation 3 above reduces to equation 4 below.

Equation 4

$$\chi_{(x,0,0;0)} = \frac{Q}{\pi \sigma_y \sigma_z u}$$

More exact means for correcting the concentrations for plume rise exist, but their application is fairly difficult. The approach entails modifying the equation used to calculate downwind concentration (χ) for plume rise generated by thermal lofting, using one of two equations. For unstable or neutral atmospheric stability conditions (see above, Meteorological Conditions at the Accident Site, and below, this section, for a discussion of atmospheric stability), the following equation is recommended by WASH-1400:

Equation 5

$$\Delta H = \frac{1.6 F^{1/3} x^{2/3}}{U}$$

where ΔH = the plume centerline height (meters above initial emission height); F = buoyancy flux = $3.7 \times 10^{-5}\, Q_H$; Q_H = thermal energy release (calories/sec); x = downwind distance (m); and U = windspeed (m/s).

For stable atmospheric conditions, WASH-1400 recommends the following equation for correcting plume rise:

Equation 6

$$\Delta H = 2.9 (F/US)^{1/3}$$

where ΔH, F, and U are as in equation 5; $S = (g/T)(2\theta/\partial_z)$ (units of sec^{-2}); g = 9.81 (m/sec^2); T = temperature (degrees Kelvin); θ is the potential temperature (degrees Kelvin); z and ∂_z = the standard deviation of plume height (meters).

An acceptable if approximate alternative to applying these equations is to estimate total plume rise at the source, and assume that diffusion begins at the peak of the estimated plume rise. The assumption of any plume rise has the effect of wafting the initial plume over the heads of nearby receptors, reducing calculated detriment near the source of the release. The assumption is vulnerable, however, to inaccuracies in estimation of initial thermal lofting.

A fourth and final simplification in the equation for downwind concentration of radionuclides in air can be realized by assuming that the distribution of radionuclides in the crosswind (y) direction is rectangular rather than Gaussian. The rectangular pattern, termed the "top-hat" distribution in WASH-1400, is recommended by the NRC. The magnitude ("amplitude") of the rectangular distribution is set at 80% of the centerline magnitude under the Gaussian assumption, because the area beneath the rectangular curve is then nearly the same as that beneath the Gaussian distribution. This results in the same total quantity of radionuclides in the air, but their crosswind dispersion in the cloud is taken as uniform rather than Gaussian, which simplifies subsequent calculation of ground deposition and dosimetry, as detailed in subsequent sections. The "top hat" distribution is achieved by modifying equation 4 above to the form of equation 7 below.

Equation 7

$$\chi_{(x,y,0;0)} = \frac{0.8Q}{\pi \sigma_y \sigma_z u}$$

Important note: It should be noted that the above equations do *not* take into account the depletion of the radioactive cloud by fallout, which is essential. The means for accomplishing this are given in equation 10 below.

Once the appropriate equation for calculating downwind air concentration of radionuclides is selected from the five possibilities described above—usually equation 7 or equation 7 modified for thermal lofting as in equation 3—the parameters of the equation must be identified or computed. The equation is then solved iteratively for increasing incremental distances from the source, usually taken as downwind intervals of 1 km or 1 mile, progressively farther from the source. In accord with WASH-1400, the calculations are performed for downwind distance corresponding to the midpoint of incremental spatial intervals, and the corresponding concentration value that is computed for the interval midpoint is assumed to apply for the entire spatial interval for which it is calculated. The alternative of integrating air concentration over the entire interval is more satisfying conceptually, but does not provide a sufficient increase in precision to justify the extra computational effort, unless the user is mathematically sophisticated and has access to a computer.

The parameters required for equation 7 are four: Q, σ_x, σ_y, and U. Q is determined by dividing the source term (Ci) by the assumed duration of release (sec). The downwind distance, x, is incorporated into the calculations by means of the distribution parameters, σ_y and σ_z. These parameters are in turn determined separately for each atmospheric stability class. Atmospheric stability refers to the capacity of the atmosphere to dilute any material released from a point source, and is determined largely by the rate of solar isolation and consequent "lapse rate," i.e., decline in temperature with increasing altitude or $\Delta T / \Delta H$, where T and H = temperature and height, respectively. Pasquill (1961, 1962) devised a simple series of calculations by which atmospheric stability could be classified and calculated from a minimal number of easily measured parameters. His classification scheme was subsequently modified by Briggs (1973, cited in WASH-1400; NRC, 1975), who devised simple interpolation equations that closely approximate the Pasquill functions out to a distance of 10 km from the source. Beyond 10 km the correspondence is good but not exact.

A qualitative guide to the six Pasquill atmospheric stability categories (class A, extremely unstable, through class F, extremely stable) is offered by Turner (1969, p. 6), as shown in Table 2.

TABLE 2
QUALITATIVE GUIDE TO PASQUILL ATMOSPHERIC STABILITY CLASSES

Wind velocity (10 m above ground, m/sec)	DAYTIME			NIGHTIME	
	Solar Radiation			thin overcast or ≥ 50% low cloud cover	≤ 38% cloud cover
	strong	moderate	slight		
<2	A	A-B	B	--	--
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

The Briggs equations for approximating the Pasquill functions, as presented in in WASH-1400, are shown in Table 3 (where χ = the downwind distance). It should be noted that these equations pertain to open-country conditions. Their application to urban areas, where turbulence in the wake of buildings is induced, is less exact, but quantitative means to deal with such turbulence appear to be unavailable.

TABLE 3
BRIGGS EXTRAPOLATION FORMULAE FOR APPROXIMATING PASQUILL FUNCTIONS

Pasquill Stability Category	σ_y	σ_z
A (extremely unstable)	$0.22\,x\,(1{+}0.0001x\,)^{-1/2}$	$0.20x$
B (unstable)	$0.16\,x\,(1{+}0.0001x\,)^{-1/2}$	$0.12x$
C (slightly stable)	$0.11\,x\,(1{+}0.0001x\,)^{-1/2}$	$0.08\,x\,(1{+}0.0002x\,)^{-1/2}$
D (neutral)	$0.08\,x\,(1{+}0.0001x\,)^{-1/2}$	$0.06\,x\,(1{+}0.0015x\,)^{-1/2}$
E (slightly stable)	$0.06\,x\,(1{+}0.0001x\,)^{-1/2}$	$0.03\,x\,(1{+}0.0003x\,)^{-1/2}$
F (very stable)	$0.04\,x\,(1{+}0.0001x\,)^{-1/2}$	$0.016\,x\,(1{+}0.0003x\,)^{-1}$

5. *Plume Depletion: Radioactive Decay and Deposition*

The radioactivity in the moving plume declines during its transport by two means: radioactive decay, and deposition of particles on the ground. Radioactive decay becomes significant mainly for relatively short half-lived isotopes such as iodine-131 (half-life 8.05 days). If one is dealing only with short term (hours) consequences, such decay can be ignored with little sacrifice in accuracy; and decay can likewise be ignored with little loss of accuracy for very long-lived nuclides such as plutonium-239.

The dispersion of radionuclides in the atmosphere can be affected strongly by vertical wind components and by atmospheric inversions. Vertical winds are known to occur, and the resultant mass transport would far exceed diffusion in the vertical (Z) direction. This could result in greater dilution of the radioactive cloud (upward-directed winds), but also complex and unpredictable "touch-down" of the radioactive cloud (downward-directed winds) in downwind directions, as in fact occurred following the Cherbonyl release. Vertical wind components are not well-understood and are not taken into account in calculating downwind radionuclide concentrations in the atmosphere.

Radioactive decay can be incorporated into the equation for downwind concentration, by adding an exponential decay function. Equation 7, for example, becomes:

Equation 8

$$\chi(x,y,0;0) = \frac{0.8Q}{\pi\sigma_y\sigma_z u} e^{[-\frac{x}{L_r}]}$$

where all terms but the exponent are defined as in equation 7; and L_r (the relaxation length) = u_x/λ = $[u_x t_{1/2}]/ln\,2$; where λ = the radioactive decay constant and $t_{1/2}$ is the half-life of the radionuclide in question.

As the cloud of radioactivity is transported downwind by prevailing winds, the radioactive particles contained in it are deposited onto the ground by two mechanisms, wet deposition and dry deposition. Wet deposition entails formation of water droplets around the radioactive particles, which thus serve as condensation nuclei, and subsequent settling of the particles to the ground. Dry deposition entails gravity sedimentation of particles to earth, as well as impact adherence of the charged radioactive particles to surfaces, including buildings, automobiles, vegetation and the earth. Neither process is well understood.

Wet deposition is assumed in WASH-1400 to be about one order of magnitude less than dry deposition. Moreover, wet deposition occurs only under conditions of fog or precipitation, in which case wash-out (short-term weathering) would at least partially mitigate ground deposition. Wet deposition can frequently be ignored, depending on site-specific meteorological conditions, in which case the calculation of ground contamination is probably conservative.

Dry deposition can be calculated in one of three ways. First, the deposition in each downwind spatial interval can be incorporated into the equation for downwind concentration. Equation 7, for example, then becomes Equation 9, below:

Equation 9

$$\chi_{(x,y,0;0)} = \frac{0.8Q}{\pi \sigma_y \sigma_z u} e^{(\frac{-x}{L_d})}$$

where $L_d = u\bar{z}/V_d$; L_d = the attenuation length; u = windspeed (m/sec); $\bar{z}$ = the mean height of the cloud (m); and V_d = the deposition velocity (m/sec).

Alternatively, dry deposition can be calculated from relatively complex equations such as those presented in Slade (1968, p. 204). Numerical solutions to these equations are available, however, in graphical form (Figure 20).

A practical third alternative is to utilize these curves to estimate numerically the depletion of the cloud within each downwind spatial interval, and to then correct the source term for the next interval by subtraction of the portion deposited in all preceding intervals. This procedure is carried out as follows. The source depletion curves (Figure 20) show the ratio of the depleted source term (Q_x') to the original source term (Q_0'), as a function of downwind distance. To determine the source depletion fraction from these curves, the distance on the abscissa corresponding to the midpoint of the downwind spatial interval under consideration is first determined. Then the corresponding ratio of the new to the original source term corresponding to that downwind distance is read on the ordinate. The original source term (Q) used in the equation to calculate downwind air concentration is then simply multiplied by this ratio prior to using it in the equation for downwind air concentration. That is, the new source term is equal to the original source term times the source depletion factor determined by the appropriate curve in Figure 20. The source depletion ratios measured from these curves are presented in Tables 4 and 5 for $H = 0$ and $H = 50$ m, respectively.

To incorporate cloud depletion into the calculation of downwind air concentration, the corresponding source depletion factor is simply multiplied times Q in the equations given earlier. To illustrate, Equation 7 above becomes:

Equation 10

$$\chi_{(x,y,0;0)} = \frac{0.8Q\,(Q_x'/Q_0')}{\pi\sigma_y\sigma_z u}$$

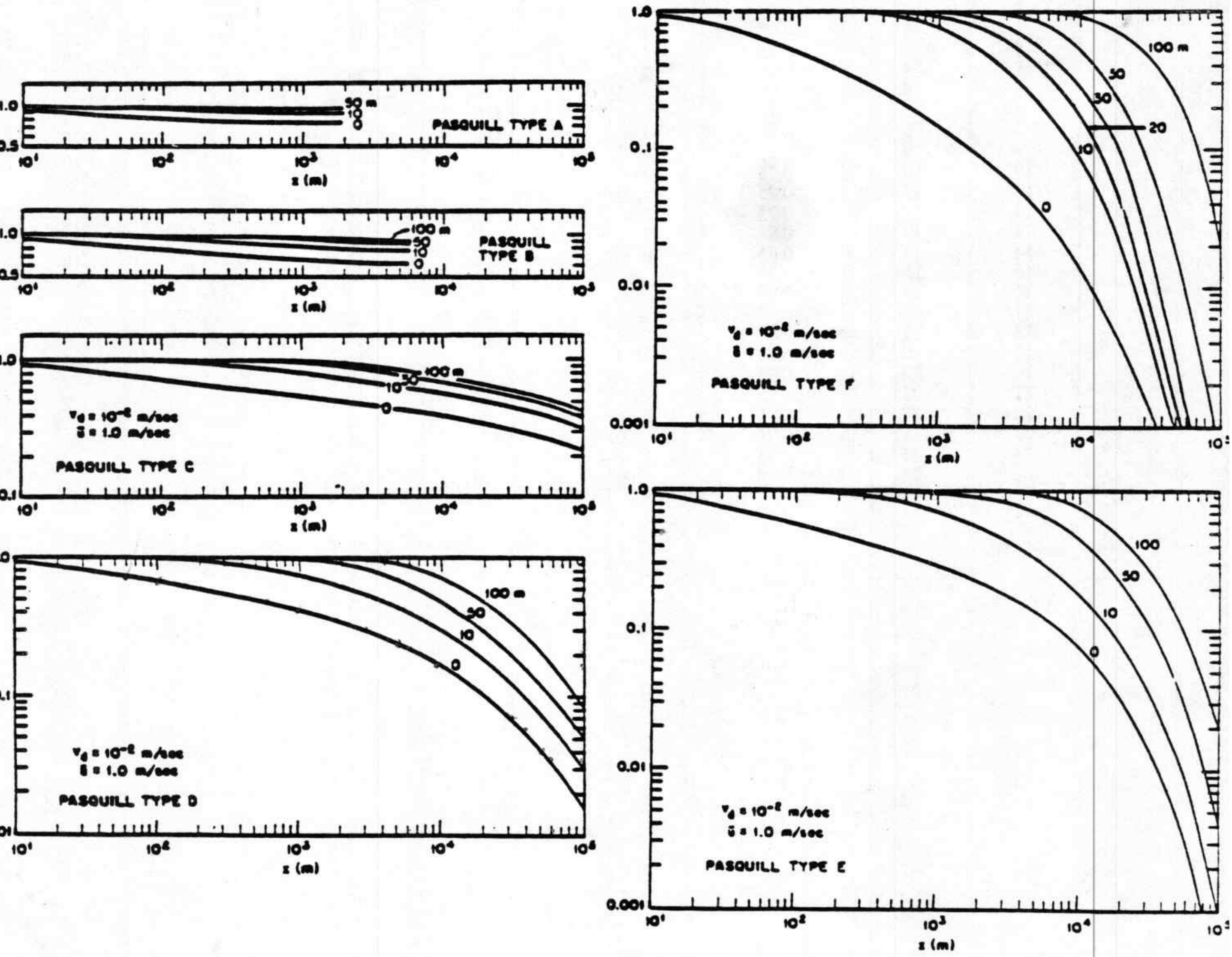

Figure 20: Source-depletion fraction, Q_x'/Q_0', for a wind speed, $\overline{U}$, of 1.0 m/sec, a deposition velocity, v_d, of 10^{-2} m/sec, for source heights from 0 to 100 m above the ground and for various stability categories.

TABLE 4
COMPUTED SOURCE DEPLETION FACTOR (Q_x'/Q_0') for H = 0 m

spatial interval	effective source distance (km)	stability class A	stability class B	stability class C	stability class D	stability class E	stability class F
0	0	1.0	1.0	1.0	1.0	1.0	1.0
1	1	0.75	0.64	0.57	0.420	0.41	0.13
2	2	0.75	0.62	0.50	0.340	0.30	0.089
3	3	0.75	0.61	0.47	0.300	0.19	0.061
4	4	0.75	0.60	0.458	0.270	0.16	0.048
5	5	0.75	0.60	0.444	0.240	0.14	0.035
6	6	0.75	0.60	0.430	0.220	0.12	0.031
7	7	0.75	0.60	0.420	0.210	0.220	0.023
8	8	0.75	0.60	0.410	0.190	0.10	0.020
9	9	0.75	0.60	0.408	0.180	0.088	0.016
10	10	0.75	0.60	0.406	0.170	0.080	0.014
11	11	0.75	0.60	0.404	0.165	0.069	0.013
12	12	0.75	0.60	0.402	0.160	0.065	0.012
13	13	0.75	0.60	0.400	0.155	0.061	0.011
14	14	0.75	0.60	0.398	0.150	0.057	0.010
15	15	0.75	0.60	0.395	0.145	0.054	0.009
16	16	0.75	0.60	0.392	0.140	0.051	0.008
17	17	0.75	0.60	0.389	0.133	0.048	0.007
18	18	0.75	0.60	0.386	0.126	0.045	0.006
19	19	0.75	0.60	0.383	0.119	0.042	0.005
20	20	0.75	0.60	0.380	0.110	0.038	0.004
21	22.5	0.75	0.60	0.340	0.090	0.025	0.002
22	27.5	0.75	0.60	0.320	0.080	0.018	0.0018
23	35	0.75	0.60	0.300	0.058	0.010	0.0001
24	45	0.75	0.60	0.280	0.046	0.0061	0
25	55	0.75	0.60	0.270	0.037	0.0035	0

TABLE 5
COMPUTED SOURCE DEPLETION FACTORS (Q_x'/Q_0') for H = 50 m

spatial interval	effective source distance (km)	stability class A	stability class B	stability class C	stability class D	stability class E	stability class F
0	0	1.00	1.00	1.00	1.00	1.00	1.00
1	1	0.90	0.90	1.0	1.0	1.0	1.0
2	2	0.90	0.87	0.90	0.88	0.99	1.0
3	3	0.90	0.85	0.83	0.80	0.92	1.0
4	4	0.90	0.83	0.75	0.73	0.89	0.91
5	5	0.90	0.83	0.72	0.69	0.81	0.88
6	6	0.90	0.83	0.71	0.61	0.76	0.83
7	7	0.90	0.83	0.70	0.59	0.70	0.71
8	8	0.90	0.83	0.70	0.53	0.62	0.63
9	9	0.90	0.83	0.70	0.51	0.60	0.58
10	10	0.90	0.83	0.70	0.48	0.56	0.56
11	11	0.90	0.83	0.64	0.41	0.47	0.43
12	12	0.90	0.83	0.63	0.40	0.44	0.40
13	13	0.90	0.83	0.61	0.38	0.41	0.33
14	14	0.90	0.83	0.60	0.37	0.40	0.31
15	15	0.90	0.83	0.60	0.33	0.34	0.29
16	16	0.90	0.83	0.60	0.32	0.31	0.27
17	17	0.90	0.83	0.60	0.31	0.29	0.25
18	18	0.90	0.83	0.60	0.30	0.24	0.22
19	19	0.90	0.83	0.60	0.30	0.23	0.21
20	20	0.90	0.83	0.60	0.29	0.21	0.20
21	22.5	0.90	0.83	0.58	0.25	0.17	0.13
22	27.5	0.90	0.83	0.56	0.21	0.12	0.11
23	35	0.90	0.83	0.51	0.15	0.089	0.062
24	45	0.90	0.83	0.50	0.12	0.050	0.022
25	55	0.90	0.83	0.38	0.10	0.033	0.014

The curves expressed in Figure 20, and the measured values in Tables 4 and 5, correspond to a deposition velocity of 10^{-2} m/sec, which is a reasonable value to use for particle sizes likely to result from a nuclear accident (aerosols 20 micrometers and lower in diameter). Smaller particles, however (less than one micron in diameter), probably deposit mainly through impact adherence. The curves in Figure 20 also assume a windspeed of 1 m/sec, however, which is not always suitable for a particular location. The source depletion ratio read from the curves of Figure 20 can be adjusted for different windspeeds using the following equation (from WASH-1400):

Equation 11

$$\left[\frac{Q_x'}{Q_0'}\right]_2 = \left[\frac{Q_x'}{Q_0'}\right]_1^{\overline{U}_1 V_{d2} / \overline{U}_2 V_{d1}}$$

where subscript 1 refers to values found in Figure 20, subscript 2 refers to the desired value, $\overline{U}$ refers to the mean windspeed, and V_d is the deposition velocity. In practice it is simplest to assume a windspeed of 1 m/sec, which is generally justifiable under the convention of 95% meteorological conditions as described above. This eliminates the need to calculate a new source depletion curve for each downwind spatial interval for a windspeed other than 1 m/sec.

Once the appropriate source depletion ratios have been determined from the curves in Figure 20 (or taken from Tables 4 and 5), the deposition of radionuclides onto the ground in spatial interval j can be determined as follows. Recalling that the source depletion fraction describes the fraction remaining in the cloud, the fraction deposited is

$$1 - \frac{Q_x'}{Q_0}$$

This fraction represents everything that has been deposited *up to and including* the interval under consideration. To obtain the amount deposited in the interval under consideration, it is necessary to subtract from the above fraction the fraction that has been deposited *prior to* the interval under consideration. That is, the fraction deposited in spatial interval j, F_j, is given by:

Equation 12

$$F_j = \left[1 - \left[\frac{Q_x'}{Q0}\right]_j\right] - \left[1 - \left[\frac{Q_x'}{Q0}\right]_i\right]$$

$$= \left[\frac{Q_x'}{Q^0}\right]_i - \left[\frac{Q_x'}{Q0}\right]_j$$

To obtain the quantity of radionuclides deposited, I_d, F_j is multiplied by the original source term for the radionuclide in question.

Equation 13

$$I_d = (F_j)(ST)$$

To obtain the surface concentration (in Curies per square kilometer), the quantity deposited is divided by the surface area of the spatial interval. The entire equation for surface deposition (SD) in interval j is therefore as follows:

Equation 14

$$SD_j = \frac{\left[\left[\frac{Q_x'}{Q_0}\right]_i - \left[\frac{Q_x'}{Q_0})\right]_j\right](ST)}{A_j}$$

where SD_j is the surface deposition in spatial interval j (Curies/m^2), $(Q_x'/Q_0')_j$ is the source depletion factor for interval j (from Figure 20 or Table 4 or 5), $(Q_x'/Q_0')_i$ is the source depletion factor for the preceding spatial interval i, ST is the source term (Curies) for the radionuclide in question, and A_j is the surface area (square meters) beneath the plume for interval j, determined as described next.

In order to determine the surface area beneath the plume for each spatial interval, the geographical parameters of the plume are computed. The projected width on the ground of the plume at the midpoint of each spatial interval is taken as $3\sigma_y$ (WASH-1400). On this basis the ground area subtended by the plume can be superimposed onto maps of the affected region. The surface area represented by each spatial interval can be approximated as the width of the interval at its midpoint times the downwind length of the interval (typically 1,000 m). This yields A for interval j, for use in the above equation 14.

6. *Population Data*

Population parameters required to determine health effects include the population density in the affected region, and the age structure of the population. Health impacts are greater for younger people, and hence a conservative simplifying assumption (one that understates the health impacts) is that all persons in the exposed region are adult.

Once the population densities in the affected regions are known, the number of persons at risk is determined by the following equation:

Equation 15

$$P = DA$$

where P = the number of exposed persons, D = the population density (persons per square kilometer) and A = the area beneath the plume in the corresponding spatial interval (square kilometers). The area may be approximated as the width of the spatial interval at its midpoint times the length of the interval (1 km). In the event that the spatial interval includes uninhabited regions (e.g., bodies of water), a corresponding reduction in the area is necessary prior to determining the populations.

7. Casualties from Radiation Doses

Exposure of individuals to radionuclides following an accidental release can occur *via* one or more of five pathways: gamma radiation from the moving cloud ("*cloudshine*"), inhalation of radionuclides caused by breathing the radioactive cloud (*inhalation exposure*), gamma irradiation from radionuclides deposited on the ground (*groundshine*), exposure to radionuclides resuspended in the air following deposition on the ground (*resuspension*), and ingestion of radionuclides in food and water (*ingestion*).

Resuspension is probably small compared with the other pathways (except in the case of long-lived radionuclides such as plutonium-239). This pathway can be ignored, resulting in a conservative analysis. Ingestion can be eliminated for many accident scenarios by presumed quarantine of the food and water supplies in a contaminated region. It too can be ignored, which adds to the conservativeness of the calculation. In cases where ignoring ingestion is not justified, such as large-scale contamination of farmlands (as from the accident at Chernobyl), methods for dealing with the ingestion pathway are given in WASH-1400.

Cloudshine and inhalation exposures are calculated directly from the downwind air concentrations as determined above, in combination with published "dose conversion factors" (DCFs). DCFs are subject to substantial uncertainty, but those published by the American Physical Society (Wilson et al., 1986) are considered most up-to-date and reliable (Tables 6-8). These represent conversion factors from concentration in the air to radiation exposure in units of Rem/sec per Curie/m^3 in the case of cloudshine, or Rem/Curie inhaled in the case of inhalation exposure. In the latter case a human respiration rate of 1 m^3/hour is assumed. For groundshine the units are Rem/week per Curie/m^2 of surface contamination. Exposure of a single individual in rems is obtained by multiplying the DCF times the calculated concentration (cloudshine, groundshine) or amount inhaled (inhalation exposure).

TABLE 6
CLOUDSHINE DOSE CONVERSION FACTORS FOR SELECT RADIONUCLIDES
(from Wilson et al., 1986)

Radionuclide	APS Whole-Body Dose Conversion Factor $\frac{Rem/second}{Ci/m^3}$	APS Whole-Body Dose Conversion Factor $\frac{Rem/hour}{Ci/m^3}$
^{95}Zr	0.162E0	5.83E2
^{95}Nb	0.166E0	5.98E2
^{103}Ru	0.111E0	4.00E2
^{106}Ru	0.431E-1	1.55E2
^{131m}Te	0.314E0	1.13E3
^{132}Te	0.475E-1	6.30E1
^{131}I	0.872E-1	3.14E2
^{134}Cs	0.350E0	1.26E3
^{136}Cs	0.478E0	1.72E3
^{137}Cs	0.122E0	4.39E2
^{140}Ba	0.444E-1	1.60E2
^{140}La	0.567E0	2.04E3
^{144}Ce	0.431E-2	1.55E1
^{239}Pu	0.230E-4	8.28E-2

TABLE 7
INHALATION DOSE CONVERSION FACTORS
FOR SELECT RADIONUCLIDES
(from Wilson et al., 1986)

Radionuclide	APS Whole-Body Dose Conversion Factor (0-50 years) Rem/Ci inhaled
^{89}Sr	0.410E4
^{90}Sr	0.240E6
^{95}Zr	0.560E4
^{95}Nb	0.190E4
^{103}Ru	0.190E4
^{106}Ru	0.620E5
^{131m}Te	0.550E3
^{132}Te	0.150E4
^{131}I	0.600E3
^{134}Cs	0.470E5
^{136}Cs	0.590E4
^{137}Cs	0.360E5
^{140}Ba	0.190E4
^{140}La	0.920E3
^{144}Ce	0.320E5
^{239}Pu	0.820E8

TABLE 8
GROUNDSHINE DOSE CONVERSION FACTORS FOR SELECT RADIONUCLIDES
(from Wilson et al., 1986)

Radionuclide	APS Whole-Body Dose Conversion Factor for 1 week of exposure	APS Whole-Body Dose Conversion Factor for 1 day	APS Whole-Body Dose Conversion Factor for 1 hour
^{95}Zr	0.177E4	2.53E2	
^{95}Nb	0.164E4	2.39E2	1.05E1
^{103}Ru	0.116E4	1.66E1	6.90E0
^{106}Ru	0.456E3	6.51E1	2.71E0
^{131m}Te	0.960E3	1.37E2	5.71E0
^{132}Te	0.308E4	4.40E2	1.83E1
^{131}I	0.708E3	1.01E2	4.21E0
^{134}Cs	0.369E4	5.27E2	2.20E1
^{136}Cs	0.410E4	5.86E2	2.44E1
^{137}Cs	0.131E4	1.87E2	7.80E0
^{140}Ba	0.365E4	5.21E2	2.17E1
^{140}La	0.180E4	2.57E2	1.07E1
^{144}Ce	0.120E3	1.71E1	7.14E-1
^{239}Pu	0.263E1	3.76E-1	1.57E-2

It is generally believed that an exposure of 500 Rem will kill all exposed persons. The short-term dose that will cause 50% mortality within 60 days (LD-50/60) is generally considered to be 350 REM. Prompt fatalities are generally not expected at doses below 150 Rem (Wilson et al., 1986). Protective action guidelines of the U.S. Environmental Protection Agency are set at 1-5 Rem.

For lower doses of radiation, the health effects are subject to substantial uncertainty. All estimates are based on backward extrapolation from higher doses (~100 rem), and hence the particular model used to relate dose to effect critically determines the health effects estimated for low doses. The BEIR III report (NAS, 1980) estimates that a population of 100,000 persons exposed uniformly to a dose of 1 rem (equivalent to 100,000 person-rem) will experience 15-50 casualties from latent cancers. An equal number of severe genetic defects is usually assumed. This corresponds to fatality from latent cancer per 2,000-6,666 person-rem. On the other hand, Gofman (1981) argues the correct cose factor is 1 latent cancer fatality per 235 person-rem.

Owing to the tremendous variation in estimates, which reflects genuine scientific uncertainty and controversy, it is necessary to express casualties associated with low radiation doses as a range which probably encompasses the actual casualties. The extremes of this range are here set at 1 latent cancer death per 10,000 person-rems (low risk factor) and 1 latent cancer death per 235 person rems (high risk factor).

To obtain the person-rems for each spatial interval, the number of persons at risk (calculated from Equation 15 above) is multiplied by the sum of calculated exposure for all pathways, according to the following equation:

Equation 16

$$PR_i = (E_c + E_I + E_G)_i P_i$$

where PR_i = person-rem in spatial interval i, E_c = the total exposure from cloudshine in spatial interval i (rem), E_I = the inhalation exposure (rem) in spatial interval i; E_G = the groundshine exposure in spatial interval i (rem), and P_i = the number of persons at risk in spatial interval i, as determined from Equation 15 above. Equation 16 omits both the resuspension pathway and the ingestion pathway, under the conservative assumption that both will be mitigated by emergency evacuation and quarantine procedures. Once the person-rem is calculated, the range of casualties is determined by dividing the person-rem by 10,000 (low risk factor) and 235 (high risk factor).

8. *Evacuation and Decontamination*

A severe accident will require evacuation and decontamination of the affected region in order to avoid "unacceptable" casualties. The level of "unacceptable casualities is a socio-political-economic decision that is reflected by publically-sanctioned exposure "limits," beyond which casualties are, by definition, "unacceptable." These limits are in turn established for total exposure to any individual, and also for different radionuclides and different exposure pathways.

In the U.S., the individual exposure limit for individual members of the general public is 2 mrem/hour for "routine" releases of radionuclides from nuclear facilities. Specific protective actions (shielding, evacuation) may be required under accident conditions for exposure exceeding 1 and 5 rem/hour (whole body and thyroid doses, respectively). Concentration limits for individual radionuclides are likewise established, both for air-concentration and for ground contamination. Limits set by the U.S. Nuclear Regulatory Commission for unrestricted use by the public are shown in Tables 3 and 4. Levels of contamination in excess of these limits render an area unfit for unrestricted public use and, by implication, trigger evacuation and decontamination of the area.

TABLE 9: NRC Limits for Air and Water Contamination for Select Radionuclides*					
Radionuclide*	Air Concentration NRC limit, Ci/m^3 (over 1 year)	Air Concentration NRC limit, Ci/m^3 (scaled to 1 hr)	Air Concentration NRC limit, Ci/m^3 (scaled to 3 hr)	Air Concentration NRC limit, Ci/m^3 (scaled to 4 hr)	Water Concentration NRC limit Ci/m^3 (over 1 year)
^{89}Sr	3E-10	2.63E-6	8.76E	6.57E-7	3E-6
^{90}Sr	3E-11	2.63E-7	8.76E-8	6.57E-8	3E-7
^{91}Y	1E-9	8.76E-6	2.92E-6	2.19E-6	3E-5
^{95}Zr	4E-9	3.50E-5	1.17E-5	8.76E-6	6E-5
^{95}Nb	2E-8	1.75E-4	5.84E-5	4.38E-5	1E-4
^{103}Ru	2E-8	1.75E-4	5.84E-5	4.38E-5	8E-5
^{106}Ru	3E-9	2.63E-5	8.76E-6	6.57E-6	1E-5
^{131m}Te	1E-8	8.76E-5	2.92E-5	2.19E-5	6E-5
^{132}Te	7E-9	6.13E-5	2.04E-5	1.53E-5	3E-5
^{131}I	1E-10	8.76E-7	2.92E-7	2.19E-7	3E-7
^{134}Cs	1E-9	8.76E-6	2.92E-6	2.19E-6	9E-6
^{136}Cs	1E-8	8.76E-5	2.92E-5	2.19E-5	9E-5
^{137}Cs	2E-9	1.75E-5	5.84E-6	4.38E-6	2E-5
^{140}Ba	4E-9	3.50E-5	1.17E-5	8.76E-6	3E-5
^{140}La	5E-9	4.38E-5	1.46E-5	1.10E-5	2E-5
^{144}Ce	3E-10	2.63E-6	8.76E-7	6.57E-7	1E-5
^{239}Pu	6E-14	5.26E-10	1.75E-10	1.31E-10	5E-6
^{241}Pu	3E-12	2.63E-7	8.76E-9	6.57E-9	2E-4
^{241}Am	2E-13	1.75E-9	5.84E-10	4.38E-10	4E-6

*Limits shown for soluble forms, from 10CFR20, Appendix B, Table II (NRC, 1981).

TABLE 10: NRC Limits for Ground Surface Contamination		
Radionuclides	Mean Surface Contamination Limited for an area not to exceed one m^2 (disintegrations/min)	Mean Surface Contamination Limit (Curies/m^2)
natural U, ^{238}U, ^{238}U, and associated decay products	5,000	1.35E-7
transuranics ^{226}Ra, ^{228}Ra, ^{230}Th, ^{228}Th, ^{231}Pa, ^{237}Ac, ^{239}Pu, ^{241}Pu, ^{125}I, ^{129}I	100	2.70E-9
Thorium (natural) ^{232}Th, ^{90}Sr, ^{223}Ra, ^{224}Ra, ^{232}U, ^{126}I, ^{131}I, ^{133}I	1,000	2.70E-8
β/γ nuclides with decay modes other than alpha except for above nuclides) (^{137}Cs, ^{134}Cs, ^{196}Ru, ^{91}Y, ^{144}Ce	5,000	1.35E-7

In the event these limits are exceeded, emergency evacuation procedures may be in order. Decontamination to levels below these limits is likewise desirable before rehabitation. Therefore, determination of the need for evacuation and decontamination is reduced to determining whether these limits are exceeded.

In the event evacuation is indicated, an evacuation plan is necessary. The U.S. General Accounting Office has concluded (1979) that such plans cannot work unless they are not only in place, but actually practiced; and that the military could and should cooperate more fully in implementing such plans (GAO, 1987).

In the event that decontamination is indicated prior to rehabitation, the main considerations are the time required to achieve the decontamination, and the corresponding expense. A significant fraction of the expense is the "indirect" effect of lost economic activity pending decontamination and rehabitation.

WASH-1400 gives methodology for calculating decontamination costs, but this represents the most uncertain facet of the document. In the absence of experience decontaminating an area, the costs are difficult to estimate with any accuracy. A recent study by the U.S. General Accounting Office (1986) indicates that the cost of cleaning up a "severe" reactor accident in a semi-rural area would range from 1-15 billion dollars U.S., and could reach 150 billion in extreme circumstances. It is safe to guess that a "severe" accident in a densely-populated urban area—i.e., one that significantly exceeds established limits—would take weeks to months to clean up and would cost many billions of dollars.

In the U.S. the recently-revised Price-Anderson act limits industry liability to 7 billion dollars—a fraction of these costs. Who would pay the balance, and how, is not explicitly discussed. In some cases it seems possible that decontamination of a severely contaminated urban area would be financially implausible, i.e., the cost of decontamination would exceed the real market value of the contaminated property. The practical alternative would be abandonment of the contaminated area.

9. *Probability of the Modeled Accidents*

This is the area of greatest uncertainty and most controversy. One approach to probability analysis, as adopted by the NRC and promulgated in WASH-1400 for nuclear reactor accidents, is to fractionate accident sequences into their sequential components, calculate the independent probabilities of these components, and then multiply the fractional probabilities together to obtain the probability of the accident. With this approach probabilities on the order of 10^5–10^6 per rector year have been calculated (i.e., 1/100,000-1/1,000,000). This approach appears logical from a physical engineering viewpoint, but herein lies its weakness as well. What it fails to deal with adequately is first, the interdependence of a complex physical system; and second and related, the human factor.

With regard to interdependence, the probabilities of failure of specific components (e.g., a valve, a heat exchanger, etc.) are often computed separately, as if they were independent events. But in fact they are components of a *system*, and their probabilities of failure are not unrelated. Failure of a heat exchanger, for example, may alter the conditional probability of a valve failure, and under extreme circumstances even increase it to certainty (1.0). In this case the probability of the entire accident may be significantly higher than the product of fractional probabilities.

With regard to the human factor, intervention by a human operator has the effect of strengthening conditional probability linkages of the kind discussed above. Human intervention also adds a highly variable unpredictable element to probability calculations—one that is often (but not always) omitted from engineering calculations. The two most important nuclear accidents, TMI and Chernobyl, were both caused largely (TMI) or entirely (Chernobyl) by unforeseeable human error.

For these reasons, accident probabilities computed from physical and engineering principles are uncertain. A perhaps more reliable but also problematical indicator is empirical, based on actual accident history. The most recent probability figure for a severe nuclear power reactor accident is 7×10^{-4} per reactor year of operation (7/10,000), significantly higher than calculated probabilities. As the nuclear industry matures, this probability may decline (with better safety standards) or increase (with aging components).

Probabilities become especially difficult to estimate empirically in the absence of an accident history. An example is spent nuclear fuel transportation, which is still infrequent but projected to rise exponentially through the coming decades to a much higher plateau. There is little choice but to attempt probability estimates for each individual case considered, in the knowledge that these will certainly be wrong, perhaps by orders of magnitude.

Probabilities become especially difficult to calculate in the case of military accidents, because the accident history is classified and so also is information on which the probability of component failure could be based. Unless this information is made available to the public by the military, accident probability cannot be assessed, and hence the risk to the public (probability × consequences) is incalculable.

APPENDIX II: SAMPLE CALCULATIONS

The following calculations illustrate the application of the methodology outlined in Appendix I to the present study. In each case the answers given may be confirmed against the corresponding values graphed in the appropriate figures within the text, as indicated next to each of the following calculations where relevant. The spatial interval chosen for these calculations is 11, approximately equivalent to the Wall Street area of Manhattan.

A. Calculation of Plume Width

Plume width is defined as $3\sigma_y$. The distribution parameter σ_y is calculated according to the Briggs equations presented in Table 3 (Appendix I). To this value, the assumed width of the release structure is then added. Calculations are as follows, for atmospheric stability class F and spatial interval 11 (midpoint 11,000 m from the source).

$$\sigma_y = 0.04x(1 + 0.0001x)^{-1/2}$$

$$= \frac{(0.04)(11{,}000)}{\sqrt{1 + (0.0001)(11{,}000)}}$$

$$= \frac{440}{\sqrt{2.1}}$$

$$\sigma_y = 303.63 \text{ m}$$

$$3\sigma_y = 910.89 \text{ m}$$

assumed width of release structure = 10 m

$\therefore$ plume width = 910.89 + 10 = 920.89 m

(graphed in FIGURE 6 of the text, p. 28, interval 11, class F).

B. Calculation of Release Rate (Q)

The initial inventory for the nuclear warhead incineration accident is taken at 5 kg of plutonium-239. One kg of ^{239}Pu contains 62.3 Curies. Therefore 5 kg = 311.5 Ci. Given a presumed fire duration of 3 hr,

$$Q = \frac{311.5\ \text{Ci}}{(3\ \text{hr})(3600\ \frac{\text{sec}}{\text{hr}})}$$

$$= \frac{311.5\ \text{Ci}}{10{,}800\ \text{sec}}$$

$$= 0.0288\text{Ci/sec}$$

C. Calculation of Downwind Air Concentration with 100 m Thermal Lofting

Equation 10 of Appendix I is used, modified for thermal lofting as shown in equation 3 of Appendix I. The equation is

$$\chi_{(x,y,0;H)} = \left\{ \frac{0.8Q\frac{Q_x'}{Q_0'}}{\pi\sigma_y\sigma_z u} \right\} \left\{ e^{[-\frac{1}{2}(\frac{H}{\sigma_z})^2]} \right\}$$

The first step is to calculate or assume values for the individual parameters of the equation. These are as follows, for spatial interval 7, stability class F.

Assumed or given:

$\pi = 3.1416$

$u = 1$ m/sec

$Q_x'/Q_0' = 0.98$ (measured from Fig. 20)

Calculated

$$Q = 0.0288 \text{ Ci/sec (Calculation B above)}$$

$$\sigma_y = 303.63 \text{ (Calculation A above)}$$

$$\sigma_z = 0.016x(1 + 0.0003x)^{-1} \quad \text{(from Table 3, Appendix I)}$$

Calculating σ_z:

$$\sigma_z = \frac{0.016(11{,}000)}{1 + (0.0003)(11{,}000)}$$

$$= \frac{176}{4.3}$$

$$\sigma_z = 40.93 \text{ m}$$

Calculating χ:

$$\chi_{11{,}000,y,0,100m} = \left\{ \frac{(0.8)(0.0288)(0.98)}{(3.1416)(303.63)(40.93)(1)} \right\} \left\{ e^{-0.5\left[\frac{100}{40.93)}\right]^2} \right\}^*$$

$$\chi = (5.78E - 7)(5.07E - 2)$$

$$\chi = 2.93E - 8 \frac{Ci}{m^3}$$

(graphed in FIGURE 8 A of text, p. 32, interval 11).

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*Note: Exponents of this general form are evaluated conveniently in Turner's *Workbook of Atmospheric Dispersion*, appendix 3, to which the reader is referred (see Bibliography).

D. Calculation of Downwind Air Concentration with No Thermal Lofting

Equation 10 of Appendix I is used. For spatial interval 11, the equation is

$$\chi_{(11{,}000\text{m},y,0;0)} = \frac{0.8Q\dfrac{Q_x'}{Q_0'}}{\pi\sigma_y\sigma_z u}$$

The required parameters are given in calculation 3 above, except for Q_x'/Q_0', which is derived for H = 0 from Table 4 of Appendix I as 0.013.

$$\therefore \chi_{(11{,}000\text{m},y,0;0)} = \frac{(0.8)(0.0288)(0.013)}{(3.1416)(303.63)(40.93)}$$

$$\chi = 7.67\text{E}{-9}\ \frac{\text{Ci}}{\text{m}^3}$$

(graphed in upper curve of FIGURE 8, A of text, p. 32).

E. Calculation of Ground Deposition

Equation 14 of Appendix I is used,

$$SD_j = \frac{[(Q_x'/Q_0')_i - (Q_x'/Q_0')_j](ST)}{A_j}$$

The quantities indicated in this equation are as follows. ST (source term) for an accident involving incineration of a single nuclear warhead is 311.5 Ci, as developed in calculation B above. Assuming a thermal lofting to 100 m above the substrate, Q_x'/Q_0' values are taken directly from FIGURE 20 of Appendix I (p. 82). For interval 11, and stability class F, Q_x'/Q_0' = 0.98. For interval 10 (i = 10 in the above equation), Q_x'/Q_0' = 1.00. The area beneath the plume for spatial interval 11 is approximated as the width of the plume at the interval midpoint (= 920.89 m; calculation A above) times the length of the spatial interval (= 1,000 m) or 9.21E5 m^2. Hence

$$SD_{11} = \frac{(1.00\text{–}0.98)311.5}{9.21E5}$$

$$= 6.76E\text{–}6 \text{ Ci/m}^2$$

(graphed in upper curve of FIGURE 10, B, p. 36 of text).

F. Calculation of Inhalation Exposure

The radiation dose from inhalation of radionuclides in air is determined by finding the quantity of the radionuclide inhaled (assuming a breathing rate of 1 cubic meter of air per hour for adults) and multiplying by the appropriate dose conversion factor (as given in Table 7 of Appendix I). Thus, for the warhead incineration accident scenario analyzed here, spatial interval 11, atmospheric stability class F, effective H = 100 m, the air concentration of plutonium-239 is given in calculation C above as 2.93E-8 Ci/m^3. The total number of Curies inhaled is therefore

$$\left(2.93E\text{–}8 \frac{\text{Ci}}{\text{m}^3}\right)\left(1 \frac{\text{m}^3}{\text{hr}}\right)$$

$$= 2.93E\text{–}8 \text{ Ci/hr}$$

The dose conversion factor for plutonium-239 is given in Table 7 of Appendix I as 0.0820E8 Rem/Ci inhaled. Therefore the exposure per hour of an individual is

$$\left(0.820E8 \frac{\text{Rem}}{\text{Ci}}\right)(2.93E\text{–}8 \text{ Ci})$$

$$= 2.40E0 \text{ Rem/hr}$$

(graphed in lower curve of FIGURE 12, B, p. 40 of text, interval 11).

G. Calculation of Casualties

Casualties from latent cancers are calculated by first determining the total number of person-rems received by the population in a particular spatial interval. This is determined by multiplying the population by the total exposure in Rem from all sources (equation 16 of Appendix I). For the nuclear warhead accident scenario, cloudshine and groundshine are taken as 0. Therefore, the total exposure for all sources, PR, is equal to the inhalation exposure alone. For spatial interval 11, atmospheric stability class F, effective H = 100 m, the inhalation exposure per hour is given above as 2.40EO Rem (calculation F). The total population within spatial interval 11, given by equation 15 of Appendix I, is P = DA. For spatial interval 11, U.S. census data indicate that the population density (averaged for all Manhattan) is 25,057.6 persons per square kilometer. The workforce population is twice this value, or 50,115.2 persons per square kilometer. For the case under consideration, plume width is 920.89 m (calculation A above). The area under the plume, therefor is,

$$A = (920.89\ \text{m})(1{,}000\ \text{m}) = 9.21\text{E}5\ \text{m}^2 = 0.921\ \text{km}^2$$

The total population at risk, therefore,

$$= P = DA = \left[50{,}115.2 \frac{\text{persons}}{\text{km}^2}\right](0.921\ \text{km}^2)$$

$$= 46{,}156\text{persons}$$

The total person-rems, therefore, is given by

$$(46{,}156\ \text{persons})\left[2.40\text{E}0\ \frac{\text{Rem}}{\text{hr}}\right]\ \text{hr})$$

$$= 3.33\text{E}5\ \text{person–rem}$$

Casualties are (Latent Cancer Fatalities or LCFs) obtained by dividing this value by the risk factor (cancers/person-rem). The risk factors employed in this study are 1 LCF/10,000 person-rem, and 1 LCF/235 person-rem. Casualties, therefore, are as follows for spatial interval 11, atmospheric stability class F, 100 m loft;

$$(3.33\text{E}5 \text{ person-rem})\left[\frac{1 \text{ LCF}}{10{,}000 \text{ person-rem}}\right] = 33 \text{ LCFs (low risk factor)}$$

(shown in the histogram of FIGURE 18, A, p. 47 of text) and

$$(3.33\text{E}5 \text{ person-rem})\left[\frac{1 \text{ LCF}}{235 \text{ person-rem}}\right] = 1{,}420 \text{ LCFs (high risk factor)}$$

(shown in the histogram of FIGURE 18, B, p. 47 of text).