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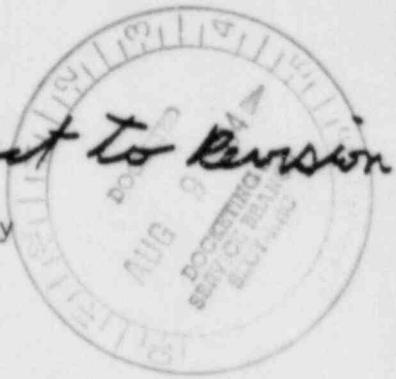

Potential Contamination of Surface Water Supplies by Atmospheric Releases from Nuclear Plants

by Richard B. Codell*

Abstract

Atmospheric releases of radionuclides, which might result from severe accidents at nuclear power plants, have the potential for contaminating drinking water supplies. The probability and consequences of the contamination of a water supply for a large city is explored using the Indian Point Nuclear Station and New York City as an example. Techniques are developed to calculate the deposition of radionuclides onto the watersheds of the New York City reservoirs, and the extent to which the runoff from the watersheds would contaminate drinking water. It is possible to demonstrate that the supplies could be contaminated above 10 CFR Part 20 drinking water limits and that population doses on the order of millions of man-rems could result from severe accidents. The relative risk of this pathway, however, would be small compared to other airborne pathway risks calculated for the same accidental release.

Introduction

For several decades, the Nuclear Regulatory Commission has been conducting analyses of the risk and consequences of hypothetical severe accidents at nuclear power plants (BR57, US75, US78, NI81). The dispersion of atmospheric radioactive releases has been the primary focus for consequence modeling, but releases of radionuclides directly to groundwater and surface water has also been explored (US75, US78, NI81).

There are circumstances where the contamination of water supplies by atmospheric fallout resulting from nuclear accidents would be of great interest for the sake of comparing risks of different postulated events. Two such cases

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are accidents at sites located beside the Great Lakes, and sites adjacent to watersheds supplying drinking water for distant cities. Other situations might also qualify but are not discussed in this paper.

Atmospheric contamination of the Great Lakes from adjacent power plant sites was considered to be potentially important because the waters are fresh, highly productive and heavily used, bioaccumulation factors for many radionuclides would be high, and the residence times in the lakes are long, from years to hundreds of years. In addition the lakes cover a large portion of the watershed, so direct deposition to the water surface would be relatively more important than for rivers, which occupy only a small fraction of the watershed area.

The NRC staff performed a study of the potential contamination of the Great Lakes from a hypothetical accident at the Fermi Nuclear Power Plant, Unit 2 (US82). Concentrations of radionuclides in the lakes were calculated with a simple model by determining the fallout from a severe airborne release directly to the water surface using the CRAC risk assessment computer program (US75) and considering the volume and flow rate through the lakes. The staff concluded that the risks from contamination of the water were small relative to the risks calculated from other direct airborne pathways, so the study was not refined further.

The second case considered was the Indian Point Nuclear Plant Units 2 and 3, located adjacent to the Hudson River near Buchanan, New York. As part of a public hearing on reactor safety, a detailed analysis of liquid pathway risks was conducted (US83a). This analysis dealt with the potential contamination of the Hudson River by a core melt accident releasing radioactive material through the ground, and also with the contamination of surface water, especially public drinking water supplies, by atmospheric releases. The remainder of this paper will describe the calculation procedures and results of the hypothetical atmospheric contamination of surface water applied to the Indian Point case as an example.

The NRC staff and the Indian Point licensees conducted detailed reviews of the safety of the Indian Point Nuclear Plant Units 1 and 2, and conducted extensive public hearings on this subject (US83a).

Part of the staff's analysis dealt with the risk to the general public from large atmospheric releases. The CRAC computer program (US75) was used to evaluate the risk from a range of atmospheric releases caused by severe accidents at the plants. Simply stated, the CRAC program calculates the doses to individuals in the affected population from exposure to the airborne plume of radionuclides released from the plant, and from contaminated ground and foodstuffs once the plume has passed. Plume dispersion and the deposition rate from the plume to the terrestrial environment depend strongly on the meteorological phenomena at the time which the release is occurring. The CRAC model therefore assumes that the accident can occur at any time within a one year period. A set of runs are made, based typically on about 90 arbitrary accident starting times within the 1-year period. The results are then presented probabilistically assuming that the 90 cases represent a statistically meaningful sample of all possible meteorological data. The potential atmospheric contamination of surface water was based on the depositions of radionuclides calculated by the CRAC analysis.

Liquid Pathway Contamination

The liquid pathways are routes by which people can be exposed to radiation released by a nuclear power plant via surface and groundwater. Exposures involving surface water can come from drinking or swimming in contaminated water, direct radiation from contaminated shoreline sediments, and ingestion of contaminated seafood. Potable groundwater can also be contaminated. In addition, radionuclides released to groundwater can migrate to surface water.

There are three possible ways in which radionuclides could be released to the hydrosphere as a result of accidents at nuclear power plants (US78):

1. Direct release to surface water - some relatively small accidental releases could occur through faulty routing of radionuclide streams through the circulating water system, the service water system, or the storm drainage system. Accidents of this type do not involve releases approaching the severity of core-melt accident releases, and would not be significant contributors to risk. Releases of radionuclides from core-melt accidents directly to surface water, while possible, would be much less likely than other liquid pathways and are not expected to be significant contributors to risk.

2. Releases to the ground - core-melt accidents involving basemat penetration could release radionuclides to the ground in the form of core debris, or in some cases, highly contaminated water from inside the containment building. Such releases could affect groundwater supplies or could migrate to surface water. Engineering measures to intercept contaminated groundwater before it could reach users are possible, and could be implemented providing that the travel time of the contaminated groundwater were sufficiently long (HA82a, HA82b).

3. Airborne releases - some core-melt accidents could release radionuclides to the air in the form of gases or aerosols. A portion of these radionuclides would be deposited on the land and water surface by such natural processes as settling and rainfall. A fraction of the radionuclides would fall directly on water surfaces. The rest would fall on land, but a portion of that could be carried to surface water by rainfall runoff or after first infiltrating to ground water.

In general, it is safe to say that the liquid pathways are less important than the airborne pathways in terms of <u>acute</u> hazard to the public. The immediate consequences from airborne exposure pathways would be difficult to avoid except by prompt evacuation of the affected population because radioactive gases and particulates would be carried at the speed of the wind, and could reach people in a matter of minutes to hours after release. There would generally be much longer delays associated with the liquid pathway, which would allow time for the monitoring, avoidance, and interdiction of the contaminated water.

It is not likely, therefore, that waterborne radionuclides would pose a risk in terms of early fatalities or even early illness because the concentrations would be below the threshold levels necessary to cause immediate health effects, and could be interdicted at any level deemed necessary. It is much more likely that contamination of the liquid pathway would cause economic losses because of cleanup and treatment costs and temporary loss of the use of affected water. There could be latent health effects caused by the accumulation of low-level doses, at or below protective actions levels.

In the Indian Point case, the direct airborne contamination of the liquid pathway appears to be more important than groundwater contamination for a number of reasons (US83):

1. The probability of a large release of contaminated water to the ground, coupled with a groundwater travel time too short to allow interception of the source, would be extremely small.

2. Once radionuclides were released to the atmosphere, they could not be effectively interdicted until they had fallen on land or water.

3. While groundwater releases would affect only the Hudson River, with little chance of contaminating drinking water supplies, airborne releases might affect surface fresh water resources over a wide area, especially drinking water sources for the heavily populated northeastern states including New York City. Airborne releases might also affect groundwater resources, but to much lower levels of contamination than surface water because of the delay and filtration associated with atmospheric water infiltration to groundwater.

An initial screening analysis with the CRAC code showed that, following an accidental release and if the wind were blowing in the proper direction, greater than half of the cesium and strontium released could be deposited onto the watershed of the Hudson River and the upper Delaware River, which contain the reservoirs serving the New York City area with drinking water. Radionuclides could also accumulate in fresh-water fish of these reservoirs and potentially contribute to individual and population doses.

Winds blowing in a more westerly direction would carry the plume toward other major drainages such as the Delaware River and Susquehanna River basins, which service the water supplies for several large cities. A wind blowing to the northeast or east could affect the water supplies of the Housatonic and Connecticut Rivers and other rivers in New England. A wind to the southeast could potentially affect the groundwater resources of Long Island as a result of the infiltration of deposited radionuclides, but it is likely that groundwater would not be as seriously affected by atmospheric fallout as would surface water, because many of the radionuclides would be effectively trapped by the soil overlying the aquifer. It should be recognized that the wind direction for maximum consequences through the liquid pathway does not necessarily correspond to the direction for maximum consequences for the (traditional) airborne pathway, so it would be incorrect to simply add the risks for both pathways.

Calculations to quantify the risk associated with an accidental contamination of the New York City water supply system from an airborne release of radionuclides at Indian Point were performed. Detailed calculations have been restricted to this water supply system primarily because good quality data were available, and the system represents the most heavily used and vulnerable water supply in the region which could be affected by an accidental airborne release at Indian Point. Later, the New York system consequences will be extrapolated to include other supplies as well.

Description of New York City Water Supply

New York City and several surrounding communities to the north and northwest are supplied with drinking water by a system of reservoirs and aqueducts. The watersheds of these reservoirs are shown in Fig. 1. The water supply is supplemented with minor amounts of groundwater (NE82). There is also a rarely used intake on the Hudson River at Chelsea, NY, which is about 20 miles upstream of Indian Point. There are three main aqueducts bringing water to New York City from areas over 100 miles from downtown Manhattan. The Croton system consists of coupled reservoirs in the watershed to the east of Indian Point. It supplies an average of 4.6×10^5 m^3/day to New York City. Although the Croton system is the smallest of the three major aqueduct systems, it is also the closest to the Indian Point plants, and is therefore most vulnerable to atmospheric contamination.

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Figure 1 Watersheds in New York City Municipal Supply System
From (NE82)

The Catskill system consists of Schoharie and Ashokan reservoirs to the north-northwest of the site. Water from this system is conveyed to New York City via the Catskill aqueduct, which supplies an average of 1.6×10^5 m^3/day.

The Delaware system consists of Cannonville, Neversink, Pepacton, and Rondout reservoirs, to the northwest of the site. An average of 3.1×10^6 m^3/day are conveyed to New York City via the Delaware aqueduct. The Delaware system is the largest, but is also the farthest from the site.

Much smaller amounts of water are supplied to public and private systems of the metropolitan area by wells in Richmond, Queens, and Long Island. The Chelsea intake on the Hudson River is capable of supplying 3.8×10^5 m^3/day to the Delaware aqueduct, but is presently not in use. There is also a minor amount of surface water supplied from the Bronx River watershed.

Once the aqueducts reach New York City, water is distributed by means of a complicated, interconnected system of holding reservoirs and underground tunnels.

Screening of Risk Factors for Atmospheric Contamination of Surface Water

Several screening analyses were performed in order to determine the factors most important to risk and to simplify the analysis. Only one of the accidental source terms, Release Category C (RC-C), was evaluated in this study because it was determined by an initial screening that this release had the highest product of probability and atmospheric pathway consequences (i.e., risk) of any of the accidents considered (US83a). Combining the probabilities and consequences of the nine release events studied by the NRC staff and the licensees led to the conclusion that the RC-C event alone would account for greater than 90 percent of the airborne/liquid pathway risk. The RC-C case considered would release 1.29×10^5 Ci of ^{90}Sr, 2.41×10^6 Ci of ^{134}Cs, 1.51×10^6 Ci of ^{137}Cs, as well as substantial amounts of other radionuclides.

The risk analysis is further restricted to the radionuclide ^{90}Sr in drinking water only. Measurements of New York City tap water (HE76) indicate that the

ratio of ^{137}Cs to ^{90}Sr is only about 10 percent, even though there is about 50 percent more ^{137}Cs in fallout than ^{90}Sr and the half-lives are about equal. A screening analysis using the population dose models and coefficients of U.S. Nuclear Regulatory Commission Regulatory Guide 1.109 (US77), which considered the potential quantities of each radionuclide released to the atmosphere from the RC-C event, its half-life, dose factor, and the relative ease at which it would be transported from the land surface to water led to the conclusion that for drinking water, ^{90}Sr alone would be responsible for about 80 to 90 percent of the long-term whole body dose. Neglecting all other radionuclides, therefore, would lead to only a small error in the drinking water dose estimates.

On the basis of another approximate analysis, drinking water contamination would contribute an overwhelmingly larger population dose than other liquid pathways which could be contaminated by airborne releases from Indian Point. This analysis was based on recreational fish catch statistics for most of eastern New York State (KR81), and assumed that these fish would be exposed to ^{90}Sr and ^{137}Cs concentrations calculated for the New York City water system. Only freshwater fish were considered, because bioaccumulation for freshwater fish is markedly higher than for saltwater fish, and the highest water concentrations would be expected in inland fresh waters. Neglecting saltwater fish and shellfish is not expected to alter the conclusions. Additionally, it is likely that the fisheries' estimate is conservative because experience with the Three Mile Island accident shows that recreational fishing diminishes dramatically for the period of concern (HI79). Even if the fish catch has been substantially overestimated in this calculation, the population dose attributable to fish ingestion would be relatively small, probably less than one percent of that from drinking water.

Development of Water Concentration Model

An empirical model relating the concentrations of ^{90}Sr in New York City water to the quantity of radionuclides deposited on the land surface was developed using published data on radioactive fallout deposition and tap water concentrations in New York City (NE82). This study was restricted to ^{90}Sr on the basis of previously discussed sensitivity studies.

Fallout of radionuclides from atmospheric nuclear weapons testing has provided an invaluable tracer for the hydrologic cycle. Radionuclides deposited on land, particularly strontium and cesium isotopes, have been used to trace the transport of soil, water, and groundwater in many watersheds (NG73, KA74, RI78). Studies with these tracers indicate that the transport of radionuclides from land to water depends on several factors such as the chemical attraction of the radionuclide for the soil, the type of soil, the slope of the land surface, and the rate of rain or snow fall. Empirical relationships for transport of dissolved or soil-bound radionuclides from watersheds to surface water bodies have been derived (ME74). A comprehensive review of runoff models for fallout can be found in Helton et al. (HE84).

A model for relating the concentration of ^{90}Sr in tap water to the rate of deposition of ^{90}Sr onto the watersheds of the supply reservoirs was derived from records of ^{90}Sr and ^{137}Cs in atmospheric fallout and New York City tap water. Published data on monthly atmospheric fallout from nuclear weapons testing programs was available from several stations in the region (HE76). It was determined that variations from station to station were not great, and that the monthly fallout data from New York City would be representative of the affected region.

The regional correlations relating fallout of ^{90}Sr to surface water concentrations compiled by Menzel (ME74) were first used in order to predict New York City tap water concentrations, but the agreement was not satisfactory. Instead a phenomenological concentration model was developed from considerations of physical phenomena and adjusted to give the best match between predicted and observed monthly tap water concentration for the observed fallout rate at the New York City measuring station (HE76).

In order to develop a tractable model, it was assumed that the fallout is uniform over the entire watershed. It is also assumed that the reported measurements of ^{90}Sr concentration in tap water (HE76) were representative of all water supplies in the New York City area, even though different parts of the region are served by separate systems and including some groundwater (NE82).

Transport of ^{90}Sr from the atmosphere to the surface water is caused by several mechanisms (KA74):

1. Direct deposition from atmosphere to water surface,

2. Runoff from the land surface during periods of heavy rain, either dissolved or attached to sediment,

3. Infiltration to various strata of groundwater, with subsequent transport to surface water.

Pathway 1 is the fastest. Transport along this pathway depends on surface area of open water bodies in the watershed and the rate of fallout.

Pathway 2 is slower than pathway 1. Transport along this pathway depends on the physical and chemical properties of the soil, the topography of the land, and the amount and intensity of rain. Transport is proportional to land surface area, rate of fallout, and quantity of accumulated fallout on the land.

Pathway 3 is the slowest. Transport along this pathway depends on, among other things, the chemical and physical properties of the soil, the rate of infiltration of water, the rate of fallout, and the accumulated fallout on land. The relatively slow transport along this pathway is important because it accounts for an effective loss of available ^{90}Sr by radioactive decay before it can reach surface water.

The present model attempts to take these known phenomena into account by empirically considering the rate of fallout, the accumulation of fallout on land, and the loss of available radionuclide from the land by radioactive decay, runoff, erosion, and groundwater transport or other phenomena. Implicit in the model is any mechanism which might have removed the radionuclide before reaching the water taps, such as sediment scavenging enroute or water treatment.

Two equations describe the accumulation of available ^{90}Sr on land and the concentration in tap water:

$$\frac{dM}{dt} = AR\,(1-k_1) - (\lambda_1 + \lambda_2)\,M \qquad (1)$$

$$C = k_2\,AR + Mk_3 \qquad (2)$$

where

M is the accumulated ^{90}Sr on land in the watershed, which is available for transport to surface water, curies

C is the tap water concentration, curies/liter

A is the area of the watershed, m^2

R is the rate of fallout, curies/(yr-m^2)

k_1 is the fraction of the affected watershed covered by open water

k_2 is the coefficient relating the rate of fallout to surface water concentration yr/liter

k_3 is the coefficient relating available accumulated fallout on land to surface water concentration, $liter^{-1}$

λ_1 is the radiological decay rate, yr^{-1}

λ_2 is the effective loss of available fallout from land due to all causes other than radiological, yr^{-1}

Beginning with reasonable estimates based on physical measurements, values of coefficients for the model were manually adjusted to give the best fit to the observed New York City tap water concentrations. The values of the coefficients chosen are given in Table 1. The measured and predicted annual average concentration of ^{90}Sr in New York City tap water is shown in Fig. 2. The model gives an acceptable fit for the purposes of this study, and is considerably better for this case than the regional correlation of Menzel (ME74).

Table 1 - Coefficients of phenomenological concentration model for ^{90}Sr

$k_1 = 0.06373$
$k_2 = 7.347 \times 10^{-16}$ yr/liter
$k_3 = 3.305 \times 10^{-16}$ $liter^{-1}$
$A = 4.57 \times 10^{10}$ m^2
$\lambda_1 = 0.0239/yr$
$\lambda_2 = 0.0822/yr$

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Figure 2 Phenomenological model predictions of New York City tap water ^{90}Sr concentrations

Watershed Model

Deposition rates of ^{90}Sr from the CRAC analyses, watershed dimensions, distance from the site, and wind direction probability are used in the Watershed Model to predict the cumulative frequency distribution of ^{90}Sr deposition on the watersheds of the Croton, Catskill, and Delaware systems either separately or combined. The average ^{90}Sr deposition in each watershed is then used to calculate the cumulative distribution function (CDF) for the concentrations in the New York City tap water using relationships derived from the Phenomenological Concentration Model.

Figure 3 is used to describe the calculational procedure. Output from the CRAC program is in the form of a table of radionuclide depositions and plume widths as a function of radial distance from the site, R meters for plumes generated at each of the N trials or starting times (usually, N=91 trials). For each plume, the deposition, D Ci/m^2, is assumed to be a function of radial distance from the site R within the boundaries of the plume, S=± W/2 meters, and zero outside of these boundaries (commonly called a "top hat" distribution). The term W is the 3 standard deviation (3σ) width of the assumed gaussian plume.

The watershed area is represented by a set of n points x_i, y_i (i = 1 to 6 in the present example shown in Fig. 3). The plume can be blowing in a limited number of incremental directions θ_k. For the j^{th} plume (trial) and the k^{th} plume direction, the deposition at point i is determined by the equation:

$$D_{i,j,k} = D(R) \qquad \text{for } S \leq W/2$$
$$D_{i,j,k} = 0 \qquad \text{for } S \geq W/2 \tag{3}$$

where R is the projected radial distance of point x_i, y_i on the plume centerline at angle θ, and can be expressed:

$$R(x,y,\theta) = \sqrt{x'^2 + y'^2} \tag{4}$$

where

$$x' = (y_i \tan \theta_k + x_i)/(\tan^2 \theta_k + 1) \tag{5}$$
$$y' = x' \tan \theta_k \tag{6}$$

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Figure 3 Watershed Model

The point x_i, y_i is determined to be either inside or outside of the plume by determining its distance from the centerline:

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$$S(x_i, y_i, \theta) = \frac{x_i \tan \theta_k - y_i}{\sqrt{\tan^2 \theta_k + 1}} \tag{7}$$

The average deposition within the watershed for plume angle θ_k is calculated by taking the weighted average of $D_{i,j,k}$.

$$\overline{D_{j,k}} = \sum_{i=1}^{n} w_i D_{i,j,k} \tag{8}$$

where w_i is the weight given the i^{th} point. For example, if all of the 6 points in the present example were equally weighted, then, $w_i = 1/6$. The weights need not be equal, but must add up to unity. The incremental probability for the watershed deposition from the j^{th} plume and the k^{th} plume direction will be:

$$P_{jk} = \overline{D_{jk}} \frac{P_k}{N}, \tag{9}$$

where P_k is the probability that the wind is blowing in the k^{th} incremental direction.

The above procedure is performed by stepping through the angles $\theta_k = \theta_1$ to θ_2 which envelop the watershed, in increments of $\Delta\theta$. The increment $\Delta\theta$ is generally chosen to be about 1 to 5 degrees. The term P_k is defined as the probability that the wind blows between the directions $\theta = \theta_k \pm \Delta\theta/2$. The wind direction probability used in the Indian Point case is shown in Fig. 4.

After all N plumes have been evaluated, the watershed depositions $\overline{D_{jk}}$ are ranked from highest to lowest. A cumulative distribution function (CDF) for deposition is then calculated by summing the probabilities of the ranked deposition quantities. Figure 5 shows the CDF for the Croton watershed case, using the deposition rates for the Indian Point CRAC output. The Croton watershed was

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Figure 4 Wind direction probabilities for Indian Point

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Figure 5 ^{90}Sr deposition in Croton Watershed

represented by 30 points with equal weighting. The angular plume increment $\Delta\theta$ was 4.2 degrees, and there were 90 plume starting times (trials).

Tap water concentrations are calculated using coefficients derived from the phenomenological concentration model, using depositions calculated from the above procedure. The concentration model assumes that the released ^{90}Sr is instantaneously deposited on the watershed, and then is no longer deposited.

After the initial deposition, the tap water concentration for deposition $\overline{D_{jk}}$ at time t is

$$C_{jk} = \overline{D_{jk}}\ A\ k_3\ (1 - k_1)\ \exp\ (-(\lambda_1 + \lambda_2)t) \qquad (8)$$

where the coefficients of Eq. 8 are given in Table 1 for the Indian Point case.

The empirical tap water concentration model was derived from slowly varying data taken over long periods of time, and cannot be used to reliably calculate concentrations for times shorter than one year following the accident. For the case of an instantaneous deposition, the model would predict an infinite concentration. This, of course, would not really be the case because of long holdups of at least several months on the land, in the reservoirs, and in the distribution system. Furthermore, since the doses from ingestion of radionuclides in tap water would be well below threshold at which acute health effects or fatalities might be observed, concentrations can be used on an annual average basis for the purposes of calculating chronic dose commitments to individuals and populations.

The average tap water concentration for the first year can be derived from Eqs. 1 and 2:

$$\overline{C_{jk}} = \overline{D_{jk}}\ A(k_2 + k_3\ (\ 1 - k_1)\ (1 - \exp\ (-(\lambda_1 + \lambda_2)))/(\lambda_1 + \lambda_2)) \qquad (9)$$

Evaluation of Affected Waters

The CRAC code used for the analysis of risk for the traditional airborne pathway was slightly modified to store intermediate values of ground depositions of ^{90}Sr and plume widths versus distance for each of the 90 assumed starting times for the release category C case (RC-C). The intermediate stored data from the RC-C event were then used in the computer program described above which factored watershed dimensions, distance, and the wind direction probability to predict the cumulative frequency distribution (CDF) of ^{90}Sr deposition on the watersheds for the Croton, Catskill, and Delaware systems, either separately or combined. The ^{90}Sr deposition was then used to calculate the cumulative frequency distribution for New York City tap water concentrations using the phenomenological concentration model, from which dose estimates could be made.

Figure 6 shows the predicted tap water ^{90}Sr concentrations for the deposition in the Croton system shown in Fig. 5, and the cumulative probability that the concentration would not be exceeded. The higher curve is the annual average concentration for the first year following the postulated accident. The lower curve is the tap water concentration 5 years after the accident, which lends perspective to the degree of persistence of the contamination problem. Also shown on the figures is the 300 pCi/liter Maximum Permissible Concentration (MPC) for ^{90}Sr (US83b) for unrestricted areas, which is used here as a benchmark or standard of acceptability for drinking water, even though MPC pertains to normal rather than accidental releases. The calculations assume that no steps have been taken to reduce the concentration by such measures as further water treatment or dilution. Using the Croton system for an example, the figure shows that following the RC-C accidental release, there will be about an 11 percent probability that MPC would be exceeded for the first year average concentration, and a 5 percent probability that the concentration would still exceed MPC after 5 years. The concentrations for the Catskill and Delaware systems are not shown, but the probabilities of exceeding MPC for these systems would be less because of their greater distances from the reactors. The probability of exceeding MPC for the first year is about 2.1 percent and 0.8 percent for the Catskill and Delaware systems, respectively.

Figure 6 Predicted New York City tap water water ^{90}Sr concentration following the RC-C event (Cronton System)

Since the water supply for New York City is derived from all three watersheds, additional runs were performed. The first considered the Catskill and Delaware systems as one watershed, weighted by their relative contribution to the New York City supply. The second run considered the Delaware, Catskill, and Croton systems as one watershed, each weighted by its relative contribution.

The significance of the combined Delaware-Catskill run is twofold. First, the outflows of both the Delaware and Catskill aqueducts physically mix in Kensico Reservoir near White Plains, NY, and it is unlikely that either of the aqueducts could be isolated without a serious interruption of the water supply to New York City (NE82). Secondly, the combined flow from the system accounts for about 91 percent of the total New York City use. Figure 7 shows that there is about a 1.1 percent conditional probability of exceeding MPC for the first year for ^{90}Sr in the combined Catskill-Delaware system.

The combined Delaware Catskill, Croton run gives the weighted average tap water concentration for the entire system. This concentration is not shown, since the Croton aqueduct water is not physically mixed with water from the other two aqueducts before being distributed, and concentrations in the parts of the city served by different aqueducts would not necessarily be the same. The average concentration calculated from this run, however, was used to calculate population doses to affected users, but not individual doses.

Concentrations of ^{90}Sr in drinking water would be well below the levels necessary to cause prompt health effects or fatalities. For example, if no restrictions on drinking water were put into effect, and water with the highest calculated concentration for the Croton system were ingested for 1 year, the maximum individual dose commitment to an adult would be roughly 20 rems for bone and 5 rems for total body, using the ingestion dose factors of Regulatory Guide 1.109 (US77). The very large population served, however, would allow the accumulation of a large population dose, even at relatively low concentration levels, if no interdictive measures were taken.

Doses were calculated for an assumed population of 11 million people in New York City and other areas served, ingesting water for the first year following the accident, and also for ingesting water for an infinite period following the

Figure 7 Predicted New York City tap water ^{90}Sr concentration following the RC-C event (Combined Delaware-Catskill System)

accident. Population breakdowns, dose factors, and ingestion rates are those suggested in (US77). Figure 8 shows the whole body population doses versus cumulative probability following the RC-C accident scenario, which would be accumulated for a 1-year ingestion period following the accident. These doses use the concentrations calculated for the combined Delaware-Catskill-Croton system. The probability-weighted doses (i.e., risk) for this case, given the RC-C accident occurs, can be calculated by integrating under the curve of Fig. 8. The first year dose is 6.3×10^5 person-rems whole body. For the infinite ingestion period, the dose is 2.2×10^6 person-rems whole body. It is worth noting that about 53 percent of the risk is contributed by the Croton system, although this supply accounts for only about 9 percent of the water used in the total system.

The public water supplies other than New York City have not been studied in detail, but estimates of the total risk in person-rems per reactor year to all drinking water users following the RC-C airborne release have been made. The estimate is based on the following factors and assumptions:

1. Because of the proximity of the New York City reservoirs to the Indian Point site, there is not likely to be any surface water supply which could be more highly contaminated from an accident at Indian Point. Including all other surface supplies would, however, would raise the calculated probability of water contamination and thereby increase the risk.

2. Population and average radionuclide deposition rates were available to a 500-mile radius from the site. It was assumed that the ^{90}Sr deposition rate onto land applied to the sources of drinking water of the population at the same radius, and that the land-water transfer factors would be the same as those used in calculating the New York City tap water concentrations. This assumption neglects the fact that a significant portion of water is supplied from underground sources that would probably be less affected by an airborne release from the plant.

Using the above assumptions, it was estimated that the total risk within a radius of 500 miles of the facility, in terms of uninterdicted population dose

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Figure 8 Whole body population dose to users of New York City supply

from all affected public drinking water, would be a factor of 2 to 3 higher than that of New York City alone.

The probabilities of Release Category C for the Indian Point reactors with certain engineering fixes have been estimated to be 3.52×10^{-5}/year for Unit 2 and 1.76×10^{-5}/year for Unit 3 (US83a). Using the average population doses for all affected water and an infinite ingestion period presented above, the risks to the total affected population would be only 194 person-rems/reactor year whole body uninterdicted dose for Unit 2 and 97 person-rems/reactor year on Unit 3. These risks would be small compared to the risk from the direct airborne pathways, estimated to be 2610 and 1430 person-rems whole body for Units 2 and 3, respectively (US83a).

Most of the uncertainty in the CRAC analysis also applies to the airborne/liquid pathway analyses, but would not necessarily be expected to affect the results of the airborne and airborne/liquid pathway analyses in exactly the same way. The contamination of surface water depends only on the deposition of the radionuclides to the land surface, while the direct airborne pathways also include the effects of inhalation and immersion in the plume itself. Also, geographical regions important to the liquid pathway might be relatively unimportant to the direct airborne pathway and vice versa. The following aspects of the CRAC code would be especially important in the liquid pathway risk analyses:

1. The deposition rate model in CRAC accounts for only two rates, wet and dry deposition, and has no dependence on the rate of rainfall.

2. Wind direction is considered to be independent of other atmospheric phenomena such as stability and rainfall, when actually these variables are likely to be correlated. This might lead to a preferred direction for wet deposition fallout which would not be correctly predicted by CRAC.

3. CRAC uses only the meteorology at the Indian Point site, and at only one elevation, even for transport calculations at great distances from the site. The 10-meter wind direction data used in the CRAC analyses (Fig. 4) clearly show the effects of the steep banks of the Hudson River valley,

with the highest probability for winds upstream and downstream along the Hudson River. These wind directions "steer" the atmospheric plumes away from watersheds of the New York City water system. If wind direction data from the 122-meter level were used, the liquid/airborne pathway risk from the New York City water supply would increase by about 20 percent. Winds at that altitude are less influenced by the Hudson River valley than the low altitude winds and, therefore, might be more representative of the dispersion direction for large distances.

Conclusions

Several conclusions can be drawn from the results of the Indian Point study:

1. In the unlikely event of a large accidental release of radioactivity, liquid pathway doses would almost certainly be accumulated by individuals and populations at levels well below the threshold necessary for early fatalities or radiation illness. Population doses would probably be accumulated at very low levels, below protective action guidelines, but because of the large populations involved, could be on the order of millions of person-rems.

2. Unlike the direct exposure to the atmospheric plume (e.g., inhalation dose), contaminated water or seafood can be interdicted at any level necessary to limit dose. Normal water supplies could be disrupted, however, causing economic damage and major inconveniences.

3. Liquid pathway contamination caused by the atmospheric release of radionuclides is potentially more serious than liquid pathway contamination from radionuclides released to the ground in a basemat melt-through accident. There is a high probability that contaminated groundwater from basemat penetration could be isolated before reaching the Hudson River, but atmospheric release to the environment probably could not. Furthermore, even for potentially large groundwater pathway releases from the site, interdiction to prevent exposure to the public would be confined to the Hudson River. Low-level contamination of water supplies by an atmospheric release, however, would be more widespread and difficult to interdict.

4. Population doses and risks associated with the contamination of the liquid pathway by the groundwater or airborne route would be a small fraction of the population doses and risks which would be accumulated from the traditional airborne pathways.

5. The conclusions concerning the relative risk of airborne/liquid pathway contamination compared to the traditional airborne pathway risks would not be highly sensitive to the quantity of released radionuclides. The consequences for either pathway would increase proportionately to the increase in the quantity of radionuclides released if no mitigation were considered. Therefore, the relative risk of the airborne/liquid pathway to the traditional liquid pathway would remain about the same.

6. Wind directions tending to maximize the airborne/liquid pathway dose would not necessarily correspond to the direction maximizing the traditional airborne pathway dose. This fact implies that there could be circumstances where the direct contamination of high density urban areas would be avoided but the water supplies serving the areas would become contaminated.

The study of the potential for airborne contamination of the liquid pathway in the Indian Point case has been helpful in putting the problem in perspective. It was possible to generally conclude from the Indian Point (US83a) and Fermi (US82) studies that airborne contamination of fresh water is of relatively low importance to overall risk, and that this conclusion would probably hold for most other nuclear power plant sites. A recent paper by Helton et al. (HE84) reaches a similar conclusion for a variety of sites and accident scenarios.

Disclaimer

The contents of this paper are the sole opinions of the author and do not necessarily represent the official policy of the Nuclear Regulatory Commission.

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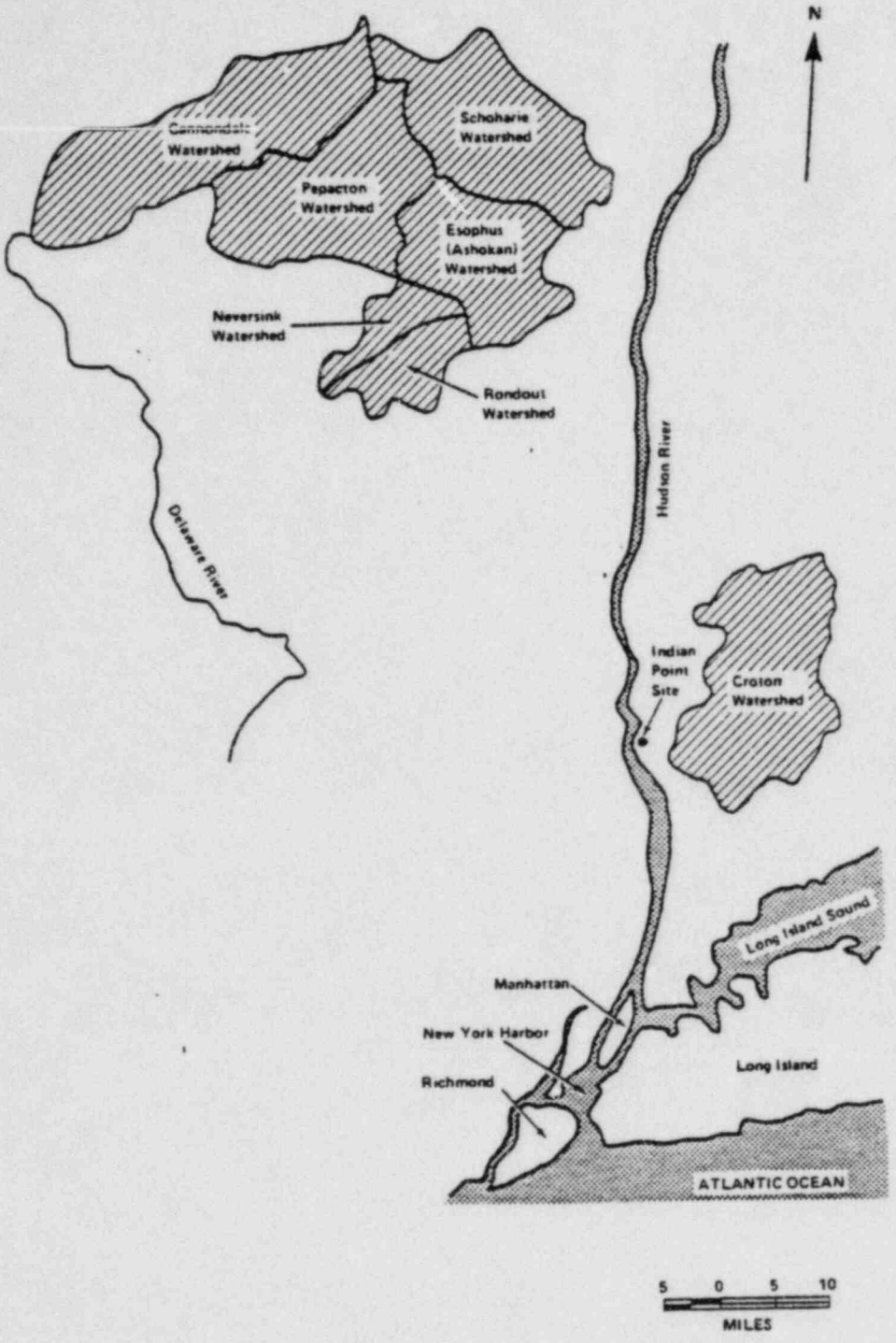

Figure 1

Figure 2

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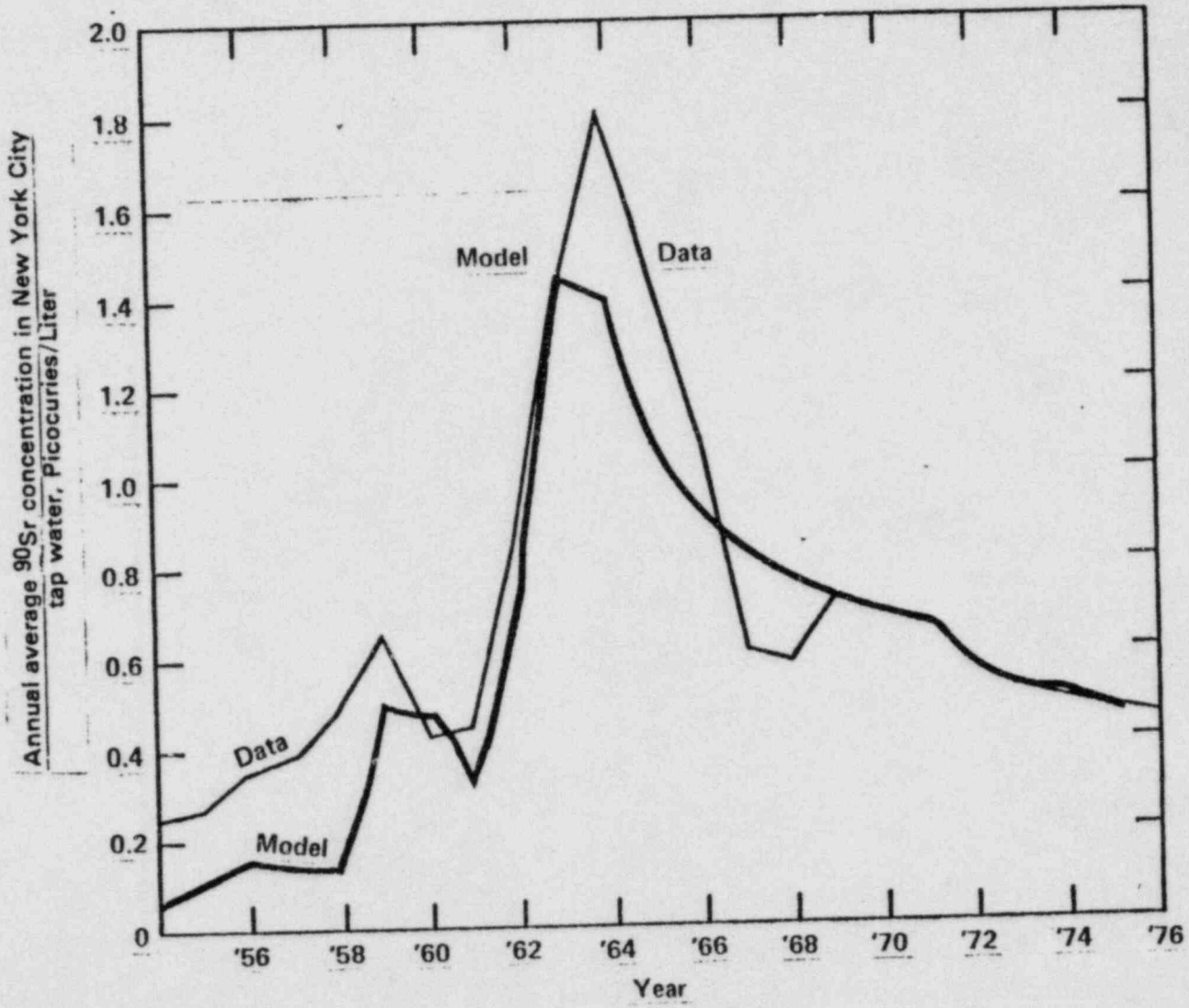

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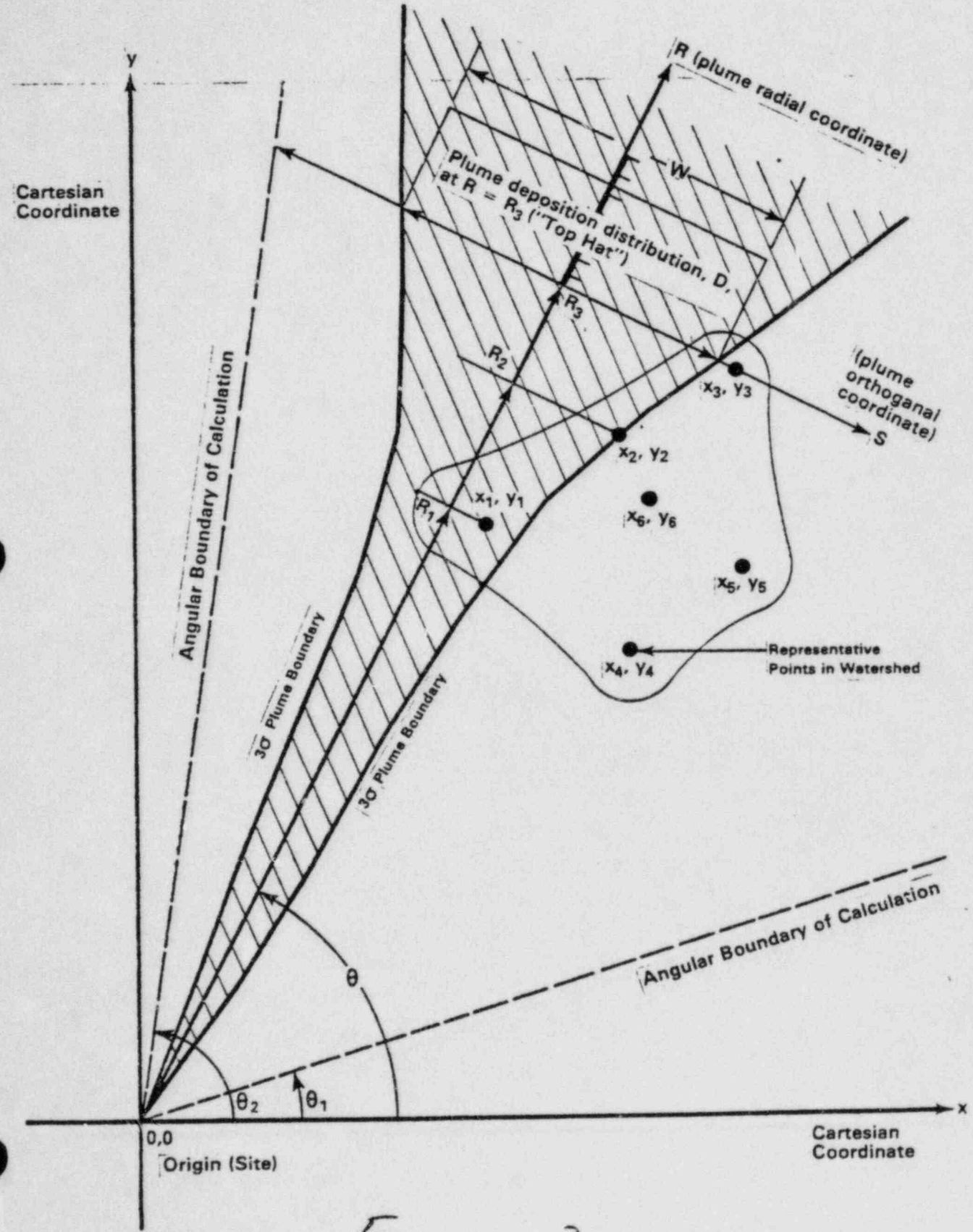
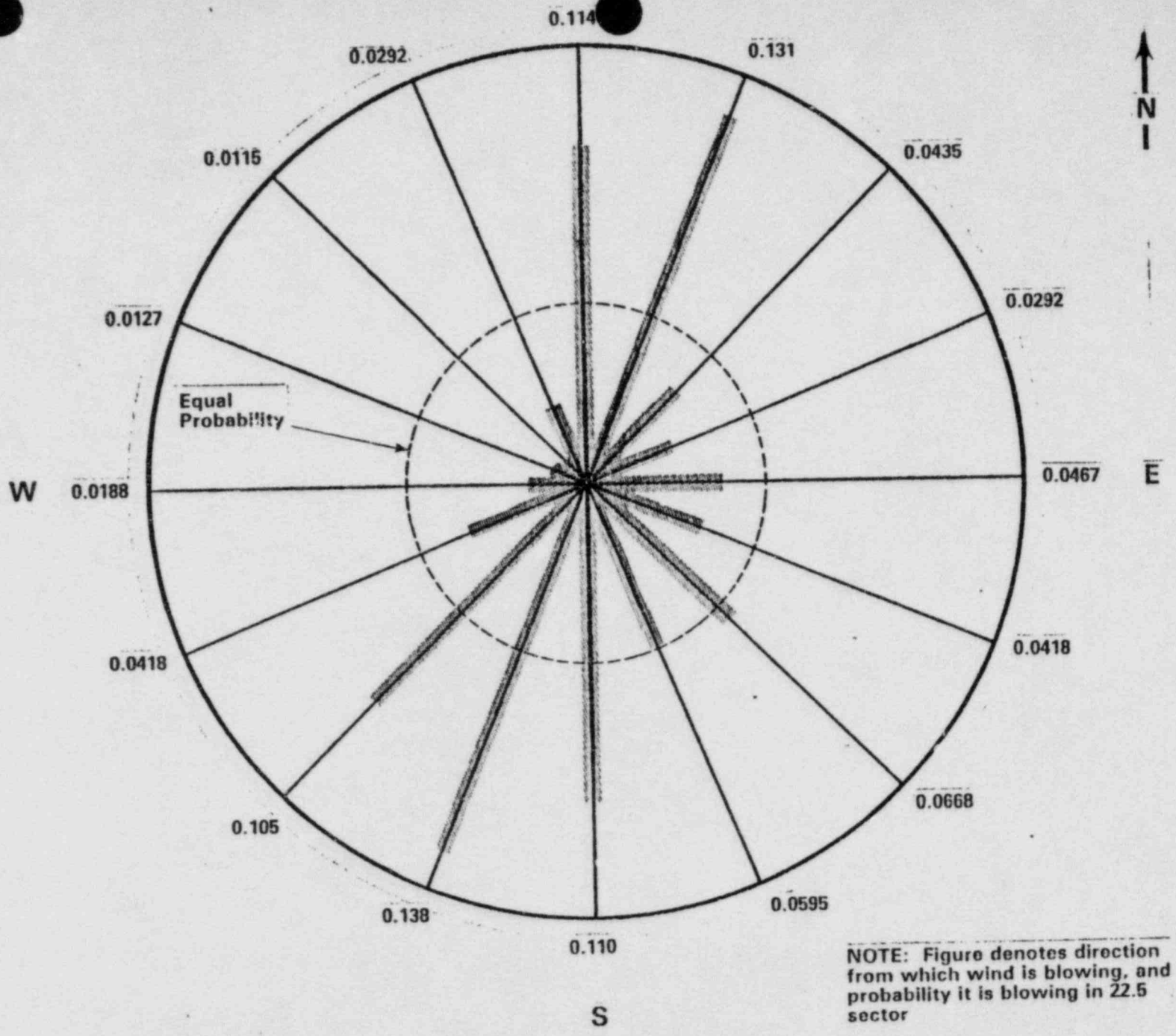


Figure 3



NOTE: Figure denotes direction from which wind is blowing, and probability it is blowing in 22.5 sector

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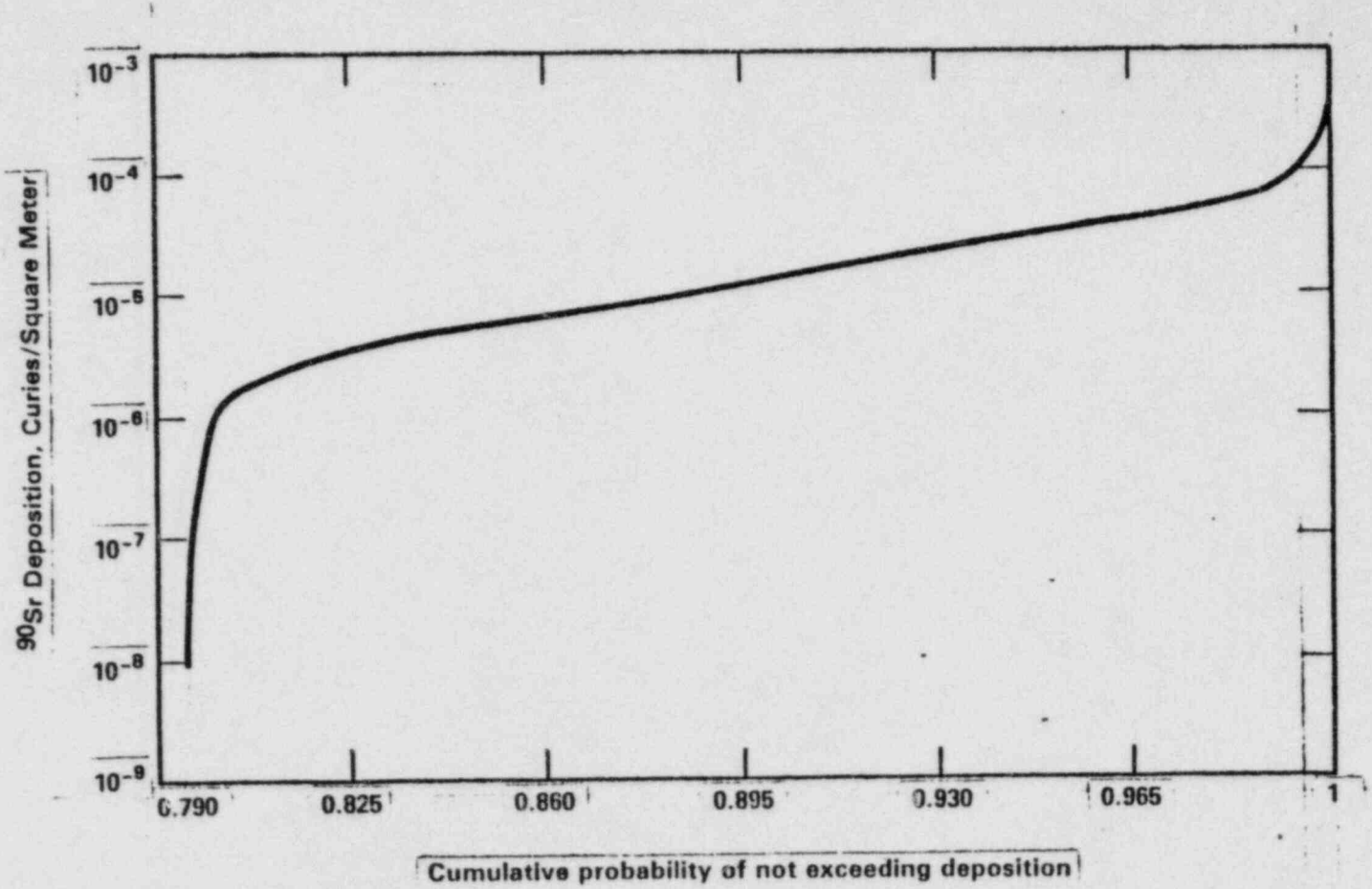
Figure 4

Figure 5



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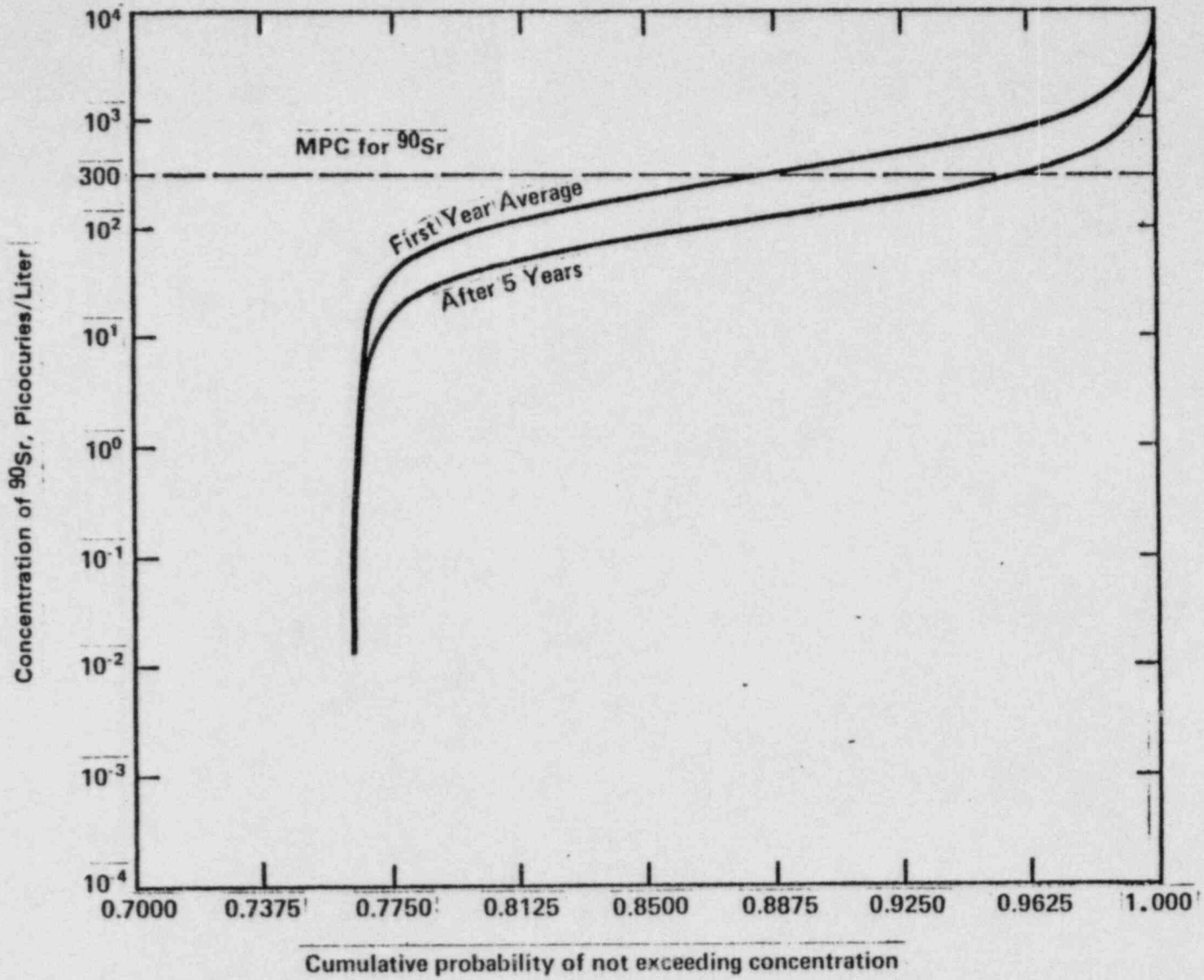
MPC for ^{90}Sr
First Year Average
After 5 Years
Concentration of ^{90}Sr, Picocuries/Liter
10^4
10^3
300
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.7000
0.7375
0.7750
0.8125
0.8500
0.8875
0.9250
0.9625
1.000
Cumulative probability of not exceeding concentration

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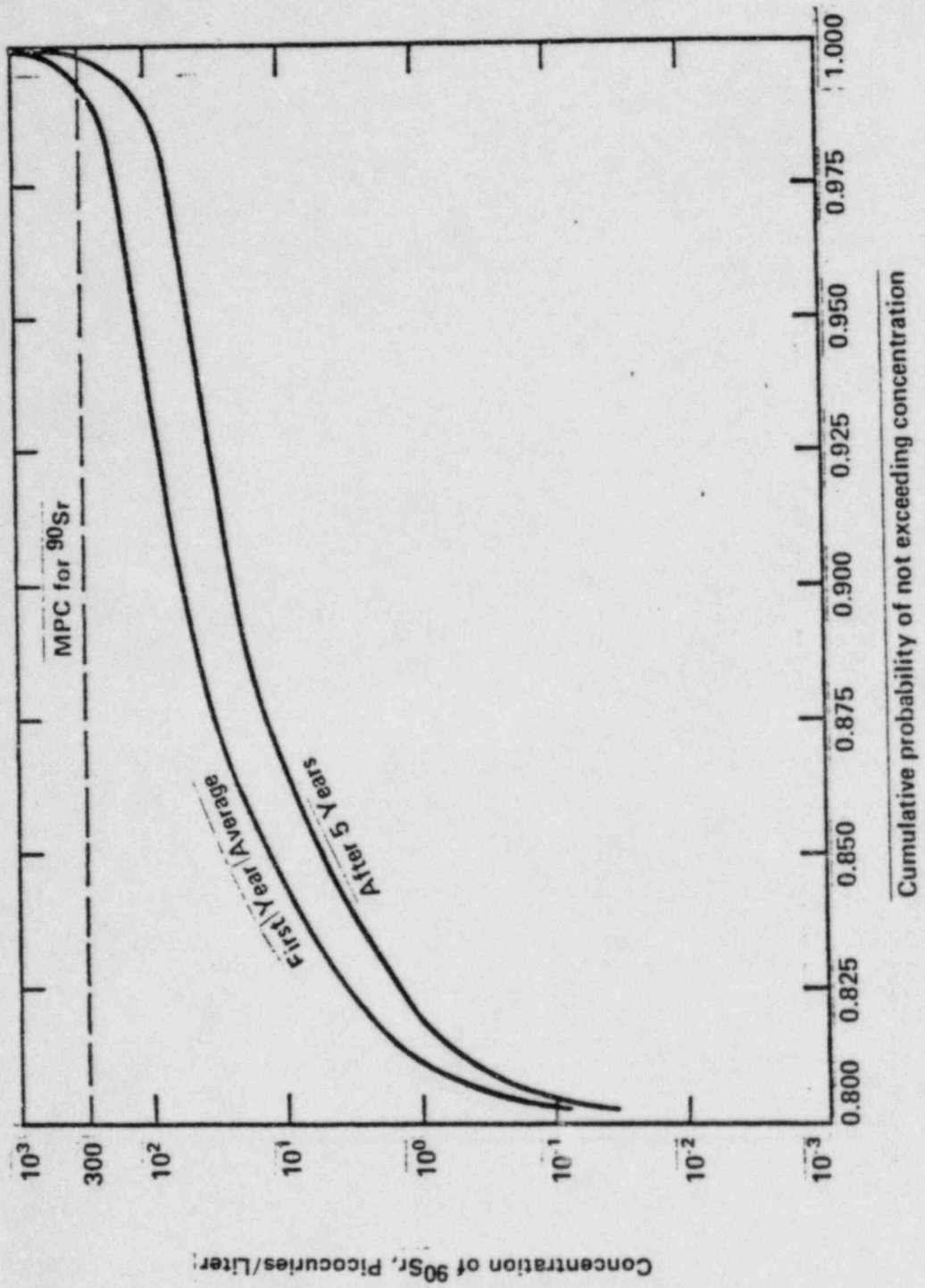

Figure 7

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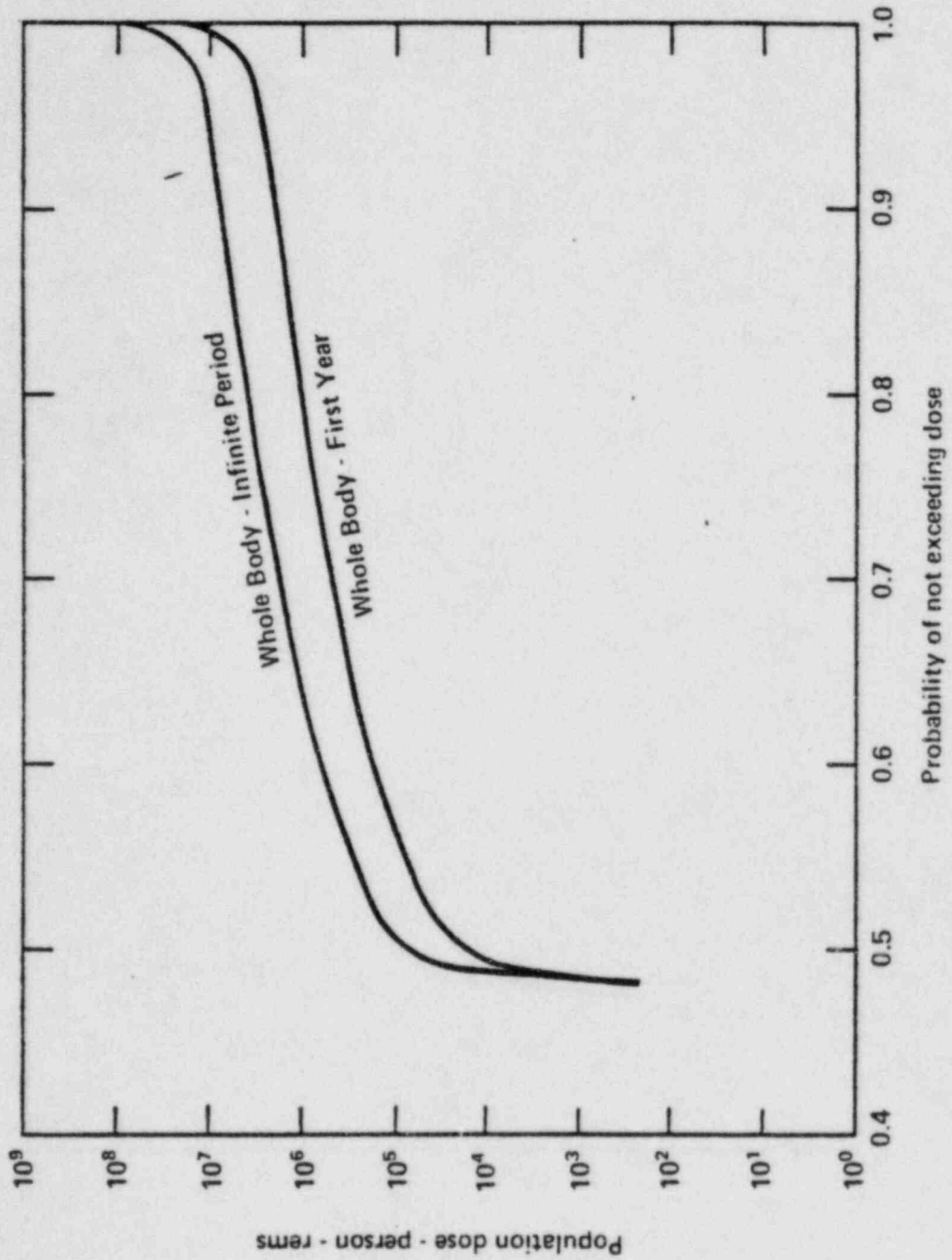

Figure 8