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OPTIMIZING RADIOLOGICAL MONITOR SITING OVER THE CONTINENTAL U.S.

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The US Environmental Protection Agency (EPA) is installing a network of sensors in the US to monitor background radiation and elevated radiation levels expected from a possible nuclear incident. The network (RadNet) of 180 fixed sensors is intended to provide a basic estimate of the radiation level throughout the US and enhanced accuracy near population centers. This report discusses one of the objective methods for locating these monitors based on criteria outlined by the EPA. The analysis employs a representative climatology of incident scenarios that includes 50 release locations, four seasons and four times of the day. This climatology was calculated from 5,600 simulations generated with NOAA-ARL's HYSPLIT Lagrangian trajectory model. The method treats the release plumes as targets and monitors are located to maximize the number of plumes detected with the network. Weighting schemes based on detection only, dose-weighted detection and population-dose weighted detection were evaluated. The result shows that most of the monitors are located around the population centers, as expected. However, there are monitors quite uniformly distributed around the less populated areas. The monitors at the populated areas will provide early warning to protect the general public, and the monitors spread across the country will provide valuable data for modelers to estimate the extent and the transport of the radioactive contamination.

I. INTRODUCTION

The Environmental Protection Agency (EPA) has requested technical assistance from the Savannah River National Laboratory (SRNL) in developing siting criteria for EPA's fixed RadNet air monitors, testing of EPA's fixed RadNet air monitors in various climatic extremes, and developing methodology for evaluating real-time data obtained from EPA's fixed RadNet air monitors.

Under the Nuclear/Radiological Incident Annex to the National Response Plan, the EPA is responsible for providing nationwide environmental monitoring data from the Environmental Radiation Ambient Monitoring System (ERAMS) for assessing national impact of a radiological accident/incident. EPA has recently renamed the ERAMS system as RadNet. The EPA plans to place as many as 180 RadNet air particulate monitors in cities across the nation to fulfill its responsibilities under the Nuclear/Radiological Incident Annex. These monitors will be capable of performing gamma spectrometry and determining gross beta radiation levels in near-real time on the airborne particulates collected on a fixed filter. The focus of the system is detection and quantification of radioactive contamination transported by air in cities not directly affected by the accident/incident. Only one monitor will be placed in a city. These data are expected to assist atmospheric dispersion modelers and decision makers during a radiological accident/incident.

There have been numerous monitors deployed to measure environmental radiation in a variety of situations. The most common are fixed station deployments near nuclear facilities such as the Department of Energy (DOE) sites[1, 2], and public utilities[3]. Typically, these are deployed in an arc at or slightly beyond the plant boundaries. In other cases, field experiments have been conducted over larger areas where an effluent tracer was to be detected[4, 5]. Generally, in all cases, the monitoring stations were located at ground level, and the siting criteria were based on capturing the spatial extent of the plume for expected releases.

One of the basic assumptions for RadNet is that the system will not serve as an early warning system. Rather, the system will detect radiological releases that have occurred well upstream (tens of kilometer) of the monitoring station. At these distances, it can also be assumed that the release will be well-mixed within the atmosphere.

This report presents results based on the siting method to maximize the probability of plume detection.

II. RADNET OBJECTIVES

The objectives of the RadNet air network have been summarized in a draft statement from the EPA[6]. Three mission objectives were given: (1) Provide radiological data for emergency response assessment to radiological accidents, (2) Measure ambient radiation levels in the environment, (3) Inform public officials of the impact of radiological incidents/accidents. RadNet is designed to measure the impact over large parts of the country and on population centers from nuclear weapon detonation, radiological dispersion devices, and domestic and foreign nuclear facility incidents/accidents. The system is not designed to monitor the immediate vicinity around incidents/accidents or act as an early warning/first detection capability.

The Radnet document listed system objectives in the timeframe surrounding incidents. First, the system should provide continuous baseline radiological measurements before the incident. Second, the system's function in the first 4 days after an incident/accident is to provide support data (1) for atmospheric modelers, (2) for understanding the national impact in affected and unaffected regions, and (3) for decision makers. In the year(s) following the incident/accident the network's objectives continue those of the first 4 days but also include reestablishment of the baseline, dose reconstruction and delayed contamination transport.

III. METHODOLOGY

The method presented to position monitors is based on the probability of detecting a plume, i.e., locations where many plumes overlap are preferred over those where few plumes overlap. Solutions were obtained for equal plume weighting, concentration weighting and population dose weighting.

III.A. Input Data

Since monitor placement will depend on release scenarios and climatology, a statistical data base is required in the design and evaluation of the network. This has been generated with the HYSPLIT Lagrangian transport model, for days and times of the day drawn from the four seasons. This plume climatology is assumed to be statistically similar to the complete range of possible scenarios.

III.A.1. HYSPLIT Model

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model[7, 8] was developed at the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (ARL-NOAA). This model can calculate simple trajectories through advection in the atmosphere, as well as more complex dispersion and deposition. The name for the model comes from a calculation methodology that allows one to use a Lagrangian approach for transport calculations and an Eulerian approach for dispersion calculations. Although a variety of methods exist within HYSPLIT to determine atmospheric concentration, it is calculated here by defining pollutants with assumed Gaussian or top-hat horizontal distributions and particle dispersion in the vertical direction. A single puff expands until its size exceeds the meteorological grid spacing at which time it then splits into several puffs.

Emissions may be specified as a point, line, or area source, and removal mechanisms include wet and dry deposition, as well as radioactive decay. The dry deposition calculations utilize the flux concept using the resistance method[9, 10] and require definition of a dry deposition velocity. For these calculations, the standard assumption of unit-density spheres (with particle diameter = 1.0 μm) with a deposition velocity of 0.1 cm/s was implemented. Wet deposition is divided into in-cloud and below-cloud removal[11]. In-cloud removal is defined by a scavenging ratio, which is the ratio of pollutant in the air to that in rain measured at the ground, while below-cloud removal is defined through a removal time constant. Default values are used in these calculations.

The large scale meteorological datasets required to perform the simulations are already available in a format suitable for ingestion into HYSPLIT. The large-scale data used in this study are taken from the National Center for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS). This is the final run of the NCEP operational runs and includes late arriving conventional and satellite data[12]. This dataset is converted to a hemispheric polarstereographic projection by NOAA-ARL and is called the FNL dataset. These FNL data are available at 6-hr increments and provide the meteorological conditions used in the HYPSLIT simulations for this study.

Validation studies for HYSPLIT are numerous, and include comparison with tracers released during long-range field experiments (e.g. Across North America Tracer Experiment, ANATEX[13]), simulations of the Chernobyl disaster, as well as application to balloon trajectories and volcanic ash eruptions. Extensive documentation may be found online[14].

An example of a HYSPLIT simulation for a San Francisco release is shown in Fig. 1. This figure shows that the plume concentration decreases by orders of magnitude as the plume increases to the size of several states.

III.A.2. Plume Climatology

The HYSPLIT model was used to generate a climatology of plume releases from the 50 population centers shown in Fig. 2. Details about the HYSPLIT simulations are given in Table 1.

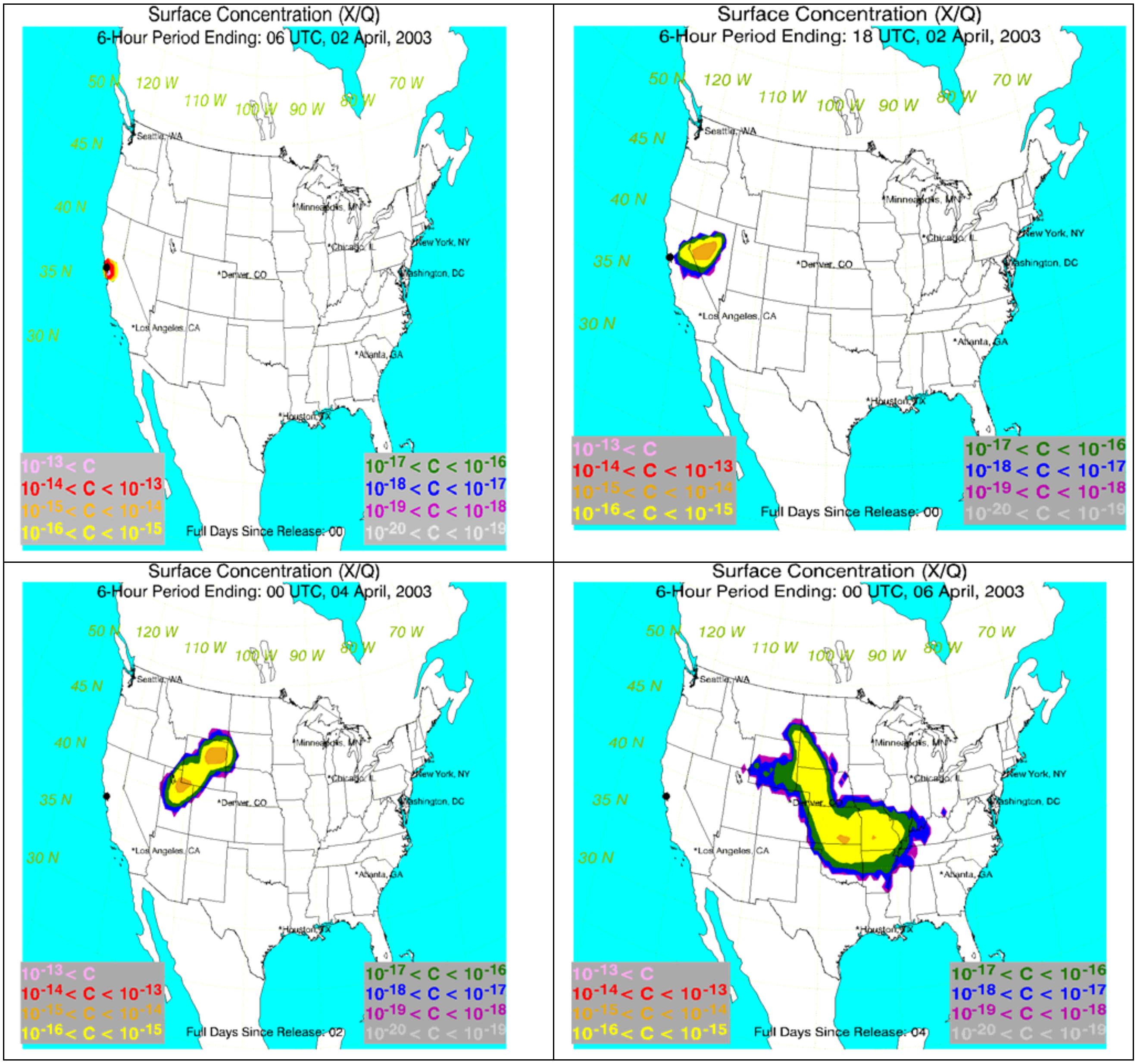

Fig. 1: HYSPLIT simulation of a release from San Francisco (a) 6 hours, (b) 18 hours, (c) 2 days, and (d) 4 days after the release.

TABLE I. HYSPLIT Simulations.

Meteorology	FNL data for 2001-2005
Release times	(0,6,12,18 UTC) for 7 days in (winter, spring, summer, fall)
Total number of simulations	5,600= (4 release hours) × (4 seasons) × (7 days) × (50 release)
Simulation duration	168 hours for each plume, output every hour
Horizontal grid size	0.5 × 0.5 degrees (121 × 53 = 6413 grid points)
Vertical grid size	20 layers (surface to 11 km)
Release height	10 meters
Source	1 Ci/hr for 1 hour
Dry and wet deposition were included	

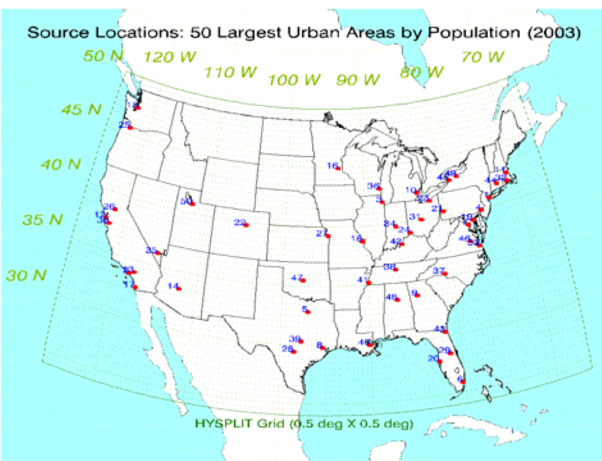

Fig. 2: Release locations for the HYSPLIT plume climatology.

III.A.3. Source Term

As indicated in Table I, the source is assumed to be a small explosion occurring over one hour with unit strength at a height of 10 meters above ground level. This study assumed equally-probable plumes and that the time and location of possible incidents are known and drawn from the 50 population centers chosen for the study. The particle size distribution is critical but only the fine particles (<1 micron) are expected to reach the RadNet monitors.

III.A.4. EPA-Selected Monitor Locations

The EPA has selected 58 monitor locations based on the population density as shown in Fig. 3. Although the focus of this work is on methods to select monitor locations, the same methodology can be used diagnostically to assess the value of the 58 pre-selected monitors, with the understanding that monitor value may depend on selection order. Note that two of the EPA monitors located in Puerto Rico and Hawaii are not included in the analysis.

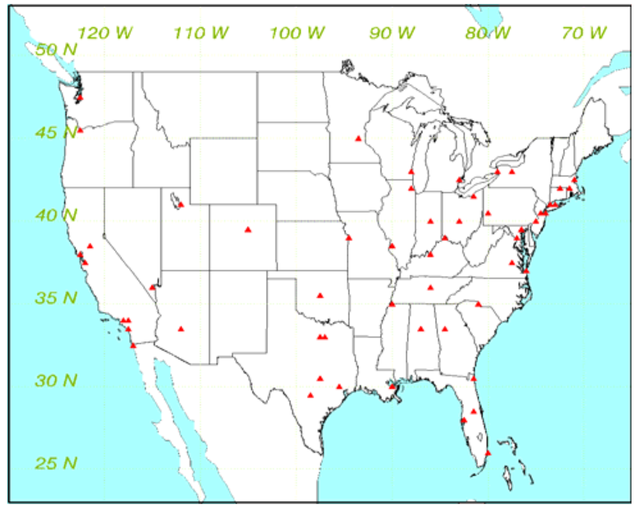

Fig. 3: The 56 EPA-selected monitor locations.

III.B. Detection Method

The Detection method optimizes the probability of detecting a released plume with at least one monitor. The objective was achieved by identifying grid points with the highest number of overlying plumes, placing monitors at these grid points, and then deleting all plumes impinging upon these grid points. Three versions of the method were obtained. The first version weighted all plumes equally, while the second and third versions weighted plumes by their concentration and population dose (concentration × population), respectively. To reduce the computational requirements, only plume concentration footprints at 6-hour intervals were used. This time interval was small enough to allow for reasonable continuity in plume evolution. This method was carried out using the following five steps:

Step 1. Define each plume boundary in terms of the maximum concentration (Max) and standard deviation (σ) of non-zero concentrations on the continental US grid.

The mean concentration, standard deviation and maximum value of a plume ($C_{i,j}$ defined on the i,j longitude-latitude grid) is,

$$\overline{C} = \frac{\sum_{i,j}^{N} C_{i,j}}{N} \qquad \text{for all } C_{i,j} > 0 \quad (1)$$

$$\sigma = \sqrt{\frac{\sum_{i,j}^{N} \left(C_{i,j} - \overline{C}\right)^2}{N-1}} \qquad \text{for all } C_{i,j} > 0 \quad (2)$$

$$\text{Max} = \text{Maximum}\ (C_{i,j}) \qquad \text{for all } C_{i,j} > 0 \quad (3)$$

where N = number of grid points where the plume concentration is greater than zero.

Step 2. A plume is assumed to be present (detected) at a grid point if the grid point concentration is greater than (Max - nσ) at least once during the plume lifetime. The integer n is chosen so that the plume includes ~90% of the above-background points.

Step 3. A grid point is assigned a score of 1 for each plume detected for the Detection-Only Method. For the Dose-Weighted Detection Method, the score is the concentration, and for the Population-Dose Weighted Detection Method, the score is the product of concentration and population.

Step 4. The grid point with the highest score (number of plumes detected) is selected for the next monitor. (The locations for the first 56 monitors are those given by the EPA, Fig. 3).

Step 5. All plumes detected at the monitor location in Step 4 are deleted and the process repeated until all 180 monitors are allocated.

IV. RESULTS AND DISCUSSIONS

A representative example of plume size and maximum concentration are shown in Figs. 4 and 5, respectively. These figures show that the plume area increased steadily over the first 100 hours and then became approximately constant with an area of 1800 to 2400 grid points. The maximum concentration decreased by 3-5 orders of magnitude during the same time.

The locations for the 180 monitors obtained with the 5-step algorithm given above (Detection -Only Method), and the first 56 specified from Fig. 3 in the continental US, are shown in Fig. 6. As expected, the monitor distribution reflects the source locations shown in Fig. 2 and the EPA monitor locations shown in Fig. 3. Note also that many monitors are dispersed to remote areas and that most states have at least 2 monitors.

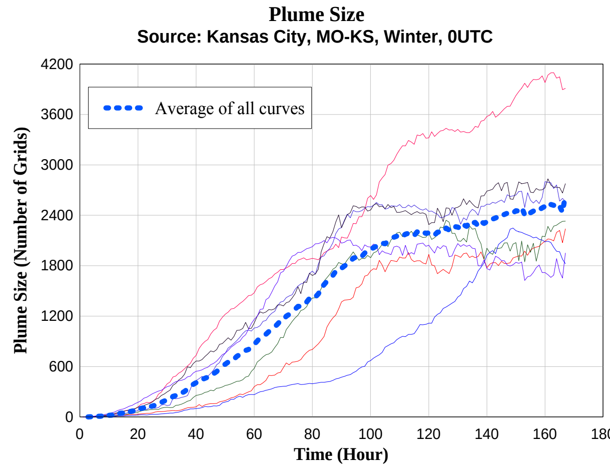

Fig. 4. The plume size of 7 plumes released from Kansas City as a function of time.

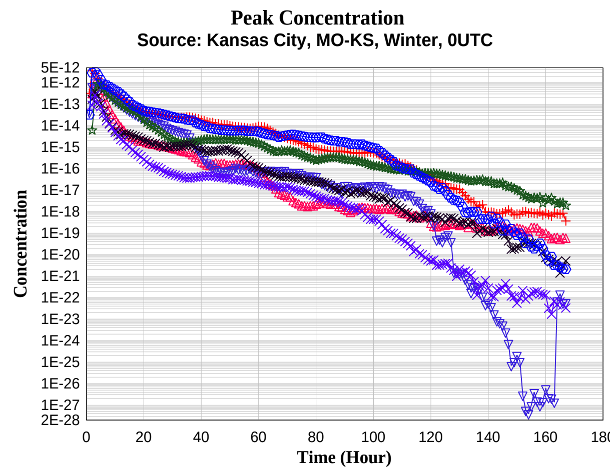

Fig. 5: The peak concentration for 7 plumes released from Kansas City as a function of time.

Figure 7 shows the number of plumes removed as a function of the number of placed monitors. Note that the total number of plumes is 156,800 (= 5,600 releases × 7 days × 4 plumes per day). Thus, the methods have sampled ~2/3 of the total number of plumes after 180 monitors are in place. The flattening of the curve between 30-60 samples and the discontinuity at monitor 58 indicates that the EPA-selected locations for monitors 30-60 are not consistent with the detection algorithm. The curve also suggests that the monitors 60-100 remedy the inconsistency. The flattening of the curve in the 100-180 monitor range implies a diminishing need for additional monitors beyond 60 – 100. This is a result of the efficiency of the single detection constraint that was used to detect and remove plumes.

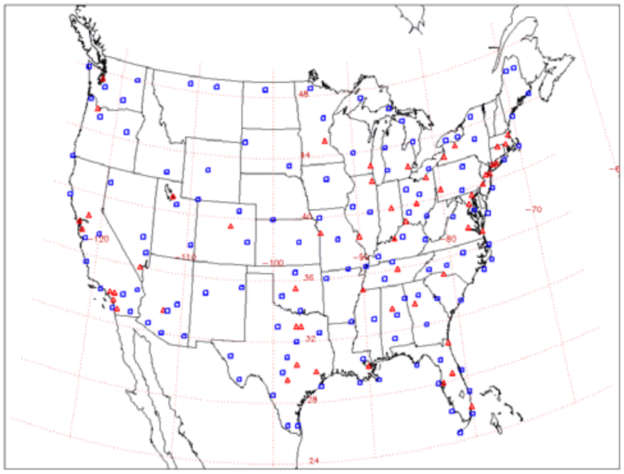

Fig. 6: Monitor locations using the Detection-Only Method. (EPA-positioned monitors are shown with red triangles).

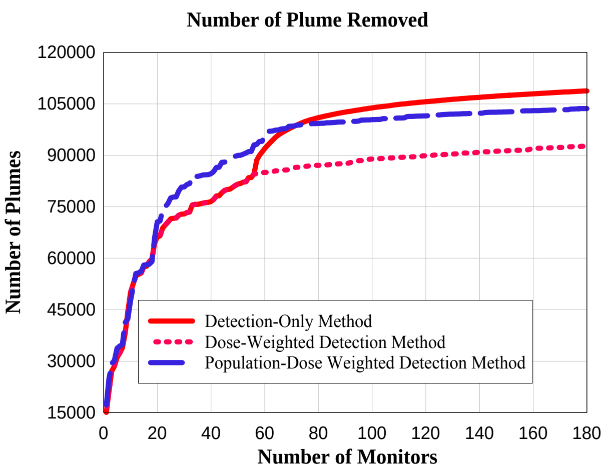

Fig. 7: Number of plumes removed as a function of the number of monitors.

The algorithm was modified to include concentration weighting (Dose-Weighted Detection Method) and population dose weighting (Population-Dose Weighted Detection Method). Figures 8 and 9 show the monitor placement with concentration weighting and population dose weighting, respectively.

As expected, Fig. 8 shows monitor clustering around the release locations. In fact, every release location has 3-5 monitors clustered around it, except in the northeast US, where monitors can service more than one release point.

When population weighting is included (Fig. 9), we observe migration of monitors from low population release locations to high population release locations. For example, the Minneapolis area loses monitors while Florida gains monitors.

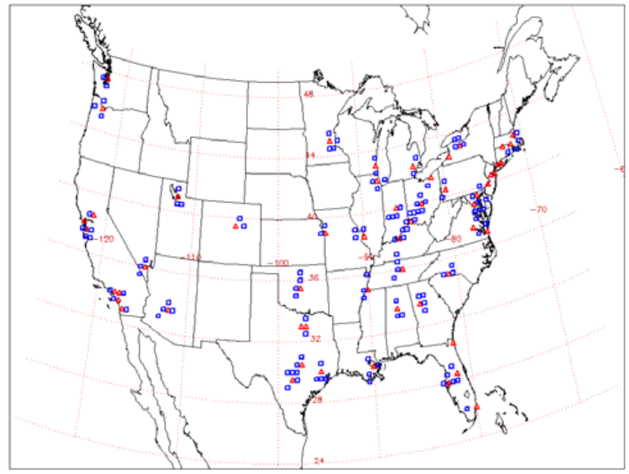

Fig. 8: Monitor locations based on the Dose-Weighted Detection Method. (EPA-positioned monitors are shown with red triangles).

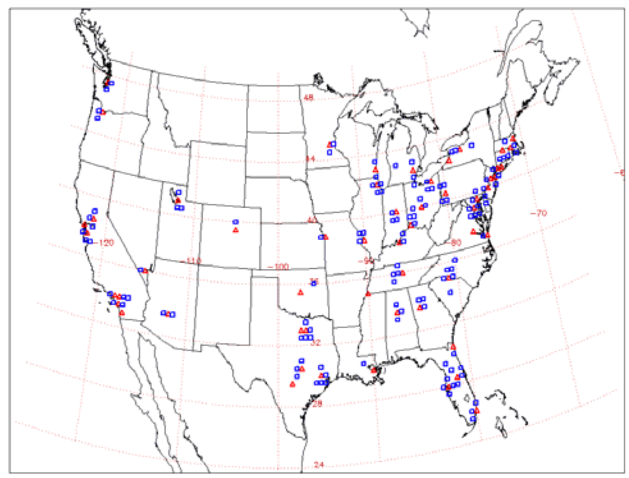

Fig. 9: Monitor locations based on the Population-Dose Weighted Detection Method. (EPA-positioned monitors are shown with red triangles).

The monitor locations based on the Detection-Only Method were determined, as shown in Fig. 6. Figure 6 shows that most of the monitors are located around the population centers, as expected. However, there are monitors quite uniformly distributed around the less populated areas. The monitors at the populated areas will provide early warning to protect the general public, and the monitors spread across the country will provide valuable data for modelers to estimate the extent and the transport of the radioactive contamination.

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