ARAC: Modeling an Ill Wind

Our ARAC system traced the spread of radioactive material in the aftermath of the nuclear reactor accident at Chernobyl.

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When news of the accident at the Chernobyl nuclear power plant first broke, the Department of Energy (DOE) asked us to actuate our Atmospheric Release Advisory Capability (ARAC) team and start calculating the extent, magnitude, and spread of the radioactive plume. The task was complicated by three major factors:

- The magnitude of the release, which forced us to enlarge our calculational grid a hundredfold to cover Europe, Scandinavia, and the western Soviet Union to start with and eventually the whole Northern Hemisphere.
- The volume of data pouring in from five times as many upper-air weather stations and almost ten times as many ground stations as we had ever used before. Until we improved our computer software (while responding to the accident), this volume threatened to swamp our data-acquisition systems.
- The initial failure of the Soviet Union to disclose exactly where and when the accident had happened and how much radioactive material had been released.

All told, predicting the spread of debris from Chernobyl was the greatest challenge in the ARAC system's 14-year history.

ARAC is a DOE-sponsored emergency-response service set up to provide real-time prediction of the dose levels and the extent of surface contamination resulting from a broad range of possible occurrences (accidents, spills, extortion threats involving nuclear material, reentry of nuclear-powered satellites, and atmospheric nuclear tests) that could involve the release of airborne radioactive material. During the past decade, ARAC has responded to more than 150 real-time situations, including exercises. The most notable responses include the Three Mile Island accident in Pennsylvania, the Titan II missile accident in Arkansas, the reentry of the U.S.S.R.'s COSMOS-954 into the atmosphere over Canada, the accidental release of uranium hexafluoride from the Sequoyah Facility accident in Oklahoma, and most recently the Chernobyl reactor accident in the Soviet Union.

ARAC currently supports the emergency-preparedness plans at 50 Department of Defense (DOD) and DOE sites within the U.S. and also responds to accidents that happen elsewhere. Our ARAC center (Figure 1) serves as the focal point for data acquisition, data analysis, and assessments during a response, using a computer-based communication network (Figure 2) to acquire real-time weather data from the accident site and the surrounding region, as well as pertinent accident information. Its three-dimensional computer models for atmospheric dispersion, MATHEW and ADPIC, digest all this information and produce the predictions used in accident assessment.

Our work has also received wide international recognition and

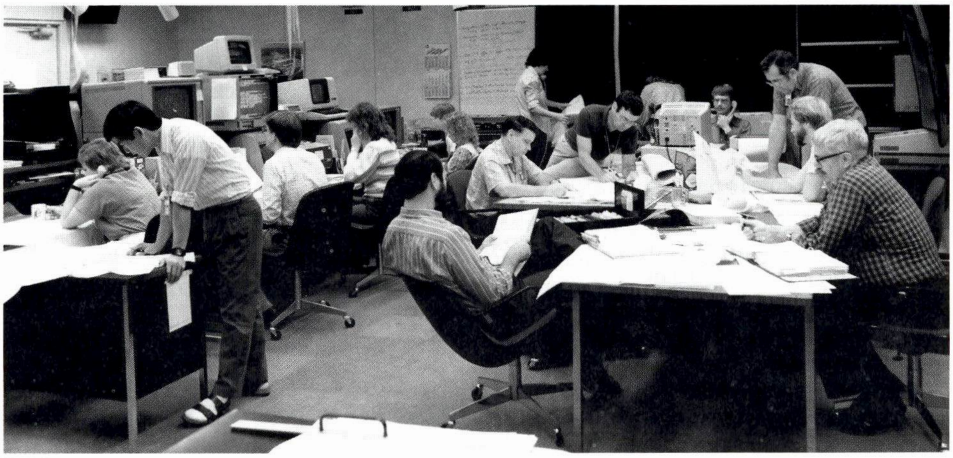

Figure 1. A general view of the ARAC center at LLNL.

acceptance. In 1980, we transferred our ARAC models to the computer system of the Italian Nuclear and Alternate Energy Agency (ENEA), and we continue to cooperate with ENEA in the areas of model evaluation and system development. In 1982, ENEA transferred our ARAC models to the computer system of the Japanese Atomic Energy Research Institute (JAERI), and we have developed a close working relationship with JAERI. In 1983 we transferred our ARAC models to the computer system of the Swedish Nuclear Development Institute (NDI), and we have pursued model evaluation studies with NDI. We have provided consulting services with regard to emergency-response atmospheric models and computerized emergency-response methods to the International Atomic Energy Agency (IAEA) and have presented a 2-1/2-day course in computerized emergency response for developing countries. In addition, we have provided various services to Spain, Korea, Brazil, Israel, West Germany, and India.

The ARAC system

The ARAC Emergency Response Operating System (AEROS) at the core of our ARAC system provides a centralized emergency-response service that can handle multiple emergencies at a wide range of possible accident sites. It can

- Assess environmental impacts, using three-dimensional atmospheric-dispersion models that include the effects of complex meteorological conditions and terrain.
- Support the emergency-preparedness plans at about 50 DOE and DOD facilities accessible through our computer system.
- Provide timely impact assessments for accidents occurring outside these sites.
- Produce initial assessments within one hour of notification during normal working hours for sites connected to our computer system. Future expansion of the system will reduce this response time to about 15 minutes.
- Produce high-quality graphical displays of the assessments of radioactivity in the form of isopleths (similar to contour lines) on a map.

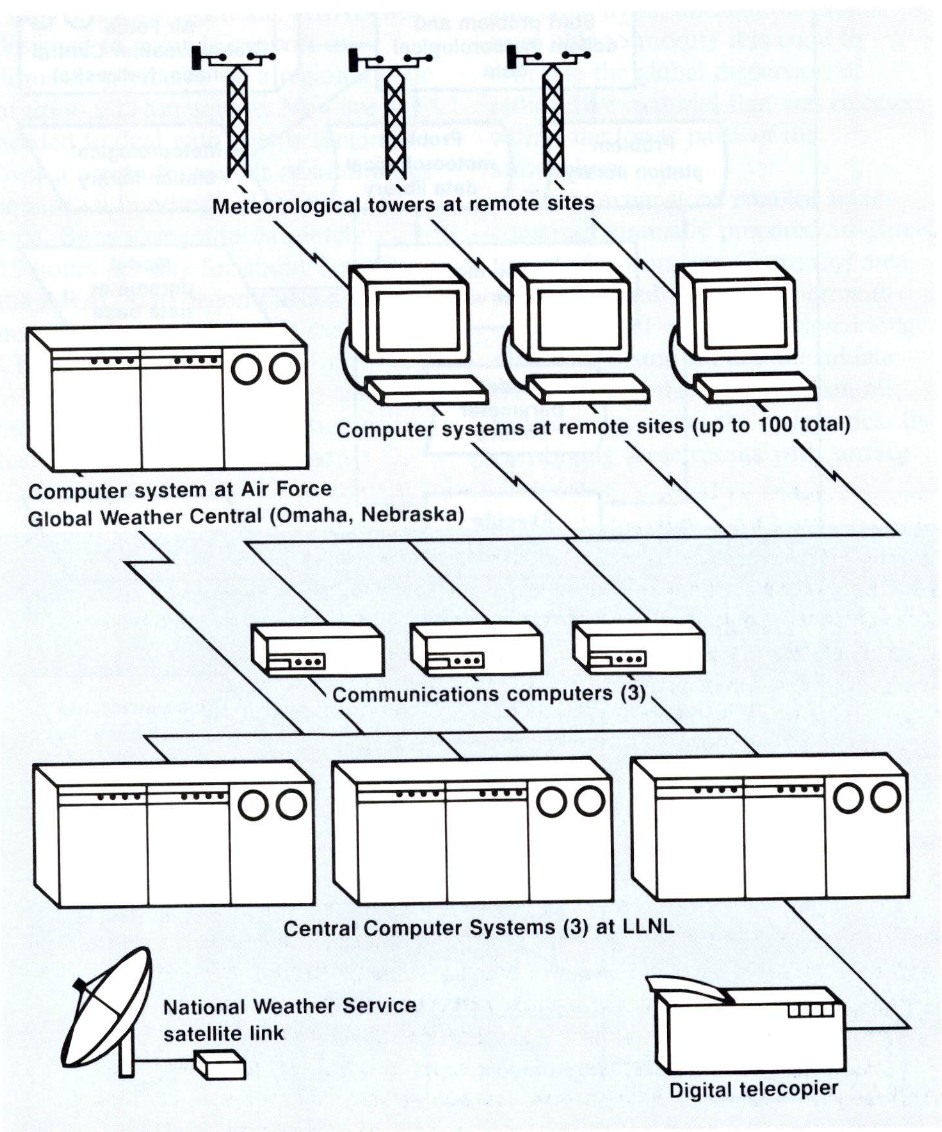

Figure 2. The AEROS network of computers that forms the core of the ARAC system. Each nuclear facility in the system has a desk-top computer for entering initial accident reports and a meteorological tower to provide up-to-the-minute weather data. High-speed data links transmit this information to our computer center for use in atmospheric models.

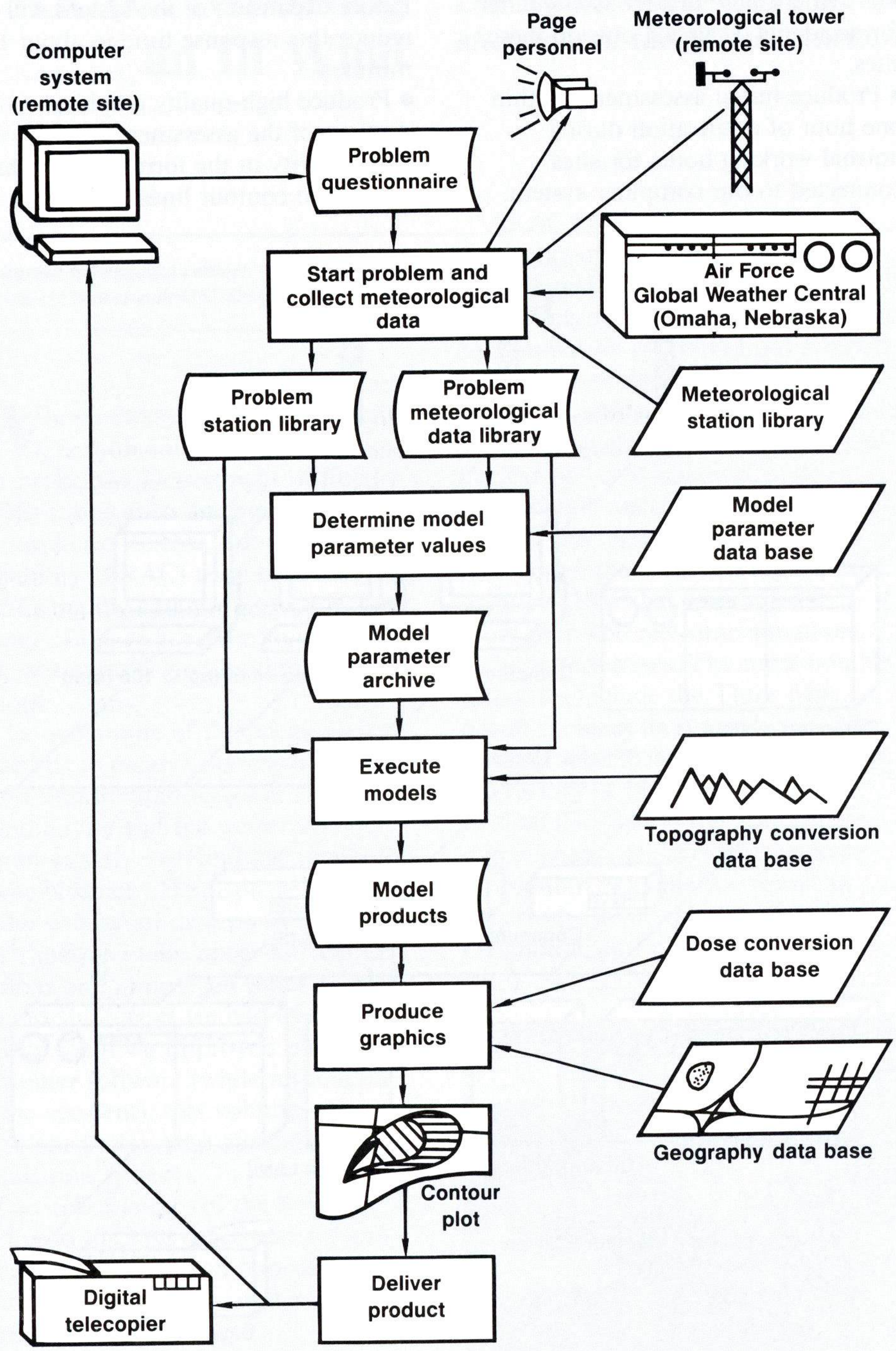

Figure 3. An outline of how the ARAC system functions. When an operator, reporting an accident, fills out a questionnaire on a computer located at a one of the remote nuclear facilities, a paging system sounds at LLNL, alerting ARAC personnel and starting the collection of weather data from the nuclear facility's weather tower and from the Air Force Global Weather Central in Omaha, Nebraska. This information, combined with site-specific and problem-specific data from other libraries, is used to determine parameter values for use in the model. These values, together with information from our topography data base, enables us to execute the models, produce graphics such as isodose plots, and distribute the results to crisis managers at ARAC and back at the site of the problem.

- Provide a simple interface for entering information and operating the system.

In developing AEROS, we used modern structured-programming techniques to make the system easy to maintain and alter. AEROS includes many features that make it highly reliable. Its meteorological data-acquisition and processing functions, as well as its model calculations, are highly automated to reduce delays and enable the system to keep pace with developments in an emergency.

Figure 2 schematically outlines the AEROS hardware, which is essentially a network of computers and communication equipment. The AEROS system includes about 50 nuclear facilities managed by DOE or DOD; at each of these facilities, there is a meteorological tower and a powerful desk-top computer (i.e., a 512-kbyte computer with a 10-Mbyte hard disk, color monitor, telephone-management system, and dot-matrix printer) for data entry. At some places the instruments on the meteorological tower read directly into the on-site computer through a modem, while at the others an operator transfers the information manually.

Information from the nuclear-facility computer, together with detailed weather data for the surrounding area obtained from the U.S. Air Force Global Weather Central (AFGWC), feeds directly into the ARAC central computer system at LLNL. The ARAC computer system consists of a VAX cluster composed of an 8-Mbyte VAX, a 16-Mbyte VAX, and a 4-Mbyte VAX, plus a disk controller that accesses a 5.6-Gbyte disk farm.

Figure 3 outlines how the ARAC system functions. To report an accident, an operator at a facility connected with the ARAC system fills out, on a computer screen, a problem questionnaire listing pertinent accident information such as time, location, description, and meteorological data (primarily wind speeds and directions, although temperature, barometric pressure, and humidity can also be important). This information is automatically transmitted to the ARAC central facility, which automatically starts a paging system that alerts the ARAC staff and sets in motion the data-acquisition system that gathers all available weather data for input into the model calculations.

One of the important inputs to the model calculation comes from the topography data base. Terrain information is needed by the models so that material is dispersed in a manner consistent with the wind and temperature fields influenced by the underlying terrain. In 2 to 5 minutes, ARAC operators can call up images of the mountains, gullies, seashores, and plains of any part of the country on their computer screens (Figure 4). The topography data base used to construct these images (produced by the Defense Mapping Agency) lists heights above sea level for some quarter-billion points averaging about 500 m apart and covering the entire continental United States.

Our main workhorse computer models are MATHEW, an air-transport (wind) model, and ADPIC, a particle-in-cell diffusion model. The MATHEW model calculates the wind field that determines the general direction the contaminant cloud takes at each elevation modeled (winds aloft can flow at different speeds and in different directions at different levels). The ADPIC model calculates the diffusion and deposition of material in the cloud.

ARAC Response to the Chernobyl Reactor Accident

At the time we were asked to assess the radiological impact of the Chernobyl accident, we had recognized the desirability of expanding our models to cover an event of such magnitude. ARAC was designed to provide support in domestic accidents on a regional scale of up to 200 km square. Now we needed to deal with events ranging over a region thousands of kilometres square—a hundredfold increase in area. By working approximately 15 hours per day for about 2 weeks, the ARAC staff accomplished the necessary expansion while making the Chernobyl assessment.

For the later stages of the assessment, when the radioactivity had spread to all parts of the Northern Hemisphere, even this expansion was not enough. For this larger task we reactivated a three-dimensional particle-in-cell code (global PATRIC) we had developed years before to track radioactive debris from Chinese nuclear tests and estimate doses to aircraft passengers and crew flying through the cloud. We were able to modify this code to estimate the global dispersion of radioactive material that was released within the lower parts of the atmosphere.

These expansions enabled us to construct manually prepared air-parcel trajectories from the Chernobyl area, which we used in conjunction with our 2BPUFFF two-dimensional long-range dispersion model to evaluate the change in the concentration of radioactivity along the trajectories. By combining these results with surface

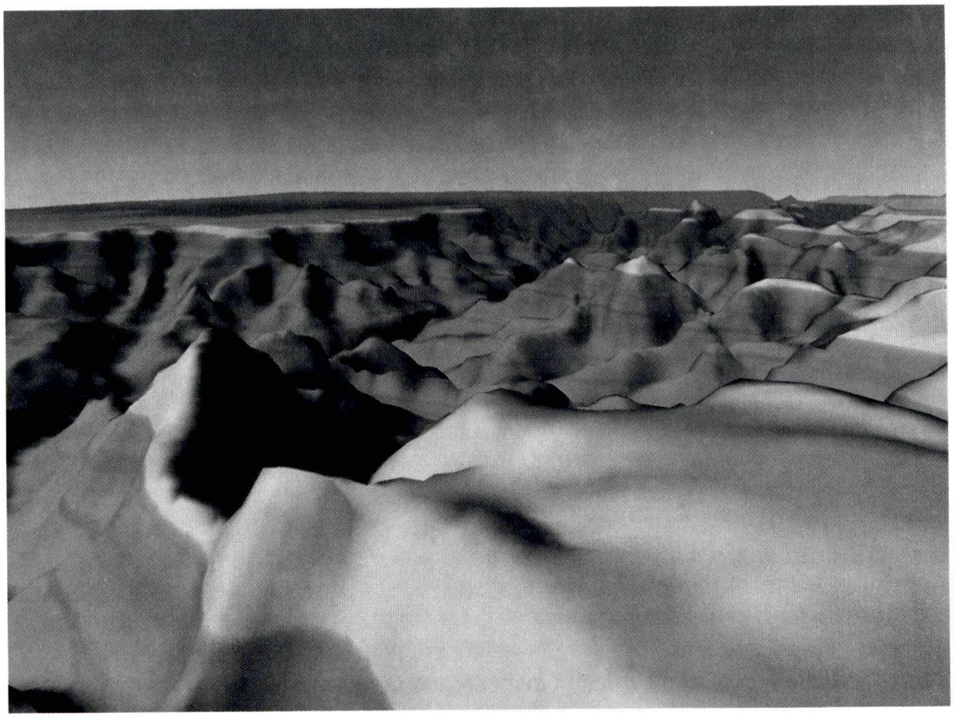

Figure 4. An example of the detailed information in our topographical data base. The computer-generated terrain pictured is part of the Grand Canyon in Arizona, looking northward from a point somewhat above the south rim, in the afternoon of a winter day. Our computers can construct similarly detailed representations of any part of the continental U.S. on demand.

and upper air measurements of airborne radioactivity in Scandinavia, we were able to estimate that 1300 PBq of ^{131}I and 89 PBq of ^{137}Cs (about half of the reactor's inventory of these radioisotopes) had been released in the accident together with corresponding amounts of other radionuclides (See Table 1). Incidentally, it has been estimated[1] that all atmospheric tests by the U.S. and the Soviet Union produced a total of 740 000 PBq of ^{131}I and 1400 PBq of ^{137}Cs.

Further calculational iterations, comparing projected air movements and radioactivity concentrations with measurements at up to 20 sites throughout the Northern Hemisphere, enabled us to refine our picture of the accident to include estimates of how the amount of radioactivity released varied with time and how the radioactivity was initially distributed in the air.

An interesting finding was that there were two clouds instead of just one. Most of the radioactive material released by the initial explosion rose very high into the middle troposphere (the cloud extended vertically from 1.5 to 7.5 km, with its center at about 4.5 km). The lower cloud, consisting mostly of material released by the fire, extended from the surface to about 1.5 km and was centered at 1.3 km.

Just why the first cloud rose so high is not clear, but there are several plausible explanations. Maybe it was hot enough to rise by itself, or maybe it was helped by thunderstorm activity (meteorological convection) or by gliding up over a frontal system. However it happened, this two-cloud system produces the best fit between our calculations and the results of radiation monitoring.

Detailed analysis of the time-varying horizontal and vertical radioactivity distributions indicate that the lower cloud is what headed northwest toward Scandinavia and later into the rest of Europe, while the upper segment went southeast across Asia to Japan, the North Pacific, and the west coast of North America. The four ARAC-generated plots in Figure 5 show the distribution of airborne radioactivity at 2, 4, 6, and 10 days after the accident.

The next step was to translate these radioactivity distributions into terms of their dose to people. Here the calculations become complicated by innumerable factors, ranging from the known (and therefore calculable) properties of the dozens of different radioisotopes to the widely varying behavior of people in the affected areas. The effects of ^{137}Cs, which distributes itself more or less uniformly throughout the body and has an effective half-life of 100 days but is lost by excretion, are very different from those of ^{131}I, which is concentrated in the thyroid and has an 8-day effective half-life. Similarly, the inhalation dose received by someone who stays in an air-conditioned building almost all the time (an office worker or invalid, for example) would be much less than that of a shepherd or construction worker who is outdoors all day.

Without taking all these various circumstances into consideration, we arrive at an estimate of the committed dose due to inhalation (the radiation dose from radioisotopes absorbed through the lungs of a person who takes no precautions, integrated over the next 50 years and plotted as a function of the person's

Table 1. **Estimated amounts of various radionuclides released by the reactor accident at Chernobyl, decay corrected to April 29, 1986 (three days after the initial release).**

Nuclide	Activity	
	PBq	MCi*
^{137}Cs	89	2.4
^{136}Cs	17	0.47
^{134}Cs	48	1.3
^{131}I	1300	36
^{133}I	340	9.1
^{141}Ce	8.5	0.23
^{144}Ce	5.2	0.14
^{140}Ba	37	1.0
^{140}La	37	1.0
^{95}Zr	8.5	0.23
^{95}Nb	8.5	0.23
^{132}Te	200	5.3
^{103}Ru	28	0.76
^{106}Ru	5.9	0.16
^{133}Xe	4400	120

* Values are given in curies for reference. See pp. 4 and 5 for a discussion of units used for radiation and radiation exposure.

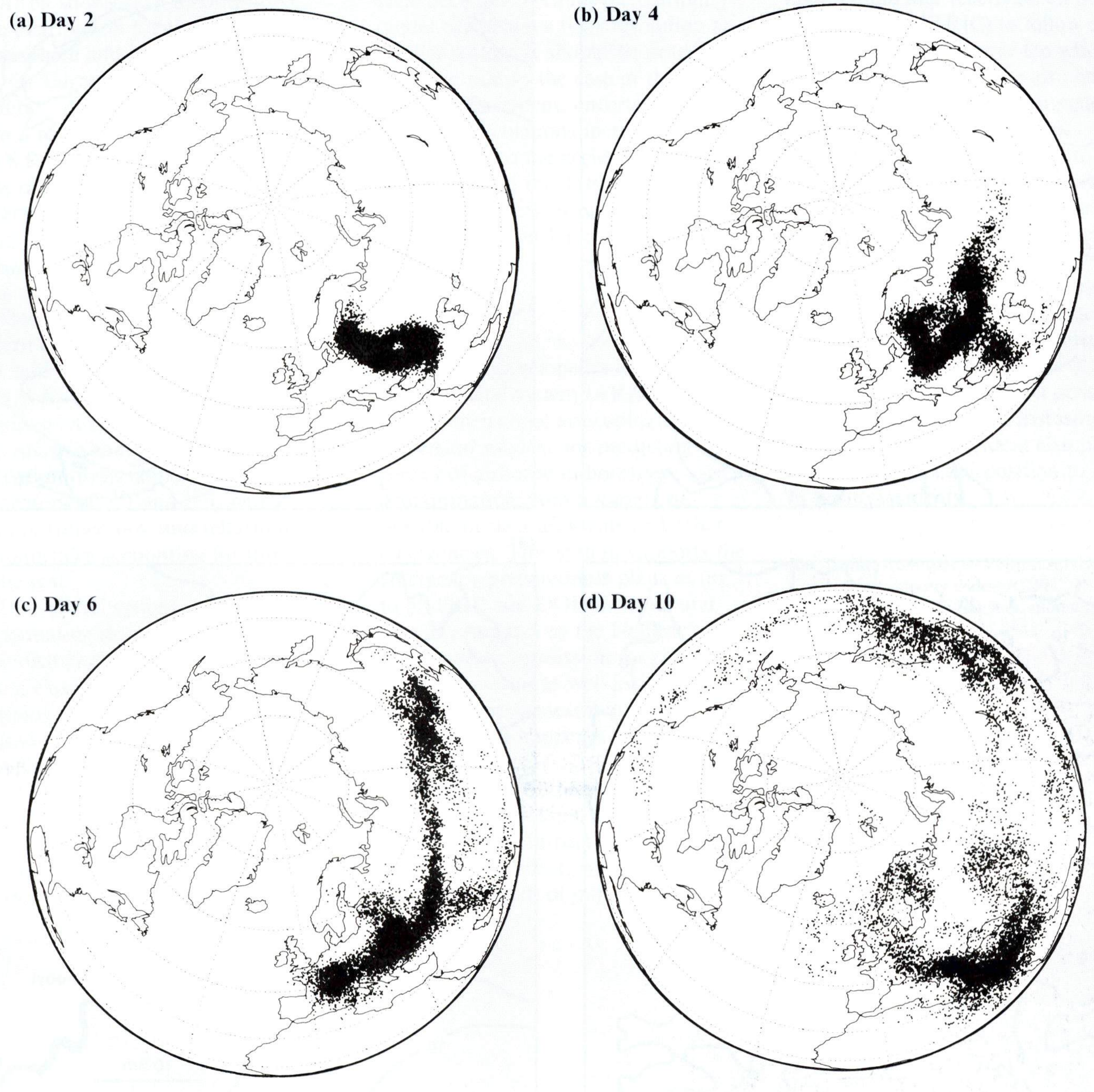

Figure 5. ARAC plots showing how the clouds of radioactive material spread around the Northern Hemisphere at (a) 2, (b) 4, (c) 6, and (d) 10 days after the initial explosion.

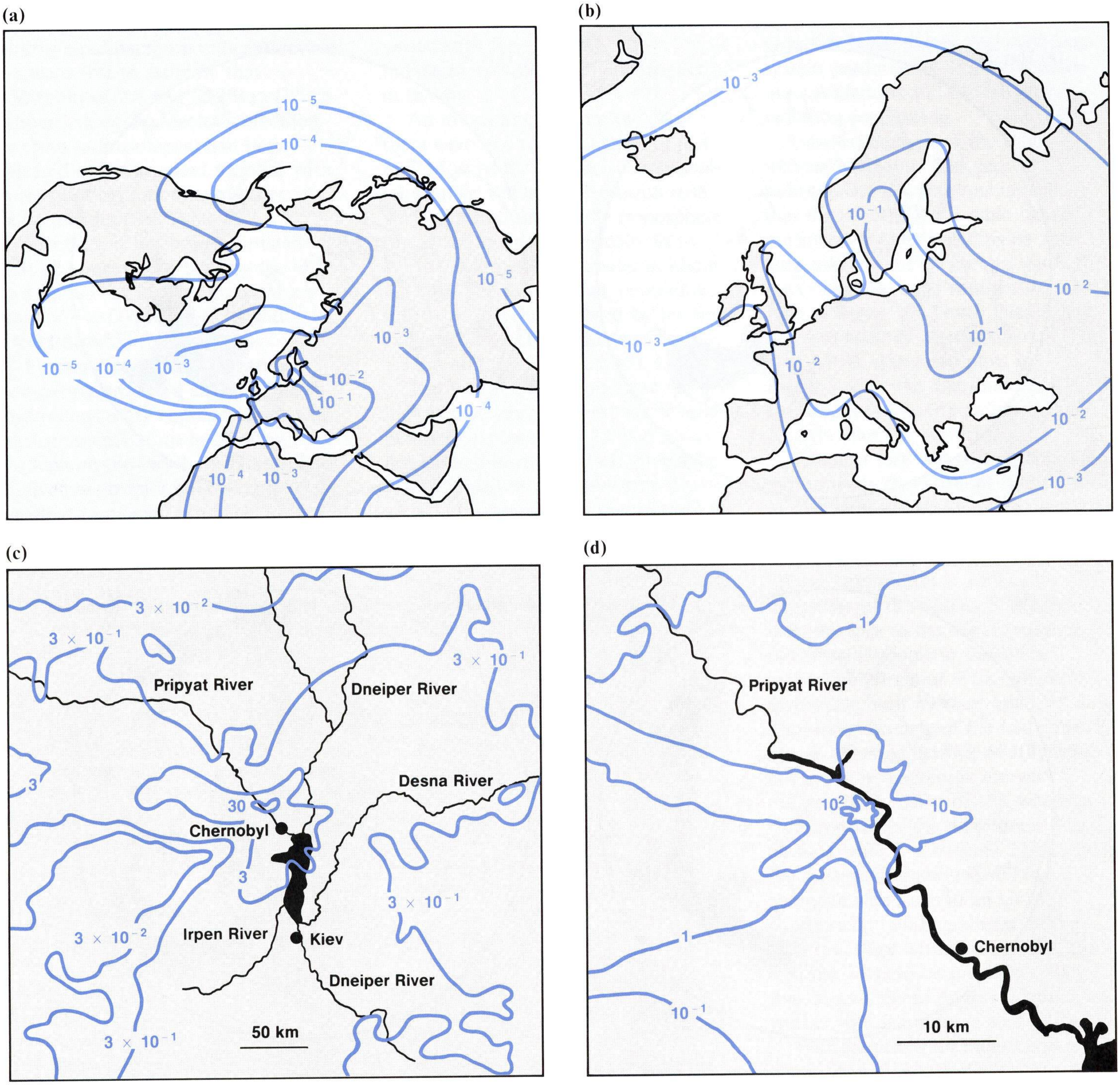

Figure 6. Isopleths showing the distribution of cumulative primary radiation dose (that due to breathing the contaminated air, integrated over the next 50 years; other pathways are of major significance and are discussed in the following article). The isopleth values are given in mGy. (a) Most of the Northern Hemisphere, in a modified polar projection. (b) Europe, the Mediterranean Sea, and the North Atlantic. (c) A 400- × 400-km area around the Chernobyl reactor. (d) A 50- × 50-km area around Chernobyl. The values for the isopleths increase slightly as the scale decreases because our computer models achieve finer resolution at smaller scales.

geographical location at the time). Figure 6a shows such a committed dose distribution for the Northern Hemisphere and Figure 6b is a similar plot for Europe and the North Atlantic.

In a region covering the western U.S.S.R., northeastern Poland, and parts of Sweden, the Ukraine, and eastern Europe, the dose from the inhalation pathway (which forms only part of the total dose) is 0.1 mGy. In most of central Europe, parts of northern Scandinavia, and the rest of eastern Europe, the dose is between 0.01 and 0.1 mGy. Denmark, the United Kingdom, Spain, and northern Scandinavia received less than 0.01 mGy. About 80% of these inhalation doses come from the absorption of ^{131}I and ^{133}I, with cesium, ruthenium, and tellurium radionuclides accounting for most of the rest.

The ARAC system is also capable of estimating detailed closeup views of dose distribution around the accident scene. Figure 6c shows a closer mapping of the distributions right around the Chernobyl reactor site. This figure shows doses exceeding 30 mGy for places closer than about 10 km from the reactor. Figure 6d shows a dose estimate for a 50- × 50-km area around the reactor, where the dose is approximately 100 mGy. (The isopleth values increase as the scale decreases because the computer model can achieve finer resolution at smaller scales.) It should be noted, however, that in the case of the Chernobyl accident, uncertainties in our dose calculations increase as we move closer to the accident site. The major cause of this loss of accuracy is the unavailability of measurements within the Soviet Union.

Summary

We have developed a highly computerized system (ARAC), using three-dimensional atmospheric dispersion models, for predicting the spread of airborne radioactive contamination from a variety of possible nuclear accidents and other emergencies. This system supports the emergency-preparedness plans at up to 50 DOE and DOD facilities and provides support to the Nuclear Regulatory Commission for civilian nuclear facilities as well as timely environmental assessments for accidents that happen away from these fixed sites.

To respond to the unexpected challenge of assessing the environmental impact of the Chernobyl accident, we had to expand the scale of both of our atmospheric models (MATHEW and ADPIC) a hundredfold and reactivate an older code (global PATRIC) to follow air-circulation patterns over the whole northern hemisphere. We also had to expand our data-acquisition system to accept weather and radiation measurements from many more sources than ever before, and adapt it to convert information from various formerly incompatible data bases into a common usable format.

Even before the Chernobyl event, our work had attracted international attention; we were already sharing our skills with other nations. The improvements that made it possible for us to make accurate assessments of this particular accident also place us in an even better position to help in future incidents.

Key Words: Atmospheric Release Advisory Capability; computer code—ADPIC, 2BPUFF, MATHEW, PATRIC; radiation monitoring; weather models.

Notes and References

1. P. H. Gudiksen, T. J. Sullivan, and T. F. Harvey, "The Current Status of ARAC and Its Application to the Chernobyl Event," Lawrence Livermore National Laboratory, Livermore, CA , Rept. UCRL-95562 (1986).