CONF-9508161--1

UCRL-JC-121765
PREPRINT

ARAC:
A Support Capability for Emergency Managers

John C. Pace, Thomas J. Sullivan, Ronald L. Baskett, James S. Ellis,
Connee S. Foster, Kevin T. Foster, John S. Nasstrom, Brenda M. Pobanz,
Walter W. Schalk III, and Philip J. Vogt
Atmospheric Release Advisory Capability
Regional Atmospheric Sciences Division

This was prepared for submittal to the
NEMA Emergency Management Information Technology Conference, Weather Mountain Facility, Berryville, VA
August 22nd-24th, 1995

August 1995

Lawrence Livermore National Laboratory

ARAC: A SUPPORT CAPABILITY FOR EMERGENCY MANAGERS

John C. Pace, Thomas J. Sullivan, Ronald L. Baskett, James S. Ellis,
Connee S. Foster, Kevin T. Foster, John S. Nasstrom, Brenda M. Pobanz,
Walter W. Schalk III, and Philip J. Vogt

Abstract

This paper is intended to introduce to the non-radiological emergency management community the 20-year operational history of the Atmospheric Release Advisory Capability (ARAC), its concept of operations, and its applicability for use in support of emergency management decision makers. ARAC is a centralized federal facility for assessing atmospheric releases of hazardous materials in real time, using a robust suite of three-dimensional atmospheric transport and diffusion models, extensive geophysical and source-description databases, automated meteorological data acquisition systems, and experienced staff members. Although originally conceived to respond to nuclear accidents, the ARAC system has proven to be extremely adaptable, and has been used successfully during a wide variety of nonradiological hazardous chemical situations. ARAC represents a proven, validated, operational support capability for atmospheric hazardous releases.

1. ARAC History

The ARAC project began in 1972 at the Lawrence Livermore National Laboratory (LLNL). Its mission was to develop a centralized means of predicting radiation dose levels and surface contamination from accidental atmospheric releases of nuclear materials. By the mid-1970s, a system of models had been developed, and a basic operating capability was achieved. Under the auspices of the U.S. Department of Energy (DOE), ARAC steadily improved and increased its capabilities, and its list of supported agencies grew rapidly. From 1983 to 1986, the system was redesigned to support a major expansion of service to the Department of Defense (DOD), and a high level of automation was implemented (Dickerson et al. 1985).

At various times, ARAC has supported over 70 facilities within the DOE and DOD with dedicated, on-site computer systems linked directly to ARAC's central computer system at LLNL. ARAC has also supported various federal, state, and international agencies with a wide variety of radiological and non-radiological predictions at locations across the United States and around the world. A key feature of the ARAC system is its flexibility, allowing its use in responding to situations unforeseen by the scientists who developed it.

Over the years, ARAC personnel have participated in assessments of a variety of actual releases ranging from small accidental ventings to the Chernobyl reactor disaster (Lange et al. 1988; Gudiksen et al. 1989). Each new situation helped identify areas in which ARAC's emergency response service could be improved. As a consequence, much of ARAC's growth has resulted from "lessons learned" being transformed into new capabilities (Sullivan 1988).

For example, in 1976, a train accident in North Carolina demonstrated that the availability of real-time meteorological data automatically formatted for use in the dispersion models was essential to a rapid response. In 1979, ARAC's largely manual response to the Three Mile Island accident indicated the need for automated, on-line, U.S. topography and geography databases (Knox et al. 1981). The 1986 Chernobyl accident propelled ARAC to implement continental-to-hemispheric scale models supported by worldwide terrain and mapping data (Sullivan 1991).

During the past 22 years, ARAC has responded to more than 70 alerts, accidents, and disasters, and to over 700 exercises. The characteristics of selected past responses are listed in Table 1. ARAC's flexibility and its capability to support simultaneous complex responses were demonstrated in 1991, when we responded to the Kuwaiti oil fires (Ellis et al. 1992, Sullivan et al. 1992a), the eruption of Mt. Pinatubo (Sullivan et al. 1992b), and a major chemical spill into the Sacramento River (Baskett et al. 1992), in addition to our routine support responsibilities.

The ARAC responses to these releases clearly indicated the potential for ARAC support to non-radiological emergencies. Over the past two years, ARAC has been conducting a multi-phase project with the aim of modeling toxic chemical releases with the same speed and accuracy we routinely achieve for radiological events.

2. Staff and Facilities

ARAC includes a staff of about 40 (roughly half operations staff and half computer scientists), a DEC ALPHA/VAX-based computer system, and about 35 remote-site computer systems. ARAC responses are coordinated by assessment meteorologists (known as assessors). A customer support center interfaces with supported sites, monitoring communications and equipment status and correcting problems. A technical staff maintains and upgrades ARAC's internal computers. Separate groups of computer scientists maintain and upgrade specific functions within ARAC: the core ARAC transport and diffusion models; the site workstation software; and the AEROS operating system (all described below). Finally ARAC is supported by research scientists within the Regional Atmospheric Sciences Division of LLNL, who develop improved algorithms for the ARAC models.

ARAC currently uses Digital Equipment Corporation (DEC) VAX 6610 computers to run the models, but will replace the 6-year-old 6610s with new DEC Alpha computers over the next year. ARAC uses microVAXs to communicate with UNIX-based Sun workstations (Abriam and Moore 1995) at supported sites. Each supported site has one or more meteorological towers that automatically transfer data directly into the on-site computer via modems every 15 min.

Currently the offices and computers of ARAC are housed in a complex of trailers at LLNL. In January 1996 ARAC will transfer to the National ARAC Center (NARAC) now under construction at LLNL. The NARAC was designed to accommodate ARAC's future growth into a national emergency response facility.

3. Concept of Operations

Figure 1 depicts the ARAC Emergency Response Operating System (AEROS) network; Figure 2 is a simplified diagram of its top-level functions. AEROS automatically assembles necessary information for the model run stream once the minimum incident data have been entered into the computer system with the on-line "problem questionnaire." Responses to hazardous atmospheric releases can be initiated in two ways:

- Assessors at the central ARAC facility can complete the on-line questionnaire using accident information received by telephone, either from supported sites or other locations, coupled with defaults from on-line databases.
- Personnel at supported sites can use their site workstations to enter accident information directly into the on-line questionnaire. This information is automatically transmitted to ARAC's central facility from UNIX-based workstations at the site via a 9600-baud modem. ARAC software engineers designed and wrote the code that runs the site workstations, specifically to meet the needs of ARAC and its customers.

In both cases, the operator can easily initiate an ARAC response with a simple menu choice that causes the questionnaire to be displayed and then prompts the operator for accident information such as time, location, and type of release. The request for an ARAC response immediately triggers a paging system that alerts ARAC's staff and sets in motion the acquisition of all available regional and site weather data for input into the model calculations. Within minutes, all model input data are in the central system. ARAC personnel then simulate the release with complex dispersion models that account for the effects of local meteorology and terrain, prepare graphical plots of the contamination overlaid on the local geography, and distribute these plots to on-site authorities. Following a quality assurance review by an assessor, plots for supported sites are transmitted digitally within seconds of completion for display on the site workstation computer. For other locations, plots are faxed or transmitted by other means.

For radiological and many toxic chemical incidents at ARAC-supported facilities, the time to create and deliver plots to the site's computer can be as short as 5 to 15 minutes after the receipt of accident information. For incidents at non-supported sites, the response time depends on the complexity of the source term, the availability of meteorological data, and the preparation of unique model-input parameters. Our chemical response project already allows us to achieve relatively rapid responses for many additional toxic chemical incidents, generally under 30-45 minutes. As we gain further expertise with toxic chemicals and further refine our databases, we expect to shorten this response time considerably.

4. ARAC Databases and Computer Codes

a. Databases

The ARAC computer codes combine real-time meteorological data with topographical data to calculate a detailed treatment of atmospheric dispersion that is three-dimensional, terrain-influenced, and spatially and temporally varying. Default data files and detailed site notebooks are maintained for all supported sites, and a worldwide library of potential accident sites is available, including locations such as nuclear power plants, fuel-cycle facilities, and similar installations. ARAC can also respond to releases at any location worldwide, adding only a few minutes to the overall response time in most cases.

During an ARAC response, hourly surface and twice-daily upper-air *meteorological data* are automatically acquired from ARAC's dedicated line (56K-baud capacity, now configured at 19.2 K-baud) to the U.S. Air Force Global Weather Central (AFGWC) . Within 2 minutes, these data can be received, decoded, and formatted for input to the model. Depending on the situation, meteorological variables, such as atmospheric stability, mixing height, and vertical-wind-power-law profile parameters, can either be determined automatically using on-line algorithms or input manually by the assessment meteorologist who is running the computer codes. A variety of *source-term inputs* such as release rate, source geometry, particle-size distribution, and deposition velocity are calculated from the questionnaire information and on-line databases. A key phase of our toxic chemical capability will be completed in December 1995, providing source term information for many chemical spills based on questionnaire input (chemical type, nature of spill, etc.), new on-line databases, and chemical source models.

The *geographic databases* provide mapping information on scales ranging from buildings and streets on the local scale to country outlines on the hemispherical scale. For general map coverage of the United States, ARAC uses the 1:1,000,000 Digital Chart of the World (DCW) database, or the U.S. Geological Survey (USGS) 1:2,000,000 Digital Line Graph (DLG) database (Walker 1989). ARAC's on-line *topographical database* is based on the Defense Mapping Agency's Digital Terrain Elevation Data, which covers most of the world with 0.1-km resolution. ARAC averages this to 0.5-km resolution for faster on-line access, but the 0.1-km data are available for specialized applications. The DOE's *dose-factor database* contains estimates of dose-conversion factors for internal and external exposure for nuclides of concern. In the future, ARAC plans to add a *population database.*

b. Computer Codes

At the foundation of the ARAC modeling effort are two three-dimensional, diagnostic, finite-difference computer codes: MATHEW (Mass-Adjust THE Wind) (Sherman 1978), and ADPIC (Atmospheric Diffusion Particle-In-Cell) (Lange 1978 and 1989). These codes are used in conjunction with TOPOG (a topographic grid generation code), MEDIC (MEteorological Data Interpolation Code), PLOT CONTOUR (a graphical contour plot generator), PERSPEC (a code for visualizing terrain), and DOSE (an application of radiological dose factors code). These codes make up ARAC's primary diagnostic dispersion modeling system. Figure 3 illustrates the basic MATHEW/ADPIC run stream that culminates in the hazard-assessment product. The typical run of this system takes about 5 to 10 min of

VAX CPU time to complete, including the automated preparation of the input files.

TOPOG uses topography databases (Walker 1985) to produce a block-form terrain representation of the lower boundary of the model system, which is used to determine how wind fields are influenced by underlying terrain. Hundreds of on-line terrain files are maintained for locations of interest; for new areas anywhere in the world, ARAC's operations staff can create a terrain file with a resolution 0.5 km × 0.5 km in 2 to 5 minutes. The model domain is typically divided into 35,000 cells with an array of 50 × 50 horizontal cells and 14 evenly-spaced vertical layers. Grids with more cells or layers can easily be generated as needed.

MEDIC uses an inverse-distance-squared ($1/r^2$) weighting of wind-speed and direction observations and wind-profile laws to extrapolate horizontal wind vectors to the face of each grid cell. MATHEW then applies a calculus-of-variations technique to create a mass-consistent, nondivergent flow field over the block-form terrain. The wind field calculated by MATHEW provides the three-dimensional mean wind components for ADPIC (described below). Because these are purely diagnostic models, thermally driven flows such as sea breezes, slope flows, or convective motion are not created in the calculations. These features can be resolved only if represented by the input wind observations.

ADPIC is a numerical, three-dimensional dispersion model capable of calculating the time-dependent distribution of air pollutants under many conditions including strongly distorted wind fields, calm conditions, wet and dry deposition, radioactive decay, and space- and time-variable turbulence parameters. It can simulate dispersion from instantaneous or continuous sources which are gases and/or poly-disperse aerosols, and which are affected by momentum or buoyancy-driven plume rise. Four inner nested grids with 2, 4, 8, and 16 times the resolution of the primary grid provide higher-resolution concentration calculations near sources.

ADPIC solves the three-dimensional advection-diffusion equation using Lagrangian marker particles. The original version of ADPIC, developed by Lange (1978 & 1989), solved the advection-diffusion equation using a hybrid Eulerián-Lagrangian particle-in-cell method incorporating K-theory gradient diffusion. A new version of ADPIC uses an option to calculate diffusion using the Random Displacement Method (RDM), a random walk, Monte Carlo method described by Ermak et al. (1995).

For radionuclides, the DOSE code determines dose factors for the desired individual organs or the whole body through inhalation, immersion, or ground-exposure pathways. Currently the models do not calculate either changes in chemical species or photochemical reactions.

PLOT CONTOUR produces a variety of plots using a geographic map overlay. Typical model results include plots of material deposited on the ground, instantaneous and time-integrated doses, or air concentrations at selected levels above the ground. Species or sources may be combined as required and contoured according to specified isopleth values. Legends describe the release, the species involved, and type, units, and valid time for the contours.

5. Model Evaluations

To quantify model accuracy, more than a dozen model-evaluation studies have been performed over the years in a variety of settings and scales. Figure 4 illustrates and Table 2 lists the MATHEW/ADPIC evaluations on the local-to-regional scales (1 to 100 km) over the last 20 years as described in many previous papers and summarized in Sullivan et al. (1993).

The studies are categorized as "simple", involving flat or rolling terrain with relatively steady meteorology, or "complex", involving rolling to complex terrain or complex meteorology, such as sea breezes, mountain-valley flows or changing winds during the tracer release.

Results show that the MATHEW/ADPIC models estimated the air concentrations of the tracer to within a factor of 2 of the measured values 20 to 50% of the time, and to within a factor of 5 of the measurements 35 to 85% of the time, depending on the complexity of the meteorological conditions, the terrain, and the release height.

Although model accuracy has been quantified for many different settings and scales, communicating the overall uncertainty on the ARAC plot remains illusive. Frequently, the emergency-response manager receiving an ARAC plot wants to know the error associated with the location of a contour or the accuracy of a concentration at a particular location. Currently, the answer is that at best the MATHEW/ADPIC models are within a factor of 2. This is true for the majority of points within the plume, especially if an allowance for the ± 5° uncertainty in reported wind direction is taken into account.

6. Toxic Chemical Response Example

An example of ARAC's capabilities took place on 26 July 1993, when a major rail car spill of oleum occurred in Richmond California (Baskett et al. 1995). The spill was caused by the failure of a pressure relief valve while a railroad tank car was being heated during a transfer operation. Midway through the 3-3/4 hour release, state and local agencies requested real-time modeling from ARAC. With approval from the DOE, ARAC responded to the accident under an Agreement in Principle with the State of California.

News reports indicated that the 10^4-kg (100-ton) tank car was loaded with 5 x 10^4 liters (13,000 gal) of 35 grade (35%) oleum ($H_2S_2O_7$). Sulfur trioxide (SO_3) gas was released to the atmosphere under high pressure and temperature, beginning at 7:15 a.m. PDT and ending when the tank was capped at about 11:00 a.m. After exiting the 7.5-cm (3-in.) diameter valve opening, the heated oleum rapidly expanded and cooled quickly condensing into a sulfuric acid liquid aerosol in the moist marine atmosphere. Initially the ARAC team was given a worst-case estimate that the full tank contents could be released over 1.5 hr. Later the source rate was revised to half the tank car over 3.75 hr.

The proximity of meteorological stations to the release and cloud location strongly affects the accuracy with which a diagnostic model can determine the plume position. Figure 5 shows that the accident was situated between three airports--Napa 32 km to the north, Concord 26 km to the east, and Alameda Naval Air Station 17 km to the south. Interpolating between these three stations produced a wind direction from 280° at 7:00 a.m. when it was known the wind was actually from the southwest. Due to the complex meteorological conditions, wind data from the airports alone were insufficient to reasonably determine the wind direction at the accident.

Fortunately ARAC was able to acquire in real time 15-minute average wind data from a Bay Area Air Quality Management District (BAAQMD) tower at Pt. San Pablo, about 5 km west of the accident. Figure 5 shows a 3 m/s wind from 221° at the start of the release at Pt. San Pablo. By 8:00 a.m., the wind shifted toward the south, and remained between 200 and 211° for the rest of the release period. Beyond the source location, the plume position was determined by interpolating between hourly observations from Napa and Concord. Figure 6 shows the mass-adjusted wind field at a single level, using all available observations.

A strength of the ARAC system is the presence of experienced meteorologists. Without the BAAQMD tower data, the diagnostic wind model would have been off by 60°. Had there been no tower data, ARAC assessors could have specified wind values to match the southwesterly flow expected due to channeling by the topography.

ARAC produced the first set of plots for the worst-case full-tank-car release just as the release was ending. These were used by the California Office of Emergency Services and the California Department of Health Services to initially scope the magnitude of the potential health effects. Later in the afternoon ARAC used the half-tank-car source rate to refine the calculation. Figure 7 shows the hour-average air concentration for the second hour after the release began for this lower source rate.

Air concentration plots describing the location and progress of the toxic cloud were faxed to the agencies managing the response. The primary protective action for the public was to shelter in place. Highways, rail lines and public transportation were blocked. The incident was significant enough that over 24,000 people sought medical attention within the week following the release. Eventually state and local agencies requested that ARAC remodel the accident after better source and meteorological data were collected. The revised contours near the source were rotated about 15 degree compared to the real-time response. Greater diffusion and the reduced source rate substantially reduced the hazard areas.

The BAAQMD took a single 3-hr average measurement of sulfuric acid on a high-volume sampler 2.3 km downwind on the east side of the plume. Each of the model results were within a factor of 2 of this value.

7. Future Directions

ARAC responded to a Sacramento River/Lake Shasta toxic herbicide spill in 1991, demonstrating that a framework for developing a toxic-chemical emergency-response modeling capability existed at ARAC in 1991. The Richmond California response in 1993 reaffirmed this fact. Significant progress in this direction has since been made, especially over the past two years. Default source terms, release mechanisms, toxic chemical properties databases and exposure indices have been added to the ARAC system, and routine training now includes the assessment of toxic chemical accidents. *We now have a real-time operational capability for responding to releases of many toxic chemicals.* To continue developing our toxics response capability, new tools will need to be engineered into the operational environment, including a dense-gas model such as the one developed by Ermak (1992). Databases will need to be expanded, chemical reactions will need to be modeled, and industrial hygienists and chemists will have to be added to the ARAC operations staff. Much of this work is underway.

Several significant enhancements are now being made to the ARAC model system. One, a "hybrid-particle" extension of ADPIC, is already quasi-operational. This improvement allows ADPIC to model an unlimited number of nuclides and the ingrowth and decay of daughter products. Consequently, sources of mixed fission products, such as those from nuclear reactor accidents, are treated in their full complexity.

In addition, research at LLNL has developed state-of-the-art treatments of diffusion using Monte Carlo techniques based on the Langevin equation and random displacement formulations in ADPIC (Rodean et al. 1992). These methods (a) improve diffusion calculations near sources, (b) use direct measures of atmospheric turbulence, (c) eliminate grid-based numerical errors in the diffusion calculation, and (d) improve diffusion calculations in unstable boundary layers.

Near-future plans include engineering the Navy Operational Regional Atmospheric Prediction System (NORAPS), a regional-scale prognostic model (Hodur 1978), into the ARAC system. Prognostic models can simulate and forecast flows dominated by local forcing (e.g., nocturnal drainage flows and sea-breeze circulations). In the future, more powerful computers will allow an even more sophisticated, non-hydrostatic meteorological model, the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (Hodur 1993) and dense-gas dispersion models (e.g., Chan 1992) to be used for very complex emergency response problems.

ARAC's model evaluation studies have revealed that routine hourly surface observations and twice-daily rawinsondes taken at airports limit the accuracy of the wind field model. ARAC anticipates improved support capability as more-frequent observations from the Automated Surface Observing System (ASOS) become available. Possibly the greatest improvement for initializing regional-scale dispersion models could be realized with hourly profiler data such as from the National Oceanic and Atmospheric Administration's Wind Profiler Demonstration Network.

8. Summary

Our ability to monitor and predict the environmental and health impact of natural and man-made hazardous phenomena is becoming ever more important as our world increasingly depends on sophisticated technologies. Over the past 22 years, ARAC has developed and evolved a computer-based, real-time, radiological-dose assessment service for the U.S. Departments of Energy and Defense. This service is built on the integrated components of computer-acquired, real-time meteorological data, extensive computer databases, numerical atmospheric-dispersion models, dose-effects models, graphical presentation codes, plus the extensive expertise of an operational assessment staff. The focus of ARAC is on the off-site problem (i.e., a few kilometers and beyond) where regional meteorology and topography are the dominant influences on the transport and diffusion of hazardous material. Numerous model-evaluation studies have confirmed the practicality of this modeling system for point-source accident/event release on local, to regional, to continental scales. Many past real-time applications of this system have resulted in significant enhancements of the ARAC emergency response system. Recent applications to toxic spills in Richmond California and in the upper Sacramento River and Lake Shasta, to oil fires in Kuwait, and to Mt. Pinatubo's volcanic eruptions have shown the program's utility and flexibility.

The ARAC modeling system provides a means for quickly determining the probable scope of an atmospheric emergency. Emergency managers can use ARAC's graphical products to develop the best response strategy to minimize hazards to life and property in the affected regions. The program continues to evolve in response to identified needs, to gain experience from actual accident responses, and to upgrade data sources. Development and incorporation of advanced atmospheric-dispersion models, both diagnostic and prognostic, and further enhancement of a real-time, toxic-chemical emergency response capability are major goals for the program during the next few years.

Acknowledgment

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

References

Abriam, R. O. and R. M. Moore, 1995: ARAC's Site Workstation Final Design and Deployment. ANS Fifth Topical Meet. on Emergency Prepared. & Response, April 18-21, 1995, Savannah, GA. UCRL-JC-118040. 3 pg.

Baskett, R. L., J. S. Nasstrom, J. J. Watkins Jr., J. S. Ellis, and T. J. Sullivan, 1992: Atmospheric modeling of the July 1991 metam sodium spill into California's Upper Sacramento River, *Proceedings of the 85th Annual Mtg. of the Air and Waste Management Association*. Kansas City, Paper 92-155.01; also Lawrence Livermore National Lab. Rep. UCRL-JC-109835.

Baskett, R. L., P. J. Vogt, W. W. Schalk,III, C.S. Foster, and J.S. Ellis. 1995: The Challenge of emergency response dispersion models on the meso-gamma urban scale: A case study of the July 26, 1993 oleum tank car spill in Richmond, California. ANS Fifth Topical Meet. on Emergency Prepared. & Response, April 18-21, 1995, Savannah, GA. UCRL-JC-118082. 5 pg.

Chan, S. T., 1992: Numerical simulations of LNG vapor dispersion from a fenced storage area. *J. Haz. Mat.*, 30, 195–224.

Dickerson, M. H., P. H. Gudiksen, T. J. Sullivan, and G. D. Greenly, 1985: ARAC status report: 1985. Lawrence Livermore National Lab. Rep. UCRL-53641, 18-pp. [Available from National Technical Information Service, U.S. Dept. of Commerce, Springfield, Virginia 21161.]

Ellis, J. S., C. S. Foster, K. T. Foster, T. J. Sullivan, R. L. Baskett, J. S. Nasstrom, W. W. Schalk III, and G. D. Greenly Jr., 1992: Daily dispersion model calculations of the Kuwait oil fire smoke plume. *Proceedings of the 85th Annual Mtg. of the Air and Waste Management Association*. Kansas City, Paper 92-76.05; also Lawrence Livermore National Lab. Rep. UCRL-JC-109830.

Ermak, D. L., 1992: Dense-gas dispersion advection-diffusion model. *Proceedings of the Joint Army-Navy-NASA-Air Force Safety and Environmental Protection Subcommittee Meeting*. Monterey; also Lawrence Livermore National Lab. Rep. UCRL-JC-109697.

Ermak, D.L., J.S. Nasstrom and A.G. Taylor, 1995: Implementation of a Random Displacement Method (RDM) in the ADPIC model framework , UCRL-ID-121742, Lawrence Livermore Nat. Lab., Livermore, CA.

Gudiksen, P. H., T. F. Harvey, and R. Lange, 1989: Chernobyl source term, atmospheric dispersion, and dose estimation. *Health Phys.*, 57, 697–706.

Hodur, R. M., 1978: Evaluation of a Regional Model with an Update Cycle. *Mon. Wea. Rev.*, 115, 2707-2718.

Hodur, R. M., 1993: Development and Testing of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). NRL/MR/7533--93-7213.

Knox, J. B., M. H. Dickerson, G. D. Greenly, P. H. Gudiksen, and T. J. Sullivan, 1981: The Atmospheric Release Advisory Capability (ARAC): Its use during and after the Three Mile Island accident. Lawrence Livermore National Lab. Rep. UCRL-85194, 41 pp.

Lange, R., 1978: A three-dimensional particle-in-cell model for the dispersal of atmospheric pollutants and its comparison to regional tracer studies. *J. Appl. Meteor.*, 17, 320–329.

Lange, R., 1989: Transferability of a three-dimensional air quality model between two different sites in complex terrain. *J. Appl. Meteor.*, 28, 665–679.

Lange, R., M. H. Dickerson, and P. H. Gudiksen, 1988: Dose estimates from the Chernobyl accident. *Nucl. Technol.*, 82, 311–322.

Rodean, H. C., R. Lange, J. S. Nasstrom, and V. P. Gavrilov, 1992: Comparison of two stochastic models of scalar diffusion in turbulent flow. Preprints: *The 10th Symposium on Turbulence and Diffusion.* Portland, Amer. Meteor. Soc., 106–109; also Lawrence Livermore National Lab. Rep. UCRL-JC-110377.

Sherman, C. A., 1978: A mass-consistent model for wind fields over complex terrain. *J. Appl. Meteor.*, 17, 312–319.

Sullivan, T. J., 1988: ARAC: Evolution by accident. *Proceedings of the Topical Meeting on Emergency Response Modeling*, Charleston, Amer. Nucl. Soc., 1–8; also Lawrence Livermore National Lab. Rep. UCRL-98033, Rev. 1.

Sullivan, T. J., 1991: ARAC: A computer-based emergency-response dose-assessment service with global application potential. *Proceedings of the Tenth International System Safety Society Conference*, Dallas, 6.1-2-1–6.1-2-16; also Lawrence Livermore National Lab. Rep. UCRL-JC-107201.

Sullivan, T. J., J. S. Ellis, C. S. Foster, K. T. Foster, R. L. Baskett, J. S. Nasstrom, and W. W. Schalk, 1992a: Modeling of air currents in the gulf region. Chapter 4 in *The Gulf War and the Environment* , F. El-Baz and R. M. Makharita, Ed., Gordon and Breach Science Publishers S.A., World Trade Center, Case postale 531, 1000 Lausanne 30 Grey, Switzerland; also Lawrence Livermore National Lab. Rep. UCRL-JC-110365.

Sullivan, T. J., J. S. Ellis, W. W. Schalk, and J. S. Nasstrom, 1992b: Ash Cloud Aviation Advisories. *Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety*, Seattle, 14 pp.; also Lawrence Livermore National Lab. Rep. UCRL-JC-111060.

Sullivan, T. J., J. S. Ellis, C. S. Foster, K. T. Foster, R. L. Baskett, J. S. Nasstrom, and W. W. Schalk, 1993: Atmospheric Release Advisory Capability: Real-Time Modeling of Airborne Hazardous Materials. *Bull. Amer. Meteor. Soc.*, 74, 2343-2361.

Walker, H., 1985: Spatial data requirements for emergency response. *Proceedings of the 1985 Conf. on Emergency Planning*. San Diego, Soc. for Computer Simulation, 15 (1), 82–86; also Lawrence Livermore National Lab. Rep. UCRL-91263.

Walker, H., 1989: Use of the 1:2,000,000 digital line graph data in emergency response. *Proceedings of the International Symp. on Cartography and Computing, AUTO CARTO IX*. Amer. Soc. Photogrammetry and Remote Sensing/Amer. Congress on Surveying and Mapping, Baltimore, 472–482; also Lawrence Livermore National Lab. Rep. UCRL-99435.

Table 1. Some ARAC responses over the history of the project.

Year	Location	Source	Release
1976	North Carolina	Train accident	Uranium hexafluoride
1978	Northern Canada	COSMOS 954 reentry	Fission products
1979	Harrisburg, Pennsylvania	Three Mile Island Nuclear Power Plant	Mixed fission products
1980	Damascus, Arkansas	Titan II missile	Missile fuel
1981	Indian Ocean	COSMOS 1402 reentry	Fission products
1982	South Carolina	Savannah River Plant	Hydrogen sulfide leak
1986	Gore, Oklahoma	Sequoyah Fuels Plant	Uranium hexafluoride
1986	Chernobyl, USSR	Nuclear Power Plant	Mixed fission products
1988	Miamisburg, Ohio	Mound Plant	Tritium gas
1989	Amarillo, Texas	Pantex Plant	Tritium gas
1991	Persian Gulf	Nuclear facilities Kuwait oil fires	Mixed fission products Smoke
1991	Philippines	Mt. Pinatubo	Volcanic ash
1991	Northern California	Railroad car spill	Toxic gas products
1992	Sosnovy Bor, Russia	Nuclear power plant	Radioactive gases
1993	Richmond, California	Railroad tank car	Sulfur trioxide
1993	Tomsk-7	Explosion in fuel rod tank	Mixed fission products
1994	ETEX	Tracer Experiment	perfluoromethyl-cyclohexane
1994	Chelyabinsk-65	Fire	Cs-137
1994	Papua New Guinea	Volcano	Volcanic ash
1995	Vandenberg AFB	Missile launch support	Hydrochloric acid

Table 2. Summary of local-to-regional-scale evaluations of MATHEW/ADPIC.

Sponsor	Location	Date	Topography/meteorology	Atmospheric stability	Release height (m)	Sampler distance (km)
NOAA	Idaho National Engineering Lab, Idaho	1971	Flat to rolling plain/ daytime flows	Slightly unstable	Surface	5 to 90
SRP	**Savannah River Plant, South Carolina**	**1974**	**Rolling coastal plain/ daytime flows**	**Slightly unstable**	**62**	**3 to 30**
DOE	Three Mile Island, Harrisburg, Pennsylvania	1980	Flat river valley/diurnal flow	All	60	1 to 8
EPRI	**Kincaid, Illinois**	**1980–81**	**Flat plain**	**All**	**187***	**1 to 50**
ASCOT	Geysers Geothermal Area, California	1980	Coastal interior valley/ nocturnal drainage	Stable	Surface and 60	0.5 to 10
ASCOT	**Geysers Geothermal Area, California**	**1981**	**Coastal interior valley/ nocturnal drainage**	**Stable**	**Surface and 60**	**0.5 to 10**
MATS	Savannah River Plant, South Carolina	1983	Rolling coastal plain/ daytime flows	Neutral to unstable	62	30
ENEL	**Montalto, Italy**	**1984**	**Coastal plain/sea breeze**	**Unstable**	**10 and 50**	**1.5 to 6.5**
ASCOT	Brush Creek, Colorado	1984	Mountain valley/ nocturnal drainage	Stable	Surface and 220	0.5 to 10
Risø	**Øresund Strait, Sweden–Denmark**	**1984**	**Flow over cold water to land**	**Neutral**	**95**	**22 to 42**
PG&E	Diablo Canyon Nuclear Power Plant, California	1986	Mountainous coast/sea breeze	Neutral	1.5 and 71	0.5 to 40
ASCOT	**Rocky Flats Plant, Colorado**	**1991**	**Plateau at base of mountain range**	**Stable and neutral**	**10**	**8 and 16**

*Plus plume rise.

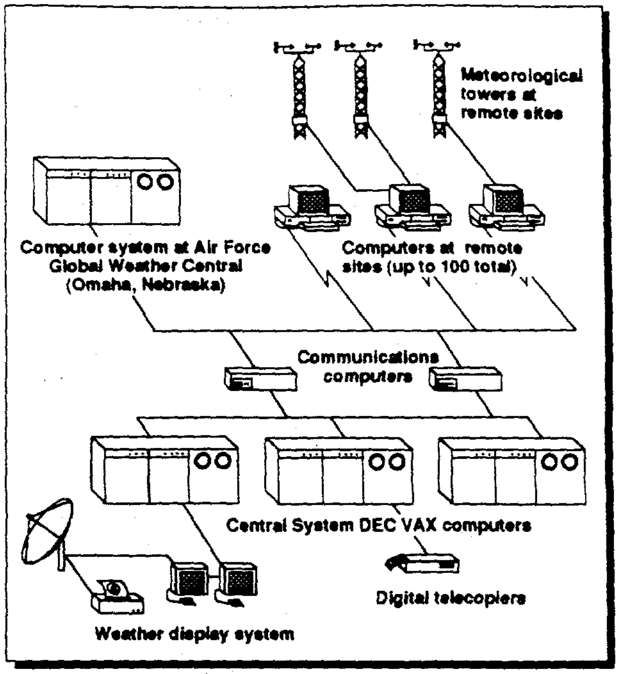

FIG. 1. The ARAC Emergency Response Operating System (AEROS) computer network. Each ARAC–supported facility in the system has a desktop computer for entering initial accident reports and one or more meteorological towers for providing the latest weather data. High-speed data links transmit this information to ARAC's computer center for use in atmospheric models.

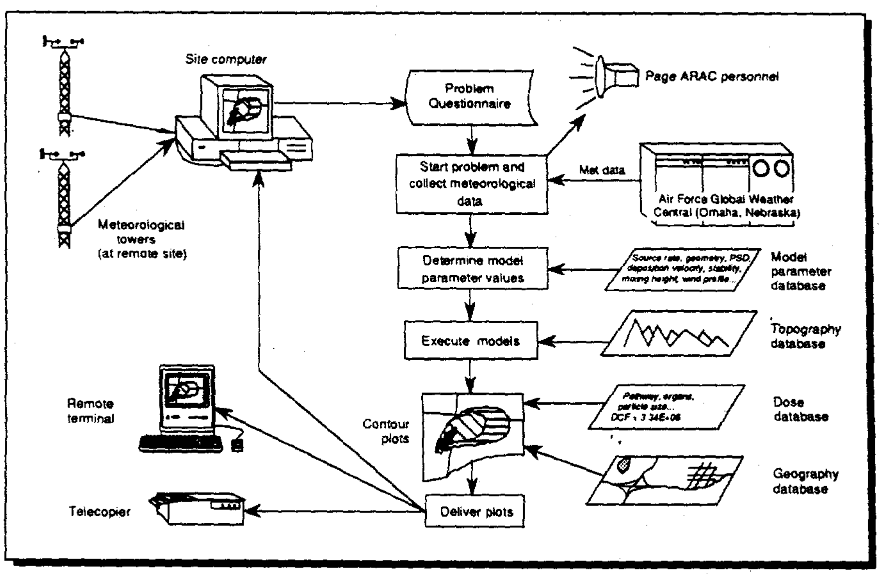

FIG. 2. The primary functions of the AEROS computer network.

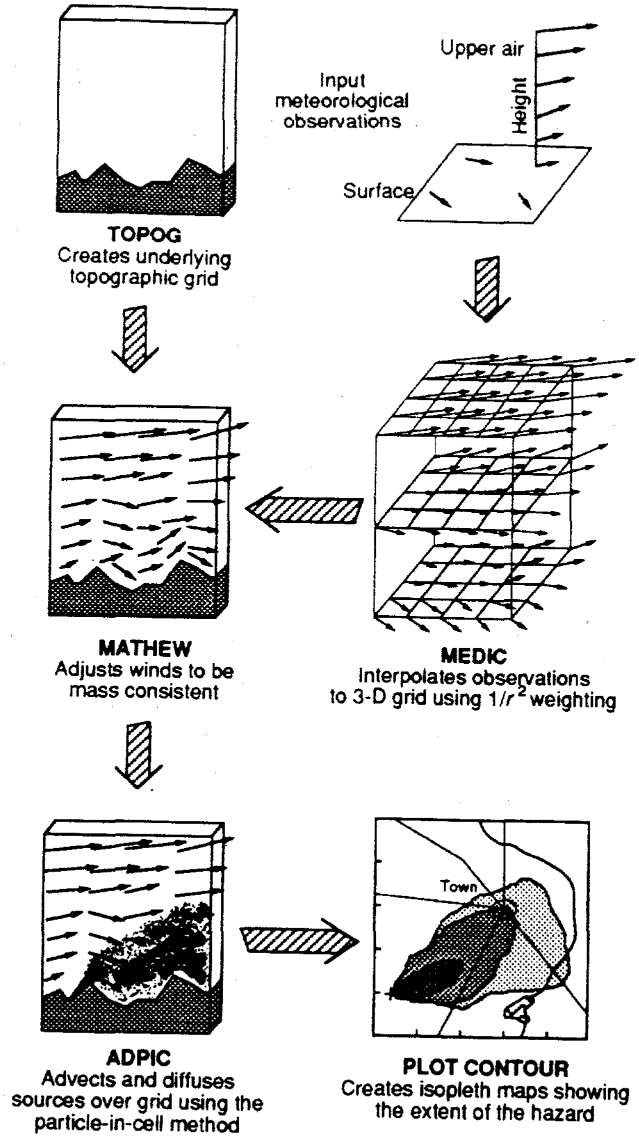

FIG. 3. Sequential run stream of ARAC's primary models used in calculating emergency response hazard assessments.

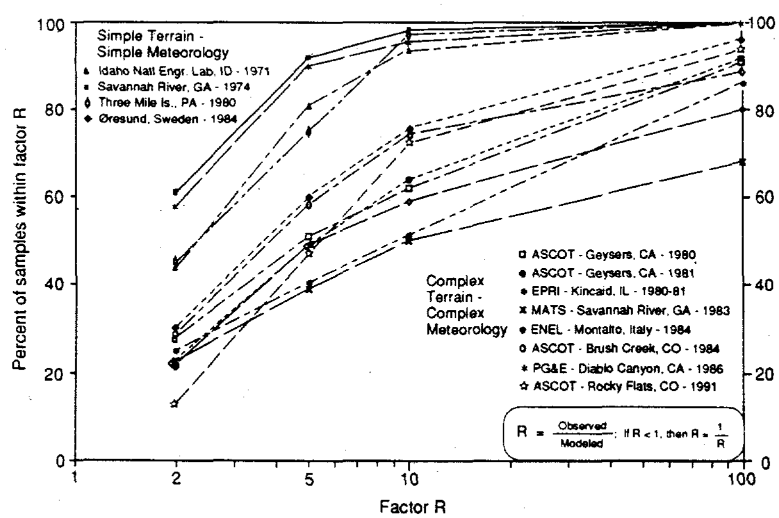

FIG. 4. Accuracy of MATHEW/ADPIC models from comparisons with 12 local- to regional-scale field studies. Each curve is derived from hundreds to thousands of ratios of individual observations to model calculations, paired in time and space.

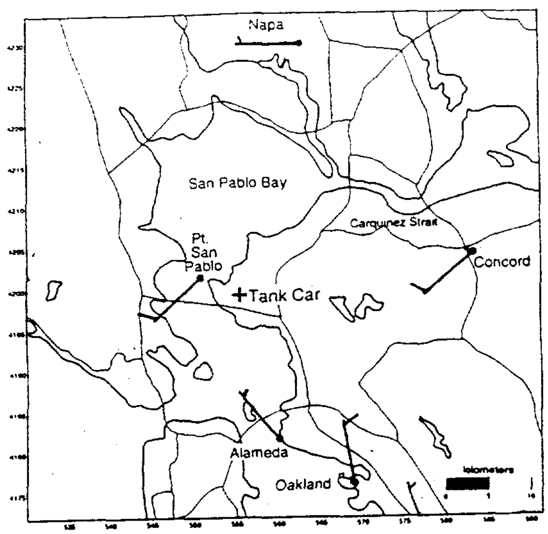

Fig. 5. Surface wind barbs from northern Bay Area at 7:15 a.m. PDT on July 26, 1993.

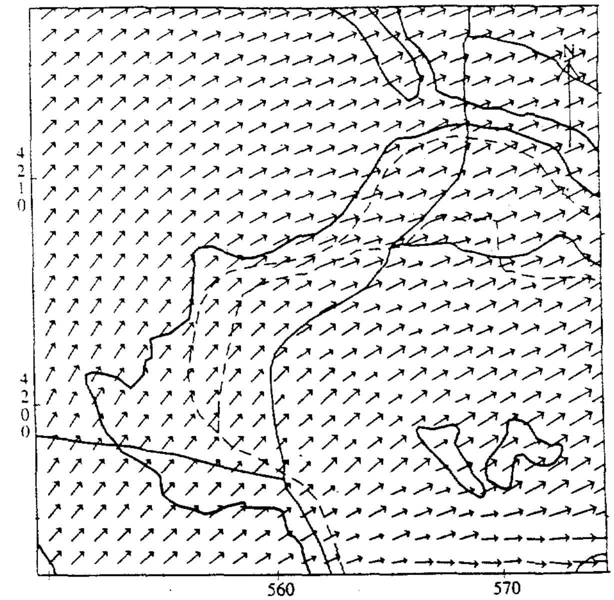

Fig. 6. Mass-adjusted wind field for 7:15 a.m. on July 26, 1993.

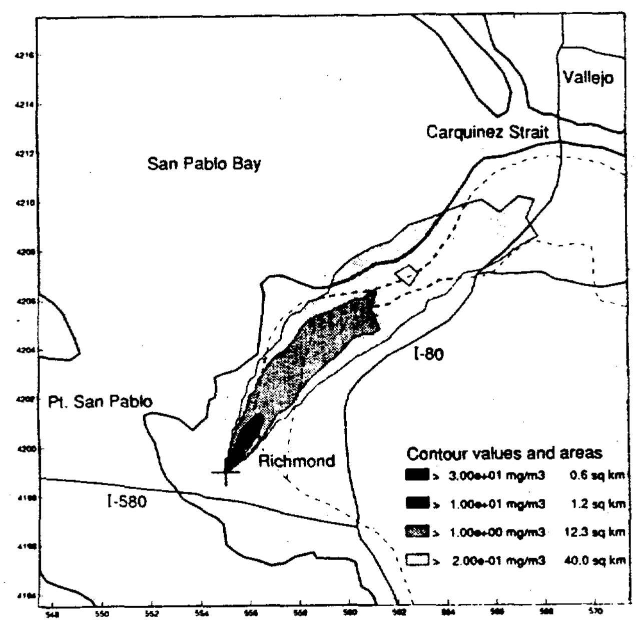

Fig. 7. Second-hour average H_2SO_4 air concentration for half-tank car release rate.