ARAC RESPONSE TO THE CHERNOBYL REACTOR ACCIDENT

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INTRODUCTION

On Monday morning, 28 April, after radioactive material was discovered on the clothing of workers entering a nuclear power plant in Scandinavia, the United States Department of Energy (DOE) requested that the Atmospheric Release Advisory Capability (ARAC),[1,2] located at Lawrence Livermore National Laboratory (LLNL), begin calculations to determine the extent and magnitude of the airborne nuclear material released from the Chernobyl nuclear power plant accident. These calculations were needed to estimate the environmental consequences in Europe, Scandinavia, and the western Soviet Union so potential health effects could be evaluated for U.S. citizens either visiting or working in these areas of the world. The two fundamental assessments ARAC calculated for the Chernobyl reactor accident were:

- I-131 and Cs-137 dose and dry deposition estimates for Europe and Scandinavia.
- Impact on the U.S. from I-131 deposition.

Although ARAC had many of the resources necessary to address a problem of this magnitude, they were not readily available (i.e., implemented in an operational emergency response system) and interfaced for calculating real-time assessments. ARAC's scope (in support commitment and resources, i.e., personnel and computers) is presently scaled to support domestic accidents on a regional scale for approximately 50 specific sites. A planned upgrade and expansion to a full response "national" center has been planned for several years, but has not been funded. Such a center would have the resources (calculational, data-flow/data-storage, model, and staff) to effectively respond in "near real-time."

The majority of the time spent during the first two to three days of work was concentrated on estimating the source term using trajectories and the 2BPUFF[3] two-dimensional long-range transport and diffusion model, which was developed in the 1960's during the Plowshare program. In addition, the MATHEW[4]/ADPIC[5] and Global PATRIC[6,10] models were expanded and modified to help estimate the consequences. The MATHEW/ADPIC computer codes are three-dimensional transport and diffusion models developed over the past twelve years for real-time dose assessments on scales of up to 200 km. To address the initial phases of the Chernobyl accident, these models required an expansion to a scale of approximately 2000 km. The PATRIC three-dimensional model, used previously for tracking and estimating doses to aircraft passengers and crew flying through radioactive debris from Chinese atmospheric tests, was modified then implemented to estimate the global dispersion of radioactive material from the reactor.

Initial environmental data available for these calculations were:

- Measurements of air concentration and ground deposition from Scandinavia for approximately 15 fission products. Of these, I-131 and Cs-137 were selected for the initial source term estimates and dose and deposition calculations. These two radionuclides were chosen because they were the most readily measured and reported, and they are significant contributors to potential doses to the public.
- Surface and upper air measurements of wind speed, wind direction, and temperature. These were obtained from the Air Force Global Weather Central (AFGWC) located at Offutt Air Force Base in Nebraska. This data link has served ARAC as a prime source of meteorological data for the past 10 years. However, observational

data on *this* space scale (2000 km), particularly from the Soviet Union, had never been requested as input for model calculations. Large data handling and software efforts were required at both LLNL and AFGWC to process and exchange the volumes of data—a fact which contributed to the delayed ARAC response using the more complete three-dimensional models.

This report describes: (1) the work required to adapt the models for the Chernobyl dose assessments, (2) source term estimates using the models coupled with the environmental data, (3) dose and dry deposition estimates for I-131 and Cs-137 for the Soviet Union, Europe, and Scandinavia, and (4) I-131 deposition estimates for the U.S. An appendix is used to provide a summary of daily ARAC activities for the two-week period directly following the accident.

DATA AND MODEL PREPARATION

ARAC emergency response and assessment calculations are based on the incorporation of all available meteorological data for the area of concern. From the outset of the Chernobyl accident, this became a major problem—initially because of the failure of the Soviet Union to provide notification of the location, time, or magnitude of the accident, and later because of the extensive data retrieval effort required to acquire all the essential data, for a four- to seven-day prior period, encompassing the western Soviet Union, Europe, and eventually the entire northern hemisphere.

ARAC's initial attempts to automatically request and process the vast quantity of data from the AFGWC failed because of complete data overload and non-processable meteorological code forms. To rectify these problems, ARAC negotiated a real-time data retrieval and support arrangement with AFGWC whereby all required surface and upper air data were preprocessed and staged for delivery during ARAC's established 12- to 14-hour workday intervals, until all data were acquired from 29 April back through 22 April. This process was successfully accomplished over the period 29 April—2 May. Thereafter, only current observational data were required. In addition, on 29 April AFGWC agreed to reduce and copy eight days worth of surface and 850 mb charts, and deliver the package to the Omaha airport for immediate shipment via air package to San Francisco. ARAC team members met the flight on the night of the 29th, therefore making charts available with which to commence trajectory preparation on the morning of 30 April. On 2 May a third major data retrieval and collection was initiated with AFGWC to acquire all the gridded northern hemisphere analyses from 26 April to the current date, for the 1000 mb, 850 mb, 700 mb, and 500 mb levels. Data from these vertical levels were necessary to commence hemispheric scale calculations—calculations required by the appearance of radioactivity over Japan on 2 May. Subsequently (~ 7–8 May), ARAC found it necessary to further request higher altitude data grids, namely 400 mb, 300 mb, and 250 mb levels, back to 26 April.

Even with all the assistance from AFGWC, this enormous volume of data needed to be organized and managed in order to preclude saturation of the ARAC computers. ARAC's two computers (VAX 11/782's) were totally committed to the Chernobyl support, occasionally along with substantial portions of a CDC 7600 in the LLNL Computer Center. The huge volumes of data were manually (via CRT) reviewed, edited, sorted, filed, backed up and managed. All the gridded hemispheric data were subsequently offloaded from the ARAC computers and transferred to LLNL's CDC 7600's and MASS storage system.

Four major calculational thrusts were undertaken during the 28 April—9 May emergency response period. The first calculations were provided by the 2BPUFF model in conjunction with the initial manually prepared parcel trajectories (Figure 1a). From the resultant concentration vs. time output, ARAC was able to commence a "source term" estimation process which was calibrated against the early (28 April) Scandinavian measurements. The second model calculations, begun on 1 May, were automated, multiple-level parcel trajectories (Figure 1b). The third modeling effort in the initial phases of the response was a two-part application of ARAC's primary MATHEW/ADPIC models.

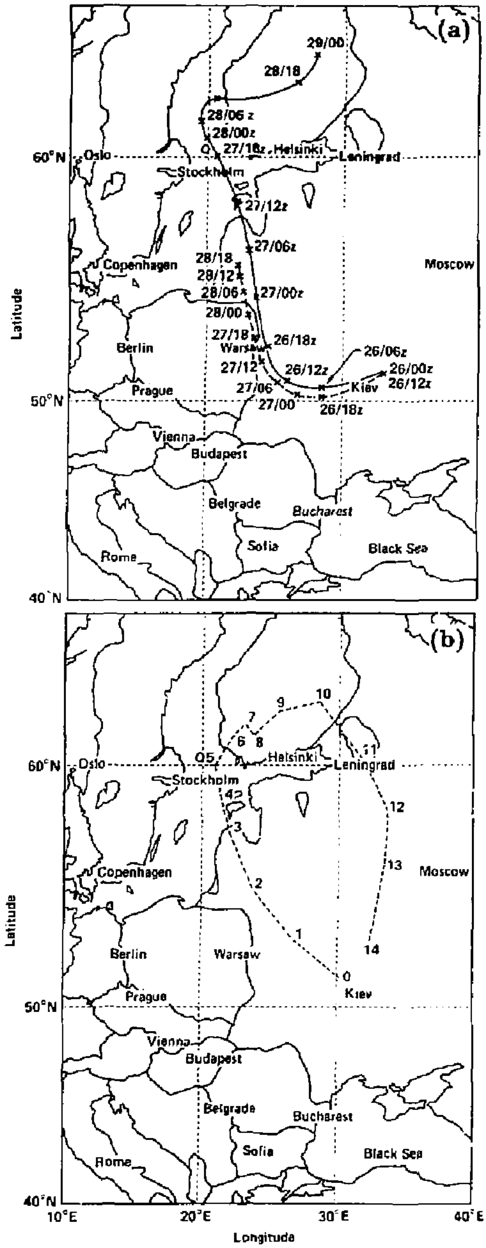

Figure 1.

Trajectory plots for parcels released at 1500 m over Chernobyl: **a)** manually prepared for three days starting at 00Z (solid) and 12Z (dash) 26 April 1986; **b)** automatically (model) prepared for seven days (14 × 12 hours) starting at 00Z 26 April 1986.

The first part was a calculation covering a 200×200 km region centered on Chernobyl (Figure 2b); it quickly became apparent that this was insufficient to answer the questions arising from the ubiquitous spread of radioactivity across Europe. Thus, the first MATHEW/ADPIC modeling effort was terminated and a second was initiated covering the largest area possible within the limitations of the model, and with acceptable and tolerable compromises.

The grid chosen was 1920 km on a side, and extended 2100 m in the vertical. The horizontal grid mesh was 48 km and the vertical grid spacing was 150 m. In Figure 2b, a nested sampling grid is shown around the source (Chernobyl) for horizontal cell sizes of 3 km, 6 km, 12 km, and 24 km respectively. These nested grids were used to sample the particles that produced concentration and deposition estimates near the reactor site. This particular grid was chosen because it represented the largest grid that could be used for the MATHEW/ADPIC models without a major revision of the computer codes being required. In addition, this grid allowed for coverage of a reasonably sized area of interest for the initial dose and deposition calculations.

An eight-hour programming and editing effort produced the background geographic map from the World Data Base II, a dataset which ARAC possesses on magnetic tape. No terrain data was available for inclusion in these calculations, a fact not too significant except in the northwest and southwest portions of the grid.

The fourth modeling effort initiated involved resurrecting a previously "shelved" R&D model (Global PATRIC) for hemispheric transport and dispersion. This model had the potential to, initially, qualitatively describe the long-range transport of radioactive material across Asia, Japan, the Pacific Ocean, and over the North American continent. Furthermore, it also accounted for the transport of material throughout Europe and the Mediterranean region. Results of these calculations are discussed later in this report.

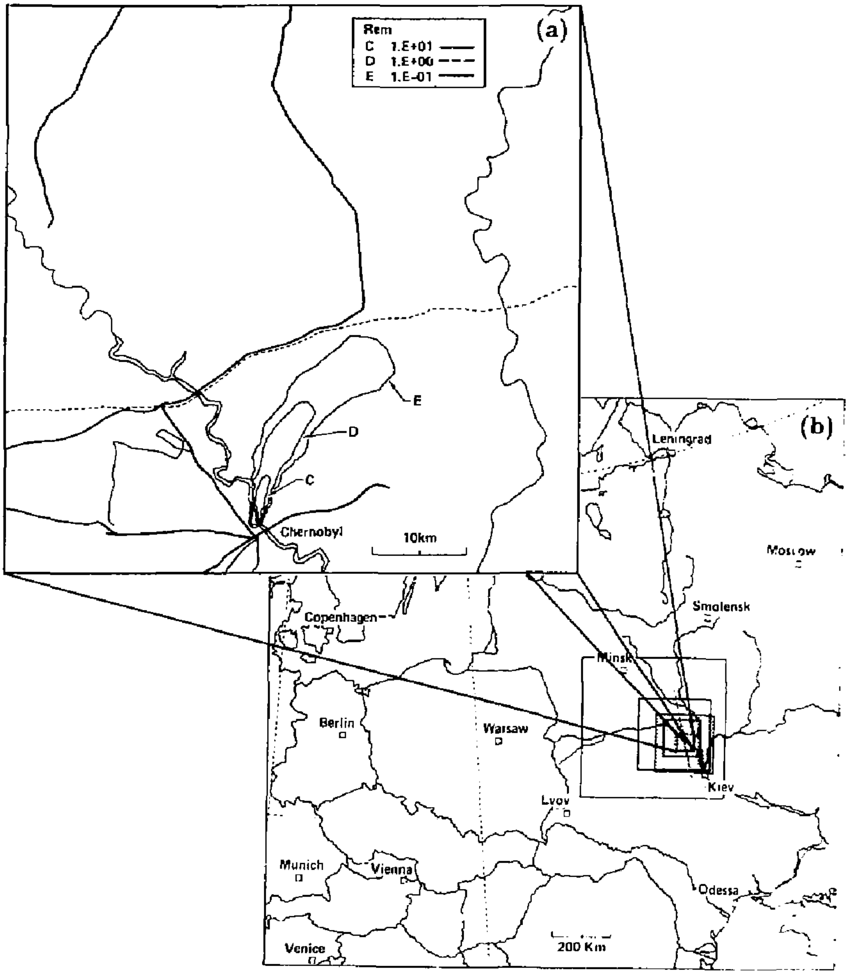

Figure 2.

The calculational grids used for the MATHEW/ADPIC models: **a**) the calculated infant thyroid dose due to I-131 inhalation for a six-hour period on 29 April shown on a 60 km expanded subregion of the 200 km grid; **b**) the final 1920 × 1920 km grid (48 km cells) with the nested subgrids (3 km, 6 km, 12 km, and 24 km cells) outlined and the initial grid (200 × 200 km) shaded.

SOURCE TERM ESTIMATES

The source term for the reactor accident was divided into two parts, a lower and an upper cloud. The lower level cloud was assumed produced over a period of six days as a result of heat from the burning reactor. The upper level cloud was assumed produced by one or more of the following: explosions followed by a hot fire for several hours, convective activity near the Chernobyl reactor site associated with thunderstorms, or lift over a warm front located between Chernobyl and the Baltic Sea. One major part of the ARAC effort during the first two weeks following the accident was associated with the determination of a lower level source term and the associated consequences.

Using the grid shown in Figure 2b and the initial source estimate derived from the previously mentioned environmental measurements of Cs-137 and I-131, in combination with the 2BPUFF results, the MATHEW/ADPIC model was used to refine the estimate of the low level source term for the first six days of the accident. Providing a reasonable description of the source term required a vertical distribution of the radioactivity as well as a time dependence of the release.

Figure 3a shows the vertical distribution of material used to define the lower level source term in the MATHEW/ADPIC calculations. This estimate was based on prior experience simulating heated plumes within air masses—air masses which contained vertical temperature distributions *similar* to those shown by vertical atmospheric soundings near Chernobyl. Eighty per cent (80%) of the released material was assumed to reside between 1000 m and 1500 m, with the remaining 20% located between the surface and 1000 m. The maximum concentration was located at 1000 m.

Table 1 lists the assumed total inventory of I-131 and Cs-137 contained in the reactor at the time of the accident. Also listed in Table 1 is the assumed released fraction of this material and its distribution in parts A and B of Figure 3a. Once this low level source term estimate was established, it was used for the calculations derived from data covering the first two weeks of the accident. This source term is now being revised using additional

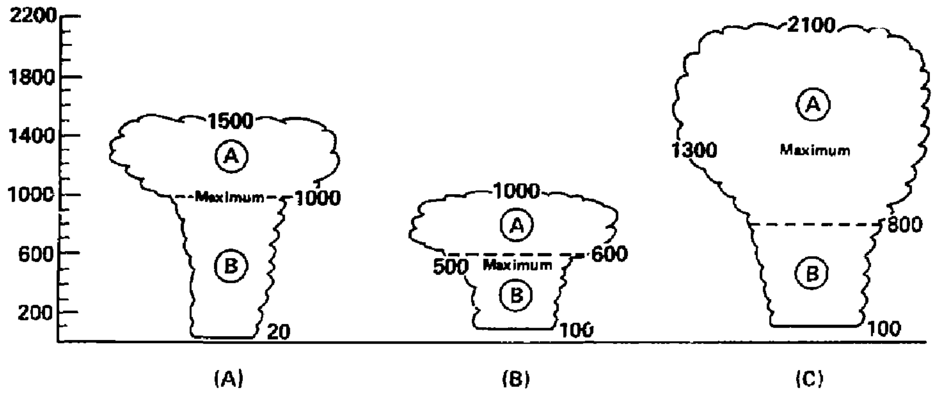

Figure 3.
Depictions of the vertical distribution of source material (explosion and fire cloud): a) average distribution as used in the ADPIC calculations; b) the night and c) day, respectively, vertical distributions calculated with a non-hydrostatic cloud model.

environmental data that have been received since the accident. A report describing this new source term and additional dose calculations will be available in the future.[7]

Table 1. Assumed Inventory and Released Fraction of I-131 and Cs-137 for the Low Level Cloud

INVENTORY (MCi)

I-131	80
C-137	6

Released Fraction (MCi)

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
I-131	32.0	1.6	1.6	1.6	1.6	1.6
Cs-137	2.4	0.12	0.12	0.12	0.12	0.12

From the PATRIC hemispheric scale model calculations, it rapidly became apparent that some radioactive material was convected or lofted (or both) to much higher altitudes than that assumed for the MATHEW/ADPIC calculations. A series of calculations with material released to 2500 m, 4200 m, and 5500 m failed to transport contamination to Japan and North America even close to the recorded arrival times—if at all. While limitations of the model reduce some of the precision desired, it presently appears that at least some material had to be injected at altitudes in the 5000–7000 m range in order to account for the long range transport of the radioactivity. Further studies regarding this matter are in progress.

Figure 4, produced by the MATHEW/ADPIC models using the AFGWC wind data, shows the particle distributions 48 hours after the accident. Air concentration patterns, derived from particle distributions similar to this one, were used to estimate the lower level source term. A radioactivity value, in curies, was assigned to each particle so that air concentration values calculated from particle distributions over Scandinavia matched environmental measurements for both I-131 and Cs-137.

Toward the end of the two-week period immediately following the accident, the vertical distribution of the low level source term was quantitatively estimated by a two-dimensional non-hydrostatic cloud model running at a high resolution.[8,9] This model was developed to simulate thunderstorms and, more recently, has been applied to simulate smoke dispersion from large-scale urban fires. The estimated source strength for the model calculations was 62 megawatts, which is the estimate for decay heat associated with this size and type of reactor accident. Figures 3b and 3c show the vertical distribution of material, calculated by this model, for both nighttime and daytime atmospheric soundings taken near the Chernobyl reactor site at the time of the accident. During the nighttime (Figure 3b), the model estimated that 80% of the material was contained between 600 m and 1000 m. The remaining 20% of the material was located between 100 m and 600 m with the maximum value located at 500 m. For the daytime (Figure 3c), 80% of the material was determined

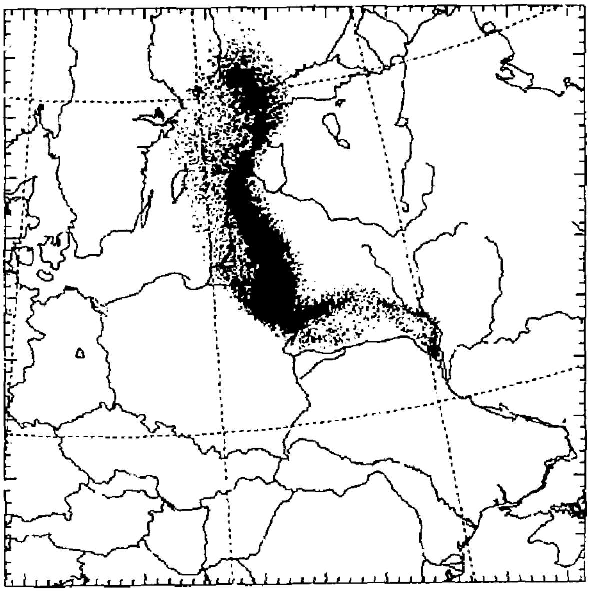

Figure 4.
Computer modeled particle locations representing the spatial distribution of radioactive material 48 hours after the accident started.

to be distributed between 800 m and 2100 m, with the remaining 20% distributed between 100 m and 800 m. The maximum value for this case was located at 1300 m. Differences between dose and deposition estimates, based on the distribution of material in the original source term estimate (Figure 3a) and the non-hydrostatic model estimate (Figures 3b, 3c), would not be large, particularly at distances of several hundred kilometers and beyond. For this reason, the dose and deposition estimates were not recalculated using the quantitatively-modeled vertical distributions of material (Figure 3).

On the basis of I-131 measurements in rainwater over Japan, it appears that approximately 50% of the released activity formed an upper level source term. During the first two weeks of the accident this source term estimate was used only to calculate expected I-131 concentrations in milk in the U.S. It was not used to quantify the source term for the PATRIC global dispersion estimates.

ARAC ASSESSMENTS

At the end of each day, beginning 30 April, a summary of both ARAC activities completed for that day and "work in progress" was prepared and transmitted to the DOE San Francisco Operations Office, and to the DOE Emergency Operations Centers (EOC's) located in Germantown, Maryland, and in the Forrestal Building in Washington, D.C. The following is a synopsis of the daily activity summaries for the specific dates noted:

- 30 April:
  - Detection of Ba-140 and Zr-95 in Sweden implied a significant meltdown.
  - Early findings suggested the majority of volatiles were vented during the first 24 hours.
  - Measurement data reported in Western Europe showed concentrations well below Maximum Permissible Concentration (MPC).
- 1 May:
  - Additional measurement data suggested approximately 50% of volatiles escaped.

- 1–3 May:
  - A change in transport direction from northwest to southwest was noted, and coincided with elevated measurements of I-131 in Italy.
- 5 May:
  - An amount of 9000 pCi/l was estimated as the maximum expected I-131 concentration in milk for the U.S., with 900 pCi/l being the most probable value.
- 6 May:
  - Three-dimensional model estimates of dose and deposition on a 1920 × 1920 km grid (shown later in this report) were sent to the DOE EOC's and NRC.
- 7 May:
  - Global dispersion estimates were announced and transmitted via telecopier to the EOC's.

For completeness, the daily activity summaries are provided in Appendix A. This mechanism for providing information to the EOC's for release to other organizations was in place for approximately two weeks.

I-131 and Cs-137 dose and deposition estimates for periods of 48 hours, 96 hours, and 168 hours respectively, after the assumed accident initiation, are shown in Figures 5–7. Figures 5a–d show material transported in a northwesterly direction from the reactor, over the Ukraine, and into Scandinavia and Finland. The adult thyroid inhalation dose (Figure 5a) shows the 1.0 Rem dose contour extending into northeastern Poland, with the east coast of Sweden and west coast of Finland on the edge of the 0.01 Rem contour. For these calculations, the dose estimated within 10–15 km of the reactor site may be low by an order of magnitude or more due to limitations imposed by the grid resolution. Figure 5b, depicting I-131 dry deposition (pCi/m^2), shows the same general pattern as Figure 5a, with the 3×10^4 pCi/m^2 contour level near the coasts of Sweden and Finland. In comparison, Figures 5c and 5d show similar patterns for Cs-137 whole body inhalation dose and deposition.

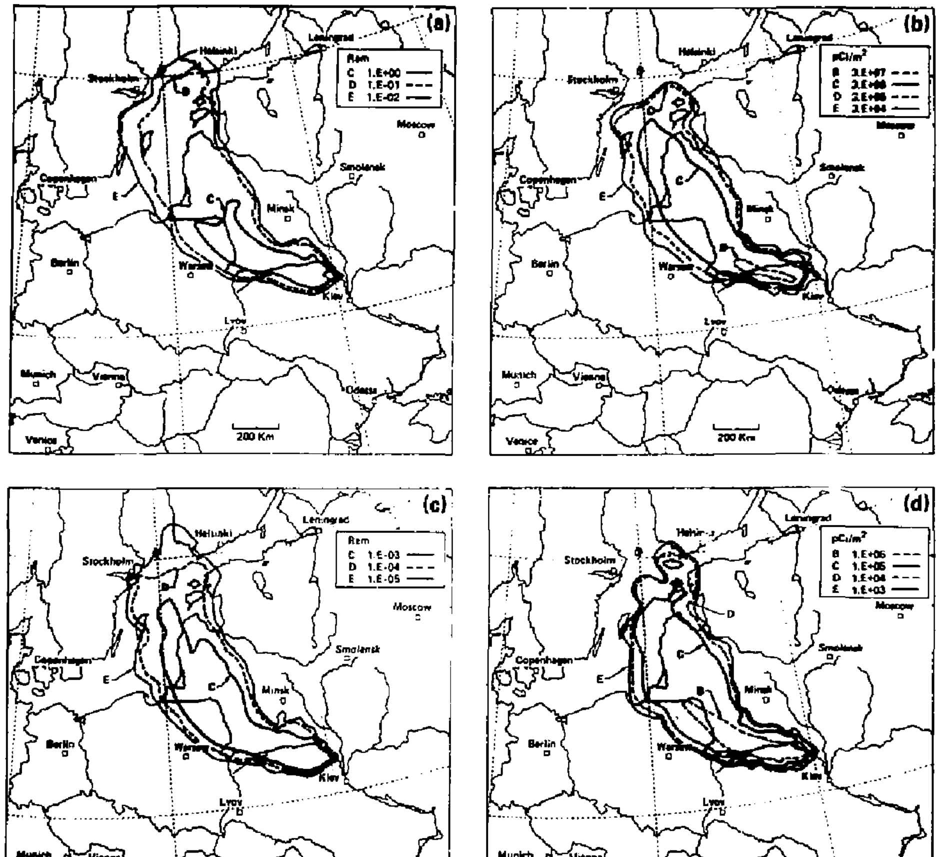

Figure 5.
Contour patterns at 00Z 28 April, 48 hours (2 days) after the estimated accident start time for **a)** I-131 adult thyroid dose (Rem) due to inhalation, **b)** I-131 dry deposition (pCi/m^2), **c)** Cs-137 whole body dose (Rem) due to inhalation, and **d)** Cs-137 dry deposition (pCi/m^2).

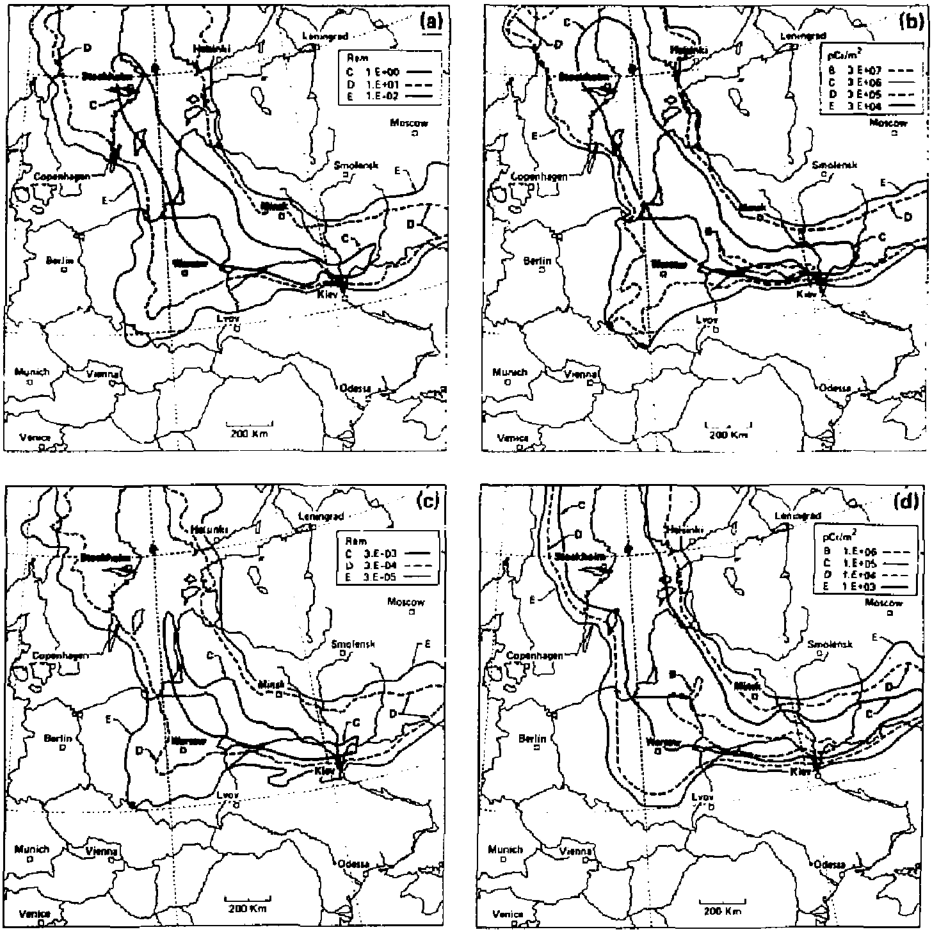

Figure 6.
Contour patterns at 00Z 30 April, 96 hours (4 days) after the estimated accident start time for **a)** I-131 adult thyroid dose (Rem) due to inhalation, **b)** I-131 dry deposition (pCi/m^2), **c)** Cs-137 whole body dose (Rem) due to inhalation, and **d)** Cs-137 dry deposition (pCi/m^2).

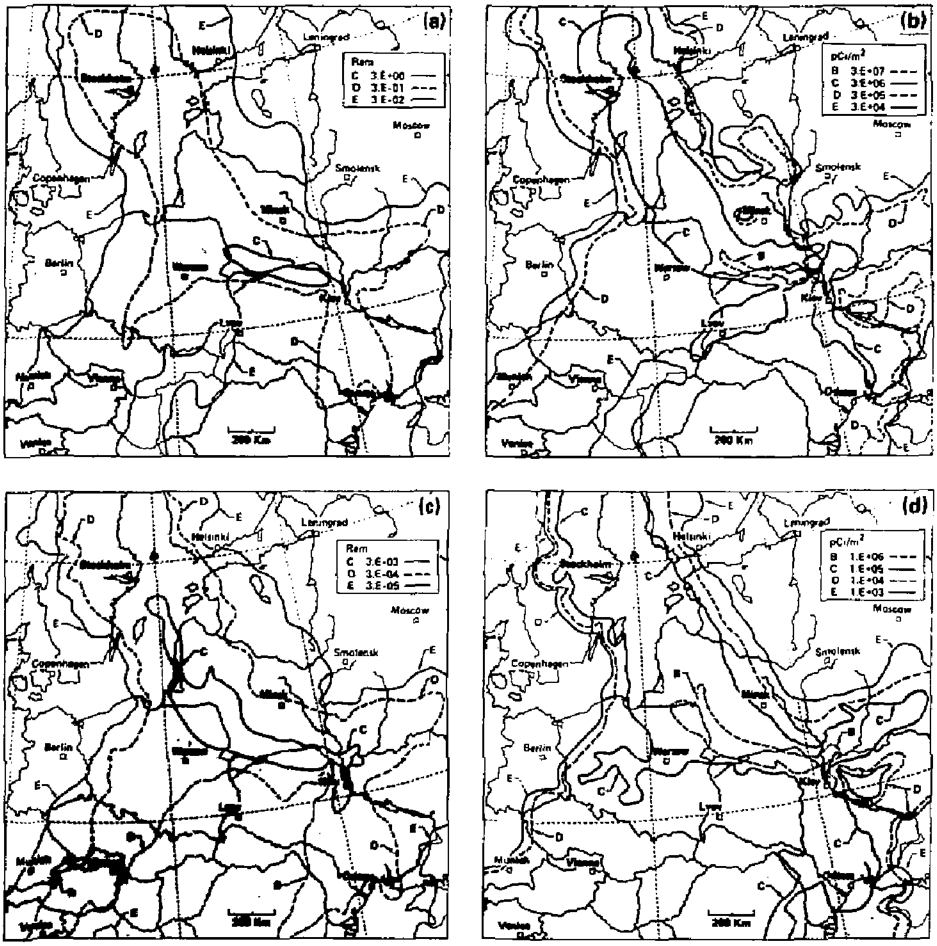

Figure 7.

Contour patterns at 00Z 3 May, 168 hours (7 days) after the estimated accident start time for **a)** I-131 adult thyroid dose (Rem) due to inhalation, **b)** I-131 dry deposition (pCi/m^2), **c)** Cs-137 whole body dose (Rem) due to inhalation, and **d)** Cs-137 dry deposition (pCi/m^2).

Figures 6a–d show dose and deposition estimates for 00Z 30 April, four days after the initiation of the accident, using the lower level source term. At this time the patterns show continued expansion into Scandinavia and Finland while starting to move through Poland toward Austria and northern Italy, as well as moving to the east of Chernobyl. The 1.0 Rem I-131 adult inhalation dose isopleth is now near the coast of Sweden and includes northeastern Poland. I-131 and Cs-137 dry deposition values in the eastern Baltic Sea region are, at this point in time, $\sim$ 100 times larger than the values in Figures 5b and 5d. Figure 6d shows northeastern Poland receiving deposition amounts of 1×10^6 pCi/m^2 for Cs-137.

The dose and deposition values for 3 May, 7 days after the beginning of the accident, are shown in Figures 7a–d. At this stage of the accident, material is dispersed over a considerable portion of the grid, but with a new extension toward Rumania and Bulgaria. The I-131 inhalation dose is now about 3.0 Rem in northeastern Poland. Cs-137 deposition in this area is about 1×10^6 pCi/m^2. The void in the dose and deposition patterns along the western border is due to the failure of incomplete meteorological input data to correctly represent transport into western Europe. More recent larger-scale studies, incorporating the gridded hemispheric data from AFGWC, show transport of radioactivity into western Europe with arrival times and concentrations closely matched to the regional measurements.[7] These calculations were prepared for every 12-hour increment from 00Z 26 April until 00Z 5 May, nine days after the assumed initiation of the accident.

Figures 8a–c show weather related phenomena plotted over those computer-generated particles representing radionuclides emitted from the Chernobyl reactor. Figure 8a shows thunderstorms (⛈) and showers ($\dot{\nabla}$) in the vicinity of Chernobyl 36 hours after the accident. Showers are reported along the southeastern coast of Sweden with a low pressure system located over Poland, and a warm front (▲) situated between Chernobyl and Scandinavia. This frontal system could have lifted the radioactivity from Chernobyl, by the warm air mass overriding the cooler surface air near the front. Twelve hours later,

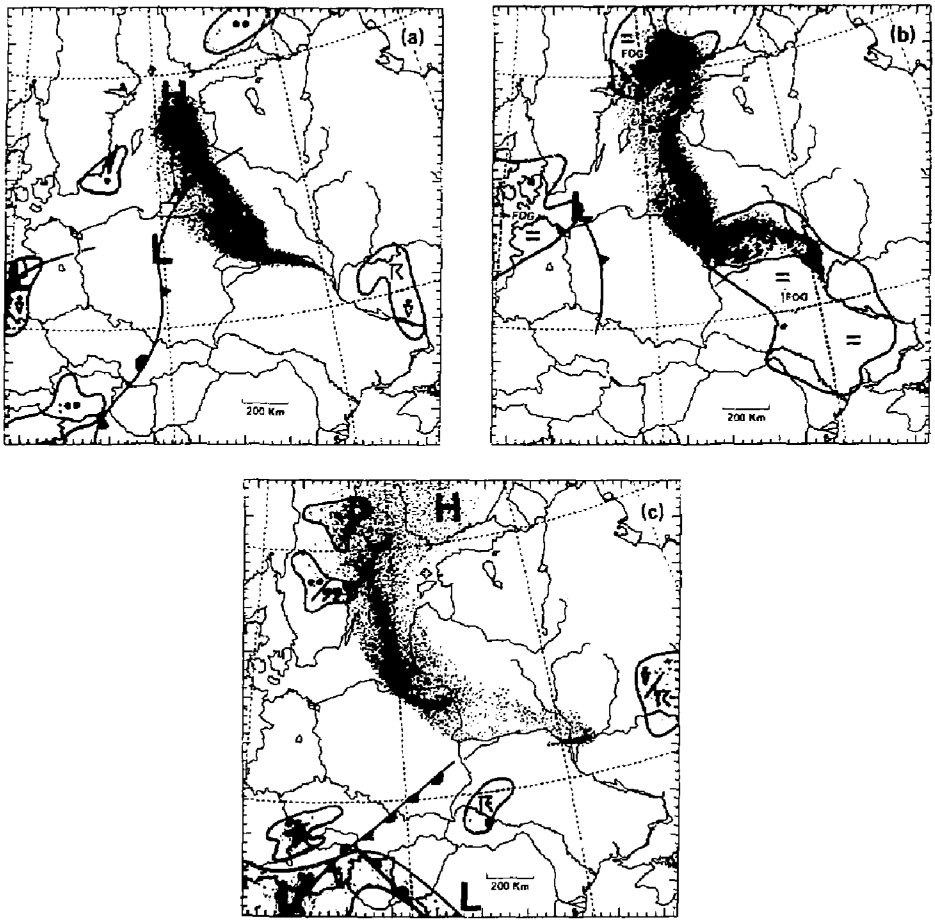

Figure 8.

Relationship between weather related phenomena, e.g., fog, rain showers, fronts, etc., and model-simulated radioactivity patterns for **a**) 12Z 27 April (36 hours), **b**) 00Z 28 April (48 hours), and **c**) 12Z 28 April (60 hours) after the beginning of the accident.

a total of 48 hours after the release began, a large fraction of the area was covered by fog (Figure 8b). Within the next 12 hours (Figure 8c), considerable precipitation activity developed along the coast of Sweden. This rain activity was likely responsible for some of the high ground contamination measurements reported in Sweden.

For the upper-level source term, quantitative deposition estimates of I-131 over the U.S. were calculated by the 2BPUFF model using forward trajectories from two locations—Chernobyl and Japan. For the estimate based on forward extrapolation from Chernobyl, 50% of the I-131 inventory was assumed to reside initially up to 5–6 km. Both of these forward extrapolations showed a maximum value of 9000 pCi/l for milk in the U.S., with an expected value of 900 pCi/l due to enroute cloud depletion by precipitation, e.g., over Japan.

Qualitative global dispersion estimates were provided by the PATRIC computer code. For these calculations the source was stabilized between the surface and 4200 m. Four vertical levels of horizontal wind speed and direction (1000 mb, 850 mb, 700 mb, and 500 mb) were used as the transport wind field. In the computer model, particles were released at the Chernobyl reactor site and followed over the northern hemisphere. Figures 9a–d show the location of particles 3 days, 5 days, 7 days, and 9 days respectively after the beginning of the accident. Figure 9a shows particles representing radioactivity moving toward Scandinavia (consistent with the lower cloud trajectories represented by Figure 5), and other material in the upper level cloud moving toward the east. By the fifth day (Figure 9b), material has moved toward the eastern Mediterranean, and south from Scandinavia back into the northcentral Soviet Union. On the seventh day (Figure 9c), material has dispersed to eastern Greenland, the Middle East near Kuwait, and the eastern part of the Soviet Union. By the ninth day (Figure 9d), material is dispersed over a considerable portion of Europe and the northern and eastern portion of the Soviet Union.

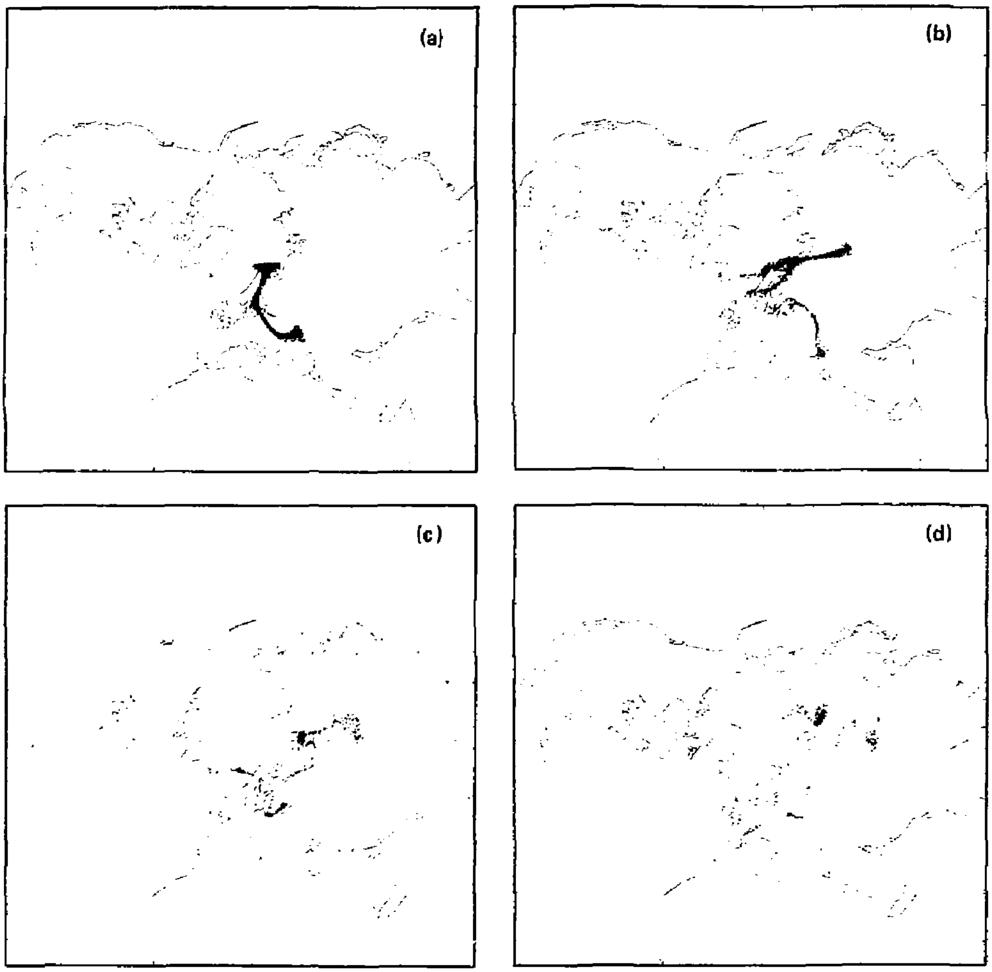

Figure 9.

Depiction of the simulations of the progressive hemispheric dispersion of radioactive material from Chernobyl (by the PATRIC model) at **a**) 00Z 29 April (3 days), **b**) 00Z 1 May (5 days), **c**) 00Z 3 May (7 days), and **d**) 00Z 5 May (9 days) respectively.

Although qualitatively correct in several respects, these (model) calculations did not correctly predict the arrival times of radioactivity over Japan, the U. S., and parts of western Europe. But by using these calculations as a starting point, along with additional measurements beyond those available during the first two weeks of the accident, new global estimates of dispersion are now being calculated and should be reported in the near future.

SUMMARY

This report summarizes the assessments provided by ARAC during the first two weeks after the Chernobyl reactor accident began. Results of this work and measurements made by European countries during that same period show that no major short-term acute health effects would be expected in Europe as a result of this accident. Statistical long-term health effects were not addressed in these studies. Both measured and calculated I-131 concentrations in milk in the U.S. were over an order of magnitude below the USDA guideline of 15,000 pCi/l.

Table 2 shows the relationship between radionuclides assumed released from Chernobyl and those released from Windscale, Three Mile Island (TMI), and a 20 kt nuclear weapon. Note that the estimated quantities of material released by the Chernobyl accident are, in general, several orders of magnitude greater than corresponding releases by the other events. Note also that the releases listed in this table are adjusted for a three-day decay. As another point of comparison, worldwide deposition of Cs-137 from nuclear testing was approximately 1.6×10^4 pCi/m^2 in 1963 when major nuclear weapon tests were stopped. Measurements and calculations for locations in Scandinavia and parts of Europe indicate values near 1×10^5 pCi/m^2 for Cs-137 after the Chernobyl accident with many locations reporting measurements of 1×10^4 pCi/m^2. Parts of northeastern Poland received 1×10^6 pCi/m^2 according to ARAC's calculations.

Table 2. Comparison (in megacuries*) of Chernobyl with other Radionuclide Releases

Nuclide	Chernobyl	TMI	Windscale	20 KT Nuclear Test
1-131	10–50	.00002	.02	2
Cs-137	1–6	None detected	.001	.004
Sr-90	.001–.07	None detected	.000004	.004
Noble gases	100–200	10	0.3–0.4	5

* Radioactivity at 3 days after shutdown or test.

Presently, work is continuing in the areas of refining the source term and estimating dose and deposition within 200 km of the reactor site. These calculations will complete the basic ARAC Chernobyl assessments unless additional data become available, particularly from within the Soviet Union near the reactor site.

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Appendix A

Daily ARAC Activity Summaries for the Chernobyl Accident Assessment

Update of LLNL/ARAC Activities—30 April 1986

Summary

- Detection of Ba-140 implying a significant meltdown should be noted.
- Trajectory shows reasonable agreement with the time the radiation was initially detected in Sweden.
- Early findings suggest the majority of the volatiles (e.g., I-131 and Cs-137) were vented early in the accident, i.e., first 24 hours.
- Data suggest that the airborne radioactivity concentrations are well below Maximum Permissible Concentration (MPC) on 30 April in western Europe.

Work in Progress

- Develop trajectory from Chernobyl beginning 00Z 26 April.
- Implement a long-range transport and diffusion model to estimate normalized concentration values for isotope measurement in Europe.
- Compute source term values.
- Use bench marked calculations to extend concentration measurements into the future.

Technical Contacts

For additional information contact either Joe Knox or Marv Dickerson on (FTS) 532-9159.

Update of LLNL/ARAC Activities—1 May 1986

Summary

- Based on more recent airborne radiation measurements in Sweden, it appears that less than 50% of the volatile nuclides were released. The lower estimates may be biased by precipitation scavenging enroute to Sweden.
- Data suggests that the airborne radioactivity concentrations continue to be well below Maximum Permissible Concentration (MPC) in western Europe, even in the new areas affected.
- Provided advisory role for the Brookhaven National Laboratory (NY) monitoring of returning tourists at JFK airport.
- Recent emissions from the reactor site have traveled southwesterly toward southern Europe. Recent radiation measurements tend to show that these emissions are less than those that traveled toward Scandinavia during the early part of the accident.

Work in Progress

- Develop trajectories from Chernobyl every 12 hours beginning 00Z 26 April.
- Continue to utilize long-range transport and diffusion model to estimate normalized concentration values for isotope measurements in Europe.
- Continue to refine source term.
- Continue to use bench marked calculations to extend concentration estimates into the future.

Technical Contacts

For additional information contact either Joe Knox or Marv Dickerson on (FTS) 532-9159.

Update of LLNL/ARAC Activities—2 May 1986

Summary

- We continue to believe that approximately 50% of the volatiles were released. This estimate may be biased (i.e., low) by precipitation scavenging enroute to Sweden.
- Measurement data from western Europe continue to indicate airborne concentration values are below Maximum Permissible Concentration (MPC).
- It is unlikely that radioactive material will reach the U.S. within the next 10 days.
- Airborne radioactive material collected over western Europe the past week will move toward the north and east over the weekend.

Work in Progress

- Continue to use trajectories for the release during the first day to track the material toward the U.S.
- Run three-dimensional models, beginning with 00Z 26 April, to simulate the original release plus continuing residual releases.
- Make deposition estimate of I-131 when it arrives over the U.S.,and compare to deposition from the 1976 Chinese atmospheric nuclear test.
- ARAC will continue working through the weekend with one-half staff level from 0700 to 1700 hours PDT.
- Analysis of the 1957 Windscale accident in the U.K. indicates that environmental levels of radioactivity may be 10^3 higher for the Chernobyl accident.

Technical Contacts

For additional information contact either Joe Knox or Marv Dickerson on (FTS) 532-9159.

Update of LLNL/ARAC Activities—3–4 May 1986

Summary

- Trajectories for 500 m, 1000 m, and 1500 m for 00Z 26 April to 12Z 27 April show material released from reactor site traveled either toward Scandinavia or toward northern Italy through Poland. After 12Z 27 April the material appears to remain in the Soviet Union.
- Airborne sampling shows radioactive cloud spread over more than half of the northern hemisphere in lateral extent and from near surface to as high as 32.000 feet over the eastern Pacific.
- Three-dimensional model calculations have been started to develop a "footprint" of activity distributions over western Europe. These calculations will be run for a 72 hour period after the start of the accident (assumed to be 00Z 26 April).

Work in Progress

- Estimate air concentrations expected over the U.S. using measurements made of radioactivity over Japan.
- Continue to refine source estimates.
- Continue to refine dose estimates for western Europe and locations in the Soviet Union where U.S. tourists have visited the past week.
- Attempt to quantify "in-cloud" doses for aircraft routes between Japan and the U.S.
- Data from the Windscale accident will be used to help estimate exposures near the Chernobyl accident site.

Technical Contacts

For additional information contact either Joe Knox or Marv Dickerson on (FTS) 532-9159.

Update of LLNL/ARAC Activities—5 May 1986

Summary

- The following statement was issued with regard to expected iodine concentrations in milk within the U.S.:

  "We expect the maximum concentration of I-131 in the milk in the U.S. to not exceed 9000 pCi/l and most probably will not exceed 900 pCi/l. The maximum value is based on the release of 50% of the reactor inventory of I-131, atmospheric dispersion enroute to the U.S., and subsequent rainout over the U.S. The more probable value includes a factor of 10 reduction due to segments of the cloud being transported over Scandinavia and central Europe, and precipitation scavenging enroute to the U.S. These values may be compared with the 400 pCi/l that was measured in milk samples from Pennsylvania shortly after the 1976 Chinese atmospheric test. The FDA protective action guide response level is 15,000 pCi/l."
- Analysis of trajectories shows parts of the radioactivity entering Romania on 00Z 2 May; however, it is possible material could have entered the country approximately 24 hours earlier.
- Initial three-dimensional model calculations have been run for 72 hours. Work has been concentrated on "benchmarking" against measurements in Scandinavia. Once this effort is completed, a more detailed analysis of public exposure in western Europe can be made.

Work in Progress

- Continue to refine I-131 analysis for the U.S.
- Continue to provide an integrated exposure assessment in western Europe using three-dimensional model calculations.

Technical Contacts

For additional information contact either Joe Knox or Marv Dickerson on (FTS) 532-9159.

Update of LLNL/ARAC Activities—6 May 1986

Summary

- Completed work on a 108-hour preliminary simulation for western Europe using a three-dimensional dispersion model, and estimated source shape in the vertical and normalized release rate. This information was shared with NRC who is working toward estimating the source term and its time dependence.
- An additional 112 hours of meteorological data have been prepared and will be used to extend the western European exposure analysis to 7 days.
- Pacific Northwest Laboratory (PNL) measured 500 pCi/l of I-131 in rainwater collected about 4 pm PDT, 5 May in Richland, WA. This concentration is consistent with that expected in the U.S. from model simulations and from measurements made in rainwater over Japan on 2 May and later.

Work in Progress

- Extend in time the three-dimensional model simulations. Continue benchmark calculations for the purpose of better source term definition. Once the source term has been better quantified, prepare an exposure pattern for western Europe.
- Continue to stay current with the I-131 measurements in the U.S. (and elsewhere) and their comparison to predicted values. Also, provide guidance on expected concentrations in milk and water of I-131 as a result of deposition from material traveling at levels in the lower atmosphere now over the Soviet Union.

Technical Contacts

For additional information contact either Joe Knox or Marv Dickerson on (FTS) 532-9159.

Update of LLNL/ARAC Activities—7 May 1986

Summary

- Estimated exposure levels from I-131 and Cs-137 for western Europe were extended to six days. Adult thyroid dose and deposition for I-131, and external whole body dose and deposition for Cs-137 were calculated. Tomorrow these estimates will be sent to DOE and EOC's for distribution, and submission to EPA Commission.
- Estimates of low level (to 15,000 feet above ground level) global dispersion of the Chernobyl emissions were calculated to 10 days after the accident by using a three-dimensional particle-in-cell model. Qualitatively, these estimates were in reasonable agreement with aircraft measurements.

Work in Progress

- Continue to provide estimates of I-131 and Cs-137 deposition and exposure to those organizations that can use the information.
- Continue to compare ARAC's calculated air concentration and deposition patterns to measurements.
- Attempt to extend the global estimates to at least 25,000 feet in the vertical, and compare particle dispersion estimates to aircraft measurements over Japan and the U.S. (May 2–7).

Technical Contacts

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Update of LLNL/ARAC Activities—9 May 1986

Summary

- The six day I-131 and Cs-137 dose and deposition estimates were forwarded to EPA by DOE, Thursday, 8 May. The President's Commission reviewed our simulations and findings and released them to the public at 3 p.m., 8 May. Once this release was made, ARAC began honoring national and international requests for these calculations. A list of organizations receiving these data will be provided Monday, 12 May as part of a package of material requested by DOE.
- Meteorological data between 15,000 and 30,000 feet were collected from the Air Force Global Weather Central (AFGWC). This data, from the beginning of the accident, will be used to augment the data base for the initial low level global dispersion of material. The new data base should provide better time estimates for the arrival of material at higher levels over Japan on 3 May.
- Meteorological data continues to be received from AFGWC and data based for future use, if required.

Work in Progress

- Continue collecting meteorological data over the weekend.
- The ARAC center will not be staffed this weekend; however, teams and team leaders will be identified and placed on-call for Saturday and Sunday.
- The center will open Monday, 0500 PDT 12 May, with a two-person crew. If the intensity of the response continues to decline, the center will return to a normal ARAC work day schedule (0730 to 1630) on Tuesday with any extended hours covered by on-call personnel.

Technical Contacts

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Update of LLNL/ARAC Activities—12 May 1986

Summary

- As a result of ARAC providing the I-131 and Cs-137 inhalation dose and deposition calculations to Sweden, Italy, and UK, additional measurements and analyses have been received from their respective agencies. ARAC plans to continue cataloging "feedback" from other organizations that have received its calculations so estimates of dose over Europe can be refined, if that is possible.
- The ARAC center staff continued to reduce activities associated with the Chernobyl accident.

Work in Progress

- Continue collection of input with regard to initial dose estimates for Europe. Continue to analyze measurements as they become available, and compare them to existing model estimates of air concentration and dose.
- An expanded set of ARAC dose and deposition measurements is being prepared for distribution on Wednesday, 14 May, to groups using this information in their analysis.
- The center staff will continue to reduce activities associated with the Chernobyl accident. On 13 May the center will be back to its normal hours (0730 to 1630 hours PDT). By the end of the week, ARAC will focus on completing the DOD site computer installations.

Technical Contacts

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REFERENCES

1. M. H. Dickerson, P. H. Gudiksen, T. J. Sullivan, and G. D. Greenly, "ARAC Status Report: 1985," Lawrence Livermore National Laboratory Report UCRL-53641, Livermore, CA (1985).
2. M. H. Dickerson, and R. Caracciolo, "Joint Research and Development and Exchange of Technology on Toxic Material Emergency Response Between LLNL and ENEA: 1985 Progress Report," Lawrence Livermore National Laboratory Report UCRL-53696, Livermore, CA (1985).
3. T. V. Crawford, "A Computer Program for Calculating the Atmospheric Dispersion of Large Clouds," Lawrence Livermore National Laboratory Report UCRL-50179, Livermore, CA (1966).
4. C. A. Sherman, "A Mass-Consistent Model for Wind Fields Over Complex Terrain," *J. Appl. Meteor.*, **17**, 320–329 (1978).
5. R. Lange, "ADPIC—A Three-Dimensional Particle-In-Cell Model for the Dispersal of Atmospheric Pollutants and Its Comparison to Regional Tracer Studies," *J. Appl. Meteorol.* **17**, 320–329 (1978).
6. R. Lange, "PATRIC: A Three-Dimensional Particle-in-Cell Sequential Puff Code for Modeling the Transport and Diffusion of Atmospheric Pollutants," Lawrence Livermore National Laboratory Report UCID-17701, Livermore, CA (1978).
7. M. H. Dickerson, report in progress (1986).
8. M. M. Bradley, "The Numerical Simulation of Orographic Storms," Ph.D. dissertation, Department of Atmospheric Sciences, University of Illinois, Urbana, IL, 263 pp, (1985).
9. M. M. Bradley, and C. R. Molenkamp, "Plume Rise and Scavenging of Smoke From Large Intense Fires," preprints, Conference on Cloud Physics, September 22–26, 1986, Snowmass, CO. Published by the American Meteorological Society, Boston, MA (1986).

10. J. B. Knox, "Long Range Transport of Air Pollutants on the Synoptic Scale," *in Air Pollution Modeling and Its Application IV,* edited by C. De Wispelaere, Plenum Publishing Corporation, 1985.