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INTRODUCTION

Japan Atomic Energy Research Institute (JAERI) has been engaged in a research project to develop technology in assessing the environmental impact of accidental releases of radioactivity since the TMI-2 reactor accident in the United States in March 1979. In 1986, this project yielded a computer-based dose prediction system SPEEDI (System for Prediction of Environmental Emergency Dose Information) (Imai, 1985). Furthermore, a new technical capability, WSPEEDI, was developed to predict the radiological impacts on the Japanese people of a nuclear accident abroad to meet the requirement caused by the Chernobyl accident (Chino, 1995). In present, WSPEEDI includes the capability of SPEEDI, and can respond to the various-scale dose assessment against domestic and overseas nuclear incidents. In parallel to the development of the system, we have conducted validation studies, exercises and responses to real events during the last decade. Through such experiences, three state-of-the-art functions needed for future WSPEEDI are under construction. These are: (1) synoptic hydrodynamic model to forecast detailed meteorological conditions; (2) source term estimation on the release point, time and amount by coupling monitoring data with atmospheric simulations; (3) prototype international data communications link to exchange information during emergency situations.

STATUS OF WSPEEDI

The response domains of WSPEEDI are typically “local” and “regional” scales (25 to 100 km) for domestic incidents, and “synoptic” (a few thousand km) and “hemispheric” scales for foreign ones. Forecast periods for domestic and foreign incidents are 48 hours and 7 days, respectively. An accidental discharge at any place in the world can be treated, assuming a point source including maximum 5 nuclides. The capability of WSPEEDI is realized by various supporting functions, combined with three-dimensional atmospheric models, e.g., data acquisition network, databases, graphical user interface (GUI) and graphic software for output. Figure 1 depicts the primary functions of WSPEEDI. The input data are divided into two types, i.e., time-dependent data like meteorological and release information and invariant data. Meteorological and release information is expected to be input in real-time from a data acquisition network and keyboard, respectively. Invariant data are extracted from the databases which contain geographical data, site data, physical constants relating to radionuclides. The system operation is carried out through GUI which minimizes input parameters for quick response. Predicted results of wind fields, airborne concentration, deposition levels, external and internal doses are output in the form of wind vectors, contours or 3-D features superimposed on a map.

The atmospheric models of WSPEEDI are listed in Table 1. A suit of models for domestic incidents consists of three models (Nagai, 1999), a hydrostatic meteorological forecast model PHYSIC, a mass-consistent wind field model WIND21 and a Lagrangian dispersion model PRWDA21. Three models are formulated in the terrain following z* coordinate system. The horizontal coordinates are Cartesian coordinates. PHYSIC simulates regional three-dimensional meteorological fields, e.g., wind, potential temperature, and turbulence characteristics, by numerically solving a set of atmospheric dynamic equations with hydrostatic assumptions. WIND21 serves to eliminate some mass imbalance which will be caused by the interpolation of regional data to “local” coordinates with a finer resolution topography. WIND21 has two successive procedures, i.e., interpolation of regional wind fields onto local grids and diagnostic analysis to adjust interpolated wind fields to mass-consistent ones. PRWDA21 models the atmospheric dispersion of radioactivity by following the trajectories of a large number of marker particles, discharged from a source and moving in the downwindward direction. The concentration at each unit Eulerian cell is calculated by summing up the contribution of each particle to the cell. The long-range dispersion models for overseas incidents still consist of two models, a mass-consistent wind field model WSYNOP (Ishikawa, 1994) and a Lagrangian dispersion model GERAN (Ishikawa, 1991). The modeling concept of these models is similar to WIND21 and PRWDA21. Regarding meteorological forecasts over synoptic and hemispheric areas, WSPEEDI completely depends on global meteorological forecasts (GSM) from JMA. The computer programs of models are revised for a vector parallel processor.
Fig. 1  The primary functions of WSPEEDI.

Table 1  List of atmospheric models in WSPEEDI.

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<thead>
<tr>
<th></th>
<th>Domestic incident</th>
<th>Overseas incident</th>
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<tbody>
<tr>
<td>Meteorological forecast model</td>
<td>RSM + Hydrostatic model</td>
<td>GSM</td>
</tr>
<tr>
<td>Wind field model</td>
<td>Mass-consistent model WIND21</td>
<td>Mass-consistent model WSYNOP</td>
</tr>
<tr>
<td>Atmospheric dispersion model</td>
<td>Lagrangian dispersion model PRWDA21</td>
<td>Lagrangian dispersion model GERAN</td>
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RSM: Regional meteorological forecasts over Japan by JMA.

DEVELOPMENT OF SYNOPTIC HYDRODYNAMIC MODEL

The increase of nuclear power plants in the Asian region necessitates the improvement of meteorological forecast capability of WSPEEDI. In the region including China, Korea and Japan, since a radioactive cloud is sometimes transported to the neighboring countries within one or two days, the diurnal and spatial variation of the mixed layer plays an important role for atmospheric transport. Moreover, the region is in the monsoon area with high humidity and, consequently, the rainout and washout processes should be also considered in detail. Nevertheless, the present WSPEEDI employs a combination of a mass-consistent wind field model and a particle random-walk model for foreign nuclear incidents, whose shortage is that the atmospheric boundary layer and precipitation are simply parameterized based on coarse global forecast data. Thus, the objective area of PHYSIC is extended for synoptic meteorological forecasts and prognostic equations for hydrometeors, cloud formation and precipitation processes are introduced in PHYSIC.

The PHYSIC is a three-dimensional, hydrostatic, primitive equation model with a terrain-following vertical coordinate. PHYSIC prognosticates horizontal wind components, potential temperature, turbulence kinetic energy, turbulence length scale and five variables of hydrometeors, e.g., vapor, cloud-water, cloud-ice, rain and snow. The Boussinesq approximation and the hydrostatic approximation are applied to the model. A second-order turbulence closure model by Yamada (Yamada, 1984) is used to calculate the turbulence diffusion terms in the prognostic equations. The ground surface heat budget equation coupled with a soil-layer heat conduction equation is used to calculate the ground surface temperature. The solar and atmospheric radiations are parameterized in terms of the cloud amount and the air temperature. The lateral boundary condition is a radiative condition of Orlanski-type (Orlanski, 1976) to prevent reflection of gravity waves at the boundaries. For the same reason, the top boundary condition by Klemp and Durran (Klemp, 1983) is employed in the model. At the bottom of air layer, the Monin-Obkhov similarity theory is applied. The model is initialized by GSM. The data are interpolated to the finer model grid.

An example of predicting wet condition is shown in Fig. 2. The calculation was carried out for 48 hours from 12 UTC 26 August, 1998. Figure 2(a) is a weather chart and a visible image of NOAA at 00 UTC 27 August. Heavy rain is often observed when an autumnal rain front lies over Japan and is stimulated by the moist and warm southerly wind blowing around a typhoon. Since the typhoon No.4 (T.4 in Fig.2(a)) moved very slowly around 1,000 km south of Tokyo during the calculation period, it continued raining heavily at the central Japan covered by clouds of the autumnal rain front. Heavy rain more than 500 mm per a day was observed in these areas.
Figure 2(b) is the calculated horizontal distributions of cloud and 48-hour accumulated precipitation at 12 UTC 28 August. The model predicted the clouds associated with the synoptic front system along the Main Island of Japan. And heavy rain more than 250 mm was also simulated at the northern part of the calculation domain. However, the calculated cloud, especially ice-cloud, and the precipitation area shifted to the north as compared with the actual distribution. This can be attributed to the facts that calculation area is not sufficiently wide and the model has no cumulus parameterization. In our simulations, values of cloud water and cloud ice at the lateral boundary are set to zero because of the lack of relevant information in the input data. Therefore, a marginal area is needed to ensure cloud development at the inflow lateral boundaries.

Development of Source Term Estimation

The past real accidental releases of radioactivity showed that we can hardly acquire the release condition in the early stage of the accidents. Consequently, one of important roles of WSPEEDI was to estimate a release condition by coupling monitoring data with prediction. For this purpose, a new systematic function to estimate source term on the release point, time and strength by using monitoring data and atmospheric simulations is being developed. Although traditional source estimation methods were based on back-trajectory models, our function consists of atmospheric transport simulations and statistical analysis of the predictions and monitoring on air dose rates and/or air concentrations.

Computational flow for source term estimation is illustrated in Fig. 3. First of all, a user determines...
candidates for possible source term parameters. Here, the source term parameters are the following four quantities, 1) release point, 2) release starting time, 3) release duration time, and 4) emission amount per hour. Many combinations of unknown source term parameters in four quantities can be made in short time using a graphical user interface (GUI). Atmospheric transport simulations for all combinations are performed at the same time on a vector-parallel computer by GEARN parallelized by message passing interface (MPI-GEARN). It is possible to carry out different cases of atmospheric transport simulations at the same time on processors in a parallel computer by using common wind fields from WSYNOP and the namelist files generated by GUI. The efficiency of this parallelization is completely proportional to the number of processors. Following the atmospheric transport simulations, the predictions from all the simulations are compared with the observation data by using two statistics, NMSE and PCC. The statistical analysis is carried out to find the combination of parameters which produces the best-fit prediction to the monitoring data.

When all the source parameters are unknown, the estimation is performed by two steps. In the first step (STEP1), atmospheric transport simulations are conducted for the possible release points and release starting times, under the assumption of unit emission for 6 hours. From the statistical analysis successively done after atmospheric transport simulations, a release point is determined strictly. However, the determination of release starting time is brought in the next step because release starting time is related closely to the duration time for the estimation of emission amount, and thereby the best fitted starting time in STEP1 for 6-hour release is not always the best fitted one for other duration times. In the second step (STEP2), simulations for the combinations of several duration times and release starting times are carried out assuming unit emission from the determined release point.

We examined the function by using the data from the first set of ETEX (the European Tracer Experiment) (JRC, 1998), on 23 October 1994. The ETEX is an international cooperative experiment with the release of harmless inert gas into the atmosphere to verify the accuracy of long-range atmospheric models and emergency response systems. The location of the release point was 2° 01′00"W and 48° 04′00"N, approximately 35 km west of Rennes, France. The tracer release was started on 23 October, 16:00 UTC and ended on 24 October, 3:50 UTC. The averaged release rate was 7.95 g/s during this 12 hr period. The samplers were deployed at 185 points over seventeen European countries.

As STEP1, the function estimates the release point and starting times. The candidates were selected based on the pre-estimation by back-trajectory model. Candidates of release points are located on the grid of 5 × 5 with resolution of 0.5° from 47° N to 49° N in the latitude and resolution of 2° from 6° W to 2° E in the longitude (25 cases). Nine candidates of starting times are prepared for 3-hr interval from 12:00, 23 to 12:00, 24 Oct. The release duration time is fixed at 6 hours and the release rate is 1 kg/h. Then, the total number of simulation cases are 225 (25 cases × 9 cases). The discharged gases for 225 cases are traced for 90 hours from the start of release. The observation data used for the statistical analysis are 3-hour averaged concentration
values at the 168 sampling sites. The estimation for the duration time is successively performed as STEP2. For the release starting time, the eleven candidates with high resolution based on the result of STEP1, e.g., 2 hr interval from 12:00, 23 Oct. to 8:00, 24 Oct., are selected. For duration time, twelve candidates from 3 hrs to 36 hrs with 3 hr interval are selected.

At the end of STEP2 calculation, the release rate $q$ is estimated by multiplying the assumed release rate $R_{cal}$ to the peak ratio of the observation $O_{max}$ to the prediction $P_{max}$ at the sampling point where the highest concentration is detected.

$$q = \left( \frac{O_{max}}{P_{max}} \right) \times R_{cal}$$

Table 2 summarizes the comparison between the estimated and the real values. It is resulted that the estimated release point is equivalent to the real one. The estimated release period, 9 hours, is involved entirely in real one and the emission rate of tracer gas, 5.47 g/s, estimated from above equation is the even order of real value, 7.95 g/s.

Table 2  Comparison between estimation results and real values.

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<thead>
<tr>
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<th>Estimation result</th>
<th>Real value</th>
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<tbody>
<tr>
<td>Release point</td>
<td>48.0° N, 2.0° W</td>
<td>48° 04' N, 2° 01' W</td>
</tr>
<tr>
<td>Release time</td>
<td>1994 10/23 from 18:00 to 10/24 3:00</td>
<td>1994 10/23 from 16:00 to 10/24 3:50</td>
</tr>
<tr>
<td>Emission rate</td>
<td>5.47 g/s (19.7 kg/h)</td>
<td>7.95 g/s</td>
</tr>
</tbody>
</table>

The time costs for STEP1 and STEP2 by a vector parallel computer VPP300 with 15CPUs are shown in Table 3. The total processing time required in the estimation is about for 4 hrs.

Table 3  Time costs for STEP1 and STEP2 on VPP300 with 15CPUs.

<table>
<thead>
<tr>
<th></th>
<th>Time cost</th>
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<tbody>
<tr>
<td>STEP1 (225 cases)</td>
<td>2 hours and 32 minutes</td>
</tr>
<tr>
<td>STEP2 (108 cases)</td>
<td>1 hours and 16 minutes</td>
</tr>
</tbody>
</table>

CONSTRUCTION OF INTERNATIONAL DATA COMMUNICATIONS LINK

Under the auspices of a US DOE-JAERI Memorandum of Understanding, JAERI and Lawrence Livermore National Laboratory (LLNL) agreed to develop and evaluate a prototype information exchange protocol between WSPEEDI and the Atmospheric Release Advisory Capability (ARAC) (Sullivan, 1993) for nuclear accident emergency situations. The purpose of this project is;
- quick exchange of atmospheric modeling products and environmental data during emergency,
- distribution of predicted results to other countries having no prediction capabilities, and
- utilization of the link for collaborative studies.

The network can be divided into hardware and software. Furthermore, the hardware can be considered as two major components - the computer platform on which this function runs, and the network, Internet, over which information is exchanged. Currently, a Silicon Graphics Indy workstation with a microphone and a video camera serves as the platform at both ends of the connection. The software can also be considered as two components, the Web site/browser portion and the video-teleconferencing tool. For the Web site, where the actual computational data and graphics is posted and exchanged, a number of password-protected pages were written in CGI and HTML. Each Web site permits privileged users to log on and review the computational results for a given facility. Accessible information includes model parameters and assumptions used in the calculations, graphical displays of wind data, and plots of predicted concentrations, dose and deposition. These plots and data can be easily extracted for use in scheduled teleconferences. The video-teleconference tool is InPerson which is bundled with the SGI workstation. Like most video-teleconferencing tools, InPerson consists of three components—a video handler, an audio handler, and a whiteboard application. Each component is highly configurable and is easy to use. Both the video and audio components allow variable sampling rates for each signal to reduce the bandwidth required by each. The default ISDN-like bandwidth of 128Kb setting allowed a clear audio signal to be transmitted, though a delay of 5-10 seconds was experienced. However, unavoidable Internet congestion problems sometimes occurred at the various bridges and gateways between the US and Japan. Similar whiteboard delays were also experienced, but the overall performance of the system was acceptable.
JAERI and LLNL intend to extend the network to the European system, RODOS at Forschungszentrum Karlsruhe GmbH (FZK) (Ehrhardt, 1998). The first trial for the International Nuclear Emergency Exercise (INEX) sponsored by OECD/NEA experienced the benefits of a direct international data exchange among JAERI, LLNL and FZK. In the near future, the triangular prototype network among the U.S., Europe and Japan will be constructed.

After starting the construction of the link between ARAC and SPEEDI, we have experienced three cooperative works against accidental releases of radionuclides into the atmosphere.

In March, 1997, a bituminization plant for radioactive waste at the former Power Reactor and Nuclear Fuel Development Corporation (PNC) in Japan was fired and discharged various radionuclides into the environment. During this accident and shortly thereafter ARAC and JAERI were able to view each system’s model assessment plots, discuss differences due to models and input data, locate measurements sites and values and then recompare and discuss results again when comparable data were used in both systems. The common activities covered the estimation of contamination area shown by accumulated air concentrations and the release amount of Cs137 by comparing predicted air concentrations with observed ones (Chino, 1997). This cooperative response to an actual event over a two-week period proved the network would have provided an advantage over the face-to-face exchange, as each participant is acting from their own institutional environments, where all local data and even colleagues are readily accessible.

An accidental discharge of Cs137 occurred at Algeciras, Spain in 30 May, 1998, was the second cooperative response to real events. JAERI received source information and monitoring data from LLNL and immediately predicted the atmospheric dispersion of Cs137 over Europe. This activity also included the estimation of accumulated air concentration and the release amount of Cs137 (Yamazawa 1999). Predicted accumulated air concentrations at the ground level by JAERI are shown in Fig. 4.

On 30 September 1999, a criticality accident occurred in the conversion building at the nuclear fuel processing facility, JCO Company in Tokai, Japan. Just after the accident, the γ dose rates increase at the several monitoring posts at the vicinity of JCO and it then returned to the background level. However, At about 16:00, when the wind direction began to change, extraordinary γ dose rates were measured at many monitoring points at the east side of JCO within 10 km. It is considered that the first increase was caused by direct γ-ray due to the criticality, and the second was from the radioactive plume of noble gases and iodine. Against this accident, JAERI and LLNL started a dense cooperation to estimate the transport of plume, release amount and radiological dose to the public. The starting day of our work was still in a confused state and even JAERI could acquire limited information, e.g., only release point, criticality period, some meteorological and radiological data. However, both tried rough sketch of atmospheric transport and the results agreed well. After several days, detailed meteorological and radiological data were arranged at JAERI and sent to LLNL. By piling up common data, both repeated dose evaluations. During this cooperative activity, the exchange of prediction results by Web were highly effective tool to compare the results. However teleconference tool which uses Internet had a problem on data traffic, and voice and video were sometimes broken. In future, the re-construction of link by using a confidential network, e.g., ISDN, are desirable.

Figure 5 shows the horizontal distribution of external doses at a height of 1.5 m above the ground accumulated until 8:00, 1 Oct. The figure indicates that external doses were higher at the region of the northeast.
and southwest where were downwindword for long time. The outside contour of the lowest value, $10^{-3}$ mSv, is comparable to the external dose from the background radiation for one day. According to the external doses estimated from observed air dose rates, only one observation at Funaishikawa exceeded $2 \ \mu$Gy ($1.6 \times 10^{-3}$ mSv) and this fact agreed well with Fig. 5. Thyroid doses to the infant (1 Age) is also predicted under the assumption of 5% release of inventory. According to the estimation, maximum dose was $4 \times 10^{-1}$ mSv and the doses did not exceed $10^{-2}$ mSv at the area 3 km far from the site. These values are considerably low, comparing with thyroid dose guideline for sheltering, 100～500 mSv. The estimation shows that the doses were considerably lower than guideline values for sheltering even at the vicinity of the site. The maximum of effective dose equivalent was 1/10 of the dose limit for 1 year to the public. Thus, it is concluded that radiological doses due to radionuclides discharged into the atmosphere have no harmful influence to the human health.

CONCLUSIONS

WSPEEDI at JAERI has been evolving its capability to provide real-time, world-wide, assessment of radiological impact due to nuclear emergencies since 1980. Various verification studies, exercises and responses to real events proved the sufficient performance of WSPEEDI against accidental release of radionuclides into atmosphere. WSPEEDI will integrate the functions of synoptic meteorological forecast, international data communications network and source term estimation until the end of 2000, and be settled as a practical version.

REFERENCES


