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MODELLING AND SIMULATION OF THE RADIOACTIVE RELEASE DURING THE FUKUSHIMA ACCIDENT

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Abstract: The nuclear accident of Fukushima raised again the discussion how operating companies and authorities can react in such a case of emergency. This paper investigates from a scientific perspective, how the tools and measures can be applied to assist the decision makers. It describes how the simulation system ABR calculates the dispersion of radioactive particles and the resulting radiological exposure in general. Furthermore it shows how the ABR system was adopted to simulate the Fukushima accident. It describes the assumptions that were made to determine the most influencing data like the source term and weather conditions and discusses finally the simulation results which were obtained by the ABR system.

Keywords: *Fukushima, dispersion of radioactive particles, simulation system, modelling, radiation exposure, disaster management.*

INTRODUCTION

On March 11th 2011 one of the heaviest earth quakes in recent history with a magnitude of 9.0 M_w occurred, which was followed by a disastrous tsunami and caused meltdowns in three of the reactors at Fukushima Daiichi. This event has aroused again the discussion about the risks concerning the peaceful use of nuclear energy and the safety of nuclear power plants, especially in Germany. Within this context it is intensively and often very emotionally discussed how the operating companies and the supervisory authorities react, which actions they take to secure people and how believable their statements are.

Taking this into account it seems reasonable to investigate from a scientific perspective, how useful the tools and measures, which had been developed after the Chernobyl accident, can be applied to assist the decision makers on the basis of the recent accident in Japan. This paper focuses on the exploitation of dispersion calculations in the context of nuclear emergency protection.

As an essential part of the nuclear power plant monitoring system (KFÜ[1]) of the federal state of Baden-Württemberg, Germany, a system called ABR[2] was developed to simulate the atmospheric dispersion of radioactive particles in order to improve the emergency management, especially with respect to prognostic estimation as well as diagnostic understanding of the radiological situation. The paper begins with a brief description of the underlying models of the dispersion calculations in the ABR system. The attempt is made to apply the system to simulate the Fukushima accident, mainly with respect to the radiological exposure of the population. This is done despite the high uncertainty of available data in the emission phase and the unknown damage of the power plant caused by the outage of most measurement devices. A comparison of the simulation results and the measured values is discussed.

ABR, a system to simulate the dispersion of radioactive particles

ABR is a modular system containing models to calculate the release, transport, and deposition of the radioactive particles, followed by the dose calculation, taking into account the meteorological data and the topography of the solution area.

The calculation of the wind regime is performed with a three-dimensional, so called diagnostic model, by interpolating the initial values, mainly from measurement devices, in horizontal and vertical direction for the underlying three-dimensional grid. In a second step, the continuity equation will be solved to ensure mass consistency. The stability of the atmosphere is described by a stability class parameter indicating whether the wind circulates around or overflows obstacles. Table 1 shows this classification as well as the associated weighting factors where higher values indicate a more likely overflow.

Table 1: Stability class parameters describing the status of the atmosphere

Stability regime	A	B	C	D	E	F
Description	highly unstable	Stable	unstable to neutral	neutral	stable	highly stable
Factor	1.0	1.0	0.8	0.5	0.1	0.05

Within the ABR, two different models are available to calculate the wind regime. The main difference amongst them is that one of them uses a Cartesian coordinate system and the second one uses a terrain following coordinate system.

The dispersion calculation is based on a Monte-Carlo / Lagrange model, a statistical model where trajectories of the particles are calculated, taking into account the atmospheric turbulence described by the advection-diffusion-equation. The advection part is determined by the wind regime described above. The turbulence part is parameterized by so-called dispersion parameters, either by Pasquill-Gifford (Gifford 1976) or by Karlsruhe-Jülich (Thomas, Dilger, Hübschmann 1981). Both sets

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[1] KFÜ is the German abbreviation for nuclear power plant monitoring system: Kernreaktorfernüberwachung

[2] ABR is the German abbreviation for the dispersion calculation: Ausbreitungsrechnung

of parameters result from experiments and describe the standard deviation of the dispersion of the particle cloud, depending on the emission height and the distance from the emission point.

For the dispersion calculations the released nuclides are grouped into four nuclide groups:

1. noble gas
2. aerosols
3. elementary iodine
4. organic iodine.

The dry deposition of aerosols and iodine are mainly described by the deposition velocity factor and the terrain roughness factor with distinct formulas calculating the deposition velocity for small and large particles. Noble gas is not considered for deposition. Concerning the wet deposition of the particles on the ground, inhomogeneous distributed rain, as determined by distributed precipitation measurements including radar data, can be considered. Chemical reactions between the radioactive particles and the rain are not considered in the current model for the washout coefficients.

The dose calculation is split in two models, the first one calculates the cloud radiation and the second one calculates the doses for different organs and age groups, based on the radiation of cloud (including inhalation) and the deposited particles on the ground.

The calculation of the cloud's gamma radiation is based on the model of adjoint fluxes, describing the activity fraction of the gamma radiation from one point in the three-dimensional grid to one point on the ground, taking into account thirty energy groups. Altogether, about 50 nuclides including the radiological most important ones are used for the calculation. The organ doses, the current dose rates as well as the over the time integrated doses are calculated, based on the activity concentration of the nuclides. Based on dose rate coefficients organ doses for the twenty-one different organs are calculated. In order to simplify the comparison of ABR results with measured data, in addition to the nuclide specific activity concentrations and depositions, the local gamma dose rate is calculated, too.

The solution area of the ABR varies from 25 km x 25 km up to 200 km x 200 km using an equally spaced grid with mesh sizes from 100 m up 1 km. In comparison to nesting algorithms where the mesh size increases with increasing distance from the emission point equally, spaced grids have the advantage that particles moving back and forth, depending on the wind regime can be traced better.

To be able to use the ABR to simulate the Fukushima accident, some adaptions had been necessary. The geographical reference system had to be changed from the German Gauss-Krüger coordinate system to the Universal Trans Mercator (UTM) based on WGS84, where WGS84 is the abbreviation of World Geodetic System 1984. In order to include Tokyo, the solution area had to be expanded to a square of 500 km side length with a mesh size of 2 km. Also a new digital elevation model (DEM) for Japan was needed. The DEM was generated from the data of the Shuttle Radar Topography Mission (SRTM). To transform the SRTM data to an equally spaced grid, gridding algorithms were used. For the visualization of the results, the underlying maps were taken from the OpenStreetMap project (OSM).

Modelling the accident of Fukushima

The terrific earth quake and the following tsunami, on March 11th 2011,disrupted the cooling of the reactor cores 1 to 3 at the site of Fukushima Daiichi and caused a station black out. As a consequence of the overheating of the reactor cores, a partial core melt down and hydrogen explosions occurred. This damage led to a release of radioactive material in the surrounding. Moreover, the spent fuel storage of plant 4 had also been heavily damaged. Figure 1 gives an overview of the time and the amount of released activity.

It was assumed that the release of radioactivity in the first days after the accident was of minor impact due to the possible use of filters, where most of the aerosol particles and iodine were retained. So the decision was taken that only the four major release phases in the time from March 14th to March 17th were considered for the calculation. Table 2 shows begin and duration of the four phases which have been modelled.

Table 2: Begin and duration of the release phases

Phase	Begin	Duration	Description
1	14.03.2011 13:30	2 h	Venting block 2
2a	15.03.2011 00:00	2 h	Explosion block 2
2b	15.03.2011 00:00	5 h	Block 4 release from fuel element storage pool
3	15.03.2011 14:30	3 h	Release from fuel element storage pool
4	16.03.2011 02:00	4 h	Explosion block 2 and 3

Later publications discuss the possibility of a partial core melt down accident caused by the earth quake, leading to earlier releases. But this information was published too late to be considered here. Moreover, the measurement data in the surrounding indicate smaller emissions in that phase (see Figure 1), at least towards land direction.

From the beginning of the accident the operating company TEPCO provided measured data from ten measurement points in the direct surrounding of the site. Beside the local gamma dose rate also data of wind speed and direction were provided but with timely gaps. Meteorological data wind speed and direction needed to be averaged in a vectorial manner in order to close these gaps and to make the data applicable for the calculation. The result is shown in Figure 2.

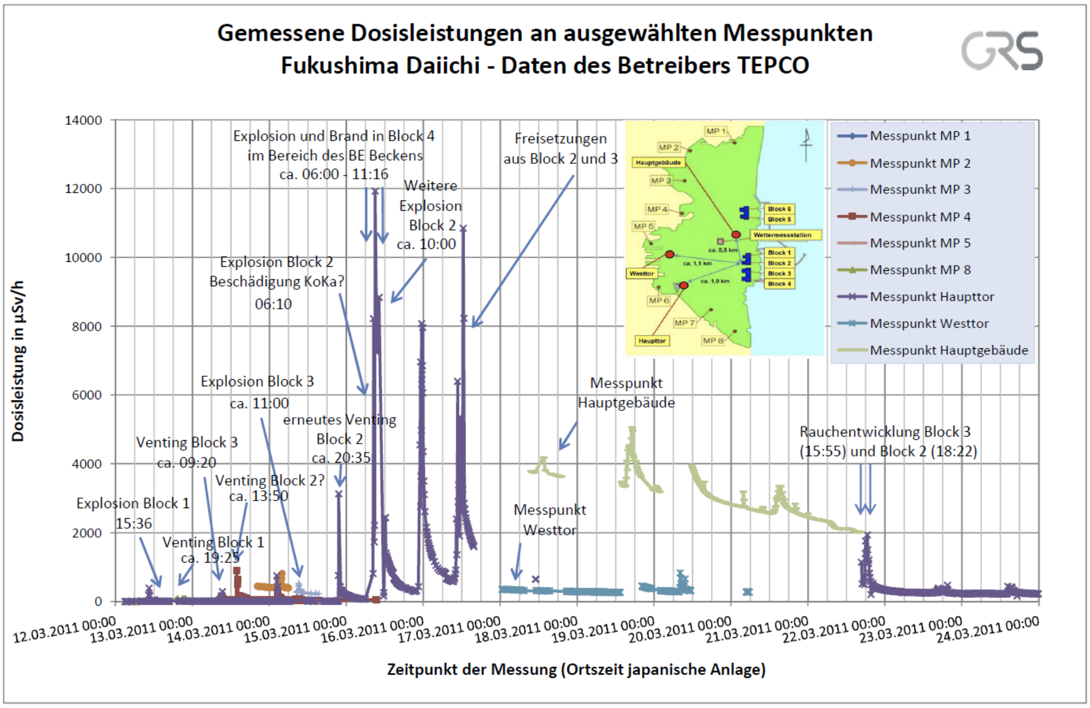

Figure 1: Measured dose rate at Fukushima Daiichi (Source: GRS, Germany)

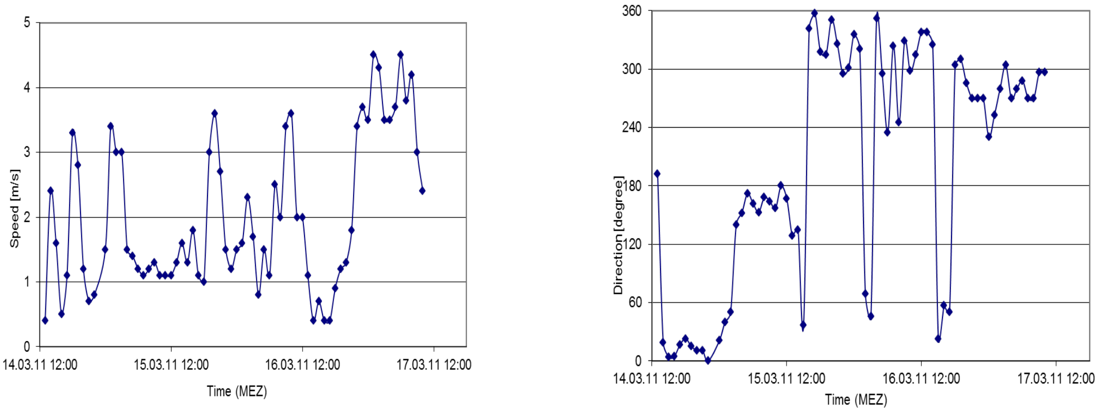

Figure 2: Wind speed and direction at the main entrance

The estimation of the released nuclides and their activity had been the most difficult part, because of the not well known damage of the building, the unknown position of the emission points and emission heights. Additionally it had to be taken into account that reactors were equipped with different fuel elements and different operation times. Especially the used MOX fuel elements in one block contain a larger portion of aerosols including heavy actinides like plutonium,

The estimation of the inventory was based on the inventory of German boiling water reactors, scaled with the power of the reactors at Fukushima. The fraction of the activity of a particular nuclide relative to the activity of the corresponding nuclide group was calculated on the basis of the release category FK1 for boiling water reactors, defined in “Leitfaden für den Fachberater Strahlenschutz” (Leitfaden), considering the possible release of plutonium from MOX fuel elements.

In a first attempt the source term was calculated under the assumption of filtered venting, resulting in lower release of iodine and aerosols. After the official announcement that the accident falls in category INES 7, and after the Nuclear and Industrial Safety Agency NISA has published values for the total activity released, the released activities used in the calculation have been adopted.

Table 3 show the resulting values in which the phases 2a and 2b denoted in Table 1 have been merged into a single phase.

Table 3: Released activity used in the calculation

Phase	Begin	Noble gas [Bq]	Iodine gas [Bq]	Aerosol gas [Bq]
1	14.03.2011 13:30	1.00 E+18	1.14 E+16	1.15 E+16
2	15.03.2011 00:00	1.00 E+18	1.50 E+17	1.00 E+17
3	15.03.2011 14:30	5.00 E+17	5.00 E+16	3.00 E+16
4	16.03.2011 02:00	1.00 E+18	1.00 E+17	5.00 E+16

It has to be noted that during the calculation the composition of the source term changes due to radioactive decay.

Results of the calculation

In the surrounding of the nuclear power plants in Japan a network of measurement devices exists. Since many stations had been damaged by the earth quake and tsunami, after the accident additional devices have been installed and numerous mobile measurements were performed. The data was published by the Ministry of Education, Culture, Sports, Science and Technology MEXT as well as the geographic location of the devices, which, however, is frequently described by expressions like “50 km northwest of Fukushima”. Beside the other uncertainties resulting from assumptions concerning emission point, emission height and the amount of released radioactivity, the eventually incorrect assignment of the location of the measurement devices introduces an additional uncertainty which has to be kept in mind analysing the results.

From the total number of 54 device locations, 16 locations plus Daini and Fukushima I have been selected for the analysis of the results (see Figure 3).

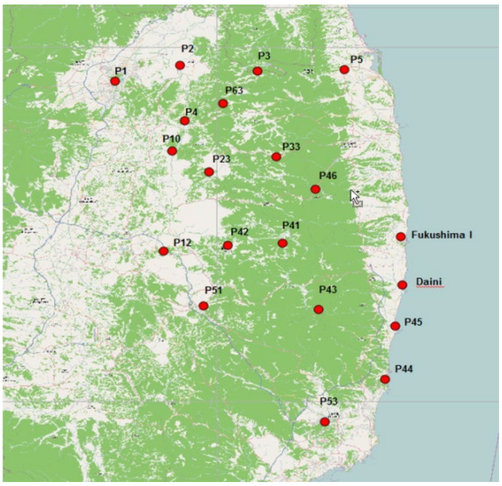

Figure 3: Location of the measurement devices

Examining the distribution of the local dose rate over time, shown in Figure 4 only measured values from the main entrance of Fukushima and from Daini have been available from the beginning of the calculation.

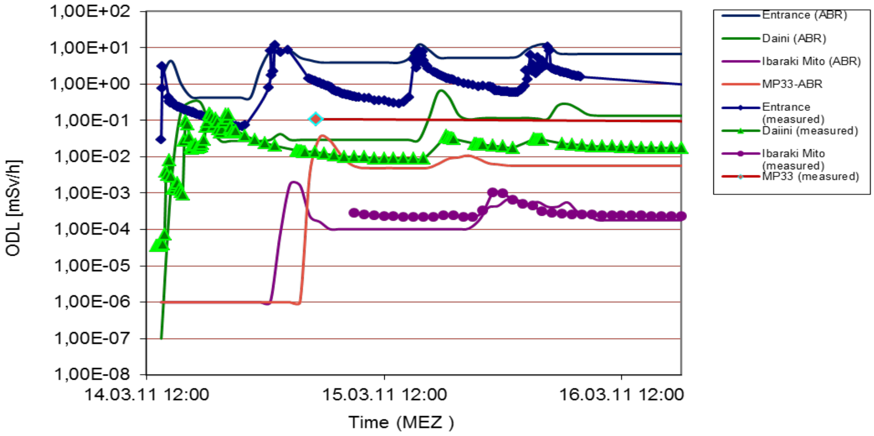

Figure 4: Local does rate over time

The calculated values at the main entrance show a very good agreement with the measured data. But this is obvious, because some of the measured data have influenced the determination of the source term used. The curves of the measured data show a decline of the local dose rate between the releases. This indicates that a larger amount of iodine has been released, where the decline results from radioactive decay of short living iodine isotopes. In the current implementation of the dose rates, the ABR does not consider the radioactive decay during the dispersion phase and of the nuclides deposited on the ground. So the dose rates predicted by the model remain constant between the releases. With respect to the integrated equivalent doses, however, the model includes the decay corrections.

The conclusion from above remains valid for the location of Fukushima Daini. The radioactive cloud arrived nearly at the same time and reached the same level of exposure. Noticeable is that the second release caused only a marginal increase of the local dose rate for the calculated values and nearly no increase for the measured values. Observing the wind direction during the second release it shows that the wind was blowing in north direction (see Figure 2).
In order to compare measured and calculated values for the location P33, the measured value given in Figure 4 is extrapolated from values dating form 17.03.2011 and later. Looking at Figure 5, the discrepancy between measured and calculated values at P33 become obvious. This difference can only be explained if non-measured rain is assumed.

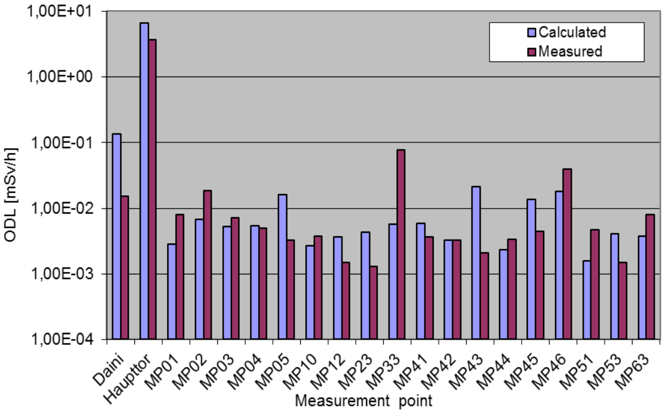

Figure 5: Comparison of the spatial distribution of the local dose rate.

The dose rates shown in Figure 5 are referred to date 17.03.2011 18:00 Japanese time after the radioactive cloud has left the solution area. As explained above, all calculated values, except for location P33 are in good agreement, indicating that the wind regime has been modelled according to the real situation.

With respect to the question concerning the use of the tools developed after the Chernobyl accident, it can be noticed that the ABR is capable to calculate realistic results, which in turn help to improve the emergency management in the case of a nuclear accident.

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