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Radiological impact assessment during all phases of nuclear and radiological events

Uncertainty of Atmospheric Dispersion Prediction

Jens Havskov Sørensen[1], Bjarne Amstrup[1], Thomas Bøvith[1], Henrik Feddersen[1], Rashpal Gill[1], Ulrik Smith Korsholm[1], Martin Sørensen[1], Flemming Vejen[1], Fredrik Schönfeldt[2], Robert Sigg[2], Jan Pehrsson[3], Poul Astrup[4], Bent Lauritzen[4], Jerzy Bartnicki[5], Heiko Klein[5], Magne Simonsen[5], Steen Cordt Hoe[6], Carsten Israelson[6], Jan Erik Dyve[7], Patric Lindahl[8], Jonas Lindgren[8]

[1]Danish Meteorological Institute (DMI), Denmark
[2]Swedish Defence Research Agency (FOI), Sweden
[3]PDC-ARGOS, Denmark
[4]Technical University of Denmark (DTU), Denmark
[5]Norwegian Meteorological Institute (MET Norway), Norway
[6]Danish Emergency Management Agency (DEMA), Denmark
[7]Norwegian Radiation and Nuclear Safety Authority (DSA), Norway
[8]Swedish Radiation Safety Authority (SSM), Sweden

Introduction

In the early phase of a nuclear power plant accident with possible off-site consequences resulting from e.g. core melt and breach of containment, accurate prediction of the atmospheric dispersion of radionuclides is of utmost importance. However, two large sources of uncertainty exist: one associated with the meteorological data employed for atmospheric dispersion model prediction, and one related to the source term, i.e. the amount of radionuclides released and the temporal evolution of the release.

In recent years, the effects of these inherent uncertainties on prediction of atmospheric dispersion of radionuclides released from nuclear accidents have been studied in a number of Nordic research projects funded by Nordic Nuclear Safety Research (NKS). Corresponding methods have been developed intended for operational use in emergency preparedness and response by national radiation protection authorities.

The methodology is implemented in the ARGOS nuclear decision-support system (DSS) (Hoe *et al.,* 1999; 2002; PDC-ARGOS) and is in operational use by the Danish Emergency Management Agency (DEMA) and the Danish Meteorological Institute (DMI) utilizing the DMI supercomputing facility.

Meteorological Ensemble Prediction

The COMEPS meteorological ensemble prediction system (Yang *et al.,* 2017), which is based on the Harmonie non-hydrostatic numerical weather prediction (NWP) model (Bengtsson *et al.,* 2017), is operational at the DMI. COMEPS includes 25 ensemble members with a horizontal resolution of 0.022°, corresponding to approximately 2.5 km, and vertically the model has 65 layers from the surface up to 10 hPa (approximately 30 km above the sea surface). The ensemble system is nested into ECMWF's global model. The geographical coverage is depicted in Figure 1.

Figure 1. Geographic domain covered by the operational EPS system at DMI.

Meteorological forecast uncertainties arise from uncertainties in the initial and lateral boundary conditions and from model short-comings, particularly short-comings associated with parameterization of physical processes that take place on spatial scales that cannot be represented explicitly by the model (Buizza *et al.,* 1999; Hou *et al.,* 2001).

The Danish Emergency Response Model of the Atmosphere (DERMA)

The Danish Emergency Response Model of the Atmosphere (DERMA) (Sørensen *et al.,* 2007; Sørensen, 1998; Baklanov and Sørensen, 2001) is a comprehensive numerical regional and meso-scale atmospheric dispersion model developed at DMI. The model is used operationally for the Danish nuclear and chemical emergency preparedness, for which the Danish Emergency Management Agency (DEMA) is responsible (Hoe *et al.*, 2002). Besides, the model is employed for veterinary emergency preparedness (Sørensen *et al.*, 2000; 2001; Mikkelsen *et al.*, 2003; Gloster *et al.,* 2010a; 2010b), where it is used for assessment of airborne spread of animal diseases, e.g. foot-and-mouth disease. DERMA is also used to simulate atmospheric dispersion of ashes from volcanic eruptions, and dispersion of biological warfare agents, and it has been employed for probabilistic nuclear risk assessment (Lauritzen *et al.,* 2006; 2007; Baklanov *et al.*, 2003; Mahura *et al.*, 2003; 2005).

Meteorological Uncertainty of atmospheric Dispersion model results (MUD)

In the NKS project MUD (Meteorological Uncertainty of atmospheric Dispersion model results), Sørensen *et al.* (2014) developed a methodology to quantify the effects of the inherent uncertainties of the NWP model data used on the atmospheric dispersion prediction.

Having available an NWP ensemble prediction system, dispersion model ensembles can be obtained for a given source term by running the dispersion model for each of the NWP ensemble members. Thereby, a dispersion model ensemble is created from which one can calculate various statistical parameters.

In Figure 2, results are shown for DERMA applied to a scenario with a release from the Ringhals NPP beginning on 2011-05-20 at 18 UTC. The results shown concern time-integrated concentration of I-131 at 54 hours after the start of the release. In the upper row, a low percentile, the median and a large percentile are displayed. Below are shown probabilities for exceeding 10^4, 10^3 and 10^2 Bq h/m^3, respectively.

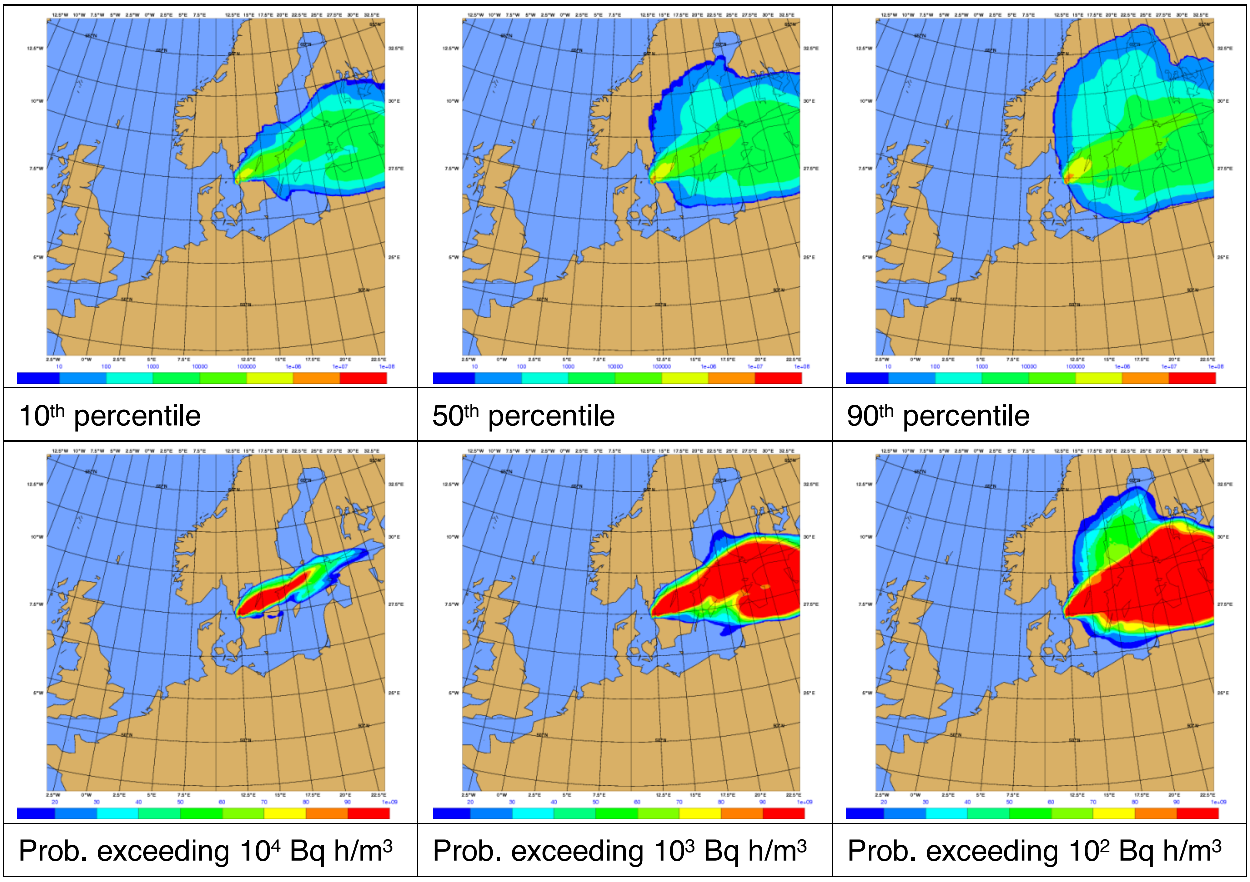

Figure 2. Valid time: 2011-05-23. NPP: Ringhals. Field: Time-integrated concentration 54 hours after start of release. Nuclide: I-131.

Fukushima Accident: UNcertainty of Atmospheric dispersion modelling (FAUNA)

In the NKS project FAUNA (Fukushima Accident: UNcertainty of Atmospheric dispersion modelling), Sørensen *et al.* (2016) applied the ensemble-statistical methodology developed in MUD to the Fukushima Daiichi NPP accident. The project addressed real-time forecasting of atmospheric dispersion and deposition of the radionuclides released taking into account the meteorological uncertainties. The source description by Katata *et al.* (2014) was used in the FAUNA project.

The objective of the FAUNA project was to apply the MUD methodology to a realistic setting of the Fukushima accident, and to investigate the implications for the emergency management of the uncertainties on the prediction of the geographical areas affected by radioactivity.

A meteorological ensemble forecasting system was set up and run on DMI's supercomputer for the period of concern and for a geographical domain covering Japan and surroundings. For the full period, two-day meteorological forecasts were generated four times a day, as would be the case for an operational system in real time. Thus, the project imitated real-time emergency management taking into account estimates of the uncertainty of the dispersion model results.

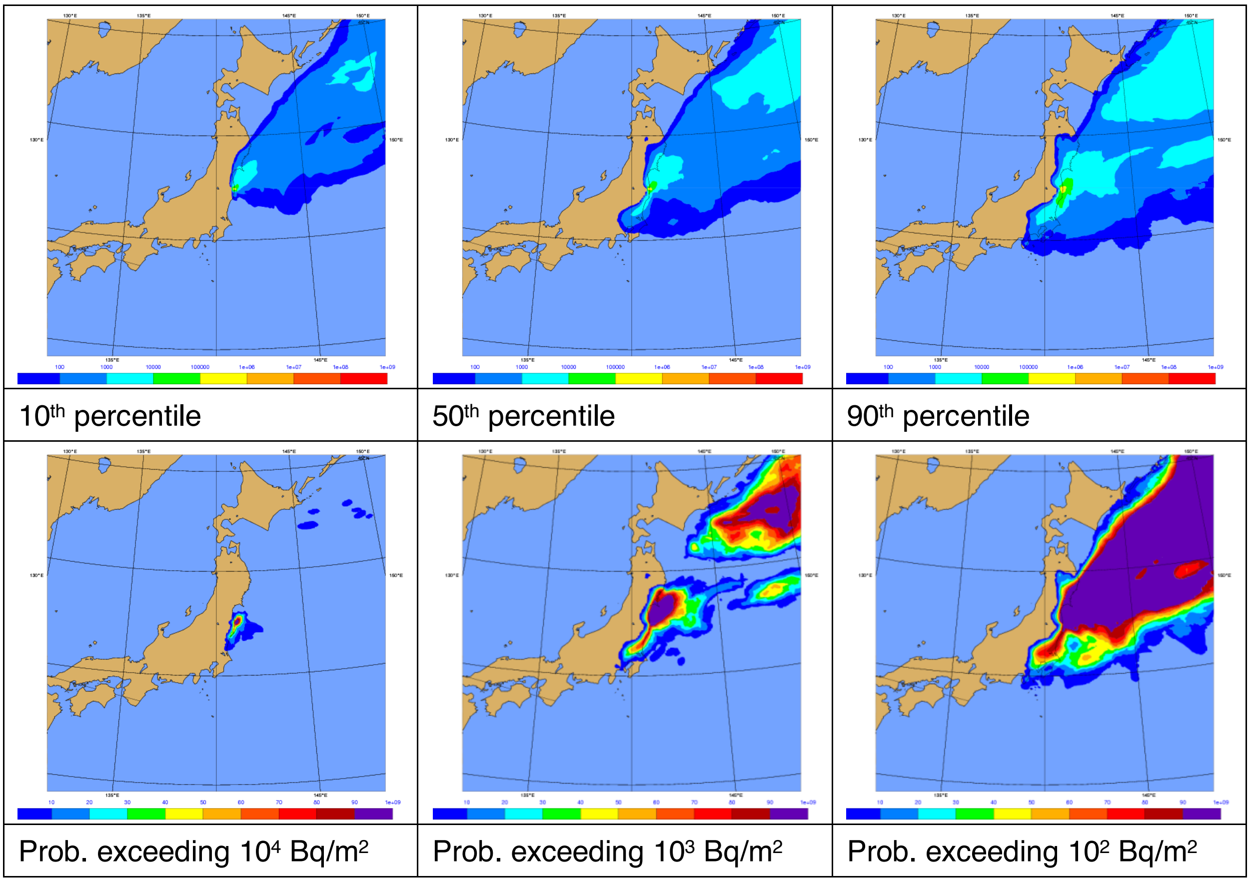

Figure 3. Plume prediction based on NWP model forecast of 2011-03-13, 00 UTC. Accumulated deposition of Cs-137 at 23 UTC on 14 March, 2011.

One of the scenarios considered is a hypothetical gathering of an expert group at the headquarters of a national radiation protection authority in the morning of 13 March 2011. The group has available the latest DERMA simulations from the 0 UTC run of the ensemble system, cf. Figure 3. Thus, the dispersion calculations are based on the latest full forecast series ranging 48 hours ahead from the meteorological analysis of 0 UTC on 13 March as well as analysed meteorological data and 1, 2, ..., 5 hours forecast data in between the analyses describing the period from 11 March until the latest analysis. During the forecast period, the plume is predominantly over the Pacific Ocean but meanders between north, east and finally south in the direction of Tokyo. In the first row of Figure 3 is shown the 10^{th}, 50^{th} and 90^{th} percentiles of accumulated deposition of Cs-137 valid at the end of the forecast period, i.e. at 23 UTC on 14 March 2011, and in the second row probabilities of exceeding threshold values of 10^4, 10^3 and 10^2 Bq/m^2, respectively. As can be seen, in this case low percentiles do not affect the Tokyo area, whereas larger percentiles do.

MEteorological uncertainty of ShOrt-range dispersion (MESO)

As shown by the MUD and FAUNA projects, the influence of meteorological uncertainties on long-range atmospheric dispersion calculations can be large, up to an order of magnitude or two depending on the weather situation, with significant implications for nuclear emergency preparedness and decision making. In the subsequent MESO (MEteorological uncertainty of ShOrt-range dispersion) project, Sørensen *et al.* (2017) studied to what extent this also applies to short-range dispersion models employed for nuclear emergency preparedness up to about a hundred kilometres from the source. Additionally, the direct use of weather radar data for the simulation of wet deposition of radionuclides was addressed including the uncertainties and potential errors associated with such use of weather radar data. These include the use of a parameterization of the precipitation rate depending on the attenuation of the reflected radar signal, filtering of false radar echoes arising from e.g. clutter or flocks of birds, precipitation from low clouds not being registered by the radar beam, and precipitation evaporating before reaching ground.

In brief, the results of MESO show that there is potentially a substantial influence of NWP model uncertainty on atmospheric dispersion also at short range, even close in at the kilometre scale (the near range). The variability is, however, less than at long range. Expressed as a factor, uncertainties of a factor of two to three can easily be observed at short range. However, in cases with well localised intense rainfalls, which are in general not well predicted by NWP models, one may observe larger effects.

Added Value of uncertainty Estimates of SOurce term and Meteorology (AVESOME)

In the NKS project AVESOME (Value of uncertainty Estimates of SOurce term and Meteorology), Sørensen *et al.* (2019) developed a methodology for quantitative estimation of the variability of atmospheric dispersion modelling resulting from both of the two largest sources of uncertainty, viz. the meteorological data and the source term. With modern super-computing facilities available e.g. at national meteorological services, the proposed methodology is well suited for real-time assessment and implementation in nuclear decision support systems (DSSs).

The methodology developed in AVESOME adapts well to the RApid Source TErm Prediction (RASTEP) system (Knochenhauer *et al.,* 2013), which provides a statistical ensemble of possible source terms and associated probabilities.

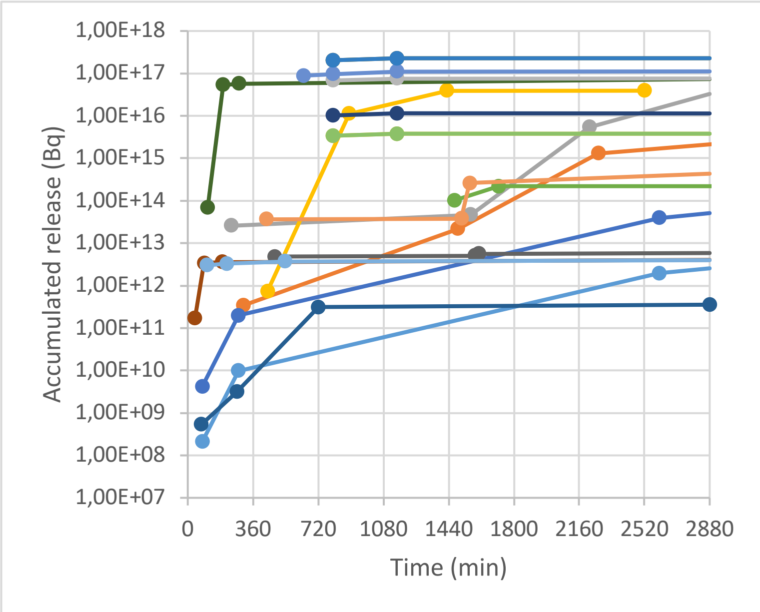

Figure 4. Accumulated release of Cs-137 as function of time since the emergency shutdown of a nuclear reactor (SCRAM) for the source-term ensemble members.

In the MUD, FAUNA and MESO projects, the atmospheric dispersion model ensembles were based on NWP model ensembles with N members. In AVESOME, the ensembles involved can be either a Source Term (ST) ensemble with M members applied to a deterministic NWP model, or an ST ensemble combined with an NWP model ensemble. In the latter case, the overall statistical ensemble is larger including $N \times M$ members. Whereas the meteorological ensemble members are equally likely, this is not the case for the source-term ensemble members, where the severe cases are highly unlikely. Therefore, weighted ensemble statistics should be employed.

A generic BWR source-term ensemble was provided to AVESOME consisting of a list of probabilities and source terms for the different release categories from the full power operation cases of a PSA Level 2, see Figure 4. The ensemble consists of 19 members. With a meteorological ensemble of 25 members, the combined ensemble thus consists of 25×19 = 475 members.

At the early phase of a serious nuclear accident with very limited knowledge on the source term, the difference between the source-term ensemble minimum and maximum is very large. Possibly, the ensemble shown in Figure 4 is too wide to be of practical value. Instead, one may decide to use a scenario-based approach limiting the ensemble members to selected ones. For each such sub-set, the weighting factors should be re-normalized.

Later, when additional information on the plant status is received, the source-term ensemble will become more focused; in the end probably to a fairly well-defined source term or a few. At this point in time, one should probably request new calculations due to the likely appearance of new NWP model forecasts available e.g. each three hours.

Few hours after the start of the event, one will likely know if the containment has been successfully isolated and if (at least one of) the mitigation systems (containment spraying and filtering) are functioning. In such case, the above 19-member source-term ensemble is reduced to 8 members. In Figure 5 are shown percentiles of accumulated deposition of Cs-137, and probabilities for exceeding given threshold values for the mitigation scenario.

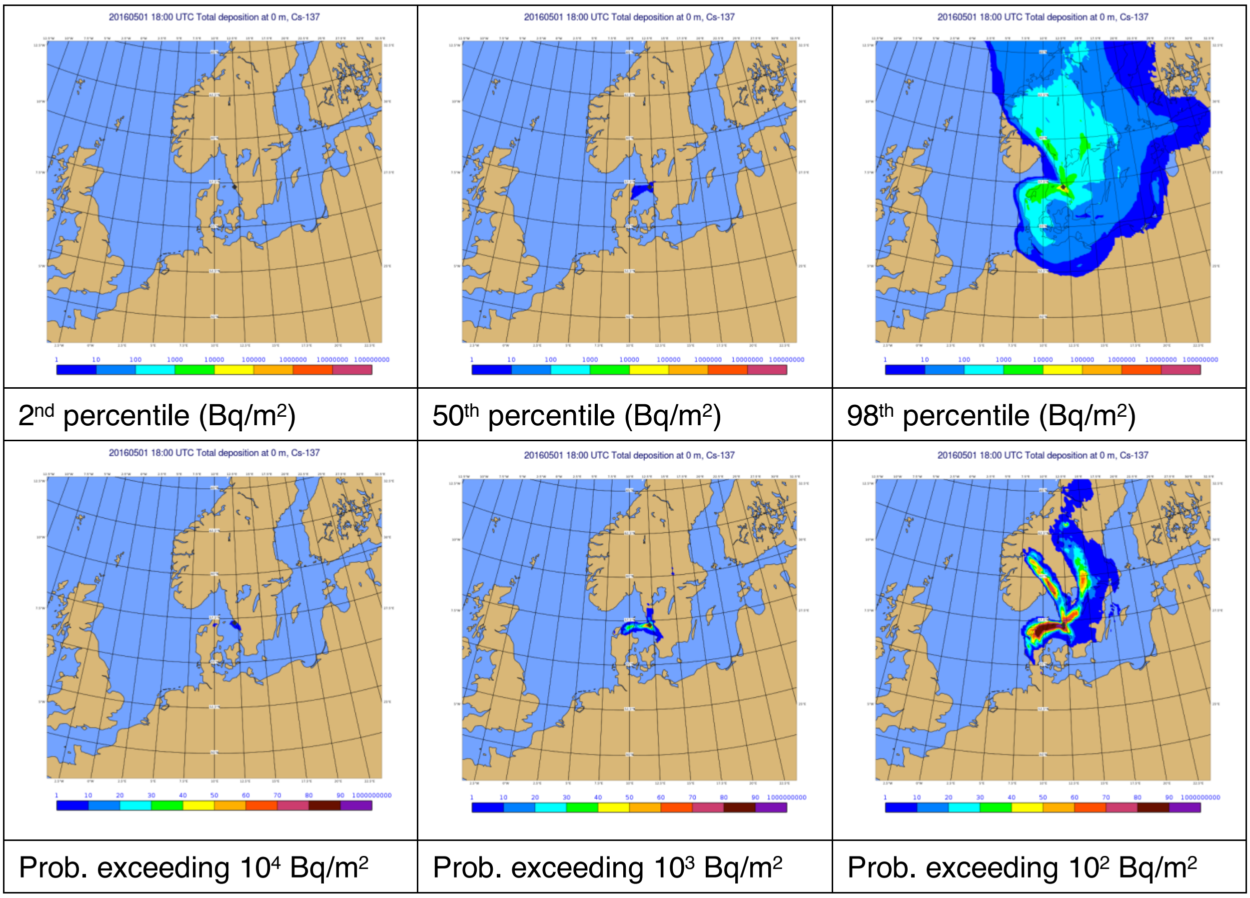

Figure 5. Percentiles of accumulated deposition (Bq/m2) of Cs-137 and probabilities (%) for exceeding threshold values for the mitigation source-term ensemble. Release starts at 2016-04-27, 12 UTC.

Conclusions

Implications of the largest sources of uncertainty on atmospheric dispersion of radioactivity from accidental releases have been addressed. These uncertainties involve both the source term, i.e. the amounts of radionuclides released and the temporal evolution of the release, and the meteorological data used. Impacts of the combined uncertainties on real-time emergency preparedness and management are further examined.

The methods developed allow for efficient real-time calculations by making use of scaling properties in the equations governing the release and the atmospheric dispersion of radionuclides. Accordingly, the computer-resource demanding calculations should be carried out at HPC facilities available e.g. at national meteorological services, whereas less demanding post-processing can be carried out at the computer hosting the DSS. The former tasks include atmospheric dispersion model calculations; the latter include interactive communication with the supercomputer as well as presentation of final results in the form of distributions of radionuclide concentrations, depositions and human doses.

The ARGOS nuclear DSS has been extended with a facility to handle multiple results from a single request for long-range prediction, including a set of statistical results from an ensemble run from either a meteorological ensemble or a source-term ensemble, or the two combined.

The facility is in operational use by the Danish Emergency Management Agency (DEMA) and the Danish Meteorological Institute (DMI) utilizing the DMI supercomputing facility.

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