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A simulation study of dispersion of air borne radionuclides from a nuclear power plant under a hypothetical accidental scenario at a tropical coastal site

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Abstract

Meteorological condition in coastal regions is diurnally variable and spatially heterogeneous due to complex topography, land–sea interface, etc. A wide range of dispersion conditions is possible on a given day in the coastal regions. In case of inadvertent accidental situations, though unlikely, it would be necessary to examine the potentially severe case among different dynamically occurring local atmospheric conditions for dispersion and its range of impact around a nuclear power plant for safety analysis. In this context, dispersion of air borne radioactive effluents during a hypothetical accidental scenario from a proposed prototype fast breeder reactor (PFBR) at an Indian coastal site, Kalpakkam, is simulated using a 3-D meso-scale atmospheric model MM5 and a random walk particle dispersion model FLEXPART. A simulation carried out for a typical summer day predicted the development of land–sea breeze circulation and thermal internal boundary layer (TIBL) formation, which have been confirmed by meteorological observations. Analysis of dose distribution shows that the maximum dose for releases from a 100 m stack occurs at two places within 4 km distance during sea breeze/TIBL fumigation hours. Maximum dose also occurred during nighttime stable conditions. Results indicate that, on the day of present study, the highest concentrations occurred during periods of TIBL fumigation rather than during stable atmospheric conditions. Further, the area of impact (plume width at the surface) spreads up to a down wind distance of 4 km during fumigation condition. Simulation over a range of 25 km has shown turning of plume at the incidence of sea breeze circulation and two different dispersion patterns across the sea breeze front. These results are significant in comparison to the expected pattern shown by Gaussian plume model used for routine analysis.

Keywords: Radionuclide dispersion; Meso-scale model; FLEXPART; Sea breeze; TIBL fumigation

1. Introduction

A prototype fast breeder reactor (PFBR) is being constructed at Kalpakkam, an eastern coastal site of India. Analysis of the environmental radiological impact under design-based probable accidental releases for any proposed nuclear plant is a regulatory requirement and therefore, as a part of it, a study of atmospheric dispersion of radionuclides and the consequent dose to the public is carried out.

The meteorological condition at Kalpakkam, like any coastal site, is non-stationary and non-homogeneous due to thermally driven land–sea breeze circulation,

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which gives rise to a variety of complex atmospheric dispersion conditions. Strong gradients of heat flux and temperature develop across the coast during clear sunny days and lead to direct circulation from sea to land during daytime and an opposite circulation from land to sea during nighttime (Estoque, 1961). The advection of cool humid air mass during sea breeze time changes the properties of the hot dry air mass over land and a thermal internal boundary layer (TIBL) forms near the coast (Vugts and Businger, 1977). TIBL is a shallow unstable layer and forms an upper limit for the mixing height. The stable boundary layer over the TIBL inhibits vertical mixing across TIBL top. While entrainment of pollutants and reflectance by TIBL leads to fumigation, the incidence of sea breeze leads to turning of the plume (Lyons and Cole, 1976; Ludwig, 1983; National Academy of Sciences, 1992). The onset, intensity, duration and inland extent of sea breeze and the horizontal and vertical growth properties of TIBL assume significance in determining the pollution dispersion in coastal regions.

The conventional practice is to calculate the radioactive dose to the public at the boundary of the site (1.5 km) and design the plant in such a way that the doses are well within the prescribed safety limit. Calculation for releases through air route is done assuming the Pasquill stability category F for the worst atmospheric condition using a Gaussian plume/puff model. While this gives the maximum dose estimate for ground release, the maximum dose for stack release would be during an unstable (Passquill category A) situation, near the site boundary, if the same wind speed were used as in the case of F category. The question is, whether the conception of worst situation (F for ground release and A for stack release) for a plain inland condition is applicable for a coastal terrain where fumigation of the plume is expected under TIBL development.

The regulatory procedures for assessing the radiological consequences use the standard Gaussian plume model (GPM) for estimating the plume concentration (Shirvaikar, 1973; IAEA, 1980; Clarke and Macdonald, 1978). Here, radioactive dose at the site boundary alone is considered important with an assumption that it decreases exponentially further away for ground level releases. So, calculations are usually made for stability category F to find out the dose at the site boundary. However, there is a short-term release of noble gases envisaged through stack and the maximum dose due to it would be during an unstable (Passquill category A) situation, near the site boundary, if the same wind speed were used as in the case of F category. Further, the distance of maximum concentration for stack release could occur beyond the site boundary even in highly mixing category A. In an earlier study, analysis of the observed radioactive Ar^{41} plume dose within the site at Kalpakkam had shown the influence of TIBL fumigation (Venkatesan et al., 2002). Dose pattern beyond the site needs to be studied using a suitable meso-scale model.

Although GPM provides conservative estimates for safe design purposes, it is nevertheless required to know the radiological impact due to complex meteorological condition at the coastal site and suitably incorporate the knowledge in accident analysis in order to ensure that the design provides adequate safety to environment beyond the site boundary. A suitable atmospheric hydrodynamic model is therefore chosen to simulate the spatial and temporal structure of the coastal atmospheric boundary layer wind field and followed by a particle dispersion model to get the ground-level concentration more realistically. A good number of meso-scale atmospheric models with advanced diffusion techniques have been reported in literature for emergency response programmes (Lyons et al., 1983; Fast et al., 1995; Camps et al., 1997; Hanna, 1982; Zannetti, 1990 among others).

The present work aims to study the dose distribution of air borne radioactive effluents released from PFBR proposed at Kalpakkam coastal site in a design basis accidental (DBA) situation for the ambient atmospheric conditions on a given day and the differences that would arise in the estimates when a standard GPM is applied for the same. The modelling system consists of a high-resolution 3-D meso-scale meteorological model (MM5) coupled with a Lagrangian particle model (FLEXPART). The simulation is selected on 24 May 2003, a typical summer sea breeze day, when meteorological measurements were carried out at Kalpakkam using a tethered balloon, a mini sodar and a meteorological tower. Dispersion calculation is made over two ranges, i.e., over a local range of 6.25 km for dose distribution near the reactor and in a range of 25 km in the meso-scale.

2. Study area

The study area Kalpakkam is located on the east coast of India (Fig. 1) at 12.50°N and 80.10°E. The terrain elevation gently rises to the west and has a linear coastline running in NE–SW direction. Along the coast, the site is about 80 km away from Chennai city in the northern side and nearly 70 km from Pondicherry on the southern side. The land use pattern indicates a corresponding average roughness length of 0.3 m except near plant area and a sandy-clay loam soil type.

3. Simulation of atmospheric parameters

3.1. Brief description of atmospheric model

A non-hydrostatic, primitive-equation, finite-difference meso-scale atmospheric model MM5 (Anthes and