Primary Dispersion Related Factors to be Considered in Nuclear Power Plant Applications

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Purpose

The purpose of this paper is to identify and discuss the primary factors affecting the determination of relative dispersion coefficients (X/Qs) for control room habitability analysis, plant design, and environmental impact assessment of nuclear power plants. The paper also includes discussions on limitations of some of the dispersion models and the recent modeling enhancements made regarding the treatment of these factors in dispersion predictions.

History

As the primary agency responsible for safeguarding nuclear power plant design and operation, the U.S. Nuclear Regulatory Commission (NRC) has issued many documents and regulatory guides dealing with the dispersion of routine and accidental releases of radioactive materials as well as onsite and offsite accidental toxic chemical releases. Most of these documents were published prior to 1985, including several that were issued prior to 1980.

In 1988, NRC issued NUREG/CR-5055 with the intention of replacing the Murphy-Campe method (1974) for estimation of X/Qs at control room air intakes or at locations in the vicinity of building structures. However, the use of this regulatory guide was short lived due to unfavorable comments made by critics particularly with regards to its accuracy. Not until 1995 did the NRC issued a new computer model, ARCON95, for determination of X/Qs at locations within build wake regions. Subsequently, a revised version of this model, ARCON96 (1997), was issued to address some glitches found in the original version and to include several minor improvements.

In parallel to the NRC, the U.S. Environmental Protection Agency (EPA), as part of its Congressional mandate, has taken the lead in developing national air regulations and various sophisticated dispersion models. Similar to the NRC's approach, most of the EPA-sponsored dispersion models were steady-state using Gaussian-type dispersion coefficients developed by Pasquill-Gifford (1961) and widely promoted by Turner (1970).

The use of the P-G curves has served the air dispersion modeling community well during the past three decades. Over the years, improvements and additional calibration efforts were made to many of the EPA models. In general, the EPA models have a factor of two accuracy in their prediction of the magnitude of the maximum pollutant concentrations, but with less accuracy in predicting the maximum impact locations due to the fact that most of the models assuming a steady-state plume. During the past three years, EPA has issued several so-called 2nd Generation dispersion models in an attempt to replace the Gaussian-type (i.e.,1st Generation) models. As a result, the use of the P-G curves in dispersion modeling may be gradually phased out in the next three years.

Primary Dispersion Related Factors

For nuclear power applications, the dispersion related factors being considered in dispersion estimates include wind speed, wind direction, stability class, mixing height, release type, and release & receptor locations.

Conventional Gaussian Models

For Gaussian dispersion models, wind speed, stability class, and release height are the most important factors affecting dispersion calculations. The stability class is used to determine the values of the horizontal and vertical dispersion coefficients. Mixing height is a secondary factor which can affect the ground-level concentration resulting from elevated releases. If the mixing layer depth is relatively shallow and the effective plume height is lower than the mixing depth, the plume can reflect back to the ground with the mixing height acting as a lid (upper boundary) for dispersion.

Conventional Wake Models

For determination of X/Qs at locations within building wakes, the cross-sectional area of a nearby building is often input into the dispersion models to estimate the building downwash effect. The reasoning is that with the advectional effect of the wind speed, the two-dimensional building area evolves into a dilution volume once the plume is caught in a wake or cavity. One of the widely used building wake model in the 1970's and 1980's was:

$$X/Q = 1 / \pi(\sigma_y \sigma_z + cA)u$$

Where: σ_y and σ_z are the horizontal and vertical dispersion coefficients,
A is the upwind cross-sectional building area affecting the release,
$c = 0.5$, and
u is the mean wind speed within the wake.

The modeling community realized for sometime that the above model could only provide a rough estimate of X/Qs. For example, Halitsky (1962) observed that the cavity concentrations were not uniformly distributed within the wake. In addition, a study made on the observations taken at Rancho Seco Nuclear Power Station (1977) had revealed that the use of the add-on "cA"term was functionally incorrect. Nevertheless, the model had been used extensively for many years in despite of those criticisms.

Other Wake Models

The EPA-sponsored Industrial Source Complex (ISC) dispersion model incorporated a building downwash subroutine based on wind tunnel studies conducted by Huber (1977) and Snyder (1976). In a subsequent revised version, the model was updated to include a modified scheme based on the work of Scire and Schulman (1980). These downwash algorithms considered direction-dependent building cross-sectional areas among other improvements. Pollutant concentration calculations for a plume under building downwash conditions have became more accurate with the introduction of the revised ISC model.

The NRC-sponsored PAVAN model (1984) which basically implemented guidance contained in Regulatory Guide 1.145 (1978), was intended for use in estimating X/Qs at the exclusive area boundary and at the low population zone. Building wake effect is evaluated in the PAVAN model utilizing the "cA" term.

The more recently released NRC-sponsored ARCON96 model, which is intended for estimating X/Qs at locations within building wakes, does not require use of the "cA" term, but the building cross-sectional area term is input as a constant. Based on the experience in using ARCON96, the model is often times insensitive to the value of "A". In addition, the X/Qs generated from the ARCON96 model are usually not sensitive to the wind direction either. If a wake mode is not sensitive to both building area and wind direction then the validity of its resulting calculations becomes somewhat questionable. ARCON96 is currently undergoing major revisions, however, building downwash subroutine modification is not one of them.

Recent Modeling Development

There have been many models developed during the past two decades in the public domain. Treatments of the relevant dispersion related factors to improve the dispersion estimates were made in many models.

Source Type

Dispersion for point, area, volume and lines sources can be simulated by many public domain dispersion models. For nuclear applications, line-type sources are seldom encountered. ARCON96 has an option to account for the effect of initial dilution from volume and/or area source releases (e.g., releases from the reactor dome or from equipment hatch doors). Although ARCON96 was developed based on numerous wind tunnel tests, NRC has expressed reservations (NRC, 2000) in accepting X/Q calculations based on some of the approaches suggested in the ARCON96 user's guide. Lack of official announcement regarding their disagreement or providing guidance on their preferred approaches has caused confusion within the model user community.

Release Height

The PAVAN model considered ground-level and stack releases in its algorithms. ARCON96 addresses ground-level, vent and stack releases. In general, a stack release is defined as a release from a point source at an elevation at least 2.5 times the height of the tallest nearby building. EPA implements Good Engineering Practice (GEP) (EPA, 1981) stack height for fossil power plants. GEP stack height is defined as the lowest height of plume release that will not cause the plume downwash in the cavity/wake zone. For release points that are lower than the GEP height, downwash analysis is mandatory. In order to consider building downwash, EPA suggests the use of Building Profile Input Program (BPIP) (EPA, 1993) to prepare the building dimension input requirement before running ISC. In the new ISC-Prime, EPA also issued a revised BPIP (EPA, 1998) to provide more detailed building information for downwash analysis. Based on the nearby building dimensions, the revised BPIP produces projected length of the building along the flow and along-flow and across-flow distances from the stack to the center of the upwind face of the projected building. With these detailed building information, the cavity/wake effects are then analyzed.

For the EPA models, no specific option for vent releases is provided because the release mode is well defined either as a GEP or sub-GEP release. If it falls in the sub-GEP category, building downwash analysis is required. On the contrary, NRC provides vent release mode in ARCON96; however, the modeling procedures is not well defined. With the exception of the ARCON96 model, the vent release mode has not been officially addressed by the NRC in any other models. The current modifications that are underway for ARCON96 will likely address the vent release mode in a more precise manner.

Plume Rise

In general, the NRC models do not consider plume rise explicitly in X/Q estimates, but it can be considered on case-by-case basis. Contrary to NRC, EPA places considerable emphasis on the plume rise issue because of the relatively large quantity of effluent exiting at high temperature and velocity from stacks associate with industrial facilities. However, some of the vent or stack releases at nuclear power plants do involve high exit temperatures, and/or significant vertical exit velocities. In order to achieve more accurate X/Q estimates, NRC should include thermal and momentum plume rise estimates in their models. Furthermore, for control room habitability analysis, streamline deflection near buildings and vertical wind speed shear and velocity deficit effects on plume rise should also be considered. The mere use of the traditional plume rise formulas probably are not sufficient for estimating X/Qs at control room air intakes located within the cavity.

Release Location

Location of the releases and receptors are crucial in X/Q estimates. However, not until the release of the ISC-Prime model, the stack location was not explicitly affecting the concentration estimates in the building wake analysis. The conventional thinking was that a plume would be uniformly mixed within the wake region, especially within the cavity zone. Thus, as long as receptors are located within the wake, the release location is irrelevant. Since numerous wind tunnel tests have show otherwise, the ISC-Prime model now takes into account of the position of the stack relative to the building in its concentration estimates.

Assumption of Uniformly Mixed Plume

As mentioned, the NRC dispersion models and the EPA 1st Generation dispersion models usually assumed uniform mixing in the wake. This simplistic approach is inadequate to describe the complex nature of dispersion under wake conditions. ISC-Prime now has considered turbulence intensity, wind speed, and streamline slope which gradually decays to ambient conditions downwind of the building. A probability density function and eddy diffusivity scheme are used for X/Q estimates in the wake. Instead of uniform mixing, the fraction of plume mass captured by and recirculated within the near wake is calculated. The captured plume is re-emitted downwind as a volume source. The re-emitted plume and the uncaptured primary plume are both accounted for in the far wake concentration estimate. Approaches similar to those used in ISC-Prime could be considered by the NRC to enable the performance of more realistic and accurate control room habitability analysis.

Meteorological Data

Meteorological data are required in all the dispersion models. Representativeness of the data is critical. The PAVAN model uses a joint frequency distribution as input, while ARCON96 uses continuous hourly data to improve X/Q estimates for short-period averages. EPA has avoided the use of frequency distributions and favors the use of representative hourly data in their dispersion modeling for air permit applications. Even for long-term (annual average) estimate, EPA now prefers to use hourly data. It seems both NRC and EPA are in sync regarding this issue.

In addition to processing hourly data , the 2nd Generation models issued by EPA also use a preprocessor to estimate the necessary hourly boundary layer parameters utilizing multiple-layer observations of wind speed and direction, temperature, and standard deviation of the fluctuation components of the wind. All nuclear power plant sites have a long history of onsite meteorological data collection, sometimes involve multi-tower observations. The future NRC-sponsored models could be enhanced by incorporating a more sophisticated meteorological preprocessor for data preparation.

Calm Wind Treatment

Instead of applying complex statistical schemes to address clam wind conditions, traditionally the NRC use a wind speed of 0.5 m/s as the lower bound of a valid wind speed. In most of the EPA dispersion models, 1 m/s for wind speed is usually assumed as the lower-bound limit. Therefore, under the same calm dispersion conditions, the NRC approach would estimate a concentration twice the amount of that estimated by the EPA-sponsored models. On the other hand, the NRC models for accidental releases allow wind meandering credits when wind speeds are lower than 6 m/s (NRC, 1978). All the models have their limitations. Dispersion estimates involving extremely low wind speed is one of them. Theoretically, dispersion under extreme low wind conditions should not be a concern for if there is no wind, there is no dispersion. Besides, under calm wind conditions the wind direction is undefined

CONCLUSIONS

Assessment of control room habitability continues to be an important topic for nuclear power plant operation. Therefore, a new generation models suitable for control room habitability evaluation is urgently need for the user community as well as for the NRC such that more accurate and realistic dispersion estimates within building wakes can be made. Too many case-by-case evaluations are not cost effective and do not provide uniformity and consistent modeling results. Currently, there are many sophisticated dispersion models in the public domain. In general, the EPA offers more variety of models due to its extensive research and the large amount of the air permit applications involving fossil-fired power plants. The recent 2nd Generating models provide many new approaches in improving concentration estimates in cavity/wake regions. Based on this foundation established by the EPA, the NRC could develop its own versions according to its specific needs.

With respect to other available modeling tools, physical modeling (i.e., wind tunnel testing) and computation fluid dynamic (CFD) modeling are options that applicants could use. However, those options are time consuming and relatively expensive. Furthermore, wind tunnel testing usually can only provide

X/Q estimates for neutral atmospheric conditions. Many worst-case scenarios occur under stable conditions are difficult to simulate using wind tunnels. on the other hand, because CFD applications require considerable modeling skills and significant computational power, it is difficult to establish CFD as a viable option for widespread use in the near future. Although the CFD results often can be used to provide supporting evidence for dispersion estimates involving complex cases. The development of agency sponsored dispersion models is still the most practical and preferred option.

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REFERENCES

Control Room Habitability Analyses Task Force NRC Meeting, March 30-31, 2000, NRC White Flint Office, Rockville, MD.

Gifford, F.A., 1961: Uses of Routine Meteorological Observations for Estimating Atmospheric Dispersion, Nuclear Safety 2(4).

Guideline fir Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulations), 1981, EPA-450/4-80-023, U.S. EPA.

Murphy, K.G. K.M. Campe, 1974: Nuclear Power Plant Control Room Ventilation System Design for Meeting General Criterion 19, 13th AEC Air Cleaning Conference.

Pasguill, F., 1961: The Estimation of the Dispersion of Windborne Material, Meteorol. Mag., 90.

Regulatory Guide 1.145, 1982: Atmospheric Dispersion Models for Potential Accident Consequence Assessment at Nuclear Power Plants, U.S. NRC.

Ramsdell, J.V., 1988: Atmospheric Diffusion for Control Room Habitability Assessments, NUREG/CR-5055, U.S. NRC.

Ramsdell, J.V., C.A. Simonen, 1997: Atmospheric Relative Concentrations in Building Wakes, NUREG/CR-6331, Rev. 1, U.S. NRC.

Schulman, L.L., D.G. Strimaitis, J.S. Scrie, 1997: Addendum to ISC User's Guide, The PRIME Plume Rise And Building Downwash Model.

Schulman, L.L., D.G. Strimatis, and J.S. Scire, 2000: Development and Evaluation of the PRIME Plume Rise and Building Downwash Model, Journal of the A&WMA.

Start, G.E., J.H. Gate, C.R. Dickson, N.R. Ricks, G.R. Ackermann, and J.F. Sagendorf, 1977: Rancho Seco Building Effects on Atmospheric Diffusion, NOAA Tech Memo, ERL-ARL-69 (NOAA/ARL, Idaho falls, ID).

Turner, D.B., 1970: Workbook of Atmospheric Dispersion Estimates, U.S. Department of HEW, 1970.

User's Guide to the Building Profile Input Program, 1993: EPA-454/R-93-038, U.S. EPA.