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Invited Paper

BLUFF-BODY AERODYNAMICS INFLUENCE ON TRANSPORT AND DIFFUSION

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Summary

Atmospheric turbulence may cause only weak dispersive effects compared to the turbulence generated by buildings, obstacles, and terrain. Yet the magnitude of the perturbed flow will in turn depend upon the incident flow turbulence scale and intensity, details of the obstacle shape and surface roughness, and the size of the obstacle compared to the boundary layer depth. Hence, the size and character of a dispersion plume frequently depends upon the shape and intensity of motion within separated flow regions about the obstacle and the stationarity or unsteadiness of these secondary flow fields. The diffusive character of a gas plume released in such situations can be described in terms of its mean concentration profile, the rate of decay of maximum concentrations, the growth in profile width or depth scales, and its statistical variability.

Keywords
Dispersion, diffusion, entrainment, building aerodynamics, building wakes, wind engineering

1. INTRODUCTION

The concentration field produced by a source located in the vicinity of a surface-mounted bluff body can be significantly modified from that predicted by conventional diffusion formulae. Such formulae contain the implicit assumptions that the flow field has straight parallel streamlines, modest velocity gradients, and distributions of turbulent energy and length scales which remain unchanged over long distances. Near buildings the flow field becomes highly complex. Curved streamlines, velocity discontinuities, and non-homogeneous turbulence disperse effluents in a complicated manner related to source configuration and body geometry.

This paper reviews recent wisdom concerning which features of bluff body flow control scalar transport (Section 2), summarizes field and laboratory data that include measurements of concentration near bluff bodies (Section 3), critiques analytic models that predict dispersion near bluff bodies (Section 4), and reports how bluff bodies can sometimes mitigate gaseous hazards (Sections 5 and 6).

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2. DISPERSION RELATED ASPECTS OF BOUNDARY LAYER FLOWS OVER BLUFF BODIES

A number of authors have discussed flow about simple surface-mounted obstacles. Extensive reviews about such flow fields and/or the subsequent character of diffusion near obstacles have been prepared by Jensen (1954), van Eimern et al. (1964), Lemberg (1973), Meroney (1982), Hosker (1984), and Taylor (1988). The description of the flow near bluff bodies is primarily based upon laboratory observations of smoke patterns, neutrally-buoyant bubble-streak photographs, and oil-film analysis. Most of such data have been obtained in low speed aerodynamic or meteorological wind or water tunnels. Recently numerical models have also contributed to the understanding of dispersion near two- and three-dimensional bluff bodies (Ukeguchi et al., 1975; Mauermayer, 1979; Gross, 1987; Murakami et al., 1987)

2.1 Flow Structure About Sharp-edged Rectangular Bluff Bodies

Typically, when the approach shear flow is normal to a rectangular obstacle, the flow separates from the ground upwind of the structure and produces a "horse-shoe" shaped vortex which wraps around the base of the body. The surface streamline reattaches on the front of the obstacle, and the fluid parcels move up and down the forward face. An elevated streamline flows over the obstacle, dips down behind, and stagnates on the surface at the end of the recirculating cavity immediately downwind of the obstacle. Sometimes separation streamlines from the forward edges reattach to a downwind face.

At one time the cavity region was considered a closed recirculation zone bounded by the separation streamlines rising from the upwind edges of a bluff body. Pollutant gases could only entrain in or out of this region by turbulent transport across the surrounding shear layer. For finite width buildings it is now generally accepted that the streamline bounding the cavity is not the separation streamline. Hence, gases which enter the cavity depart through turbulent mixing across the dividing streamlines, mingle with downwind pointing vortices and are ejected laterally out of the cavity, or leave suddenly during an exhalation when the entire cavity appears to collapse and reform.

Nonetheless, the separation streamlines play an important role in defining the initial transport of pollutants released near a bluff body. Effluent released from surface vents at mid-height or below on the windward face of an object will be carried downward to ground level and around the building sides. Vents releases on the front half of the windward side and other faces of the object will enter the cavity and wake region. If the along-wind dimensions of the body are large, the edge-separated flow will reattach to the roof and sides and transport the gases closer to the body. Flow with reattachment to the body sides or roof will reseparate at the lee edge of the body.

When a rectangular obstacle is oriented obliquely to the air stream, flow over the front side walls does not separate, but strong recirculation occurs on the downwind faces. Flow over the roof often produces counter-rotating "delta-wing" vortices which increase mixing over the top and in the wake of the body. These vortices can cause reattachment of the flow in the middle of the roof and high downwash in the near wake. This downwash may produce an increase in ground-level concentrations from sources released above ground. Other features of the flow near the building include vertical vortices produced by the vertical corners of the structure. Measurements of recirculating region characteristics at Reynolds numbers of 5000 and upwards show no significant differences in fluid residence time or recirculation region length.

2.2 Flow Structure About Curved or Cylindrical Bluff Bodies

Flow around a smoothly curved obstacle is generally strongly Reynolds number dependent. Separation often depends upon upwind and downwind curvatures, surface roughness, incident turbulence, and atmospheric stability. This dependence reflects changes in the nature of the boundary layers that form over the curved surface. A number of studies report flow measurements about ground-mounted obstacles -- cylinders, hemispheres, spheres, cones, and cone frustrums. All studies report the presence of a horseshoe vortex on the ground, elevated vortex pairs due to the bending over at roof level of the spiral vortices generated behind the sides of the bodies, and other qualitative features similar to those observed in high speed turbulence flow over sharp edged bodies. Only the flow details for curved obstacles seem to depend on Reynolds number. Diffusion downwind or over such curved obstacles reflect the changes in flow field produced by the perturbation and non-stationarity of separation streamlines.

2.3 Stratification Effects on Dispersion Near Bluff Bodies

Stratification does not affect flow and dispersion in the near vicinity of sharp edged objects very strongly (Meroney and Yang, 1970; Hatcher and Meroney, 1977). Examination of some 242 field releases near nuclear reactors produced no conclusive evidence of an effect of stability on concentrations (Ramsdell, 1988). However, a multi-linear regression performed over the data sets considered by Ramsdell did suggest a modest increase in concentration with more stable flows. The stratification effects evident in the laboratory and field concentrations measured around the Rancho Seco Nuclear Power Station, USA, performed by Start et al. (1978) and Allwine et al. (1980) were primarily produced by strong direction meandering and not by any apparent change in transport about the buildings.

Stratification has been found to strongly affect dispersion over terrain. Wide obstructions may cause partial blocking of the approach flow and create a stagnant region of high pollution. Lee-wave induced separation may bring plumes near the ground. Tall hills may induce a dividing streamline below which flow goes around the sides of an obstacle rather than over it. Moderately stratified flows may supress separation on the lee side of a hill (Hunt, Snyder, and Lawson, 1978).

3. BLUFF-BODY-WAKE DIFFUSION DATA

Many measurements have been made of the behavior of gas plumes in the vicinity of bluff bodies. Indeed, sometimes the diffusion data were used to infer the fluid motions about the body in cases where direct velocity measurements were difficult. Frequently measurements in the laboratory are for dispersion about simple geometries, such as fences, cubes, rectangular blocks, cylinders, spheres, hemispheres, cones, etc. Other laboratory measurements were made over geometrically scaled building complexes to permit hazard evaluation or evaluate environmental impact of smoke plumes or process emissions (unfortunately these data are often proprietary). But in a few situations both field and laboratory measurements were made around the same bluff body arrangement.

3.1 Character of the Field and Laboratory Experiments

Table 1 summarizes some of the better docmumented cases known to the author that are also available in the open literature. Table 1 reveals that sources were placed at ground level, roof height and on short stacks, and that receptor locations were well distributed from the body surface out to the far wake. Experiments include cases for both neutrally buoyant and heavy gas releases, for a wide range of wind speeds , and for all atmospheric stratification conditions.

3.2 Trends Observed in the Dispersion Data

The additional turbulence produced by bluff-body separation and wake regions enhances entrainment into a pollutant cloud; thus, concentrations are generally less downwind of an obstacle, and effluents spread quickly over a width and height associated with the bluff body dimensions. The additional entrainment associated with the wake region often persists out to 20 to 40 obstacle lengths downwind (characteristic body length should be lessor of height or width), but the concentrations generally asymptote to values found without the obstacle present after 50 obstacle lengths.

The paths gas parcels may follow moving from a source on a body to a receptor on or nearby the body are so varied that an accepted approach is to determine the minimum dilution likely to occur rather than absolute concentrations. Sagendorf et al. (1980) used such an approach while evaluating the EOCR and Rancho Seco Nuclear Station field data. Li and Meroney (1983a, 1983b) extended earlier work by Halitsky (1974) and Wilson and Netterville (1976) to bodies oriented obliquely to the wind.

Ramsdell (1988) recently reviewed seven of the listed data sets (marked with * in table) to determine characteristics of near-field cloud dilution for nuclear station control room habitability. As expected he found that concentrations decayed with downwind distance, but he detected only weak stratification effects, and, surprisingly, the normalized concentrations measured increased with wind speed|

Meroney et al. (1988) examined 13 experiments of the dispersion of dense gases near fences, water spray curtains, tanks, and buildings (marked with + in Table 1). They found that gas clouds were diluted by factors ranging from 2 to 10, that only small changes occurred in cloud arrival, peak concentration arrival, and departure times at most near and far positions in the obstacle wake, and excess dilution did not persist beyond about 50 characteristic body lengths.

4. EMPIRICAL, ANALYTICAL AND NUMERICAL MODELS FOR DISPERSION NEAR BLUFF BODIES

Analysis of bluff-body-wake diffusion data has been historically directed toward some modification of the Gaussian plume diffusion model to include the flow perturbations introduced by the obstacle. Such an approach implicitly assumes that all concentrations should vary directly with source strength, inversely with flow velocity, and inversely as the square of some characteristic body dimension. The most common form of the Gaussian diffusion equation is:

$$C/Q = F(y)\ F(z)/(\mathrm{pi}\ U\ \mathrm{sig}_y \mathrm{sig}_z),$$

where C/Q = normalized concentrations,
sig_y, sig_z = lateral and vertical diffusion coefficients,

U = mean wind speed, and
$F(y)$, $F(z)$ = exponential terms that adjust for off-axis distributions.

The Gaussian model has been modified in several ways to account for initial dilution in the cavity region, enhanced mixing in the wake, and adjustment for the effective height of an elevated plume. Most models add a term that includes the projected area of the building or adjust the diffusion coefficients so that they have minimum values that are related to building dimensions. Gifford (1960) proposed an enhanced dispersion model based on additional dilution of effluent proportional to building cross-sectional area, A, i.e.:

$$C/Q = 1/((\mathrm{pi}\ \mathrm{sig}_y\ \mathrm{sig}_z + cA)\ U),$$

where c is a wake constant between 0.5 and 2. Halitsky (1975), Yansky et al. (1966) and Gifford (1968) have also proposed dilution models which retain a Gaussian distribution at the lee end of the cavity. Huber and Snyder (1976) recommended a model for enhanced dispersion based on the decay of turbulent-intensity excess in the building wake and on characteristic building length scales. Huber (1977, 1988) also suggested a wake model based on Gifford's meandering plume model. Measurements made downwind of typical building complexes do not seem to justify any degree of numerical complexity (Hatcher and Meroney, 1977).

An alternative simple approach is that provided by a virtual source displaced by a distance x_s upwind from, and a distance z_s above the actual release point (Robins, 1975; Barker, 1982). Measurements provided by Robins (1975) permit one to estimate upper or lower bounds on the surface concentrations (See Table 11.2; Meroney, 1982)

A method suitable to interpolate between the cases of aerodynamic downwash and full cavity entrainment situations has been developed by the author based on the ideas proposed by Wilson (1976). First, one calculates the K_o versus x/sqrt(A) distribution based on Giffords relation above; then, one prepares the extremum-ratio as follows:

$$\frac{K_{2.5}}{K_o} = \exp\left(- \frac{6.25}{2(\mathrm{sig}_z^{\,2}/A + 1/\mathrm{pi})}\right),$$

where $K_{2.5}$ equals K for $h_e/h_B = 2.5$. Finally, one calculates the desired concentration coefficient for the actual effective stack height as:

$$K_e = K_{2.5}\left(\frac{K_{2.5}}{K_o}\right)\left[\left(\frac{h_e/h_B}{2.5}\right)^2 - 1\right],$$

producing the curves shown in Figure 1.

The US Nuclear Regulatory commission currently uses a set of equations based on the work of Murphy and Campe (1974). This method was intended to provide an upper bound to concentrations resulting from bluff-body perturbation. Ramsdell (1988) has shown these relations do not display much skill in predicting maximum concentrations (account for less than 20% of variability) and underpredict concentrations (25% of the time). Ramsdell (1988) performed a multiple linear regression on field data and produced a composite model which explains about 60% of the variance in ground-level concentration data:

$$C/Q = 1/(F_o + F_w + F_p)$$

where F_o = the volumetric flow at the release point,
$F_p = (\mathrm{pi}\ U\ \mathrm{sig}_y\ \mathrm{sig}_z)$,
$F_w = 100\ x^{-1.2}\ A^{-1.2}\ U^{0.68}\ S^{0.5}$,

S is stratification (Turner number), A is projected bluff-body areas, and U is the wind speed at 10 m. The linear regression expression for F_w is limited to diffusion in the wakes of objects with projected areas less than 2000 m^2, downwind distances less than 20 times the square-root of the projected body area, and bodies with height to width ratios between 0.4 to 1.1. Ramsdell recommends using a modified Split-H procedure to account for the effects of an elevated release. The Split-H procedure assumes that the release is distributed proportionately between an elevated release and one at ground level. Hence,

$$C/Q = M\ (C/Q)_{entr} + (1 - M)\ (C/Q)_{elev},$$

where M is the fraction of the time the plume is entrained in the building wake. The fraction M is determed from the ratio of the effluent vertical velocity, Wo) to the release height wind speed, Ur, according to:

$$M = \begin{cases} 1 & Wo/Ur < 1.0 \\ 2.58 - 1.58(Wo/Ur) & 1.0 <= Wo/Ur < 1.5 \\ 0.30 - 0.06(Wo/Ur) & 1.5 <= Wo/Ur < 5.0 \\ 0 & Wo/Ur >= 5.0 \end{cases}$$

These models are limited to predictions of mean concentrations averaged over times greater than 20 minutes; they are not appropriate for predicting surface concentrations on the body next to the source; and the increase in C/Q with wind speed predicted by Ramsdell (1988) does not agree with physical intuition.

5.0 FLUCTUATING CONCENTRATIONS NEAR BLUFF BODIES

Many situations involving odorants or flammable and toxic gases require estimates of concentration variability near buildings and other obstacles. Re-entry of furnace effluents, smoke, air-conditioning exhausts or chemical hood exhausts into occupied buildings often results in complaints of stench and odor. High concentrations of toxic or flammable gases in the near wake of a building result from the intermittent or non-stationary character of the flow field which develops around obstacles immersed in turbulent shear layers.

Wilson (1976, 1977) and Netterville (1980) examined fluctuating concentrations of plumes released near a variety of rectangular obstacle shapes. Li and Meroney (1983b) considered the statistical characteristics of plumes dispersing near a cubical obstacle. Subsequently, Meroney (1985) suggested semi-empirical procedures for estimating intermittent odor hazards based on such wind-tunnel measurements. Wilson, Robins, and Fackrell (1982) have proposed numerical models to solve transport equations for concentration standard deviation or other properties of the concentration probability distributions. There appear to be no fast response concentration data from field experiments available to verify or extend these concepts.

6. HAZARD MITIGATION USING BLUFF BODY INDUCED ENTRAINMENT

A survey of the hazards associated with the release of chemicals during storage, transport or process operations reveals that the greatest uncertainty in risk estimates are associated with the initial source configuration (Crum, 1986). The most likely accidents will occur under complex flow situations, where gases must diffuse over and among many bluff-body obstacles. Very little field data exists to evaluate these situations, and most analytic or numerical methods used by major chemical companies remain unverified.

Hosker and Pendergrass (1986) reviewed field and laboratory data about dispersion near clusters of buildings. Plate and Bachlin (1987) made measurements of plume dispersion within a model of a generic chemical complex, and Petersen (1987) measured relative rates of dispersion in different fields of homogeneous roughness, tank farms, and a generic chemical complex. Large building compexes are found to increase the relative roughness of the surface and the associated entrainment rates, but they also permit channeling and trapping of the gas cloud within the roughness and building elements.

Meroney et al. (1988) calibrated a simple section-averaged dispersion model for dense gas dispersion using cases from thirteen sets of field and laboratory data for dispersion over bluff-body elements. The model accounts for water-spray and vapor barrier dilution and water-spray removal of a some fraction of a gas plume. Subsequent calculations with the model predict that a) dilution with water spray curtains increases at lower wind speeds, b) dilution downwind of fences is only slightly dependent upon wind speed, c) increased depth averaged velocities downwind of sprays and fences results in shorter arrival times in the far wake, d) perturbations in concentrations produced by dilution alone do not persist beyond about 50 length scales downwind, and e) removal of cloud mass results in a persistent downwind reduction in concentration.

Unfortunately, these data have not led to any universally applicable rules for predicting plume transport among groups of obstacles. Indeed, if one also includes the variabilities associated with different obstacle geometries, release from pressurized storage, ground level versus elevated exhaust, and two-phase gas streams during the calculation of gas cloud or plume mixing, it is evident a great deal of work remains to be accomplished.

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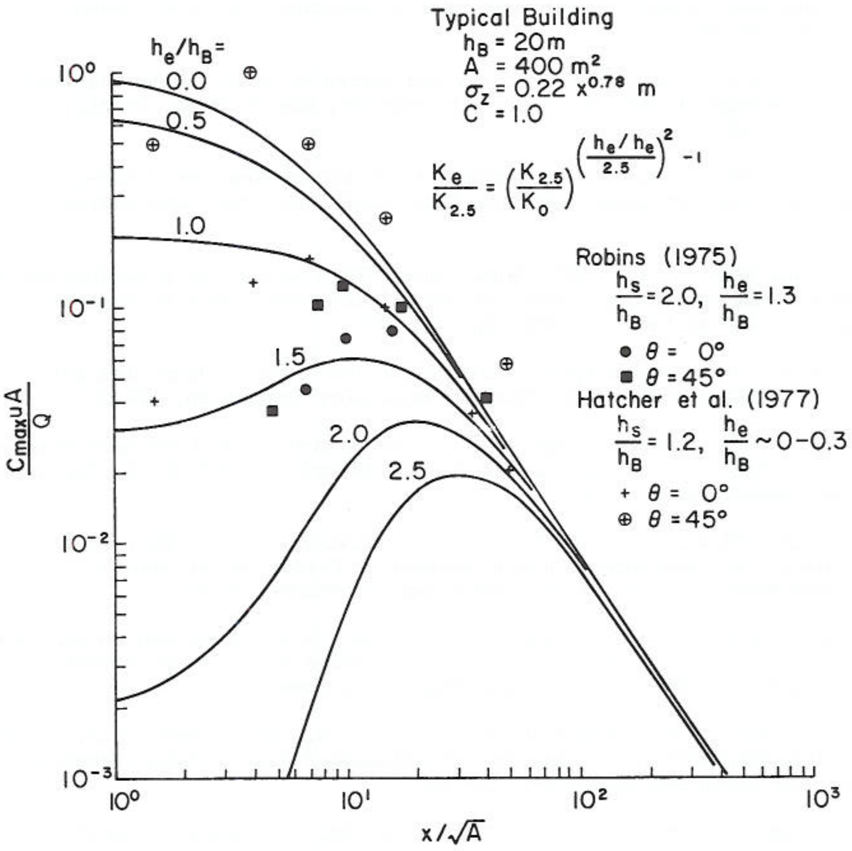

Fig. 1. Centerline ground level concentrations downwind of a typical isolated building. Extracted from Meroney (1982), "Turbulent Diffusion Near Buildings," Engineering Meteorology, (E. Plate, editor), Elsevier Pub. Co., pp. 481-525.

Table 1a: Experimental Data Sets for Dispersion Near Bluff Bodies

						Receptor Location							
	Field and Wind Tunnel Studies	Authors of Field Study	Authors of Laboratory Study	Dense Gases	Source Ht (m)	On Body	Near Wake	Far Wake	Area (m2)	Height (m)	Width (m)	Release Periods	No. of Releases
1	Phonenix Memorial Reactor,	Martin, 1965	Martin, 1965		17		XX	XX	836	12	15	33	33
	U. of Michigan				2 to 4	XX	XX		6	2	3	31	31
2	Cube, MI, USA	Smith, 1975	Yang & Meroney, 1970										
3 *	EBR-II, Idaho Falls NRTS, ID, USA	Start & Markee, 1969	Halitsky, 1977 Halitsky et al., 1963		1		XX	XX	665	29	27	15	15
4 * #	EOCR Reactor, Idaho Falls NRTS, ID, USA	Start et al., 1980 Sagendorf et al., 1980	Hatcher & Meroney, 1977 Hatcher et al., 1978		1,23,30	XX	XX	XX	1090	25	52	22	64
5 * #	Rancho Seco Nuclear Power Station, CA, USA	Start et al., 1978 Sagendorf et al., 1980	Allwine et al., 1980 Kothari, et al., 1981		4,18.5,43	XX	XX	XX	2050	43	48	22	42
6 *	Duane Arnold Energy Center, IA, USA	Thuillier & Mancuso, 1980 Thuillier, 1982	Kothari et al., 1980		1,23.5,45.7	XX		XX	1850	43	51	39	39
7	Cube, Japan	Ogawa, et al., 1983a Ogawa, et al., 1983b	Ogawa, et al., 1983a Ogawa, et al., 1983b		1.8	XX	XX		3.2	1.8	1.8		
8 +	Thorney Island Tests - Fences,	McQuaid & Roebuck, 1984	Davies & Inman, 1986	XX			XX	XX	500,1000	5,10	100	6	6
	Buildings and Enclosures, UK		Hall, Hollis & Ishaq, 1982						130	2.4	26	13	13
			Konig & Schatzman, 1987						81	9	9	4	4
9	Oldbury Power Station, UK	Foster & Robins, 1985	Foster & Robins, 1985		1,24.6,54		XX	XX	7500	54	150	20	20

* Ramsdell (1988) + Meroney et al. (1988) # Sagendorf et al. (1980)

Table 1b: Experimental Data Sets for Dispersion Near Bluff Bodies

	Field Studies	Authors, Date	Dense Gases	Source Ht (m)	Receptor Location On Body	Receptor Location Near Wake	Receptor Location Far Wake	Area (m2)	Height (m)	Width (m)	Release Periods	No. of Releases
10 *	MTR-ETR, Idaho Falls NRTS, ID, USA	Islitzer, 1965		1			XX	1700	24	60	13	13
11	Central Heating Plant, UK	Munn & Cole, 1965; Lawson, 1965		21		XX	XX	725	18	15	20	20
12	Small cubical building, Hanford, WA, USA	Hinds, 1969		1		XX		385	11	24	4	4
13	CANDU Nuclear Power Station, Canada	Munn & Cole, 1967		46		XX		2400	44	46	11	11
14	Hinkley Pt. A Nuclear Stat., UK	Rodliffe & Fraser, 1971		60		XX		6000	60	60		
15 *	Three Mile Is. Nuclear Station, NY, USA	GPUSC, 1975		1			XX	2000	44	46	5	5
16	Peach Bottom Nuclear Station, PA, USA	Philadelphia Elect. Co., 1974										
17	Cal. Tech. Spalding Lab., CA, USA	Drivas & Shair, 1974		0.3,1.2,12		XX		848	16	17		
18 *	Millstone Nuclear Station, USA	Johnson et al., 1975 Thuillier, 1982		27.6,48.3			XX	1950	45	50	36	62
19	Casaccia Nuclear Res. Center, Italy	Cagnetti, 1975		14		XX	XX	120	6	32	9	9
20	Single-story, flat roofed bldg	Jones & Griffiths, 1984		1			XX	18	2.9	12	8	8

* Ramsdell (1988) + Meroney et al. (1988) # Sagendorf et al. (1980)

Table 1c: Experimental Data Sets for Dispersion Near Bluff Bodies

	Wind Tunnel Studies	Authors, Date	Dense Gases	Source Ht (m)	Receptor Location On Body	Receptor Location Near Wake	Receptor Location Far Wake	Area (m2)	Height (m)	Width (m)	Release Periods	No. of Releases
21	NIH Clinical Center, MD, USA	Halitsky, 1962		160,200	XX			14000	63	110	50	50
22	Berkley & Bradwell Nuclear Stations, UK	Davies & Moore, 1964		stack		XX				50	10	10
23	Shoreham Nuclear Station, NY, USA	Meroney, Cermak & & Chaudhry, 1968a, 1968b		60		XX	XX	6000	60	40	15	15
24	Cone Frustrums	Symes & Meroney, 1970		0,H/2,H		XX	XX					
25	Cube & stacks	Yang & Meroney, 1971		0,H/2,H		XX	XX					
26	Rocky Flats Plut. Plant, CO, USA	Meroney & Chaudhry, 1972		0,76		XX	XX				40	40
27	Cube & stacks	Hoot et al., 1973	XX	H,1.5H,2H,2.5H								
28	Avon Lake Power Station, OH, USA	Meroney et al., 1974		117 to 182		XX	XX				102	102
29	Floating Nuclear Power Station, NJ, USA	Meroney et al., 1974		27 to 75	XX			4500	45	100	35	35
30	Cube	Robins, 1975, Robins & Castro, 1977a,1977b		.125H,.875H,H		XX	XX	H^2	H	H		
31	Cubes & Rectangular Blocks	Vincent, 1977, 1978		H		XX						
32	Rectangular prisms	Wilson & Netterville, 1976		H	XX							
33	Square building	Koga & Way, 1979		H to 3.5H		XX	XX				35	35
34 +	Green Point Energy Center, NY, USA	Kothari & Meroney, 1980	XX	0		XX	XX				150	150
35	Model reactor buildings	Fackrell & Pearce, 1981		H		XX					26	26
36 +	Energy Terminal Service Corp, NJ, USA	Kothari & Meroney, 1981a	XX	0		XX	XX	2460	30	41	51	51
37 +	Tanks, buildings, tree lines	Kothari & Meroney, 1981b	XX	0		XX	XX				88	88
38 +	Fences and vortex generators	Kothari & Meroney, 1982	XX	0		XX	XX				204	204
39	Rectangular Building	Huber & Snyder, 1982										
40	Cubical building	Li & Meroney, 1983a, 1983b		0,H/2,H								
41	Savannah River Nuclear Station, SC, USA	Neff & Meroney, 1983, 1988		62,107,152	XX	XX	XX				64	64
42	Rectangular Buildings	Ohba & Kobayashi, 1984		H	XX							
43	Fence Enclosures, Vortex Gener.	Neff & Meroney, 1986	XX	0		XX	XX					
44	Tank farms, chemical complex	Petersen & Radcliff, 1987				XX	XX					
45	Chemical complex	Bachlin & Plate, 1987				XX	XX					
46	Tunnel vent building	Neff, Tan, & Meroney, 1988		30 to 69	XX	XX	XX	2300	23	37	120	120
47	Rectangular Building	Huber, 1988				XX						

* Ramsdell (1988) + Meroney et al. (1988) # Sagendorf et al. (1980)