Bounding atmospheric dispersion factors for nuclear facility siting without site meteorological data

Adam Stein[a]*

[a]The Breakthrough Institute, Washington, D.C.

*adam@thebreakthrough.org

ORCID: 0000-0002-4043-7499

Abstract

Atmospheric dispersion factors (χ/Q) are typically used in accident dose analysis for nuclear regulatory compliance. Regulatory guidance supplies two routes: an onsite record of a year or more, or qualified offsite data from representative nearby stations. At many proposed advanced reactor sites, the second is unavailable because no representative station exists: remote siting, sparse networks, complex terrain, or coastal exposure. A third route needs no site meteorology: a dispersion factor demonstrated conservative rather than representative, but has never been supplied with a bound or an acceptance basis. This paper provides both. ARCON96 was characterized by full-factorial parameterization and one-factor sensitivity over the admissible design region, in 3,386 code executions using constant-condition meteorology that removes weather as an input. Common intuitive bounds are non-conservative: a low-wind file understates the bound by up to 2.8 times near the source, and a near-field file is non-conservative by up to 40 percent at 1,200 m. The highest values occur at a moderate wind rather than the lightest: χ/Q is non-monotonic in wind speed, and the worst case switches regime with distance. The presented per-distance envelope bounds two real records at every distance and interval evaluated, by factors of 1.07 to 2.68. The results provide dispersion factors for an envelope at the exclusion area boundary and low population zone distances when considered with the building-area stated applicability conditions.

Keywords: atmospheric dispersion; dispersion factor; ARCON96; advanced reactor siting; regulatory guidance

I. INTRODUCTION

An application to build a nuclear power plant in the United States must evaluate accident doses at the exclusion area boundary (EAB) and in the low population zone (LPZ). The dispersion input to that evaluation, the atmospheric relative concentration χ/Q (s/m³), has conventionally been computed from an onsite meteorological record collected under Regulatory Guide (RG) 1.23 [1]. Guidance asks for at least one and preferably more annual cycles, and the record must be in hand before the safety analysis can be completed, so meteorological monitoring is among the earliest site commitments an applicant must make and routinely adds a year or more to the licensing critical path before any review begins.

A second route comes from recent guidance: the NRC has proposed Revision 2 to RG 1.23, issued for public comment as Draft Regulatory Guide DG-1463 [2], whose Appendix B would permit qualified *offsite* meteorological data in place of or in addition to onsite measurements, responding to direction in the ADVANCE Act of 2024 [3] to license advanced reactors more efficiently. Where two or more suitable offsite stations exist, and comparability among them can be demonstrated, an applicant may forgo or suspend onsite measurements.

That route depends on a precondition that cannot be satisfied by a class of sites. The onsite-program trigger of Appendix B returns an applicant to a full onsite program where there is no suitable nearby station: remote locations, sparse offsite coverage, terrain settings dissimilar to the modeling domain, large elevation differences, and coastal environments. Spatial correlation of surface wind and stability declines with separation distance and with dissimilarity of terrain and exposure, so representativeness cannot be asserted at such sites, and the deficiency cannot be cured by adding stations that are themselves unrepresentative. For these applicants, the practical choice under existing guidance is a monitoring program of a year or more, or no application.

A third route requires no site meteorology at all. Instead of a dispersion factor asserted to be *representative* of the site, the applicant may use one demonstrated to be *conservative* with respect to it—a bounding χ/Q, computed from the approved dispersion model at the worst combination of inputs the model admits. Conservatism and representativeness are different claims requiring different showings, and the representativeness criteria of Appendix B do not apply to the former. The bound does not answer what dispersion the site actually produces; it answers what dispersion the endorsed model can produce there under the worst inputs the model admits. A design with margin between its dose consequences and the applicable criteria can accept a conservative dispersion factor and proceed, deferring characterization of the site's actual dispersion climatology to the monitoring program that supports operation.

The option is not new or controversial in principle. The present author recommended that applicants be permitted to forgo weather studies by submitting a bounding χ/Q constructed from static weather inputs to ARCON, and reported that both the code's original developer and its current maintainer regarded the approach as technically feasible [4]. RG 1.249 was issued without the option.

DG-1463 now names it—Figure B-1 refers to "screening Met data" and §B.4 to "bounding assessments"—but defines neither the pathway nor any acceptance basis for it. A bounding χ/Q is useful only if it is computed over the model's admissible input space, states the conditions under which it applies, and demonstrates that it is in fact conservative against real weather. To date that analysis has not been published, and, further, it cannot be supplied by intuition, because the intuitive worst case is not conservative. The conventional worst case for a ground-level release—the most stable atmosphere at the lowest wind speed—reflects a plain Gaussian plume, in which χ/Q is inversely proportional to wind speed. ARCON96 does not model a plain Gaussian plume: it applies empirical corrections to the diffusion coefficients for low-wind-speed meander and building wakes [5], and those corrections make χ/Q *rise* with wind speed through the range where the intuitive construction sits, until at longer distances the worst case migrates back toward the calm limit. A bound built from either fixed intuition fails somewhere in the applicable range.

This paper supplies the bound and its basis. Regulatory Guide 1.249 [6] endorses ARCON96—developed originally for control-room habitability assessment and endorsed for that use by RG 1.194 [7]—for accident χ/Q at offsite receptors out to 1,200 m, as an alternative to the PAVAN/RG 1.145 approach [8]. This paper reports a full-factorial characterization of the ARCON96 code over the design region that RG 1.249 admits, using degenerate constant-condition meteorology that removes weather as an input. ARCON is the appropriate model at these distances because EABs are proposed for some advanced reactors where building-wake effects dominate dispersion and PAVAN, which does not model wakes, represents the physics poorly; the near-field applicability of ARCON-class modeling has been examined previously [9].

The results comprise: the bounding envelope by stability class and receptor distance across the full 15 to 1,200 m range, with a mapped building-area correction and the bounding values of every remaining geometry input; the structural finding that governs how such a bound must be built; the applicability conditions under which the envelope may be cited; the sensitivity of the envelope to the physical-admissibility position taken on stability and wind speed; and a demonstration, through the RG 1.249 §2.4 statistical procedure, that the envelope bounds two real meteorological records at every distance and averaging interval evaluated. The envelope is then restated as the allowable effective source term a design must meet to use it, and the stability of the controlling statistic to record length is examined. The characterization also surfaced two behaviors of the distributed code that any user of the regulatory method must handle, one of which silently suppresses a statistic the guide prescribes.

All values presented in this article are derived from the NRC-validated ARCON96 code.

II. METHOD

II.A. Code, Execution Environment, and Validation

All analyses used the ARCON96 Fortran console executable as distributed by the NRC (build date June 25, 1997 per its output header), the implementation documented in NUREG/CR-6331 Revision 1 [5]. The code was driven through its documented text-file interface: a run-specification file naming the meteorological file(s), release and receptor geometry, and processing options; an hourly meteorological input file (wind speed and direction at two measurement heights plus Pasquill stability class A–G); and outputs comprising a log file, which echoes all inputs and reports per-interval diagnostics, and a cumulative frequency distribution (CFD) file of hourly-average χ/Q for ten standard averaging intervals (1, 2, 4, 8, 12, 24, 96, 168, 360, and 720 hours).

Execution was automated with a Python harness that templates the run-specification file, invokes the binary in an isolated working directory per run, and parses the log and CFD outputs [10]. Before use, the harness was successfully tested against the code's distributed sample problem and against an archive of prior production runs spanning the code's input space. Two implementation details discovered during validation are reported as findings in Sec. III.E because they relate to any application of the code.

II.B. Degenerate Constant-Condition Meteorology

ARCON96 normally consumes a real hourly weather record and reports, for each averaging interval, the χ/Q value exceeded in no more than 5% of intervals (the 95th-percentile value), extracted from the CFD. To characterize the *model* rather than any particular weather record, each parameterization run substitutes a degenerate meteorological file: a full year (8,760 hours) of a single stability class, a single wind speed, and a constant wind direction aimed from the release point at the receptor. This construction has three properties that make it the correct instrument for a bounding analysis:

1. **It removes site meteorology as an input.** The response becomes a deterministic function of the (class, wind speed) pair and the geometry — precisely the quantity a site-independent bound must be built from.
2. **It is exact.** Under constant conditions every hour is identical, so the hourly centerline χ/Q is single-valued and can be read exactly from the log file, free of the CFD's bin quantization (approximately 25 bins per decade, or about ±5% on any percentile read from the CFD).
3. **It is conservative by construction with respect to direction.** The wind blows at the receptor for every hour of the record, which no real record approaches.

Two consequences define what the construction is *not*. First, the cumulative frequency distribution degenerates to a point mass: the 95th-percentile value is simply the single hourly value, so a degenerate run *bounds* the output of the RG 1.249 §2.4 statistical procedure without *performing* that procedure on a distribution. Any submittal citing such a bound must say so explicitly. Second, the long averaging intervals carry no weather-persistence information: with constant weather, the 96 to 720 h values differ from the short-interval values only through ARCON96's transition from centerline to sector-average concentrations beyond eight hours, not through meteorological variability. Whether the construction bounds real records at long intervals is an empirical question, answered in Sec. III.F.

II.C. Design Region and Factorial Grid

RG 1.249 prunes most of ARCON96's input space for the offsite design-basis use case, and the parameterization adopts the pruned region rather than the code's full domain:

1. **Release mode:** Ground-level point release. RG 1.249 §2.3.1 identifies ground-level release as the preferred conservative treatment (under which the code ignores vent release velocity, radius, and flow), §2.3.3 states that the vent-release mode should not be used in design-basis assessments, and §2.3.4 identifies the ground-level point source (initial diffusion coefficients $\sigma_{y0} = \sigma_{z0} = 0$) as most conservative.
2. **Stability class:** All seven Pasquill classes A–G, treated as *strata,* never as a sampled numeric coordinate, because the class is categorical inside the code.
3. **Wind speed:** A fine sweep of 19 levels from 0.5 to 10 m/s, with additional resolution (0.25 m/s steps) around the response maximum. The 0.5 m/s floor is ARCON96's minimum modeled wind speed (its calm threshold).
4. **Distance:** Thirteen distances spanning the guide's applicability range: 15 m as a near-field reference at control-room scale; 80, 100, 150, 200, 250, 300, and 400 m across the EAB range RG 1.249 identifies for small modular reactors (SMRs) and advanced reactors; and 500, 600, 800, 1,000, and 1,200 m out to the guide's offsite applicability limit, remaining inside its ~10 m lower limit throughout.
5. **Geometry baselines:** Building area 800 m², surface roughness treated at 2.5 m, intake (receptor) height 0 m, terrain elevation difference 0 m. Each of these was then varied separately at the bounding points (Sec. III.C), and the building-area response was mapped densely at 15 levels from 1 to 10,000 m² at every class × distance worst case.
6. **Direction window:** 90° total width centered on the source–receptor bearing for the grid runs; the window's role in the §2.4 statistics is treated separately (Secs. II.D and III.E).

The core grid is 7 classes × 19 wind speeds × 13 distances = 1,729 runs, with 1,657 additional runs for the area map, roughness checks, and one-factor sweeps; every cell is a direct code execution.

Two physical-admissibility variants of the resulting envelope are reported. The *unconstrained* envelope takes the worst (class, U) pair the code admits; this is consistent with the NRC's stability classification basis, since RG 1.23 classifies stability by vertical temperature difference alone and imposes no wind-speed cap on any class. The *capped* variant additionally imposes conventional Pasquill–Gifford–Turner (PGT) co-occurrence limits on wind speed within each class (taken here as A ≤ 3, B ≤ 5, C ≤ 6, D uncapped, E ≤ 5, F ≤ 3, G ≤ 2 m/s at 10 m), representing the position that, for example, extremely stable stratification does not co-occur with 4 m/s winds.

II.D. The RG 1.249 §2.4 Statistics and Percentile Extraction

RG 1.249 §2.4 requires the dose-input χ/Q for each averaging interval to be the larger of two statistics: (a) the 95th-percentile *overall-site* value, computed with a wind-direction window intended to admit all hours regardless of direction, and (b) the 99.5th percentile of the *maximum 45° sector*, over the sixteen 22.5°-spaced sector centers. Percentiles are extracted from the CFD by the exceedance method of RG 1.249 Appendix A—exceedance % = $(H_{total} - H_{exceeded})/H_{total} \times 100$, with H_{total} taken from the log file per averaging interval—interpolating linearly between bracketing CFD rows. In the conservatism evaluation of Sec. II.E this interpolating extraction was applied *identically* to the real records and to the degenerate construction, so the comparison is like-for-like; for a *cited* bounding product, taking the upper bracketing row instead of interpolating is the documented conservative choice (Sec. IV.A), and the sensitivity of the results to the extraction basis is quantified in Sec. III.F.

Implementing this procedure surfaced two behaviors of the code that materially affect results and are reported as findings (Sec. III.E): the code's construction of the direction window makes the literal §2.4.1 "360-degree" instruction fail silently at nearly every source–receptor bearing, and the CFD file's two column blocks are scaled independently per the log's per-interval upper limits although the file prints only the first block's bin-edge labels, so edges must be reconstructed per interval (with the above-range hours from the log's "Abv. Lim." row added back). Both behaviors are held under a regression test. Additionally, ARCON96 terminates on a divide-by-zero whenever a run contains no in-window hours. With constant-direction input that occurs at any window width excluding the source bearing, so for degenerate records the aimed 45° sector was used for both legs of the §2.4 comparison, after verifying that widths of 45°, 90°, 180°, and 359° aimed at that bearing give identical results.

II.E. Conservatism Evaluation Against Real Records

Whether a degenerate-weather construction actually bounds real weather was tested. For each of two real hourly records, at nine distances (15, 80, 100, 200, 300, 400, 600, 800, and 1,200 m) and all ten averaging intervals, the full RG 1.249 §2.4 procedure was executed—both statistics, all sixteen sectors, Appendix A extraction with linear interpolation—to produce the record's controlling χ/Q per (distance, interval) cell. The same procedure was applied to the degenerate construction, and the conservatism ratio formed:

$$R = \frac{\chi/Q(degenerate construction)}{\chi/Q(real record, controlling §2.4 value)}$$

R ≥ 1 in every cell is the success criterion for a bound. Three constructions were evaluated: the envelope construction—class G at its per-distance worst-case wind speed (4.0 m/s at ≤500 m, 0.5

m/s at ≥600 m, from Sec. III.B)—plus two fixed constructions used as controls: the intuitive low-wind construction (class G at 1 m/s) at all nine distances, and the near-field construction (class G at 4 m/s) applied outside its regime at 600 to 1,200 m. Bound-side and real-record runs used identical fixed settings (building area 800 m², roughness 2.5 m, intake height 0, terrain difference 0, $\sigma 0 = 0$), so the ratios are like-for-like.

Record 1 — distributed annual record, 1992. The one-year hourly record is distributed with ARCON96 (8,782 valid hours; measurement heights 10.1 and 57.8 m). The site identity is not verified, and the label is treated here as a name only. Class mix A/B/C/D/E/F/G = 6.3/3.7/4.1/41.6/29.4/8.1/6.9%; combined F+G frequency 15.0%; calms (<0.5 m/s) 0.1%; mean lower-level wind speed 3.5 m/s.

Record 2 — meteorological tower record, 2007–2018 (11.6 years). An hourly record from the meteorological tower that matches NRC nuclear power plant site specifications, used here in anonymized form (measurement heights 10.0 and 97.5 m; 99,931 valid hours, 98.4%, exceeding the 90% recovery criterion of RG 1.23). Stability was classified from the vertical temperature difference using the plant's RG 1.23 ΔT intervals scaled to the tower's measurement layer, with a shallower fallback layer used for 559 hours; calm hours were carried forward in direction at zero speed, and variable-direction hours (<2.5% of level-entries) were written as missing. Class mix A/B/C/D/E/F/G = 1.8/2.0/4.4/48.8/32.1/8.2/2.8%; F+G 11.0%; calms 0.9%; mean 10 m wind speed 2.33 m/s; prevailing westerlies with the worst sector at 270–293°.

To examine period-of-record sensitivity, Record 2 was additionally split into its eleven complete calendar years, each run through the identical §2.4 procedure and compared with the pooled 11.6-year result.

II.F. Bias Controls and Reproducibility

The design controls the main sources of error. Surrogate error is eliminated by policy: response surfaces were used only to choose where to run the code, and no fitted value is reported as a result. CFD quantization is eliminated for the parameterization results (Secs. III.A to III.D) by reading exact hourly centerline values from the log under constant conditions; for the conservatism evaluation, both legs are CFD-extracted like-for-like, and the sensitivity of R to the extraction basis is quantified in Sec. III.F. Input-formatting error—a live hazard, as Sec. III.E shows—is controlled by emitting fixed-width fields identical to regression-tested reference files and by cross-checking the echoed averaging-interval line in every log against the intended values. Harness error is controlled by the byte-identical reproduction baseline (Sec. II.A). Envelope values were cross-checked at three distances against a separately implemented one-factor sweep, with exact agreement.

Limitations of the datasets and of the degenerate construction are discussed in Sec. IV.E. Complete inputs, outputs, scripts, and result tables underlying every figure and table are archived as the underlying-data deposit for this article [10].

III. RESULTS

III.A. χ/Q Is Non-Monotonic in Wind Speed, and the Worst Case Switches Regime with Distance

Fig. 1 shows the exact hourly centerline χ/Q at 15 m as a function of wind speed for all seven stability classes. The response is non-monotonic in every class: χ/Q rises with wind speed to an interior maximum and only then begins the 1/U decay a plain Gaussian plume would show everywhere. The mechanism is the pair of low-wind-speed corrections ARCON96 applies to the diffusion coefficients [5]. On axis at ground level the concentration varies inversely with the product of the two corrected coefficients and the wind speed. As the wind drops, both the horizontal and the vertical coefficient acquire a term proportional to 1/U, so that product grows and χ/Q *falls*. Both terms are required: freeze either correction and the product tends to a constant instead, so the response flattens toward the calm limit rather than turning over. The interior maximum follows from the two corrections acting together, not from horizontal meander alone.

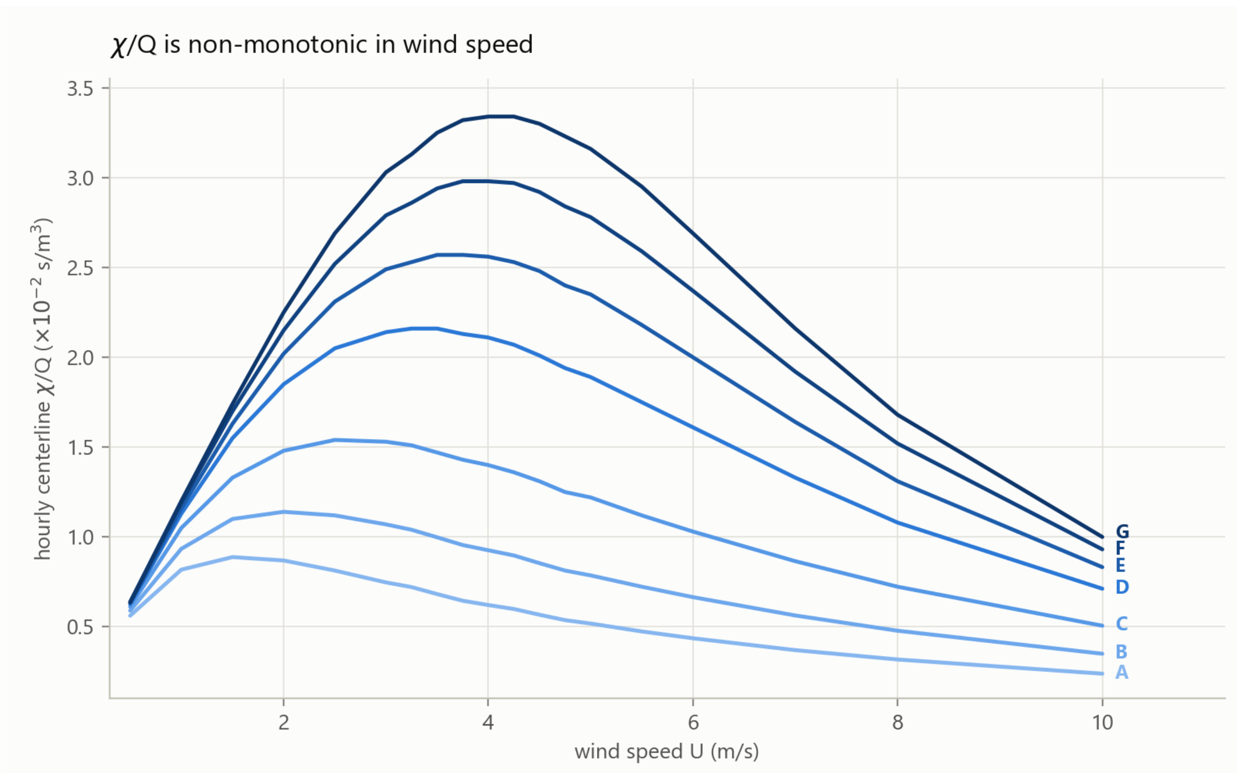

Fig. 1. *ARCON96 χ/Q is non-monotonic in wind speed. Exact hourly centerline χ/Q versus wind speed at a 15 m receptor for stability classes A (lightest) through G (darkest); ground-level point release, building area 800 m². Each class rises to an interior maximum before the inverse decay begins, and that maximum moves to higher wind speed as stability increases. The peak location shifts with receptor distance: class G holds it to 500 m and classes E and F to 400 m, beyond which a calm-limited maximum at 0.5 m/s takes over. That transition is outside this figure; see Table I and Sec. III.A.*

In the near field the worst-case wind speed rises monotonically with stability, from approximately 1.5 m/s (class A) through 2.0 (B), 2.5 to 3 (C), 3.25 to 3.5 (D), and 3.5 to 3.75 (E) to 3.75 to 4 (F) and 4.0 to 4.25 m/s (G), and for the controlling stable classes the peak location is stable from 15 m out to 500 m. Beyond that, the response becomes bimodal, and a calm-limited lobe at the 0.5 m/s floor overtakes the meander peak. For class G the crossover falls between 500 and 600 m (at 500 m the two lobes are within 4% of each other); the less stable classes switch earlier (class A by 200 m, D by 400 m, E and F by 500 m), consistent with their weaker meander correction. From 600 m to the guide's 1,200 m limit the worst case for every class is the 0.5 m/s calm limit—visible in Table I, where at 1,200 m the 0.5 m/s value *is* the peak and the 4 m/s value has fallen to 53% of it.

For class G at 15 m, the meander peak (3.34×10^{-2} s/m³ at 4.0 m/s) is 2.8 times the value at 1 m/s (1.20×10^{-2}); at 100 m the factor is 2.3, declining to about 1.4 at 400 m. Table I gives the class-G response versus wind speed at four distances as fractions of the per-distance peak.

No fixed wind-speed assumption is conservative across the applicability range. Low wind understates the bound by up to 2.8 times in the near field, and the meander peak understates it at LPZ distances; Sec. III.F quantifies both failures against real records. The worst case is a property of the model *and* the receptor distance, and must be located by executing the code.

III.B. The Bounding Envelope by Stability Class and Distance

Table II gives the maximum exact hourly centerline χ/Q over the wind-speed sweep for every class × distance cell, with the class-G worst-case wind speed listed per distance. Three structural findings:

1. **Class G controls at every distance.** The class ordering G > F > E > D > C > B > A is strict at all thirteen distances, so the bounding envelope is the class-G column: 3.34×10^{-2} s/m³ at 15 m, 1.30×10^{-3} at 80 m, 8.54×10^{-4} at 100 m, 7.30×10^{-5} at 400 m, declining to 2.90×10^{-5} at 1,200 m.
2. **The envelope is defined by two constructions**, per the Sec. III.A regime switch: class G near its meander peak (4.0 to 4.25 m/s) at 15 to 500 m, and class G at the 0.5 m/s calm limit at 600 to 1,200 m.
3. **The envelope is 1.20 to 2.78 times the low-wind construction**, with the largest understatement at the shortest distances and the minimum near the 500 to 600 m regime crossover (Fig. 2).

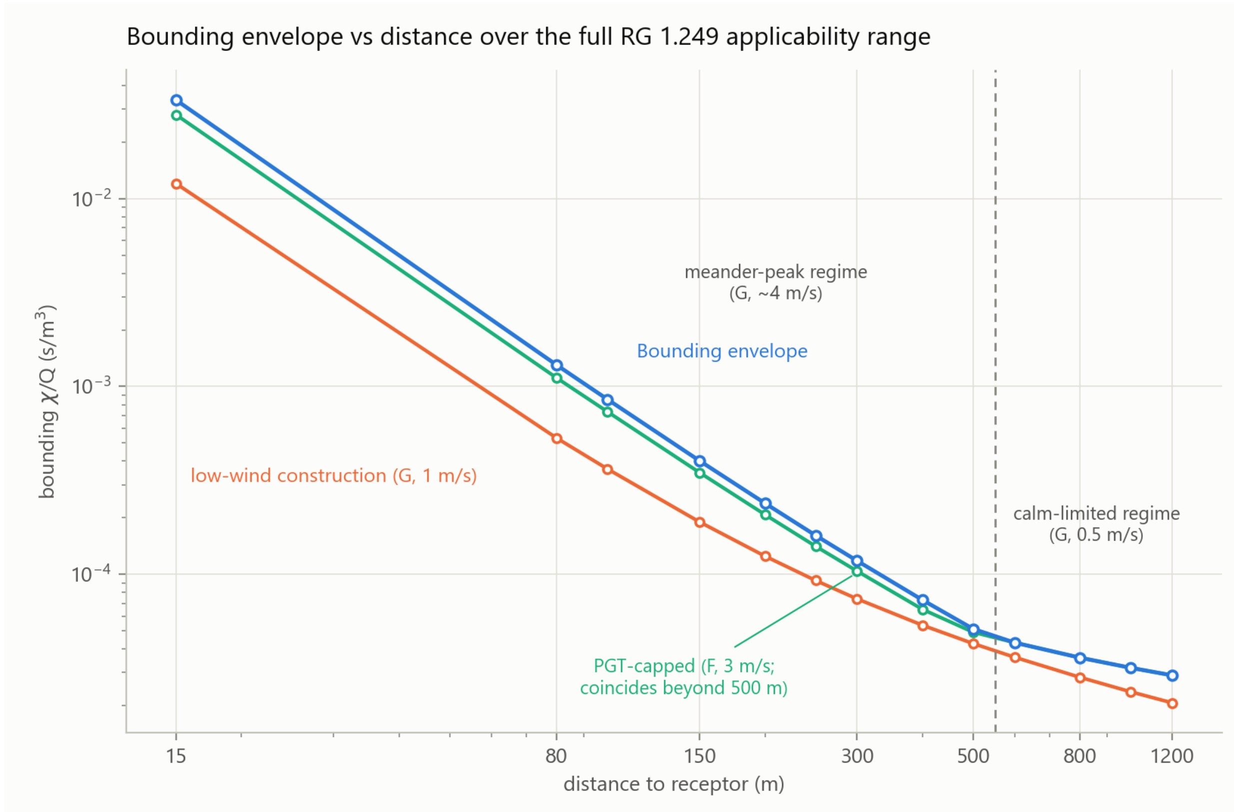

Fig. 2. Bounding envelope versus distance over the full applicability range. Optimized envelope (class G at the per-distance worst-case speed), Pasquill–Gifford–Turner-capped variant, and the conventional low-wind construction (class G, 1 m/s), on log–log axes; building area 800 m². The worst-case regime switches from the meander peak (about 4 m/s) to the 0.5 m/s calm limit between 500 and 600 m, where the capped variant merges with the envelope. The low-wind construction understates the envelope by 2.8 times at 15 m, 1.2 times at the crossover, and 1.4 times at 1,200 m.

III.C. Behavior of the Remaining Inputs, and the Building-Area Factor Map

Each remaining site and geometry input was varied one at a time at the near-field bounding point (class G, 4 m/s, 15 m unless noted), with checks across the class × distance worst-case cells where indicated (Fig. 3):

1. **Initial diffusion coefficients (σ_{y0}, σ_{z0}):** Monotonically decrease χ/Q from zero (to 1.17×10^{-2} at 2.3/1.4 m). Bounding value 0, confirming the RG 1.249 §2.3.4 ground-level point-source position.
2. **Intake (receptor) height:** Monotonically decreases χ/Q from grade (3.34×10^{-2} at 0 m to 2.33×10^{-2} at 10 m). Bounding value 0.
3. **Terrain elevation difference:** Monotonically decreases χ/Q from zero, with values identical to the intake-height response at the checked levels (2.33×10^{-2} at 10 m). Bounding value 0.

4. **Surface roughness:** *No effect at any of the bounding points*: ratios of exactly 1.000 at roughness 0.1 m and 5.0 m relative to 2.5 m at all 91 class × distance worst-case cells across the full distance range. Since a bounding product needs only the maxima, roughness can be dropped from the bounding problem; the roughness response away from the maxima was not characterized.
5. **Building area:** The only input where the bounding value is a modeling *choice* rather than an endpoint. χ/Q increases monotonically as area decreases, and the code fails hard (runtime divide-by-zero, no output) at exactly zero area, so the supremum sits at the smallest credible building, not the largest. Table III maps the correction factor at fifteen area levels from 1 to 10,000 m², as the worst case over all 91 class × distance worst-case cells: ×1.28 at 1 m², ×1.15 at 100 m², ×1.05 at 400 m², unity at the 800 m² baseline and above. Reductions for areas above 800 m² (up to −13% at 10,000 m²) occur in some cells but not others, so the smallest building the design can credibly claim sets the factor and no generic credit is available for large buildings; because the response is monotone, the factor for a stated minimum-credible area Amin bounds every actual area at or above it. The area sensitivity is also configuration-dependent: at 1 m/s the response is flat in area, and the sensitivity switches on near the meander-peak wind speed (*another instance of intuition failing where the corrections dominate*).

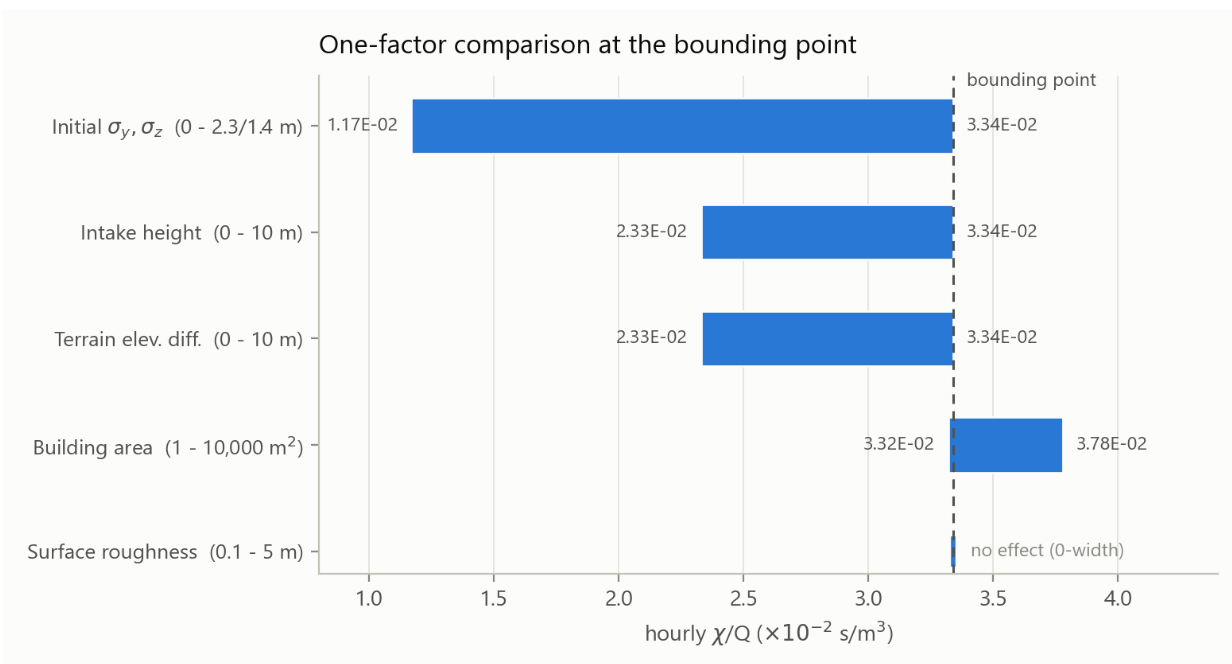

Fig. 3. *One-factor swings at the near-field bounding point (class G, 4 m/s, 15 m). Ranges of exact hourly χ/Q as each remaining input is varied across its checked range, all others held at the bounding configuration. All responses are monotone: each varies in one direction only across its checked range. Surface roughness is shown to have no effect on χ/Q at the bounding point, while building area is identified as the only input where the worst case is a design-dependent parameter.*

III.D. Physical Admissibility of the Bounding (Class, Wind Speed) Pair

Class G at 4 m/s invites the objection that extremely stable stratification is conventionally associated with light winds. Both defensible positions were computed (Table IV). Under the NRC's own classification basis (RG 1.23 Table I, vertical temperature difference alone, no wind-speed cap per class), Stability G at 4 m/s is admissible and the Table II envelope stands. Admissibility here follows from the classification convention the endorsed method uses, not from a claim that class G stratification is commonly realized at 4 m/s. Imposing conventional PGT co-occurrence caps instead moves the bounding pair to Stability F at 3 m/s at 15 to 400 m; the capped variant is 11 to 16% below the unconstrained envelope there. At 500 m the difference is 4%, and from 600 m outward the two envelopes coincide, because the calm-limited worst case (Stability G, 0.5 m/s) is admissible under any co-occurrence position.

The choice between the two positions is a ≤20% effect confined to the near field, dwarfed by the 2 to 3 times understatement of the naive low-wind construction there. A conservative product cites the unconstrained envelope; the capped variant quantifies exactly what an admissibility argument could purchase, and any use of it should anchor the caps to a specific classification scheme or to the joint (class, wind speed) frequency of regional records.

III.E. Findings Material to Any Execution of the Method

Three findings bear on any application of the RG 1.249 method, including any use of the envelope reported here. The first two are silent behaviors of the distributed code; the third is a property of the §2.4 procedure itself.

(a) The §2.4.1 overall-site direction window fails silently. RG 1.249 §2.4.1 instructs analysts to obtain the overall-site 95th-percentile χ/Q by applying "a 'wind direction window' width of 360 degrees," which it states "will effectively include all the hours in the data set." In ARCON96, that instruction does not do what the guide intends. The code constructs the window as (direction ± width/2) and normalizes each bound into 0 to 360°; at a width of 360°, the two bounds coincide after normalization at every source–receptor bearing except 180°, and the code treats coincident bounds as a *zero-width* window.

Table V shows a direction sweep with one real annual record, a ground-level release, and a 15 m receptor, varying only the bearing. At 180°, the run is correct (window echoed as 000–360; 95th-percentile 0 to 2 h $\chi/Q = 2.73 \times 10^{-2}$). At the other nine bearings tested, the reported value is exactly 1.0×10^{-5}—the lowest value the output format resolves, roughly 2,700 times below the correct result—and every failing run terminates with "NORMAL PROGRAM COMPLETION" and no warning. The hour counts the code provides in the output confirm the window admits 8,755 of the record's 8,782 valid hours at 180°, and between 8 and 38 hours at every other bearing, so the reported percentile is drawn from a few tens of hours rather than from the whole record. The CFD file is corrupted identically, so a percentile extracted from it by the RG 1.249 Appendix A method inherits the error rather than revealing it (a 99.5th percentile extracted from the same corrupted CFD emerges roughly 4 times low rather than pinned at the floor). The error can only be non-conservative.

A width of 359° achieves the guide's stated intent (350° and 359° agree exactly; 270° agrees within one CFD bin), and the harness used here refuses width = 360 outright. Because the failure is invisible at the one bearing (180°) a reviewer might spot-check, and because the suppressed overall-site leg can then essentially never control, analysts applying §2.4.1 literally would systematically report that the max-sector statistic controls, with no indication anything was wrong. Any submittal executing this method should document the echoed window bounds and the in-window hour count for each run, which makes the failure visible on review at negligible cost.

(b) Fixed-width parsing of the averaging-interval lines. The run-specification lines carrying the averaging intervals are read in fixed 4-column fields, not list-directed. The sample input distributed with the code has these lines misaligned; ARCON96 silently parses the intended intervals (1, 2, 4, 8, 12, 24, 96, 168, 360, 720) as (1, 2, 4, 81, 22, 49, 616, 836, 72, 0), produces corrupted long-interval output, and again reports normal completion. There is no input validation; any automation must emit exact fixed-width fields and should cross-check the echoed averaging-interval line in the log against intent.

(c) Which statistic controls depends on the averaging interval. With the window defect corrected, executing both §2.4 legs across both real records shows that the controlling statistic is not a site property alone: at 1 to 8 h the 99.5th-percentile max-sector value governs (roughly 10% above the overall-site 95th percentile); the two legs cross near 24 h; and at 96 to 720 h the overall-site 95th percentile governs, by up to 2.6 times. Across all (distance × interval) cells over the full 15 to 1,200 m range, the sector leg governed in 46% of cells for Record 1 and 29% for Record 2. This indicates the mechanism is structural to the model: a 45° sector admits roughly one-eighth of hours, so its long-duration averages are increasingly diluted by out-of-window hours as the interval lengthens, while the all-directions distribution is not. Both statistics should be computed and reported for every averaging interval rather than assuming which controls, and Sec. III.F shows that this behavior, not the persistence conservatism of the degenerate file, sets the long-interval margin of the bound.

III.F. Does the Envelope Bound Real Weather?

Fig. 4 and Tables VI and VII give the conservatism ratio R against both records, per distance and averaging interval, with the real-record denominator always the controlling §2.4 statistic.

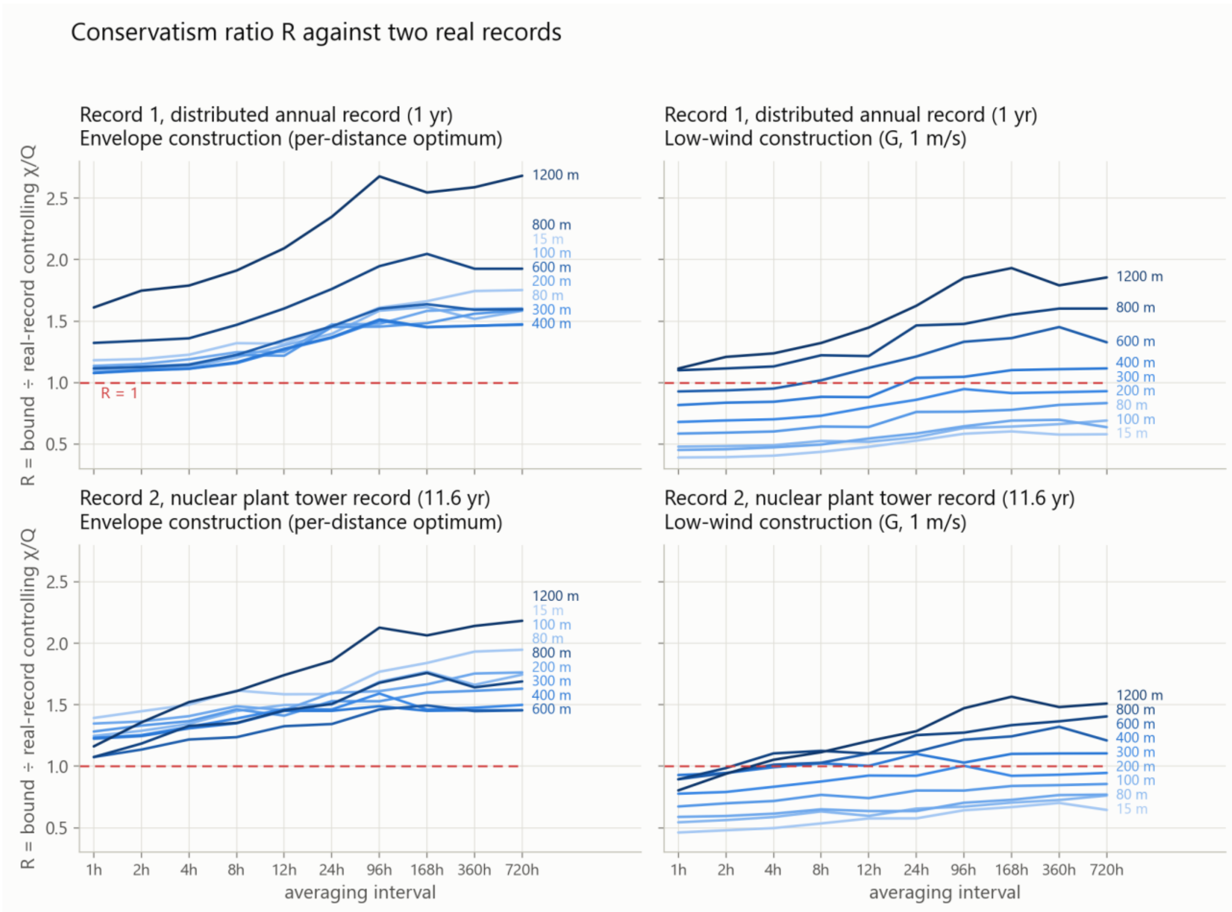

Fig. 4. *Conservatism ratio R against two real records over 15 to 1,200 m. R = bound ÷ real-record controlling χ/Q (RG 1.249 §2.4 controlling statistic) per distance and averaging interval. Left column: the envelope construction (class G at the per-distance worst-case speed) holds at every cell for both records (R = 1.07 to 2.68). Right column: the low-wind construction (G, 1 m/s) fails across the near field and at short intervals farther out (R = 0.39 to 1.93). The converse control, the near-field (G, 4 m/s) construction applied at 600 to 1,200 m, also fails, reaching R = 0.61 (Sec. III.F).*

The envelope construction bounds both records everywhere, with quantified margin. Against Record 1, the per-distance envelope construction gives R = 1.08 to 2.68; against Record 2, R = 1.07 to 2.18. R ≥ 1 in all 180 (record × distance × interval) cells. The margin is thinnest at short averaging intervals in the 300 to 800 m band (R = 1.07 to 1.08) and grows both with averaging interval (to 1.5 to 2.7 at 720 h) and with distance beyond the regime crossover; at 1,200 m the calm-limited construction carries a 1.16 to 2.68 times margin, because real records cannot hold calm-stable hours aimed at one receptor for sustained periods. The 11.6-year length of Record 2 strengthens the result: its percentiles are drawn from about 10^5 hours including multi-year extremes, and the bound holds at every cell. At every distance and averaging interval tested the envelope value sits at least 7% above the value the real record actually produced, and in most cells well above that.

Both fixed constructions fail, in opposite regimes. The low-wind construction (G, 1 m/s) gives R = 0.39 to 1.93 (Record 1) and 0.46 to 1.57 (Record 2): below unity at essentially every EAB distance for intervals up to 24 h, and still below unity at short intervals as far out as 600 to 1,200 m in some cells (for example 0.80 at 1,200 m, 1 h, Record 2). This is due to the response shape from Sec. III.A: a real record's controlling hours in the near field are stable hours near the meander-corrected worst speed, which a 1 m/s file never visits. Conversely, the near-field construction (Stability G, 4 m/s) applied beyond its regime is non-conservative at LPZ distances: against Record 2 it falls to R = 0.61 at 1,200 m (1 h), failing in 9 of 30 extended-range cells (3 of 30 for Record 1, minimum 0.85). An applicant who tuned a bounding file at the EAB and reused it at the LPZ would understate the controlling χ/Q by up to 40% with no indication of it—the mirror image of the low-wind failure, and the same lesson: the bound must be optimized against the code *per distance*.

Sensitivity to the extraction basis. For a point-mass CFD, the extracted value lands at the upper edge of the occupied bin, so the §2.4-derived bound sits 1 to 8% above the exact hourly centerline value depending on distance. Recomputing R on the least favorable basis—the exact hourly value in the numerator against the interpolated real-record value in the denominator—leaves R ≥ 1 at every cell, with minima of 1.04 (Record 1, 400 m, 1 h) and 1.07 (Record 2, 600 to 800 m, 1 h). A 4% minimum margin is, however, within the ±5% CFD quantization the real-record denominator carries, so at its tightest cells the bound holds with no margin to spare, which is the operative motivation for the explicit margin factor recommended in Sec. IV.A.

The expected long-interval blowout does not occur. Because the degenerate file holds worst-case weather for every hour while real weather does not persist at that severity, one might expect R to grow to 10 to 100 times at the 96 to 720 h intervals. It does not; R rises only to 1.5 to 2.7 because of the leg switch of Sec. III.E(c): at long intervals the controlling real-record statistic becomes the all-directions 95th percentile, which does not decay with averaging the way a sector-restricted distribution does. The persistence conservatism of the degenerate construction is largely offset by the leg switch in the §2.4 procedure, and analyses that evaluated only the sector statistic would overstate long-interval margin by up to 2.6 times.

III.G. Period-of-Record Length

Splitting Record 2 into its eleven complete calendar years and applying the identical §2.4 procedure to each: a single year reproduces the pooled 11.6-year controlling value to within 0.95 to 1.02 times at 15 m and 0.98 to 1.01 times at 100 m (1 h interval). The controlling *value* is stable to record length at this site, so a single annual cycle is substantially adequate for the dose-controlling statistic. The controlling *sector*, by contrast, is not stable at this site: the worst 45° sector migrates across four different sector centers over the eleven years. Anything sector-specific—effluent monitor siting, sector-by-sector acceptance tests—rests on a far less stable quantity than the dose input does.

III.H. The Envelope in Dose Space

A bounding χ/Q is useful only if designs can clear their dose criteria through it. Table VIII restates the envelope as the *allowable effective source term* S = (dose criterion) ÷ (χ/Q), where S aggregates the nuclide release, breathing rate, and dose conversion (rem·m³/s), for the 10 mSv (1 rem) total effective dose equivalent (TEDE) criterion used to size plume-exposure emergency planning zones (EPZs) and for the 250 mSv (25 rem) criterion of 10 CFR 50.34 [11]. At a 100 m EAB, a design clears 10 mSv (1 rem) TEDE if its effective source term is below about 1.2×10^3 rem·m³/s; at 400 m, below about 1.4×10^4; at the 1,200 m applicability limit, below about 3.4×10^4. The 10 mSv (1 rem) EPZ criterion, not the 25 times looser Part 50.34 limit, is the binding one for designs seeking a site-boundary EPZ. Whether a specific design clears these thresholds requires its nuclide inventory and release fractions and is outside the scope of this paper.

IV. DISCUSSION

IV.A. Using the Envelope

Tables II and III are the bounding product of this work: a χ/Q envelope over the full RG 1.249 applicability range, constructed at the code's worst admissible configuration, evaluated through the same §2.4 procedure the dose calculation uses, and demonstrated conservative against two real meteorological records at every distance and averaging interval evaluated (nine distances, ten intervals; Sec. III.F). An applicant whose design tolerates the envelope's conservatism uses it directly: take the Table II value at the EAB or LPZ distance, apply the Table III factor for the design's minimum-credible building area A_{min}, and carry the applicability conditions below into the safety analysis, with no site meteorological data anywhere in the chain. Applicants may re-execute the construction—the archived harness, inputs, and outputs [10] make that routine—to confirm the values, to resolve an untabulated distance exactly, or to adjust the geometry to configuration-specific needs; the evidence of Sec. III.F attaches to the construction, not only to the tabulated points.

The applicability conditions, which constitute the acceptance basis this work's evidence can carry:

1. **Ground-level point release** per RG 1.249 §2.3 ($\sigma_{y0} = \sigma_{z0} = 0$), receptor at grade, zero terrain elevation difference—each confirmed as the worst case (Sec. III.C). Surface roughness is inert at the bounding points.
2. **A stated minimum-credible building area A_{min}**, with the Table III factor applied. The envelope's supremum sits at the smallest credible building; no generic credit exists for large buildings.
3. **The worst case located per distance.** The construction is class G at its per-distance worst-case wind speed: the meander peak (about 4 m/s) at and inside 500 m, the 0.5 m/s calm limit at and beyond 600 m. Neither low wind nor the meander peak may be carried across regimes (Sec. III.F).

4. **Evaluation through the §2.4 procedure**, with a direction window that admits all hours (359°, not 360°), the upper CFD bracket taken rather than interpolated for a cited value, and the aimed-sector equivalence documented for constant-direction input.
5. **The construction** bounds the output of the RG 1.249 §2.4 procedure, produced from a degenerate record whose CFD is a point mass and whose long-interval values carry no persistence information, with conservatism at long intervals demonstrated empirically (Sec. III.F) rather than asserted from the persistence argument.
6. **An explicit margin or site-parameter screen.** The two-record evidence gives R = 1.07 to 2.68 on the like-for-like basis and no less than 1.04 on the least favorable extraction basis, with the minima at short intervals in the 300 to 800 m band. Because the minimum margin is thin and neither record is stagnation-prone, a submittal-grade use should either apply a stated margin factor on top of the envelope or accompany it with an admissibility screen on regional climatology—the joint frequency of stable-class hours in the 3 to 6 m/s band being the quantity that stresses the bound at EAB distances (Secs. III.A and III.F)—with stagnation-prone climates excluded pending their evaluation (Sec. IV.E).

The dose-space table of Sec. III.H converts the envelope into a design test. A microreactor or SMR whose effective source term at its proposed EAB distance falls below the Table VIII threshold can, on this evidence, support its permitting-stage dispersion basis with no site meteorological record, deferring characterization of site representativeness to the operational monitoring program. The conservatism can be quantified: 7 to 168% above two real records' controlling values.

IV.B. Where Representative Offsite Data Are Unavailable

The envelope is most valuable where sufficient alternative data are unavailable, and for confirmatory analysis. An applicant with dense, similarly exposed offsite stations can satisfy the representativeness route of the draft guide's Appendix B, and for that applicant the bound is a convenience that trades margin for schedule. An applicant at a remote site, in complex terrain, with large elevation contrast, or on a coast has no such option: the guide's own trigger returns them to an onsite program of a year or more, not because the dose calculation is harder but because the evidence needed to claim representativeness does not exist nearby and cannot be manufactured. For that applicant the bound is not a convenience but the only route to a permit-stage dispersion basis, and the comparison it must survive is against the alternative of deferring the project by the length of a monitoring campaign.

A bounding pathway is most needed where site conditions are least ordinary, which is an argument for defining it rather than leaving it undefined: the population it serves is the population current guidance serves least well. The sites that lack representative offsite data may also be, disproportionately, those whose climatology stresses the bound: interior valleys, persistent-inversion basins, and drainage-flow regimes are both poorly served by distant stations and more likely to concentrate stable, light-to-moderate wind hours in one sector than either record evaluated here. This work characterizes neither the joint distribution of station coverage against climatology nor any stagnation-prone record, so the point is offered as a reason for caution rather than as a result. The evidence base for conservatism is thinnest where the bound would be most used. That is not a reason to withhold the envelope, which is demonstrably conservative against an 11.6-year record and carries stated conditions, but it is the reason condition 6 of Sec. IV.A is not optional, and it makes adverse-climate coverage a necessary part of extending this work rather than a refinement.

A graduated structure resolves the tension without requiring new methodology. Conservatism substitutes for representativeness at the permitting stage, where the finding is provisional and confirmable; the operational monitoring program supplies representativeness before the finding becomes final. That is the same two-stage logic the draft guide already applies to offsite data—initial use, later verification—extended to the case the guide currently handles by requiring the monitoring program up front. The period-of-record result of Sec. III.G supports the extension, since at the site examined a single annual cycle reproduced the pooled multi-year controlling value to within about 5%, so the later confirmation does not require a long record to be informative.

IV.C. Why the Code Must Be the Guidepost

Physical intuition mislocated the bounding configuration in both directions: the low-wind construction sits at about 36% of the true peak at 15 m, and the meander-peak construction understates the code's own worst case by about 47% at 1,200 m. The response shape that defeats intuition—an interior maximum created by a pair of empirical corrections, which then yields to a boundary maximum as distance grows—is also structurally beyond a low-order response surface fitted to widely spaced design levels, because no polynomial in coded units can represent a peak between the levels, let alone a bimodal response whose controlling lobe switches with a second variable. Only executing the code through the region establishes where the maximum sits.

For legacy regulatory codes whose source is unavailable and whose runtime is milliseconds, the exchange rate is decisively in favor of exhaustive parameterization: the full parameterization here cost about a minute of compute, against an open-ended argument about surrogate validity. Where the input space is larger, surrogates retain a legitimate role in deciding where to run the code, but every published number should be a code output.

Two silent failure modes (Secs. III.E(a) and III.E(b)) appeared in the distributed code's ordinary use, both yielding normal completion status with corrupted output, and one of them sits directly on the path RG 1.249 §2.4.1 prescribes. Any automation of ARCON96—which the sixteen-sector requirement of §2.4 makes effectively necessary—should reproduce reference runs byte-for-byte before production use, refuse the 360° window, and verify echoed inputs against intent.

IV.D. Relationship to the Offsite-Data Framework

Two of the results reported above bear on premises in the current draft revision to RG 1.23 [2], and are noted here because they affect how an applicant using offsite data should interpret that guidance.

Section B.3.3.3 of the draft restricts the safety-related representativeness comparison to wind speeds at or below 3 to 4 m/s, on the stated basis that χ/Q is inversely proportional to wind speed. That premise holds for PAVAN and fails for the ARCON stable classes in the near field (Sec. III.A). Points in the stable classes at 4 to 6 m/s produce χ/Q within roughly 80 to 100% of the per-class maximum, while the sub-1 m/s points, which the window emphasizes, fall a factor of 2 to 5 below it at 15 to 100 m. For both records evaluated here it largely does not change the value of the information: 98% or more of their class F and G hours fall at or below 4 m/s, the co-occurrence effect of Sec. III.D, so the drafted window retains the hours that control. This is not uniform, however: one record places 14% of its stable hours in the 4 to 6 m/s band once class E is counted, and no part of the criterion tests whether a site's stable hours occur at moderate speeds. Beyond approximately 500 m the calm-limited response returns and a low-speed emphasis becomes appropriate again, so the appropriate screening band depends on the model and the receptor distance, which favors defining it functionally: the wind speeds producing χ/Q within a stated fraction of the per-class maximum of the model actually proposed, at the applicable distances. The class-E response, within about 15% of class F at the same speeds, similarly argues against excluding class E from such a comparison.

The same section weights wind-direction agreement most heavily, on the premise that the sector statistic controls. Which §2.4 statistic controls in fact switches with averaging intervals as well as with the site (Sec. III.E(c)): the sector value at 1 to 8 h, the all-directions value at 96 to 720 h. For the long intervals, which are frequently dose-limiting for designs with extended release durations, wind speed and stability agreement carry the weight and directional agreement is the least significant of the three. Reporting both statistics per interval, as Sec. III.E(c) recommends on independent grounds, also resolves this.

IV.E. Limitations

1. **Two records, neither stagnation-prone.** The available evidence spans one unremarkable annual record and one long nuclear plant tower record with strong prevailing westerlies. A stagnation-prone site—persistent stable conditions with light-to-moderate drainage flows concentrated in one sector, or a high joint frequency of stable-class hours near 4 m/s—is the configuration most likely to stress R at short intervals, and is plausibly also, as Sec. IV.B notes, a site at which representative offsite data are unavailable. The conservatism claim is accordingly checkable and falsifiable: a real hourly record processed through the identical §2.4 procedure that returns $R < 1$ at any distance and averaging interval inside the applicability range would establish that the envelope as tabulated does not bound, and would

require either a margin factor sized to that record or a narrowing of the applicability conditions of Sec. IV.A.

2. **The construction bounds the §2.4 output; it does not perform the §2.4 method.** The degenerate CFD is a point mass and long-interval values carry no persistence information. Sec. III.F shows empirically that the construction bounds two real records at all intervals and distances, but the demonstration is empirical rather than structural and must be re-established as record coverage grows.
3. **The period-of-record finding is single-site.** The result of Sec. III.G comes from one low-terrain-complexity site with a strong prevailing direction, and Sec. IV.B leans on it only as supporting evidence for a graduated structure, not as a general rule. Sites with weak directional preference or interannual regime switching could behave differently.
4. **Record 2's stability classification carries method uncertainty.** Stability was classified from the vertical temperature difference over the tower's deep measurement layer using the plant's RG 1.23 intervals; classification-method sensitivity (layer depth, ΔT versus σ_θ schemes) was not evaluated and would propagate into the class mix and hence into R.
5. **ARCON96, not ARCON 2.0.** This work characterizes the distributed ARCON96 executable, the implementation RG 1.249 endorses through its diffusion-coefficient restriction. ARCON 2.0 [12] implements the same dispersion methods with modernized input handling, so the model-response findings (Secs. III.A to III.D) should transfer, but the implementation findings (Secs. III.E(a) and III.E(b)) are ARCON96-specific and their status in ARCON 2.0 was not established here.
6. **Real-record percentiles carry CFD quantization** of about ±5%, which the R ratios inherit; the parameterization results are exact, and the sensitivity of R to the extraction basis is bounded in Sec. III.F.
7. **The admissibility caps of Sec. III.D are conventional textbook** values and should be anchored to a specific classification scheme or to regional joint-frequency data before use in a submittal. The question is moot beyond 500 m, where the two envelopes coincide.
8. **Dose conclusions are framing only** (Sec. III.H); no specific design's source term was evaluated.

V. CONCLUSIONS

This work provides a bounding χ/Q envelope for ARCON96 over the full RG 1.249 applicability range of 15 to 1,200 m, by stability class and receptor distance, with a mapped building-area correction, stated applicability conditions, and conservatism demonstrated against real meteorological records. It is intended for the applicant who cannot satisfy the representativeness route to a dispersion factor because no suitably representative offsite station exists at the proposed site, and for whom the alternative under current guidance is a pre-application monitoring program of a year or more.

The characterization behind the envelope has one structural finding with three practical consequences. ARCON96's χ/Q is non-monotonic in wind speed, and the worst case switches regime with distance: a meander-correction maximum near 4 m/s controls inside about 500 m, and the 0.5 m/s calm limit controls beyond about 600 m. First, neither fixed intuition bounds. The conventional "most stable, lightest wind" construction understates the envelope by up to 2.8 times in the near field, and by 2.4 times at the shortest EAB distances, and fails against both records tested, while the meander-peak construction carried out to LPZ distances is non-conservative by up to 40%. Second, the per-distance envelope, optimized against the code and evaluated through the RG 1.249 §2.4 procedure with a correctly configured direction window, bounds both records at every distance and averaging interval evaluated, by factors of 1.07 to 2.68. Third, a bounding construction cannot be built from an assumed relationship between χ/Q and wind speed; it must be located by executing the endorsed model over its admissible region.

One implementation finding and one procedural finding accompany the envelope, and both apply to any execution of the method: the code silently returns floor values when the overall-site direction window is specified as the guide instructs, at every source–receptor bearing but one, and the statistic that controls the dose input switches with averaging interval rather than being a property of the site alone. Both are trivial to guard against once known, and both are non-conservative if not.

The margin the envelope carries is real but not generous at its tightest cells, and the sites that most need it may be those whose climatology is least represented in the evidence base. The priority extension of this work is a method, and the supporting data, for establishing a dispersion basis where no meteorological record is available; extending the conservatism demonstration to deliberately adverse, stagnation-prone records and setting a margin factor or site-parameter screen accordingly are components of that work rather than its object. A complementary path is to determine a realistic upper bound from the experience of existing sites, as against the model-interrogated upper bound established in this paper.

Nomenclature

A = building cross-sectional area normal to the wind (m^2)

d = distance from the release point to the receptor (m)

H = number of hours in the meteorological record

Q = release rate, in units consistent with χ

R = conservatism ratio, bounding value divided by real-record controlling value

S = allowable effective source term ($rem \cdot m^3/s$)

U = wind speed at the lower measurement level (m/s)

ΔT = vertical temperature difference used to classify stability (°C/100 m)

σ_y, σ_z = crosswind and vertical diffusion coefficients (m)

σ_θ = standard deviation of the horizontal wind direction fluctuation (deg)

χ = airborne concentration at the receptor

χ/Q = atmospheric relative concentration, or dispersion factor (s/m^3)

Subscripts

0 = initial, or source-term, value

exceeded = hours for which χ/Q exceeds a stated value

min = minimum credible value

total = all valid hours in the record

y, z = crosswind and vertical directions

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Data availability statement

The data underlying this article, together with the execution harness and all analysis and figure scripts, are openly available in Zenodo at https://doi.org/10.5281/zenodo.22117548 [10]. Record 2 derives from proprietary meteorological data, with site-identifying fields removed. ARCON96 itself is distributed by the U.S. NRC and is not redistributed with this article.

Tables

Table I. Class-G χ/Q versus wind speed at four receptor distances. *Exact hourly centerline values (s/m³) and fraction of the per-distance peak, from the log file under constant-condition meteorology; ground-level point release, building area 800 m², receptor at grade. Per-distance maxima fall at 4.0 to 4.25 m/s for distances ≤500 m and at the 0.5 m/s calm limit for distances ≥600 m.*

U (m/s)	15 m	% of peak	100 m	% of peak	400 m	% of peak	1,200 m	% of peak
0.5	6.38E-03	19%	2.52E-04	30%	5.83E-05	80%	2.90E-05	100%
1.0	1.20E-02	36%	3.64E-04	43%	5.36E-05	73%	2.07E-05	71%
2.0	2.25E-02	67%	5.95E-04	70%	6.04E-05	83%	1.70E-05	59%
3.0	3.03E-02	91%	7.75E-04	91%	6.88E-05	94%	1.59E-05	55%
4.0	3.34E-02	100%	8.53E-04	99.9%	7.29E-05	99.9%	1.53E-05	53%
5.0	3.16E-02	95%	8.17E-04	96%	7.11E-05	97%	1.47E-05	51%
6.0	2.69E-02	81%	7.07E-04	83%	6.44E-05	88%	1.39E-05	48%
8.0	1.68E-02	50%	4.52E-04	53%	4.57E-05	63%	1.15E-05	40%

Table II. Bounding χ/Q by stability class and receptor distance. *Maximum exact hourly centerline value (s/m³) over the wind-speed sweep in each cell; class G (bold) controls at every distance. Rightmost column: class-G worst-case wind speed, showing the regime switch between 500 and 600 m.*

d (m)	A	B	C	D	E	F	G	highest **U for G (m/s)**
15	8.88E-03	1.14E-02	1.54E-02	2.16E-02	2.57E-02	2.98E-02	**3.34E-02**	4.00
80	3.70E-04	4.76E-04	6.44E-04	8.99E-04	1.05E-03	1.20E-03	**1.30E-03**	4.00
100	2.45E-04	3.14E-04	4.25E-04	5.93E-04	6.90E-04	7.91E-04	**8.54E-04**	4.25
150	1.19E-04	1.51E-04	2.00E-04	2.77E-04	3.25E-04	3.74E-04	**4.02E-04**	4.25
200	7.00E-05	8.95E-05	1.19E-04	1.64E-04	1.93E-04	2.22E-04	**2.39E-04**	4.25
250	4.69E-05	6.17E-05	7.94E-05	1.11E-04	1.31E-04	1.50E-04	**1.61E-04**	4.00
300	3.25E-05	4.78E-05	5.79E-05	8.05E-05	9.54E-05	1.10E-04	**1.18E-04**	4.25
400	1.71E-05	3.13E-05	4.09E-05	5.05E-05	5.90E-05	6.79E-05	**7.30E-05**	4.25
500	1.01E-05	2.22E-05	3.10E-05	4.07E-05	4.48E-05	4.78E-05	**5.12E-05**	4.00
600	6.44E-06	1.67E-05	2.46E-05	3.42E-05	3.84E-05	4.16E-05	**4.33E-05**	0.50
800	3.19E-06	1.06E-05	1.71E-05	2.60E-05	3.04E-05	3.40E-05	**3.60E-05**	0.50
1000	1.87E-06	7.50E-06	1.29E-05	2.11E-05	2.56E-05	2.94E-05	**3.18E-05**	0.50
1200	1.16E-06	5.74E-06	1.03E-05	1.80E-05	2.24E-05	2.63E-05	**2.90E-05**	0.50

Table III. Building-area correction factor for the bounding envelope. *Ratio of χ/Q at the stated area to the 800 m² baseline, evaluated at all 91 class × distance worst-case cells. "Apply" is the worst case over cells, the citable factor for a minimum-credible area A_{min}; "largest reduction" is the largest decrease observed in any cell, which is configuration-dependent and not generically creditable.*

Area (m²)	Apply (worst-case factor)	Largest reduction observed
1	1.28	none
5	1.25	none
10	1.23	none
25	1.20	none
50	1.18	none
100	1.15	none
200	1.10	none
400	1.05	none

800	1.00	(baseline)
1,200	1.00	0.97
2,000	1.00	0.94
3,000	1.00	0.92
5,000	1.00	0.89
7,500	1.00	0.88
10,000	1.00	0.87

Table IV. Physical-admissibility variants of the bounding envelope. *Unconstrained: worst (class, U) the code admits, consistent with the RG 1.23 ΔT classification basis. Capped: conventional Pasquill–Gifford–Turner per-class wind-speed limits imposed. The two coincide from 600 m outward, where the calm-limited worst case is admissible under either position. Values in s/m³.*

d (m)	Unconstrained	Capped construction	Capped χ/Q	Ratio
15	3.34E-02	F, 3 m/s	2.79E-02	1.20
80	1.30E-03	F, 3 m/s	1.11E-03	1.17
100	8.54E-04	F, 3 m/s	7.34E-04	1.16
150	4.02E-04	F, 3 m/s	3.48E-04	1.16
200	2.39E-04	F, 3 m/s	2.08E-04	1.15
250	1.61E-04	F, 3 m/s	1.41E-04	1.14
300	1.18E-04	F, 3 m/s	1.04E-04	1.13
400	7.30E-05	F, 3 m/s	6.51E-05	1.12
500	5.12E-05	G, 0.5 m/s	4.92E-05	1.04
600	4.33E-05	G, 0.5 m/s	4.33E-05	1.00
800	3.60E-05	G, 0.5 m/s	3.60E-05	1.00
1000	3.18E-05	G, 0.5 m/s	3.18E-05	1.00
1200	2.90E-05	G, 0.5 m/s	2.90E-05	1.00

Table V. The RG 1.249 §2.4.1 overall-site direction window fails silently in ARCON96. *Direction sweep with one real annual record, ground-level release, 15 m receptor, window width 360°; all runs report "NORMAL PROGRAM COMPLETION." The window is correct only at bearing 180°; elsewhere the reported 95th-percentile value is pinned at the output floor (1.0E-05 s/m³), approximately 2,700 times below the correct value. The record contains 8,782 valid hours.*

Bearing, intake to source (°)	0	45	90	135	180	202	225	270	315	360
Window echoed in log (°)	180–180	225–225	270–270	315–315	000–360	022–022	045–045	090–090	135–135	180–180
Hours admitted to the window	29	38	24	32	8,755	10	8	17	37	29
Reported 95th-pct χ/Q, 0–2 h (s/m³)	1.0E-05	1.0E-05	1.0E-05	1.0E-05	2.73E-02	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05

Table VI. Conservatism ratio R, envelope construction, versus Record 1. *R = bound ÷ real-record controlling §2.4 χ/Q per distance and averaging interval; Record 1 is the distributed annual record (1992). The construction is class G at the per-distance worst-case speed (4 m/s at rows ≤400 m; 0.5 m/s at rows ≥600 m). R ≥ 1 everywhere; range 1.08 to 1.61 across the 80 to 400 m EAB range and 1.08 to 2.68 overall.*

d (m)	1 h	2 h	4 h	8 h	12 h	24 h	96 h	168 h	360 h	720 h
15	1.18	1.19	1.23	1.32	1.32	1.46	1.61	1.66	1.74	1.75
80	1.10	1.11	1.12	1.20	1.30	1.40	1.59	1.61	1.52	1.58
100	1.14	1.15	1.19	1.25	1.25	1.47	1.48	1.58	1.60	1.60
200	1.12	1.13	1.15	1.22	1.22	1.45	1.46	1.48	1.56	1.59
300	1.08	1.10	1.11	1.16	1.27	1.36	1.50	1.45	1.46	1.47
400	1.08	1.10	1.11	1.17	1.28	1.37	1.51	1.45	1.46	1.47
600	1.12	1.13	1.14	1.23	1.35	1.46	1.60	1.64	1.59	1.60
800	1.32	1.34	1.36	1.47	1.60	1.76	1.95	2.05	1.93	1.93
1200	1.61	1.75	1.79	1.91	2.09	2.35	2.68	2.55	2.59	2.68

Table VII. Conservatism ratio R, envelope construction, versus Record 2. *R = bound ÷ real-record controlling §2.4 χ/Q per distance and averaging interval; Record 2 is the nuclear plant tower record, 2007 to 2018 (11.6 years). Construction as in Table VI. R ≥ 1 everywhere; range 1.07 to 2.18.*

d (m)	1 h	2 h	4 h	8 h	12 h	24 h	96 h	168 h	360 h	720 h
15	1.39	1.45	1.50	1.62	1.59	1.59	1.77	1.84	1.93	1.95
80	1.25	1.29	1.34	1.45	1.50	1.50	1.69	1.77	1.66	1.75
100	1.35	1.36	1.41	1.49	1.46	1.60	1.61	1.67	1.75	1.76
200	1.28	1.33	1.37	1.46	1.41	1.53	1.53	1.60	1.61	1.63
300	1.23	1.25	1.32	1.39	1.47	1.46	1.59	1.46	1.48	1.50
400	1.22	1.25	1.31	1.35	1.45	1.45	1.49	1.45	1.46	1.46
600	1.07	1.14	1.22	1.24	1.33	1.34	1.46	1.49	1.45	1.45
800	1.07	1.18	1.33	1.35	1.45	1.51	1.68	1.76	1.64	1.69
1200	1.16	1.36	1.52	1.61	1.74	1.86	2.13	2.06	2.14	2.18

Table VIII. Allowable effective source term implied by the bounding χ/Q envelope. *S = dose criterion ÷ bounding χ/Q (rem·m³/s); S aggregates nuclide release, breathing rate, and dose conversion factors over the inhalation pathway, with ground-shine terms additional where applicable.*

d (m)	Bounding χ/Q (s/m³)	S at 10 mSv (1 rem) TEDE (EPZ criterion)	S at 250 mSv (25 rem) (10 CFR 50.34)
15	3.34E-02	3.0E+01	7.5E+02
80	1.30E-03	7.7E+02	1.9E+04
100	8.54E-04	1.2E+03	2.9E+04
150	4.02E-04	2.5E+03	6.2E+04
200	2.39E-04	4.2E+03	1.0E+05
250	1.61E-04	6.2E+03	1.6E+05
300	1.18E-04	8.5E+03	2.1E+05
400	7.30E-05	1.4E+04	3.4E+05
500	5.12E-05	2.0E+04	4.9E+05
600	4.33E-05	2.3E+04	5.8E+05
800	3.60E-05	2.8E+04	6.9E+05
1000	3.18E-05	3.1E+04	7.9E+05
1200	2.90E-05	3.4E+04	8.6E+05