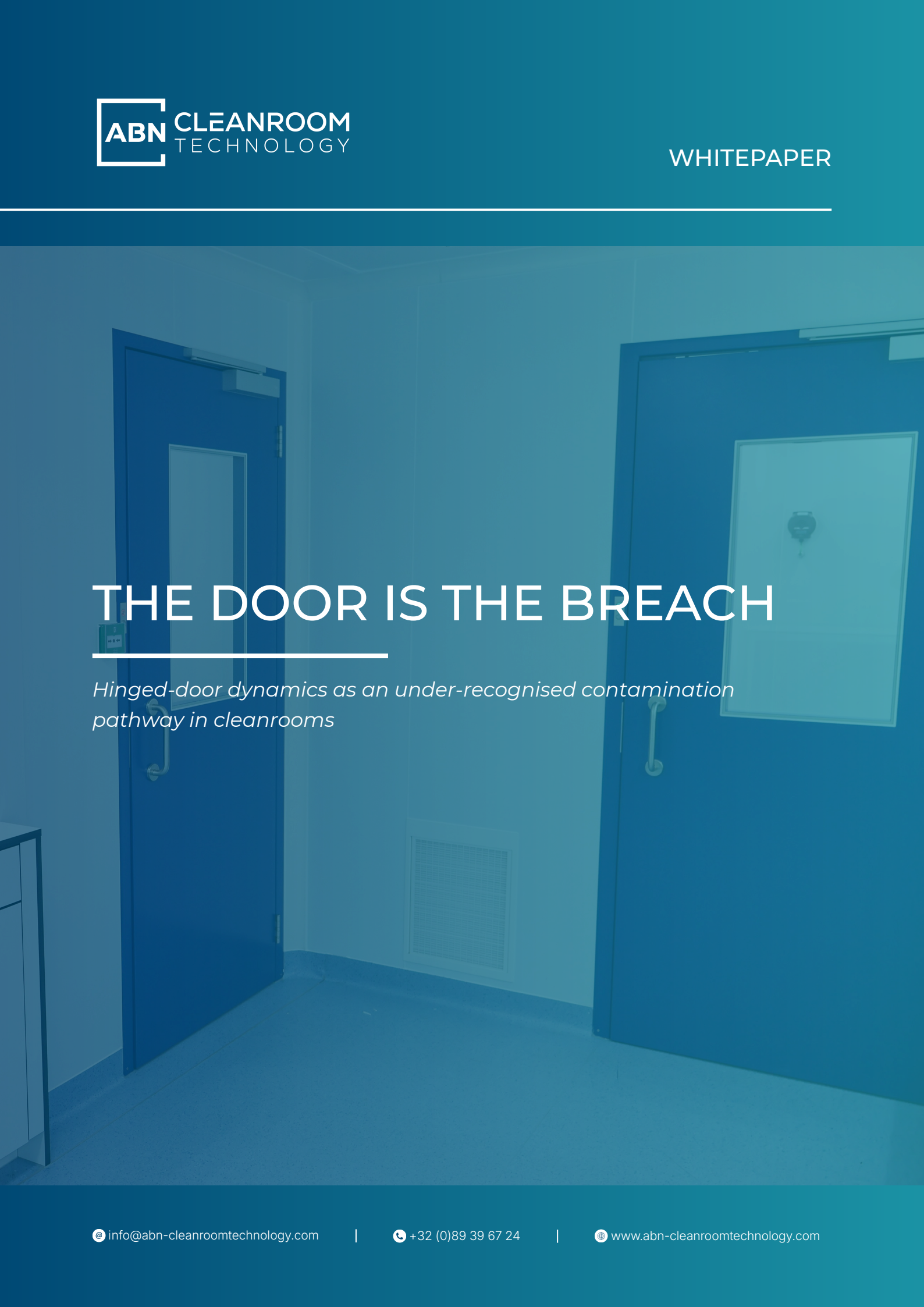




THE DOOR IS THE BREACH

Hinged-door dynamics as an under-recognised contamination pathway in cleanrooms

Introduction

Cleanrooms are engineered to hold airborne particle concentrations within defined limits, as codified by ISO 14644. The dominant levers of contamination control — high-efficiency filtration, elevated air-change rates and a maintained pressure cascade between zones of differing cleanliness — are all conceived as steady-state provisions. Design and validation typically certify a cleanroom in a static condition, with doors closed and the cascade intact.

This framing overlooks a transient event that recurs many times each working day: the opening and closing of a door. When a hinged door swings, it does not merely provide passage; it physically displaces a volume of air and, in doing so, momentarily annihilates the pressure differential that isolates the protected zone. The breach is brief, but it is repeated, and its cumulative contribution to contamination ingress is easily underestimated precisely because it falls outside the static paradigm in which cleanrooms are conceived and qualified.

Recent computational work quantifies this pathway with new precision. Raji, Saidi and Eslami (2026) modelled a cleanroom connected to an airlock and simulated hinged-door rotation using a dynamic-mesh, Eulerian–Lagrangian CFD framework, validated against the experimental data of Chen et al. (2006). Their central contribution is twofold: they isolate the aerodynamic effect of door rotation from confounding factors such as personnel movement, and they propose a quantitative metric — the Normalized Particle Exposure Index (NPEI) — for comparing operational strategies on a like-for-like basis. This white paper synthesises that evidence and considers its implications for cleanroom design and protocol.

The remainder of the paper is organised as follows. Section 2 characterises the door as a contamination pathway. Section 3 summarises the modelling approach. Section 4 presents the principal findings, including the variable-speed strategy and the NPEI. Section 5 discusses design and operational implications. Section 6 states the limitations, and Section 7 concludes.



The door as a contamination pathway

A maintained pressure cascade — typically on the order of 15 Pa across an airlock and a further step into the cleanroom — establishes a directional airflow from clean to less-clean spaces that resists contaminant ingress. This defence is predicated on the differential being sustained. Door rotation subverts it along three coupled mechanisms.

- **Volumetric displacement.** When a hinged leaf sweeps through its arc, it acts as a paddle, displacing a volume of air proportional to the arc swept and the time held open. It is this displaced volume, rather than any imbalance in supply and exhaust flow rates, that predominantly governs cross-contamination.
- **Pressure-cascade collapse.** The source study reports that within one second of a door beginning to open, the 15 Pa differential between airlock and cleanroom collapses to approximately 1 Pa; shortly thereafter the two zones equalise entirely. For the duration of the swing, the cascade that isolates the cleanroom effectively ceases to exist.
- **Vortex entrainment.** Rotation generates distinct vortices behind the leaf and a relative vacuum that intensifies with distance from the hinge and with rotational speed. These unsteady structures entrain and transport particles across the threshold, and persist after the door has closed.

These three mechanisms do not act uniformly across the door cycle: the opening and open phases differ markedly in the size and reach of the particles they mobilise, a distinction with direct consequences for containment.

During the opening phase, the leaf's own movement generates the vortex described above: a brief, high-energy airflow able to entrain larger particles, which their inertia then carries well into the cleanroom before it decays. During the subsequent open phase, with the leaf stationary, the driving airflow is instead the slow, low-energy consequence of the collapsed differential itself; it is able to move only smaller, lower-mass particles, which travel a short distance before settling near the threshold.

This distinction matters for containment. Because open-phase contamination stays concentrated in the immediate vicinity of the doorway rather than dispersing into the room, it is comparatively straightforward to intercept: a strategically placed local extraction point can capture a disproportionate share of it. Opening-phase contamination is harder to contain by the same means, precisely because its higher energy carries it beyond the reach of a point-source extractor.

Figure 1 depicts this pair of regimes: panel A traces the pressure collapse across the threshold in plan view, and panel B contrasts the high-energy, large-particle throw of the opening phase with the low-energy, small-particle spread of the open phase in elevation

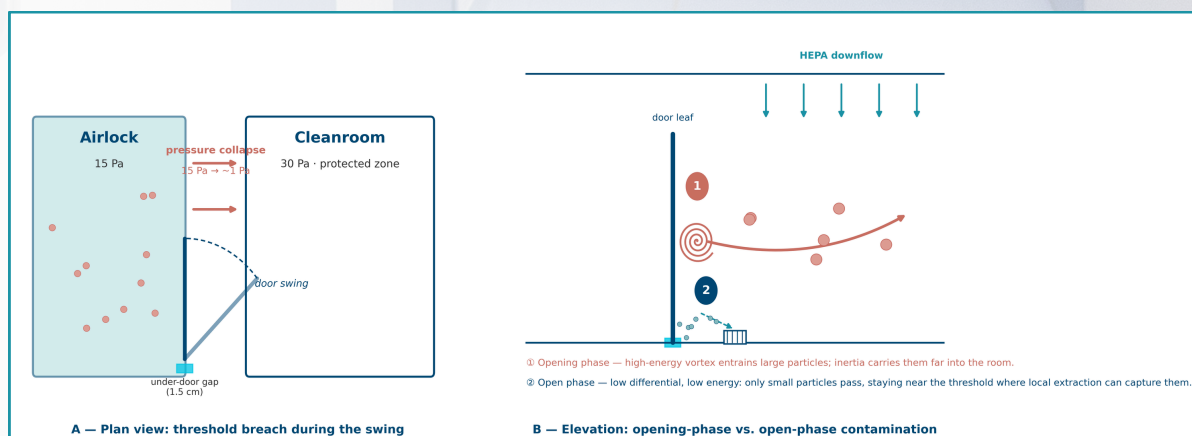


Figure 1 — (A) Plan view: hinged-door rotation collapses the pressure cascade across the threshold. (B) Elevation: the opening phase throws large particles deep into the cleanroom via a high-energy vortex, while the open phase pushes only small particles through at low energy, concentrated near the threshold.

Clinical implication: what the standards miss

The source study modelled a 400 × 400 cm cleanroom connected to an airlock of 250 × 180 cm, both 270 cm high, separated by a single hinged door (210 × 80 cm) opening into the cleanroom with a 1.5 cm under-door clearance. Airflow was resolved in ANSYS Fluent using the RNG k- ϵ turbulence model — selected for its superior treatment of low-Reynolds-number, near-wall and swirling flows characteristic of leakage scenarios — within a dynamic-mesh framework that deforms the grid in response to the moving boundary. The particle phase was treated in a Lagrangian frame via the Discrete Phase Model, tracking individual trajectories under drag and gravity; for the 5 μ m particles considered, secondary forces (Saffman lift, Brownian motion, Basset history) were justifiably neglected.

The cleanroom was pressurised to 30 Pa and the airlock to 15 Pa, at 20 air changes per hour. Both the velocity field and the particle-concentration distribution were validated against the experimental measurements of Chen et al. (2006), with discrepancies remaining within an acceptable range; grid- and particle-independence studies established a mesh of ~1.2 million cells and an injection of ~90,900 particles as the working resolution. Four door-operation scenarios were examined, holding total angular displacement constant while varying speed and phasing, as summarised in Table 1.

Case	Opening (rad/s)	Closing (rad/s)	Cycle time (s)	Relative NPEI
1	$\pi/8$	$\pi/8$	8	reference
2	$\pi/6$	$\pi/6$	6	baseline
3	$\pi/4$	$\pi/4$	4	baseline
4	$\pi/8$	$\pi/4$	6	-17% / -15%

Table 1 — Door-operation scenarios (after Raji et al., 2026). Case 4 phases a slow opening with a fast closing.



Principal findings

SPEED AND DIRECTION GOVERN TRANSPORT

Higher rotational speeds initially induce greater turbulence and a larger relative vacuum behind the leaf, increasing the instantaneous flux of particles across the threshold. Lower speeds attenuate this mixing but hold the door open longer, affording contaminants a more prolonged window for ingress. The two effects oppose one another, which implies that neither uniformly slow nor uniformly fast operation is optimal — the phasing of the swing matters as much as its speed.

A VARIABLE-SPEED PROTOCOL

Exploiting this tension, the source study proposes a variable-speed protocol: open slowly ($\pi/8$ rad/s, 4 s) to minimise the vacuum and vortex strength during the vulnerable opening phase, then close rapidly ($\pi/4$ rad/s, 2 s) to curtail the exposure window. Total cycle time (6 s) equals that of constant $\pi/6$ operation, isolating the benefit of phasing from that of duration. The strategy reduces the residual contaminant count in the cleanroom at 20 s by 21 per cent relative to constant $\pi/6$ operation.

QUANTIFYING PERSISTENCE: THE NPEI

To compare strategies on a single, physically meaningful scale, the study introduces the Normalized Particle Exposure Index (NPEI): the time-integrated count of particles present in the cleanroom, normalised by the initial particle population and the total observation time. In effect the NPEI captures not merely how many particles enter, but how long the environment remains exposed to them — a more faithful proxy for contamination risk than an instantaneous count. As Figure 2 shows, the variable-speed protocol lowers the NPEI by 17 per cent relative to constant $\pi/6$ operation and by 15 per cent relative to constant $\pi/4$.

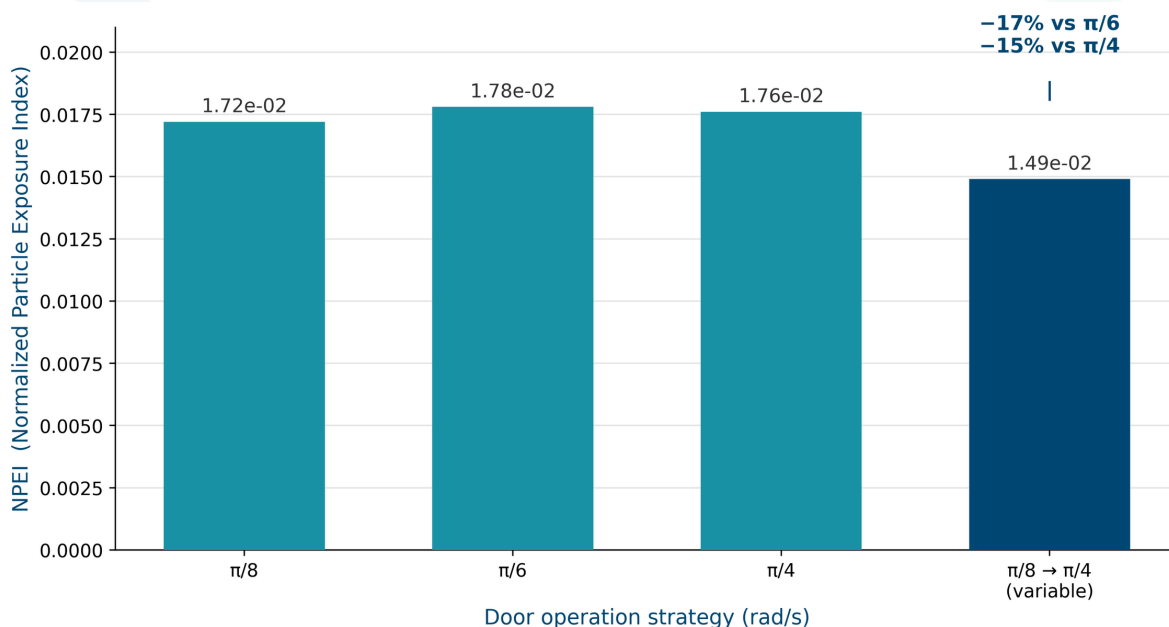


Figure 2 — Normalized Particle Exposure Index across door-operation strategies. The variable-speed protocol (navy) minimises contamination persistence.

Implications for Design and Practice

The evidence carries consequences on two planes that are often treated separately but are in fact complementary: the physical configuration of transfer zones and the procedures that govern their use.

DESIGN

The airlock is not an incidental vestibule but a functional buffer whose value is realised precisely at the moment of a door swing. A well-configured airlock, holding even a modest differential, absorbs the transient breach that door rotation creates. Design measures that reinforce this buffering — appropriate diffuser placement to sustain a protective downflow at the threshold, considered exhaust balancing, and attention to the under-door gap through which residual pressure influence propagates — all attenuate the ingress that the door would otherwise permit. Door type is itself a design variable: while hinged doors predominate, their aerodynamic footprint is larger than that of sliding alternatives, a trade-off worth weighing where contamination margins are critical.

This design logic extends directly to the two contamination regimes described in Section 2: because open-phase contamination stays concentrated near the threshold rather than dispersing, a strategically placed local extraction point at the doorway can intercept a meaningful share of it before it spreads — a targeted, low-cost complement to diffuser placement and exhaust balancing. Opening-phase contamination, carried further by the higher-energy vortex, is better addressed at the source, through the variable-speed protocol discussed below.

OPERATIONS

That a change in operating protocol alone — requiring no additional hardware — can reduce contamination persistence by 17 per cent is a result of considerable practical significance. It argues for encoding door dynamics into standard operating procedures and, where feasible, into the control logic of automated doors: a slow, controlled opening followed by a brisk closing. This is the operational analogue of the design principle above — both seek to shorten and soften the interval during which the cascade is breached.

These effects originate in the leaf's own motion, so the door-opening protocol should not stop at prescribing speeds: it should make personnel aware of how their everyday behaviour at the door governs cleanroom performance. Small, repeated adjustments to daily and hourly habits — opening deliberately, closing promptly, minimising hold-open time — compound over hundreds of cycles into a significant, no-cost contribution to contamination control.

The pressure cascade that defines a cleanroom is, by design, a steady-state guarantee. A door swing suspends that guarantee for the duration of the arc. Contamination control must therefore extend beyond static provisions to govern the transient events — door dynamics foremost among them — that momentarily undo them. Both the airlock and the operating procedure are instruments for managing that transient.



Limitations

Several boundaries qualify the source findings. The analysis isolates the aerodynamic effect of door rotation and does not model concurrent personnel movement, which in practice accompanies most door operations and contributes its own displaced volume and wake. Thermal effects were neglected under the high-inlet-velocity assumption, so buoyancy-driven exchange — which becomes dominant for prolonged hold-open times — falls outside the present scope. Finally, hinged and sliding doors were not directly compared within the same framework. These constitute natural extensions rather than deficiencies, and do not diminish the core result: that variable-speed door operation measurably reduces contamination persistence.

Conclusion

Door movement is a routine, transient and under-recognised contamination pathway in cleanrooms. High-resolution CFD demonstrates that hinged-door rotation collapses the isolating pressure cascade within a second and drives aerosol from the airlock into the protected zone, with the magnitude of transfer governed by the speed and phasing of the swing. A variable-speed protocol — open slowly, close quickly — reduces contaminant levels by 21 per cent and contamination persistence, as measured by the Normalized Particle Exposure Index, by up to 17 per cent, at no hardware cost. For contamination-sensitive environments, the door deserves the same deliberate engineering attention as the filtration and pressurisation systems with which it is inextricably coupled. Design the transfer zone to buffer the breach; operate the door to minimise it.



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