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Particle Contamination from Flexible Polymer Components in Semiconductor Equipment: Mechanisms, Materials, and Mitigation

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Abstract: Flexible polymer components—electrical cables and process tubing—are a systematically underappreciated source of particle contamination in semiconductor fabrication equipment. These components are exposed to repetitive mechanical, thermal, chemical, and electrical stresses during normal tool operation, each capable of generating wear debris and surface particles that directly threaten process yield. Material selection is the most influential engineering lever: fluoropolymer and expanded PTFE (ePTFE) constructions exhibit the lowest particle generation risk, while PVC and unqualified commodity materials are incompatible with ISO-classified cleanroom environments.The central gap identified in this review is the absence of a motion-inclusive qualification standard for flexible components. No harmonized protocol currently specifies the mechanical loading parameters, environmental conditions, and reporting conventions required to evaluate and compare cable and tubing assemblies across vendors and laboratories. This gap allows non-cleanroom pigtails from subsystem vendors to enter semiconductor tools at the point of integration without systematic qualification. This paper presents a structured evaluation framework covering motion, material, environment, and installation parameters; introduces a material summary and standardization gap analysis as primary contributions; and identifies the development of a motion-based qualification standard and supply-chain requirements for cleanroom-qualified pigtails as the highest-priority actions for contamination reduction in next-generation semiconductor equipment.

Keywords: *Particle Contamination; Polymer Degradation; Cleanroom Cables; Semiconductor Equipment; Flexible Component Qualification; Motion-Induced Particulation*

I. Introduction

Particle contamination is among the most consequential yield-limiting factors in semiconductor fabrication, affecting device performance, process repeatability, and cleanroom throughput. Significant engineering effort has been directed at reducing particles from rigid metal and ceramic components; however, the contribution of flexible polymer-based components—electrical cables and process tubing—has been less systematically characterized. Yet these components are ubiquitous: they traverse wafer-handling systems, robotic motion platforms, gas-delivery lines, and subsystem interconnects throughout semiconductor process tools [1], [2].

Flexible cables and tubing are not structural elements; they are subject to cumulative mechanical stresses during normal tool operation—bending, twisting, sliding, vibration, and pressure cycling—that progressively degrade polymer surfaces, generating micro-cracks, surface oxidation, embrittlement, and fragmentation. These degradation pathways are well-documented in the polymer tribology and materials aging literature, though originally for non-semiconductor applications [3], [4]. The translation of these mechanisms into cleanroom particle release events is increasingly recognized as a significant contamination risk, one that the industry has not yet addressed with sufficient standardization.

A further systemic vulnerability arises from commercial off-the-shelf (COTS) subsystems—motors, valves, actuators, sensors, and encoders—that arrive pre-configured with permanently attached pigtail cables and tubing fabricated from commodity materials such as polyvinyl chloride (PVC), thermoplastic polyurethane (TPU), or thermoplastic elastomers (TPE). These materials are not designed for ISO-classified cleanroom environments and introduce contamination risk at the point of integration that cannot be resolved through tool-level engineering alone [5].

This paper makes three primary contributions. First, it establishes a structured evaluation framework organizing the relevant parameters—motion profile, material properties, environmental conditions, and

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installation discipline—into a coherent qualification logic. Second, it presents a comparative material summary and a standardization gap analysis (Table 1) that together define the current state of the field and its key deficiencies. Third, it proposes engineering priorities and future research directions targeting the identified qualification gap. The analysis covers particle generation mechanisms, material-specific behavior, current industry practices, and the path to a motion-inclusive qualification standard.

II. Mechanisms of Particle Generation Under Mechanical and Environmental Stress

Particle generation from polymer cables and tubing results from degradation of material surfaces under the combined action of mechanical loading, thermal exposure, chemical attack, electrical stress, and physical installation damage. Two distinct transport pathways exist and should be distinguished early: in cables, particle generation is primarily external—wear debris shed from the jacket surface into the surrounding environment, depositing on wafer surfaces or entering process volumes through airborne or surface-borne pathways; in process tubing, particles are primarily generated internally—detached from inner surfaces by flow shear and mobilized directly into the process gas or fluid stream. Both pathways require separate assessment but are addressed by the same underlying material and qualification logic.

Figure 1 illustrates the principal particle generation zones for both external cable wear (Panel a) and internal tubing flow mechanisms (Panel b), referenced throughout the subsections below.

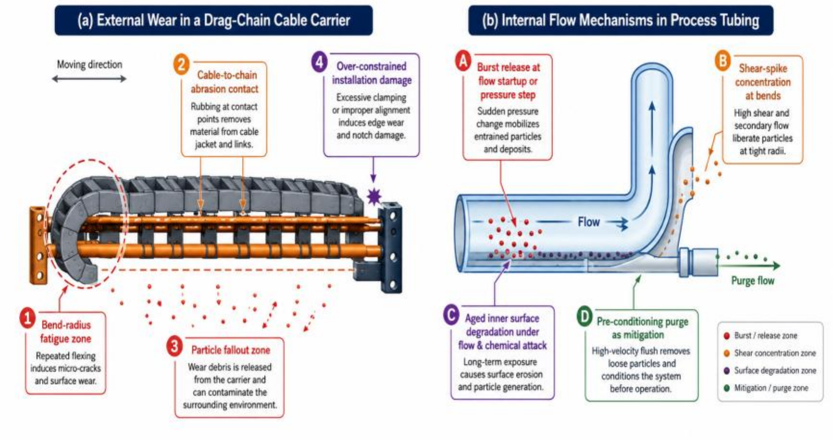

Figure 1. Particle Generation Zones in Flexible Polymer Components. (a) External wear in a drag-chain cable carrier: bend-radius fatigue zone (①), cable-to-chain abrasion contact (②), particle fallout zone (③), and over-constrained installation damage (④). (b) Internal flow mechanisms in process tubing: burst release at flow startup or pressure step (A), shear-spike concentration at bends (B), aged inner surface degradation under combined flow and chemical attack (C), and pre-conditioning purge as mitigation (D).

2.1 Mechanical Wear

Mechanical wear is the most extensively validated cause of particle release from flexible components. Cyclic bending, torsional, sliding, and vibrational stresses imposed on cables routed through drag-chain carriers, robot arms, pivots, and wafer stage mechanisms progressively erode jacket surfaces and initiate micro-cracks. Controlled testing has demonstrated that motion alone is sufficient to generate detectable levels of wear particles and that particle release correlates directly with the jacket material's coefficient of friction (COF) [1].

Low-COF fluoropolymer jackets release substantially fewer particles than polyethylene or thermoplastic elastomer jackets under identical motion profiles. Flat cable constructions outperform round bundled designs by reducing inter-cable contact area, torsion, and shear forces along confined routing paths [1].

Drag-chain cables in wafer-handler motion axes, reciprocating at bend radii below 100 mm, generate detectable wear particles within the first few thousand cycles. This is the primary generation scenario for surface-borne contamination in horizontal transport modules.

2.2 Thermal Aging

High-temperature environments near servo motors and process heaters accelerate thermo-oxidative degradation of polyolefin jackets, causing chain scission, surface oxidation, crystallinity modification, and brittle-skin formation [3], [4]. Crosslinked polyethylene (XLPE), the most widely used jacket polymer in semiconductor wiring, is particularly susceptible: thermal cycling progressively diminishes crystallinity at spherulite boundaries, generates micro-cracks, and reduces fracture toughness, transitioning the failure mode from ductile to brittle. In multilayer jackets, differential thermal expansion between dissimilar polymers induces interfacial shear stress, leading to delamination and the generation of lamellar flake debris [7].

XLPE cables routed within 50 mm of servo motor housings, experiencing repeated excursions above 70°C, show progressive embrittlement over service lifetime. Surface flex events that would not cause particle release in a new cable generate spallation events in a thermally aged cable.

2.3 Chemical and Environmental Exposure

Semiconductor tool environments expose cable jackets and tubing to nitrogen purge streams, oxidizing process by-products, plasma effluents, and cleaning solvents. Cables with jacket materials susceptible to hydrolysis, swelling-shrinkage cycling, or oxidative chain scission are particularly vulnerable. Elastomers such as EPR and EPDM are susceptible to ozone-induced surface oxidation and fatigue from humidity cycling. After softening or embrittlement, damaged surfaces require substantially less mechanical energy to generate a particle-releasing event than intact surfaces [8].

EPR/EPDM cables routed near plasma-assisted etch chambers, where ozone by-products are present, develop oxidized, friable outer surfaces that shed particles under moderate vibration within months of installation.

2.4 Electrical Stress

In proximity to high-frequency drives, plasma sources, and power-dense modules, cable jacket insulators are subject to charge injection, partial discharges, and electro-oxidation. These phenomena form micro-voids, carbonized surface channels, and brittle dielectric skins that fracture under subsequent mechanical loading [9]. Space-charge accumulation in XLPE and polypropylene insulators amplifies local field gradients and accelerates oxidation-assisted micro-cracking [10]. A critical synergistic failure mode occurs when surfaces pre-damaged by electrical aging fail under mechanical stresses that would not otherwise cause particle release.

Motor pigtails routed alongside variable-frequency drive cabling experience partial discharges at insulation surfaces that form carbonized micro-channels; subsequent flexing fractures these channels, releasing carbonaceous particles into the cable management environment.

2.5 Installation-Induced Damage

Installation damage is a frequently underappreciated but practically significant source of latent particle risk. Routing cables below their minimum bend radius, over-tightening cable ties, forcing multi-axis bending, and contact with sharp-edged brackets create localized stress concentrations that generate micro-cracks and crazing in jacket polymers at the time of installation [11]. These damage sites are typically invisible but serve as crack initiation sites during subsequent cyclic operation, generating brittle flaking and surface spallation once the component enters service.

A cable tied at less than its minimum bend radius over a sharp bracket edge during robot arm assembly develops localized crazing that initiates fatigue cracks; particle shedding begins on the first operational cycles, well before any wear-related surface degradation would otherwise occur.

2.6 Flow-Induced Particle Generation in Process Tubing

Process tubing for pneumatic, chemical delivery, and vacuum systems is subject to a distinct set of internal particle generation mechanisms driven by fluid dynamics rather than surface abrasion. Shear forces on the tubing's inner wall can erode poorly adhered surface layers, dislodge pre-existing particulates, and detach weakened polymer fragments from aged inner surfaces. The highest particle release rates occur at flow startup or pressure step changes—a 'burst-and-settle' mode in which loosely adhered debris is mobilized at the initial shear transient and settles to a lower steady-state rate [13]. Laminar-to-turbulent flow transitions at fittings and bends generate localized shear spikes that dislodge particles not mobilized under steady-state conditions.

An important distinction applies here: these are internal contamination events that introduce particles directly into the process gas or fluid stream, in contrast to the external surface-borne particles generated by cable jacket wear. High-purity fluoropolymer tubing (PFA, PTFE, and FEP) generates the lowest internal particle levels due to chemically inert, hydrophobic inner surfaces. Pre-conditioning purge protocols—extended purging at operational flow rates before tool qualification—are established good practice for reducing baseline burst counts in new tubing installations [13].A note on metrology: polymeric particles, particularly sub-micron fragments from fluoropolymer tubing, may be significantly under-detected by standard optical particle counting methods calibrated for spherical latex particles. The refractive index, morphology, and transparency of polymer debris differ substantially from counting calibration standards, meaning that reported particle counts for polymer-containing systems likely understate the true contamination contribution. This metrology limitation must be acknowledged when interpreting qualification data and comparing materials.

III. Material-Specific Behavior and Particle Generation Risk

The particle-shedding propensity of a cable jacket or tubing polymer is governed by intrinsic material parameters—coefficient of friction, fracture toughness, thermal stability, and chemical resistance—as well as microstructural changes induced by aging. Table 1 provides a consolidated comparison of materials commonly used in semiconductor cable and tubing applications, summarizing their key properties, limitations, contamination risk ratings, and typical use cases.

Material	Key Properties	Limitations	Contamination Risk
PTFE / PFA / FEP	Lowest COF (0.02–0.10); chemically inert; low outgassing	Cold-flow creep at tight bend radii under sustained load	Very Low — minimal wear debris; tribofilm stable in static/low-motion use
ePTFE	Node-fibril microstructure; excellent flex life; ultra-low COF	Higher cost; specialized manufacturing	Very Low — redistributes bending stress; lowest particle shed in dynamic testing
XLPE	Good chemical resistance; flexible; electrically robust	Thermal cycling causes micro-crack growth at spherulite boundaries; space-charge accelerates aging	Medium — acceptable short-term; increases over service life with cyclic thermal and electrical stress
PUR	Torsionally compliant; flexible at low torque	High COF (0.50–0.65); hydrolysis in humid environments; tacky surface causes burst particles	Medium–High — snap-motion particle bursts in carrier channels; limited cleanroom grades available
PVC	Low cost; widely available; easy to process	Highest COF (0.49–0.76); plasticizer outgassing; brittle on thermal aging; fog-generating	High — NOT compatible with ISO-classified cleanrooms; primary source of molecular and particulate contamination
TPU / TPE	Good flexibility; moderate chemical resistance	Commodity formulations not cleanroom-rated; they are typical on subsystem pigtails	Medium–High—contamination risk introduced at point-of-integration via subsystem pigtails
Nanocomposite polyolefin (XLPE/PP + nanofiller)	Improved thermal stability; reduced space charge; delayed aging	Wear and particle generation during dynamic operation still under investigation	Low–Medium (projected) — long-term dynamic behavior not yet fully characterized

Table 1: Material Summary for Flexible Polymer Components — Properties, Limitations, Contamination Risk, and Typical Use [1], [5], [6], [10], [12]

Fluoropolymers (PTFE, PFA, FEP) represent the highest-performance class for cleanroom environments. Their exceptionally low COF (PTFE: 0.02–0.10), chemical inertness, and low outgassing rates make them the preferred choice for process tubing and static cleanroom wiring [12]. Under tribological contact, PTFE forms stable transfer films on mating surfaces; tribofilm stability is the primary determinant of particulate output, with stable films correlating to lower debris levels [12]. The principal limitation for dynamic applications is cold-flow creep under tight-radius bends over extended service, which can develop surface stress concentrations.Expanded PTFE (ePTFE) constructions resolve the flex-life limitation of standard fluoropolymer jackets through a node-and-fibril microstructure that redistributes bending loads over a larger effective volume. Under the same motion profiles, ePTFE jackets consistently produce lower particle counts than conventional fluoropolymer jackets, establishing them as the standard for high-duty-cycle robotic cable paths in contamination-critical applications [1].XLPE presents medium contamination risk. Its flexibility and chemical resistance make it widely used for general semiconductor wiring, but micro-crack generation under cyclic thermal loading is a documented long-term concern: thermal cycling diminishes spherulite crystallinity, and micro-cracks nucleate preferentially at spherulite boundaries, progressively reducing the surface's resistance to particle-generating fracture events [6]. Space-charge accumulation from electrical stress further accelerates this morphological degradation [10].

Polyurethane (PUR) jackets offer torsional compliance and low-torque flexibility useful for multi-axis robotic paths, but their higher COF (0.50–0.65) and susceptibility to hydrolysis in humid environments make them a moderate-to-high contamination risk in cleanrooms [5]. Unconditioned PUR surfaces exhibit stiction in carrier channels, generating snap-motion particle bursts. Cleanroom-grade PUR formulations with low-friction coatings partially mitigate this but remain unsuitable for aggressive humid environments.PVC is not compatible with ISO-classified semiconductor facilities and should be explicitly excluded from cleanroom specifications. Its high COF (0.49 static / 0.76 kinetic), plasticizer outgassing, and progressive thermal embrittlement make it the highest-contamination-risk material in common use. Plasticizer volatiles additionally fog optical surfaces in metrology, lithography, and inspection subsystems [5]. The persistence of PVC as the default jacket material for COTS subsystem pigtails represents the most consequential systemic vulnerability in current semiconductor tool supply chains.Nanocomposite polyolefin formulations (XLPE or PP with nanoclay, carbon nanotube, or metal oxide nanofiller) represent an emerging material class with improved thermal stability, reduced space-charge accumulation, and delayed aging behavior. However, the particle generation characteristics of these composites under sustained dynamic operation remain less systematically characterized and require further experimental validation before cleanroom qualification can be assigned.Table 2 below summarizes the five primary particle generation mechanisms with their dominant effects, affected components, and practical examples to aid in component-level risk assessment.

Stress Category	**Primary Effect on Polymer**	**Component Most Affected**	**Practical Example**
Mechanical wear (bending, torsion, sliding)	Surface erosion, micro-crack initiation, abrasion debris	Cable jackets in drag-chain carriers and robotic joints	Drag-chain cables in wafer-handler motion axes: reciprocating flex at <100 mm bend radius generates detectable wear particles within thousands of cycles
Thermal aging and cycling	Chain scission, embrittlement, brittle-skin formation	Polyolefin jackets near motors and heaters	XLPE cables routed within 50 mm of servo motor housings: thermal cycling above 70°C progressively reduces fracture toughness, transitioning from ductile to brittle fracture mode
Chemical and environmental exposure	Hydrolysis, oxidative chain scission, surface softening	Elastomeric jackets in process-chemical zones	EPR/EPDM cables exposed to ozone by-products near plasma-assisted etch chambers: surface oxidation embrittles the jacket, enabling particle release under moderate vibration
Electrical stress and space-charge effects	Micro-void formation, carbonized channels, dielectric cracking	Insulation near high-frequency drives and plasma sources	Motor pigtails routed alongside variable-frequency drive cabling: partial discharge at XLPE insulation surfaces forms carbonized micro-channels that fracture under subsequent flexing
Installation-induced damage	Latent micro-cracks, crazing, shear deformation	All flexible components at routing and clamping points	Cable tied at <1x minimum bend radius over a sharp bracket edge during robot arm installation: localized crazing initiates fatigue cracks that shed particles on first operational cycles

Table 2: Primary Particle-Generation Mechanisms in Flexible Polymer Components — Effects, Affected Components, and Practical Examples [1], [3]–[5]

IV. Industry Practices, Testing Methods, and Standardization Gaps

Current practice for reducing particle contamination from flexible components has evolved through vendor-specific solutions, third-party certification programs, and equipment-level test protocols. No universal qualification standard exists that covers motion-induced particle generation with prescriptive mechanical loading parameters, environmental conditions, and reporting conventions—this is the central gap that constrains the field [2], [14]. Table 3 formalizes this gap as a structured set of identified deficiencies, consequences, and requirements. It represents the primary contribution of this review, synthesizing the fragmented state of standardization into a directly actionable gap map.

Gap Identified	Consequence	Requirement to Address Gap
No unified motion-inclusive particle standard for cables	Cross-vendor results incomparable; qualification inconsistent	Standard specifying bend radius, cycle count, torsion angle, vibration, and load profile
No prescribed environmental conditions for flex tests	Temperature and humidity variability confounds results	Standard defining controlled temperature, humidity, and airflow during testing
No standardized sensor positioning or reporting format	Emission data non-transferable between laboratories	Harmonized measurement conventions and reporting templates
No tubing-specific internal flow and pressure-stress protocol	Flow-induced particulation unaddressed by mechanical standards	Dedicated protocol covering flow velocity, pressure cycle amplitude, and tubing geometry
Persistent use of non-cleanroom pigtails from subsystem vendors	Cleanroom contamination introduced at point of integration	Supply-chain requirements mandating cleanroom-qualified flexible components from subsystem suppliers

Table 3: Standardization Gaps and Requirements for Motion-Inclusive Flexible Component Qualification [14], [15]

On the engineering side, cleanroom-rated cable constructions have advanced significantly. Best-practice jacket materials are low-friction, low-outgassing, and halogen-free. Flat cable geometries, which reduce inter-cable torsion, contact area, and shear forces within carrier systems, have become the preferred format for dynamic cleanroom applications [1], [2]. Complementary carrier systems with low-friction internal liners, controlled clearances, and vibration-damping construction are available at ISO Class 1 ratings, and custom cleanroom-manufactured cables are used where the tightest contamination requirements apply [2].

Third-party motion-based testing provides the most reliable basis for comparing cable constructions under controlled conditions. Published test data consistently demonstrate that flat cleanroom cable designs produce lower particle counts than round constructions under the same motion profiles and carrier configurations [1]. For example, GORE's cleanroom cable studies, conducted using defined flex-cycle protocols with real-time particle monitoring, show particle count reductions of one to two orders of magnitude for ePTFE-jacketed flat cables versus standard round PUR cables under equivalent drag-chain duty cycles [1]. igus cleanroom carrier systems tested to ISO Class 1 conditions with internal flat cable assemblies demonstrate sustained low-emission performance across millions of cycles [2].

Despite this progress, the high sensitivity of particle results to test-rig geometry, carrier spacing, motion parameters, vibration, and ambient conditions means that results from different test programs—even when following broadly similar procedures—are not reliably comparable [14]. ISO 14644-1 (airborne cleanliness classification) and ISO 14644-14 (equipment-level emission evaluation) do not define the mechanical loading conditions required for realistic flexible component assessment [14], [15]. Equipment-level particle adder testing in accredited laboratories captures realistic cable stresses and identifies emission hot spots but operates at the tool level and cannot qualify an individual cable or tubing assembly before integration.

The most persistent systemic gap is the use of non-cleanroom pigtails on COTS subsystems. Motors, sensors, actuators, and valves are commonly supplied with permanently attached PVC, TPU, or TPE pigtails that cannot be replaced by the tool OEM without voiding the warranty. This introduces cleanroom contamination vulnerability at integration that no tool-level engineering can fully remediate—the solution requires supply-chain specifications mandating cleanroom-qualified flexible components from subsystem vendors.

Table 4 below maps the current landscape of available testing methods against their scope, mechanical loading coverage, and applicability to individual cable and tubing qualification.

Testing Method	Scope	Mechanical Loading Included	Applicability to Individual Cables/Tubing
ISO 14644-1 airborne particle classification	Room-level cleanliness verification	None	No—room classification only
ISO 14644-14 equipment-level emission assessment	Fully assembled tool evaluation	Operational stresses captured at system level	Limited—tool-level only; cannot isolate individual cable assemblies
Third-party motion-based certification (e.g., GORE, igus protocols)	Cable constructions under defined flex cycles	Bending and vibration included; carrier-specific	Yes—but results are protocol-dependent and not cross-comparable between labs
Vendor-specific flex-life and abrasion tests	Jacket durability and bend endurance	Bending and torsion	Yes—but non-standardized, limited environmental controls
Air-purge and pressure-cycle tubing tests	Internal particle burst and stabilization	Flow and pressure cycling	Yes—for tubing only; no mechanical flex component
Outgassing / TML-CVCM screening (ASTM E595)	Molecular contamination potential	None	Yes—but excludes all wear-generated particles and underestimates total contamination risk

Table 4: Current Testing Methods and Their Applicability to Flexible Component Qualification [2], [14], [15]

V. Future Research Directions

Three priority research areas would most directly advance the field toward systematic contamination reduction from flexible polymer components.

The highest-priority need is the development of a harmonized, motion-inclusive qualification standard for flexible components. Such a standard would specify prescribed mechanical loading parameters (bend radius, cycle count, torsion angle, vibration frequency and amplitude, load profile), environmental conditions (temperature, humidity, and airflow during testing), standardized particle sensor positioning relative to the component under test, and reporting conventions enabling cross-laboratory comparison. The existing SEMI standards infrastructure and ISO 14644 working groups represent appropriate venues for developing this standard, which would resolve the most consequential gap identified in Table 1.

A second priority is experimental validation of the mechanism-to-material relationships quantified in this review. Controlled studies comparing particle generation rates across material classes under representative semiconductor motion profiles—with systematic variation of temperature, humidity, and electrical stress—are needed to move material selection guidance from qualitative risk ratings to quantitative design criteria. This is particularly critical for nanocomposite polyolefin formulations, whose dynamic particle generation behavior remains less systematically characterized.

Third, metrology development is needed to address the under-detection of polymeric particles in standard optical particle counting. Detection methods calibrated for the specific refractive index, morphology, and size distribution of polymer wear debris—particularly sub-micron fluoropolymer fragments—would substantially improve the reliability of qualification data. Integration of complementary techniques such as scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS) for material identification and aerosol mass spectrometry for organic particle characterization, into standard qualification workflows would reduce systematic underestimation of contamination risk from flexible components.

Conclusion

Flexible polymer components—electrical cables and process tubing—are a less systematically characterized but practically significant source of particle contamination in semiconductor fabrication equipment. Five mechanisms drive particle generation: mechanical wear from cyclic flex motion, thermal aging near heat sources, chemical and environmental exposure in process zones, electrical stress near high-frequency drives and plasma sources, and installation-induced latent damage. Each mechanism operates on a different timescale and responds to different mitigation strategies, requiring a multi-parameter evaluation framework rather than a single-axis qualification approach.

Material selection is the most influential engineering lever. Fluoropolymer and ePTFE constructions provide the lowest contamination risk and should be the default specification for dynamic cleanroom applications. PVC is incompatible with ISO-classified environments and should be explicitly excluded, including from COTS subsystem pigtails.

The central finding of this review is the absence of a motion-inclusive qualification standard—the gap identified and formalized in Table 1. No harmonized protocol currently specifies the mechanical loading parameters, environmental conditions, and reporting conventions needed for cross-vendor, cross-laboratory comparison of flexible component particulation. This gap allows the highest-contamination-risk materials to persist in semiconductor tools through COTS subsystem pigtails, where they introduce systemic contamination vulnerability that tool-level engineering cannot fully address.

The two highest-priority actions for reducing contamination from flexible components in next-generation semiconductor equipment are (1) development of a harmonized motion-inclusive qualification standard within the SEMI or ISO 14644 framework and (2) supply-chain requirements mandating cleanroom-qualified flexible components from subsystem vendors. Together, these actions address both the measurement gap and the materials gap that currently limit systematic contamination reduction

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