



High-Viscosity Materials Integrity Challenges in Advanced Packaging

White paper

INTRODUCTION

Advanced packaging is producing yield and reliability failures that are difficult to trace and harder to correct. Devices pass inspection and electrical test, only to fail later during integration, bonding, or reliability stress. When root cause investigations are performed, process conditions often appear well tuned and stable, yet failures persist.

The issue is not the introduction of new materials, but the reduction in process tolerance. As redistribution layers, dielectrics, polymers, and bonding materials become structurally and electrically critical, small imperfections that were previously absorbed now propagate. Defect precursors introduced early in the materials lifecycle persist through processing and surface later, when corrective action is no longer possible.

This paper examines why bubble-driven defects have become persistent in advanced packaging and how materials handling influences interface integrity before interfaces are formed.

High-Viscosity Materials Flow and Defect Mechanisms

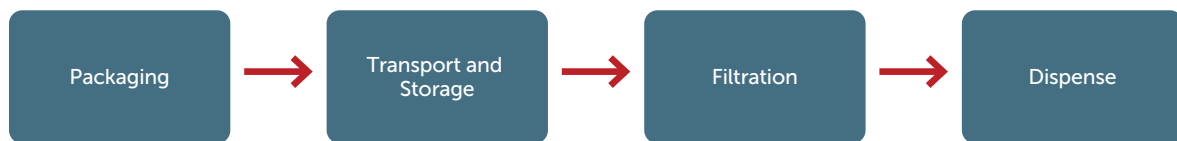


Figure 1. Gas behavior evolves across the materials lifecycle.

WHY FRONT-END AND ADVANCED PACKAGING REQUIRE DIFFERENT CONTROL PRINCIPLES

Front-end lithography evolved around low-viscosity materials where gas escape times were short relative to process times. Under these conditions, defects could often be mitigated through localized process adjustments.

Advanced packaging breaks these assumptions. Materials span from several centipoise to over 10,000 cP, films are thicker, and cure windows are tighter. Many materials now serve structural and interfacial roles rather than simply defining patterns.

Once the time required for gas to migrate through a material exceeds the time before that material immobilizes, bubbles become geometrically trapped. Downstream correction becomes ineffective, and outcomes are instead determined by upstream material conditions.

In advanced packaging, bubble-driven defects are rarely generated at a single process step. Instead, defect precursors accumulate across the materials lifecycle and are amplified as the system enters an escape-limited regime.¹

Understanding where bubbles originate, and where they can no longer be removed, requires viewing packaging, delivery, filtration, and dispense as a continuous system.

This behavior is sometimes described as bubbology, the evolution of gas within high-viscosity materials systems as a function of pressure, flow, and time.

EXPERIMENTAL EVIDENCE OF UPSTREAM ORIGIN

Experimental results demonstrate that upstream gas directly contributes to downstream defectivity. Removing gas prior to dispense significantly reduces defects under otherwise identical process conditions.²

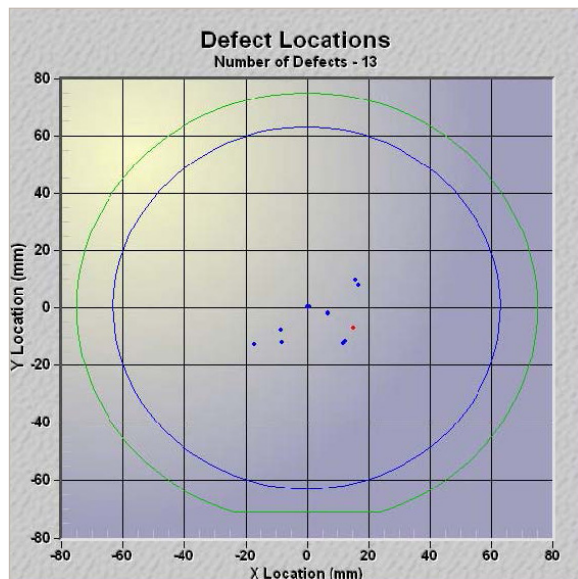


Figure 2. With 0.5 µm filter – 8% killer defect count.

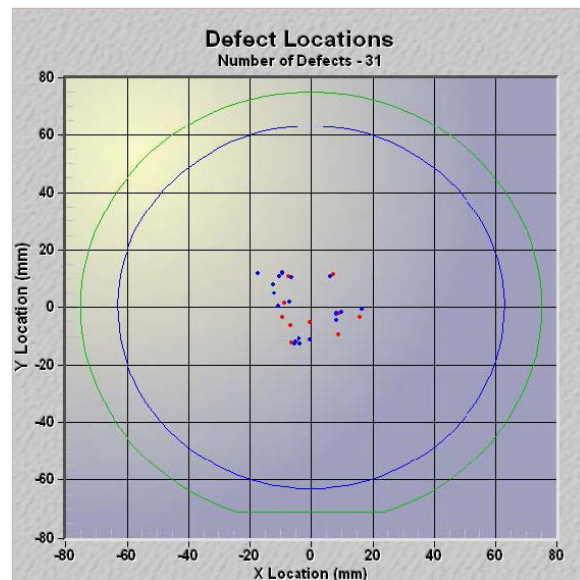


Figure 3. No filter – 32% killer defect count.

Across the materials lifecycle, gas behavior follows a consistent pattern:

- Gas is introduced during packaging and storage
- It evolves during transport and idle conditions
- It is activated under pressure and flow during processing
- It becomes embedded during coating or bonding

These defect precursors persist into the dispense phase, where their presence can be observed as deviations in flow behavior, confirming that upstream material conditions propagate directly to the point of application.¹² Once material reaches the substrate, the process enters an escape-limited regime where defects cannot be removed.³

MECHANISMS THAT DRIVE BUBBLE FORMATION AND PERSISTENCE

Packaging and Storage

Packaging establishes initial gas content and pressure history. Headspace exposure and pressure cycling promote gas dissolution and subsequent outgassing. Reducing headspace and isolating chemistry from external gas reduces bubble precursors.^{4,5}

Filtration and Delivery

Membrane architecture determines pressure drop and shear. When pressure exceeds rheological tolerance, microbubbles can nucleate at wetted interfaces. Filtration can become a defect source if not designed for high-viscosity operation.⁶

Dispense and Pressure Control

Two-stage dispense architectures decouple filtration and dispense, enabling low-pressure filtration, stable delivery conditions, and controlled pressure management within the delivery system. By stabilizing pressure downstream of filtration and applying small positive pressure during idle and ready states, gas that would otherwise nucleate or grow can remain dissolved. Experimental studies demonstrate that increasing controlled downstream pressure reduces measured particle counts and tightens distribution, indicating both lower defectivity and improved process stability under dwell and restart conditions.⁷

Pressure stability becomes a governing control parameter for managing gas behavior in high-viscosity materials systems. Internal studies using high-viscosity surrogate materials demonstrate that indirect pressurization maintains lower bubble generation over extended dispense periods compared with direct container pressurization. These results suggest that bubble formation depends not only on pressure magnitude but also on how pressure is transferred to the material, making delivery architecture an important factor in materials integrity. Decoupling filtration from dispense helps isolate filtration performance from downstream variability and reduce pressure-induced defect formation. Variations in pressure propagate directly to the dispense point, influencing valve response and flow formation and appearing as measurable deviations in pressure and flow behavior during operation.^{8,9}

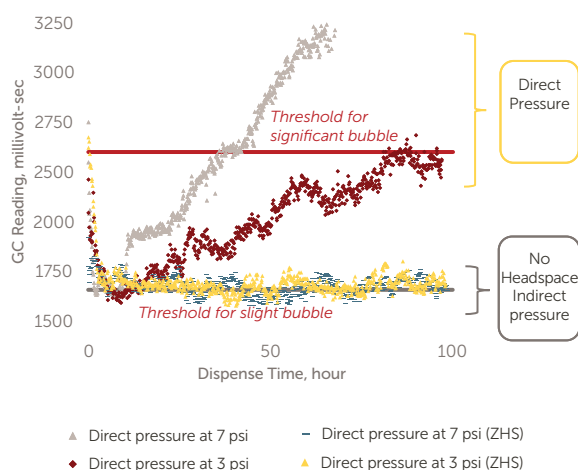


Figure 4. Measured gas chromatograph (GC) response versus dispense time for direct and no-headspace indirect pressure delivery systems.

Once material reaches the substrate, opportunities for correction collapse. Thin gaps, large coating areas, and rapid solidification prevent gas escape. Defects embedded in the material state are expressed as yield loss or latent reliability risk.

Figure 5 demonstrates that downstream processing does not remove defects introduced upstream, reinforcing the need for defect prevention prior to coating.

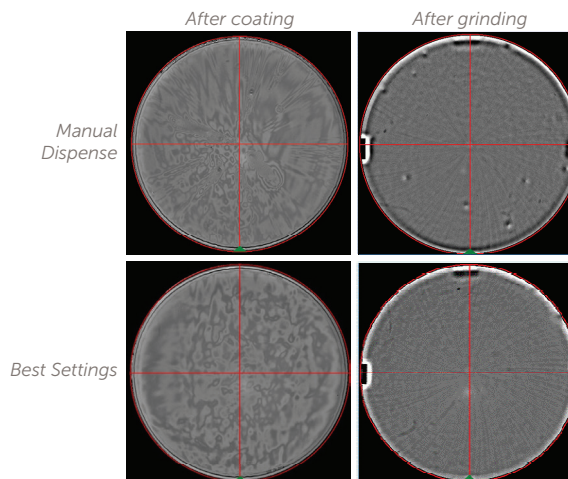


Figure 5. Wafer maps show that non-uniformities and bubble-driven defects present after coating remain visible after grinding, demonstrating that defects are not corrected by subsequent processes.

MONITORING, DETECTION LIMITS, AND SYSTEM OBSERVABILITY

While upstream control determines material integrity, process engineers rely on monitoring to verify system behavior. In high-viscosity systems, however, observability is inherently limited.

Gas present during dispense alters flow behavior in measurable ways. Flow-based sensing demonstrates that bubbles passing through the system distort the flow rate profile relative to a reference dispense. Even small gas volumes can produce measurable deviations, confirming that bubble populations established upstream persist into the dispense phase and directly influence fluid delivery conditions.

Size of Detectable Bubble by Various Confirmation Tools

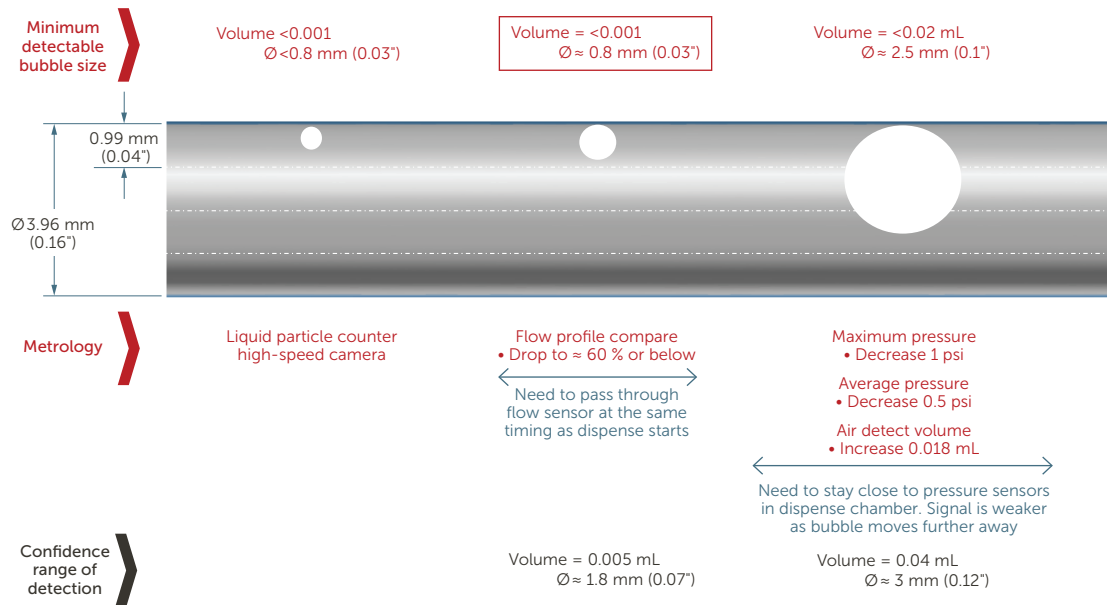


Figure 6. Diagram comparing size of bubbles that are detected by a liquid particle counter (left).

This disparity implies that defect-relevant bubbles may remain undetected during operation. Monitoring provides visibility into system behavior, but not

completeness. Defect-relevant bubbles may remain undetected, making prevention more reliable than detection after formation.

Control Points for High-Viscosity Gas Management

Effective defect prevention requires coordinated control across the materials lifecycle:

Packaging and Storage - Minimize headspace - Isolate chemistry from external gases - Manage pressure exposure during transport	Filtration and Delivery - Match membrane design to material rheology - Avoid excessive pressure drop - Maintain stable flow conditions
Dispense and Pressure - Decouple filtration and dispense - Maintain stable downstream pressure - Apply controlled positive pressure during idle states	System Operation - Standardize dwell and restart conditions - Reduce variability across lots

The most effective reductions in defectivity come from pressure stability and reduced dwell-induced variability upstream of coating. Systems that maintain stable pressure and isolate filtration from dispense consistently improve defect performance without requiring changes to materials or process recipes.

In many implementations, these parameters are adjusted within the constraints of single stage delivery systems, where filtration, dispense, and pressure response are inherently coupled. Under these conditions, pressure fluctuations and dwell related variability cannot be fully eliminated, and defect precursors remain sensitive to system dynamics.

By contrast, systems that decouple filtration from dispense and actively manage downstream pressure state allow these variables to be controlled independently, reducing sensitivity to dwell conditions and stabilizing the material state prior to coating.

In practice, this results in lower defectivity variation across lots and more consistent performance under restart and extended idle conditions, where conventional systems often exhibit drift. These behaviors are typically observed as increased defect variability following idle periods, sensitivity to restart conditions, and gradual drift in process performance over extended runs.

DEFECT MECHANISMS ENABLED BY BUBBLE PRECURSORS

These defects often escape inline inspection and appear during reliability stress or field operation. During coating, entrained gas disrupts flow uniformity, creating localized thickness variation and flow instabilities that can result in microbridging or incomplete coverage in pattern-defining materials.

Microbubbles enable multiple downstream defects:

- Voids and delamination under thermal stress
- Microbridging from flow disruption
- Adhesion loss and dielectric breakdown

These defects ultimately originate from the disruption of interfacial continuity during coating and cure and often escape inline inspection and appear during reliability stress or field operation. Sensitivity to bubble-driven defectivity is concentrated in material systems where continuity, uniformity, and interfacial integrity are critical.

- Pattern-defining materials
- Large-area dielectrics
- Stress-mitigating polymers
- Structural and bonding materials

Across all categories, once escape is no longer possible, prevention must occur upstream.

YIELD STABILITY AND RELIABILITY ARE THE SAME PROBLEM

Yield loss and field failures increasingly share the same origin: material states established upstream that propagate through the process and are expressed differently depending on when they are observed. Bubbles that escape detection during coating can persist as voids, adhesion defects, or electrical discontinuities that only appear under thermal or mechanical stress. Removing these defect precursors before dispense therefore improves both immediate yield and long term reliability outcomes.

Effective control requires coordination across packaging, filtration, and dispense systems rather than optimization of individual steps. This dual expression explains why processes that appear stable during inline inspection can still produce downstream reliability failures.

CONCLUSION

High-viscosity materials place advanced packaging in an escape-limited regime where gas introduced upstream cannot be removed once coating begins. Under these conditions, defects are not created during coating but are instead inherited from earlier stages of the materials lifecycle and embedded during application.

Process engineers often rely on monitoring to assess system stability, but detection capability remains limited relative to the full distribution of defect-relevant bubbles. As a result, process outcomes are governed by the material state entering the dispense step rather than by downstream correction or inspection.

This dependency on upstream material state reflects the same pattern observed throughout the process: once escape pathways are restricted, defects can no longer be removed and must be prevented before coating. Effective control therefore requires establishing materials integrity upstream by managing pressure, filtration, and material handling as a coordinated system that preserves interface integrity before coating and minimizes defect precursors prior to application.

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