Distribution of Combustion Particles in Buildings

In this first installment of a multipart series of guidelines on the investigation of fire and smoke damage claims, the authors examine "sudden and accidental" combustion particle distribution.

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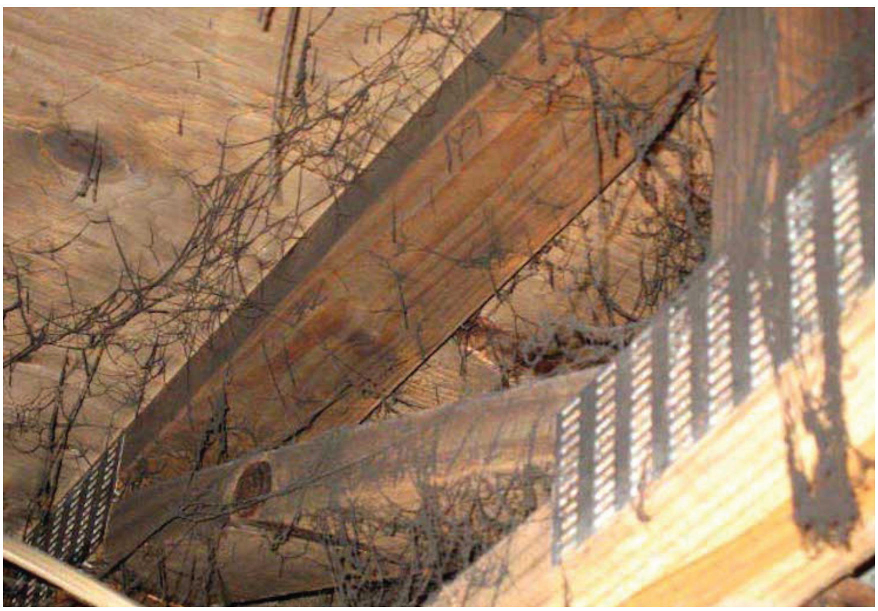

Despite the interests of building owners and occupants, it is generally acknowledged that the availability of insurance funds often determines the nature of repairs, or whether repairs occur at all. Since property insurance policies commonly deny coverage for pre-existing or ongoing conditions, a high priority may attach to distinguishing a "sudden and accidental" occurrence from ongoing effects. Authoritative studies have not addressed this question. Hygienists and laboratories are concerned with the nature and source of pollutants as they currently exist. There appears to be little need to explore the sequential aspect of particle deposition.

The experience-based world of damage repair has coined terms such as *ghosting, filtration stains, nail pops,* and *smoke webs* to describe some patterns of settled combustion particles, neglecting the fact that identical mechanisms may characterize the behavior of domestic dust. This paper will attempt to analyze the pathways and deposit patterns of particles in buildings as they relate to domestic dust and combustion particles from fire events.

Temperature/Pressure

Building surfaces are heated and cooled by a variety of external and internal sources, some continuing, others fluctuating or seasonal. In general, building design seeks to minimize external influences in order to maintain a uniform and comfortable interior environment. However, temperature variation between surfaces is unavoidable. External temperatures may pressurize or depressurize attics and exterior walls. Fenestration and insulation add local temperature variations. Ventilation systems impose their own pathways.

Air molecules are energized by heat, which increases their kinetic pressure, and with fewer molecules occupying a given volume of air, warmer air rises and moves towards areas of lower energy. Greater energy also increases the ability of warmer air to carry particles. In this context, cool and warm are relative terms independent of specific temperatures.

Particle settling and accumulation involves general principles of air movement. For the purposes of this analysis, particles are defined as solid materials of a mass capable of being conveyed by air moving at relatively low velocity. The distance that airborne particles travel is inverse to their mass and proportional to their velocity. Mass in this case relates roughly to size, with the result that larger/heaver particles tend to settle out of an airstream earlier than smaller/lighter particles. As warmer air becomes diluted with cooler air, it becomes less able to carry particles, which progressively deposit as air movement slows. Minute particles (<100 nanometer) may stay airborne for extended periods of time, limited by air movement and the tendency to agglomerate. Differences in surface temperature may induce a selective accumulation of particles on cooler surfaces.

Particles

Dust

Particles are always present in air. Within buildings, airborne particles comprise an array of substances generated by materials and activities within the building as well as from exterior sources. The agglomeration of airborne particles into larger particles comprises the general category we call *dust.* Typical components of interior dust are granular particles, fiberglass fragments, textile fibers, hair, gypsum particles, epithelial (skin) tissue, plant spores, and insect fragments. Combustion particles also appear in domestic dust. Normally the individual components of dust are not separately visible, but an overwhelming presence of a single material such as sawdust or drywall debris may be visibly dominant after remodeling or refinishing. Absent such concentrations, the normal coloration of dust is grey. As dust accumulates it obscures underlying surfaces, and with sufficient time forms an opaque grey coating. Major dust components can be identified with standard reflected light microscopes at 100× – 200× magnification.

Particles and their relative interaction with surfaces are dynamic in an occupied environment. There are several forces and principles which govern particle movement, suspension and resuspension. Dust particles travel on normal convection currents and tend to deposit wherever an airstream meets obstructions, is deflected or slowed. An example of this is the downward flow of air adjacent a cold exterior wall or window. As the cooled falling air is deflected at floor level, some of the entrained particles settle out. The accumulation may become visible, since convection currents of this type tend to continue as long as the temperature differential exists. Gaps in the building envelope are often highlighted by an accumulation of dust particles filtered from air leaking through and around insulation. These dust filtration marks may be mistaken for smoke stains, especially when discovered after a fire event.

Dust particles exhibit polarity, the presence of discrete opposing electrical charges. Since opposite charges attract, dust particles tend to link together in chains, particularly where air is still. Often mistaken for spider webs (cobwebs), dust webs and strands may reach a foot or more in length. Polarity also explains the attraction of ionized dust to television and computer screens, whose polarity is inherent in their function.

Combustion Particles

Smoke is the visible airborne product of combustion, and consists of particles, liquids, aerosols and gasses, some of which condense as solids. As noted previously, combustion particles are a typical component of dust, generated by cooking, heating, smoking, fireplaces and external sources. Uncontrolled fires often generate concentrations of smoke particles sufficient to affect the appearance and utility of building surfaces and contents. Heavy smoke deposition is evident as a dark coating, often accompanied by a characteristic pungent odor. Depending on the fuel and fire temperature, combustion residues may be corrosive or exhibit other unwelcome chemical effects.

Settled combustion particles are called *char particles* and range in size from 1µ (.001 mm) to >500µ (.5 mm). The quantity, character and size of char particles vary with the fuel, term, and temperature of combustion. Char particles contain unburned fuel fragments, carbon, tars, resins and other substances. Very fine particles < 1µ (e.g. carbon), may be present in sufficient quantity to darken a test wipe.

The heat of combustion produces ionized particles, which, like dust, readily link together in chains and webs. For the same reason, settled combustion particles tend to bond preferentially with plastics, synthetic fibers and polymer-based coatings.

Rapid vs. Slow Combustion

Blazing fires produce particles distinctly different from those emitted by smoldering fires. Blazing fires are oxygen-rich and burn vigorously. Cellulosic fuels are more completely consumed (oxidized) and their particles tend to be small. Propelled by high heat, smoke rises swiftly and follows a visible path.

In contrast to rapid combustion, smoldering fires tend to be oxygen-deficient and burn at lower temperatures. As a result they consume fuel less completely, often smoldering for long periods before breaking out as full combustion. Particles from smoldering fires tend to be more ionized, viscous and malodorous than the products of blazing fires. Because they are not driven by high heat, particles from smoldering fires tend to travel on normal air currents. Moving slowly, they permeate a wider area and find their way into crevices and cavities bypassed by more turbulent smoke. It should be noted that blazing fires can pass through a smoldering phase, so the characteristic residues of both may be present. After active ignition ceases, air currents gradually return to their normal patterns, distributing entrained particles as they go.

Odors Smoke odors are usually thought objectionable, sometimes extremely so. However, the perception of odor is an individual experience: the character and intensity of an odor cannot be objectively characterized. Char particles are often the source of smoke odors, and the odor potency appears to increase with particle quantity. Smoke odor is not always related to visible particles: the slow combustion of proteinaceous matter may emit no visible residue but affected surfaces often emit an obnoxious and persistent odor. The absence of discernible odor in dust provides a clear distinction from smoke particles and may explain the greater toleration that dust enjoys, compared to the urgency of locating and removing malodorous smoke particles.

Furnace Soot A distinction exists between the products of active fires and furnace soot. Furnace soot is the product of a controlled combustion system (the furnace) that fails to adequately burn its fuel. Soot accumulation in the fire box increasingly disrupts the flow of combustion air. A sudden ignition may result in a mini-explosion popularly termed a *puff-back*. Forced-air systems distribute the dislodged soot along with the heated air. If air ducts are not present (such as in steam or hot water systems) the soot is broadcast from the furnace and the accumulation can be tracked to that area. Lacking propulsion from heat, furnace soot is conveyed by normal air currents, its path marked by visible accumulations of dark particles. Like dust, furnace soot does not emit the smoky odors associated with the products of accidental combustion.

Candle smoke Candles are used in residences for visual effect and for their scent. Commonly employed at formal dinners, they are also used for ceremonial purposes and are often displayed unlit for their aroma. Candles may be housed in glass cylinders or vases, with scented varieties reaching two or more inches in diameter. Aroma-producing devices may plug into wall receptacles and vaporize perfumed oils. So-called "smokeless" candles have been found to create visible combustion particles when ignited. The quantity of particles produced by candles varies from areas of severe darkening to faint deposits on lift samples. Candle emissions tend to accumulate near their source, minute particles often clustering at ceiling/wall angles.

External sources Externally produced combustion particles can infiltrate buildings in significant quantities. Wildfire smoke is a common example. Wildfire particles tend to accumulate on exterior surfaces and at building penetrations, and may include wind-borne granular materials from the fire area. Within the structure, infiltrated particles respond to normal air flow.

Particle Distribution

Ventilation systems Air ducts are conveyers of particles as well as targets for particle settlement. Ventilation systems create their own distribution patterns of heated or cooled air. Even when a system is dormant, ducts may transport air by convection. The temperature difference between ducts and ambient air may cause particles to accumulate on both the interior and exterior of ductwork. After a fire, settled combustion particles may become re-entrained by air movement and continue to distribute via the ventilation system. Particulates collected by filters and blowers can provide a snapshot of particle identity and concentration.

Open and Enclosed Spaces

Particle deposition in building interiors is moderated by the differing characteristics of open and enclosed spaces. Open spaces consist of rooms and areas that are accessible, visible, and directly served by the building's ventilation system. Enclosed spaces are the cavities within partitions, walls, ceilings, chases and soffits. These voids are sometimes referred to as *interstitial spaces.*

Not subject to the temperature variations and air currents that characterize habitable areas, air within enclosed spaces is relatively still and its ability to retain particles substantially diminished. Air that is able to infiltrate loses entrained particles, resulting in long-term dust accumulations that are commonly found in enclosed spaces. Combustion products sometimes find avenues into enclosed spaces and may generate lingering smoke odors.

Interstitial spaces Building architects sometimes design intermediate spaces between floors to house HVAC units, communications equipment, electric cables and other utilities designed to serve a specific floor. Called interstitial spaces, these cavities commonly have concrete floors with lowered ceilings and may extend over a full floor or a portion of it. Large buildings may have alternating interstitial floors, constructed to free the functional space from penetrations and chases that might inhibit modification or redesign.

An interstitial area acts as an enclosed space. Even though floor and ceiling penetrations are intended to be sealed, dust and combustion particles find their way in. During a fire, smoke particles may deposit on the tangle of electronic cables and hardware, raising problems of corrosion and odor.

Deposit Patterns

The physics of combustion, air currents and particle transport often produce characteristic deposit patterns. While many patterns are shared by dust and combustion particles, after a fire or furnace mal-

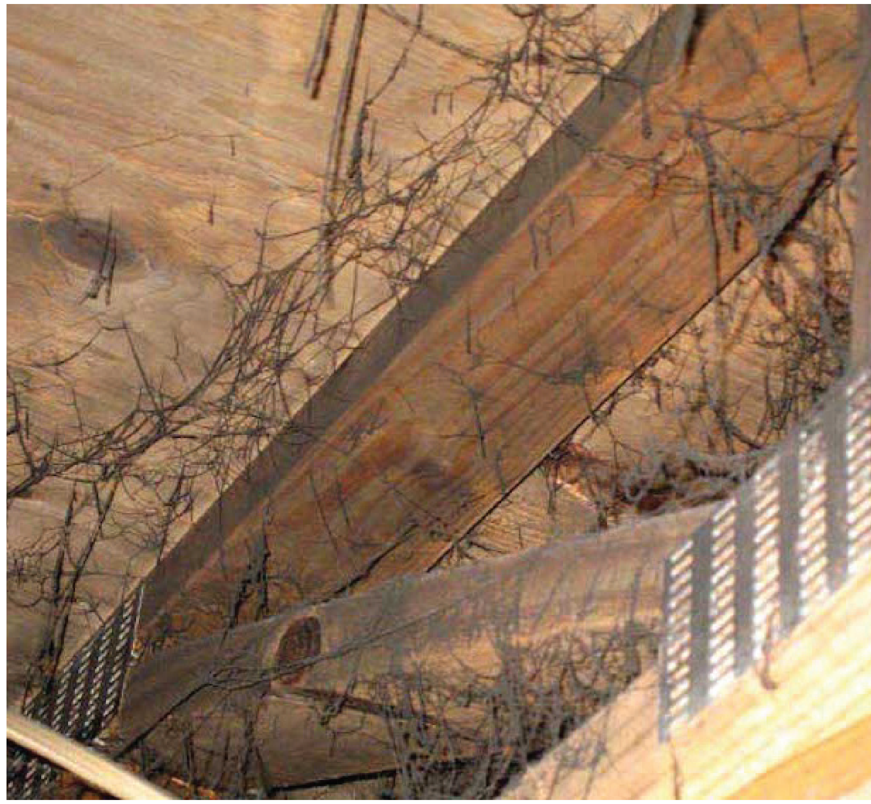

Figure 1. Smoke webs and chains

function the high contrast of combustion particles tends to attract immediate attention. Some typical patterns of particle settlement are listed below:

Smoke webs and smoke chains (Figure 1) These are sometimes mistaken for existing cobwebs that have attracted smoke particles. Actually the strands consist entirely of linked combustion particles. A source of the confusion may be the tendency of both smoke-webs and dust-webs to form in areas of still air, such as wall/ceiling corners. Smoke-webs do not require pre-existing dust webs for support.

Ghosting (Figures 2 and 3) This is a term applied to the shadowy outlining of electrical outlets and wall-hung graphics that often appears after fires. The air behind a wall-mounted artwork is still. As

Figure 2. Ghosting of electrical outlet

Figure 3. Ghosting of smoke detector

Figure 4. Nail pop

warmer smoke-laden air approaches the perimeter and slows, graduated shading reflects the release of particles. A similar mechanism may appear as vertical stripes on exterior walls when studs provide a thermal bridge between the exterior sheathing and interior drywall. Junction boxes displace insulation when installed within exterior walls, resulting in a colder surface around wall outlets and a typical deposit pattern of combustion particles.

Nail pop (Figure 4) This describes an optical illusion created by ionized particles attracted to metal nails hidden beneath the joint compound of drywall. The graduated particle accumulation suggests a protruding nail head, which disappears with cleaning. Painted drywall ceilings are especially prone to this effect.

Filtration marks (Figures 5 and 6) This describes dark streaks or splotches on the surface of insulation and dark lines on carpets. In both cases the discoloration consists of particles filtered from air in response to a pressure differential. The same mechanism may produce a dark horizontal shadow above a baseboard heater. These discolorations are not necessarily caused by a smoke incursion, since accumulated dust can develop considerable opacity. Negative pressure at a lower floor sometimes creates streaks on carpeting that mirrors the outline of subfloor joints. These accumulations reflect ongoing air flow, but often leap into prominence after a fire or furnace puff-back.

Threshold streaks These are filtration marks that appear in carpeting at an entry door. A pressure imbalance sometimes arises when remote supply vents do not adequately feed a central air return, creating a zone of negative pressure. The constricted air passage permits carpeting to filter particles from the air stream, creating a visible streak. The same mechanism may lead to filtration lines in carpeting along baseboards.

Selective deposition This describes the variable attraction of dust and combustion particles to specific surfaces. The selectivity may be a response to transient differences in temperature (see ghosting, above) or inherent differences in polarity. The latter explains smoke particles adhering to vinyl and acrylic paint more readily than to oil paint. A chair upholstered in nylon will attract more particles than an identical chair covered in cotton fabric, and will retain the particles more tenaciously. Dust exhibits the same response, as attested by its accumulation on computer monitors and TV screens.

Geometry of Interior Spaces

An accurate assessment of smoke impact requires sufficient knowledge of construction to anticipate the affect of airborne combustion particles on building components. This is especially important when combustion particles are corrosive or emit strong odors. For example, a failure to recognize the potential of a suspended ceiling to hide corrosive particles may have a substantial impact on vulnerable metals. Weeks of shutdown have been spent searching for the source of a strong smoke odor whose location was fairly predictable, based on the physics of building layout and air movement.

Ceilings Ceilings may form a continuous unbroken surface or employ modular elements such as acoustic panels and supporting tracks. In residences and many

Figure 5. Filtration marks on insulation

Figure 6. Filtration marks on carpet

commercial buildings, the ceiling is directly affixed to solid joists or rafters, creating discrete channels blocked at the ends. Horizontal chases and lighting fixtures may interrupt the exposed ceiling as well as the enclosed air space.

Commercial construction often employs web joists over suspended ceilings to form an open cavity that houses air ducts, light fixtures, wiring and other utilities. The ceiling cavity itself may serve as a return air plenum. Thus, ceiling cavities may be open, filled or partially filled with insulation and utilities. Some ceilings permit air movement while others retard it.

The presence of ceilings as barriers to rising air currents renders them vulnerable to incursions of smoke as well as dust. The still air over a suspended ceiling often attracts heat driven smoke particles and is often a primary focus of post-fire inspections. When a ceiling is breached by fire, the tracking of smoke and settled particles becomes more pressing because of potential corrosion and remote odor sites.

Exterior Walls In traditional frame construction, exterior walls consist of uniformly spaced studs separated by fire stops and horizontal framing. Studs may be solid wood, or preshaped metal. The latter will be affixed to metal channels. Metal studs allow air movement by virtue of precut openings for wiring. The exterior wall surface is usually enclosed by some form of sheathing. The vertical pockets between studs are filled with insulation. The assembly is covered with an interior finish, usually drywall, paneling, or in older homes, plaster. The sole and top plates have penetrations for wiring and plumbing lines that may form channels for airflow.

Solid masonry or concrete walls often employ metal studs or horizontal furring for drywall. Both provide air space between the masonry and the interior finish if not filled with insulation.

Masonry veneer construction introduces an inaccessible drainage plane (air space) between the sheathing and masonry. Sheathing for masonry veneer walls is usually attached to traditional stud framing. If fire breaches the sheathing, the combustion particles between the masonry and sheathing cannot be accessed directly. Insulation above and below windows (and often other areas) is sometimes casually installed and subject to air seepage and resultant filtration stains. These dust accumulations are sometimes interpreted as evidence of infiltrated smoke.

Partitions Partitions are essentially closed boxes. Occasional penetrations may be cut for electrical outlets or switches, and in top or bottom plates for wiring. Studs may be drilled to permit a horizontal run of electric cable. Metal studs have spaced perforations that permit airflow between stud pockets. However, the absence of connections to other assemblies tends to restrict air circulation within partitions.

Chases and soffits Chases are finished enclosures designed to house plumbing, electrical or other utilities. Horizontal chases often enclose air ducts. Vertical chases most often enclose plumbing and electrical lines. Kitchens and bathrooms are often stacked vertically, connected by chases or wider chase walls. Ceiling penetrations may allow convection currents to carry particles to higher floors. The interior dynamics of a chase may depend on the system it houses. For example, the air surrounding HVAC ducts may be warmer or cooler than the ambient air. During a smoke incident, positive or negative pressure within a chase can determine if it attracts particle accumulation. After a kitchen fire, substantial combustion products and odors are often encountered in an upper bath.

Soffits cover structural voids and irregularities for cosmetic reasons. Soffits over kitchen cabinets are a common example, and may be open to wall and ceiling cavities, a factor in their ability to convey combustion particles.

Stairs Soffits covering the underside of stairs are both repositories and conveyers of smoke, often connecting the ceilings of adjacent levels. Stair soffits are vulnerable to heat-driven smoke particles and odor because of the stack effect and the fact that stair carriages may be inaccessible to treatment when adjacent a wall. Tread mortises may be loosely-fitted, providing voids for particle deposit. For these reasons, stair assemblies tend to retain combustion particles and odors.

Attics In residential construction attics are usually vented at gable ends, eaves, or both. The vents supply a continuing flow of exterior air which deposits an array of particles on exposed framing and insulation. Attic particles may contain combustion particles from chimney smoke and automotive exhausts, in addition to other external fire products. As a result, attics are not reliable indicators of interior combustion damage unless smoke odor is present or interior paths clearly exist. When attics are directly involved in a fire, the unfinished framing is able to absorb combustion products, amplified by the inaccessible corners and minimal headroom that usually exists at the eaves. Opening ceiling access from below is one way to reach these areas.

Bathrooms Cold ceramic tile and porcelain finishes make bathrooms conspicuous targets for combustion products. The condensation of combustion vapors may cause permanent stains. Chase walls for plumbing may facilitate smoke distribution between floors. The space surrounding bathtubs is a frequent repository of particles and odor, with Jacuzzi equipment especially vulnerable. Use of hot showers or baths may activate smoke odors long after repairs have been completed.

Kitchens Since fires often originate in stoves and ovens, the spaces behind and between cabinets become candidates for accumulating and transmitting combustion products. This normally unobstructed space may also serve as a route to a soffit or ceiling cavity. Access to this area via the soffit or ceiling may be less disruptive than cabinet removal. Treating smoke odors may be impeded by the absence of visible fire residues after so-called *protein fires*.

Fireplaces and chimneys While sharing the general characteristics of chases and soffits, fireplace surrounds and chimney chases may be independent sources of combustion particles and smoke odors. Clearance requirements create vertical cavities around chimneys that may permit downdrafts and carry odors into the living space. Faulty or aging flue sections often have cracks or voids that permit combustion products to escape and coat interior walls of the chase. Such on-going smoke odors may be mistakenly blamed on fire damage elsewhere in the building.

Ambiguous deposits The scrutiny that follows a smoke incursion may reveal dust accumulations that are mistakenly perceived to be new. Despite evidence to the contrary, the error sometimes hardens into certainty. Areas susceptible to misinterpretation include:

- *Recessed light fixtures.* These are frequently surrounded by insulation which filters particles from the convection currents generated by the fixture's heat. A dark ring on insulation surrounding the fixture is an ongoing condition unrelated to a single incursion of smoke.
- *Hanging fixtures and Chandeliers.* The convection currents created by a fixture's heat tend to deposit dust particles at any deflection or interruption to the vertical flow of air. Thus, the canopy, junction box and adjacent ceiling tend to accumulate visible dust. The plastic or cardboard "candles" that enclose the bulb sockets on chandeliers often display a noticeable buildup of dust particles. Electrostatic attraction may play a role in this accumulation. When located over a table where candles are burned, the prisms and arms of a chandelier may collect combustion particles as well as dust.
- *Ceiling fans.* The blades of circulating fans create a zone of negative pressure above the blades. As a result, the upper surfaces of revolving fan blades tend to accumulate dust, and cannot serve as accurate indicators of combustion products. Insulation around ceiling exhaust fans often displays smoke-like streaks from induced air currents.
- *Electronics.* Since opposing polarities attract, audio speakers, computer monitors, television screens, and many other electronic devices tend to attract particles by virtue of their opposing static charges. In computers, the power supply tends to attract more particles than other components and may provide a quick estimate of particle concentration.

Dust or smoke?

For insurance, the distinction may be critical: a "sudden and accidental" loss may be covered, while an ongoing accumulation of particles is not. Since dust and smoke particles respond to the same forces, the distinction between them is not always clear. Long-term dust accumulations may approach the opacity of combustion particles.

Tracking settled particles to a source is based on the principle that particle accumulation is greatest near the point of origin. A trail of progressive intensity (or its absence) may indicate a source. Examples of this are the typical deposit patterns of tobacco smoke and fire place emissions. However, a layer of combustion particles will be significant no matter how dense the underlying dust may be, and the sudden appearance of a smoke odor tends to resolve identity questions. Microscopic analysis of lift samples offers a swift and inexpensive way to distinguish settled combustion particles from normal dust components.

Damage

Particles may be chemically described, weighed, measured and counted, but the existence of damage is a subjective judgment. The authors are aware of no generally accepted standard that relates the presence of combustion particles to damage. There has been no attempt in this paper to address the issue.

Conclusion

Since dust particles and combustion products are often similar in their distribution patterns, identification may hinge on their relative intensities. A problem sometimes arises when combustion particles are not readily visible or have penetrated enclosed areas. Unlike dust, combustion particles may corrode metals and generate odors. For these reasons, analysis of likely collection sites is more than an academic exercise. Combining knowledge of buildings with the principles of particle distribution can provide a logical basis for investigating hidden odors and distinguishing settled combustion residues from dust.

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